

Technical Report

Performance Evaluation of the Direct Acquisition of GPS-like VBOC Signals against Noise and Interference

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Abstract— This technical report provides the results from the [extremely high] performance evaluation of the direct acquisition of the GPS-like VBOC signals against noise, channel impairments, and interference using real GPS or GNSS signals.

We initially compare and contrast the performance of VBOC1(1,1,0.5) and VBOC2(1,1,0.4) against noise and channel impairments, no data and only four GPS-like satellite signals in the lab.

We, then, graduate include one effect at a time as the test setup gradually manifests a more realistic scenario from where it is shown that a high-performance acquisition engine for direct acquisition of GPS-like VBOC signals can achieve time to first fix (TTFF) of 100 seconds with initial time uncertainty (ITU) of 100 ns and jamming/signal ratio (JSR) of 90 dB against additive white Gaussian noise (AWGN) or other “unknown” jammers with bandwidth of $-/+$ 1 or 4 MHz.

Giftet Inc. Indoor Geolocation Systems MATLAB library offers unique and unlimited capabilities for analysis, simulation, and design tool for the Radio Frequency (RF), Intermediate Frequency (IF), and Baseband (BB) sections analysis and simulation of future Keysight, Locata, NovAtel, etc. products.

Index Terms— VBOC1, VBOC2, BOC, GPS, GNSS, interference, noise, high-performance, acquisition, TTFF, ITU, JSR.

1 Introduction

This technical report is a continuation of the study that we have performed previously on the “VBOC1(α) and VBOC2($\alpha, 1-\alpha$) generalized multidimensional geolocation modulation waveforms—technical report” [1] which includes performance evaluation of the direct acquisition of GPS-like VBOC signals against interference and noise and channel impairments.

In order to evaluate the performance of the direct acquisition of GPS-like VBOC signals against interference and noise the simulation test-setup was enhanced to include performance against noise, channel impairments, and interference.

Receiver noise was assumed to be additive white Gaussian noise (AWGN) which is perhaps a good assumption within the receiver bandwidth [2]-[11].

Channel impairments are modeled after an innovative Giftet 4-parameter channel model. The detailed discussion of this model will be published in a separate journal paper. At the moment the 4-parameter channel model includes only the ionospheric model [2]. Later on, this model will include also the tropospheric and multipath 4-parameter channel model [2].

Giftet receiver anti-jam acquisition and tracking module includes some of Giftet Inc. most innovative algorithms [4]-[8] that even today eleven or twelve years after there were invented their performance is still spectacular: GPS-like VBOC signals can achieve time to first fix (TTFF) of 100 seconds with initial time uncertainty (ITU) of 100 ns and jamming/signal ratio (JSR) of 90 dB against additive white Gaussian noise (AWGN) or other “unknown” jammers with bandwidth of ± 1 or 4 MHz.

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This paper is organized as follows: system description is given/discussed next followed by simulation results and hardware implementation. Conclusion is given afterwards and followed by a list of references.

2 System Description

The vulnerabilities of the GPS C/A code as discussed in [12]-[15] have been exaggerated mainly because the assessment of

the performance of the C/A code is based on a cross-correlator type receiver [4]-[8].

The question is not posed very well. When people make the statement that C/A code is vulnerable to jamming they typically mean that a cross-correlator type C/A receiver is vulnerable to jamming.

It is not that the C/A code does not have issues. C/A code has a limit performance due to poor autocorrelation and cross-correlation properties of the gold codes that were selected for the GPS C/A code family. Nevertheless, when it comes to jamming the poor performance of the C/A code has been exaggerated. Why is this important?

This is important because even if we were to design a receiver based on the direct cross-correlation that were used on the C/A code then the receiver would have exhibited sub-optimum performance and it will still be susceptible to stronger jammers.

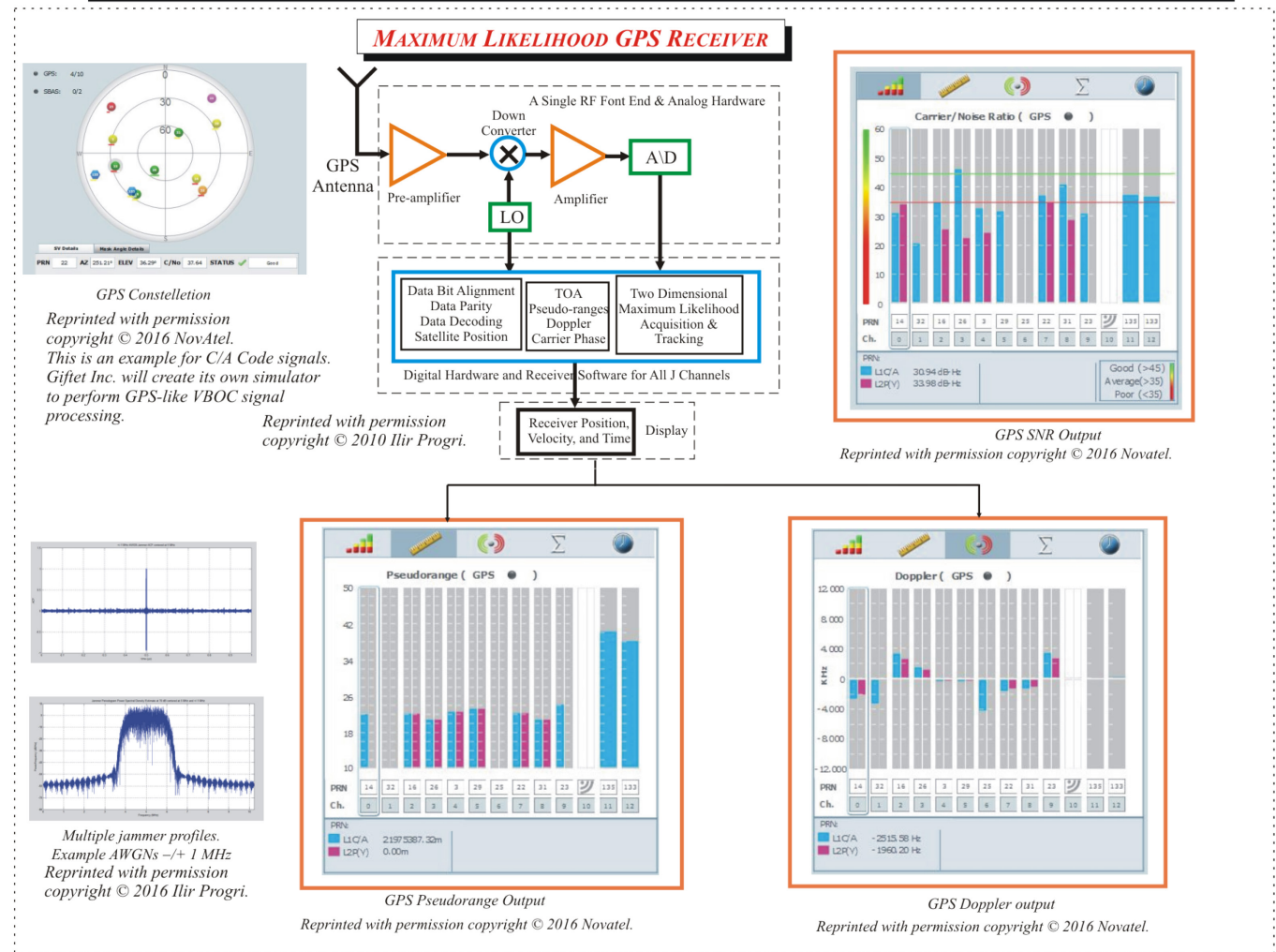
The question should have been stated like this: Are there other types of receivers other than the cross-correlator GPS receiver that can be used to mitigate both the poor performance of the cross-correlation properties of the C/A code have superior anti-jamming capability even with a single antenna?

A VBOC GPS-like receiver is expected to work well both under harsh environments and in benign jamming conditions. Under these conditions any type of poor cross-correlation properties of the C/A code will highly affect the GPS acquisition and tracking.

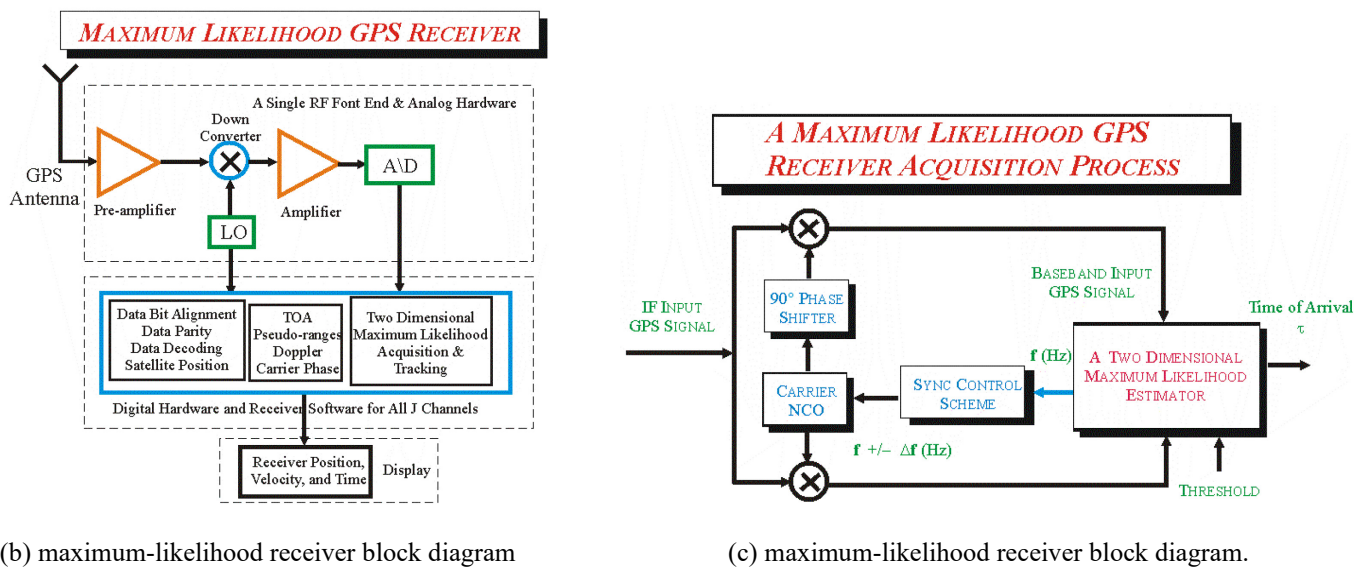
Giftet Inc. has not developed a C/A acquisition engine against jamming but it has developed a very successful “Maximum likelihood GPS parameter estimation” [4] and “Markov Chain, Monte Carlo global search and integration for Bayesian, GPS, parameter estimation” [8] that exploit the poor cross-correlation properties of the GPS C/A code and provide superior performance as good as if you only had one GPS signal and noise even when one of the signals is considered a “jamming” signal.

