Cloud Computing and Data Science
http://ojs.wiserpub.com/index.php/CCDS/

Review

A Review on GNSS-Threat Detection and Mitigation Techniques

Omid Sharifi-Tehrani*, Mohammad Hadi Ghasemi

Department of Electrical and Communication Engineering, Imam Hossein Comprehensive University, Tehran, Iran
E-mail: omidsht@gmail.com

Received: 08 July 2022; **Revised:** 16 September 2022; **Accepted:** 09 October 2022

Abstract: Global navigation satellite systems (GNSS) have played an important role in commercial, military and industrial navigation as well as cloud computing, Geospatial analysis and digital modeling. Nowadays, with the advancement of science and technology, the capabilities of electronic warfare, including signal jamming, interference, and spoofing, have also advanced. Attacks and threats at simple, intermediate and advanced levels, endanger the security and reliability of GNSS in the commercial, industrial and military fields such as geolocation, geospatial techniques and digital twins. Therefore, coping with this problem and challenge is very important in maintaining security and reliability. At present, various methods and algorithms have been designed and utilized based on statistical properties, moving receiver, artificial array, wavelet transform and etc., each of which has advantages, disadvantages and blind spots. In this paper, the necessity and requirements for dealing with GNSS threats are emphasized, and the most important researches in the field of GNSS threat (jamming/interference/spoofing) detection and mitigation are studied and reviewed. Their advantages and disadvantages are discussed, and improving areas are also proposed.

***Keywords*:** GNSS, jamming, spoofing, detection, mitigation, geospatial analysis

Abbreviations

GNSS	Global Navigation Satellite Systems
PRN	Pseudo-Random Noise
RF	Radio Frequency
EW	Electronic Warfare
EA	Electronic Attack
EP	Electronic Protection
ES	Electronic Support
AoA	Angle of Arrival
LOS	Line of Sight
DLL	Delay Locked Loop
PLL	Phase Locked Loop
SQM	Signal Quality Monitoring
WVD	Wigner-Ville Distribution
SVN	Support Vector Machine

DOI: https://doi.org/10.37256/ccds.4220231678

CNN	Convolutional Neural Network
RMT	Random Matrix Theory
MP	Marcenko-Pastur
FOS	Fast Orthogonal Search
INC	Interference-Plus-Noise Covariance
IAA	Iterative Adaptive Approach
PMU	Phasor Measure Unit
GIS	Geographic Information System
GCP	Ground Control Points
DEM	Digital Elevation Models
RTK	Real-Time Kinematic
CW	Continuous Wave
IMU	Inertial Measurement Unit
RFI	Radio Frequency Interference
STFT	Short-Time Fourier Transform
RSPWVD	Reassigned Smoothed Wigner-Ville Distribution
NMLCB	No main-lobe and multi virtual null constraints
UAV	Unmanned Aerial Vehicle
MDDR	Minimum Dispersion Distortionless Response
KLT	Karhunen-Loeve transform
TKLT	Toeplitz KLT
CKLT	Covariance KLT
TACAN	Tactical Air Navigation
DME	Distance Measure Equipment
WPT	Wavelet Packet Transform
FFT	Fast Fourier Transform
BAM	Bordered Autocorrelation Method
STAP	Space-Time Adaptive Processing
MVDR	Minimum Variance Distortionless Response
ISDP-RAB	Iterative Semidefinite Programming-based Robust Adaptive Beamforming
IL-RAB	Iterative Linearization-based Robust Adaptive Beamforming

1. Introduction

Apart from the increasing demand for accurate and reliable services for GNSS in different applications such as navigation aids, PMUs, cloud computing, geospatial techniques/analysis, mapping, digital modeling and etc., one of the main disadvantages of GNSS is their vulnerability to interference, jamming and spoofing. In general, jamming and interference signals reduce the signal to the noise of the received satellite signals in such a way that the receiver may no longer be able to measure the correct values of pseudo-distances and carrier phases. Therefore, even risk with low power can easily result in the denial and neglect of GNSS services within a radius of a few kilometers. In general, jamming and interference can be detected and mitigated by applying time or frequency domain processing, as well as a combination of them. Methods to detect and mitigate time/frequency narrowband interference have been studied [1]. Performance degrades when dealing with broadband interference or rapid changes in the center frequency of interference/jamming signal. Techniques using antenna arrays can automatically and efficiently act against wide and narrow band threats [2]. Rapid advances in antenna technology and electronic systems are leading to antenna array-based solutions to further increase the performance of GNSS receivers. Timing and positioning systems such as GPS and GLONASS are widely used and common. Many mobile phones and vehicles are equipped with GNSS systems. GNSS applications include safety, animal and vehicle tracking, land, sea and air transportation, criminal treatment services, rescue and police, time synchronization, mapping, power grids, space applications, agriculture and many other applications.

GNSS also plays an important role in GIS, modeling, geospatial technologies, geomatics, and digital twins [3-5].

The components of geospatial technology (including GNSS) are depicted in Figure 1.

In [6], a spatial data management methodology to focus on enabling free access and viewing interesting data in real time for supporting emergency managers is proposed. In [7], two dense point clouds, extracted from the same spatial data center, were compared to analyze the discrepancies outputted from two different relative orientations: the first is according to the UAV frame GPS position and the second is according to the GCPs, measured through GNSS positioning. In [8], rapid mapping systems for GIS-based detection of terraced landscape heritage using regional DEMs and UAV data are described.

In [9], web-based sensors and geoprocessing services utilizing GNSS are studied. In [10], a monitoring system based on a couple of non-expensive GNSS receivers is utilized and evaluated in the field. In [11], by utilization of the combined synthetic-aperture-radar data, integrated GPS/GNSS data and UAVs aerial images, an integrated ground deformation monitoring vision is developed and tested in the field. In [12], outcomes of comparing four-UAV performances, are evaluated in terms of photogrammetric quality. The quality was verified by comparing the ground targets' coordinates extracted from the point clouds to the measured ones on the field with indirect geo-referencing utilizing GNSS. In [13], the quality of altimetry surveys with GNSS RTK receiver aboard an all-terrain vehicle is evaluated.

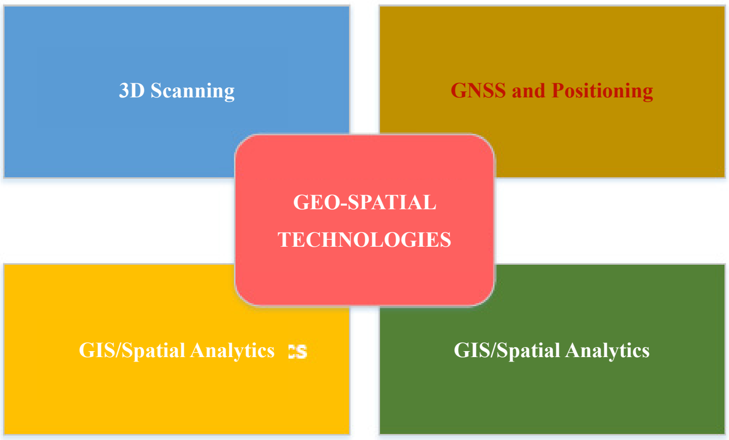

Figure 1. Components of geospatial technology (including GNSS)

In [6], a spatial data management methodology to focus on enabling free access and viewing interesting data in real time for supporting emergency managers is proposed. In [7], two dense point clouds, extracted from the same spatial data center, were compared to analyze the discrepancies outputted from two different relative orientations: the first is according to the UAV frame GPS position and the second is according to the GCPs, measured through GNSS positioning. In [8], rapid mapping systems for GIS-based detection of terraced landscape heritage using regional DEMs and UAV data are described.

In [9], web-based sensors and geoprocessing services utilizing GNSS are studied. In [10], a monitoring system based on a couple of non-expensive GNSS receivers is utilized and evaluated in the field. In [11], by utilization of the combined synthetic-aperture-radar data, integrated GPS/GNSS data and UAVs aerial images, an integrated ground deformation monitoring vision is developed and tested in the field. In [12], outcomes of comparing four-UAV performances, are evaluated in terms of photogrammetric quality. The quality was verified by comparing the ground targets' coordinates extracted from the point clouds to the measured ones on the field with indirect geo-referencing utilizing GNSS. In [13], the quality of altimetry surveys with GNSS RTK receiver aboard an all-terrain vehicle is evaluated.

The analysis of displacement monitoring according to the earth-filled flood embankment utilizing surveying and radar measurements approaches, is concerned in [14]. Reference [15], discusses how the positioning and location strategies can affect the true estimation of coordinates and tropospheric parameters. The UAV state-of-the-art related to Geomatics applications, providing an overview of different UAV applications, platforms, and demonstrating the latest enhancements of UAV image processing, is evaluated in [16]. More applications of GNSS can be studied in [17-22].

GNSS is vulnerable to in-band interference, which makes these signals very weak. For example, GPS signals that are sent from satellites at a distance of about 20,000 km from the earth, have a power of about -158.5 dB for L1 C/A and -160 dB for L2 band [1]. Generally, EW technology has been used in EA, EP and ES scenarios utilizing different systems and techniques and in different areas (including airborne, maritime, ground-based and space-borne scenarios) [23-29].

GNSS interferences are classified into two categories: 1) Intentional interferences (which are called jamming in electronic warfare literature for GNSS), 2) Unintentional interferences. Interference can be produced by GNSS jammers, for example by sending a strong continuous signal, Gaussian noise in the GNSS frequency band, or by intelligent jammers as fake instruments. Unintentional interference can be caused by a group of electronic devices and can produce strong electromagnetic harmonics in the GNSS frequency bands, or by broadband telecommunication systems such as radio stations and Televisions that have harmonics in GNSS frequency [30].

From the perspective of bandwidth, jamming and interference signals can be divided into narrowband and wideband categories. In the narrow band mode, only a small part of the GNSS frequency bands is affected, while in the wide band mode, it occupies almost the entire frequency band. For example, CW interference is a narrowband interference signal and Gaussian noise jammers produce broadband interference signals. In recent years, cheap GNSS jammers have become available to the public under the name of privacy devices, whose purpose is to disrupt GNSS receivers at distances of several meters. Although sometimes due to the low quality of the electronic components used in these systems, GNSS receivers outside these defined distances and WAAS systems used in air navigation are also severely affected [31]. Therefore, jamming not only reduces the performance of GNSS receivers but can seriously endanger human health and safety. Thus, the detection and reduction of GNSS jamming have a high priority for research and development in GNSS associations. Jammer and spoofer can be classified in different ways. In [32] jammers are classified as AM jammers, chirp jammers, FM jammers Pulse jammers and narrowband jammers. In general viewpoint, jammers are classified as noise jammers (including spot noise, barrage noise and swept noise) and deceptive jammers [33]. A spoofer can be simple, intermediate or sophisticated, according to the level of smartness and complexity of its design.

In general, jamming and interference can be neutralized by using time, frequency, space domain processing or a combination of them. Furthermore, interference reduction techniques using antenna arrays can effectively neutralize broadband and narrowband interference signals independently of their time and frequency characteristics. Here, strong narrowband and wideband interference refers to any unwanted radio frequency signal including tones, sweep waveforms, broadband and pulse noises and any multi-frequency and time-varying types associated with them [34]. These signals are generally powerful because they must have enough power to have a bad effect on the receiver's performance even after extensive removal and separation and removal of the Doppler. In the array processing literature, all these jamming signals are considered as narrowband plane waves until the inverse of the maximum propagation delay across the array is much larger than the signal bandwidth [35]. Therefore, regardless of the characteristics of these jamming signals, they can be neutralized by applying a proper spatial filter. GNSS signals are defenseless against interference signals within the high power band, such as jamming signals and fake signals. The fake (spoofing) signal is known as the most dangerous intentional interference signal that targets GNSS receivers and forces them to produce wrong spatial and temporal outputs. A spoofing attack is more dangerous than a jamming attack because the target receiver is not aware of the threat. Increasing advances in the field of electronic technology have reduced the cost of manufacturing jammers and fake GNSS devices, as well as their greater flexibility for misuse and misapplication in the military and even civilian fields [36]. Therefore, in summary, it is necessary to consider the importance of using and protecting GNSS systems in the commercial, industrial and military fields, according to the development of GNSS jammers from the simple and inexpensive range to the complex and expensive ones. The issue of maintaining security and functional reliability, revealing/reducing threats of jamming and counterfeiting of GNSS receivers for current and future needs, has been of increasing importance in GNSS associations, cloud computing, geospatial analysis/techniques and military applications.

