INVITED PAPER

Protecting GNSS Receivers From Jamming and Interference

The paper provides an overview of various approaches for protecting GNSS receivers against interference. External aiding using inertial systems, spatial filtering via antenna array beamforming, signal conditioning and filtering in the time-frequency domain, and vector tracking are among the discussed approaches.

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ABSTRACT | Critical government and industry sectors (such as law enforcement, transportation, communication, and finance) are growing increasingly dependent on Global Navigation Satellite Systems (GNSS) for positioning, navigation, and timing. At the same time, the availability of low-cost GNSS jamming devices are presenting a serious threat to GNSS and increasing the likelihood of outages to infrastructures relying on GNSS. The attacks range from malicious parties intentionally jamming GNSS signals within a targeted geographical region to uninformed users causing accidental interference. This paper is an overview of different approaches adopted to date to mitigate GNSS disruption caused by intentional and unintentional jamming. The first approach outlined in this paper is the use of inertial systems to aid GNSS. The second and third approaches are the filtering of jamming/interference in the spatial and time-frequency domains, respectively. The fourth approach is vector tracking of GNSS signals in the receiver.

KEYWORDS | Anti-jamming; GNSS; GPS; jamming

I. INTRODUCTION

Global Navigation Satellite Systems (GNSS) have been designed to withstand a certain level of radio frequency interference (RFI) [1]. This is made possible through the Direct Sequence Spread Spectrum (DSSS) technique used in GNSS. However, the rapid growth of the wireless telecommunication sector has made the spectrum very crowded and quite saturated. Signal harmonics from other systems in the GNSS frequency band can cause incidental interference and are a serious problem to the reliable estimation of user position, velocity, and time (PVT) [5]–[7]. This is because strong interference exceeding the processing gain of the DSSS results in rapidly deteriorating performance for the affected GNSS receivers [3]. GNSS receivers used for civil applications are especially vulnerable since signal characteristics of the GNSS civil signals, such as the carrier frequency, polarization, and modulation parameters, are open and always made known to the public [4].

Besides interference from telecommunication signals, there is intentional jamming. There are two main reasons as to why jamming devices are being used. One reason is to attack others' use of GNSS, and the second reason is to defend one's own privacy, particularly through so-called personal privacy devices (PPDs). An example of the first situation is the several GNSS outages experienced by South Korea since 2010 [8]. These outages were a result of North Korea's ability to jam GPS signals within a radius of 50–100 km near the border, an operational range sufficient to affect scores of civilian flights. In 2012, more than 319 aircraft were affected by a similar cyber-attack.

The second kind of intentional jamming is to date the most frequent. In the name of privacy, PPDs are used to overpower weak GNSS signals to prevent people and vehicles from being tracked [9], [10]. An example is the

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Fig. 1. ***GNSS jamming devices (PPDs) tested at Institute of Communication and Navigation, German Aerospace Center.***

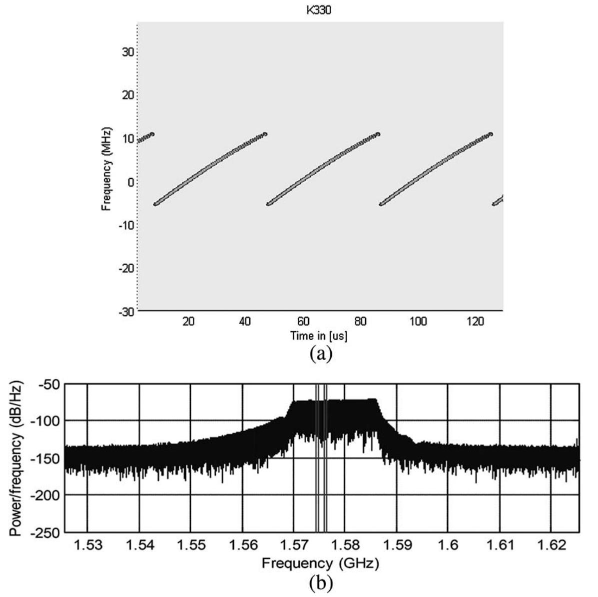

Fig. 2. ***Chirp-like PPD generated by a K330 Jammer: (a) Spectrogram. (b) Power spectral density.***

use of PPDs by some truck drivers who feel uncomfortable having their routes being continuously monitored through GPS. They not only worry about their personal privacy, but also fear that their companies can use the telematics data to enforce driving policies or, even worse, to undertake legal action against them. As a result, some of them use PPDs to prevent themselves from being tracked, without understanding the severe consequences of such a countermeasure. For example, in late 2009, multiple reference receivers installed at Newark Airport, Newark, NJ, USA, simultaneously experienced severe drops in the carrier-to-noise ratio (C/N_0) of several GPS satellites' L1 C/A code. After an investigation by the Federal Aviation Administration (FAA), it was discovered that a truck driver had installed a low-cost PPD on his vehicle [11]. Similarly, in July 2013, GPS signals near the London Stock Exchange were made unavailable for nearly 10 min each day. The cause was again a delivery driver hiding from management [12]. Another potential user of PPDs is criminal gangs, who use them to overwhelm anti-theft devices of cars and trucks carrying valuable loads.