The next question is? Does a GPS receiver algorithm exist that will go another step further than we have gone in [4]-[8] that will be able to offer a GPS C/A code or even GPS-like VBOC performance as good as if you only had one GPS signal and noise even when we have multiple GPS signals and AWGN jammer with bandwidth of ± 1 MHz and JSP in excess of 90 dB?

GIFTET® HIGH PERFORMANCE GPS-LIKE VBOC CA-CODE ANTI-JAM ACQUISITION ENGINE



(a) Giftet® Reconfigurable RF FE for Multi-GNSS/communications maximum-likelihood SDR Receiver.



(b) maximum-likelihood receiver block diagram

(c) maximum-likelihood receiver block diagram.

FIGURE 1: Giftet® high performance GPS-Like VBOC CA-code anti-jam acquisition engine (a) Giftet® Reconfigurable RF FE for Multi-GNSS/communications maximum-likelihood SDR Receiver [4], [5]. Reprinted with permission Copyright © 2016 Giftet Inc. All rights reserved.

Most of my research and area of expertise is in mitigating the near-far effect and I have been able to successfully mitigate this problem both from the signal design point of view [1]-[11], [16]-[41], [22] and from the receiver design [4]-[8].

However, the question raised by this proposal is more fundamental than the near-far effect so the assumptions arose by this paper on jamming and the type of GPS receiver that is needed to mitigate jamming are more fundamental.

Giftet Inc. will propose two alternatives to enable a high performance GPS VBOC CA-Code anti-jam acquisition engine. The first alternative will examine how GPS receiver algorithms proposed in [4]-[8] can be modified to enable direct acquisition of GPS CA-code signals with TTFF of 100 with ITU of 100 ns and JSR of 90 dB against AWGN jammers with bandwidth of ± 1 MHz.

The second alternative will be an entire examination of the GPS jamming assumptions and the possibility of coming up with an entirely new algorithm that will permanently mitigate jamming for a GPS receiver whether it be a C/A code and offer superior performance as good as if it were only one GPS signal and noise.

Why is this important? This is important because improving the technology that we have, it creates the foundation for us to produce new and more innovative algorithms. It will also be important for us to protect the technology that we have and protect the new technologies that we will create in this proposal. So, the end result will be that Giftet Inc. will meet and exceed the requirements of this proposal.

A conceptual model of the complete Giftet® high performance GPS-like VBOC CA-Code anti-jam acquisition engine is illustrated in Fig. 1(a). As shown in Fig. 1(a), the system contains multiple satellite signals and jammers. Initially, this will be done in a MATLAB simulation environment using the C/A code and then using other spreading codes.

Similarly to the operation of the GPS every jamming signal is modulated by a known pseudo random code at a rate commonly known as the chipping rate (the bandwidth of the resulting signal is proportional to the chipping rate). A typically jamming signal would be an AWGN with bandwidth of ± 1 MHz at a particular carrier frequency ex. 5 MHz at the baseband frequency after down-conversion assuming that the baseband GPS signal is sampled at 10 MHz or at a higher rate.

In one version of the system, jammers are distributed in an ad-hoc manner. Jamming power can be controlled.

Jammers can be assumed either with a “known seed” or “unknown seed”. If jammers have unknown seed then their pseudorandom sequence must be estimated before it is processed by the maximum likelihood GPS receiver.

The proposed Giftet evaluation of the direct acquisition of GPS-like VBOC signals against interference and noise as shown in Fig. 1 (b) and (c) [4] whose detailed discussion is provided in “Proposed Giftet® high performance GPS-like VBOC CA-code anti-jam acquisition engine” Subsect. in the Simulation Results Sect.

This concluded the discussion on system description.

3 Theoretical, Numerical Results

One efficient way of achieving substantial improvements of the GNSS signal design is by means of the generalized multidimensional geolocation modulation waveforms such as $VBOC1(\alpha)$ and $VBOC2(\alpha, 1 - \alpha)$ whose properties are discussed in great detail in [16]-[19].

An original set of very accurate simulation results on $VBOC1(\alpha)$, $VBOC2(\alpha, 1 - \alpha)$ ACFs/PSDs are presented in Chap. 7 of [2] and in [21].

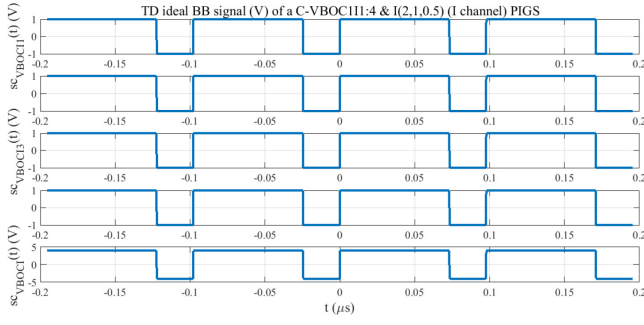
Simulation results are grouped into two categories: performance against noise and channel impairments; proposed Giftet® high performance GPS-like VBOC CA-code anti-jam acquisition engine.

3.1 Performance against Noise and Channel Impairments

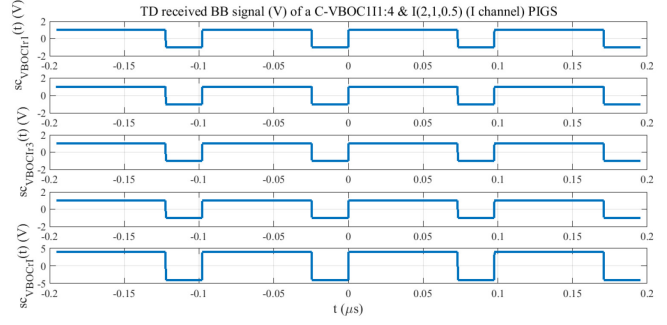
Performance against noise and channel impairments include C-CDMA simulation results in L1-band 1575.42 MHz-1.75 GHz. A similar performance can be obtained from a MC-CDMA simulation results in C-band 4-8 GHz or X-band 8-12 GHz.

3.1.1 C-CDMA Simulation Results in L-band 1575.42 MHz-1.75 GHz

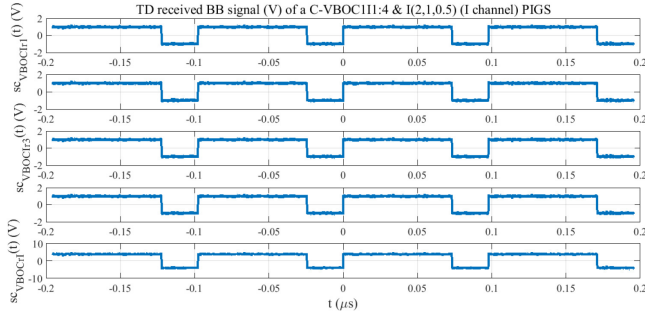
Figure 2 (a) illustrates the 0.4- μ s TD reference baseband (BB) signal of a $C-VBOC1I_{1:4(2,1,0.5)}$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS. As shown in Fig. 2 (a) there are five TD BB waveforms: the first four corresponding to individual transmitters and the fifth waveform corresponds to the sum waveform: i.e., the sum waveform of the four individual transmitter waveforms. All the four individual transmitter waveforms have a subcarrier frequency equal to zero Hz.



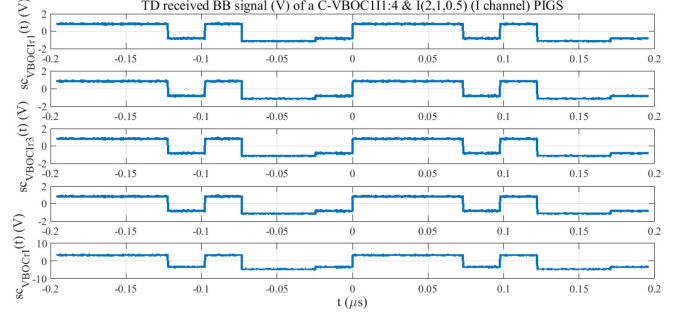
(a) 0.4-μs TD reference BB signal of a $C\text{-}VBOC111:4$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS.



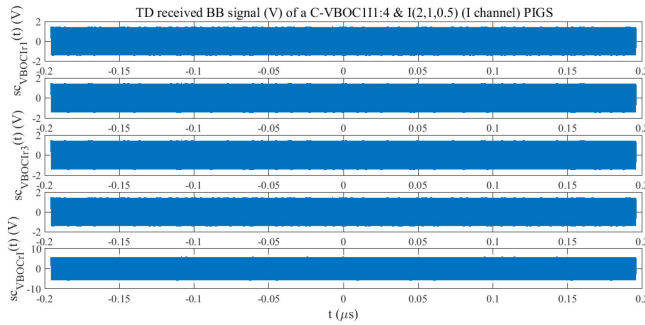
(b) 0.4-μs TD received BB signal of a $C\text{-}VBOC111:4$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS. (Neither noise nor channel impairments)



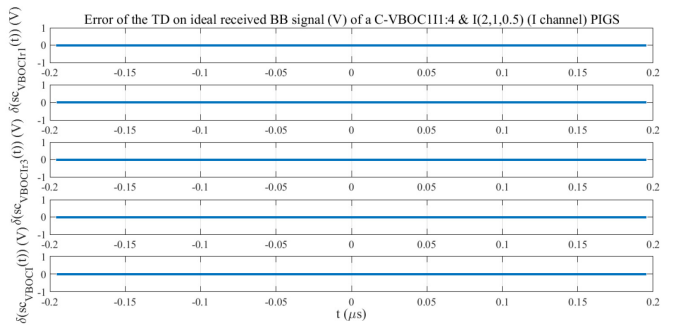
(c) 0.4-μs TD received BB signal of a $C\text{-}VBOC111:4$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on)



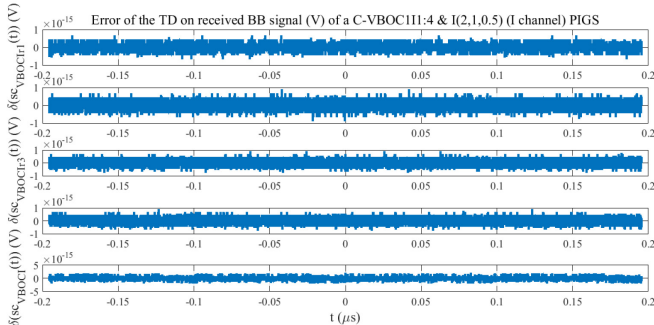
(d) 0.4-μs TD received BB signal of a $C\text{-}VBOC111:4$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off).