2. Signal modeling

The signal received from the i^{th} GNSS satellite is modeled as [37-38]:

$$y_i(t) = A_i(t)C_i(t-\tau_i)d_i(t-\tau_i)\mathrm{Cos}\left[2\pi(f_c + f_d^i)t + \varphi_i\right] \tag{1}$$

in which, f_c is the carrier frequency, A_i, f_d^i and φ_i, are the amplitude of signal, the Doppler frequency and the random phase of the i^{th} GNSS signal, respectively. C_i, d_i and τ_i are the spreading code, the navigation message and the channel delay, respectively. The signal received at the GNSS receiver input is written as:

$$x(t) = x_{sat}(t) + J(t) + \eta(t),$$

$$x_{sat}(t) = \sum_{k=1}^{K} y_k(t) \tag{2}$$

in which, K is the number of satellites in view, $J(t)$ and $\eta(t)$ demonstrates the narrow-band jammer signal, and the receiver additive white Gaussian noise, respectively. It is assumed that $J(t) = A_J\cos(2\pi f_J t + \varphi_0)$, in which A_J, f_J and φ_0 are the jammer signal amplitude, jammer frequency and jammer initial phase, respectively. The jamming to noise ratio is formulated as $J/N = A_J^2/2\eta$ in which η represent the power spectral density of additive noise. The jamming to signal ratio is formulated as $J/S = A_J^2/\sum_{k=1}^{K} A_k^2$ [31, 34]. The noise power is calculated as KTB, and K is the Boltzmann constant, T is the absolute temperature and B is the receiver bandwidth. In a general scenario, the received signal at the receiver input is considered as:

$$x(t) = x_{sat}(t) + x_{threat}(t) + \eta(t) \tag{3}$$

in which $x_{sat}(t)$ and $x_{threat}(t)$ are the received signals from the authentic satellites and the threat source, respectively. The general GNSS receiver block diagram and general field scenario are depicted in Figure 2 and Figure 3 respectively.

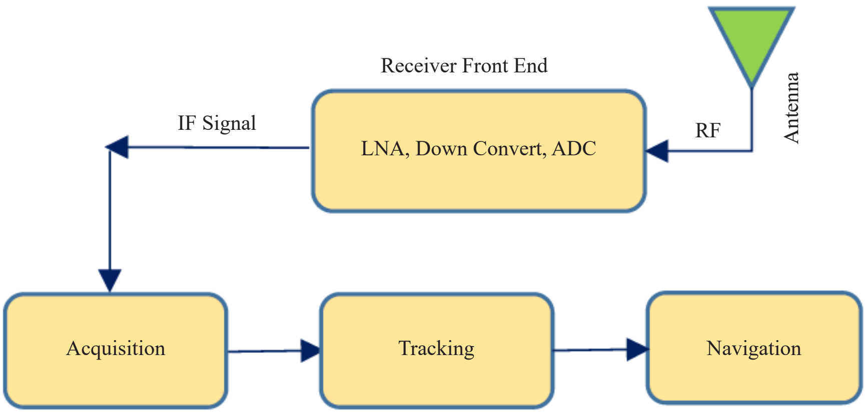

Figure 2. General GNSS receiver block diagram.

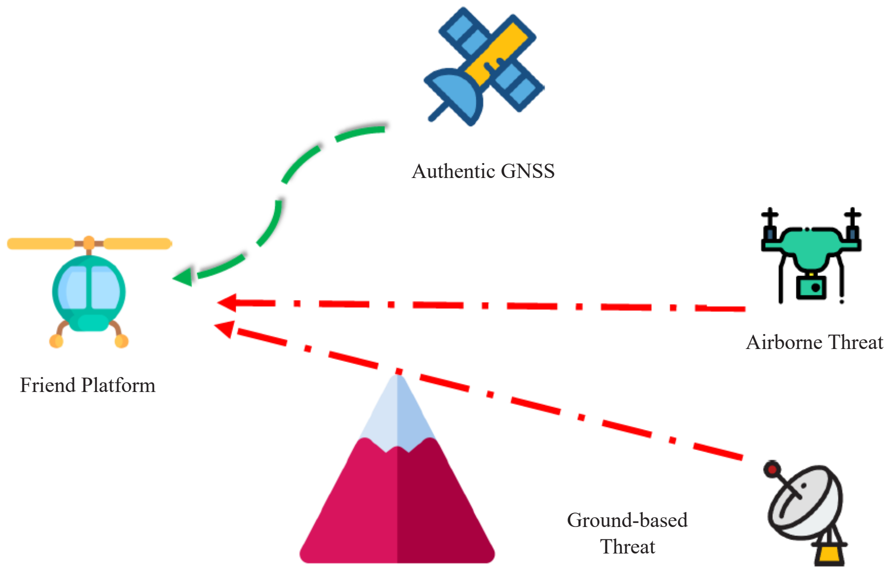

Figure 3. General Field Scenario. (For example in geospatial analysis and mapping application)

3. Literature survey

Techniques for dealing with threats (as well as jamming, interference and spoofing), are usually divided into two main categories: threat detection and threat mitigation. Jamming detection algorithms focus on identification of the jamming attack, while jamming mitigation techniques aim to neutralize the jamming threat. Most of the proposed techniques focus on interference detection rather than interference reduction. Some of the famous detection techniques are as follows [36, 39-42]:

1-Amplitude separation and differentiation
2-Separation and differentiation of arrival time
3-Consistency Cross-Check with IMU
4-Separation and differentiation of polarization
5-Separation and differentiation of AoA
6-Cryptographic Authentication
7-Artificial neural networks and wavelet transform

Spoofing countermeasures using multiple antennas is one of the effective techniques devised against this threat [41, 43-46]. These techniques are generally based on the fact that a faker usually sends several PRN codes from the same antenna, while reliable and correct signals are sent different satellites and from different routes. Extensive studies have shown that antenna array processing is an effective tool to neutralize GNSS interference. Antenna array processing in GNSS applications is more focused on neutralizing jamming and interference [47-52]. In reference [52], beamforming with a response without distortion and the lowest power is used for GPS applications to remove jamming and interference signals whose power was significantly greater than GPS signals. In reference [49], the advantage of a periodic mode of GPS signals is used and also the usefulness of special vector beamformer for GNSS applications is highlighted, with the difference that unlike conventional subspace beam-formers, which project the received signal into signal subspace, the received signal is projected into the subspace of the GNSS signal plus noise. The received signals are then boosted in such a way that the beamformer maximizes the signal-to-interference plus noise ratio. Despite the effectiveness and efficiency of antenna array based methods, they suffer from hardware complexity. Considering the fact that the number of antennas determines the number of unwanted signals that can be reduced, the limitation of the number of antennas, dimensions and shape of the array can be considered as the main problem of these methods. These methods combine temporal and spatial filters to neutralize RF signal interference by increasing the degree of freedom without increasing the physical dimensions of the antenna array.

Moving antenna arrays and hybrid/artificial array processing are other solutions to increase the degree of freedom without increasing the number of physical antenna elements. Recently, antenna movement in the form of artificial antenna array processing has been used to add the correlation matrix to be used in the estimation of the arrival angle [53-55]. In reference [53], a new method based on a moving antenna array is proposed to synthesize a larger array and increase its degree of freedom. In addition, a spatial filter has been applied to this synthesized array to prevent signal dropout and reduce multipath components. This filter estimates the multipath vector and maximizes the signal-to-noise ratio of the line-of-sight signal. Correlation between the LOS signal and unwanted signals leads to the phenomenon of signal elimination and decreasing the order of the temporal correlation matrix [56]. Locations provided by GNSS can be completely changed by spoofing attacks. Recently, several anti-counterfeiting techniques have been introduced to deal with counterfeiting attacks. However, usually existing anti-counterfeiting techniques are either computationally complex or limited to a specific scenario. Anti-jamming using antenna array processing is one of the most effective techniques that has been studied by engineers [57].

Although jamming/spoofing countermeasures using antenna arrays are effective techniques against the threat, the proposed methods usually operate after the tracking and acquisition steps of the GNSS receive. This task imposes a high computational load and a long processing time on GNSS receivers. For example, in reference [46], a mitigation approach using an antenna array is proposed. This method compares the estimated AoA of both authentic and fake PRNs after they have been completely tracked by the GNSS receiver. Although this is an effective method, it requires the receiver to perform a complex computational process. In addition, most of the previously introduced techniques have been studied in open space conditions and may be used in multipath environments where decomposable (resolvable) and non-decomposable (unresolvable) reflections are present. Both authentic and fake signals through PRN codes have direct sequence spread spectrum modulation and their power when received by the antenna array is much lower than the noise floor. However, the spoofer is a point source transmitter that emits several PRN codes, each of which has a power level comparable to the authentic signals, and therefore, the spatial power of the spoofing signal is significantly higher than that of the signal. This common characteristic has already been used to design a beam former, to direct a zero to the direction where the signal attacks the antenna array in open spaces [58]. However, this mitigation strategy is challenging in multipath environments and may not work properly.

In reference [59], the effect of the spoofing signal parameters on a target receiver in overlapping spoofing attack scenarios has been investigated. In this article, it is assumed that the receiver is operating in the tracking loop and the forger tries to steal the correlation function without losing the lock. In order to check the performance of the method, the forgery parameters to successfully acquire the tracking point as a function of DLL and PLL parameters of the target receiver are investigated. The problem of interest is to detect the forgery attack using different signal quality monitoring metrics and to characterize the pseudo-distance measurement error induced by the forger as a function of the delay lock loop parameters. The statistical characteristics of counterfeiting detection criteria are examined and appropriate detection threshold levels are calculated. In reference [60], a review of the studies conducted in the field of GNSS receiver anti-counterfeiting methods has been done. The vulnerability of GNSS receivers to spoofing attacks has been studied and the anti-spoofing algorithms in the baseband digital signal processing layer and the receiver information processing layer have been discussed and investigated. Also, the limitations, cost and applicability of anti-counterfeiting methods and the direction of anti-counterfeiting research in the future have been examined.

In reference [35], a robust method for neutralizing GNSS array antenna jamming based on sample covariance matrix reconstruction is provided. In anti-jamming applications of satellite navigation systems, if active interference is received from the main lobe of the array antenna, when the adaptive filtering algorithm forms the zeroing and neutralization of the main lobe, distortion of the main lobe will occur. In this article, a jamming neutralization method for satellite navigation is proposed by using sample covariance matrix reconstruction, without neutralizing and zeroing (nulling) the main lobe. In this method, no zeroing (nulling) of the main lobe occurs when neutralizing the main lobe, which prevents distortion of the direction of the main lobe. In addition, along with the control of the adaptive pattern, the adaptive pattern of the array antenna is close to the interference-free pattern in order to receive the appropriate and suitable navigation signal. Theoretical analyzes and numerical simulations prove that this method neutralizes the jamming without distorting the main beam. In addition, in this method, the output SINR will not be reduced by the distortion of the main lobe, which leads to the improvement of the anti-jamming performance.

In reference [61], the performance of SQM techniques under different multipath scenarios have been investigated.

At first, SQM change profiles are examined as critical requirements in evaluating the theoretical performance of SQM criteria. Then, the sensitivity and efficiency of SQM approach for detecting and reducing multipath are defined and analyzed by comparing SQM profiles and multipath error envelopes. The results show that although SQM is sensitive to multipath with medium and long delays, its efficiency in reducing this range of multipath errors varies based on the tracking strategy and signaling scheme. For multipath scenarios with a short delay, the effect of multipath on pseudo-distance measurements remains mostly unrevealed due to the low sensitivity of SQM criteria.

