

Real-Time Low-Cost Multipath Mitigation Technique Calibrated through Real Data Repeatable Testing

Marc-Antoine Fortin, Jean-Christophe Guay and René Jr Landry
Navigation Research Group (NRG), LaCIME
École de technologie supérieure, Montréal (Canada)

BIOGRAPHY

Marc-Antoine Fortin is currently pursuing his Ph.D. in the field of GNSS receivers' robustness at École de technologie supérieure (ÉTS) in Montréal, Canada. He previously received an Electrical Engineering Master's degree from École Polytechnique de Montréal (Canada) in 2005 and a Bachelor's degree in the same field from Université de Sherbrooke in 2003 (Canada). He is interested in new methods for universal GNSS acquisition and tracking to be used in severe environments with weak signal levels, multipath and interferences.

Jean-Christophe Guay is a Master Engineering student in the electrical Engineering department at ÉTS. He has received an electrical Engineering degree at the same University in 2007. As part of his master degree project, he has already integrated the SBAS capabilities in the LACIME GNSS receiver. His major interest concerns real-time digital signal processing, software defined radio (SDR) and the development of a SDR-based GNSS receiver for severe environment.

René Jr. Landry received a B.Eng. in electrical engineering at the École Polytechnique (Montréal, Canada), in 1992, with a major in space technology. He completed a M.Sc. in satellite communication engineering at the University of Surrey (Guildford, U.K.) in 1993, a Master in space electronics and a DEA in microwaves at SupAéro (Toulouse, France), in 1994. He obtained his Ph.D. degree at University Paul-Sabatier and SupAéro, in 1997, in digital signal processing applied on GPS anti-jamming technologies for the French civil aviation. After a year of post-doctoral fellowship at CNES Toulouse and since 1999, Professor Landry has joined the electrical engineering department of ÉTS. His major interest concerns the development of new mitigation

techniques for GNSS receiver robustness in non-ideal environment including cognitive software-defined GNSS receiver, robustness technologies and aided-systems (DGPS, inertial navigation systems combined with communication and new sensor technologies).

ABSTRACT

Thanks to the continuously improving measurement corrections, signals' characteristics and receivers' performances, the satellite navigation solution can now be freed from most error sources, basically leaving a potential <10 m position error due to multipath, which cannot be differentially corrected, modeled nor predicted (except for static reference stations monitored over long periods). Most multipath mitigation techniques only address the static specular case of multipath, which is the simplest form to simulate and test. Nevertheless, commercial receivers cannot usually afford the extra resources required by such techniques. Thus, current navigation receiver technology is still afflicted by multipath, which it cannot efficiently act upon.

In response to this important problem, this paper reviews an adaptive, low-cost multipath mitigation technique solely based on the measurements obtained from an additional correlator per channel. As introduced at ION 2008, the Variable Spacing Correlator (VSC) allows a fine scanning of the Auto-Correlation Function (ACF). In order to use this tool as a real-time multipath mitigation technique, three VSC configurable parameters (i.e. chip span of the ACF, number of measurement points and coherent integration time per point) are set to obtain a real-time scan.

Although VSC calibration was performed on generated 0.5 chip delayed multipath, 12-ms ACF

continuous scans still allowed detection and characterization of very short delayed multipath (i.e. 0.1 ± 0.05 chip) in a real outdoors dynamic environment with low-profile obstructions. Also, a by-product, a standard deviation study of the ACF peak's position gives a further insight on multipath characterization.

In order to maintain a representative progressive ACF scan, the Delay Lock Loop (DLL) feedback is kept as fast as possible (i.e. 1 ms). Another non-coherent smoothing parameter is made available to average out noise over time. Thus, different optimum "real-time" total scan time may be achieved according to the signal's characteristics and user dynamics. This constraint allows for a snapshot of the multipath to be characterized and used to correct the Pseudo-Range (PR) measurement, thus improving the navigation solution's accuracy.

After a brief review of current receiver errors, including multipath and its existing mitigation techniques, the VSC approach is formally introduced and compared in terms of resources to other existing techniques. According to the further described methodology, recorded real-world multipath scenarios (after using simulators for initial calibration) are used to test the VSC performances on GPS L1 C/A. To speed up testing and to ensure fine-tuning through repeatability, the same real GNSS recordings were played back several times with Avera's tunable RF Record&Playback equipment. The paper then sums up the current findings and opens up onto the upcoming multipath challenges.

1.0 INTRODUCTION

With all the enthusiasm brought up by the Global Navigation Satellite Systems (GNSS) being deployed or modernized; lots of efforts have been invested into successfully mitigating the different navigation error sources. Furthermore, over the past years, satellite positioning has known an increasing popularity across a variety of application fields, most of which are now consumer-based hand-held products [1]. Indeed, GPS receivers are now being included in Personal Device Assistants (PDA) and smart phones through limited-resources hardware (HW) chips for consumer mobile applications. Used in urban canyons, such receivers are mostly affected by signal attenuation, interference, satellite blockage and multipath (MP), as seen in the following paragraphs. The problem with multipath is that it cannot be differentially corrected, modeled nor predicted (except for static reference stations monitored over long periods) [2].

Hence, this paper proposes a GNSS-ready low cost real-time multipath mitigation solution to be integrated into consumer-market chips. After a short description of the receiver error sources, the Variable Spacing Correlator (VSC) approach [3] is applied to multipath mitigation and compared with other multipath detection techniques. The proposed technique is first calibrated through generated signal and then tested on repeatable real-world signals, as described in the applied methodology. Note that any simulation, despite how detailed it may be, will always remain only an attempt to represent the full richness of real world conditions, which are critical for this type of application. The following paragraphs support the fact that multipath is the remaining main GNSS error source.

1.1 RECEIVER EXTERNAL ERROR SOURCES

GNSS receivers may suffer from external error sources, such as interferences, atmosphere, multipath, signal's integrity to name a few. This section shortly reviews the external error sources.

Civil GPS positioning receivers have known a wide commercial interest, especially after 2000 when the GPS Selective Availability (SA) has been deactivated. The Standard Positioning Service's (SPS) accuracy had then improved from roughly 30 to 5 m, thus making atmospheric delays and multipath the most important error sources to overcome. When activated, SA intentionally induced jitter onto the publically available L1 C/A signal in a pseudo-random way, making civil navigation less interesting without the required correction.

Concerning atmospheric delays, as the signal propagates from the satellite to Earth, it passes through all the atmosphere layers, two of which have an impact on the signal's properties [4]. More precisely, the ionosphere polarizes the waves to an extent that is proportional to its Total Electron Content (TEC), delaying the code offset, but advancing the carrier phase. The troposphere, which contains a high level of humidity, also induces an error which can be realistically be modeled with both its dry and wet components.

Regarding multipath, it results from the reflection of the direct Line Of Sight (LOS) signal onto surfaces surrounding the receiver, such as buildings. Basically, two types of reflections are considered depending on the reflective surfaces' type: specular and diffuse [5]. Hence, many attenuated carrier phase- and code-delayed versions of the LOS are constructively (or destructively depending on the

multipath's relative phase) superposed at the receiver's antenna. The resulting Auto-Correlation Function (ACF) is then composed of the sum of the triangular-shaped ACF – in the case of Binary Phase Shift Keying (BPSK) signals – of each incoming version of the LOS, as seen in Figure 1. A single LOS reflection delayed by a duration corresponding to more than two chips would appear as a distinct triangle.

