Analysis of multipath detector for antenna array based GNSS receiver

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ABSTRACT

Although hundreds of millions receivers are used worldwide, the performance of location-based services provided by Global Navigation Satellite Systems (GNSS) is still compromised by interference which can range from intentional distortion due to multipath propagation to intentionally menacing signals. Hence, the requirement for proper mitigation techniques becomes a must in GNSS receivers for robust, accurate and reliable positioning. Recently, interference mitigation techniques utilizing antenna arrays have gained significant attention in GNSS communities. Rapid advances in electronic systems and antenna design technology make previously hardware and software challenging problems easier to solve. Furthermore, due to the significant effort devoted to miniaturization of RF front-ends and antennas, the size of antenna array based receivers will no longer be an issue. Given the above, this paper investigates the use of antenna arrays in GNSS interference mitigation applications. The multipath detection method proposed in this paper, targeted at multiple antenna GNSS receivers, is based on the relation between the arithmetic and the geometric means of the covariance matrix Eigen values. This relation is used to build a metric, whose theoretical distribution is known in the absence of multipath. Comparison between the empirical and theoretical distributions is done by the kolmogorov-smirnov test, which is the basis of the proposed algorithm. It operates directly on the digitized signal in parallel to tracking loops and has no need of inferring the number of multipath components or computing their delays. The new spatial processing technique is capable of mitigating both high power interference and coherent and correlated GNSS multipath signals.

General Terms

Global Navigation Satellite System, Multipath Mitigation.

Keywords

Array signal processing in satellite navigation system, multipath detection analysis.

I. Background and Motivation

Positioning and timing systems such as GPS are widespread in today's human life. Currently, most mobile phones as well as vehicles are equipped with GNSS receivers. GNSS applications include safety of life, tracking of animals and vehicles, air, marine and ground transportation, criminal offenders' surveillance, police and rescue services, timing synchronization, surveying, electrical power grids, space applications, agricultural and so many other applications. In fact, it is not an exaggeration to say that GNSS is now affecting in any aspect of human life. However, GNSS signals are vulnerable to in–band interference because of being extremely surface with a power of approximately -158.5 dBW for L1 C/A and -160 dBW for L2. Such signals have spectral power densities far below that of the ambient thermal noise (for L1 C/A signal, 16.5 dB below the noise floor for a receiver with a 2 MHz bandwidth). Although the despreading process performed in both acquisition and tracking stages brings these signals above the background noise, they are still susceptible to interference. The spread spectrum technique applied in the structure of GNSS signals provides a certain degree of protection against interference for narrowband interfering signals and multipath however, the spreading gain alone is not sufficient to avoid interference whose power is much stronger than the GNSS signal power or to mitigate non-resolvable multipath components GNSS interference can be classified in two groups, namely intentional and unintentional interference. Unintentional interference can be generated by a variety of electronic devices working on their non-linear region so as to emit strong electromagnetic harmonics in GNSS frequency bands or from broadband communication systems such as television and radio broadcasting stations which have also harmonics in GNSS frequency bands. Considering bandwidth, interfering signals can be categorized into narrowband and wideband. In the case of narrowband interference, only a small portion of the GNSS frequency bands is affected whereas wideband interference almost occupies the entire frequency band. For example, CW interference is a narrowband interfering signal and Gaussian noise jammers produce wideband interfering signals Past decades have seen significant advances in electronic technology. However, these rapid changes have also had some drawbacks influencing GNSS. In recent years, low cost GNSS jammers have become available such as so-called personal privacy devices (PPDs). The main target of these devices is to disturb GNSS receivers within a radius of a few meters.

However, this is not always the case due to the poor quality of electronic elements used in PPDs. For instance, it has been observed that these jammers can dangerously impact GNSS receiver’s interference not only degrades the performance of GNSS receivers but also can seriously jeopardize the security and safety of human life. This makes GNSS interference detection and mitigation a high research and development priority in GNSS communities.

II. Introduction

Despite the ever increase in demand for accurate and reliable global navigation satellite system (GNSS) dependent services, one of the main drawbacks of GNSS signals is their susceptibility to interference. Interference ranges from unintentional distortion due to multipath propagation to intentionally menacing spoofing signals. Generally effects can be reduced in hardware, software or both parts of a GNSS receiver. In hardware, multipath can be mitigated by using a special antenna design such as choke-ring to put mask on low elevation multipath signals and prevent reflected signals from below the local horizon from reaching the antenna, or employing right hand circularly polarized (RHCP) antennas to at least suppress those weak received signals. For instance, GPS includes satellites orbiting at approximately 20,000 km above the interference decreases the effective signal-to-noise ratio (SNR) of received satellite signals such that a receiver may not be able to measure the true values of pseudo ranges and carrier phases. Therefore, even a low-power interfering signal can easily deny GNSS services within a radius of several kilometers. Interference can generally be detected and suppressed by using time, frequency and spatial domain processing or a combination of them. Time/frequency narrowband interference detection and suppression methods have been widely studied and reported in the literature. However, their performance degrades when dealing with wideband interference or rapid changes of interference centre frequency. On the contrary, interference mitigation techniques utilizing an antenna array can effectively detect and suppress both narrowband and wideband interfering signals regardless of their time and frequency characteristics.