In reference [62], by using independent (self-sufficient) sensors including the outputs of the inertial measurement unit and vehicle odometer, jamming/counterfeiting is detected. In this paper, a jamming/spoofing detection approach is proposed based on compatibility analysis between mechanized GNSS and IMU/Odometer. In order to detect the forgery (jamming) attack, the proposed method analyzes the GNSS and IMU/Odometer measurements independently during a pre-selected viewing window and cross-checks the outputs provided by the GNSS and INS/Odometer mechanization. In normal mode, GNSS and INS operate independently and provide separate navigation outputs. In order to improve the output, the position or speed provided by GNSS is given to an optimal estimator, which is a Kalman filter. The INS output is also entered into the corresponding filter and the difference between the two is calculated and the INS errors are estimated based on the error models. The average detection time and the detection performance in terms of operational properties of the receiver in the suburbs and dense urban environments have been investigated in this article. In reference [63], the authors, by applying the results of decision theory, aim to investigate the performance of the compliance rate test when it is used to detect jamming in GNSS receivers. This article proposes two versions of the signal quality monitoring algorithm: one that works exclusively and in a pre-correlation way, and the other one provides post-correlation information as well. In this article, it is assumed that the received data can be modeled as random processes, and therefore, the field of statistical characteristics and the chi-square measure have been used. Also, the probability density function of the reliable signal is considered normal. The results indicate the ability of the proposed method to detect jamming even at very low power levels (which cannot be detected in the time and frequency domains). Among the features of the method proposed in this article, we can mention the low computational volume and also the ability to use it as an early warning.

In reference [64], the detection and reduction of broadband interference of artificial aperture radar of high resolution have been discussed. For each instantaneous spectrum, the existence of an interference signal can be detected based on a statistical test based on negative entropy. In reference [65], a blind detection method based on G-T normality test is presented to check the presence of disorder and non-Gaussian interference of narrowband and wideband. This method has been compared with other methods of normality test by referring to the auto-cumulants of the 4th order sample. The asymptotic covariance matrix related to the estimated auto-cumulant vector has been determined analytically, which leads to the reduction of the complexity of the proposed technique. In this method, two types of continuous wave jamming are considered, continuous wave jamming with fixed frequency and continuous wave jamming with sweeping frequency. Also, the bandwidth of the receiver is 2B and the phase distribution is assumed to be uniform. The simulation results indicate that the proposed method performs better than the A-G method in exchange for a higher amount of calculations. The proposed method is more sensitive to jamming and narrowband interferences, which means that this method needs more calculations to reveal the sweeping jamming. With this new method, in exchange for increasing the number of calculations, the ability to detect jamming and weaker interferences can be improved. The main shortcoming of the G-T method is its need to calculate the covariance matrix of the estimated cumulative vector, which increases the complexity of the algorithm.

In reference [66], the aim of the article is to provide an algorithm for detecting jamming and interference for GNSS receivers based on the subspace adaptive tracking technique. An estimator is proposed to determine the number of jamming and interference signals and a method to detect the interference frequency in the narrowband interference environment. According to the authors of this article, the estimator, by using the statistical characteristics of the eigenvalues of the sample covariance matrix as well as the noise level of the GNSS receiver, is more accurate than the standard information theory criteria. In reference [67], a method for detecting and reducing RFI pollution by using a threshold level from a statistical criterion, based on a spectrogram technique, is proposed. The mean and skewness spectrograms are generated using a 2-D window to clean the symmetric distribution mode. In the previous methods, a threshold level equal to the average plus three times the standard deviation of the measured values was used, which itself can lead to detection errors in the presence of strong jamming. In reference [68], a regrouping method based on the smoothed pseudo-Wigner-Ville distribution is proposed for the detection of time-varying interference and jamming for single-antenna receivers of GNSS systems. The performance of the proposed method has been evaluated through real signals contaminated by sweep interference. The results have shown that this method not only completely removes cross-term interference, but also removes energy leakage and has a better detection performance in time-varying jamming compared to classical time-frequency analysis methods for the receiver.

STFT has been used in the separation of jamming and interference in direct sequence spread spectrum systems. Although STFT does not lead to cross-term error, the time-frequency resolution is limited by the shape and width of the window function. WVD is famous because it provides almost the best time-frequency resolution among all time-frequency distributions and has good characteristics. Of course, this method creates limited cross-term interferences, and to reduce them, the RSPWVD distribution is introduced, which improves the sharpness of the focus of the signal components through the reassignment of the energy distribution in the time-frequency plane. Although RSPWVD itself can lead to energy leakage at the beginning and end of the time-frequency plane. This energy leakage exists in the WVD and the distributions derived from it, which can lead to large errors in the estimation of the instantaneous frequency. In reference [69], a noise reduction system based on short-time Fourier transform is proposed, which uses several windows to increase the resolution of the time-frequency plane. Also, a technique for using almost optimal windows is proposed. A notch filter with infinite impulse response is used for the noise removal process. The increase in resolution reported in this paper has been achieved in exchange for greater computational volume. The presented method has the ability to reduce interference up to a ratio of 60 dB. Of course, damage to the original signal is also unavoidable. In reference [70], a hybrid anti-jamming system is proposed for kinematic GPS receivers. The proposed system uses a pre-correlation block based on a short-time Fourier transform to ensure the acquisition of at least 4 satellites in a disturbed environment. In the navigation part of the receiver (post-correlation), an anti-noise block based on discrete wavelet transform is used to increase the positioning accuracy. The simulation results indicate a better anti-jamming performance of this system compared to previous methods. It has been shown that the average positioning accuracy of the proposed system is better than the reduction methods based on standard short-time Fourier transform, filters based on wavelet transform and hybrid systems based on wavelet transform.

In reference [71], the technique of reducing the interference in the Beidou system by combining the subspace orthogonal projection with the space-time processing, which has the ability to reduce the interference in multiple frequencies and arrival angles, is proposed. The simulation results show that the interferences that have the same arrival angles but different frequencies are reduced in the time domain and the interferences that have different arrival angles but the same frequencies are reduced in the space domain. The number of time delays has an important effect on performance. When the number of time delays is less than the number of interference frequencies, the beam gain will not have the highest value in the direction of the signal and the frequency of interest, although zeros (nulls) will be formed in the direction and frequency of the interference. Otherwise, the gain of the desired signal will be the highest and the interference will be properly reduced. With a sufficient number of array elements and time delay units, this method will have effective and sufficient performance against multiple narrowband interferences. In the simulations, a uniform linear array with 16 elements, 4 narrowband interferences was used.

In reference [72], a null guidance control technique based on the binary image algorithm, which can effectively increase the null depth, is proposed. First, the dynamic model between the interference and the receiver is created. Based on this model, the rate of change in the direction of the interference input is analyzed and the widening and shallowing of the spatial filtering is simulated and investigated. Then, the binary image algorithm is introduced to effectively deepen the null. The simulation results indicate that the depth of null has increased to more than 30 dB by the proposed method, which significantly improves the anti-jamming performance of spatial filtering in dynamic scenarios. Traditional anti-interference algorithms are used to reduce interference by using convex optimization methods based on output power minimization. These algorithms can reduce the interference, but the satellite signal is also reduced like the interference. In conditions with high dynamics, the signal rate is seriously affected by interference and output noise, and the success rate in acquiring satellite signals decreases [73]. In this reference, an expanded model based on the NMLCB method based on maximizing output power and limiting interference sources is introduced. By this proposed method, GNSS receivers can receive satellite signals more easily in high dynamic conditions.

A key challenge in UAV satellite communication is the unstable beam aiming due to the movement of the UAV, which is a scenario of a type of satellite communication in motion. In reference [74], a blind beam tracking approach is proposed for the UAV satellite communication system in the Ka band, in which the UAV is equipped with a large-scale hybrid antenna array. At first, the mechanical adjustment of the antenna to point to the satellite is done, and then the precise adjustment of the antenna array orientation is performed blindly and through the electronic weighting of the antennas based on the Perturbation algorithm at the same time. The simulation results indicate that this method performs better than other methods. The global positioning system is an important method in locating an aircraft, while the deception disorder can affect the positioning accuracy of such navigation systems. In reference [75], a method of detection and removal of decoy interference based on a specially designed array is proposed for the aircraft direction. Jamming is detected by comparing the observed binary difference of the carrier phases of two different signals with a certain threshold level according to the measurement errors of the receiver. To estimate the jamming direction with high accuracy, an array with a new structure is designed and a fast method to solve the ambiguity is discussed. After detecting the disorder, the null of the array is directed toward the source of the disorder through orthogonal vector weighting to reduce the disorder. The accuracy and validity of the proposed method are verified through computer simulations.

Fast moving jamming creates a great challenge for UAV navigation. This was the motivation for the development of the new technique of adaptive guidance of the resistant beam, by the authors of reference [76], which has the ability to increase the navigation signal and reduce the jamming effectively. The MDDR beamformer along with the minimum power constraint is used to formulate the optimization problem, which forms a quadratic constraint. In the following, instead of the quadratic limit, a linear version under the power limit is extracted in order to achieve the zero sector in the direction of the interference, and as a result, the linear limited MDDR beamformer is created. The simulation results indicate the ability of the proposed beamformer to effectively reduce the fast moving jamming for UAV navigation. In reference [77], a real-time algorithm with low complexity is proposed to direct the beam of the patch panel antenna array to the maximum received signal strength, which is used to improve the telecommunication link. This algorithm uses received signal strength measurements and is simulated on a moving drone. Due to its low cost and simplicity, this algorithm is suitable for mobile platform applications. The multipath signal is usually considered as interference that should be eliminated. The existence of a correlation between the main signal and the multipath signal makes it difficult to use traditional methods of estimating the arrival angle in the smart antenna system.

In reference [78], a new arrival angle estimation technique is presented. In this method, first, the complex fast independent component analysis algorithm called cFastICA is applied to obtain the direction vectors with multipath information related to each source signal. Then, according to the specific structure of the obtained steering vectors, the algorithm uses the solution of the signal reconstruction problem in the theory of compact sensors and the estimation of the multipath signal arrival angle is translated into a Norm L1 minimization problem. Finally, the spatial spectra are searched to obtain the arrival angles of each of the main (direct) components and multipath components. The simulation results indicate the effective performance of the proposed method. When the signal-to-noise ratio is equal to 10 dB, the mean square error is less than 0.05 degrees, which is better than the SS-MUSIC algorithm. Sensor arrays have been used in most applications, but the performance impact of independent component analysis has not yet been sufficiently investigated [79]. In this reference, this issue is investigated on a typical antenna array. The factors considered in this matter include the environmental noise level, the characteristics of the array and the characteristics of the radiation sources. Analytical relationships between noise variance, source variance and optimal ratio of signal to interference plus noise are investigated. The data of GNSS time series related to the observation stations includes extensive information. This information includes changes in geographical space, changes in the shape of the earth, movement of the materials of the lower surfaces and other blind signals. In order to analyze these hidden blind signals in GNSS time series, independent component analysis has been applied to the daily time series of the integrated GPS network of Southern California to separate the source signals [80]. In reference [81], a comprehensive overview of the research background of this field is presented.

In reference [82], a new structure including spoofing detection, spoof/authentic signal classification and spoofing removal is proposed for mobile GNSS receivers. The movement of the receiver has been used to classify the intercepted signals into two groups reliable and fake signals. Then, a sequential de-spoofing method is developed to remove fake signals from raw digital samples. In [83], a hybrid algorithm for dealing with interference and spoofing based on antenna array is presented. In this algorithm, the jamming is removed by subspace projection, and then a compact sensing framework is used to extract the navigation signal and identify the spoofing signal. According to the direction of arrival of reliable and fake signals, the receiver, by using multiple adaptive beam-formers, simultaneously receives the reliable signal without distortion and reduces the fake signal. In [84] an improved subspace-specific approach for radio interference filtering of artificial aperture radar images is developed. In the pre-processing class, the datasets that need further processing can be selected in two domains: time and frequency. Then the data are processed by traditional approaches based on special subspace. According to the authors, the proposed method has better efficiency and performance than other traditional methods. In reference [85] an innovative detection and jamming mitigation technique is presented to deal with threat sources. This technique is based on Karhunen-Loeve transformation. By this technique, the jamming signal received is displayed in such a way that the jamming components are better identified, isolated and removed. Also, the least amount of damage is done to the desired GNSS signal. The simulation results indicate the very favorable performance of this method. One of the main bottlenecks of this method is the computational complexity and high volume of required calculations.