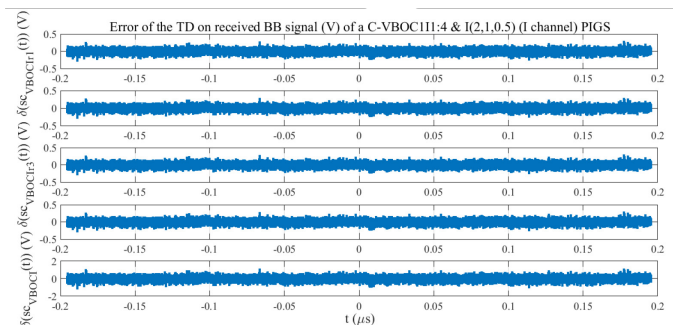
(e) 0.4-μs TD received BB signal of a $C\text{-}VBOC111:4$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on)



(f) 0.4-μs TD received BB signal of a $C\text{-}VBOC111:4$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off).



(g) 0.4-μs error of the TD received BB signal of a $C\text{-}VBOC111:4$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS. (Neither noise nor channel impairments).



(h) 0.4-μs error of the TD received BB signal of a $C\text{-}VBOC111:4$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on)

FIGURE 2: Giftet® high performance GPS-Like VBOC CA-code simulation results 1. Reprinted with permission Copyright © 2018 Giftet Inc. All rights reserved.

The chipping rate is 5,115 MHz. The signal design waveform modulation is the same for all four transmitter waveforms. VBOC type is I or the first VBOC, $m = p = 2$, $n = 1$, $\alpha = 0.5$: there are two subcarrier periods for every code chip (or transition) equal to $1.955 \mu\text{s}$. For every signal subcarrier the $+1$ time is equal to $0.733125 \mu\text{s}$ and the -1 time is equal to $0.244375 \mu\text{s}$; i.e., half period of the subcarrier is equal to $0.48875 \mu\text{s}$. Figure 2 (a) illustrates two periods or chips or code transitions of the reference BB signal equal to $3.91 \mu\text{s}$ or $0.9775 \times 4 \mu\text{s}$. Figure 2 (a) presents what is known as the ideal transmitted and received waveform.

Figure 2 (b) depicts exactly the TD reference received BB signal of $C\text{-}VBOC1I1:4_{(2,1,0.5)}$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS with neither noise nor channel impairments or in an ideal environment but with “almost perfect” synchronization. Figure 2 (b) shows what is known as “almost ideal” received waveform.

Figure 2 (c) represents the TD received reference received BB signal of $C\text{-}VBOC1I1:4_{(2,1,0.5)}$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS when both noise and channel impairments are turned on the received down-conversion and channel correction are turned on. This is the realistic case: channel noise consists of additive white Gaussian noise AWGN and channel impairments are generated from of an ionospheric 4-paramater channel model [2]. The detailed discussion of this innovative ionospheric 4-paramater channel model will be published soon in the pioneer publication of Chap. 8 of *Indoor Geolocation Systems—Theory and Applications, I* [2] and perhaps in the Nov. 2019 issue of *Giftet Journal of Geolocation, Geo-Information and Geo-Intelligence* [20], [21].

Figure 2 (d) portraits the TD received reference received BB signal of $C\text{-}VBOC1I1:4_{(2,1,0.5)}$ and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS when both noise and channel impairments are turned on the received down-conversion is turned on and channel correction is turned off. The only difference between Fig. 2 (d) and Fig. 2 (c) is that in Fig. 2 (d) channel correction model is turned off and in Fig. 2 (c) is turned on.

Figure 2 (e) illustrates the same as Fig. 2 (d) with both down-conversion and channel correction model turned off.

By looking at Figs. 2 (a) through (e) the user has the ability to turn on and off certain blocks or models and access the performance of the output of every block and or model. Since the processing of the IF and RF signals blocks and or model have been shown previously so as not overload the reader with redundant information, we have omitted from showing these

blocks in this paper.

Figures 2 (f) through 3 (b) depict the error which is the difference of the received waveform from the transmitted waveform.

In Fig. 2 (f) the error is zero; i.e., if we were to have an ideal environment and perfect synchronization then the error will be zero.

Figure 2 (g) illustrates that the error is on the order of 10^{-15} . Under almost perfect conditions the error is within the numerical precision of the MATLAB.

Figure 2 (h) presents what we should see in a realistic scenario. When both channel models are turned on and the receiver down conversion and channel correction model are turned on we observe errors on the order of $-0.2787/0.2616$ (V). This is what we should expect to see in a realistic scenario that the received is able to mitigate channel impairments and not be influenced by AWGN or appears to be AWGN.

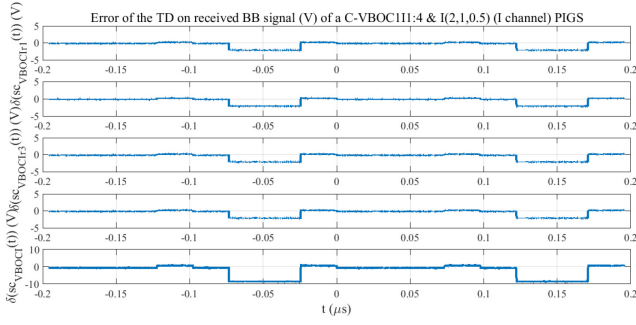
Figure 3 (a) depicts the error when channel correction model in the receiver is turned off. As seen from Fig. 3 (a) that there is a noticeable bias that cases the error to be $-2.2891/0.3968$ (V). The error is not AWGN and is asymmetrical or not zero centered.

Figure 3 (b) depicts the error when both the receiver down-conversion and channel correction model in the receiver are turned off. As seen from Fig. 3 (b) that there is a noticeable high frequency error on the order of $-2.4697/2.4559$ (V). The error appears to be a mixture of signal plus AWGN and channel impairments and it is symmetrical or zero centered.

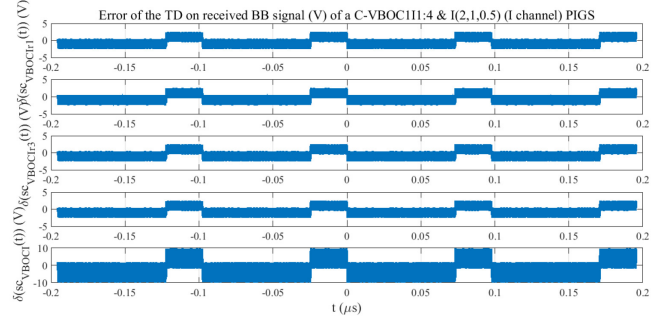
Figure 3 (c) presents the $0.4\text{-}\mu\text{s}$ ACF signal, $r_{VBOC1I1:3_{(2,1,0.5)}}$, of a $C\text{-}VBOC1I1:3_{(2,1,0.5)}$, and $VBOC1I_{(2,1,0.5)}$, (I channel) PIGS. We can see how much the out-of-phase autocorrelation peaks are reduced which is exactly the reason why $VBOC1I1:3_{(2,1,0.5)}$ has superior properties compared to $BOC_{(2,1)}$ [2], [21]. We can see that out-of-phase autocorrelation peaks for $VBOC1I1:3_{(2,1,0.5)}$ do not exceed 0.5 as opposed to the out-of-phase autocorrelation peaks for $BOC_{(2,1)}$ come as close as -0.75 [2], [21]. Figure 3 (c) presents what is known as ACF of the ideal transmitted and received waveform. There are absolutely no distortions of the ACF.

Figures 3 (c) through (g) are produced by taking the ACF of signals from Figs. 2 (a) through (f).

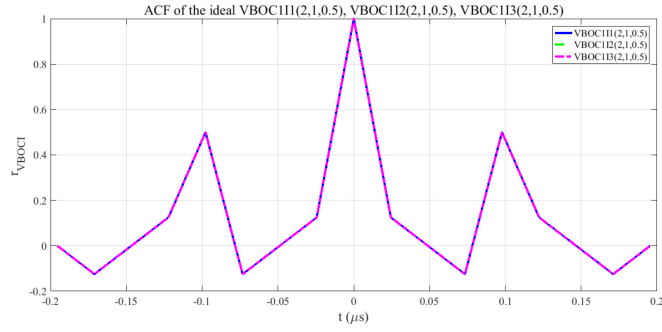
Figures 3 (f) through 4 (d) are produced by taking the difference between the signals from Figs. 3 (c) through (g) with the signal from Fig. 3 (c).



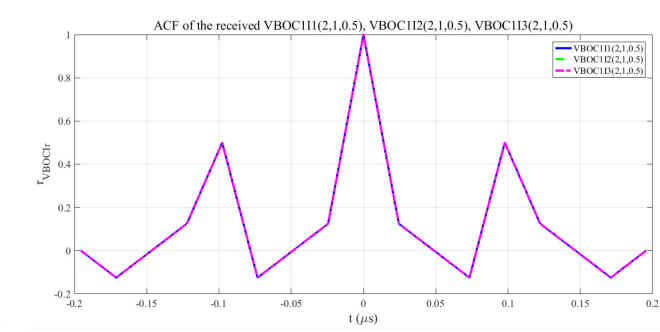
(a) 0.4- μ s error of the TD received BB signal of a $C\text{-}VBOC111:4_{(4,1,0.5)}$ and $VBOC11_{(2,1,0.5)}$, (I channel) PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off)



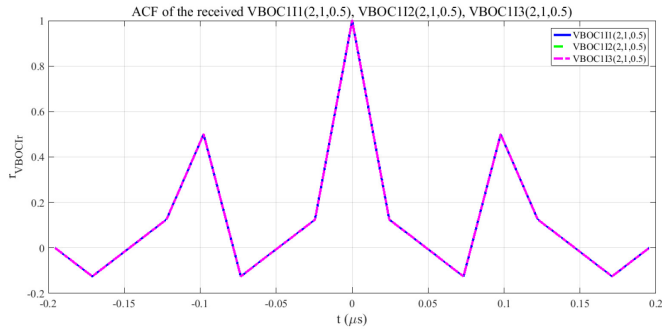
(b) 11. 0.4- μ s error of the TD received BB signal of a $C\text{-}VBOC111:4_{(4,1,0.5)}$ and $VBOC11_{(2,1,0.5)}$, (I channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction off).