Finally, in the scope of this paper, other external error sources may be clustered under the noise category as they are difficult to predict by their random nature (although some corrections are provided for system errors): satellite clock bias, drift and jerk; receiver clock bias, drift and jerk; ephemerides error; receiver noise, bandwidth; tidal waves; antenna phase center, etc.

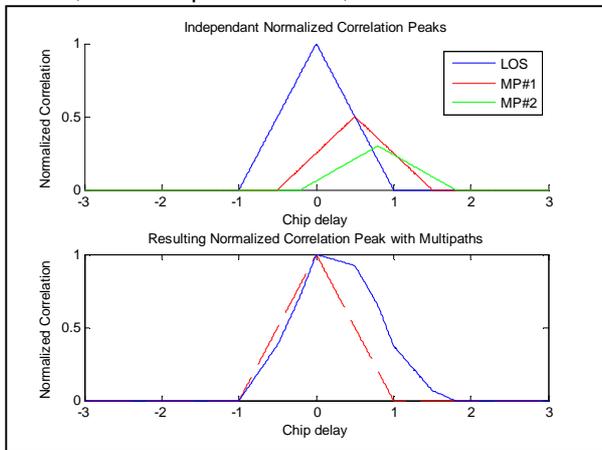


Figure 1: Two multipath effect on a GPS L1 C/A's correlation peak shape in a noise-free simulation

Most of the errors listed above may now be well mitigated. Indeed, ionosphere delays are globally addressed through Satellite Based Augmentation System (SBAS) interpolation corrections. Since it is dispersive (i.e. it is inversely proportional to the square of the satellite's transmission frequency), a more precise ionosphere mitigation is achieved with dual- or triple-frequency measurements, which are becoming more and more available as new/modernized constellations are being deployed. Furthermore, troposphere delays can be modeled for standard weather conditions. Also, thanks to the mobile phones' communication link, ephemerides can be transferred by an alternate system, which improves signal reception sensitivity by up to 25 dB [ION 2009, A6b]; knowing the satellites' position helps narrowing down the acquisition search grid while knowing the navigation data being transmitted allows longer coherent integration times. This is known as Assisted Global Positioning System (AGPS), which could also be applied to reduce

ionosphere impacts based on short baseline Differential GPS (DGPS) corrections' transmission. Hence, most of the errors listed above can now (or soon!) be eliminated or at least greatly attenuated.

1.2 RECEIVER INTERNAL ERROR SOURCES

Apart from these external error sources, receivers' performances also depend on their available resources and internal characteristics. As a matter of fact, sampling rate imposes an upper limit on the admitted signal's bandwidth as well as a lower limit on the correlator spacing, thus admitting greater multipath's biases according to the Early Minus Late (EML) discriminator approach. Also, its internal channel architecture (input and processing quantization level, correlators and discriminator) affects signal acquisition and tracking sensitivity. Finally, the embedded algorithms set the robustness of the solution in presence of satellite blockage, interferences or any integrity issue.

New GNSS signals with higher bandwidths (as a consequence of higher chipping rates) will help resist to interferences by diluting the impact of narrow Continuous Wave Interferences (CWI) over a wider bandwidth. These signals should also provide better positioning accuracy and resistance to multipath since the chip's period is shorter, requiring smaller correlator spacings and thus higher sampling rates.

Coherent integration provides better post-correlation Signal to Noise Ratios (SNR) than non-coherent ones, where navigation bit removal introduces squaring losses. That is to say that the navigation data period limits the coherent integration time, thus imposing a lower limit on the working environment of a receiver [6]. Satellite navigation being increasingly widely used, potential applications are now looking into indoors (where multipaths are the only signals available to obtain a position fix), as well as other hostile environments characterized by low SNR. To address this issue, most new signals will include a data-free pilot component on top of the traditional data one, where the integration times will be only limited by the Doppler effect, which alters the measured frequency according to the user-satellite Line Of Sight (LOS) dynamics [7].

Despite all these advances dealing with error mitigation, the cheapest way to produce a navigation receiver is through an Application Specific Integrated Circuit (ASIC), which provides high volumes of devices at low cost. Therefore, GNSS tracking channels' resources are still important to consider. A real-time GNSS-ready low cost multipath mitigation

technique is thus of a paramount importance, such as the VSC technique described next.

2.0 MULTIPATH DETECTION/MITIGATION REVIEW

Over the years, multipath has become an increasing concern while detection and mitigation techniques have evolved a great deal. In a first attempt to restrain multipath, narrow correlator spacings have been proposed to minimize the impact on traditional Early Minus Late (EML) discriminators for multipath delayed by more than $1+\Delta$ chip, where Δ is the correlator spacing [8]. Nevertheless, for shorter-reflected multipath, such discriminators would simply provide biased measurement, offsetting the computed receiver position by typically less than 10 m. To give a general idea (i.e. non-exhaustive list), multipath mitigation has then progressively evolved from Multipath Eliminating Technique (MET) in 1994 [9], to Multipath Eliminating Delay Lock Loop (MEDLL) in 1996 [10], to Pulse Aperture Correlator (PAC) in 1999 [11] and into the Vision Correlator in 2005 [12].

Another category of approaches based on Code Correlation Reference Waveforms (CCRW), has been developed: the strobe correlator in 1996 [13], the Shaping Correlator in 2005 [14] and the S-Curve Shaping in 2007 [15], whose application have been especially designed to account for Binary Offset Carrier (BOC) family of modulations. Despite good multipath performances, these types of approach suffer from higher noise levels as they are not based on the Maximum Likelihood "Matched Filter"-like Correlator, achieving the Cramer-Rao lower bound. Furthermore, S-Curve Shaping has shown that a minimum sampling frequency reaching 200 MHz was necessary for MBOC signals tracking.

Signal Quality Monitoring (SQM) techniques [16, 17] may provide some multipath detection using fewer resources. Nevertheless, these partial multipath assessments may not be sufficient to truly mitigate multipath, while still requiring 7 to 23 extra correlators.

Finally, even more computationally intense mitigation techniques based on the Maximum-Likelihood principle also exist [18], but are not considered here due to their very high complexities.

2.1 VISION CORRELATORS' REVIEW

The proposed algorithm will hence be compared to the Vision correlator [12], analyzed here for

completeness. As depicted in Figure 2, at every given number of chips (i.e. multiples of $\sim 1\mu s$ time intervals in the case of GPS L1 C/A), n extra complex integrator measurements are taken at slightly different time offsets in order to assess the chip's transition in the time-domain. Most probably, measurements would be averaged during at least 1 ms (i.e. over a code period) to ensure correlation properties are applicable: de-spreading gain allows signal's recovery from under noise.

More precisely, the proposed Vision HW suggests that the PRN Code Generator's enable signal triggers the Code Phase Decode's n delayed 1-sample long pulses used to enable the n complex accumulators one after the other. Now, considering the GPS L1 C/A's 1023 chip-long balanced (as many 0s as 1s) PRN code, there are a maximum of 511 chip transitions per ms (there are actually only 508 in average), which reduces the de-spreading gain by at least 2. Hence, longer navigation bit-synchronized coherent integration times would be required to achieve the full potential de-spreading gain. Equivalently, non-coherent integration combinations would also be admissible, although introducing squaring losses.

