Adaptive Tracking Techniques in Non-Stationary Environments

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BIOGRAPHY

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Gonzalo Seco-Granados received the M.Sc. and Ph.D. degrees in Telecommunication Engineering in 1996 and 2000, respectively, from UPC. He also received an MBA from IESE-University of Navarra, Barcelona, in 2002. From 2002 to 2005, he was member of the technical staff at the European Space Research and Technology Center (ESTEC), European Space Agency (ESA), Noordwijk, The Netherlands, involved in the Galileo project and leading the activities concerning indoor GNSS. Since 2006, he is Associate Professor at the Dept. of Telecom. Engineering, UAB, and member of the SPCOMNAV group. He was a co-guest editor for a special issue of the IEEE Signal Processing Magazine.

Miguel Angel Ribot received his B.Sc. degree in telematics engineering from the Universitat de les Illes Balears (UIB), and his M.Sc. in information and communication technologies from Universitat Politècnica de Catalunya (UPC), in 2008 and 2011, respectively. He is currently working toward his Ph.D. in the Electronics and Signal Processing Laboratory (ESPLAB) at École Polytechnique Fédérale de Lausane (EPFL), Switzerland. His Ph.D. is supported by the Swiss National Science Foundation. His research interests include GNSS signal processing, and remote sensing using GNSS signals.

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Cyril Botteron received his Ph.D. degree in electrical and computer engineering in 2003 from the University of Calgary, Canada, where he was the recipient of a Natural Sciences and Engineering Research Council of Canada postgraduate scholarship and an Alberta Informatics Circle of Research Excellence graduate fellowship. Since 2003, he is leading, managing, and coaching the research

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Pierre-André Farine is professor in electronics and signal processing at EPFL, and is head of the ESPLAB. He received the M.Sc. and Ph.D. degrees in micro technology from the University of Neuchâtel, Switzerland, in 1978 and 1984, respectively. He is active in the study and implementation of low-power solutions for applications covering wireless telecommunications, ultra-wideband, global navigation satellite systems, and video and audio processing. He is the author or co-author of more than 100 publications in conference and technical journals and 50 patent families (more than 270 patents).

Rigas Ioannides is a radio navigation signal engineer currently working at ESTEC, ESA. He was awarded his Ph.D. in 2001, for studies of atmospheric and ionospheric effects on satellite signal propagation. Since then, he has being working in several areas of GNSS systems including development and validation of GNSS receiver DSP techniques, integrity algorithms and architectures, and on the analysis of new GNSS signals.

ABSTRACT

The continuously changing environments have been the main challenge for classical GNSS receiver implementations, as they can have a great impact on signal tracking performance and positioning.
For this reason techniques capable of mitigating the impact of time-varying phenomena by adapting to changing conditions, thus improving performance are of great interest.

This study reports the benefits of using adaptive techniques for standalone GNSS receivers in three different scenarios.
The first scenario compares an adaptive Kalman filter against a classical DLL/PLL architecture in interference environments with user dynamics. The second scenario uses a multipath propagation channel to test alternative carrier tracking architectures which provide better results in terms of robustness. The third scenario uses the same multipath propagation channel to test the adaptive switching technique, 2-Step, in order to evaluate its capacity of guaranteeing and maintaining unambiguous tracking for BOC-type modulations.

In order to assess the performance of these techniques a semi-analytical platform has been used. The results presented here show the benefits and trade-offs of different techniques taking into account different propagation channels and scenarios.

1. INTRODUCTION

Tracking of the synchronization parameters is the core element of GNSS receivers. In classical navigation receiver approaches, this process is put in place by the use of DLL, PLL and/or FLL architectures, where these tracking loops estimate the parameters required for adjusting the correlation process of a local replica with the incoming signal. However, the main challenge posed to these classical implementations of GNSS receivers, in terms of performance, is the continuously changing environment, affecting the quality of the received signal (which is already, by inherent design, a very low power signal).
In terms of signal characteristics and propagation, the performance and quality of the GNSS signal tracking processes are very dependent on the propagation channel and varying environment.

Recent developments in signal tracking techniques, especially in communication systems, have targeted mitigating the impact of such time-varying effects through the use of adaptive tracking techniques. The goal is to devise mechanisms at receiver level to cope with the different changes in the signal propagation channel and environment. Ultimately, the tracking techniques are devised to dynamically adapt the processing chain and tracking algorithms to a changing environment as best as possible, mitigating the potentially harmful impact on the receiver's accuracy and robustness.