In reference [86], a new method for calculating applied KLT to mixed voltage data is introduced to detect and reduce the noise level in astronomical signals. According to the authors of this article, the introduced technique has made a significant improvement in the calculation time and the Monte Carlo simulation results indicate significant results in low signal-to-noise conditions. The two proposed methods are called TKLT and CKLT. In reference [87], the authors have proposed a method based on wavelet transform with the ability to separate the desired signal from interfering components in the transform domain. Decomposing the wavelet packet and selecting the appropriate threshold level makes it possible for the introduced algorithm to show a very good performance in the conditions of multi-pulse jamming as well as narrowband jamming (two scenarios where traditional coping methods may not be effective). The proposed method is suitable for use against TACAN and DME system signal interferences. In [88], a new method for removing continuous wave jamming in GPS receivers is proposed. The proposed filter consists of a series combination of an adaptive FIR filter and a filter based on wavelet packet transform. By combining these two filters, the internal noise created by the FIR filter as well as the residual effects of jamming on the GPS signal can be removed by the wavelet packet transform filter.

In [89], an anti-jamming system is proposed using two blocks of interference/jamming reduction based on wavelet packet transform. The proposed pre/post-correlation technique uses lower decomposition levels for WPT-based noise reduction algorithm. Also, the first block of the proposed method can be disabled in low power jamming scenarios. The performance of the proposed system has been evaluated for single-tone continuous wave jamming mode and linear sweep jamming mode. According to the authors, the obtained results as well as the theory prove that the computational cost of the proposed method is far less than similar reduction methods based on WPT, and therefore the proposed method is a fast jamming reduction technique. In reference [90], the authors have proposed a new pre-correlation interference reduction technique for GPS receivers. This new reduction technique is based on the thresholding of wavelet packet coefficients and uses thresholding of adaptive levels to reduce the effect of GPS jammers. The authors of this article have compared the proposed method with the thresholding method of discrete wavelet coefficients. In this article, the interference is generated by the RF signal generator device and the received GPS signal and the interference signal are combined by a combiner. Then the combined signal is processed by a software GPS receiver that includes the proposed reduction technique. The simulation results indicate the advantage of the proposed method in improving the signal-to-noise ratio and MSE (50% and 80%, respectively) compared to the previous methods.

Recently deep neural networks, deep learning and machine learning have gained attention in jamming detection, classification and mitigation. In [32] the problem of jammer classification utilizing machine learning algorithms such as SVNs and CNNs are studied. In [91] deep learning is used for handling multipath in GNSS receivers. The results show improvement in receiver performance in comparison with standard methods. Jammer classification utilizing transfer learning and CNN is investigated in [92]. The simulations show that the classification accuracy has been enhanced in accordance with standard algorithms previously introduced. Authors in [93] used deep learning for GNSS jamming detection and to classify at different levels of power. Their method can identify different jammers and the positive point is different kinds of jamming, multipath components and spoofing are utilized. There are other papers in this regard that interested readers can refer to [92, 94-104].

In [105], a main beam (lobe) interference reduction method based on subspace projection processing and covariance matrix reconstruction are presented. In the proposed method, the specific matrix is calculated based on the special vector of the interference of the main beam to reduce it in the received data. After the main beam interference eigenvalue is replaced by the average value of the noise eigenvalues, the interference covariance matrix is reconstructed to eliminate the effect of the main beam interference on the adaptive weight vector. Finally, using the processed data and the adaptive weight vector obtained from the reconstructed covariance matrix, the output of the adaptive beamformer is calculated. The simulation results show the good performance of the proposed method in reducing the interference of the main beam. In reference [106], a review of the literature on detecting and reducing RFI has been done, and various parametric and non-parametric methods have been investigated along with their advantages and disadvantages. In this article, considering that there is no single technique to overcome all kinds of interference sources, it is suggested to use a suitable combination of different techniques to achieve an effective result.

In reference [107], different orthogonal projection methods are examined and three new algorithms are introduced to reduce interference. The main key in the orthogonal projection algorithm is the selection of secondary data to obtain the interference subspace. The simulation has been done using real data measured in interference and ionosphere clutter. In [108], KLT is used to detect very weak signals. Compared to the FFT method, this transformation has the ability to detect signals with low SNR, but its disadvantage is that the volume of calculations is more than FFT. For an autocorrelation matrix with size N, the KLT algorithm has a complexity of N^2, while the FFT method has a complexity of $N.Log(N)$. Recently, the BAM-KLT method has been introduced to reduce the complexity of the KLT method, but this method also has limitations (such as the sampling rate). Some modifications and advancements of BAM-KLT method have been introduced utilizing RMT [23, 37, 109-111]. Figures 4 and 5, depict MP law and semi-circle law, recently utilized in this concept. For more information refer to [37, 109].

In [112], a covariance matrix shrinkage method is proposed to improve the arrival angle estimation under a uniform linear array, in a scenario where the number of sensors is large and the sample size is relatively small. The innovation of this work is in presenting the Shrinkage objective with the Toeplitz structure and deriving the closed form estimation of Shrinkage coefficients. Closed form estimation of Shrinkage coefficients is calculated based on consistent and unbiased estimates of Trace and covariance matrix moments with Wishart distribution. The RMSE simulations related to the arrival angle estimation indicate the improvement of the performance of the MUSIC method in low SNR and small sample size and also provide satisfactory performance at high SNRs. In high dynamic environments, due to rapid changes in the path of interference, the output performance of the STAP beamformer can be significantly reduced. Wang et al., presented a STAP-based robust beamforming algorithm for use in GNSS receivers to spread null toward interfering signals while dealing with steering vector mismatch (due to arrival path estimation error) [113]. First, the received signal model is implemented in the high dynamic environment for the STAP structure. Then, the noise-plus-interference time-space covariance matrix is obtained by reconstructing the interference covariance matrix and the noise covariance matrix. This work is done to prevent the estimation of the arrival path of reliable GNSS signals, which can lead to the removal of the interested signal components from the sample covariance matrix. Finally, requirements and restrictions are designed to solve the weight vector. The simulation results indicate the effective performance of the proposed algorithm in spreading nulls, and it also has better results in the output carrier-to-noise ratio (C/N). The presence of disruptors in ad hoc networks can disrupt the data flow in links between nodes. The effect of such attacks can be worse when the intruder is on the move. As a countermeasure for such attacks, adaptive beamforming techniques can be used for spatial filtering of interference signals.

In reference [114], the performance of adaptive beam nulling as a mitigation technique to deal with interference attacks in ad hoc networks is investigated. The proposed method is distributed and uses intermittent measurements of the RF environment to reveal the path of the jamming signal and reduce the incoming signals from the current and predicted locations of the interference. In reference [115], an algorithm for improving anti-jamming detection capability in GPS receivers equipped with uniform linear array and uniform circular array is presented. The proposed algorithm uses the FOS method to accurately detect the arrival direction of in-band CW jammers. According to the authors, the proposed algorithm provides three major advantages, more accurate estimation of the direction of arrival, the range and the correct number of intruders. In reference [116], an interference reduction approach, based on antenna arrays with the ability to detect and reduce interference and falsification (spoofing), is proposed. At first, by using sub-space projection, high power jamming signals are removed. The output signal is still a multidimensional vector and therefore spatial processing techniques can be used in the next step. Then, by using the property of distance stability of GNSS signals, the noise components in the spatial correlation matrix are reduced or eliminated. Therefore, the signal subspace, which includes power information and the path of GNSS signals, can be achieved. Then, a new distance correlation eigenvalue test is presented to detect the presence of spoofing attack. Finally, by re-using subspace projection, fake signals are eliminated and a higher gain for reliable signals is created through beamforming. All the operations are performed on the raw digital signal of the baseband and therefore it does not add additional computational complexity to the GNSS receiver.

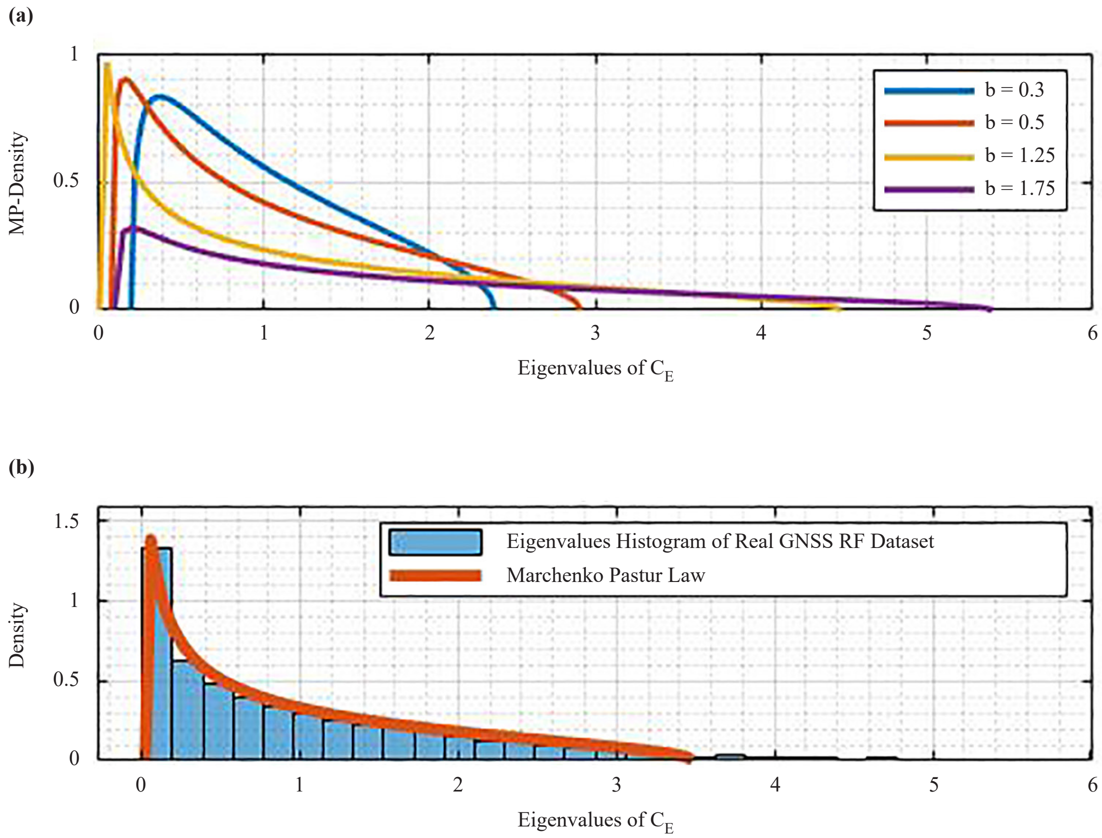

Figure 4. MP distribution for different values of *b* (a), and the empirical distribution of ensemble-eigenvalues, related to realistic GPS data (b). (Note: *b* is dimension ratio of ensemble covariance matrix C_E) [37].

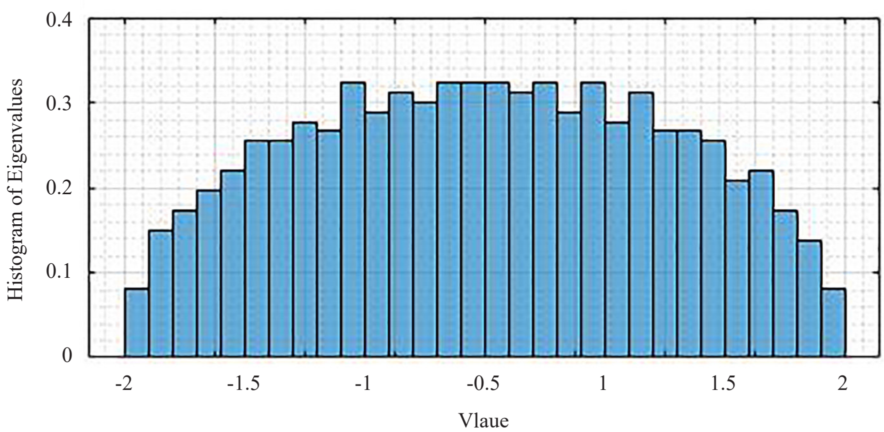

Figure 5. Empirical spectral density histogram of a typical modified Wigner-matrix with Gaussian independent-identically-distributed (i.i.d) terms [109].