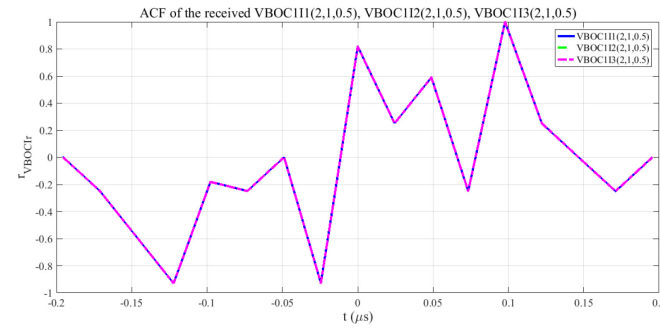
(c) 0.4- μ s TD received BB signal of a $C\text{-}VBOC111:4_{(4,1,0.5)}$ and $VBOC11_{(2,1,0.5)}$, (I channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on)



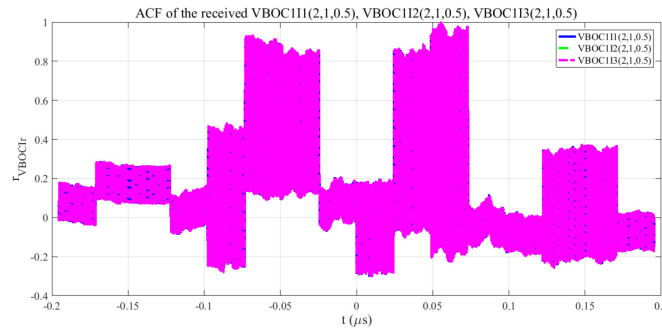
(d) 0.4- μ s TD received BB signal of a $C\text{-}VBOC111:4_{(4,1,0.5)}$ and $VBOC11_{(2,1,0.5)}$, (I channel) PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off).



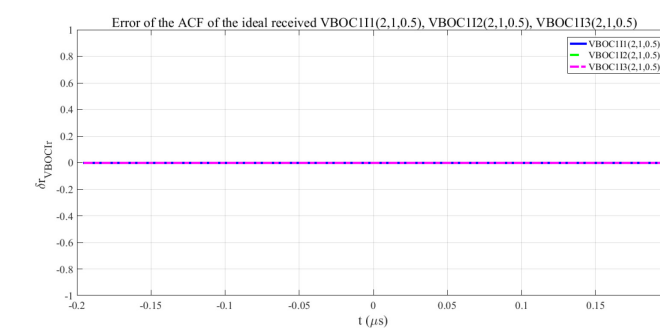
(e) 0.4- μ s ACF of the received I Ch: $VBOC111:3_{(2,1,0.5)}$ PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on).



(f) 0.4- μ s ACF of the received I Ch: $VBOC111:3_{(2,1,0.5)}$ PIGS. (Both noise and channel impairments; down-conversion on and channel correction off).



(g) 0.4- μ s ACF of the received I Ch: $VBOC111:3_{(2,1,0.5)}$ PIGS. (Both noise and channel impairments on; both down-conversion channel correction and off).



(h) 0.4- μ s Error of the ideal received ACF I Ch: $VBOC111:3_{(2,1,0.5)}$ PIGS.

FIGURE 3: Giftet® high performance GPS-Like VBOC CA-code simulation results 2. Reprinted with permission Copyright © 2018 Giftet Inc. All rights reserved.

Figure 4 (e) waveforms parameters are identical to those of

Fig. 2 (a) with the only difference the signal design modulation:

$VBOC2Q_{(2,1,5/12)}$; i.e., VBOC type is II or the second VBOC, $m = p = 2$, $n = 1$, $\alpha = 5/12$. There are two subcarrier periods for every code chip (or transition) equal to $1.955 \mu\text{s}$. For every odd signal subcarrier, the $+1$ time is equal to $0.68425 \mu\text{s}$ and the -1 time is equal to $0.29325 \mu\text{s}$; i.e., half period of the subcarrier is equal to $0.48875 \mu\text{s}$; and for even signal subcarrier the $+1$ time is equal to $0.29325 \mu\text{s}$ and the -1 time is equal to $0.68425 \mu\text{s}$.

Figure 4 (e) illustrates two periods or chips or code transitions of the BB signal equal to $3.91 \mu\text{s}$ or $0.9775 \times 4 \mu\text{s}$.

Figure 4 (f) waveforms parameters are identical to those of Fig. 2 (b) with the only difference the signal design modulation: $VBOC2Q_{(2,1,5/12)}$; i.e., with other signal parameters identical to those of Fig. 4 (f).

The same can be said for Fig. 4 (g) through 5 (a).

Figures 5 (b) through (f) are produced by taking the difference between the signals from Figs. 4 (e) through 5 (a) with the signal from Fig. 4 (e).

Figure 5 (g) shows the $0.4\text{-}\mu\text{s}$ Q Ch: $VBOC2Q1:3_{(2,1,5/12)}$ PIGS. We can see how much the out-of-phase autocorrelation peaks are reduced which is exactly the reason why $VBOC2Q1:3_{(2,1,5/12)}$ has superior properties compared to $VBOC1I1:3_{(2,1,0.5)}$. We can see that out-of-phase autocorrelation peaks for $VBOC2Q1:3_{(2,1,5/12)}$ do not exceed -0.35 as opposed to the out-of-phase autocorrelation peaks for $VBOC1I1:3_{(2,1,0.5)}$ come as close as 0.5 .

The $VBOC2_{(2,1,\alpha)}$ type of modulation reduces the out-of-phase autocorrelation peaks by almost half compared to $VBOC1_{(2,1,\alpha)}$ while at the same time offering a very simple waveform modification. Moreover, the phase of the out-of-phase autocorrelation peaks for $VBOC2_{(2,1,\alpha)}$ is different from the phase of the out-of-phase autocorrelation peaks for $VBOC1_{(2,1,\alpha)}$; i.e., when there is an out-of-phase autocorrelation peak for $VBOC2_{(2,1,\alpha)}$ there is a minimum value of the out-of-phase autocorrelation peaks for $VBOC1_{(2,1,\alpha)}$ and vice versa. Therefore, not only does this type of modulation reduces the number of the out-of-phase autocorrelation peaks but it also offsets them as a function of the type of the VBOC modulation and the parameter of the signal design modulation α .

Figures 5 (g) through 6 (c) are produced by taking the ACF of signals from Figs. 4 (e) through 5 (a).

Figures 6 (d) through (h) are produced by taking the

difference between the signals from Figs. 5 (g) through 6 (c) with signal from Fig. 5 (g).

Figure 7 (a) illustrates the 62.5-MHz FD reference BB PSD I Ch: $VBOC1I1:4_{(2,1,0.5)}$, Q Ch: $VBOC2Q1:4_{(2,1,5/12)}$ PIGS. Pretty much the same comments can be made for PSD of $VBOC2Q1:4_{(2,1,5/12)}$ in contrast to PSD shown in Fig. 52 [21]; i.e., the PSD of $VBOC2Q1:4_{(2,1,5/12)}$ is a much quasi-flatter waveform than the PSD of $VBOC2Q1:4_{(2,1,0)} = BOC_{(2,1)}$. All waveforms are centered at 0 MHz .

The minimums for $VBOC1I1:4_{(2,1,0.5)}$ are at $5, 15, 25$, and 35 MHz . Contrast with the minimums for PSD of $VBOC2Q1_{(2,1,5/12)}$ are at $7, 25, 27$, and 31 MHz which is the reason why PSD of $VBOC2Q1:4_{(2,1,5/12)}$ has a quasi-flatter spectrum as expected. The maximum values for the PSD of $VBOC2Q1:4_{(2,1,5/12)}/VBOC1I1:4_{(2,1,0.5)}$ are $-72/-78 \text{ dB}$ respectively.

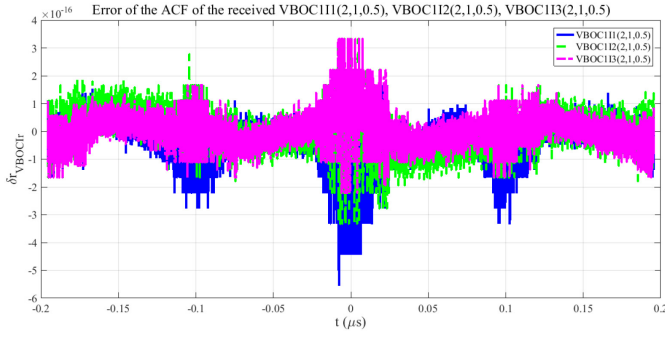
Figures 7 (a) through (e) are produced by taking the PSD of signals from Figs. 2 (a) through (e) for the I channel and 4 (e) through 5 (a) for the Q channel.

Figures 7 (f) through 8 (b) are produced by taking the difference between the signals from Figs. 7 (a) through (e) with the signal from Fig. 7 (a).

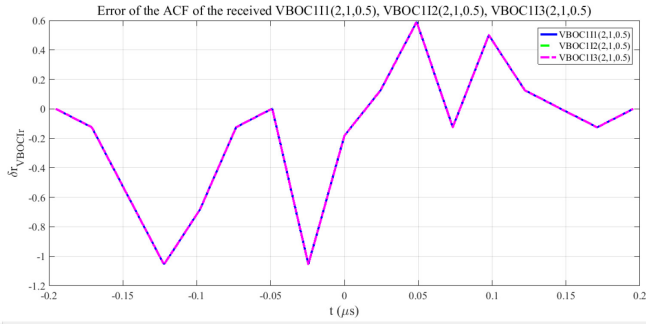
This concludes the summary of $VBOC2Q_{(2,1,5/12)}/VBOC1I_{(2,1,0.5)}$ the C-CDMA simulation results in L-band 1575.42 MHz - 1.75 GHz in which we have illustrated: (1) the waveforms in TD and FD; and (2) ACF in TD and PSD FD.