In GNSS receivers, the use of such adaptive techniques has been quite limited to this day, mainly due to the fact that GNSS has been primarily envisaged for open field applications, where the propagation environment is prone to fewer and/or slower variations.

This work is built from the main outcomes of a study that analyzed the performance of adaptive techniques in time-varying environments. For that purpose, it focuses on the most promising technique/environment combination, highlighting the obtained benefits.

2. ADAPTIVE TECHNIQUES

Three adaptive tracking techniques are considered in this work.

A. Adaptive-R Kalman Filter

In the recent years, Kalman filters have received an increasing interest as robust and optimal alternatives to conventional GNSS tracking techniques. Their main advantage is their systematic derivation and the capability to easily incorporate both statistical and dynamic a-priori through their state-space formulation. Typically, this information is set at the design phase and leads to some given steady-state tracking performance. This is similar to what happens with conventional tracking techniques, whose behavior is mainly determined by the loop filter configuration, which is set during the design phase and then remains fixed henceforth. Such approach, however, does not fit well in time-varying working conditions where sudden drops in the received C/N0 are likely to be experienced (e.g. due to signal blockage when moving from outdoor to soft-indoors, or when operating in urban canyons). In these circumstances, it would be interesting to adapt the tracking technique so as to cope with such time-varying behavior.

Kalman filters already take this possibility into account, since their formulation allows the statistical information to be updated at every time instant. For the problem at hand, this means updating the measurement noise covariance matrix $\boldsymbol{R}$ by estimating its value at every time instant. In this work, this is done by using Myers' method, which involves the following estimate [MYE76]:

$$\hat{\boldsymbol{R}} = \frac{1}{N-1}\sum_{k=0}^{N-1}(\boldsymbol{e}_k - \bar{\boldsymbol{e}})^2 - \frac{1}{N}\sum_{k=0}^{N-1}\boldsymbol{H}\boldsymbol{\Sigma}_{k+1|k}\boldsymbol{H}^H$$

where $\bar{\boldsymbol{e}} \doteq \frac{1}{N-1}\sum_{k=0}^{N-1}\boldsymbol{e}_k$ with $\boldsymbol{e}_k$ stands for the Kalman innovations (i.e. the code/carrier discriminator outputs, according to the setup in Fig. 1) and $\boldsymbol{\Sigma}_{k+1|k}$ is the covariance matrix of the transitioned Kalman state vector. That is, $\boldsymbol{\Sigma}_{k+1|k} = \boldsymbol{F}\boldsymbol{\Sigma}_k\boldsymbol{F}^H + \boldsymbol{G}\boldsymbol{Q}_k\boldsymbol{G}^H$ with $\boldsymbol{\Sigma}_k = (\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{H})\boldsymbol{\Sigma}_{k|k-1}$ and $\boldsymbol{Q}_k$ the process noise covariance matrix. When the magnitude θ to be tracked (either code/carrier phase) is modeled by a second-order polynomial, the Kalman state vector becomes $\boldsymbol{x}_k = \left[\theta_k, \dot{\theta}_k, \ddot{\theta}_k\right]^T$ so that the transition matrix and the process noise matrices appearing above become, respectively:

$$\boldsymbol{F} = \begin{pmatrix} 1 & T_s & T_s^2/2 \\ 0 & 1 & T_s \\ 0 & 0 & 1 \end{pmatrix} \qquad \boldsymbol{G} = \begin{pmatrix} T_s^3/3! \\ T_s^2/2 \\ T_s \end{pmatrix}$$

with T_s the pre-detection integration time. Finally, the observation matrix for the problem at hand becomes $\boldsymbol{H} = [1,0,0]^T$.

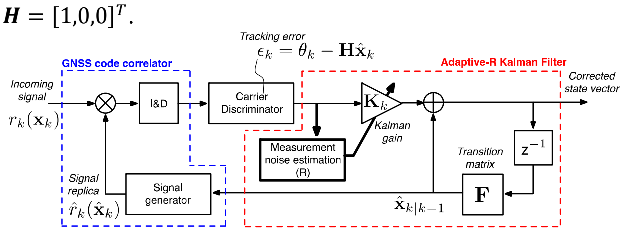

Figure 1: Block diagram of an AR-KF implementation for GNSS signal tracking.