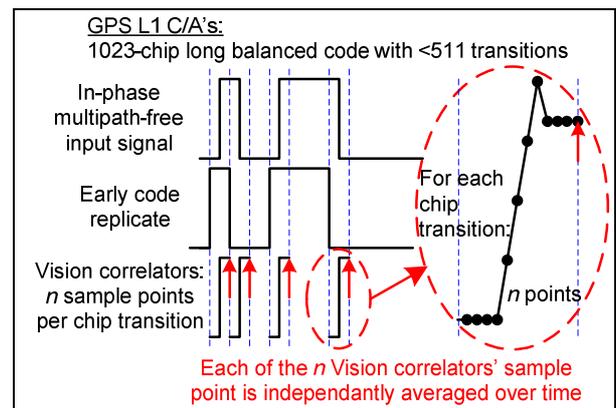


Figure 2: Vision Correlators Principle

In order to scan for all multipath possibilities, the n parallel accumulators are spread over ± 0.5 chip with respect with the Prompt replicate; the first accumulators would detect any multipath delayed by more than 0.5 chip on the previous chip, while the last accumulators would detect the current chip's multipaths delayed by less than 0.5 chip. To position all these complex integrators at n offsets within a chip, the sampling frequency must be at least n times the chipping rate (but not an integer multiplication factor to ensure precision over time [7]). Hence, it is our understanding that a minimal sampling frequency is imposed by the obtained reference chip's transitional shape. The presented results suggest that a >124.8 MHz sampling

frequency is required to discriminate the LOS from its MP (i.e. 122 samples per chip) unless an unsuspected approach is used.

Implementation details require that the carrier and early code wipe-offs provide a complex base-band signal, which is then sampled at different time delays, as seen in Figure 2. In fact, scanning ± 0.5 chip implies ± 0.5 Early and Late correlator spacings, resulting in EML traditional DLL discriminator inputs suffering from 3 dB loss compared to the Prompt correlator; i.e. this is not a narrow correlator approach. Indeed, early code wipe-off is required to then sample n complex points of the always rising chip transitions. These $2n$ points can then be averaged over time (low-pass filtered). Hence, in its presented implementation, the Vision correlator appears to require many resources: 244 accumulators per tracking channel, a >124.8 MHz sampling rate and a 2 ms integration period to achieve the usual de-spreading gain.

Furthermore, analyzing the chips' transition may require simultaneous measurements. But how reliable would it be to scan every point one after the other? In fact, it would depend on both the number of sample points and the tracking performances: i.e. how well is the Prompt correlator keeping track from one integration period to the next and how long performing a total scan takes. Keeping this in opposite trend in mind, this paper proposes a real-time progressive scan of the slower varying ACF with minimal resources. As will be seen later, a 12 MHz sampling frequency could be used to scan half the ACF in 12 ms with a single Variable Spacing Correlator, thus using a 10 times slower sampling frequency, 122 fewer complex integrators and providing MP assessment fast enough to account for low user dynamics. Moreover, a narrow EML discriminator 1 kHz feedback approach would keep track of the signal while slower rated multipath corrections are directly integrated in the navigation solution.

3.0 REAL-TIME VSC-BASED MULTIPATH ASSESSMENT

The proposed multipath mitigation technique is based on a single additional correlator per channel, thus providing a low cost solution. In order to achieve the real-time criterion, four design parameters are made user configurable: 1) the ACF chip span, 2) the number of measurement points, 3) the coherent integration time per point, and 4) the running average count. Note that the first three parameters are configured to obtain a total scan time, while the last is made available to average out

noise over time without compromising real-time response time. It should nevertheless be noted that a running average damps short-term effects and delays events' detection. This constraint allows for a snapshot of the multipath to be characterized and used to correct the PR measurement. The scanning principle is illustrated at Figure 3.

The integration time used for the Delay Lock Loop's (DLL) feedback is also configurable. This parameter has an interesting effect since all the VSC sample points are always taken relative to the DLL Prompt correlator; as a result of the code discriminator, the progressive scan evolves in time with the prompt correlator. The DLL feedback must also allow following user dynamics. Hence, it is important to spend as little time as possible at each scan point in order to obtain an ACF whose first points are coherent with the last. A partial code correlation allows integration times as low as 0.1 ms, although de-spreading gain is not fully achieved and noisier ACF are to be expected for low integration times.

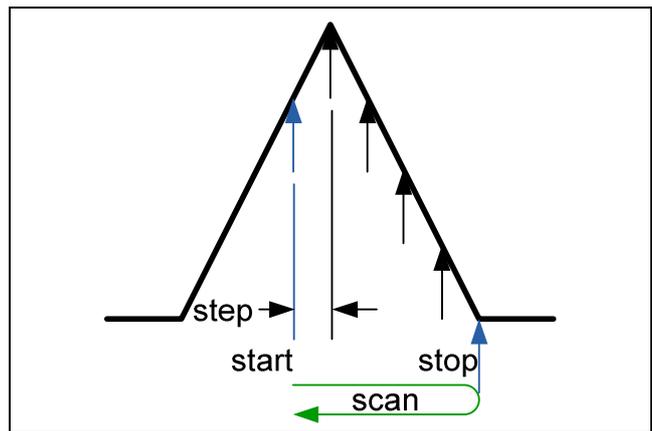


Figure 3: Real-time ACF VSC parameters

To compensate for this effect, the ACF span may be larger to begin with and adaptively reduced to narrow down and mitigate the impact of multipath on the ACF.

In order to reliably reproduce a sharp ACF, the current implementation of the LACIME's GNSS receiver uses a 20 MHz double-sided front-end bandwidth and digitizes the signal at a 60 MHz sampling rate [3]. Also, one must be reminded that not all available points need to be analyzed. Also note that the middle 120 measurement points cover ± 1 chip of the GPS L1 Coarse Acquisition (CA) signal and are implemented through an equivalently wide shift register running at 60 MHz. The inverse of the sampling frequency imposes the maximum resolution achievable (although a rising/falling edge approach could double it), while the large bandwidth

minimizes the impact of high-frequency filtering, thus preserving the triangular shape of the ACF.

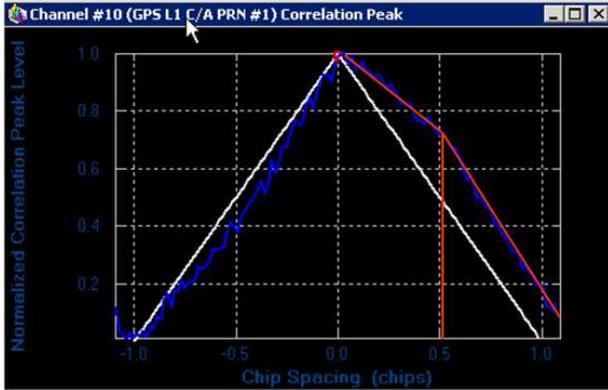


Figure 4: 0.5 chip delayed -10 dB multipath's identification from the ACF scan.

Once a region of the ACF is obtained in real-time, any SQM metric can be applied for multipath characterization: distortion, slope and slope intersection to name a few. This is a considerable improvement over multipath's presence detection only, as it was the case in the previous VSC publication [3]. Hence, instead of removing a PR measurement from the Extended Kalman Filter (EKF), the measurement can now be preserved and corrected, achieving even better, more reliable, results and performances.