Adaptive beamforming methods suffer performance loss in the presence of model mismatch, especially when the training samples are contaminated with the signal of interest. In reference [117], in order to remove the signal of interest from the sample covariance matrix, an iterative adaptive approach based on the angular sector reconstruction algorithm is proposed to reconstruct the interference-plus-noise covariance matrix. Traditional INC matrix reconstruction methods are based on the Capon spectrum estimator and obtain the spatial power spectrum. However, the Capon spectrum cannot provide an accurate estimate of the power, and this is due to its sensitivity to the array calibration error. The authors of the article used the IAA spectrum to get an accurate estimate of the power and use it in the reconstruction of the interference covariance matrix as well as the revision of the direction vector of the desired signal. The simulation results indicate the better performance of the proposed adaptive beamformer compared to the previous methods and the output SINR is close to the optimal values. References [118, 119] have also presented similar approaches for forming a resistant adaptive beam. In scenarios where disruption and spoofing attacks occur simultaneously, reducing interference becomes more complicated.

In reference [120], by examining the effects of simultaneous threats, an adaptive blind algorithm based on the negative diagonal loading technique is proposed to deal with interference. The proposed method can simultaneously and adaptively remove interference and falsification without estimating their input path and receive a reliable signal. The simulation results show the good performance of the proposed method. There have been various uncertainties in real sensor arrays that can effectively reduce the performance of adaptive beamformer. In reference [121], the authors have proposed a simple three-diagonal loading method called automatic three-diagonal loading to increase the strength of the adaptive beamformer. This method uses a symmetric three-dimensional matrix to regularize the sample covariance matrix and applies a soft constraint on the beamforming weight vector. A parameter-independent method is also presented to determine the loading level based on the output power of a beam with a lower side lobe. The main problem of the diagonal loading approach, which is one of the most well-known resistant techniques of adaptive beamforming, is the difficulty of reliably determining the loading factor. Recently, Capon's resistant beamformer based on a general linear combination has been proposed to determine the loading factor fully automatically and only from the available data.

In reference [122], an improved beamforming technique based on the general linear combination and based on the assumption of Gaussianity is proposed. This method provides an analytical solution for the loading factor that can be calculated much more effectively. The simulation results show that in the proposed method, the computational load has been reduced without weakening the performance. Reference [123] mentions that little research has been done on the variable loading technique. In this article, a low-complexity VL-based beamformer is proposed, in which the weight vector of the beamformer is deliberately prevented from converging to noise components. Then, according to the traditional loading method, the loading factor is adjusted. Numerical results show the excellent performance of the proposed beamformer compared to other similar beam former approaches, such as similar diagonal loading and resistant capon. Currently, MVDR is one of the common beamforming algorithms. However, the performance of the MVDR algorithm depends on the accuracy of the covariance matrix, and if there is an imprecise covariance matrix, its performance decreases significantly. In reference [124], the MVDR algorithm is improved by using the estimated diagonal loading. The range of diagonal loading compensation is reduced based on the matrix theory. The optimal diagonal loading value in this range is determined experimentally. The simulation results indicate the effective and practical performance of the proposed method.

Recently, several efforts have been made in the field of adaptive beamformer using an uncertainty set to achieve robustness against the misalignment of the steering vector. Of course, these robust adaptive beam-formers based on performance optimization in the worst conditions suffer from the difficulty in choosing the appropriate dimensions of the uncertainty set. In addition, if there is a large mismatch in the steering vector, their performance will be greatly reduced. In reference [125], instead of using a single large set, several small uncertainty sets are used to fully cover the large uncertainty area. Two efficient algorithms, ISDP-RAB and IL-RAB, have been developed to solve the non-convex problem. The simulation results show a significant improvement in the performance of the methods in the presence of a large mismatch in the steering vector. In reference [126], a new approach of adaptive resistant beamformer based on repeated variable loading in a new structure is introduced. The proposed method iteratively searches for the direction vector of interest in the array. This work is done based on the relationship between the optimal weight vector and the assumed steering vector of the standard Capon beamformer. This work avoids the Lagrange multiplier method or convex optimization in each iteration. The simulation results show the excellent performance of the proposed method.

A new robust design algorithm based on covariance matrix signal direction vector estimation is developed in reference [127]. First, the theoretical covariance matrix is estimated. In the following, the direction vector of the desired signal is estimated using the maximization of the output power of the array, under the constraint of correlation coefficient and soft constraint. The original non-convex quadratic programming problem, under the analysis of hidden concave features, can be solved by Relaxed Semidefinite programming methods. In addition, the interference-plus-noise covariance matrix is estimated by the corrected steering vector and the sub-space theory, and its efficiency is proven analytically. The simulation results indicate the advantages of the proposed method in high accuracy and efficiency. A new diagonal loading algorithm resistant to direction vector mismatch is presented in reference [128]. The beam-to-reference ratio is first estimated and then used as a weighting factor for variable diagonal loading. Finally, the Bayesian framework is applied to obtain the weight vector. In contrast to traditional methods, the proposed method shows good performance without using any optimization toolbox or matrix analysis. In reference [129], an extended linear resistive beamformer is presented for non-circular signals in the presence of the arrival angle error or random jamming of the array. The block conjugate structure of the covariance matrix is used to prevent the complete update of the weight vector. This reduces the computational load. A variable diagonal loading term is added to the weight vector to improve the strength of the beam former. In addition, block matrix orthogonality is not required to calculate the amount of diagonal loading.

Determining the number of common factors is an important issue in high-dimensional models. The existing articles in this field are mostly based on the eigenvalues of the covariance matrix, and it is not easy to find a precise relationship between these eigenvalues and the number of common factors. To overcome this limitation, it is proved in reference [130] that under certain conditions, the number of eigenvalues greater than 1 of the original covariance matrix is similar to the number of common factors. The theory of random matrices is examined and the biases created in the estimation of eigenvalues are corrected. In some applications, estimating the number of eigenvalues located in a given interval, is of particular importance. Usually, the exact number is not required and methods based on random estimation can be used to achieve a suitable approximation. In reference [131], a number of methods used in this field, including polynomial filtering methods, have been investigated.

Table 1 summarizes the studied methods, and Table 2 provides discussion and criticism.

Table 1. Summary of studied methods

References	System models/ structures	The methods used	Achievements	Suggestions
[23, 35, 38, 41, 43, 46-52, 132]	-Antenna Array/ Spatial Filtering	-Reconstruction of sample covariance matrix -Beam forming with response without distortion and minimum power -The advantage of periodic mode of GPS signals and special vector beamformer -Comparison of the estimated AoA of both valid and fake PRNs after they have been fully tracked by the GNSS receiver -Outdoor conditions -Directing a null (zero) to the direction where the fake signal attacks the antenna array in open spaces	-Neutralization of jamming without neutralization and zeroing of the main lobe -Removing jamming and interference signals whose power is significantly greater than GPS signals -Maximize signal-to-jam/ interference-plus-noise ratio -Adaptive pattern control -Support for both narrowband and wideband jamming and interferences	-Applying reliable signal fading and multi-pathing conditions in the proposed algorithms -Using the spatial covariance matrix reconstruction to direct zero (null) without damaging the reliable signal-applying compression to the received time-space signal to reduce the implementation complexity -Applying changes in post-correlation techniques to be used in the pre-correlation stage -Using multi-stage beam formers for sub-arrays -Adaptation approach for antenna array processing -Evaluating the effectiveness of algorithms in different disruption scenarios in the operational environment -Investigating and evaluating the application of techniques on military GNSS signals -Using GNSS signals to improve the calibration process -Increasing the degree of freedom of the array without increasing the number of array elements (for example, by applying the concept of thinness)
[38, 45, 53-55, 64, 81]	-Moving Receiver -Artificial/ Synthetic Array	-Concatenation of the correlation matrix -Reduction of correlation -Statistical test based on negative entropy	-Increasing the degree of freedom without increasing the number of antenna array elements -Estimation of entry angle -Detecting and reducing jamming and interference of high-resolution airbase artificial aperture radar data -Identification of jamming and interference for any momentary spectrum -Removal of correlation	-Extrapolation of the removed components of the added covariance matrix to reduce the artifacts of the results -Improving the artificial array technique of the aerial base for the situation where the jamming spreads in a wide range of frequency ranges. -Utilizing the property of inherent periodicity to improve the time-space filter without distortion -Reduce high correlation between line of sight and multipath signal to improve multipath detection
[36, 39, 42, 59, 60, 133]	-Performance Evaluation	-Examining the effect of fake signal parameters on a target receiver in attack scenarios -Examining the forgery parameters to successfully acquire the tracking point as a function of DLL and PLL parameters of the target receiver -Investigating anti-counterfeiting algorithms in the baseband digital signal processing layer and receiver information processing layer	-Detection of spoofing attack using different signal quality monitoring criteria and specifying pseudo-distance measurement error -Calculation of appropriate detection thresholds	-Applying changes in post-expansion techniques to be used in the pre-expansion stage -Considering the multi-antenna mode for the counterfeiter and jammer in order to not have the same angle of interference signals. -Development of cryptographic verification methods
[38, 40, 57, 134]	-Single Antenna	-Using a single antenna receiver and moving it on a trajectory -Spatial sampling to form an artificial array -The use of parallel broad-spectrum channels to estimate signal parameters -Measuring the correlation of signals in a matrix form	-The possibility of the trajectory being random-lower cost -Less complexity -Detection of forgery	-Considering multipath signals and fading phenomenon -Hardware implementation for the air base platform and considering the mutual effect of the antennas -Support for broadband interferences

[38, 44, 63, 65-68, 83, 84, 135]	-Statistical and Spectral Characteristics (separation) -Time-frequency Processing -Space-Time Processing -Subspace Processing	-Decision theory -Examining the compliance test performance -Statistical features and chi square measure -Self-accumulators of the 4th order sample -Adaptive Subspace Tracking -Statistical characteristics of the eigenvalues of the sample covariance matrix -Spectrogram -Regrouping based on smoothed Wigner-Ville quasi-distribution	-Providing two versions of the signal quality monitoring algorithm in the form of pre-correlation and post-correlation -Disruption and interference detection even at very low power levels that cannot be detected in the time and frequency domains -Can be used as an early warning -Relatively low computational volume -Blind detection based on G-T normality test -Support for the presence of narrowband and wideband non-Gaussian interference -Analytical determination of the asymptotic covariance matrix related to the auto-cumulant vector and the resulting complexity reduction -Better performance of the proposed G-T method than the A-G method in exchange for a higher calculation volume -Determining the number of jamming and interference signals and detecting the frequency of jamming/interference in narrow band jamming/interference environment -Revealing interferences and jamming that vary with time -Removal of Cross-Term interactions and End Effects	-Cleaning the disorder and other types of errors in RAIM Hardware implementation methods of algorithms -Overcoming the blind spot of the stretching algorithm -Support for multiple jamming and interference environments -Using the scanning correlator to view different delays and alert when a signal outside the correlation peak is observed. -Optimizing the performance of algorithms based on computational volume
[62, 136]	-Kalman Filter	-Optimized estimator -Compatibility check -Analysis of measurements independently during an observation window	-Improved position and speed output -Improved detection performance (average detection time)	-Optimization with more appropriate coefficients to fit the jitter curve more appropriately -Reducing the average time of detection of jamming/interference in multiple jamming/interference environments
[62, 137]	Integration/ Coupling	-The use of independent sensors, including the outputs of the inertial measurement unit and distance meter -Compatibility check -Independent analysis of measurements during a pre-selected viewing window and cross-checking of outputs -Optimized estimator	-GNSS system prevents deviation of INS system outputs and INS provides continuity in navigation outputs. -Improved position and speed output -Investigating the average detection time of jamming/forgery and the detection performance according to the operating properties of the receiver in the suburbs and dense urban environments	-Improved RIO mechanism -Improved average detection time
[32, 69, 70, 87-104]	-Artificial Neural Networks/ Artificial Intelligence, Deep Learning, Machine Learning and Wavelet Transform	-Use of multilayer perceptron network -Using wavelet transform -Using wavelet packet decomposition -Using the KNN network -Using CNN -Using Deep Learning -Using Machine Learning	-Using learning networks -Classification of new entries -Improved accuracy in identification and classification -Better signal acquisition -Enhanced multipath handling	-Improving the volume of calculations -Improved output accuracy -Reduction of computational complexity and runtime
[23, 120-124, 126, 128]	-Diagonal Loading/ Unloading	-Fixed loading -Variable loading -Repetitive loading -Negative loading	-Robustness against errors in covariance matrix estimation -Robustness against the misalignment error of the steering vector Increasing the accuracy and quality of the beamformer	-More accurate determination of weighting factor analytically -Using the characteristics of the input data in determining the weighting factor