It is interesting to bear in mind that changing the value of the measurement noise variance allows us to control the equivalent loop bandwidth of the Kalman filter. For the problem at hand we have $B_L = \frac{5}{6T_s^{5/3}}\left(\frac{\sigma_v^2}{R}\right)^{1/6}$ [JWO01], where σ_v^2 is some process noise variance that is set at the design phase in order to preserve some target performance in nominal working conditions (i.e. a given bandwidth B_L for a nominal value of R). Thus, by letting σ_v^2 fixed while we change the value of R according to the current working conditions, we are able to automatically (and optimally) adjust the equivalent loop bandwidth of the Kalman filter.

B. FLL-aided PLL

The availability of assistance information becomes of paramount importance when time-varying working conditions are to be faced at the tracking stage. The reasons are twofold. On the one hand, a-priori information is known to reduce the estimation error, thus improving the overall tracking accuracy. On the other hand, a-priori information helps in mitigating the presence of outliers, thus improving the tracking stability by preserving the signal lock. Typically, a-priori information is obtained by external sources such as inertial sensors, but in some other cases, it may readily be obtained from the same set of measurements to be processed at the tracking stage. This is the case of FLL-aided PLL schemes (also referred herein as FPLL), where an FLL is in charge of estimating the coarse user dynamics and then feeding this "a-priori" information to a conventional PLL. Because of the presence of this assistance information, the PLL loop bandwidth can be significantly reduced when compared to conventional implementations, thus allowing us to improve the noise rejection without compromising the capability to track high user dynamics. Consequently, FPLL implementations are well-suited for scenarios where sudden changes in the user dynamics may be faced, but at the same time, signal fades may also be present. It is for this reason that this is one of the selected techniques for this study.

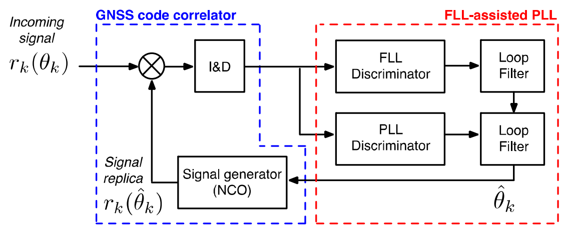

Figure 2: Block diagram of an FPLL implementation for GNSS signal tracking.

C. Adaptive Switching

In BOC-type modulations, the subcarrier signal splits the power spectrum's main lobe into two side-lobes centered at ± $f_{subcarrier}$. Instead of using the entire bandwidth as in Full Band (FB) tracking, the receiver can also band-pass filter each side-lobe and process each lobe as a simpler BPSK signal. In Single Side Band (SSB) tracking only one of the side-lobes is used, while in Double Side Band (DSB) both side-lobes are processed individually and the correlation output is combined within the tracking loop.

In FB tracking, the BOC-type autocorrelation function (ACF) is sharper when compared to a BSPK ACF using the same bandwidth, resulting in increased accuracy and multipath mitigation. However, if no unambiguous tracking technique is used, the BOC-type ACF's additional peaks might lead to false-lock situations, where instead of the main peak, a side peak is being tracked, resulting in a biased code delay estimation. In contrast, SSB or DSB tracking are more robust against potentially larger code errors. Moreover, the ACF obtained has a single peak, which prevents false-locks, and for SSB tracking a smaller front-end bandwidth is required. The price to pay is a diminished accuracy and weaker multipath rejection.

The purpose of adaptive switching is to make the receiver dynamically select the most appropriate tracking scheme, either SSB, DSB or FB, according to the estimated channel conditions. For this purpose, a modified version of the 2-step algorithm, introduced in [JOV12], is proposed. This algorithm uses the Carrier to Noise ratio (CNO) estimates and the Phase Lock Indicator (PLI) [DIE96] to compute a metric that reflects the current channel conditions. By analyzing the behavior of this metric over time and comparing it with a predefined set of thresholds, the 2-step logic decides when to switch between FB and DSB and vice versa (SSB was not considered as always providing worst performance than DSB). The threshold values are tweaked depending on the BOC modulation considered and the type of scenario.

The proposed 2-step switching technique is benchmarked against a classical DLL/ PLL implementation in order to understand its benefits as unambiguous tracking technique for BOC modulations which are foreseen in modernized GPS/ Compass and Galileo systems.

3. SIMULATION ENVIRONMENT

A. Platform

A semi-analytical platform is used to assess the performance of each technique in the selected environments. The proposed architecture is devised to realistically characterize the propagation channel models, the signal modulations, the correlation process and the tracking loops. The simulator is based in a so-called semi-analytical approach, in which the signal is generated at correlator output level, based on the closed-form analytical expression of a GNSS receiver's correlation function, and taking into account relevant propagation models, such as multipath (e.g. [JAK12]). Note that the correlation generation is also dependent on the tracking loops, due to the impact of the error estimation and residuals feedback to the replica generation.