3.1 GNSS-READY MULTIPATH ASSESSMENT

As most existing SQM techniques are based on the triangular-shaped ACF's analysis through comparison of given points' level or slope [3], signals with more complex modulation schemes must be simplified to obtain a traditional BPSK ACF for universal multipath mitigation. As demonstrated by the Triple Estimator approach [19], wiping-off the carrier, sub-carriers and code of any GNSS signal always leads to a triangular-shaped ACF.

Thus, different optimum "real-time" total scan times may be achieved according to the considered GNSS signal's characteristics and user dynamics. Moreover, combined to the current implementation of a universal acquisition/tracking channel [20], the proposed real-time ACF scan via VSC is fully compliant with any civil GNSS signal. It comes in two versions: with or without sub-carrier removal. Hence, producing the rather complex ACF associated with the BOC family of modulations may be simplified to a shorter base triangle, typical of BPSK signals. This comes at the cost of a tracking pull-in region reduced by $n = 2 \cdot f_s / f_c$, according to the modulation

BOC(f_s, f_c), which is of minor impact for multipath detection. On the other hand, the maximal multipath delay is automatically reduced by half. It also allows always using the same ACF's distortion metrics for all GNSS signals to characterize their multipath.

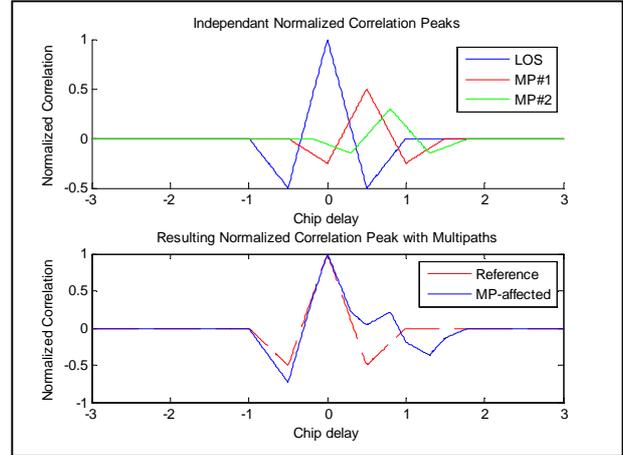


Figure 5: Near-multipath's effect on a BOC(1,1) correlation peak shape in a noise-free simulation

The following section details the observed methodology to calibrate and validate the VSC-enabled real-time ACF behavior.

4.0 TESTS METHODOLOGY

Typically, larger multipath errors are observed at satellite rising or setting, which implies lower LOS power and thus, lower post-correlation SNR. Another interesting fact is that real urban multipath supposes other satellites' blockage by the reflective surfaces. Also, although multipath is often addressed as if it were static, it may suffer from higher dynamics than those of the LOS, according to the obstacles' landscape. Hence, multipath mitigation techniques should not be evaluated solely on the basis of multipath, as it never comes alone: real multipath often implies bad DOP, low SNR and depends on user dynamics.

Keeping this in mind, since it is practically impossible to completely simulate real multipath scenarios with a deterministic algorithm (i.e. simulations, no matter how complex they may be, never account for 100% of the targeted phenomena's interaction), this multipath mitigation technique has first been calibrated with generated signals and then validated through repeatability analysis based on playing back pre-recorded live, 20 MHz wide signals.

All tests are based on Avera's single-channel tunable RF Record and Playback (R&P) [21]. The

16-bit recorder module tuned to L1 frequency was connected (via a 60 dB preamplifier gain) to an active 40 dB Low Noise Amplifier (LNA), L-Band filtered 3.5" circular Right Hand Circularly Polarized (RHCP) Antcom antenna with a hemispherical radiation pattern (3 dB noise figure) and a 5" ground-plane. 25 complex Mega-Samples per second (MSps) were recorded, resulting in a 20 MHz wide recorded signal. Static and low dynamics scenarios were recorded. The signals were then played back at L1 directly into the receiver's RF front end, without any amplification.

Nevertheless, before introducing this equipment in the test setup, a 2-step validation methodology was used. First, the real-time version of the VSC multipath mitigation technique was tested with known generated GPS L1 C/A signals using Spirent's 7700 simulator to determine an optimal configuration of the VSC parameters. Then, to validate that the insertion of the R&P does not compromise the signal processing chain, the same generated signals were recorded and played back, achieving the same multipath mitigation results with the same configurations of parameters. Then, its insertion in the test scheme was further validated by recording real signals that were simultaneously logged by the GNSS receiver. The receiver's logs obtained during playback were compared to the original (live) ones. Since no differences were observed on the PR measurements, it is assumed no observable impacts were introduced by the R&P [21]. Once characterized, the R&P is used to analyze real multipath-affected signals, offering new insights

on true multipath behavior, reproducing in the lab true repeatable signals (with real multipath, blockage, attenuation, etc.).

In the current experiment, the advantage of replaying several times the same RF data is fourfold: 1) VSC parameters' fine tuning, 2) post-process multipath-affected satellite identification and 3) multipath characterization and analysis. Nevertheless, this paper will concentrate on the former point. The last section presents the results obtained with this test methodology.

5.0 RESULTS AND DISCUSSION

Results presented here are grouped into three paragraphs: 1) generated static multipath, 2) generated dynamic multipath and 3) real played back multipath.

5.1 VSC COARSE CALIBRATION

Before submitting the proposed mitigation technique to real signals, a trial and error coarse tuning is performed with generated static multipath signals. As it can be seen in Figure 6, the running average appears to be beneficial for constant multipath as noise is diluted over time while the ACF shape remains. Nevertheless, scanning 128 points with 1 ms integration time takes 128 ms, which may not be acceptable in dynamic multipath scenarios.

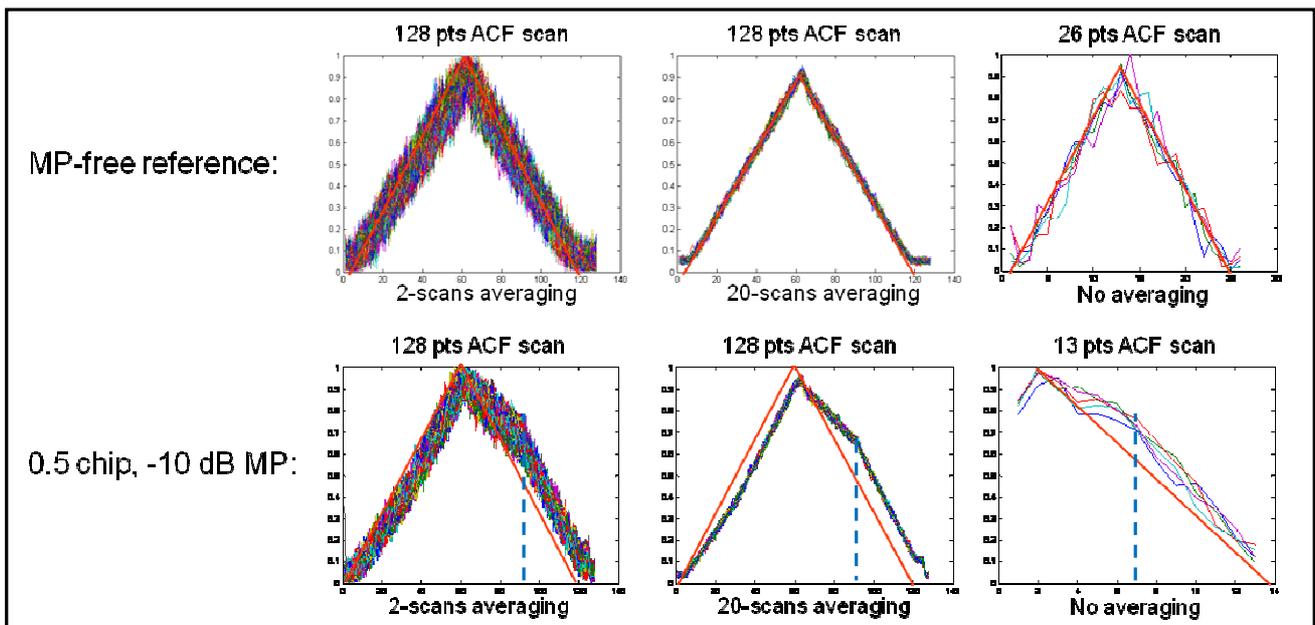


Figure 6: VSC Parameters' Calibration through Generated Static 0.5 chip delayed -10 dB Multipath Signals