Cases of inadvertent jamming of GNSS systems are also commonplace. In January 2007, two US Navy ships in San Diego, CA, USA, harbor, conducting an experiment on jamming radio signals, accidentally disrupted GPS reception over a large part of the city.

Despite its low power, a jamming device is able to corrupt GNSS signals over a wide area range, especially when it has high time-frequency dynamics (e.g., a chirp-like signal) affecting the GNSS signal spectrum [13]. The PPD jammers shown in Fig. 1 have been tested at the Institute of Communication and Navigation of the German Aerospace Center. Fig. 2(a) and (b) illustrate the spectrogram and the power spectral density, respectively, of one of the cigarette-lighter-type PPD. The frequency sweep of this jammer is 17 MHz within a time of about 40 μs. Since the frequency of the interfering carrier is rapidly varying compared to the receiver integration time, it acts like wideband interference. This prevents many standard interference mitigation techniques from functioning.

The effects of different jamming devices on a GNSS receiver have been studied in [14]–[17]. The results of the aforementioned studies all confirm that a jamming device can disable GNSS signal reception of consumer-grade receivers over a range of several kilometers.

Jamming devices like PPDs are small, portable, and inexpensive. Clearly, jamming presents a serious threat to safety-of-life (SoL) applications and critical sectors like law enforcement, transportation, communication, and finance [18].

In such critical applications, it is important that the GNSS receiver fulfill a minimum level of reliability and robustness even at the cost of increased price and complexity. To meet this need, receiver manufacturers and research institutions have been developing GNSS receivers equipped with anti-jamming capabilities.

In this paper, we provide an overview of various approaches, namely, inertial aiding, spatial filtering, time-frequency filtering, and vector tracking. In inertial aiding and vector tracking, the minimum required C/N_0 level for receiver acquisition and tracking is lowered. Therefore, a GNSS receiver can operate in the presence of relatively strong interfering signals; whereas in the spatial and time-frequency filtering approaches, the incident interfering signals are suppressed before entering the receiver. Since PPDs are identified as the most frequent jamming sources, it is worthwhile to note that inertial aiding, spatial filtering, and vector tracking techniques are helpful with respect to PPD jamming. All the four approaches discussed in this paper can either operate individually or be combined to further improve the anti-jamming protection of a GNSS receiver.

II. INERTIAL AIDING

Inertial navigation is a self-contained navigation technique in which measurements provided by accelerometers and gyroscopes are used to track the position and orientation of an object relative to a known starting point, orientation, and velocity. Inertial measurement units (IMUs) typically contain three orthogonal rate-gyroscopes and three orthogonal accelerometers, measuring angular velocity and linear acceleration, respectively. By processing signals from these devices, it is possible to track the position and orientation of a device. The advantage of an inertial system (INS) is that it is not influenced by jamming signals, as it does not use radio signals at all. The main shortcoming is that the accuracy of an inertial system degrades greatly over time [19].

There are three types of INS/GNSS integration—namely, loosely, tightly, and deeply (also named ultra-tightly) coupled integration.

A. Loosely and Tightly Coupled INS/GNSS Integration

The loosely coupled approach integrates the position outputs from GNSS and INS systems. Loosely coupled integration is the easiest and simplest approach because it is based on the independence of the GNSS and INS navigation functions. Although it provides some tolerance to failures of subsystem components, loosely coupled integration cannot function when the GNSS receiver is unable to track at least four satellites at the same time.

In tightly coupled integration, a GNSS receiver is not regarded as a navigation subsystem, but as a sensor that provides pseudo-range and delta pseudo-range. This tightly coupled approach provides navigational measurement updates even when there are less than four satellites available for a complete GNSS navigation solution. Given the same inertial instruments and the same GNSS receiver, a tightly coupled INS/GNSS outperforms its loosely coupled counterparts in terms of both accuracy and robustness [20].

In loosely and tightly coupled integration, the inertial navigation solution is used to aid GNSS acquisition and tracking [24]. Acquisition aiding provides the GNSS ranging processor with the approximate position and velocity, reducing the number of cells that needs to be searched to acquire the signal. For reacquisition, if the satellite position and velocities are known and the receiver clock is calibrated, the number of cells that needs to be searched can be very small, allowing very long dwell times. GNSS tracking-loop bandwidth is a tradeoff between dynamics response and noise resistance. Narrow tracking-loop bandwidth resists noise, but is not responsive to high receiver dynamics. Vice versa, wide tracking-loop bandwidth is sensitive to receiver dynamics, but sacrifices the processed signal-to-noise ratio (SNR). However, if the tracking loops are aided with the inertial navigation solution, which provides information on the dynamics of the user antenna, the receiver will be able to use narrower tracking-loop bandwidths, improving noise resistance, allowing continued tracking at lower C/N_0 [26]. Furthermore, adaptive tightly coupled (ATC) integration in [27] adaptively sets tracking-loop bandwidth according to the measured C/N_0 and the measurement noise covariance. ATC integration enables GNSS code to be tracked at a C/N_0 much lower than a conventional tightly coupled system tuned for optimum INS calibration [27]. Since the loosely and tightly coupled inertial aiding to GPS is easy to implement, it has been used in some commercial off-the-shelf (COTS) GPS receivers.