Rapid advancements in electronic systems and antenna technology are resulting in powerful antenna array based solutions to further enhance the performance of GNSS receivers in terms of signal to interference-plus-noise ratio (SINR). This chapter begins with a brief introduction of GNSS interference, mitigation strategies and antenna array processing. Those constitute the motivation for this research. It then goes on to objectives and contributions of this thesis and ends with the dissertation outline.

A. Multipath

Another type of interference in GNSS applications is caused by multipath propagation. This phenomenon in outdoors is mostly caused by reflection and diffraction of the signals off nearby objects such as buildings, mountains, trees and so on. Although the spread spectrum technique is also resistant to multipath, it is only able to mitigate the resolvable multipath components whose delays are more than 1.5 chip duration. Multipath may cause significant errors in pseudorange measurements (e.g. for L1 C/A, up to 100 m). Multipath results in one or more additional propagation paths which always have longer propagation time than the line of sight (LOS) signal and the same as the LOS signal their power density is far below the noise floor. This leads to the distortion of the correlation ambiguity function (CAF) and produces negative or positive biases on pseudorange and carrier phase measurements depending of the received phases of multipath components. Multipath propagation is generally modeled as diffuse. In diffuse multipath scattering environments such as indoor, the magnitudes of the signals arriving by the various paths can be approximately modeled by a Rayleigh distribution. On the other hand multipath model, multipath can be assumed as several deterministic replicas of the LOS signal with unknown delays and attenuation factors. Multipath signals should be considered as wideband interference since their power spread over the GNSS frequency bands. However, due to the high correlation between these signals and the LOS one, in acquisition and tracking stages, these signals are also despread which causes the distortion of CAF and degradation of the receiver’s performance. They may induce significant errors in pseudorange measurements. Therefore, multipath generally should be mitigated after despreading process. The correlation between the LOS signal and the undesired signals causes the signal cancelation phenomenon and the rank deficiency of the temporal correlation matrix. In other words, steering the beam pattern in the direction of the LOS signal and simultaneously suppressing the highly correlated multipath components in other directions requires special considerations

III. Proposed Methodology Signal Model

A GNSS antenna receives measurements which are considered to be multipath components reflected once. In software, there is a large volume of published studies describing time-frequency domain algorithms. Although correlation-based techniques achieve much better results than the conventional standard delay locked loop (DLL) in terms of multipath timing bias, they may fail to mitigate the effect of closely spaced multipath components or when a multipath component that is stronger than the LOS signal exists (e. g. foliage obstructions). In these situations, the performance of GNSS receivers degrades significantly and the timing synchronization may fail. In general, the important common property between most of these correlation-based techniques is that their stable lock point is at the maximum power of the correlation function, no matter how much this peak has been shifted with respect to the peak which corresponds to the actual LOS. On the other hand, multipath mitigation methods based on spatial processing are theoretically able to mitigate multipath components stronger than the LOS signal, no matter how much the multipath components are close to each other and the LOS one. Section 1.2.2 briefly reviews the research conducted on GNSS multipath mitigation employing an antenna array.

GNSS signals are defenseless against high power in–band interference signals such as jamming and spoofing. Spoofing is well-known to be the most hazardous intentional interfering signal that targets GNSS receivers and forces them into generating false time and position solutions. A spoofing attack is more treacherous than jamming since the target receiver is not aware of the threat. Ever-increasing advances in electronic technology have made GNSS spoofers and jammers more flexible and less costly such that interferers impacting GNSS can be developed at a low cost for civilian misapplications.

B. Multipath Mitigation

In the context of multipath mitigation using an antenna array in GNSS applications, much work has been proposed in which Gaussian noise that includes the contribution of all undesired signals such as reflections, interferences, and thermal noise and applied the ML function to this model. Therefore, a simple model for interference is obtained at the expense of a mismatch with the actual interface model. These assumptions may not be realistic in practice for some applications. Another group of methods first finds direction of multipath components by direction finding (DF) methods such as the multiple signal classification (MUSIC) algorithm and then puts nulls in these directions which may be computationally complex in some applications. The most difficulty for multipath mitigation arises from this fact that there is a high degree of correlation between the LOS signal and multipath components and, thus, the conventional antenna array processing techniques fail to cope with low-rate data bits, with TbI being the bit period. denoted by LcI and, respectively. Therefore, $TPNI = LcITcI$ cI, $(t) \in \{-1, 1\}$ is the PRN spreading sequence. The chip length of the codeword and the chip period are is the codeword period. NcI are the number of code epochs per data bit.· the energy-normalized chip shaping pulse is denoted by gI (t). In Binary Offset Carrier (BOC) modulations (used for instance in the GPS L5 and Galileo E1 links) there are square subcarriers that can be included in the definition of (t) without loss of generality.