Furthermore, the running average will initially take more time to come up with the first curve, while preserving its refresh rate at every new scan (i.e. the resulting curve is based on the current and previous scans). Nevertheless, as foreseen in section 2.0, the averaging will damp any sudden artifact and delay new components' impact on the observations. These two drawbacks may compromise any real-time dynamic multipath analysis to further investigate and better model its true behavior.

On the other hand, it has been determined that because of the delayed intrinsic characteristic of multipath, most impacts were apparent on the ACF's falling slope, which could hence sufficiently be assessed in 12 points in order to detect and characterize a single -10 dB multipath identified by a dashed blue line on the bottom graphs of Figure 6. This minimal 12 ms half ACF real-time assessment is faster than most commercial navigation solution's computation rate. Being totally configurable, the real-time VSC mitigation approach could therefore easily be integrated to the solution and greatly improve its general performances.

5.2 VSC PARAMETERS VALIDATION

Now that a reasonable configuration has been achieved, its performances are assessed on two distinct multipath variations: 1) phase cycling from $0-2\pi$ in 1s (corresponding to an aggressive 1 Hz Doppler, which is equivalent to varying the amplitude) and 2) decreasing a -6 dB multipath chip delay from 1.0 to 0.1 chip. These two test scenarios isolate all the single multipath model parameters to validate the VSC configuration.

A first plot shows 5 consecutive 12-ms scans of the ACF's falling slope. The first, important, observation made from Figure 7 is the presence of distinct null chip offset references (i.e. the normalized maxima is expected on sample 2, but also found on samples 3). This is due to the 1 ms code tracking feedback during the 12-ms ACF scan period: in this specific case, the DLL received a correction between the first and second scan points. Slower DLL feedback would give even worse results as the scan points may drastically deteriorate in time, i.e. diverge from the true ACF.

As seen in Figure 8, a symmetric variation of the 12 ms right ACF slope (with a 20-scan average to lighten the displayed curves) is observed. The ± 0.33 amplitude sweep is lower than expected (± 0.5 corresponding to the multipath's 6 dB amplitude attenuation). It can be explained by two phenomena: 1) the running average of 20 curves damps the short

term extrema of the phase loop and 2) normalizing artifacts.

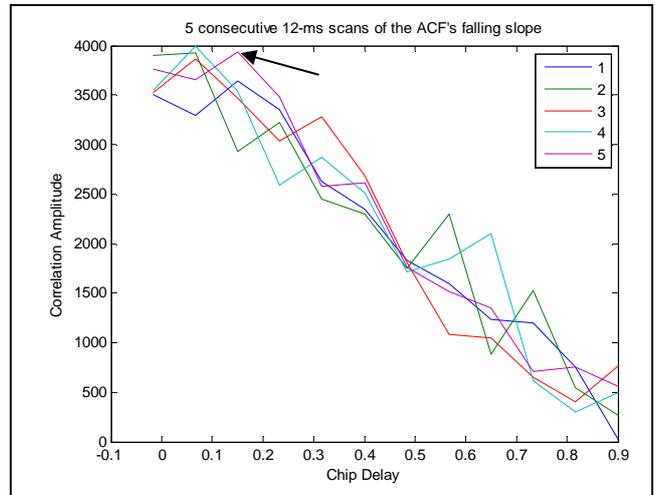


Figure 7: Variations of Consecutive 12-ms Scans of Normalized BPSK ACF's Falling Slope

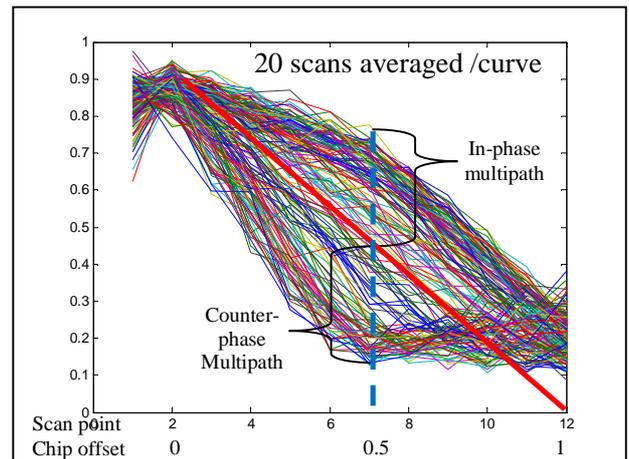


Figure 8: 1 Hz Doppler ($2\pi/s$ phase variation) of a 0.5 chip delayed -6 dB Multipath

Next, Figure 10, a normalized zoom of Figure 9, shows us the different impact of a -6 dB multipath delayed by 1.0 to 0.1 chip with 0.1 chip steps. Once again, the display is softened by 20 scans averaged curves, where the expected 10 different slopes and corresponding intersection points can be identified. One can notice that the falling slope appears to be steeper for longer delayed multipath. Finally, a very low number (~ 20) of scan results lay above the standard ACF curve. These 9 sets of variations are due to the manual transition of the different delayed multipath signals: a shorter delayed multipath is added before the current one is removed, resulting in a three-signal transitional (LOS + 2 MPs) ACF of greater amplitude, as clearly seen in Figure 9.