[23, 105, 112, 117-119, 127, 131]	-Shrinkage, Estimation of Steering (Direction) Vector, Estimation of Covariance Matrix	-Using the inherent characteristics of the input data -More accurate estimation of signal entry angle and jamming to reduce the error in the steering vector -Use of sub-space analysis and matrix theory -Separation of noise/ interference covariance matrix and original signal	-More accurate estimation of the covariance matrix and the direction vector and as a result reducing the overall error -Higher accuracy in calculating the weight vector and as a result reducing the overall error -Improving the performance of the beamformer	-Using the inherent characteristics of the input data in order to more accurately estimate the direction vector and covariance matrix -Accurate estimation of the number of eigenvalues in a specific interval (as an example of dominant eigenvalues in the Marcenko-Pastur relation) -Compensating and correcting eigenvalues and eigenvectors of the sample covariance matrix
[23, 113, 114, 138-141]	Null Widening/ Broadening/ Deepening	-Deliberately expanding null width	-Compensation of platform movement effects -Compensation for the effects of movement of the threat source Improved anti-jamming and anti-deception performance in scenarios where there are multiple threat sources	-Beam depth reduction compensation -Shallowing compensation
[37, 85, 86, 108, 109, 130, 142]	Karhunen-Loeve Transform	-Separation of desired and undesired signal through unique sub-space transformation -Separation of random and non-random signals	-Providing uncorrelated output coefficients	-Reducing the amount of calculations and complexity -Accurate estimation of the number of eigenvalues in a specific interval (as an example of dominant eigenvalues in the Marcenko-Pastur relation) -Compensating and correcting eigenvalues and eigenvectors of the covariance matrix
[37, 109, 110, 142-146]	Random Matrix theory	-eigenvalues distribution -eigenvectors distribution -thresholding -subspace projection	-analytic thresholding of eigenvalues -efficient separation of strayed (migrated) eigenvalues -Low SNR performance	-Reducing Computational Complexity -Exploiting eigenvectors -Extending to general signal scenarios including non-Gaussian and non-independent inputs

Table 2. Discussion of model/system structures of studied methods

System models/structures	Discussion/Disadvantages
Antenna array/Spatial filtering	Previous researches conducted in the field of dealing with jamming and interference usually include techniques (detection/reduction) that are applied after tracking and acquisition, which leads to computational overhead and hardware cost. In fact, it is not independent and self-sufficient. One of the goals is to apply the proposed method before tracking/acquisition. Fixed and non-adaptive methods do not work properly in dynamic environments with variable characteristics. Some methods are only suitable for narrowband jamming and in the presence of broadband jamming, their efficiency decreases significantly. Damage to reliable signal in null direction, implementation complexity, calibration process, degree of freedom dependence on the number of antenna elements.
Movable receiver-synthetic array	The presence of artifact in the output results, high correlation between direct line of sight and multipath signals and the adverse effect on detection, the presence of omitted components in the added covariance matrix.
single antenna	Conventional techniques based on a traditional single antenna also do not have the accuracy and quality of antenna arrays, except in addition to the use of methods that have a relatively high calculation overhead. Detection/reduction methods such as independent negative entropy algorithms, stretching and conventional single antenna are not suitable in all operating scenarios and jamming and have weak points and blind spots. The future approach will be to create a compromise between accuracy/quality and complexity of implementation/ high calculation overhead.
Statistical and spectral features (separation, time-frequency processing, time-space processing, subspace processing)	The amount of calculations and the amount of hardware required for implementation is one of the bottlenecks of some previous researches, such as the 6th and 8th order moment algorithm, multi-dimensional FFT or STFT. Detection/reduction approaches, such as independent negative entropy, stretching and conventional single antenna algorithms, have blind spots and weaknesses in operational scenarios and jamming, and therefore can be improved. The future scope could be to achieve a compromise between accuracy/quality and complexity of implementation/high calculation overhead.
Kalman filter	The need to reduce the average jamming detection time in multiple jamming environments, the need to develop cryptographic authentication methods, the need to improve the coefficients to fit the jitter curve
Integration	The methods that are based on the integration of previous anti-jamming and anti-interference algorithms with auxiliary systems such as INS are also not independent and have hardware overhead costs and their accuracy decreases during long usage times.
Rotating antennas	Due to the movement and rotation of the antenna, mechanical speed and the need for a pedestal, they may not always be suitable for all applications and also have depreciation.
Artificial neural networks (generally artificial intelligence), deep learning, Machine Learning and wavelet transform	Improving the amount of calculations and the amount of hardware required for implementation, as well as improving the accuracy of the output compared to other methods, reduction of runtime and complexity are areas that can be improved in this category of methods.
Diagonal loading	It is necessary to accurately determine the loading factor, preferably analytically, to avoid adverse effects.
Shrinkage, estimation of direction vector, estimation of covariance matrix	Applying the inherent characteristics of the input data in order to more accurately estimate the direction vector and covariance matrix, as well as the more accurate estimation of the weight vector, is one of the topics needed in this field.
Broadening the null of the antenna	Widening/Broadening the null of the antenna can lead to a decrease in the depth of the main beam, which should be compensated for where it causes problems.
Karhunen-Loeve Transform	Apart from excellent performance in separating desirable and undesirable signals, it has high complexity and computational volume. The techniques of reducing the computational volume for this method can be one of the subjects of need and interest. Accurate estimation of the number of dominant eigenvalues as well as eigenvalues in a specific range is an attractive research topic.

4. Conclusion

The utilization of GNSS in different applications such as navigation aids, UAVs, digital modeling, mapping, geospatial analysis/techniques and cloud computing was studied. The research area background of GNSS-threat detection and mitigation was also studied. Existing methods and algorithms related to the subject area were reviewed as well as their advantages and disadvantages. The classification of methods, and strengths and weaknesses, as well as areas for improvement, were presented. It is necessary to design and develop algorithms with more capabilities and performance in the field of detection rate, detection range, estimation accuracy, and quality with reasonable complexity, and remove some weaknesses and bottlenecks of some existing methods.

Conflicts of interest

The authors declare no competing financial interest.

References

[1] Kaplan ED, Hegarty CJ. *Understanding GPS: Principles and applications*. Artech House; 2006.

[2] Pickholtz R, Schilling D, Milstein L. Theory of spread-spectrum communications-a tutorial. *IEEE Transactions on Communications*. 1982; 30(5): 855-884.

[3] Caroti G, Piemonte A, Redini M. Geomatics monitoring and models of the insalination of the freshwaters phenomenon along the Pisan coastline. *Applied Geomatics*. 2015; 7(4): 243-253.

[4] Lobo A, Ara F, Baró F, Camino C. Geospatial analysis for conservation: Applications with open-source software in the Natural Parks of Barcelona. *Applied Geomatics*. 2012; 4(2): 113-122.

[5] Hloupis G, Pagounis V, Tsakiri M, Doxastakis G, Zacharis V. Low-cost warning system for the monitoring of the Corinth Canal. *Applied Geomatics*. 2017; 9(4): 263-277.

[6] Alamouri A, Hassan M, Gerke M. Development of a methodology for real-time retrieving and viewing of spatial data in emergency scenarios. *Applied Geomatics*. 2021; 13(4): 747-761.

[7] Saponaro M, Tarantino E, Fratino U. Geometric accuracy evaluation of geospatial data using low-cost sensors on small UAVs. *International Conference on Computational Science and its Applications*. Springer; 2018. p. 364-374. Available from: https://doi.org/10.1007/978-3-319-95174-4_29.

[8] Spanò A, Sammartano G, Calcagno TF, Cerise S, Possi G. GIS-based detection of terraced landscape heritage: Comparative tests using regional DEMs and UAV data. *Applied Geomatics*. 2018; 10(2): 77-97.

[9] Brovelli MA, Li S, Dragicevic S, Veenendaal B. Introductory editorial: web-based sensors and geoprocessing services. *Applied Geomatics*. 2013; 5(1): 1-2. Available from: https://doi.org/10.1007/s12518-013-0102-z.

[10] Poluzzi L, Tavasci L, Corsini F, Barbarella M, Gandolfi S. Low-cost GNSS sensors for monitoring applications. *Applied Geomatics*. 2020; 12(1): 35-44.

[11] Themistocleous K, Danezis C, Gikas V. Monitoring ground deformation of cultural heritage sites using SAR and geodetic techniques: The case study of Choirokoitia, Cyprus. *Applied Geomatics*. 2021; 13(1): 37-49.

[12] Mugnai F, Longinotti P, Vezzosi F, Tucci G. Performing low-altitude photogrammetric surveys, a comparative analysis of user-grade unmanned aircraft systems. *Applied Geomatics*. 2022; 14(1): 211-223.

[13] de Oliveira Rabelo MW, Griebeler NP, Nazareno NRX. Quality of altimetric surveys in sugarcane agricultural lands performed with GNSS RTK receiver mounted on an all-terrain vehicle. *Applied Geomatics*. 2019; 11(2): 111-119.

[14] Kuras P, Ortyl Ł, Owerko T, Borecka A. The geodetic detection of the variable load impact on the earth-filled structure. *Applied Geomatics*. 2021; 13(1): 19-35.

[15] Fermi A, Realini E, Venuti G. The impact of relative and absolute GNSS positioning strategies on estimated coordinates and ZWD in the framework of meteorological applications. *Applied Geomatics*. 2019; 11(1): 25-38.

[16] Nex F, Remondino F. UAV for 3D mapping applications: A review. *Applied Geomatics*. 2014; 6(1): 1-15.

[17] Costantino D, Angelini M, Alfio V, Claveri M, Settembrini F. Implementation of a system WebGIS open-source for the protection and sustainable management of rural heritage. *Applied Geomatics*. 2020; 12(1): 41-54.

[18] Dabove P, Manzino AM, Taglioretti C. GNSS network products for post-processing positioning: Limitations and peculiarities. *Applied Geomatics*. 2014; 6(1): 27-36.

[19] Moisa MB, Dejene IN, Gemeda DO. Geospatial technology-based analysis of land use land cover dynamics and its effects on land surface temperature in Guder River sub-basin, Abay Basin, Ethiopia. *Applied Geomatics*. 2022; 14: 451-463. Available from: https://doi.org/10.1007/s12518-022-00445-z.

[20] Lindenbergh R, Pietrzyk P. Change detection and deformation analysis using static and mobile laser scanning. *Applied Geomatics*. 2015; 7(2): 65-74.

[21] Masykur M. Analysis of accuracy the InaCORS BIG online post-processing service. *Applied Geomatics*. 2021; 13(2): 227-233.

[22] Lindner G, Schraml K, Mansberger R, Hübl J. UAV monitoring and documentation of a large landslide. *Applied Geomatics*. 2016; 8(1): 1-11.

[23] Sharifi-Tehrani O, Sabahi MF, Danaee M. Null broadened-deepened array antenna beamforming for GNSS jamming mitigation in moving platforms. *ICT Express*. 2022; 8(2): 161-165.