PRN sequence and the chip-shaping pulse are known at the receiver, (t) can be considered also known, up to 180o phase variations due to data-bit changes.

In this paper, we operate at the output of a bank of correlators. After integration-and-dump, the receiver operates with a set of accumulated signals. The accumulation interval T is typically set to the duration of a code period. A superposition of plane waves corrupted by noise and, possibly, interferences and multipath. An antenna receives M scaled, time-delayed, and Doppler-shifted signals with known waveform structure. These signals correspond to the LOSSs of M visible satellites. The received complex baseband signal is

$$y(t) = \sum_{i=1}^{M} a_i(t) s_i(t - \tau_i(t); f_{d_i}(t)) + \nu(t)$$

Where (t) is the transmitted complex baseband low-rate navigation signal spread by the pseudorandom code of the i-th satellite, considered known. Signal parameters are (t), its complex amplitude; (t), the time-delay; and $fdi(t)$, the Doppler deviation. Finally, (t) is a zero-mean, temporally white, additive Gaussian process that gathers thermal noise and all other non-modeled terms.

In the sequel, we focus on a single satellite's signal, thus neglecting the contribution of the rest of satellites. This assumption is realistic, considering that GNSS systems use pseudorandom noise (PRN) codes with a high processing gain and relatively small cross-correlation among satellite codes. Therefore, the influence of other satellites can be considered as Gaussian noise and included in the thermal noise term since those signals are well below the noise floor The Direct Sequence Spread Spectrum (DS-SS) signal of the i-th satellite was denoted by $si(t)$, its complex baseband model reads as

$$s_i(t; f_{d_i}(t)) = (s_{I,i}(t) + js_{Q,i}(t)) \exp\{j2\pi f_{d_i}(t)t\}$$

Where its in-phase and quadrature components are defined as

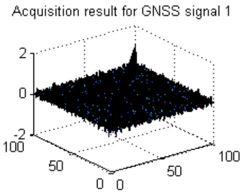
$$\begin{aligned} s_{I,i}(t) &= \sqrt{2P_I} \sum_{m_I=-\infty}^{\infty} b_{I,i}(m_I) p_I(t - m_I T_{b_I}) \\ s_{Q,i}(t) &= \sqrt{2P_Q} \sum_{m_Q=-\infty}^{\infty} b_{Q,i}(m_Q) p_Q(t - m_Q T_{b_Q}) \end{aligned}$$

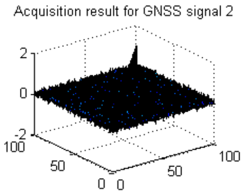
Where

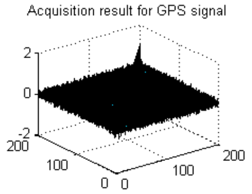
$$\begin{aligned} p_I(t) &= \sum_{u_I=1}^{N_{c_I}} \sum_{k_I=1}^{L_{c_I}} c_{I,i}(k_I)\, g_I(t - u_I T_{\mathrm{PN}_I} - k_I T_{c_I}) \\ p_Q(t) &= \sum_{u_Q=1}^{N_{c_Q}} \sum_{k_Q=1}^{L_{c_Q}} c_{Q,i}(k_Q)\, g_Q(t - u_Q T_{\mathrm{PN}_Q} - k_Q T_{c_Q}) \end{aligned}$$

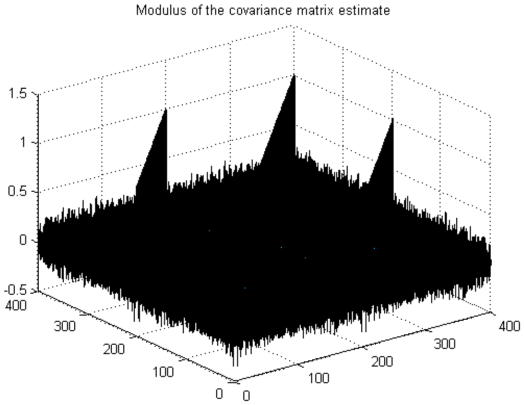
PI is the transmitted power, considered equal for all satellites and elevation-dependant $bI,(t) \in \{-1, 1\}$ is the sequence of

