GNSS Multipath Estimation and Mitigation Using a Rotating Antenna

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INTRODUCTION

Multipath interference is the main source of naturally occurring errors affecting Global Navigation Satellite Systems (GNSS) receivers. Its effects are hard to mitigate, since they depend on each specific reception scenario, and they can degrade the pseudorange and carrier-phase measurements, thus decreasing the accuracy of the position, velocity and timing estimates obtained by the receiver. Research has shown that among the different existing techniques to fight multipath effects on GNSS receivers, the use of antenna arrays to achieve controlled reception patterns is particularly effective [1]. Antenna arrays can perform spatial filtering, also known as beamforming, which in turn allows to estimate the direction of arrival (DoA) of incoming signals. The spatial filtering is achieved by adjusting the amplitude and phase of each individual antenna output to later combine these into a single output signal. Unfortunately, antenna arrays usually require calibration and, given the carrier frequency of the GNSS signal, they can also be too bulky for many applications. On top of that, if we want to perform the spatial signal processing within the digital domain, the receiver must have as many front end channels (all of them synchronized) as elements of the antenna array. In the end, this increases the data throughput to be processed proportionally to the number of elements of the array. Alternatively, synthetic aperture techniques can enable spatial filtering using only a single moving antenna element. Synthetic aperture has been used for decades in the radar field, and its use on GNSS signals has been proposed in the past years in [2]–[4], for either known or estimated trajectories of the moving antenna.

We have developed an experimental framework to further study the use of synthetic aperture in GNSS receivers. We have mainly focused our efforts on multipath mitigation, but synthetic aperture techniques can also be effectively used for spoofing detection and mitigation. Our final goal is to assess the use synthetic aperture in receivers moving along any arbitrary trajectory, predetermined or estimated by an additional sensor, such as an inertial measurement unit. Basically, synthetic aperture has the potential to be used in any kind receiver, as long as it is in movement. As in [2]–[4], and for simplicity, we started considering a receiver (or more precisely its antenna) moving in uniform circular motion. This movement is periodic, easy to reproduce in practice, and it allows us to synthesize the equivalent of a circular antenna array. Moreover, it can be described (ideally) with only the radius, which can be accurately known, the rotation speed and the initial azimuth of the antenna.

THE GNSS SYNTHETIC APERTURE FRAMEWORK

Our proposed experimental framework has two main elements. The first element is a GNSS software receiver implemented in MATLAB to support synthetic aperture in post-processing. The architecture for a single tracking channel of our software receiver is shown in Figure 1. The receiver uses an auxiliary tracking channel, in which the carrier frequency of the locally generated replica is set using the “static” carrier Doppler frequency estimate. In practice, the main challenge of synthetic aperture techniques in GNSS receivers is isolating the carrier phase shift only due to the antenna motion. This must be done before attempting any spatial filtering. Without considering noise and interferences, the carrier tracking loop observes a Doppler shift that can be expressed as the sum of two contributions: the “static” Doppler, i.e. the Doppler shift that would be observed by a static receiver located at the center of the trajectory followed by the moving antenna; and the “relative” Doppler, i.e. the Doppler shift to due to the movement of the antenna with respect to the center of the trajectory. To isolate the “relative” Doppler at the correlation output, we have estimated the “static” Doppler using the “linear curve fitting” method proposed in [2], [3]. This method extrapolates the linear trend from previous carrier Doppler observations. The correlation outputs, corresponding to