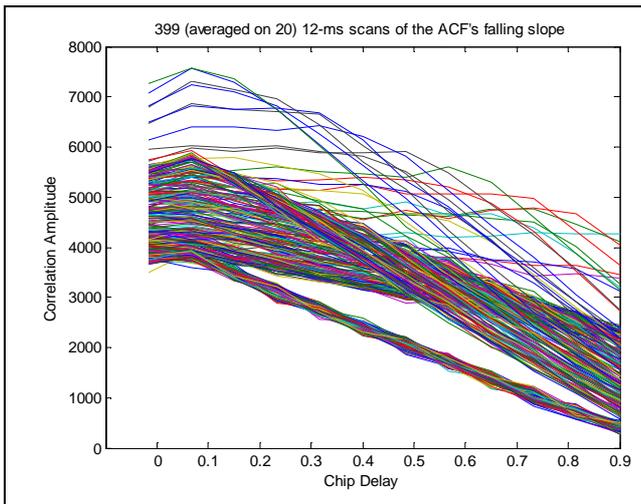


Figure 9: Decreasing chip delays of a -6 dB MP

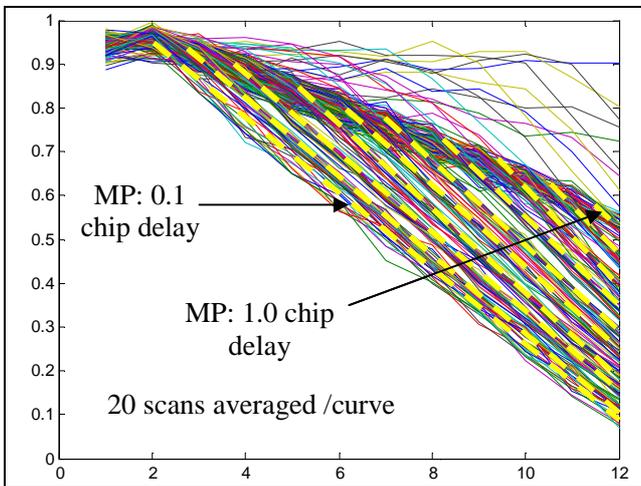


Figure 10: Successive decreasing chip delays (1 to 0.1 chip in 40 s) of a 6 dB attenuated multipath

5.3 REAL-WORLD MULTIPATH VSC ASSESSMENT

Recordings were made in an empty parking lot in the north of Montréal (Canada) with 10° visibility, as represented on Figure 11. First, multipath-free in static (1.) and then in dynamic (2.A) were performed, validating the VSC-enabled real-time ACF curves. Then, a low dynamic van, with a GNSS antenna standing 0.5 m above its roof, travelled at ~ 10 km/h in greater rounded corners superposed rectangles (2.B) delimited by cones and following as much as possible the side-walk edges. As can be seen in Figure 12, half of the rectangle trajectory was obstructed by low profile, ~ 3 m distant buildings. Thus, very short multipath was expected from low elevation satellites in test 2.B.

Since the receiver's Graphical User Interface (GUI) has a refresh rate limit of 10 Hz, 100-point ACFs were initially visually inspected. Thanks to the R&P, low-elevation multipath-suspected satellites were identified in post-process and further investigated. The current section presents analysis of PRN6, on clear sky day on September 2nd, 2009 in the early afternoon.

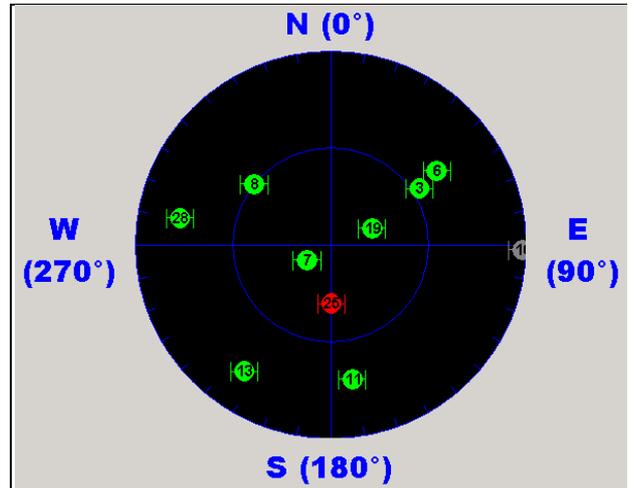


Figure 11: Real recorded and played back sky plot

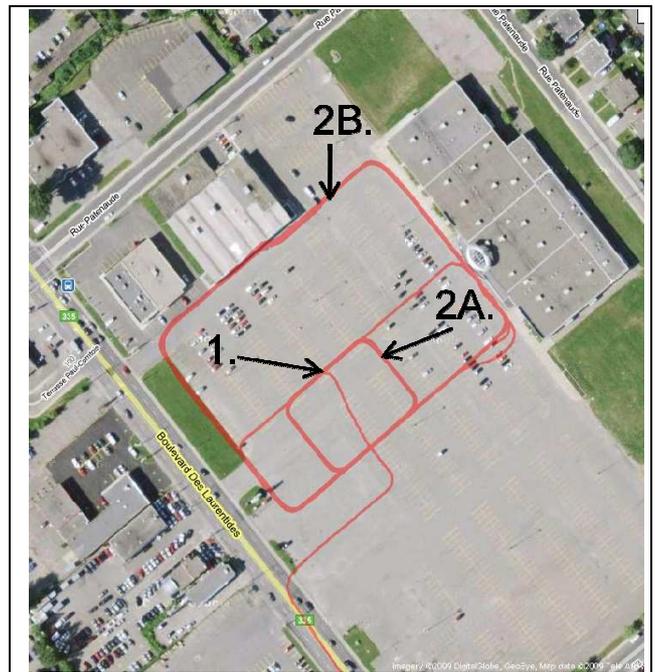


Figure 12: GPS L1 C/A RF recordings in static (1.) and dynamic (2.) with (A) and without (B) MP

Its ACF was then compared to those from satellites at zenith. Because of the lower SNR typical of low-elevation satellites, tracking performances were diminished, thus making the observed ACF very

noisy, which demanded for averaging. It was then noticed that low dynamics made the short-delayed multipath (6-7 m delayed multipath coming from ~3 m away low buildings) difficult to clearly observe on the obtained ACF plots. Nonetheless, MP could be suspected in the 0.05-0.15 chip delays from Figure 13. Hence, the same number of scan points and step were shifted to the left to cover the MP, confirming the hypothesis in Figure 14, where 0-chip offset peak divergence and multi-peak are clearly observed.

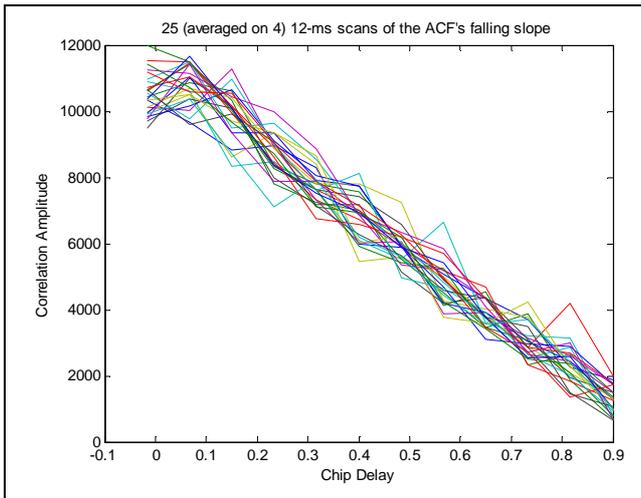


Figure 13: Real-world low-dynamics short-delay MP

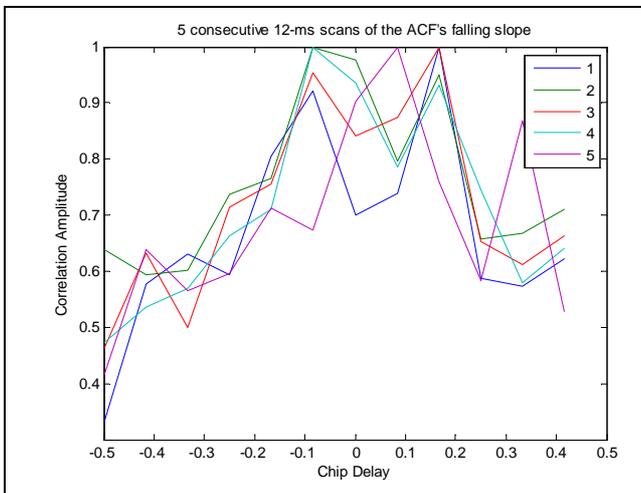


Figure 14: Real-time MP suspected centered ACF

A more convincing image of the same test is presented in Figure 15 where the slopes are slightly offset from a perfect symmetry. Figure 16 displays the same results with averaging, confirming the trend.

