N-GENE GNSS SOFTWARE RECEIVER FOR ACQUISITION AND TRACKING ALGORITHMS VALIDATION

Andrea Molino[*], *Mario Nicola*[*], *Marco Pini*[+], *and Maurizio Fantino*[+]

[*]Politecnico di Torino, Cso Duca degli Abruzzi 24 – 10124 Torino, Italy
[+]Istituto Superiore Mario Boella, Via Pier Carlo Boggio 61 – 10138 Torino, Italy
[*]http://www.polito.it – [+]http://www.navsas.ismb.it

ABSTRACT

N-Gene is a GNSS receiver completely designed in software, able to run in real-time on a common Personal Computer. This kind of receiver implements the concept of Software Defined Radio (SDR) and can be used as a test-bed for the development of innovative algorithms and for their validation in a real-time environment. This paper presents the solutions adopted for the signal acquisition and tracking tested on N-Gene. The acquisition algorithm is a variant of the classical "fast acquisition algorithm" where the signal correlation is obtained in time domain by means of two Fast Fourier Transforms (FFTs) and a single Inverse Fast Fourier Transform (IFFT). A solution for improving the tracking performance in case of low C/N_0*, is also proposed. The work on the signal tracking focuses on a robust normalization of the discrimination functions within the tracking loops. The algorithms are presented highlighting the advantages in terms of computational complexity, robustness and performance.*

1. INTRODUCTION

The last decade has seen the success of satellite based navigation applications in the ordinary people's life. In this context the navigation technology rapidly evolved towards more complex signal processing techniques for GNSS systems. Such advances mainly aimed at improving the quality of the positioning services, and enhancing robustness of user receivers. Algorithms able to increase sensitivity and performance of the GNSS receivers as well as multipath mitigation techniques are just some of the most common examples of this advanced signal processing algorithms. All the aforementioned new signal processing techniques have in common the need for processing signals sampled at high rate, which dramatically increases the computational load. At the same time, the rapid evolution of navigation applications led to the development of several software based GPS and Galileo receivers mainly for their high level of flexibility. For this reason, in the receiver design phase it is necessary to match the strategies for algorithms implementation with the hardware capabilities in order to carefully balance performance versus complexity, looking for the best trade off.

In order to relax the computational burden, especially in the case of correlation function computation, it is often possible reduce the number of samples to be processed by means of signal compression techniques.

In literature, examples of signal compression techniques can be found in [1][2], while the main idea of applying a compression to the signal in the acquisition phase can be found in [3][4]. The contribution of this work is to propose a signal compression strategy that can dramatically simplify the acquisition phase of the current GPS systems, and that can be extended to other Code Division Multiple Access (CDMA) based GNSS systems. At the same time, the paper also gives a contribution in presenting a normalization strategy for the Delay Lock Loop (DLL) discrimination functions; such technique is based on real time estimate of the correlation statistics, and it allows to increase the robustness of the tracking stage in weak signals conditions. These innovative strategies have been implemented in a fully software receiver called N-Gene that has been developed by the authors. Using N-Gene, performance of the algorithms have been evaluated and their compliance with a real time elaboration of the signal received from satellites has been verified. This work can be viewed also as a proof of the efficiency reachable using fully software receivers in the verification of new algorithms.

2. SIGNAL ACQUISITION

In a CDMA based GNSS system, each satellite continuously transmits a periodic code signal, which is modulated by information symbols. The code signal is a spreading sequence made of L_C chips and the sequence length (or repetition period) is denoted by T. Each satellite is characterized by a unique code. The cross correlation properties of such codes allow the receiver to efficiently separate satellite signals which, when received, are superimposed in the time domain. The first operation performed by any GNSS receiver, when switched on, is called signal acquisition. The receiver signal acquisition stage provides to the following tracking stage a list of the acquired satellites, and for each of them, a coarse estimation of the code delay and a rough estimation of the Doppler frequency shift. The code delay τ is the offset of the received code with respect to a locally generated instance of it; the Doppler shift f_d is due to the relative velocity between satellite and receiver.