The generic architecture of the platform is depicted in Figure 3; the user may select different code and phase/ frequency tracking loops combinations and configure them independently (e.g. different integration times).

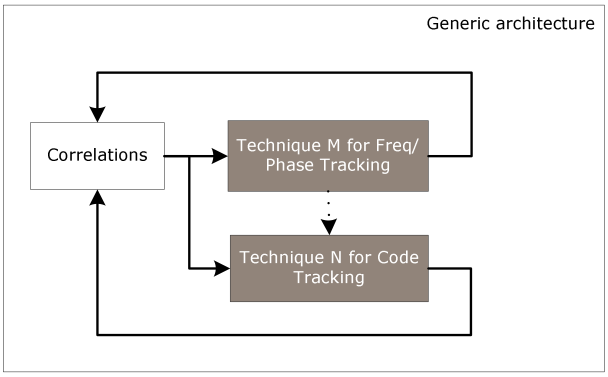

Figure 3: Platform Generic Architecture

Apart from the configurations related to the techniques themselves, the platform configuration parameters also include the time series of the propagation models (e.g. multipath) and outputs code, phase and Doppler measurements as well as a loss of lock indicator.

B. Figures of Metrics

A post-processing module is incorporated in the platform and allows the analysis of results using figures-of-merit which include robustness, accuracy and adaptability. The post-processing of results follows the next steps.

Firstly the platform corrects the code false-locks and phase cycle-slips, and removes code and phase drifts from the measurements. Based on these results the robustness metrics are computed (e.g. probability of false-lock, probability of cycle-slip).

After these corrections are made the accuracy metrics are computed using the corrected measurements and the known references (e.g. standard deviation and RMSE).

Finally the adaptability metric evaluates the convergence time after a transition in the environment conditions.

C. Scenarios

The scenarios that best showcase the benefits of the selected techniques are described hereafter.

1- <u>AWGN-varying environment</u>

This scenario includes a CN0 drop, representative of open areas with occasional signal blockage or driving near a jammer.

A vehicular user was simulated and both the velocity and the CN0 profiles are depicted in Figure 4.

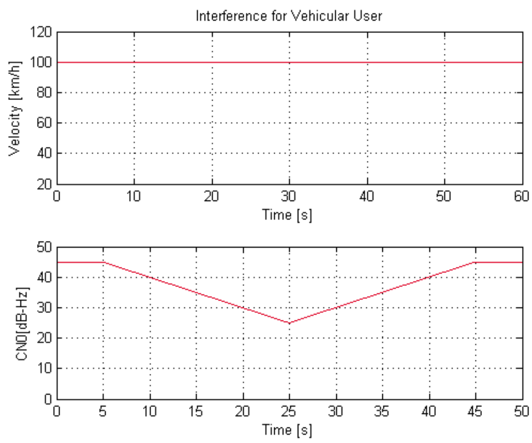

Figure 4: Scenario 1 – user dynamics and AWGN-varying

2- <u>Urban environments driven by multipath</u>

The urban environment is simulated using the DLR model, standardized in ITU-R P.681-7 (10/09), which is based on both deterministic and stochastic processes within artificial scenery parameterized by the user.

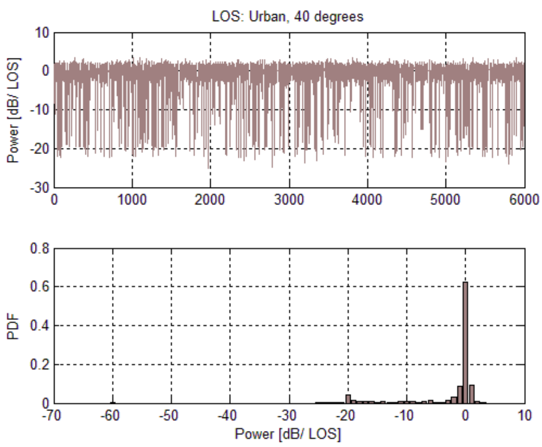

Figure 5: Scenario 2 – Urban Multipath, 40 degrees

The DLR model generates a few tenths of multipath components (in general, less than 50 multipath components) for urban environments and it includes time dispersion effects hence providing a highly realistic model of the multipath channel. Figure 5 depicts the Line Of Sight (LOS) profile considered, for a satellite elevation angle of 40 degrees and Figure 6 the user dynamic profile.