3.1.2 Proposed Giftet® high performance GPS-like VBOC CA-code anti-jam acquisition engine

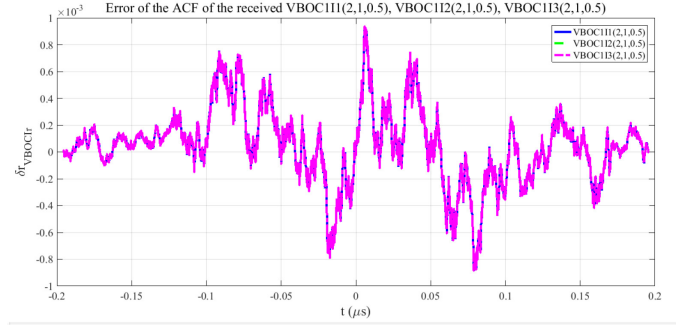
Before introducing the VBOC, VBOC1, and VBOC2 signal designs signal model, consider a “maximum likelihood” GPS receiver as presented in Fig. 1 (b), which contains a GPS antenna, a single reconfigurable RF FE and analog hardware section, digital software and receiver hardware section for all J channels, and a display section. GPS signals coming from all visible satellite are superimposed at the entrance of a GPS receiver antenna. The RF signal is pre-amplified and down-converted at the intermediate frequency (IF) by means of a down-converter driven by a local clock oscillator (LO). The IF GPS waveform is amplified and sampled by means of an analog-to-digital (A/D) converter [4].



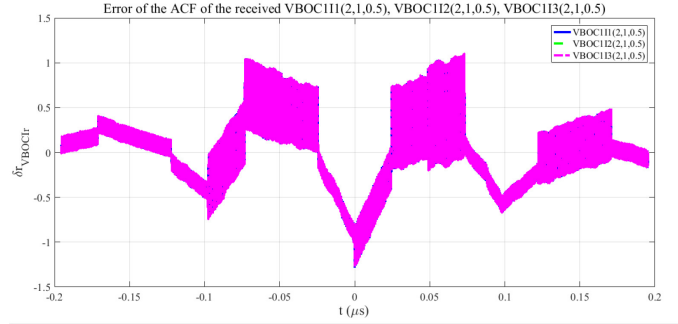
(a) 0.4-μs Error of the received ACF I Ch: $VBOC111:3_{(2,1,0.5)}$ PIGS. (Neither noise nor channel impairments)



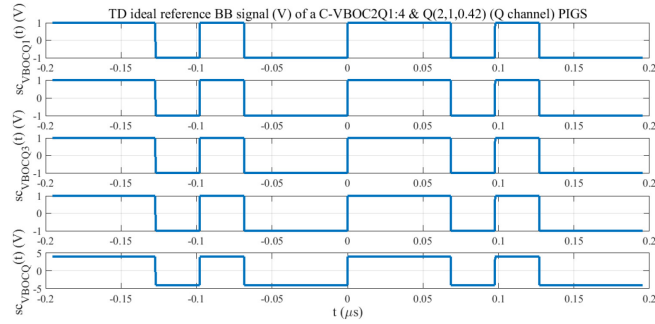
(c) 0.4-μs Error of the received ACF I Ch: $VBOC111:3_{(2,1,0.5)}$ PIGS. (Both noise and channel impairments on; both down-conversion and channel correction off).



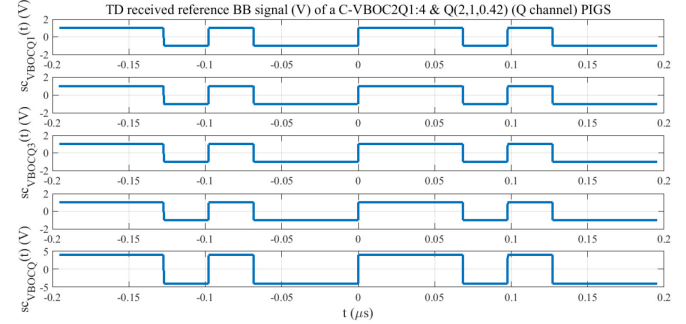
(b) 0.4-μs Error of the received ACF I Ch: $VBOC111:3_{(2,1,0.5)}$ PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on)



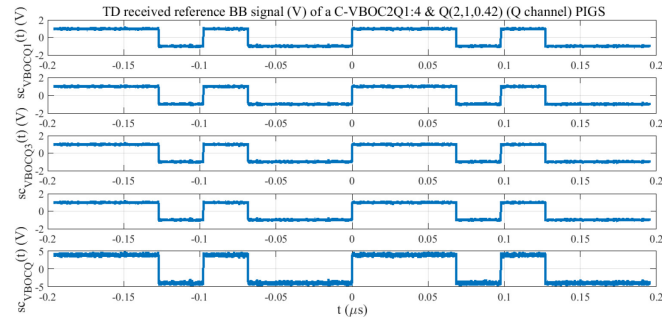
(d) 0.4-μs Error of the received ACF I Ch: $VBOC111:3_{(2,1,0.5)}$ PIGS. (Both noise and channel impairments on; both down-conversion and channel correction off).



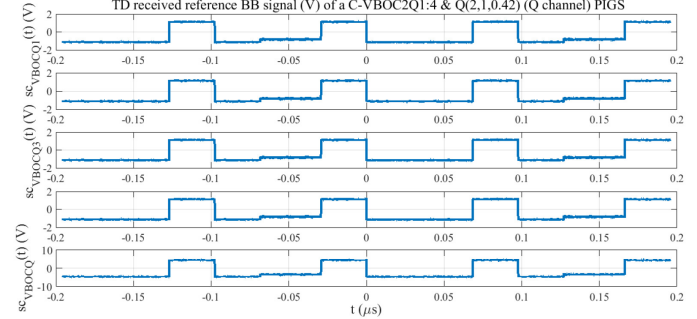
(e) 0.4-μs TD reference BB signal of a $C-VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS.



(f) 0.4-ns TD received BB signal of a $C-VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS. (Neither noise nor channel impairments)



(g) 0.4-ns TD received BB signal of a $C-VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on).



(h) 0.4-ns TD received BB signal of a $C-VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off).

FIGURE 4: Giftet® high performance GPS-Like VBOC CA-code simulation results 3. Reprinted with permission Copyright © 2018 Giftet Inc. All rights reserved.

The acquisition process of a “maximum likelihood” GPS receiver is illustrated in Fig. 1 (c). As shown in Fig. 1 (b) and (c) we assume that the IF GPS signal is employed to excite a two-dimensional maximum likelihood Doppler and Code estimator. The acquisition process contains the maximum likelihood detection and estimation model and the Doppler and delay offset estimation. The reader is reminded that in this paper we use interchangeably the terms Doppler estimation for Doppler search and delay offset estimation for Code search and vice versa [4], [5].

By treating all the signals in the environment jointly, it is possible to greatly outperform the “sliding correlator” technique especially in situations where the satellite signals are received with widely varying powers.

For a simple numerical example, consider a simulated environment wherein one satellite is received at -15 and three jamming signals at 80 , 53 and 70 dB signal to white noise power (SWNR). The received environment is modeled at complex baseband assuming the reception of a 1 ms, 1023 chip Gold codes from one GPS satellite and three jammers. We have also assumed that a standard deviation on the GPS receiver clock error is half of the chipping period, T_c . We assume that the GPS Doppler frequency is normally distributed with 0 mean and 100 Hz standard deviation [4], [5].

The reason we have assumed very high jamming power is because there are already in place requirements to test anti-jam system in completely jammed environments [30]-[33].

The U.S. Air Force 746th Test Squadron has declared Initial Operational Capability (IOC) for its new truth reference, the Ultra High-Accuracy Reference System (UHARS) at the White Sands Missile Range in New Mexico [32], [33]. Even when GPS — or any other GNSS system — is being completely jammed, UHARS [31] provides extremely accurate positioning, navigation, and time (PNT) over the large area that the system was designed to cover.

Therefore, the assumptions made in this scenario are completely realistic and I believe that Giftet Inc. Indoor Geolocation System MATLAB Library will further enhance these already tighter requirements for system to operate in completely jammed environments.

The normalized cross correlator for the weakest signal, at -15 dB is shown in Fig. 8 (c) (top). The simple cross-correlator cannot detect the weakest signal at -15 dB because the strongest jamming signals at 80 , 53 and 70 dB can jam the weakest signal. This result is in total agreement with the

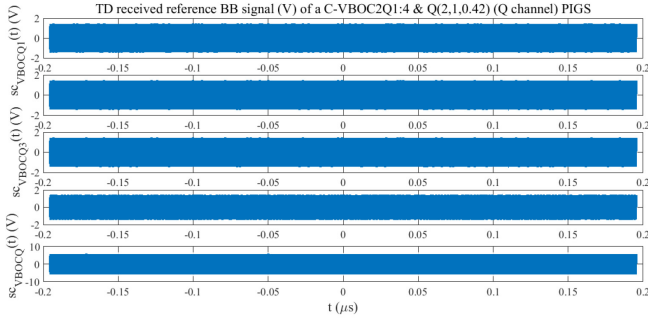
results reported in literature using real data and employing either a Tong search detector or a FFT search detector for 1 ms integration time. In contrast the maximum likelihood estimator (i.e., objective function), shown in Fig. 8 (c) (bottom), can detect the weakest signal almost all the time. Because the strong GPS satellite codes have been cancelled, the maximum likelihood estimator can still pick up a clear peak at the correct delay most of the time [4].

This same receive scenario was run over 200 Monte Carlo trials while randomly varying the thermal noise, delay offsets gold sequence seeds, and Doppler frequencies. The standard moving cross-correlator achieved a median absolute delay estimation error of $\{356.1278\ 0.0772\ 269.2089\ 0.0276\}$ μ s and was never really able to detect the first weakest signal and rarely able to detect the second weakest signal. The maximum likelihood estimator was successful in all 200 trials; however, it achieved a median absolute delay error of $\{67.2\ 77.2\ 80\ 27.6\}$ ns [4].