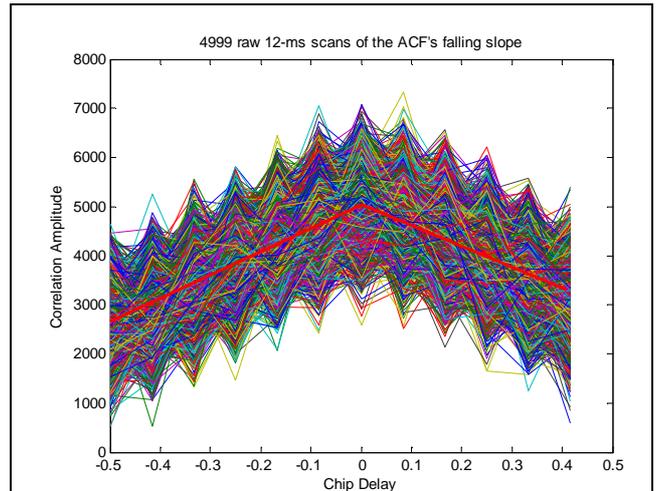


Figure 15: 1-min. MP suspected ACF scan period

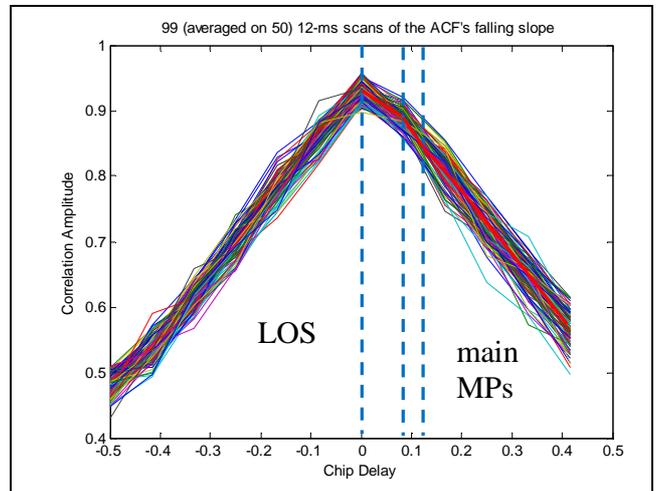


Figure 16: Averaged 1-min ACF observations

Finally, Figure 17 provides another metric to characterize multipath. Indeed, the peak's distribution on the chip axis shows a high concentration on the 0-chip offset, as well as a second high score on the next sample (i.e. 1/12 chip offset is 50% higher than at -1/12 chip offset).

To validate the reliability of this dynamic multipath results (2.B), the same test was performed on real static multipath-free data (1.), as displayed on Figure 18 for a full ACF scan, still on PRN#6. The finer 128-point full ACF scan (blue) appears a little noisy due to the satellite's low elevation angle. Nevertheless, this phenomenon is not observable with a scan step of 5: it can be seen that the 25 point full ACF scan (red) presents a balanced normal Gaussian distribution curve (with only 6% deviation between the two values around the 0-chip offset). Note that this corresponds to the 12-point half ACF scan presented in Figure 16. These results prove that the

above results are truly due to multipath. Furthermore, although not real-time, this approach could also be used as a multipath mitigation technique. Nonetheless, further study of such a distribution should help in detecting and characterizing multipath.

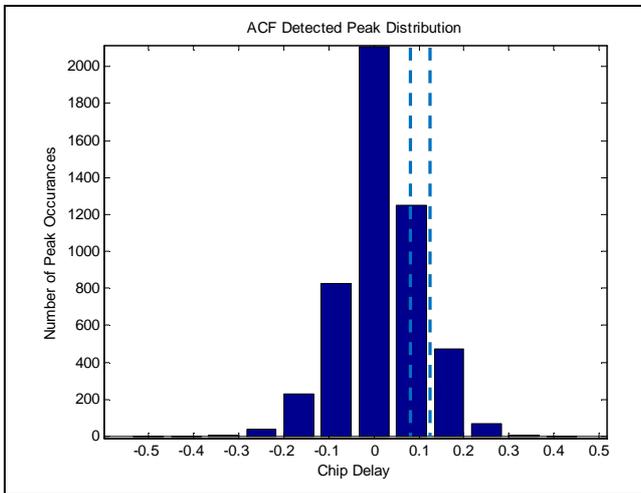


Figure 17: 4999 ACFs' peak distribution

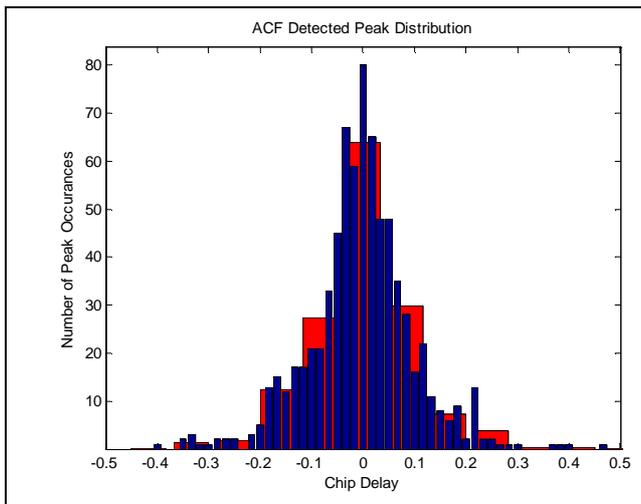


Figure 18: Static multipath-free full ACF's peak distribution for scans of 128 points (blue) and 25 points (red)

CONCLUSION

This paper has shown that multipath appears to be more complex to assess in real outdoors signals. Therefore, fast, precise and flexible tools are required to adapt to any multipath scenarios. The proposed real-time VSC approach is a low-resource implementation of such a tool (based on a single additional correlator per channel) that can reliably attest of all the typical multipath scenarios (modeled

by phase, amplitude and delay). Nevertheless, after the VSC parameters' configuration based on a single multipath generated signal, it was observed that real-world multipath were much more complex and not quite well accounted for with the proposed configuration. Therefore, a calibration phase on more than one multipath component would be advisable, and caution must be taken while testing such scenarios in real environment to ensure the presence of suspected types of multipath, despite lower SNR and satellite blockage. Although VSC calibration was performed on 0.5 chip delayed multipath, it still allowed detection and characterization of very short delayed multipath (i.e. 0.1 ± 0.05 chip).

Furthermore, the proposed technique is GNSS-ready as sub-carriers may be wiped-off from the complex BOC ACF, which is then reduced to a typical BPSK shorten-base triangular ACF. By normalizing the ACF, the same multipath detection, characterization and mitigation algorithms may then easily be adapted for all GNSS signals. Hence, it is the most versatile (i.e. it equally applies to any GNSS signal tracking channel with sub-carrier wipe-off) and least consuming real-time multipath mitigation technique capable of characterizing multipath simultaneously on any tracking GNSS channels.