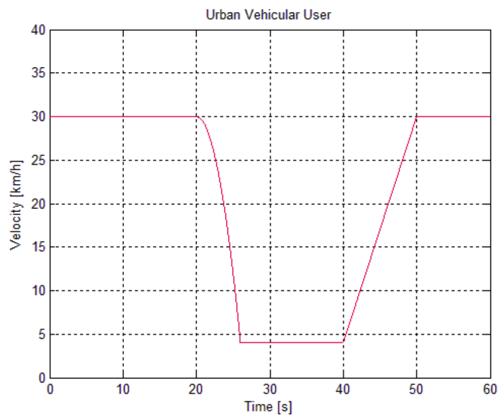

Figure 6: Scenario 2 – User dynamics Profile

3- <u>Urban environments driven by code false-lock situations.</u>

The objective of this environment is to assess the benefits of the adaptive switching technique in terms of false-lock correction for higher BOC order modulations, such as BOCcos (15,2.5) used in modernized GNSS signals.
On top of the urban multipath profile depicted in Figure 5, a more stringent profile for a satellite elevation angle of 30 degrees is also considered, Figure 7, in order to increase the false-lock occurrence probability.

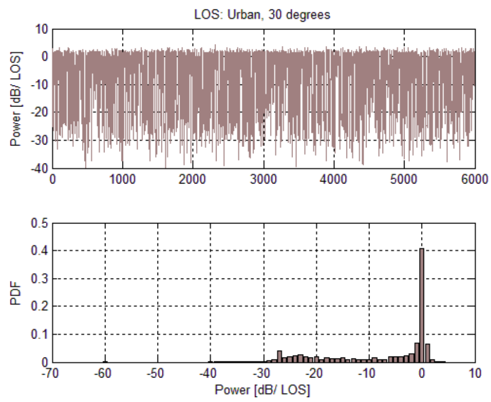

Figure 7: Scenario 3 – Urban Multipath, 30 degrees

4. SIMULATION RESULTS

The benefits of each technique are highlighted by comparing the performance of the most performant technique against the classical DLL/ PLL architecture in each relevant environment, as in Table 1.

Table 1: Scenarios Considered

	Environment	Technique
Scenario 1	Interference (vehicular user with CN0 drops, see Figure 4)	ARKF
Scenario 2	Urban (multipath see Figure 5)	FLL-aided PLL and FLL
Scenario 3	Urban (multipath see Figure 5 and Figure 7, for higher order BOC modulations)	2-step adaptive switching

The techniques used in the simulations have been configured according with Table 2.

Table 2: Techniques configuration

Technique	Order	Bandwidth	Integration time (ms)
PLL	3rd	15 Hz	4ms for CBOC and 10ms for BOCc(15,2.5)
FPLL	3rd PLL 2nd FLL	PLL = 10 Hz FLL = 5 Hz	4ms
FLL	2nd	100 Hz	4ms
DLL	2nd	1 Hz	20ms for CBOC and 10ms for BOCc(15,2.5)
FKF/ ARKF	3rd	Equivalent bandwidth: Code: 1 Hz Phase: 15 Hz	4ms for carrier and 20ms for code tracking

A. Scenario 1: Interference

The ARKF technique is designed for this type of environments since its adaptability mechanism allows it to adjust its equivalent bandwidth to the CN0 conditions optimally. At the same time, since the user dynamics are not too stringent and that the signal level variations are rather slow, this process is very robust.

The temporal results CBOC(6,1,1/11) modulation using an integration time of 20ms for a single iteration are depicted in Figure 8.

Note that the ARKF provides better results in terms of stability and with lower jitter, especially noticeable for phase error. The ARKF's adaptive mechanism allows it to reduce its equivalent bandwidth during periods of lower CN0, thus providing a better noise rejection.

The results averaged over 100 independent iterations are provided in Table 3, including a Fixed Kalman Filter (FKF) for reference.