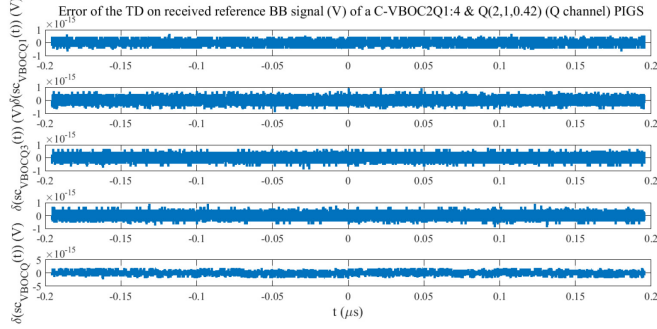
Figures 8 (d) - (f) present the normalized cross correlator for the jamming signals, at 80 dB, 53 dB and 70 dB [4]. As shown from Figs. 8 (d) - (f) the cross-correlator type of receiver is only able to correctly estimate the delay for the first and third jammers. It fails to estimate the delay for the second jammer. The maximum-likelihood GPS receiver is always able to correctly estimate the delay for both the jammers and the GPS signal.

This example perfectly illustrates that jamming is no longer an issue for the maximum-likelihood GPS receiver regardless of the frequency, signal shape waveform, spreading modulation waveform etc.; i.e., the maximum-likelihood GPS receiver will perform as good as if there was only one signal and noise; i.e., the ideal case. In order to get better performance than you would have to improve the signal via innovative signal design.

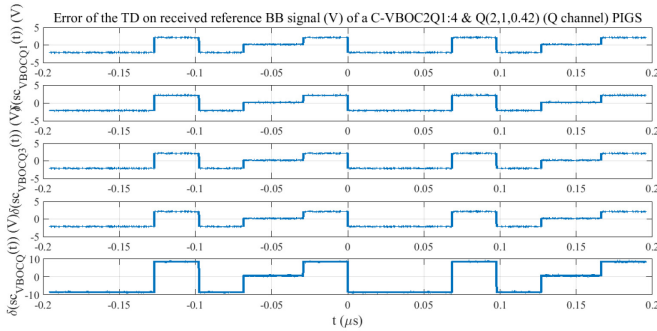
We propose a “maximum likelihood” GPS receiver for processing the received GPS signals of the L_1 , L_2 , or L_5 frequencies. The “maximum likelihood” GPS receiver performs a simultaneous, two-dimensional, search of both the Doppler frequencies and GPS Gold codes. The Doppler bin search size should be not more than 100 Hz. Moreover, we have identified a new approach for improving TOA estimation performance by considering it as multi-user statistical estimation problem and employing maximum likelihood estimation techniques. A simple example has been provided showing nearly an order of magnitude improvement in TOA performance.



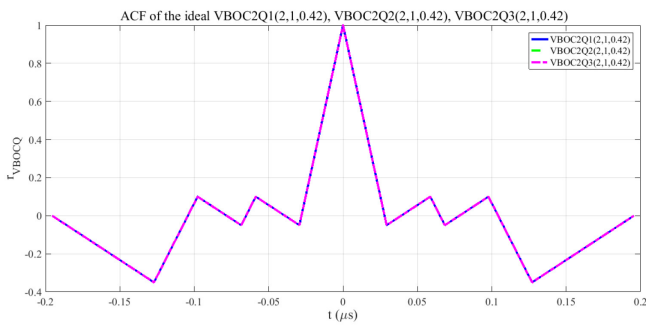
(a) 0.4-ns TD received BB signal of a $C\text{-}VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction off).



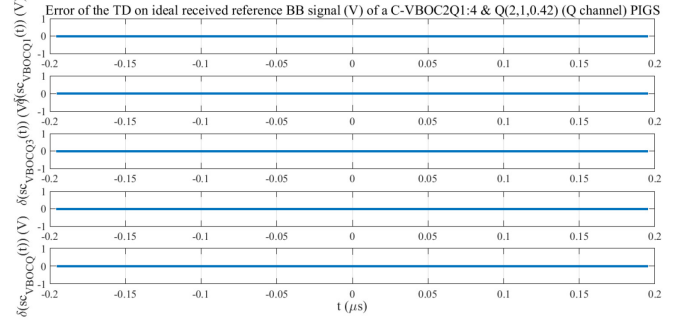
(c) 0.4-μs error of the TD received BB signal of a $C\text{-}VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS. (Neither noise nor channel impairments).



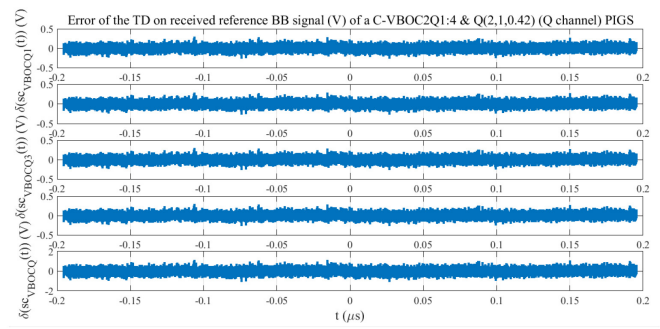
(e) 0.4-μs error of the TD received BB signal of a $C\text{-}VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off).



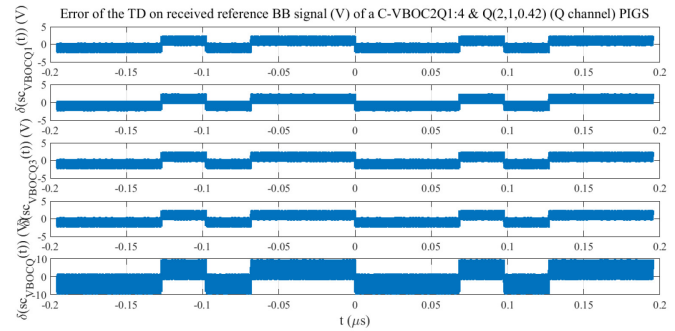
(g) 0.4-μs ACF Q Ch: $VBOC2Q1:3_{(2,1,0.42)}$ PIGS.



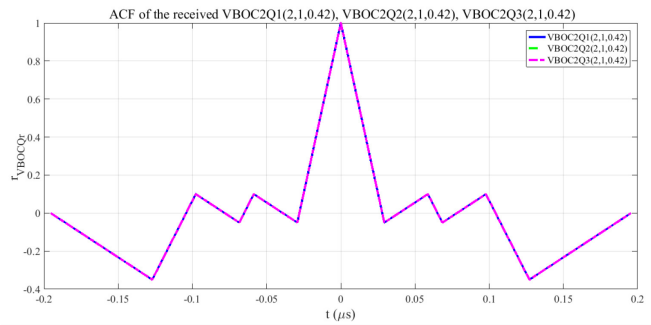
(b) 0.4-μs error of the TD ideal received BB signal of a $C\text{-}VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS.



(d) 0.4-μs error of the TD received BB signal of a $C\text{-}VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on).

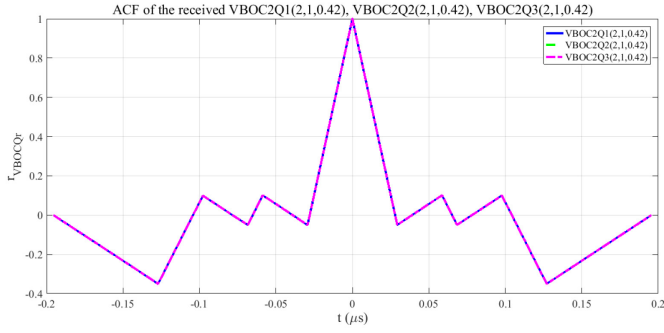


(f) 0.4-μs error of the TD received BB signal of a $C\text{-}VBOC2Q1:4_{(2,1,0.42)}$ and $VBOC2Q_{(2,1,0.42)}$, (Q channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction off).

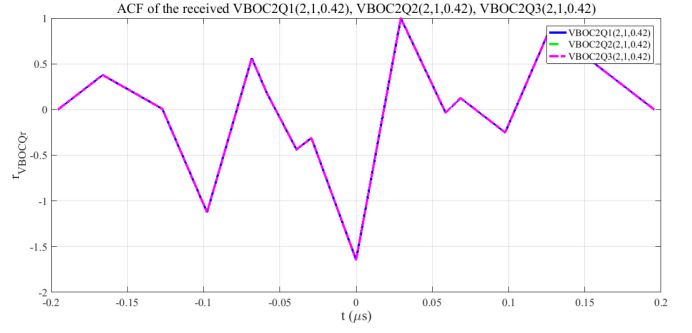


(h) 0.4-μs ACF of the received Q Ch: $VBOC2Q1:3_{(2,1,0.42)}$ PIGS. (Neither noise nor channel impairments)

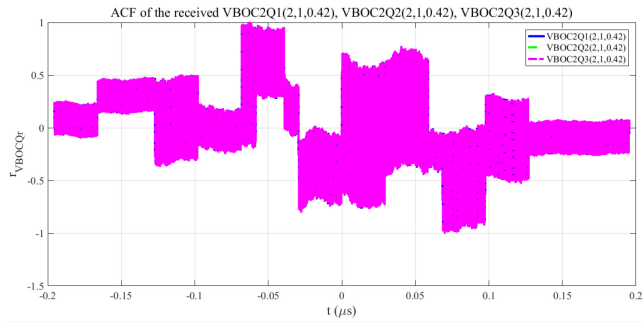
FIGURE 5: Giftet® high performance GPS-Like VBOC CA-code simulation results 4. Reprinted with permission Copyright © 2016 Giftet Inc. All rights reserved.



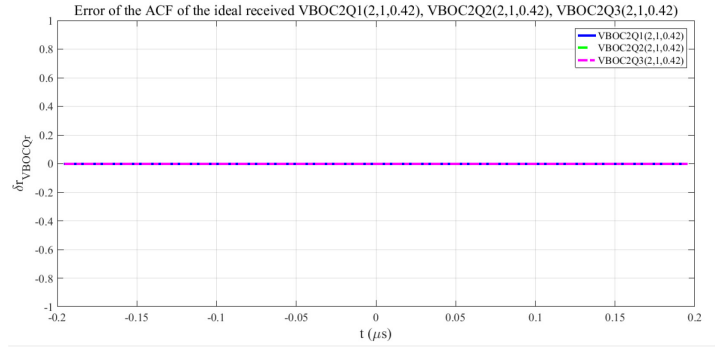
(a) 0.4- μ s ACF of the received Q Ch: $VBOC2I1:3_{(2,1,0.42)}$ PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on).