As seen with the real multipath results, an adaptive ACF analysis based on its previous scans would greatly improve performances: progressively narrowing down onto multipath according to the user dynamics and the general perceived environment. For example, one could periodically scan before the prompt correlator to ensure the LOS is being tracked and not any other maxima resulting from constructive MP. Also, narrowing down onto the slopes' intersection point would provide better multipath observations, hence improving the characterization of real world multipath's evolution in time.

With the proposed methodology combining R&P and real-time VSC-enabled ACF analysis, a more representative study of multipath could now be performed, maybe improving multipath characterization and developing its classification. Finally, the proposed methodology could just as well be applied to characterize and compare the performances of other multipath mitigation techniques on new signals/frequencies under realistic scenarios. Moreover, this technique could also be used to assess the impact of interferences of all sorts on GNSS channels). This better understanding of multipath (and interference

sources in general) could also influence the way its simulation and mitigation are performed.

FUTURE WORK

Unfortunately, not all GNSS civil signals have been studied in this paper. It is believed that interesting findings may result of further investigations, as new signals become available, at least on one satellite that may be recorded and played back at will. However, higher sampling rates may be required to efficiently analyze 10.23 MHz chipping rate signals. The LACIME Software-defined GNSS receiver is ready for such an investigation.

An even more promising avenue is the multi-band mitigation of multipath. Joint analysis of multi-frequency signal's auto-correlation curves may teach us something new. Now, introducing multi-frequency signals, the proposed multipath analysis on L1 C/A could provide corrections to be applied on all the signals transmitted from any given satellite. Hence, determining on which GNSS signal multipath mitigation is more effective (precision achieved at a given sampling frequency compared to the additional resources required) would reduce the tracking complexity of other signals, assuming the Kalman filter may deduce the corrections to be applied from a single ACF. Note that the Avera's Multi-Frequency Record and Playback is also ready to empower such a study.

ACKNOWLEDGMENTS

The authors would like to acknowledge Min Liu for assuming the presentation on a last minute notice. They would also like to thank Avera for lending the RF R&P equipment as well as the outdoors data libraries that made these realistic tests possible.

M.-A. Fortin is financially supported by Avera Technologies, the *Fonds Québécois de Recherche sur la Nature et les Technologies* (FQRNT) and the Natural Sciences and Engineering Research Council of Canada (NSERC) in the form of a BMP industrial innovation scholarship.

REFERENCES

- [1] ABIresearch, "Global Navigation Satellite Positioning Solutions - Markets and Applications for GPS, Galileo and GLONASS", 2008, p. 122.
- [2] K. W. Ulmer and E. Sutton, "Performance Improvements Achieved Using Differential Phase Map Compensation in a Direction Finding System,"

in *Proceedings of the 11th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GPS 1998*, Nashville, TN September 15-18 1998, pp. 563-572.

- [3] J.-C. Guay, B. Sauriol, and M.-A. Fortin, "Real-time Multipath Monitoring and Characterization with a variable Spacing Correlator on a FPGA-Based Software GNSS Receiver," in *Proceedings of the Institute of Navigation - ION GNSS 2008* Savannah, Georgia: Institute of Navigation, , 2008.
- [4] E. D. Kaplan and C. Hegarty, *Understanding GPS principles and applications*, Second ed. Boston, Mass.: Artech House, 2005.
- [5] J. Bickerstaff, R. Frayling-Cork, and T. Haddrell, "Capture, Analysis and Mitigation of Multipath in a High Sensitivity GPS Receiver," in *Proceedings of the 19th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GNSS 2006*, Fort Worth, Texas September 26 - 29, 2006, pp. 1696 - 1705.
- [6] B. Chibout, C. Macabiau, A. C. Escher, L. Ries, J. L. Issler, S. Corazza, and M. Bousquet, "Comparison of acquisition techniques for GNSS signal processing in geostationary orbit," San Diego, CA, United states, 2007, pp. 637-649.
- [7] P. Misra and P. Enge, *Global Positioning System: Signals, Measurements, and Performance*, 2e édition ed. Lincoln, Massachusetts: Ganga-Jamuna Press, 2006.
- [8] A. J. Van Dierendonck, P. Fenton, and T. Ford, "Theory and Performance of Narrow Correlator Spacing in a GPS Receiver." vol. 39 No. 3, 1992, pp. 265 - 284.
- [9] B. Townsend and P. Fenton, "Practical approach to the reduction of pseudorange multipath errors in a L1 GPS receiver," Salt Lake City, UT, USA, 1994, pp. 143-148.
- [10] R. Van Nee, P. Fenton, and B. R. Townsend, "The Multipath Estimating Delay Lock Loop Approaching Theoretical Accuracy Limits," in *IEEE Position, Location and Navigation Symposium*, Las Vegas, Nevada, April 11-15, 1994.
- [11] J. Jones, B. Fenton, and B. Smith, " Theory and Performance of the Pulse Aperture Correlator."
- [12] P. C. Fenton and J. Jones, "The theory and performance of NovAtel Inc.'s Vision Correlator," in *Proceedings of the 18th International Technical*

Meeting of the Satellite Division of the Institute of Navigation ION GNSS 2005, Long Beach, CA, United States, September 13 - 16, 2005, pp. 2178-2186.

- [13] F. M. G. Sousa, F. D. Nunes, and J. M. N. Leitao, "Code Correlation Reference Waveforms for Multipath Mitigation in MBOC GNSS Receivers," in *Proceedings of the European Navigation Conference ENC-GNSS 2008*.
- [14] L. J. Garin, "The "Shaping Correlator", Novel Multipath Mitigation Technique Applicable to GALILEO BOC(1,1) Modulation Waveforms in High Volume Markets," in *The European Navigation Conference GNSS 2005*.
- [15] M. Paonni, J.-A. Avila-Rodriguez, T. Pany, G. W. Hein, and B. Eissfeller, "Looking for an optimum S-Curve shaping of the different MBOC implementations," Fort Worth, TX, United states, 2007, pp. 269-281.
- [16] J. Bickerstaff, R. Frayling-Cork, and T. Haddrell, "Capture, analysis and mitigation of multipath in a high sensitivity GPS receiver," Fort Worth, TX, United states, 2006, pp. 1696-1705.
- [17] M. Irsigler and G. W. Hein, "Development of a real-time multipath monitor based on multi-correlator observations," Long Beach, CA, United states, 2005, pp. 2626-2637.
- [18] M. Sahnoudi and R. J. Landry, "Multipath - Mitigation Techniques Using Maximum-Likelihood Principle," in *InsideGNSS*. vol. November/December 2008, 2008, pp. 24-29.
- [19] M. S. Hodgart, R. M. Weiler, and M. Unwin, "A triple estimating receiver of multiplexed binary offset carrier (MBOC) modulated signals," Savannah, GA, United states, 2008, pp. 2295-2304.
- [20] M.-A. Fortin, J.-C. Guay, and R. Landry Jr, "Performances of a Universal GNSS Tracking Channel," in *Proceedings of the Institute of Navigation - ION GNSS 2009* Savannah, Georgia: Institute of Navigation, , 2009.
- [21] I. Ilie and M.-A. Fortin, "Multi-channel Record and Playback System for GNSS RF/IF Receivers Design Validation and Fine-tuning," in *Proceedings of the Institute of Navigation - ION GNSS 2009* Savannah, Georgia: Institute of Navigation, , 2009.