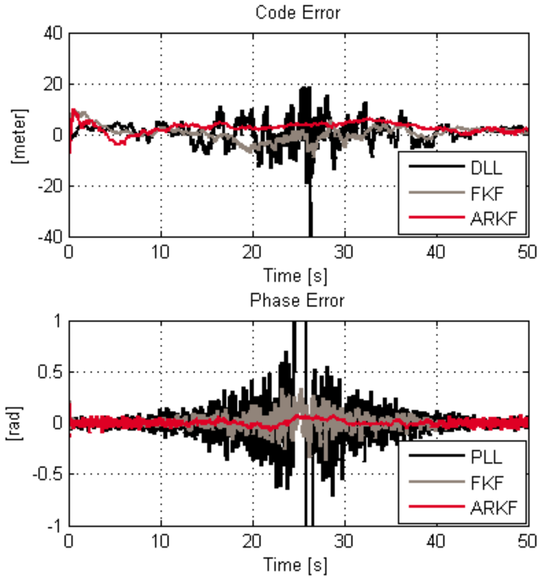

Figure 8: Temporal results for a single iteration

Table 3: Full Results for 100 independent iterations for CBOC(6,1,1/11) with 20ms integration time

Metric\ Technique	DLL/ PLL	FKF	ARKF
Probability of Code Drift (Code LoL) [%]	0.2	0	0
Probability of Phase Drift (Phase LoL) [%]	3.3	0	0
Probability of Cycle Slips [%]	10.2	0	0
Code Jitter [m]	5.20	3.48	3.06
Phase Jitter [rad]	0.30	0.07	0.03
Doppler Jitter [Hz]	2.19	0.06	0.03
Mean Time to Code Recovery [s]	0.33	0.29	0.29
Mean Time to Phase Recovery [s]	0.63	0.29	0.29

These results highlight the improvement of the Adaptive-R Kalman Filter over the classical DLL/ PLL and the fixed Kalman Filter implementations.

From a robustness point of view both the kalman filters present a clear improvement over the DLL/PLL, with lower probability of code/phase drifts and phase cycle-slips.

From the ARKF results it is important to emphasize a tenfold reduction in phase jitter when compared to the DLL/PLL. Regarding adaptability note that the ARKF also presents an improvement, being able to adapt during environment transitions in half the time for phase than DLL/PLL.

Even though in the interference scenarios, the Fixed Kalman Filter (KFK) already shows an important improvement with respect to the classical architecture, the proposed implementation, ARKF, is able to optimize the filter configuration parameters according to the external conditions.

B. Scenario 2: Urban

In urban environments where the combination of user dynamics and heavy multipath play a major role in the receiver performance, the technique robustness becomes one of the most desirable features.
In this scenario it is shown that the FPLL and FLL can be used as alternative architectures to the PLL in order to improve tracking robustness in this type of environments.
Results for a single iteration for the CBOC(6,1,1/11) modulation are presented in the following figure.

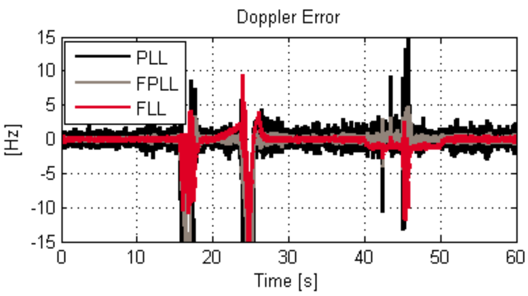

Figure 9: Temporal results for a single iteration

Note that in these simulations, the DLL/ FLL is penalized since a second order filter is used and therefore it is not able to cope with the periods of jerk in the user dynamics. This is most evident during 20-26 and 40-50 seconds.

The results averaged over 100 independent iterations are provided in Table 4.

Table 4: Full Results for 100 independent iterations for CBOC(6,1,1/11) with 20ms integration time

Metric\Technique	**DLL/ PLL**	**DLL/ FPLL**	**DLL/ FLL**
Number of Loss-of-Lock (LoL)	218	154	89
Probability of Phase Drift (Phase LoL) [%]	10.6	12.5	35.4
Probability of Cycle Slips [%]	32.3	42.4	25.8
Code Jitter [m]	4.49	3.97	3.76
Phase Jitter [rad]	0.51	0.36	-
Doppler Jitter [Hz]	0.95	0.39	0.17

A comparison between the techniques show the FPLL to be good at handling simultaneously CN0 drops due to multipath attenuation and dynamics. We can conclude that FPLL is a good trade-off between the accuracy given by PLL and robustness necessary to handle CN0 drops.
Furthermore because the PLL is being aided by a FLL it is possible to decrease the bandwidth of the PLL, improving the accuracy of the estimates, phase and Doppler, and still be able to withstand dynamic transitions, thus minimizing the number of runtime losses-of-lock.