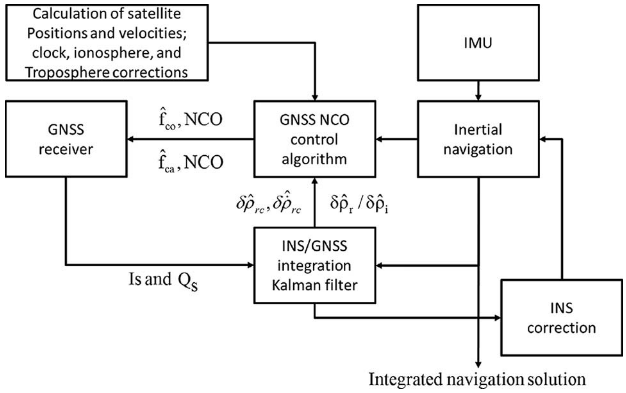

Fig. 3. *Deep INS/GNSS integration architecture [18].*

B. Deeply Coupled INS/GNSS Integration

In the deeply coupled approach, the problem is formulated directly as an estimation problem in which the optimum (minimum-variance) solution is sought for each component of the multidimensional navigation state vector. The navigation algorithms are derived directly from the dynamical, measurement, and noise models [21]. Fig. 3 shows Deep INS/GNSS integration architecture. The code and carrier Numerically Controlled Oscillator (NCO) commands are generated using the corrected inertial navigation solution, the satellite position and velocity from the navigation data message, and various GNSS error estimates. The correlation outputs (I's and Q's), are input directly to the integration algorithm, usually Kalman-filter-based, where a number of INS and GNSS errors are estimated. Deep INS/GNSS integration has the advantage that only the errors in the INS solution need be tracked, as opposed to the absolute dynamics. This enables a lower tracking bandwidth to be used, therefore increasing noise resistance. Deep integration can

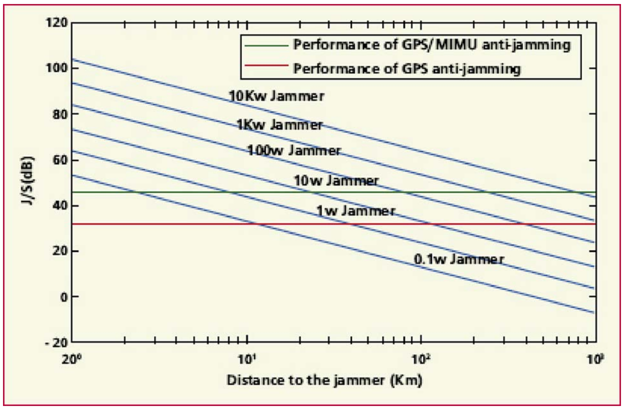

Fig. 4. ***Performance of GPS/MIMU anti-jamming versus GPS anti-jamming [18].***

also operate with fewer than four GNSS satellites for limited periods [22], [23].

There are two classes of deep integration algorithms: coherent and noncoherent integration [28]. Coherent deep integration inputs the I's and Q's as direct measurements to the Kalman filter, while noncoherent integration uses discriminator functions. Coherent integration is more accurate, as it avoids discriminator nonlinearities and has reduced code-tracking noise compared to that of a noncoherent discriminator. However, it can only operate when there is sufficient signal-to-noise ratio to track the carrier phase. In this sense, noncoherent deep integration is more robust.

The deep INS/GNSS integration provides the following manifold advantages [20], [21]:

1) Jamming-to-signal (J/S) ratio improvement. Fig. 4 compares the performance between a GPS only receiver and a GPS/Miniature IMU (MIMU) integrated receiver. A GPS only receiver loses track of the signal when there is a 0.1-W jammer 10 km away. Anti-jam improvements in deeply coupled integration relative to non-inertial-aided loop are 11 dB. That was evaluated for a scenario in the presence of broadband jamming.
2) Improving system accuracy. First, the accuracy of the raw GNSS measurements are increased due to lower tracking loop bandwidths aided by inertial data in deeply coupled integration. Second, INS error, mainly gyro/accelerometer bias and scale factor errors, are calibrated periodically by integrated filter outputs. Third, the integrated filter (usually a Kalman filter) in loosely and tightly coupled integration is an optimal fusion, including GNSS signal tracking loops and correlators.
3) High dynamic performance. Inertial data provide the dynamic reference trajectory for the GNSS signal integration within the receiver's correlators, which results in "dynamic-free" performance. This facilitates a significant reduction in the carrier tracking loops' bandwidth, providing accurate carrier and code phase measurements.