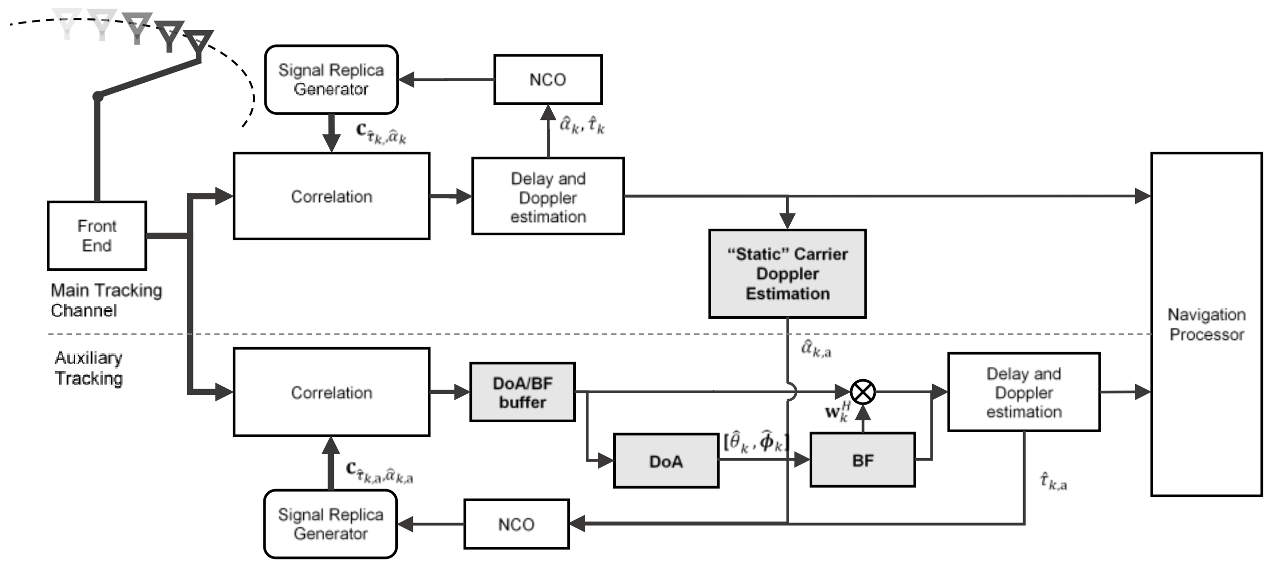

Figure 1 - Architecture for a single tracking channel. The blocks in light gray are specific to beamforming and DoA estimation. $\hat{\tau}_k, \hat{\alpha}_k$ represent $\mathbf{c}\tau k,,\alpha k$, $\mathbf{c}\tau k,a,\alpha k,a$ are the locally generated replicas for the main and auxiliary channels; [θk ,ϕk] are the LOS signals' estimated elevation and azimuth; $\mathbf{w}_k$ is the vector of beamforming weights; and the subscripts $_k$ and $_a$, are used for the *k*th correlation interval and to refer to the equivalent "static" case, respectively.

different positions along the receiver's trajectory, are stored in a buffer to be used as input for DoA estimation. Then, the DoA estimate of the line-of-sight (LOS) signal is used as input to compute the beamforming weights. We have adapted well-known DoA (beamscan, Capon and MUSIC) and beamforming algorithms (delay-and-sum, MPDR) for its use with synthetic aperture instead of with a fixed array.

Our software receiver's tracking stage can operate in two different modes: the traditional closed-loop mode, where it uses the classical delay-locked loop (DLL) + phased-locked loop (PLL) combination for delay and carrier tracking; and an open-loop mode. [5]. Open-loop tracking increases the receiver robustness in harsh environments and it is well suited to potentially integrate advanced techniques to detect spoofing attacks. To the best of our knowledge, this is the first time that synthetic aperture has been used in combination with an open-loop tracking in a GNSS receiver. So far, synthetic aperture processing has been applied after or during the receiver's signal tracking stage. This constrains the possible scenarios to those where the receiver was able, somehow, to successfully acquire and track the signal without any beamforming. However, our end goal is to obtain a receiver that can perform synthetic aperture in the signal acquisition stage, thus allowing its operation when standard acquisition and tracking is not possible.

The second element of our experimental framework is a rotating arm supporting a GNSS antenna, shown in Figure 4. We built the arm in order to implement circular trajectories of adjustable radius (0.5 to 1 m) and angular speeds of up to 1.5 rev/s. A magnetic sensor installed in the arm's rotation axis allows us the accurately measure its instantaneous angular speed.