[24] Sharifi-Tehrani O, Lashgarian H, Soleymanzade M, Ghasemian MH. Futurology of electronic warfare systems for IR. IRAN's fast crafts. *Majlesi Journal of Telecommunication Devices*. 2019; 8(2): 51-55.
[25] Sharifi-Tehrani O, Sadeghi A, Razavi SMJ. Design and simulation of IFF/ATC antenna for unmanned aerial vehicle. *Majlesi Journal of Mechatronic Systems*. 2017; 6(1): 1-4.
[26] Sharifi-Tehrani O. Design, simulation and fabrication of microstrip hairpin and interdigital BPF for 2.25 GHz unlicensed band. *Majlesi Journal of Telecommunication Devices*. 2017; 6(4): 1-5.
[27] Sharifi-Tehrani O. Hardware design of image channel denoiser for FPGA embedded systems. *Przegląd Elektrotechniczny*. 2012; 88(3b): 165-167.
[28] Sharifi-Tehrani O. Novel hardware-efficient design of LMS-based adaptive FIR filter utilizing Finite State Machine and Block-RAM. *Przeglad Elektrotechniczny*. 2011; 87(7): 240-244.
[29] Sharifi-Tehrani O. Design, simulation and implementation of an active sound-noise cancellation system for use in a cockpit intercommunication system. *Journal of Applied Research and Technology*. 2012; 10(5): 731-736.
[30] Borio D. *A statistical theory for GNSS signal acquisition*. PHD Dissertation Polytecnico di Torino; 2008.
[31] Grabowski J. Personal privacy jammers: Locating Jersey PPDs jamming GBAS safety-of-life signals. *Gps World*. 2012; 23(4): 28-37.
[32] Ferre RM, de la Fuente A, Lohan ES. Jammer classification in GNSS bands via machine learning algorithms. *Sensors*. 2019; 19(22): 4841. Available from: https://doi.org/10.3390/s19224841.
[33] Dovis F. *GNSS interference threats and countermeasures*. Artech House; 2015.
[34] Poisel RA. *Modern communications jamming principles and techniques*. Norwood, MA: Artech House; 2004.
[35] Gong Y, Wang L, Yao R, Zhang Z. A robust method to suppress jamming for GNSS array antenna based on reconstruction of sample covariance matrix. *International Journal of Antennas and Propagation*. 2017; 2017: 1-12. Available from: https://doi.org/10.1155/2017/9764283.
[36] Humphreys TE, Ledvina BM, Psiaki ML, O' Hanlon BW, Kintner PM. Assessing the spoofing threat: Development of a portable GPS civilian spoofer. *Radionavigation Laboratory Conference Proceedings*. 2008.
[37] Sharifi-Tehrani O, Sabahi MF, Danaee MR. Efficient GNSS jamming mitigation using the Marcenko-Pastur law and Karhunen-Loeve decomposition. *IEEE Transactions on Aerospace and Electronic Systems*. 2022; 58(3): 2291-2303.
[38] Sharifi-Tehrani O, Sabahi MF, Danee MR. Low-complexity framework for GNSS jamming and spoofing detection on moving platforms. *IET Radar, Sonar & Navigation*. 2020; 14(12): 2027-2038.
[39] Jafarnia-Jahromi A, Broumandan A, Nielsen J, Lachapelle G. GPS vulnerability to spoofing threats and a review of antispoofing techniques. *International Journal of Navigation and Observation*. 2012; 2012: 127072. Available from: https://doi.org/10.1155/2012/127072.
[40] Bencze WJ, Galusha B, Ledvina BM, Miller I. An in-line anti-spoofing device for legency civil GPS receivers. *Proceedings of the 2010 International Technical Meeting of The Institute of Navigation*. San Diego, CA; 2010. p. 698-712.
[41] Montgomery PY. Receiver-autonomous spoofing detection: Experimental results of a multi-antenna receiver defense against a portable civil GPS spoofer. *Radionavigation Laboratory Conference Proceedings*. 2011. Available from: https://doi.org/10.15781/T2GB1Z038.
[42] Wen H, Huang PYR, Dyer J, Archinal A, Fagan J. Countermeasures for GPS signal spoofing. *ION GNSS*. 2005; 5: 13-16.
[43] Daneshmand S, Jafarnia-Jahromi A, Broumandan A, Lachapelle G. Low-complexity spoofing mitigation. *GPS World*. 2011; 22(12): 44-46.
[44] Daneshmand S, Jahromi AJ, Broumandan A, Nielsen J, Lachapelle G. GNSS spoofing mitigation in multipath environments using space-time processing. *European Navigation Conference (ENC 2013), Session B2*. Vienna, Austria; 2013. p. 23-25.
[45] Nielsen J, Broumandan A, Lachapelle G. Spoofing detection and mitigation with a moving handheld receiver. *GPS World*. 2010; 21(9): 27-33.
[46] McDowell CE. *GPS spoofer and repeater mitigation system using digital spatial nulling*. Google Patents. 2007.
[47] Fante RL, Vaccaro JJ. Wideband cancellation of interference in a GPS receive array. *IEEE Transactions on Aerospace and Electronic Systems*. 2000; 36(2): 549-564.
[48] Amin MG, Zhao L, Lindsey AR. Subspace array processing for the suppression of FM jamming in GPS receivers. *IEEE Transactions on Aerospace and Electronic Systems*. 2004; 40(1): 80-92.
[49] Amin MG, Sun W. A novel interference suppression scheme for global navigation satellite systems using antenna array. *IEEE Journal on Selected Areas in Communications*. 2005; 23(5): 999-1012.
[50] Brown A, Gerein N. Test results of a digital beamforming gps receiver in a jamming environment. *Proceedings of*

ION GPS. 2001. p. 1-10.
[51] Fante RL, Vacarro JJ. Cancellation of jammers and jammer multipath in a GPS receiver. *IEEE Aerospace and Electronic Systems Magazine*. 1998; 13(11): 25-28.
[52] Zoltowski MD, Gecan A. Advanced adaptive null steering concepts for GPS. *Proceedings of MILCOM'95*. IEEE; 1995. p. 1214-1218.
[53] Daneshmand S, Broumandan A, Sokhandan N, Lachapelle G. GNSS multipath mitigation with a moving antenna array. *IEEE Transactions on Aerospace and Electronic Systems*. 2013; 49(1): 693-698.
[54] Broumandan A, Nielsen J, Lachapelle G. Practical results of high resolution AOA estimation by the synthetic array. *2008 IEEE 68th Vehicular Technology Conference*. IEEE; 2008. p. 1-5.
[55] Draganov S, Harlacher M, Haas L, Wenske M, Schneider C. Synthetic aperture navigation in multipath environments. *IEEE Wireless Communications*. 2011; 18(2): 52-58.
[56] van Trees HL. *Optimum array processing: Part IV of detection, estimation, and modulation theory*. John Wiley & Sons; 2004.
[57] Nielsen J. Broumandan A, Lachapelle G. GNSS spoofing detection for single antenna handheld receivers. *Navigation*. 2011; 58(4): 335-344.
[58] Daneshmand S, Broumandan A, Lachapelle G. GNSS interference and multipath suppression using array antenna. *Proceedings of the 24th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2011)*. 2001. p. 1183.
[59] Broumandan A, Jafarnia-Jahromi A, Daneshmand S, Lachapelle G. Effect of tracking parameters on GNSS receiver vulnerability to spoofing attack. *Proceedings of ION GNSS+*. 2016.
[60] Xiao L, Ma P-C, Tang X-M, Sun G-F. GNSS receiver anti-spoofing techniques: a review and future prospects. *Electronics, Communications and Networks V*. Springer; 2016. p. 59-68.
[61] Pirsiavash A, Broumandan A, Lachapelle G. Characterization of signal quality monitoring techniques for multipath detection in GNSS applications. *Sensors*. 2017; 17(7): 1579.
[62] Broumandan A, Lachapelle G. Spoofing detection using GNSS/INS/odometer coupling for vehicular navigation. *Sensors (Basel, Switzerland)*. 2018; 18(5): 1305. Available from: https://doi.org/10.3390/s18051305.
[63] Motella B, Presti LL. Methods of goodness of fit for GNSS interference detection. *IEEE Transactions on Aerospace and Electronic Systems*. 2014; 50(3): 1690-1700.
[64] Tao M, Zhou F, Zhang Z. Wideband interference mitigation in high-resolution airborne synthetic aperture radar data. *IEEE Transactions on Geoscience and Remote Sensing*. 2015; 54(1): 74-87.
[65] Nunes FD, Sousa FM. GNSS blind interference detection based on fourth-order autocumulants. *IEEE Transactions on Aerospace and Electronic Systems*. 2016; 52(5): 2574-2586.
[66] Wu Q, Zheng J, Dong Z, Su M, Liang H, Zhang P. Interference detection algorithm based on adaptive subspace tracking and RAIM for GNSS receiver. *IET Radar, Sonar & Navigation*. 2018; 12(9): 1028-1037.
[67] Oh M, Kim Y-H. Statistical approach to spectrogram analysis for radio-frequency interference detection and mitigation in an L-band microwave radiometer. *Sensors*. 2019; 19(2): 306.
[68] Lv Q, Qin H. An improved method based on time-frequency distribution to detect time-varying interference for GNSS receivers with single antenna. *IEEE Access*. 2019; 7: 38608-38617.
[69] Rezaei MJ, Abedi M, Mosavi MR. New GPS anti-jamming system based on multiple short-time Fourier transform. *IET Radar, Sonar & Navigation*. 2016; 10(4): 807-815.
[70] Rezaei MJ, Mosavi MR. Hybrid anti-jamming approach for kinematic global positioning system receivers. *IET Signal Processing*. 2018; 12(7): 888-895.
[71] Zhao L, Mao Y, Ding J. A STAP interference suppression technology based on subspace projection for Beidou signal. *2016 IEEE International Conference on Information and Automation (ICIA)*. IEEE; 2016. p. 534-538.
[72] Wang H, Chang Q, Xu Y. An anti-jamming null-steering control technique based on double projection in dynamic scenes for GNSS receivers. *Sensors*. 2019; 19(7): 1661.
[73] Chen L-W, Zheng J-S. A broadened and deepened anti-jamming technology for high-dynamic GNSS array receivers. *IEICE Transactions on Communications*. 2016; 99(9): 2055-2061.
[74] Zhao J, Gao F, Wu Q, Jin S, Wu Y, Jia W. Beam tracking for UAV mounted SatCom on-the-move with massive antenna array. *IEEE Journal on Selected Areas in Communications*. 2018; 36(2): 363-375.
[75] Ni S, Cui J, Cheng N, Liao Y. Detection and elimination method for deception jamming based on an antenna array. *International Journal of Distributed Sensor Networks*. 2018; 14(5): 15501477187. Available from: https://doi.org/10.1177/1550147718774466.
[76] Zhang L, Huang L, Li B, Huang M, Yin J, Bao W. Fast-moving jamming suppression for UAV navigation: A minimum dispersion distortionless response beamforming approach. *IEEE Transactions on Vehicular Technology*.