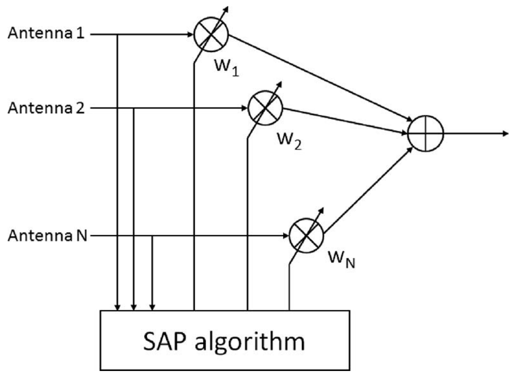

Fig. 5. ***Diagram of SAP.***

III. SPATIAL FILTERING

Spatial filtering uses antenna arrays to point the receiver antenna beam towards the GNSS satellites and away from jammers.

A. Concept of Spatial Filtering

Antenna array processing techniques were first used in the field of radar signal processing [29]. The idea is to linearly combine the received signals at the sensors in a weighted fashion to steer the array response in the direction of target signals while spatially filtering out the jamming sources. In the array processing signal model, the signals at each sensor can be represented as a time-delayed version of the signal received at a reference sensor if the incoming sources are plane waves. In the narrowband situation, the time delay between the sensors can be replaced by a phase delay. In this way, a linear relation between signals received at the sensors is constructed. As a result, the signals at different sensors can be linearly combined with weighting factors to compensate for the phase delay, thus enhancing the target signals and filtering the jamming signals [30].

B. Implementation of Spatial Filtering

Spatial filtering is currently widely used in GNSS applications to filter out jamming signals [31]–[34]. The effect of receiving GNSS signals and rejecting interference is determined by the weights in Fig. 5. There are some different approaches for calculating the weights in spatial filtering [18]: maximum signal-to-interference ratio (MSINR), minimum mean square error (MMSE) and minimum variance (MV). The MV principle, which achieves an output power minimization, is most widely

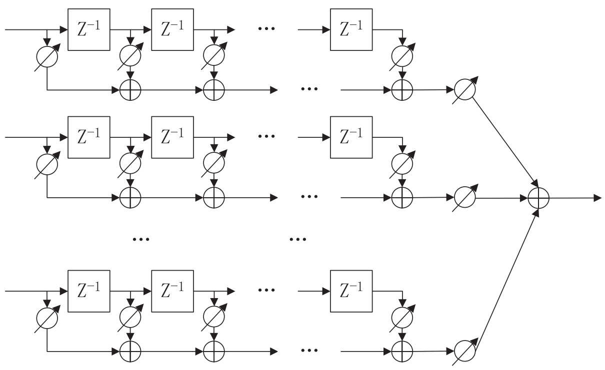

Fig. 6. ***Diagram of STAP.***

used in GNSS receivers since the interference is always much stronger than the satellite signals. A linear constraint is applied on the weights of spatial filtering to preserve the gain in the signal direction (minimum variance distortionless response, MVDR) or the output of a certain reference sensor (power inversion, PI) [36]. Since the directions of satellite signals are not known *a priori*, the PI principle is more widely used in GNSS receivers. In this way, spatial adaptive processing (SAP) is accomplished and spatial degrees of freedom are employed to place nulls in the directions of interference.

SAP can process $N-1$ jamming signals using an N-element array. Nevertheless, SAP has some shortcomings. First, the number of incoming interference sources, whether narrowband or wideband, should be less than the number of antenna elements; otherwise, the jamming signals cannot be mitigated. Furthermore, the satellite signals may also be rejected if their directions are aligned with the jamming sources. Moreover, the performance of SAP deteriorates in the presence of correlated signals such as multipath signals [37]. To overcome the shortcomings mentioned above, temporal degrees of freedom are also employed, and a space-time processor is introduced, leading to the space-time adaptive processing (STAP) technique [38], which has been widely used in radar and wireless communication [39]. In STAP, a finite impulse response (FIR) filter is placed after each sensor. A diagram of STAP is given in Fig. 6.

Employing temporal degrees of freedom, STAP can process many more narrowband interference sources than SAP and maintains better robustness to multipath signals. In STAP, the dimension equals the product of the number of antenna elements and the order of the FIR. Since the computational complexity of the matrix inversion is $O(N^3)$ for an N-order problem, STAP has a much higher complexity than SAP, which limits its application. Rank-reducing algorithms have been proposed to make it possible to accomplish the STAP process [40], [45]. For antennas utilizing spatial and temporal filters, they have the possibility to introduce significant bias errors into the code and carrier phase measurements, and there are various approaches to mitigate the bias [41]–[44].

There is a suboptimal approach that reduces the computational complexity without severely affecting the performance. Spatial frequency adaptive processing (SFAP) has been proposed to process the GNSS signals in the spatial frequency domain rather than the spatial temporal domain [46]. SFAP first splits the frequency band of the incoming signals into many subbands through the discrete Fourier transform or the bandpass filter bank. It then completes an SAP anti-jamming process within each frequency subband. SFAP effectively lowers the computational load while achieving a suboptimal anti-jamming performance. The leakage between the adjacent frequency bins has a negative effect on the performance [38].