Using our experimental framework, we tested our implementation of the beamforming and DoA algorithms with synthetic GPS L1 C/A signal generated with a Spirent GSS8000 simulator. In Figure 2 we show an example of how the beamforming is able to mitigate the bias in the code delay estimate introduced by the presence of a strong coherent multipath signal. For the results in Figure 2, we simulated a single satellite signal with a C/N_0 = 45 dB-Hz, plus a controlled multipath component with an attenuation of 6 dB and an additional delay of 0.5 chips (i.e. ≈ 146.5 m). The DoA of the LOS signal was set to [60°,0°] (Elevation, Azimuth), while the multipath's DoA was set to [40°,90°]. The receiver was working in closed-loop tracking mode using beamscan for DoA estimation, and then delay-and-sum with the array manifold vector of the DoA estimate. Then, we used Spirent to simulate a complete scenario with strong multipath [more details], and computed the navigation solution with our software receiver. Our intention was to

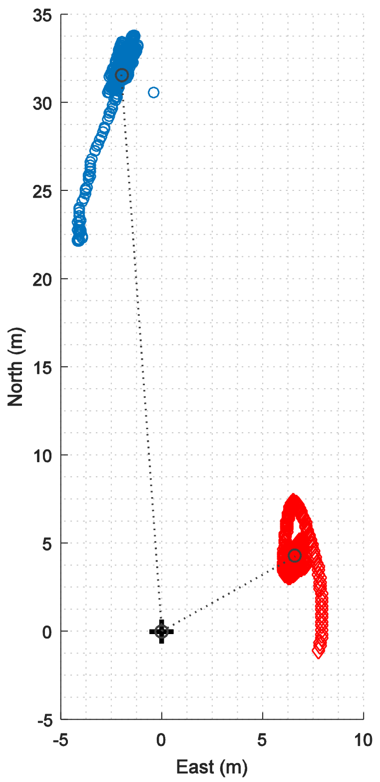

Figure 3 - Comparison of navigation solutions for the static antenna case (blue) and the rotating antenna using beamforming (red), in an multipath scenario simulated with Spirent. Each sample was computed using 100 ms of signal. The origin of coordinates corresponds to the receiver's true position.

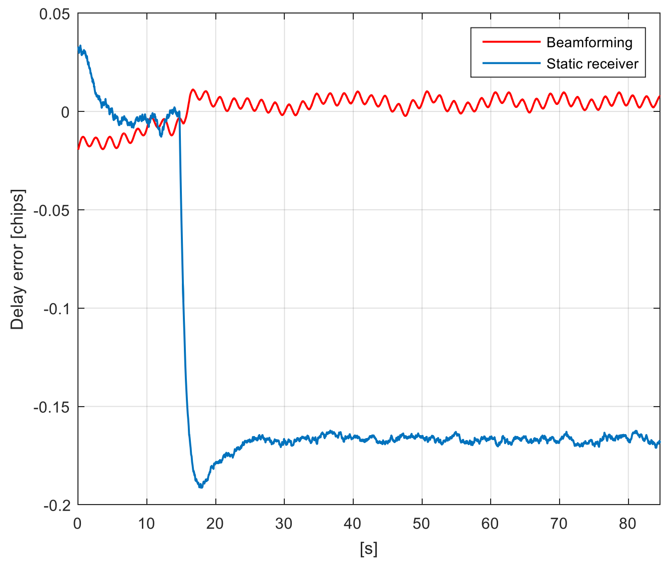

Figure 2 – Code delay error comparison for a single satellite signal using closed-loop tracking. At time *t*=15 s a coherent multipath component is introduced. As a consequence, the static receiver shows a bias that the tracking loop is unable to correct.

assess the impact of using beamforming over the receiver position accuracy. In Figure 3, we show how the use of beamforming reduced the multipath effect over the computed position's bias from 31.63 m to 7.85 m.

In addition to the synthetic data, we recorded real signal data using our rotating antenna in two different scenarios. The first one was the rooftop of Neuchâtel's Microcity building. It had little multipath interference and no signal blockage. It is shown in Figure 4 (antenna picture). The purpose of this scenario was double: to validate our algorithms with real signal, and to verify the rotating antenna's RF chain operation. The second scenario, the terrace in the same Neuchâtel's Microcity building, shown in Figure 5, was deliberately chosen to be significantly harsher in terms of multipath. In Figure 6 we show some examples of the results obtained in this scenario using different DoA algorithms.