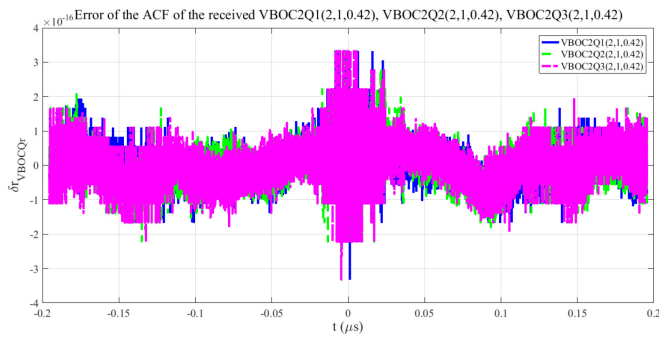
(b) 0.4- μ s ACF of the received Q Ch: $VBOC2I1:3_{(2,1,0.42)}$ PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off).



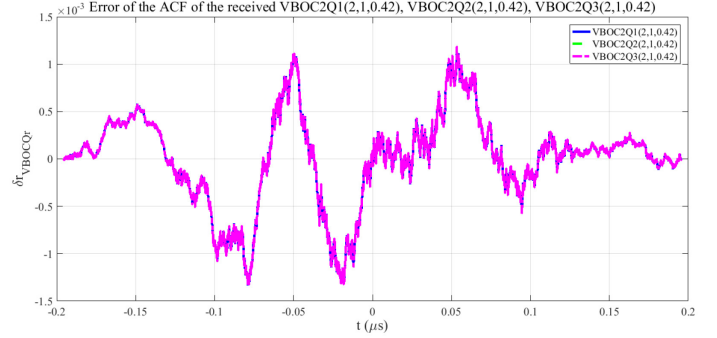
(c) 0.4- μ s ACF of the received Q Ch: $VBOC2I1:3_{(2,1,0.42)}$ PIGS. (Both noise and channel impairments on; both down-conversion and channel correction off).



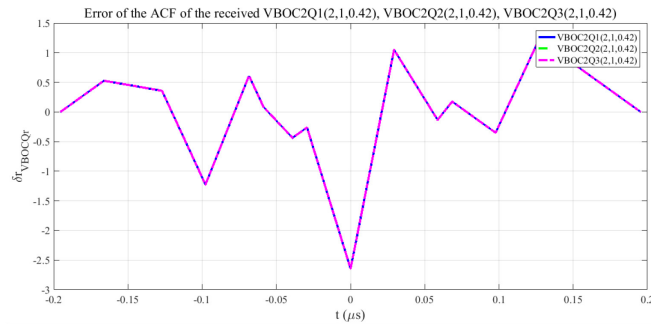
(d) 0.4- μ s error of the ideal received ACF Q Ch: $VBOC2I1:3_{(2,1,0.42)}$ PIGS.



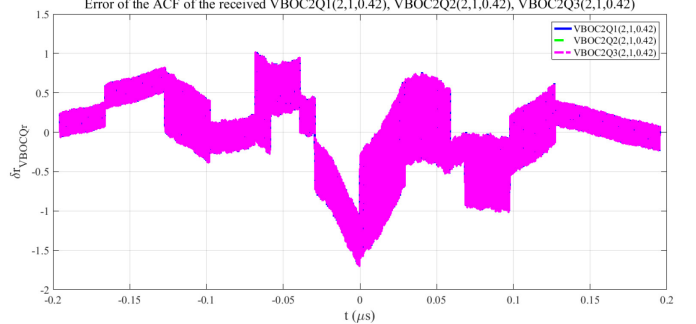
(e) 0.4- μ s error of the received Q Ch: $VBOC2I1:3_{(2,1,0.42)}$ PIGS. (Neither noise nor channel impairments).



(f) 0.4- μ s error of the received Q Ch: $VBOC2I1:3_{(2,1,0.42)}$ PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on)

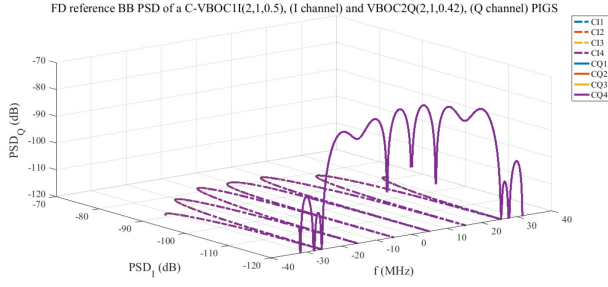


(g) 0.4- μ s error of the received Q Ch: $VBOC2I1:3_{(2,1,0.42)}$ PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off)

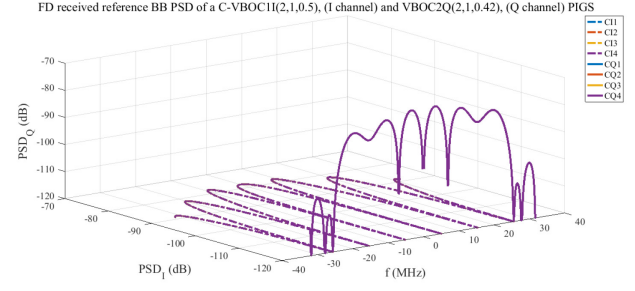


(h) 0.4- μ s error of the received Q Ch: $VBOC2I1:3_{(2,1,0.42)}$ PIGS. (Both noise and channel impairments on; both down-conversion and channel correction off).

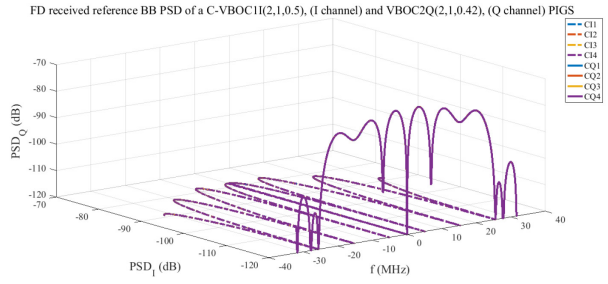
FIGURE 6: Giftet® high performance GPS-Like VBOC CA-code simulation results 5. Reprinted with permission Copyright © 2016 Giftet Inc. All rights reserved.



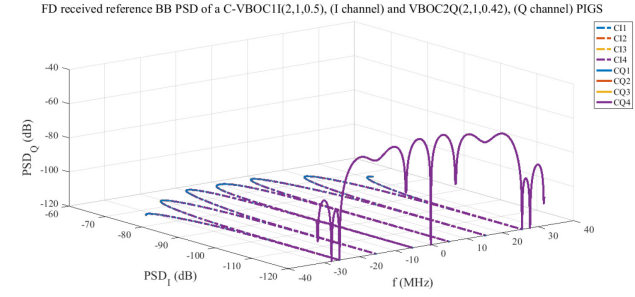
(a) 62.5-MHz FD reference BB PSD of a $C-VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS.



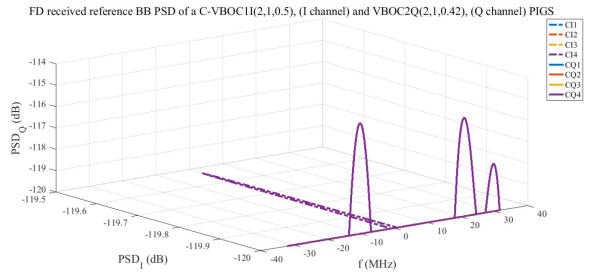
(b) 62.5-MHz FD received reference BB PSD of a $C-VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS. (Neither noise nor channel impairments)



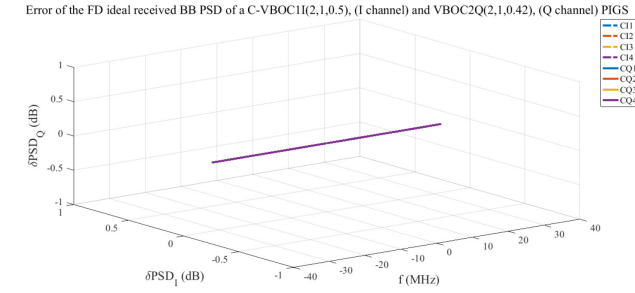
(c) 62.5-MHz FD received reference BB PSD of a $C-VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on).



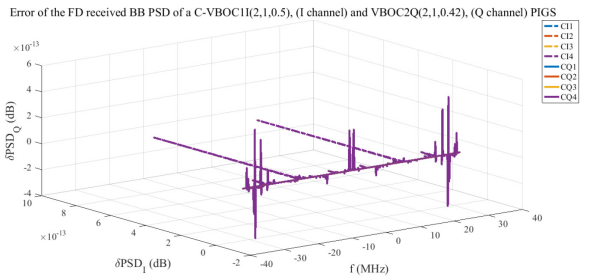
(d) 62.5-MHz FD received reference BB PSD of a $C-VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off)



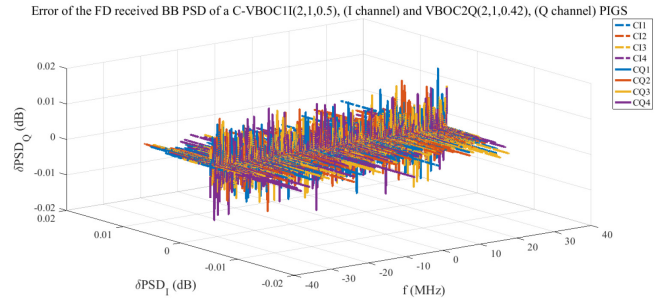
(e) 62.5-MHz FD received reference BB PSD of a $C-VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction off).



(f) 62.5-MHz error FD received reference BB PSD of a $C-VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS.



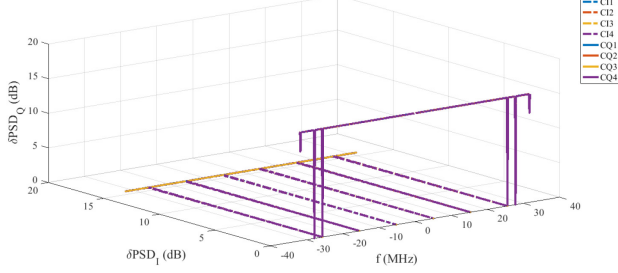
(g) 62.5-MHz error FD received reference BB PSD of a $C-VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS. (Neither noise nor channel impairments).