IV. RESULTS:

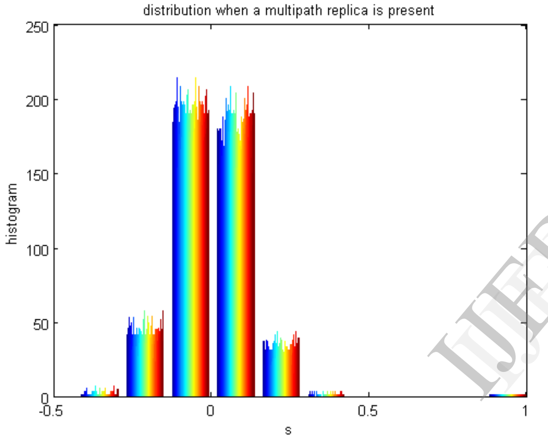




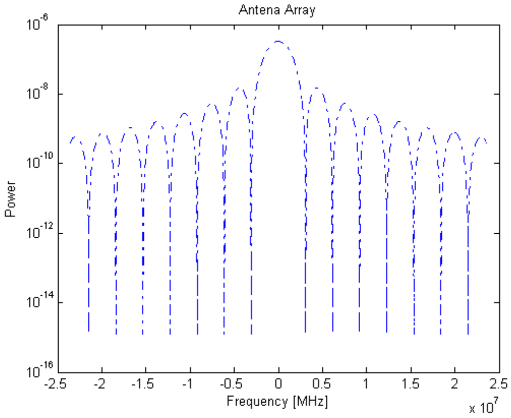




Result of the acquisition of the covariance matrix estimate is shown in first three graphs and the modulus of the covariance matrix estimate is shown in the last graph.



Distribution of the multipath replica



Antenna array output.

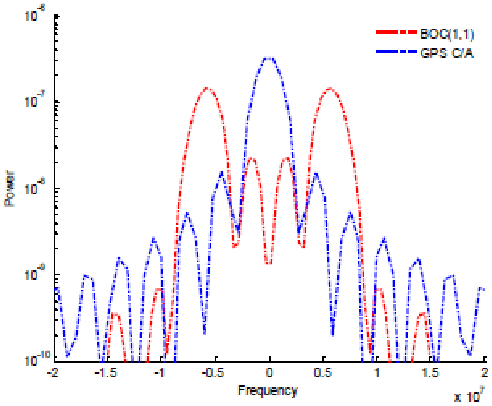


Fig 5. Acquisition of GPS and BOC Signal

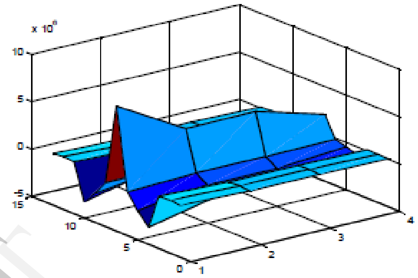


Fig 6. Multipath corrupted Scenario

The proposed algorithm can be used to design a device that could adapt its correlation strategies according to the results of the scenario sensing. The software defined radio approach allows the co existence of different algorithms for the synchronization that can be stored in the memory and applied as required. The formulation of this new detector is generic and thus it can be used as a metric to assess the existence of the LOSS echoes in the scenario. The use of correlator comes at no additional cost to the receiver. The computational cost is more in the first algorithm. Thus this algorithm is only recommended in high precision GNSS receivers, being highly dependent on these errors. For the other applications, we have found out that the other algorithm proposed does not require synchronization, can be used.

V. CONCLUSION

The multipath detection method proposed in this paper, targeted to multiple antenna GNSS receivers, is based on the relation between the arithmetic and the geometric means of the covariance matrix eigen values. This relation is used to build a metric, whose theoretical distribution is known in the absence of multipath. Comparison between the empirical and theoretical distributions is done by the Kolmogorov-Smirnov test, which is the basis of the proposed algorithm. It operates directly on the digitized signal, in parallel to tracking loops, and has no need of inferring the number of multipath components nor computing their delays.

Therefore, the proposed algorithm can be used to design a device that could adapt its correlation strategies according to the results of a scenario sensing. The use of the detector comes at almost no additional cost to the receiver. The operation with the associated largest computational cost in Algorithm 1 is the estimation of the covariance matrix. This operation is already performed by most array-based synchronization algorithms. We analyzed the effect of synchronization errors. From these results, the use of the covariance matrix (Algorithm 1) is only recommended in high-precision GNSS receivers, being highly dependent on such errors. For other applications, we found that the use of the sample covariance matrix (Algorithm 3), which does not require synchronization, offers similar performance to the MDL algorithm. Also, improvements to the MDL algorithm in terms of detection probability can be attained if false alarm probability is increased.

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