As stated previously the DLL/ FLL has some problems dealing with high order user dynamics due to the filter order. Still, the DLL/ FLL architecture is actually quite interesting in terms of minimizing the Doppler jitter and declaring loss-of-lock. In fact the number of losses-of-lock between PLL and FLL has decreased 2.5 times. Therefore it is a very promising solution to be used as a kind of soft reacquisition in harsh periods of multipath avoiding going into a reacquisition stage. A possible option could be to fall down to this architecture whenever a drift is identified.

C. Scenario 3: Urban with higher order BOC modulation

The objective of this scenario is to assess the capability to correct from a false-lock in one of the side peaks of the autocorrelation function. For that purpose, all iterations are initialized in false-lock in order to force at least one false-lock per iteration. Please note that for the BOCcos(15,2.5), the false-lock is injected in the fourth peak modulation (counted from the main one). In practical terms, spontaneous false-locks are seen to occur especially in periods of stronger multipath and higher dynamics stress (i.e. transition periods between velocity, acceleration or jerk).
Finally the adaptive switching was configured with CN0 thresholds of 30 dB-Hz for CBOC(6,1,1/11) and 35 dB-Hz for BOCcos(15,2.5) and 0.7 for the PLI.

Before showing the results the following figure illustrates the method of operation of the 2-Step. Note that the technique allows switching between FB and DSB, guaranteeing unambiguous tracking, during periods of more intense code jitter which corresponds to more intense signal attenuation due to multipath or dynamic stress.

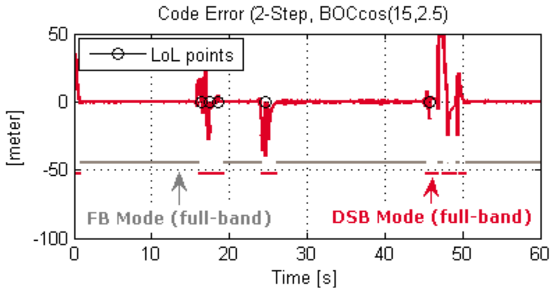

Figure 10: Temporal results for a single iteration for BOCcos(15,2.5) with the 2-Step switching technique

The following figures illustrate the results of the 2-Step switching technique against a classical DLL/PLL architecture for a single iteration.

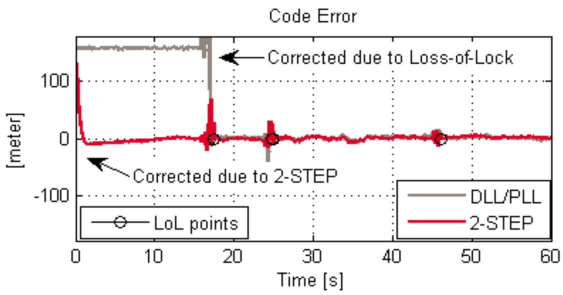

Figure 11: Temporal results for a single iteration for CBOC(6,1,1/11)

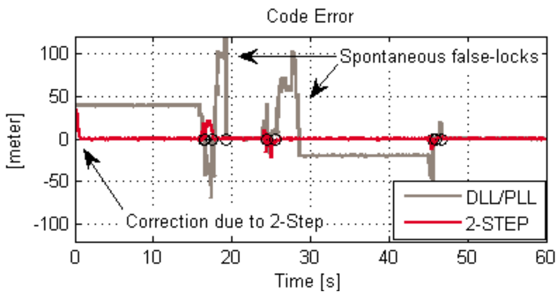

Figure 12: Temporal results for a single iteration for BOCcos(15,2.5)

When looking at the figures 11 and 12 it is possible to see the 2-Step technique can actively correct code false-locks and maintain code tracking stability.
This is particularly evident in Figure 12, where the iteration with DLL/PLL suffers from multiple false-locks while the 2-Step maintains unambiguous code tracking.

The full results averaged over 100 iterations are compiled in the following table.

Table 5: Full Results for 100 independent iterations for CBOC with 20ms integration time and BOCcos(15,2.5) with tint=10ms

Modulation	**CBOC(6,1,1/11)**		**BOCcos(15,2.5)**	
Metric\Technique	**DLL/ PLL**	**2-Step**	**DLL/ PLL**	**2-Step**
Probability of Code False-Lock [%]	26.1	0	47.3	1.6
Code Jitter [m]	3.90	7.06	1.18	1.19
Phase Jitter [rad]	0.44	0.49	0.26	0.28

In this scenario, the 2-Step adaptive switching technique was able to correct all false-lock situations for CBOC modulation and virtually all for the BOCcos(15,2.5) modulation. When compared to the DLL/PLL architecture, the only comment is that the code jitter may be worse in some situations, i.e. when the technique is working in DSB mode. Note that the phase jitter presents similar values between DLL/PLL and 2-Step, since no operation is done by the 2-Step technique at carrier level.