CONCLUSIONS AND ONGOING WORK

Our preliminary results show that a synthetic aperture generated using uniform circular motion can be used in combination with open-loop tracking. Moreover, these results validate the proposed framework, which could potentially be used as the basis for a GPS reference station, resilient to multipath interference, and capable of detecting interferences and spoofing attacks. We are currently working towards the performance characterization of the DoA and beamforming algorithms implemented. For the DoA estimation, we are quantifying the accuracy (in terms of root mean square error) and resolution of the different algorithms, while for the beamforming we are looking at the synthesized patterns and the resulting C/N_0 estimates. The use of open-loop tracking allows us to observe the effect of the beamforming over the estimated cross-ambiguity function. Finally, we are also analyzing the impact of the use of beamforming over the navigation solution obtained in the real scenarios described.

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Figure 4 – Rotating arm supporting the GNSS antenna for a circular trajectory. Scenario 1: Neuchâtel’s Microcity rooftop. 46° 59' 51.3276’’ N, 6° 56' 44.916'' E; 28-Nov-2016 14h49 GMT+1.

Figure 5 – Scenario 2: Neuchâtel’s Microcity building, 3rd floor terrace. 46° 59' 52.0188'' N, 6° 56' 44.7648'' E; 15-Nov-2016 14h49 GMT+1. Only the west-oriented side of the terrace is open (as seen in the picture). The building façade is covered with metal plates.

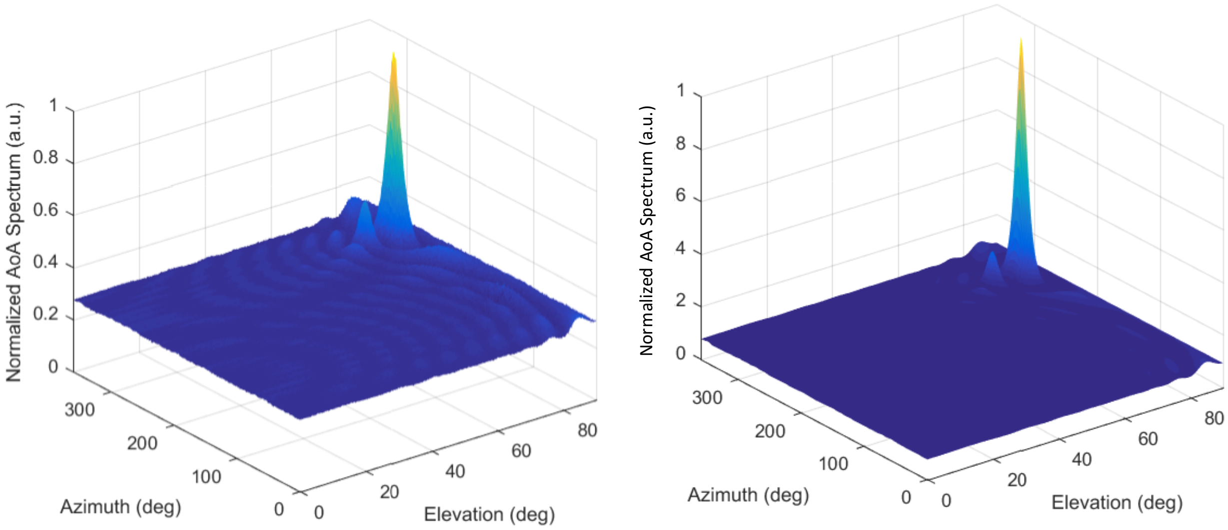

Figure 6 - Direction of arrival maps (or equivalently, angle of arrival (AoA) Spectrums) obtained in Scenario 2 for the GPS PRN 9 using CAPON's algorithm (Left), MUSIC (Right), and beamscan (Down). The rotating antenna was set to 0.9 m radius with an angular speed of 0.5 rev/s. The true elevation and azimuth were 84° and 267°, respectively. The second peak, with the azimuth of the LOS signal but with lower elevation, was identifiable with the three algorithms and is likely to be a coherent multipath contribution. In all cases, the input samples for the DoA estimation were the correlator outputs for a coherent integration time of 20 ms.