2019; 68(8): 7815-7827.
[77] Ibrahim MA, Sharawi MS. Real time RSS based adaptive beam steering algorithm for autonomous vehicles. *Progress in Electromagnetics Research*. 2014; 52: 13-25.
[78] Zhao L, Xu J, Ding J, Liu A, Li L. Direction-of-arrival estimation of multipath signals using independent component analysis and compressive sensing. *Plos One*. 2017; 12(7): e0181838.
[79] Cai X, Wang X, Huang Z, Wang F. Performance analysis of ICA in sensor array. *Sensors*. 2016; 16(5): 637.
[80] Yan J, Dong D, Chen W. *The effectiveness of blind source separation using independent component analysis for GNSS time series analysis*. EGU General Assembly, Vienna Austria; 2016. p. EPSC2016-12691.
[81] Daneshmand S. *GNSS interference mitigation using antenna array processing*. Phd Thesis, University of Calgary; 2013.
[82] Broumandan A, Jafarnia-Jahromi A, Lachapelle G. Spoofing detection, classification and cancelation (SDCC) receiver architecture for a moving GNSS receiver. *GPS Solutions*. 2015; 19(3): 475-487.
[83] Yang Q, Zhang Y, Tang C, Lian J. A combined antijamming and antispoofing algorithm for GPS arrays. *International Journal of Antennas and Propagation*. 2019; 2019: 8012569. Available from: https://doi.org/10.1155/2019/8012569.
[84] Zhou C, Li F, Li N, Zheng H, Wang R, Wang X. Improved eigensubspace-based approach for radio frequency interference filtering of synthetic aperture radar images. *Journal of Applied Remote Sensing*. 2017; 11(2): 025004.
[85] Dovis F, Musumeci L. Use of the Karhunen-Loève Transform for interference detection and mitigation in GNSS. *ICT Express*. 2016; 2(1): 33-36.
[86] Trudu M, Pilia M, Hellbourg G, Pari P, Antonietti N, Maccone C, et al. Performance analysis of the Karhunen-Loève Transform for artificial and astrophysical transmissions: Denoizing and detection. *Monthly Notices of the Royal Astronomical Society*. 2020; 494(1): 69-83.
[87] Musumeci L, Dovis F. Use of the wavelet transform for interference detection and mitigation in global navigation satellite systems. *International Journal of Navigation and Observation*. 2014; 2014: 262186. Available from: https://doi.org/10.1155/2014/262186.
[88] Pashaian M, Mosavi M, Moghaddasi M, Rezaei M. A novel interference rejection method for GPS receivers. *Iranian Journal of Electrical and Electronic Engineering*. 2016; 12(1): 9-20.
[89] Mosavi MR, Rezaei MJ, Pashaian M, Moghaddasi MS. A fast and accurate anti-jamming system based on wavelet packet transform for GPS receivers. *GPS Solutions*. 2017; 21(2): 415-426.
[90] Mosavi MR, Pashaian M, Rezaei MJ, Mohammadi K. Jamming mitigation in global positioning system receivers using wavelet packet coefficients thresholding. *IET Signal Processing*. 2015; 9(5): 457-464.
[91] Li H, Borhani-Darian P, Wu P, Closas P. *Deep neural network correlators for GNSS multipath mitigation*. IEEE Transactions on Aerospace and Electronic Systems; 2022. p. 1-23. Available from: https://doi.org/10.1109/TAES.2022.3197098.
[92] Swinney CJ, Woods JC. GNSS jamming classification via CNN, transfer learning & the novel concatenation of signal representations. *2021 International Conference on Cyber Situational Awareness, Data Analytics and Assessment (CyberSA)*. IEEE; 2021. p. 1-9.
[93] Elango A, Ujan S, Ruotsalainen L. Disruptive GNSS signal detection and classification at different power levels using advanced deep-learning approach. *2022 International Conference on Localization and GNSS (ICL-GNSS)*. IEEE; 2022. p. 1-7.
[94] Xu P, Hay C, Kumar R, Surti I, Tjhai C. Detect GNSS spoofing signals using a machine learning method. *Proceedings of the 2022 International Technical Meeting of The Institute of Navigation*. 2022. p. 112-126.
[95] Navarro V, Grieco R, Soja B, Nugnes M, Klopotek G, Tagliaferro G, et al. Data fusion and machine learning for innovative GNSS science use cases. *Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021)*. St. Louis, Missouri; 2021. p. 2656-2669. Available from: https://doi.org/10.33012/2021.18115.
[96] Borhani-Darian P, Closas P. Deep neural network approach to GNSS signal acquisition. *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)*. IEEE; 2020. p. 1214-1223.
[97] Zahran S, Moussa A, El-Sheimy N, Sesay AB. Hybrid machine learning VDM for UAVs in GNSS-denied environment. *Navigation: Journal of The Institute of Navigation*. 2018; 65(3): 477-492.
[98] van der Merwe JR, Nikolikj A, Kram S, Lukcin I, Nadzinski G, Rügamer A, et al. Blind spoofing detection for multi-antenna snapshot receivers using machine-learning techniques. *Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020)*. 2020. p. 3294-3312. Available from: https://doi.org/10.33012/2020.17564.
[99] Klus R, Talvitie J, Valkama M. Neural network fingerprinting and GNSS data fusion for improved localization in

5G. *2021 International Conference on Localization and GNSS (ICL-GNSS)*. IEEE; 2021. p. 1-6.
[100]Semanjski S, Semanjski I, De Wilde W, Gautama S. GNSS spoofing detection by supervised machine learning with validation on real-world meaconing and spoofing data-part II. *Sensors (Basel, Switzerland)*. 2020; 20(7): 1806. Available from: https://doi.org/10.3390/s20071806.
[101]Abdallah AA, Kassas ZM. Deep learning-aided spatial discrimination for multipath mitigation. *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)*. IEEE; 2020. p. 1324-1335.
[102]Wang C-Z, Kong L-W, Jiang J, Lai Y-C. Machine learning-based approach to GPS antijamming. *GPS Solutions*. 2021; 25(3): 1-12.
[103]VOIGT JM. Classification of GNSS jammers using machine learning: Multivariate time series and image classification based approaches. University of Agder; 2021.
[104]Gao P, Sun S, Zeng Z, Wang C. GNSS spoofing jamming recognition based on machine learning. in *International Conference On Signal And Information Processing, Networking And Computers*. Springer; 2017. p. 221-228.
[105]Yang X, Zhang Z, Zeng T, Long T, Sarkar TK. Mainlobe interference suppression based on eigen-projection processing and covariance matrix reconstruction. *IEEE Antennas and Wireless Propagation Letters*. 2014; 13: 1369-1372.
[106]Querol J, Perez A, Camps A. A review of RFI mitigation techniques in microwave radiometry. *Remote Sensing*. 2019; 11(24): 3042.
[107]Chen Z, Xie F, Zhao C, He C. An orthogonal projection algorithm to suppress interference in high-frequency surface wave radar. *Remote Sensing*. 2018; 10(3): 403.
[108]Maccone C. The KLT (Karhunen-Loève Transform) to extend SETI searches to broad-band and extremely feeble signals. *Acta Astronautica*. 2010; 67(11-12): 1427-1439.
[109]Ashourian M, Sharifi-Tehrani O. Application of semi-circle law and Wigner spiked-model in GPS jamming confronting. *Signal, Image and Video Processing*. 2022. p. 1-8.
[110]Sharifi-Tehrani O, Sabahi MF, Danee MR. GNSS jamming detection of UAV ground control station using random matrix theory. *ICT Express*. 2021; 7(2): 239-243.
[111]Sharifi-Tehrani O, Sabahi MF. Eigen analysis of flipped Toeplitz covariance matrix for very low SNR sinusoidal signals detection and estimation. *Digital Signal Processing*. 2022. p. 103677.
[112]Liu Y, Sun X, Zhao S. A covariance matrix shrinkage method with Toeplitz rectified target for DOA estimation under the uniform linear array. *AEU-International Journal of Electronics and Communications*. 2017; 81: 50-55.
[113]Wang H, Yao Z, Fan Z, Yang J, Liu G. A robust STAP beamforming algorithm for GNSS receivers in high dynamic environment. *Signal Processing*. 2020; 172: 107532.
[114]Bhunia S, Behzadan V, Regis PA, Sengupta S. Adaptive beam nulling in multihop ad hoc networks against a jammer in motion. *Computer Networks*. 2016; 109: 50-66.
[115]Moussa M, Osman A, Tamazin M, Korenberg MJ, Noureldin A. Direction of arrival estimation of GPS narrowband jammers using high-resolution techniques. *Sensors*. 2019; 19(24): 5532.
[116]Zhang J, Cui X, Xu H, Lu M. A two-stage interference suppression scheme based on antenna array for GNSS jamming and spoofing. *Sensors*. 2019; 19(18): 3870.
[117]Meng Z, Shen F, Zhou W. Iterative adaptive approach to interference covariance matrix reconstruction for robust adaptive beamforming. *IET Microwaves, Antennas & Propagation*. 2018; 12(10): 1704-1708.
[118]Zhu X, Xu X, Ye Z. Robust adaptive beamforming via subspace for interference covariance matrix reconstruction. *Signal Processing*. 2020; 167: 107289.
[119]Liu F, Du R, Bai X. A virtual space-time adaptive beamforming method for space-time antijamming. *Progress in Electromagnetics Research*. 2017; 58: 183-191.
[120]Bao L, Wu R, Lu D, Wang W. A novel adaptive anti-interference algorithm based on negative diagonal loading for spoofing and jamming in global navigation satellite system. *Journal of Communications Technology and Electronics*. 2016; 61(2): 157-164.
[121]Zhang M, Chen X, Zhang A. A simple tridiagonal loading method for robust adaptive beamforming. *Signal Processing*. 2019; 157: 103-107.
[122]Gan L, Yi Z. Automatic computation of diagonal loading factor for robust adaptive beamforming based on Gaussian distribution. *AEU-International Journal of Electronics and Communications*. 2013; 67(7): 570-573.
[123]Zhuang J, Ye Q, Tan Q, Ali AH. Low-complexity variable loading for robust adaptive beamforming. *Electronics Letters*. 2016; 52(5): 338-340.
[124]Xiao Y, Yin J, Qi H, Yin H, Hua G. MVDR algorithm based on estimated diagonal loading for beamforming. *Mathematical Problems in Engineering*. 2017; 2017: 1-7.
[125]Feng Y, Liao G, Xu J, Zhu S, Zeng C. Robust adaptive beamforming against large steering vector mismatch using

multiple uncertainty sets. *Signal Processing*. 2018; 152: 320-330.
[126]Li X, Wang D-W, Ma X, Xiong Z. Robust adaptive beamforming using iterative variable loaded sample matrix inverse. *Electronics Letters*. 2018; 54(9): 546-548.
[127]Qian J, He Z, Liu T, Huang N. Robust beamforming based on steering vector and covariance matrix estimation. *Circuits, Systems, and Signal Processing*. 2018; 37(10): 4665-4682.
[128]Wu C, Guo Y, Na Y, Wang X, Fu Q, Yan Y. Robust beamforming using beam-to-reference weighting diagonal loading and Bayesian framework. *Electronics Letters*. 2015; 51(22): 1772-1774.
[129]Song A, Wang A, Luan S, Qiu T. Widely linear generalized sidelobe canceling beamforming with variable diagonal loading. *AEU-International Journal of Electronics and Communications*. 2017; 76: 77-85.
[130]Fan J, Guo J, Zheng S. Estimating number of factors by adjusted eigenvalues thresholding. *Journal of the American Statistical Association*. 2020. p. 1-10.
[131]Di Napoli E, Polizzi E, Saad Y. Efficient estimation of eigenvalue counts in an interval. *Numerical Linear Algebra with Applications*. 2016; 23(4): 674-692.
[132]Hartman RG. *Spoofing detection system for a satellite positioning system*. Google Patents. 1996.
[133]Broumandan A, Lin T. Performance of GNSS time of arrival estimation techniques in multipath environments. *Proceedings of the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2008)*. 2001. p. 632-643.
[134]McMilin E. *Single antenna null-steering for GPS & GNSS aerial applications*. Stanford University; 2016.
[135]Manfredini EG. *Signal processing techniques for GNSS anti-spoofing algorithms*. Doctoral Dissertation, Politecnico di Torino; 2017.
[136]Chen H. *Kalman filter aided tracking loop in GPS signal spoofing detection*. University of Cincinnati; 2014.
[137]Daneshmand S, Lachapelle G. Integration of GNSS and INS with a phased array antenna. *GPS Solutions*. 2018; 22(1): 3.
[138]Yang J, Lu J, Liu X, Liao G. Robust null broadening beamforming based on covariance matrix reconstruction via virtual interference sources. *Sensors*. 2020; 20(7): 1865.
[139]Wei S, Xia W, Xie M, Li H, Liu C, Li P. A null broadening method for high dynamic GNSS space-time interference suppression based on the uniform circular array. *2018 14th IEEE International Conference on Signal Processing (ICSP)*. IEEE; 2018. p. 209-213.
[140]Qian J, He Z, Xie J, Zhang Y. Null broadening adaptive beamforming based on covariance matrix reconstruction and similarity constraint. *Eurasip Journal on Advances in Signal Processing*. 2017; 2017(1): 1-10.
[141]Li W, Zhao Y, Ye Q, Yang B. Adaptive antenna null broadening beamforming against array calibration error based on adaptive variable diagonal loading. *International Journal of Antennas and Propagation*. 2017; 2017: 1-9.
[142]Sharifi-Tehrani O, Sabahi MF, Danaee MR. *Improvement of jamming confronting in GPS system based-on signal separation*. PhD Thesis, Imam Hossein Comprehensive University; 2021.
[143]Lakshminarayana S, Kammoun A, Debbah M, Poor HV. Data-driven false data injection attacks against power grid: A random matrix approach. *IEEE Transactions on Smart Grid*. 2021; 12(1): 635-646.
[144]Paul D, Aue A. Random matrix theory in statistics: A review. *Journal of Statistical Planning and Inference*. 2014; 150: 1-29.
[145]Sen A, Virág B. The top eigenvalue of the random Toeplitz matrix and the Sine kernel. *The Annals of Probability*. 2013; 41(6): 4050-4079.
[146]Hoydis J. *Random matrix theory for advanced communication systems*. Other. Supélec; 2012.