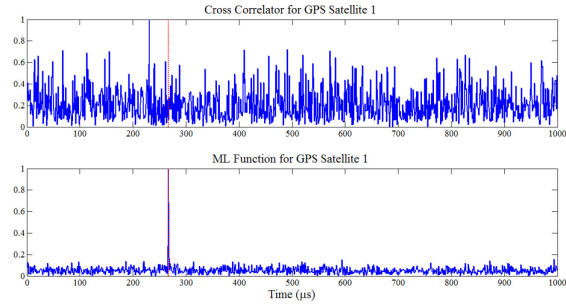
(h) 62.5-MHz error FD received reference BB PSD of a $C-VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS. (Both noise and channel impairments on; both down-conversion and channel correction on)

FIGURE 7: Giftet® high performance GPS-Like VBOC CA-code simulation results 6. Reprinted with permission Copyright © 2018 Giftet Inc. All rights reserved.

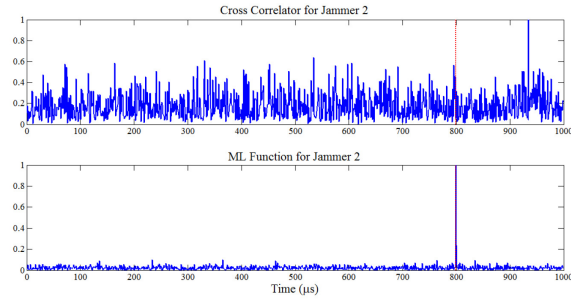
Error of the FD received BB PSD of a C-VBOC1I(2,1,0.5), (I channel) and VBOC2Q(2,1,0.42), (Q channel) PIGS



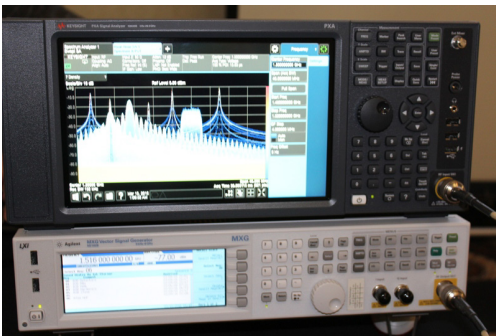
(a) 62.5-MHz error FD received reference BB PSD of a $C\text{-}VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS. (Both noise and channel impairments on; down-conversion on and channel correction off)



(c) The estimated and true τ_1 using the cross-correlator (top) and maximum likelihood estimator (bottom) for GPS Satellite 1.

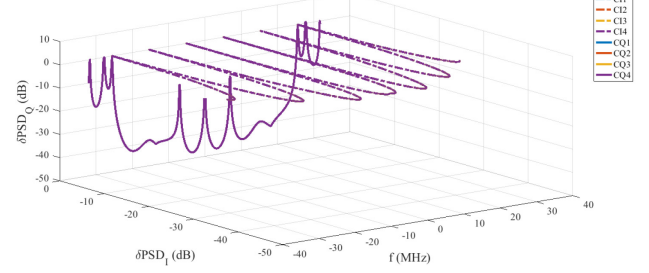


(e) The estimated and true τ_2 using the cross-correlator (top) and maximum likelihood estimator (bottom) for Jammer 2.

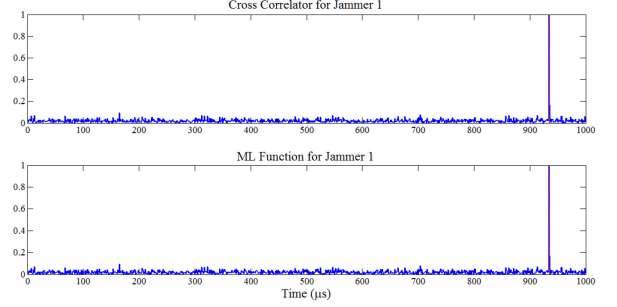


(g) Keysight test setup of N5182A MXG Vector Signal Generator, 100 kHz to 6 GHz [38] (as transmitter) and N9030A PXA Signal Analyzer, 3 Hz to 50 GHz [39] as (receiver). Reprinted with permissions. Copyright © 2016 Giftet Inc. All rights reserved.

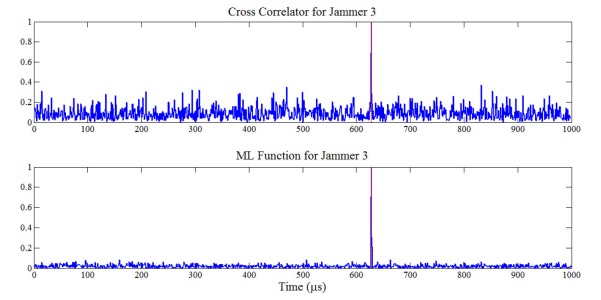
Error of the FD received BB PSD of a C-VBOC1I(2,1,0.5), (I channel) and VBOC2Q(2,1,0.42), (Q channel) PIGS



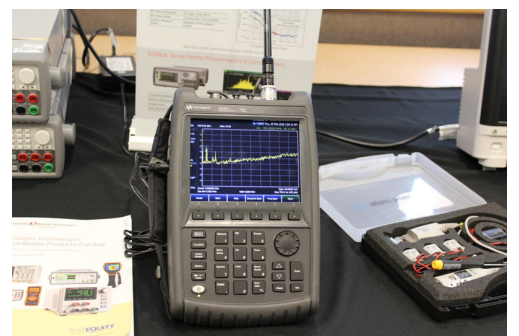
(b) 62.5-MHz error FD received reference BB PSD of a $C\text{-}VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS. (Both noise and channel impairments; both down-conversion and channel correction off)



(d) The estimated and true τ_1 using the cross-correlator (top) and maximum likelihood estimator (bottom) for Jammer 1.



(f) 62.5-MHz error FD received reference BB PSD of a $C\text{-}VBOC1I_{(2,1,0.5)}$, (I channel) and $VBOC2Q_{(2,1,0.42)}$ (Q channel) PIGS.



(h) Keysight test setup of N5182A MXG Vector Signal Generator, 100 kHz to 6 GHz [38] (as transmitter) and N9912A FieldFox Handheld RF Analyzer, 4 GHz and 6 GHz [40] as (receiver). Reprinted with permissions. Copyright © 2016 Giftet Inc. All rights reserved.

FIGURE 8: Giftet® high performance GPS-Like VBOC CA-code simulation and implementation results 7. Reprinted with permission Copyright © 2016 Giftet Inc. All rights reserved.

Moreover, there are a number of numerical procedures that can be employed to reduce the computational burden of the more powerful estimation technique. It is expected that this approach can yield additional benefits in GPS performance in environments where the “near-far” problem limits acquisition of weak GPS signals by the “sliding-correlator” estimation. It is additionally expected to yield further gains as these techniques are extended to environments containing significant multipath [4], [5].

Giftet Inc. is the BEST source to produce a pioneer solution in terms of performance *200% to 500% better than anyone else solution* for Giftet® High Performance GPS-like VBOC Acquisition Engine. Why? (1) pioneer Ph.D. dissertation on an assessment of indoor geolocation systems [9]; (2) pioneer patent in reconfigurable geolocation system [25]; (3) pioneer journal publication on Maximum likelihood GPS parameter estimation [4]; (4) pioneer peer review conference publications [21]; (5) pioneer book publications [10], [22], [23].

4 Hardware Implementation

Consider for example, the NovAtel ProPack and FlexPack OEM6 products or documentation [34]-[37] or any other receiver products, there is no shred of evidence that describes in detail the RF section signal propagation as described in this paper.

Giftet Inc. Indoor Geolocation Systems MATLAB library becomes a unique analysis, simulation, and design tool for the RF section analysis and simulation of future NovAtel Products.

Consider for example, Keysight Technologies vector generators [38] and signal analyzers [39], [40], as great as a company Keysight Technologies is, ask them to give you the closed form expression of a signal in the FD is you know the closed form expression in TD. They cannot do it.

Giftet Inc. Indoor Geolocation Systems MATLAB library becomes a unique analysis, simulation, and design tool for the RF section analysis and simulation of future Keysight Technologies Products.

4.1 Hardware Test-setup Implementation Configuration

The hardware test-setup implementation configuration may consist of the two following scenarios:

(1) Keysight test-setup of N5182A MXG Vector Signal Generator, 100 kHz to 6 GHz [38] (as transmitter) and

N9030A PXA Signal Analyzer, 3 Hz to 50 GHz [39] as (receiver) as shown in Fig. 8 (g).

(2) Keysight testsetup of N5182A MXG Vector Signal Generator, 100 kHz to 6 GHz [38] (as transmitter) and N9912A FieldFox Handheld RF Analyzer, 4 GHz and 6 GHz [40] as (receiver) as depicted in Fig. 8 (h).

The first configuration is in the price range of greater than \$56,463 vs. the second greater than \$8,334.

It is very important that a reader gets first familiar with the Technical overview: real-time spectrum analyzer (RTSA) X-series signal analyzers N9040B/N9030A/N9020A-RT1 & -RT2 in [41] and Application note: understanding and applying probability of intercept in real-time spectrum analysis [42] before understanding the capability of test-setup.

5 Conclusions

This technical report provides the results from the performance evaluation of the direct acquisition of the GPS-like VBOC signals against interference and noise using real GPS or GNSS signals.

We initially compare and contrast the performance of VBOC1(1,1,0.5) and VBOC2(1,1,0.4) against noise and channel Impairments, no data and only four GPS-like satellite signals in the lab.

Receiver noise model performance against additive white Gaussian noise (AWGN) [2]-[11] was almost ideal.

We were also able to demonstrate the performance under channel impairments modeled after the innovative Giftet 4-parameter channel model. The detailed discussion of this model will be published in a separate journal paper. At the moment the 4-parameter channel model includes only the ionospheric model [2]. Later on this model will include also the tropospheric and multipath 4-parameter channel model [2].

Giftet receiver anti-jam acquisition and tracking performance was also excellent which included some of Giftet Inc. most innovative algorithms [4]-[8] that even today eleven or twelve years after there were invented their performance is still spectacular: GPS-like VBOC signals can achieve time to first fix (TTFF) of 100 seconds with initial time uncertainty (ITU) of 100 ns and jamming/signal ratio (JSR) of 90 dB against additive white Gaussian noise (AWGN) or other “unknown” jammers with bandwidth of ± 1 or 4 MHz.

In summary Giftet Inc. Indoor Geolocation Systems

MATLAB library offers unique and unlimited capabilities for analysis, simulation, and design tool for the RF, IF, and BB sections analysis and simulation of future Keysight, Locata, NovAtel, etc. products.

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ⁱ Look at the 2019 issue of Giftet Journal of Geolocation, Geo-Information and Geo-Intelligence for the innovative ionospheric 4-paramater channel model.

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