Spatial filtering algorithms such as SAP, STAP, and SFAP can process $N-1$ wideband jamming signals using an N-element array. Moreover, STAP and SFAP continue to work when narrowband jammers coexist with $N-1$ wideband jammers. When the number of interference sources is less than that of the antenna elements, spatial filtering promises unlimited anti-jamming performance under ideal conditions. In practice, the upper bound of the jamming and interference power that a spatial filtering can process is determined by the linear range of the radio frequency devices and analog-to-digital convertors (ADCs). Currently, GNSS receiver with spatial filtering can reject interference with a jammer-to-signal ratio (JSR) up to 60 dB.

Another performance metric of spatial filtering is the effect on GNSS signals. For simple algorithms such as SAP, weighting on the outputs of multiple sensors has little negative effect on the satellite signals since the narrowband array assumption still works. However, GNSS signals may be distorted during STAP or SFAP due to the introduction of FIR filters in each channel, leading to estimation errors in the final result [48], [49]. Constraints have been introduced to solve the above problem [50].

The MVDR beamformer mentioned above can reject interference while preserving the gain in a certain direction. Since GNSS positioning requires four or more satellites, a multibeamforming multichannel GNSS receiver has been introduced, which steers multiple beams in the direction of all satellite signals by implementing multiple linear constraints on MVDR weights or constructing an independent channel that consists of a group of weights for each satellite [51]. In this way, signals from all satellites can be enhanced.

IV. TIME-FREQUENCY FILTERING

In addition to the spatial filtering approaches, there are several interference detection and suppression methods based on GNSS signal conditioning and filtering [52]. They differ by the domain in which they operate and in the way they try to separate useful signals from

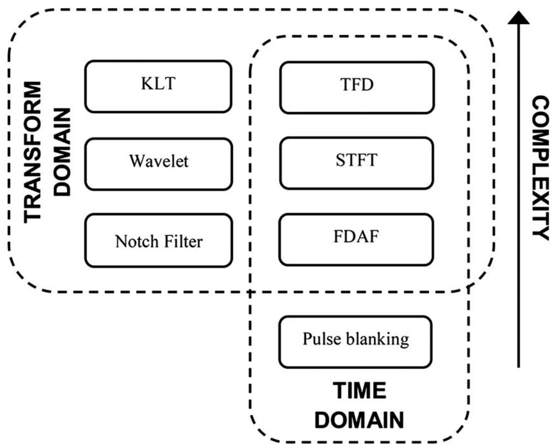

Fig. 7. ***Classification and computational complexity of the interference mitigation techniques in time and transform domains examined in this section.***

interfering signals. Examples are time-domain techniques mostly based on "pulse blanking," frequency-domain techniques [53], [54], time-frequency domain techniques, and other orthogonal signal domain based techniques like Wavelet and Karhunen–Loève Transform (KLT). The different mitigation methods analyzed in this section are summarized and classified in Fig. 7.

Pulse blanking is a simple technique and can be easily executed in real time. It zeros out the signal whenever its amplitude exceeds a certain threshold. It is efficient in those scenarios where the number of interfering sources is limited and the interference signal has low duty cycle and is sparse in time [55], [56]. Besides this limitation, pulse blanking has several flaws. In [56], pulse interference with peak power 15 dB above thermal noise was shown to saturate the low noise amplifier (LNA) of a typical GNSS receiver front end. In such a case, the amplifier needs a certain "recovery" time to return to the normal operation. During this anomalous phase, pulse blanking may perform signal excision even if no interfering pulses are present. Another complication concerning the use of pulse blanking is related to the low dynamics of the automatic gain control (AGC). Indeed, the amplification gain of the AGC is set in accordance to the average power of the input signal over a certain observation time, which is in general longer than the pulse duration. This may cause the blanking of parts of useful signal unaffected by interference. In [56], nonideal pulse blanking has been implemented to partly overcome these problems. The author proposed that the blanking shall continue after the signal drops below the blanking threshold, and the extended blanking-on time shall be equal to the amplifier recovery time. Simulations have been performed considering the case of a composite pulsed interference. In this case, the interference consisted of a superposition of multiple DME/TACAN pulses. The results showed that signal acquisition could be improved by using nonideal blanking compared to standard pulse blanking.