In order to further push the technique, additional tests were run for a more stringent multipath environment, corresponding to a satellite elevation angle of 30 degrees, Figure 7.
The following figures illustrate the results for similar technique configuration.

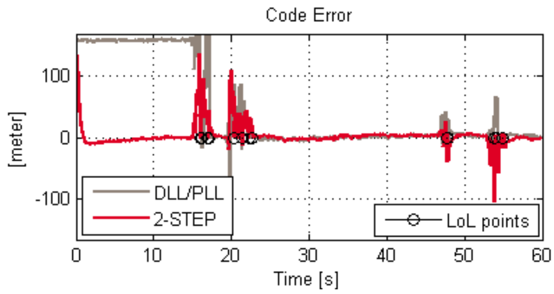

Figure 13: Temporal results for a single iteration for CBOC(6,1,1/11)

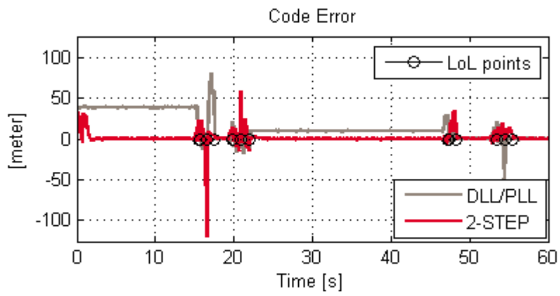

Figure 14: Temporal results for a single iteration for BOCcos(15,2.5)

Table 6: Full Results for 100 independent iterations for CBOC with 20ms integration time and BOCcos(15,2.5) with tint=10ms

Modulation	**CBOC(6,1,1/11)**		**BOCcos(15,2.5)**	
Metric\Technique	**DLL/ PLL**	**2-Step**	**DLL/ PLL**	**2-Step**
Probability of Code False-Lock [%]	25.6	0	34.8	1.1
Code Jitter [m]	6.99	10.76	1.42	1.81
Phase Jitter [rad]	0.78	0.83	0.20	0.19

In this scenario, the two-step adaptive switching technique was still able to correct a large percentage of false-locks for the CBOC(6,1,1/11) modulation and about 90% of the occurrences for the BOCcos(15,2.5) modulation. Once again it is possible to see that the trade-off of unambiguous code tracking is an increase of code jitter.

5. CONCLUSIONS AND FUTURE WORK

This work proposes clear recommendations for adaptive techniques in two different environments.

Firstly, the benefits of an innovative Kalman filter implementation are showcased against the classical DLL/ PLL implementation, in an AWGN scenario with signal level variations. In fact, the Adaptive-R Kalman filter is able to decrease the probability of cycle-slips and phase losses-of-lock. In terms of accuracy we have seen a tenfold reduction of phase jitter. Furthermore it shows a faster adaptability, reducing by half the time of convergence after CN0 drops.

Secondly, in multipath-driven environments, it has been seen that robustness is one of the key features and therefore relying on an FLL to aid the information on the PLL improves performance especially when user dynamics are present. If on one hand, the architecture complexity increases slightly, on the other hand results are quite promising especially in what concerns varying user dynamics. Note that with this technique both the phase and Doppler jitter were reduced, while robustness was improved. Furthermore, when the objective is to reduce loss of lock and "hard" acquisition then a DLL/ FLL architecture should be considered as a fallback configuration in order to improve robustness. By using this architecture, the number of losses-of-lock is reduced 2.5 times when compared to the PLL.

Finally, the results obtained show that using adaptive switching significantly increases the success rate when it comes to false lock correction, even for higher order BOC modulations such as the BOCcos (15,2.5). In fact, even in the most stringent environment (corresponding to multipath for a satellite elevation angle of 30 degrees), the adaptive switching technique is able to correct all false lock occurrences for CBOC(6,1,1/11) and 90% of the occurrences for the BOCcos(15,2.5) modulation.

6. ACKNOWLEDGMENTS

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The content of the present article reflects solely the authors' view and by no means represents the official ESA or GALILEO views.

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