Mitigation algorithms operating in the frequency domain have proven to be very effective in countering the threat of narrowband interference, in particular the so-called continuous wave (CW) interference. The nature of CW interference is, in general, of unintentional origin [1], [6]. In the literature, there are plenty of publications on frequency-domain mitigation algorithms. The survey can be narrowed by focusing on the most widely accepted method to cope with CW interference, namely the adaptive notch filter. Such a filter has time-variant coefficients updated continuously by an optimization criterion. In [57], the use of a notch filter based on Least Mean Square (LMS) algorithm ensured a power attenuation of the CW interferer from 30 to 55 dB. In [58], an adaptive all-pass filter was used. The proposed adaptive algorithm makes use of the Gauss–Newton algorithm to improve the convergence rate. This algorithm was individually and successfully tested in presence of a multitone CW interference and a swept CW interference. In [59]–[61], an infinite impulse response (IIR) filter was used. The main advantages lie in the fact that the IIR filter has low computation cost and has better statistical performance than the FIR filter. In [60], a complex adaptive notch filter has been implemented using the complex Gauss–Newton algorithm to update its coefficients. The algorithm has been also used to estimate the parameters of multiple chirp signals. In [61], a multipole IIR filter has been obtained by cascading a certain number of two-pole notch filters, based on LMS algorithm. The number of two-pole notch filters required by the system can vary with time and matches the number of CW signals affecting the receiver. The system has a detection unit, which monitors the mean value of the filter zeros of each single-notch filter and compares them to a threshold to assess the presence of interference.

However, both time-domain-only and frequency-domain-only mitigation algorithms have some major limitations. Time-domain methods do not consider that only few frequency bins may be affected by the jammer at a given time. On the contrary, frequency-domain methods ignore the fact that only few time samples may be affected by the jammer for a given frequency. Furthermore, none of the above techniques are capable of properly mastering the high dynamics of a PPD jammer.

In [62] and [63], a time-frequency (TF) joint mitigation algorithm, named hybrid blanking, was proposed. Its simplified hardware implementation is known as frequency-domain adaptive filter (FDAF), and its principal aim is to counteract pulsed interference coming from DME/TACAN systems. The algorithm takes advantage of the synergy between time pulse blanking and notch filtering. The signal is passed through a sliding window, and its amplitude is compared to a detection threshold.

In case a pulse is detected, the pulse duration is estimated, and only the portion of signal affected by the interference is passed through an adaptive filter. The adaptive filter operates in the frequency domain. It consists of a notch filter that blanks all the frequency bins exceeding a given threshold. The signal is then converted back to the time domain.

Time-frequency distribution (TFD)-based methods have been shown to be very effective in improving the receiver performance when a broadband interference with narrowband instantaneous bandwidths affects the system. Instantaneous frequency of interference is estimated from the TFD and can be used to represent single as well as multiple component signals in time and frequency. There are several techniques that can be used in place of the TFD. Some of these methods are simpler to implement and have comparable performance if only a single component instantaneous frequency needs to be estimated, but they are likely to fail under rapidly changing environment or in the case of multiple component interference scenarios.

One type of method based on TFD makes use of the information about the instantaneous frequency to adaptively adjust the coefficients of an excision filter, which adaptively removes the interference [64]–[66]. In [65], the instantaneous frequency estimate is used to adjust an FIR filter in a typical open-loop adaptive filter configuration. In [64], the Wigner distribution (WD) has been used as kernel. WD allows high resolution in TF plane, and therefore it is considered one of the most appropriate kernels. Although WD generates sharp and precise signal localization on the time-frequency plane, it introduces unwanted cross-terms when multiple signal sources are present. Furthermore, the signal recovered after interference mitigation from the modified version of the WD suffers from a constant phase offset. In [66], the algorithm was optimized with regards to GNSS signals, and an analytical threshold based on false alarm probability was derived. An IIR filter was used for interference excision, and the IIR filter showed better performance than an FIR filter for mitigation of chirp-like interference. However, the IIR filter introduces a self-noise that may reduce the system performance. In [66], the spectrogram and the WD have been used as kernel for TF representation.

Another type of TFD method performs interference excision directly on the TF plane [67], [68]. In [67], a short-time Fourier transform (STFT) was used. Since STFT suffers from the tradeoff between time and frequency resolution, a set of different STFTs was generated, each of which used a different window and had different characteristics. Interference excision was performed by either clipping or masking the principal components of the optimum STFT. At each data block analyzed by the algorithm, the optimal impulse response or window could change and therefore could vary with time. In [69], a Hanning window was used to improve time–frequency resolution. The estimation of the interference in time-frequency domain was then subtracted from the signal to obtain an interference-free signal. In [70], an excision mask on TF plane is achieved based on an analytical threshold derived as in [66]. The nonideal front-end filter of a generic GNSS receiver was also taken into account. The masked STFT is synthesized using the orthogonal-like Gabor expansion and the resulting signal, namely the estimation of the interference, was subtracted from the original signal to obtain the interference-free signal. An alternative approach makes use of the estimation of the instantaneous interference frequency to down-convert the incoming signal. Interference excision is then performed by a linear time invariant (LTI) filter, which removes the resulting constant frequency component of the interference [71].

For broadband jamming, it has been shown that time-frequency methods using wavelet transforms are very effective in improving receiver robustness [72]–[74]. Interference excision is performed in the wavelet transform domain. The idea is to choose a basis function, called the primitive or mother waveform, for which the interference representation in the wavelet transform domain is confined in a small region, ideally a delta function. In [72], the potential of a wavelet-based mitigation algorithm was demonstrated in mitigating both high-power and low-power pulsed interference, in particular DME. In [74], narrowband interference mitigation was evaluated for two different wavelet families, namely the Meyer mother waveform and the modified Gaussian mother waveform.

Among interference excision algorithms, it is worth mentioning those algorithms operating in the KLT domain [75], [76]. KLT has been used to detect and mitigate narrowband and chirp-like interference by applying a rank reduction filter. In [76], the reassessment of two assumptions commonly taken as granted is noteworthy. First, the algorithm considers the GNSS satellite signals buried under the noise as not negligible. In fact, the presence of these signals impairs the estimate of the sample covariance matrix, which has to be properly compensated to reduce degradation of the system performance. Furthermore, the non-Wishart nature of the noise sample correlation matrix is highlighted, and the impact evaluated in terms of interference detection and mitigation performance degradation.

For all the aforementioned algorithms, particular attention has to be drawn to reduce distortion of the desired signal when applying interference removal. Figure 8 gives guidelines about which mitigation domain should be preferred to mitigate a certain type of interference, taking into account the computational complexity of the algorithm.

None of the aforementioned mitigation techniques alone can assure a satisfactory level of robustness against

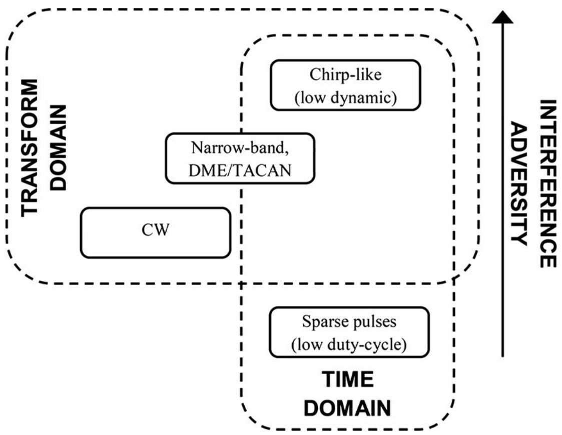

Fig. 8. ***Guidelines on recommended mitigation operating domain for different interference sources.***

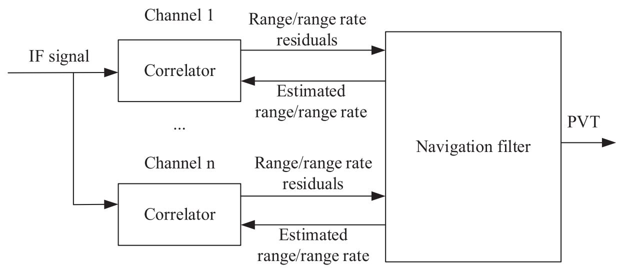

Fig. 9. ***Vector tracking block diagram. Unlike classical scalar tracking, the tracking effort of individual GNSS channels are coupled through the shared receiver states of position, velocity, and time.***

disruptive PPD jammers. Up to now, space-time-frequency domain techniques are the most promising technique for mitigation of wide-band and high dynamic interferences like PPDs. However, they make use of antenna arrays, which implies higher costs both for the antenna and the receiver hardware and, in general, does not always allow fulfillment of SWaP (Space, Weight and Power) and form factor requirements coming from the relevant applications.

V. VECTOR TRACKING

A. Concept of Vector Tracking Versus Classical Scalar Tracking

The conventional method of GNSS receiver baseband signal processing is classical scalar tracking. In classical scalar tracking, signal parameters of in-view satellites are tracked separately. In other words, there is an individual tracking loop for each satellite, and they operate independently. Each tracking loop would output code and carrier measurements that will then be used in the navigation module to estimate the user's position, velocity, and timing. Due to its simplicity and its effectiveness under benign operating conditions, classical scalar tracking is still widely implemented. However, the performance of classical scalar tracking is limited under signal-deteriorated environments caused by urban canyons, electromagnetic interference, etc. For continued signal tracking under challenging conditions, we turn to the concept of vector tracking.

Vector tracking achieves enhanced tracking robustness as compared to classical scalar tracking under degraded conditions, such as weak signals, interference, and jamming, by acknowledging and utilizing the fact that the signal channels are coupled through the shared receiver states of position, velocity, and time [77], [78]. This is achieved through feedback of the receiver states from the navigation module to the signal tracking channels as *a priori* information and constraints. In this manner, the individual channels are jointly tracked through the receiver states. The block diagram of vector tracking is shown in Fig. 9.

Since its inception in 1996, there have been many variations to the implementation of vector tracking. In Section V-B, we will be introducing two main categories of vector tracking algorithms: Vector Delay Lock Loop (VDLL) and Vector Delay-Frequency Lock Loop (VDFLL).

B. Vector Delay Lock Loop

VDLL jointly estimates the code phase delay of each tracking channel through the receiver position and time [77]. In the noncoherent implementation of VDLL, the code phase delay residuals obtained from the code phase discriminators of each tracking channel is first scaled into pseudorange residuals between the corresponding satellite and the receiver. These pseudorange residuals are then used to compute the user position and timing residuals. The updated user position and time is fed back to the tracking channels, closing the VDLL.

[79] provides the VDLL equations and demonstrates the anti-interference performance of VDLL over classical scalar tracking. References [80] and [81] propose several other implementations of the VDLL, such as using the outputs from the loop filters and phase discriminators as measurements. They also provide an analysis on parameter tuning and their influence. References [82] and [83] propose a VDLL based on searching the position and timing cells surrounding the current receiver estimate, and determining the most likely cell according to some *a priori* knowledge.

C. Vector Delay-Frequency Lock Loop

VDFLL, an extension of VDLL, uses the entire navigation vector of position, velocity, and time as a feedback to replicate and jointly track the code phase/frequency and carrier frequency of the individual channels.

Compared to VDLL, VDFLL more effectively exploits the coupling between the individual tracking channels, thus generating better tracking estimates.

There are many researchers focusing on the VFDLL. References [84]–[86] implemented a model of the VDFLL on a software GNSS receiver. A cascaded filter is used within the VDFLL in [87]. References [88] and [89] realized a noncoherent VDFLL scheme on an open-source post-processing software receiver. Reference [90] analyzed and compared the performance of several Kalman-based filters with different measurement sets, design matrices and residuals. References [91] and [92] derived the discrete parametric model and transfer function model of the VDFLL. In addition, they discussed the equivalent bandwidth settings and investigated the VDFLL integrity monitoring algorithm. In [93], the centralized filter and federated design implementation schemes are compared. The VDFLL software implementation given in [94] and [95] combines and jointly tracks received signals from multiple antennas and outputs both the navigation and attitude solutions of the rigid receiver carrier. An adaptive filtering method that rescales the covariance of low-quality channels is used to alleviate the impact of the low SNR signals in [96]. In [97], an adaptive iterative extended Kalman filter (EKF) is used to reduce the truncation error of the conventional EKF. Reference [98] uses signal compression and fading parameters to monitor channel status. References [99] and [100] integrated this parameter that senses environmental changes to increase the robustness of the VFDLL. Another augmentation technique using differential GPS observations and ultrawideband measurements is presented in [101] and [102].

An extension of the VDFLL is the vector delay phase lock loop (VDPLL) where the carrier phase is tracked as well. This was first implemented by [103] as the "Co-OP" technique that has both narrow and wide bandwidth loops for tracking carrier phases independently and jointly through receiver dynamics and clock drift aiding. Reference [104] modeled the receiver and satellite trajectories into the tracking algorithm, then jointly tracked the code and carrier phases. Reference [105] extends [104] by using a projection method to separate the ranging errors into position drifts, clock drifts, ionospheric errors, and tropospheric errors. Reference [105] also studied the Receiver Autonomous Integrity Monitoring (RAIM) technique of vector tracking. In [106], vector tracking is used to assist scalar tracking, and an integrity check is applied to prevent interchannel error spreading. Similarly, in [107], a scalar phase lock loop (PLL) assisted by VDFLL is designed.

D. Vector Correlator

Another distinct class of vector tracking is the vector correlator. Vector correlator, also referred to as the "direct positioning" technique, directly uses the received baseband signal to estimate the user navigation parameters of position, velocity, and time without obtaining the intermediate tracking parameters such as pseudoranges and pseudorange rates [108]. Instead of employing individual joint tracking loops and generating signal replicas for each channel, the vector correlator directly correlates the received satellite signal with the combined receiver signal replica that was generated based on the estimated receiver navigation parameters. This technique presents the most natural, deep integration of the individual tracking channels. It has been shown to be an effective approach for positioning in weak signal environments and is robust against interference and jamming.

In [109], maximum likelihood (ML) estimation was applied to formulate the vector correlator architecture, where signal parameters were converted to spatial estimations. Reference [110] implemented the vector correlator navigation domain tracking architecture on a software GNSS receiver. References [111] and [112] presented a direct position estimation approach aimed at minimizing the distance between the received baseband signal and the local replica. The above direct position estimation approach is improved in [113]–[117] by using different filter states along with a coherent code phase discriminator.

VI. SUMMARY

This paper provides an overview of various methods used to protect GNSS receivers from jamming and interference. The approaches are categorized as: 1) external aiding using inertial systems; 2) spatial filtering by antenna array beamforming; 3) signal conditioning and filtering in the time-frequency domain; and 4) robust GNSS receiver design using vector tracking instead of traditional scalar tracking. Inertial aiding and vector tracking improves the receiver robustness by lowering the minimum required C/N_0 level for receiver acquisition and tracking; whereas, in the spatial and time-frequency filtering approaches, the incident interfering signals are suppressed before entering the receiver. Each of these approaches is beneficial and effective for GNSS anti-jamming by itself. They can also be integrated and applied together for greater robustness and protection against jamming. ■

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