In the acquisition procedure, the declaration of presence or absence of a satellite and, consequently, the determination of both code delay and Doppler shift, is obtained by computing

a two dimensional matrix called search space. Each entry of such a matrix contains the value of the two-dimensional correlation (cross ambiguity function) between the received signal and a locally generated copy, the latter characterized by a specific value of code delay, $\hat{\tau}$, and Doppler shift, $\hat{f}_d$.
It is well known that one of the most efficient way to obtain the search space is by implementing a fast parallel acquisition technique [7], where the correlation function is evaluated by means of FFT operations. Unfortunately, the sampling rate of modern GPS receivers might be on the order of 10-20 MHz, depending on the receiver applications, thus leading to large FFT processing blocks, which increase the cost of the receiver [3]. For example, assuming a sampling frequency of $f_s = 1/T_s = 16.367$MHz and an integration period of 1ms (corresponding to T for GPS signals), the FFT would have to be evaluated over 16368 points.
In [3], the authors introduce a more efficient technique for the acquisition process, called Averaging Correlations (AC), which requires shorter FFT blocks. The basic idea in [3] is to pre-process the signal by averaging the samples over each single chip, thus reducing the FFT to a number of points equal to the number of chips in the given integration period. In the GPS case averages are then stored in vectors of size 1023. The concept described above is depicted in Figure 1, where a section of the sampled signal is shown on the left. Each sample is denoted by a bullet and each chip is sampled 5 times. The choice of the first sample in the average operation is also a key point: in the figure 2 possible choices, namely “phase 0” and “phase 1”, are depicted.

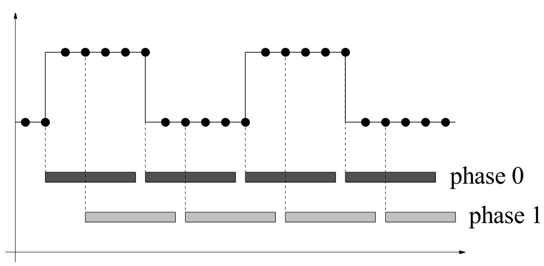

Figure 1- Average or compression operation

This work proposes to combine the AC operation with the fast acquisition technique. With this technique the fast acquisition is applied over the vectors of averaged values instead of on the original signal vector. Consequently the FFT can be applied over much shorter signal blocks thus improving the computation speed. However, since the incoming signal is masked by noise, there is not enough information to determine the first sample of the chip where starting the average. This problem forces the algorithm to repeat the FFT several times, one for each possible phase. When the right phase is chosen the correlation reaches a maximum.
The presented acquisition scheme is very similar to the classical fast acquisition, and it’s shown in Figure 2. The scheme is different from the classic fast acquisition because of the presence of the labeled “Average” block implementing the AC technique.

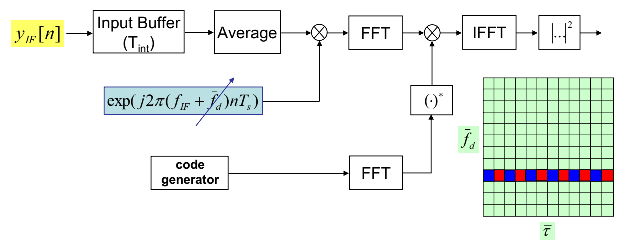

Figure 2 - Fast acquisition method with signal compression

This technique is particularly appealing for fast signal acquisitions in real time GNSS software receivers, since it provides a fast, flexible, and reconfigurable signal acquisition block. The averaging technique, reducing the number of samples, induces a loss in the sensitivity performance of the acquisition stage (see Figure 4). However, the large saving in the processing time allows to implement statistical tests on the acquisition outputs, more complex than in usual schemes, yielding to an improved detection probability.

3. TRACKING NORMALIZATION

After the acquisition stage has accomplished a rough alignment between the incoming and the local codes, a DLL refines such an initial estimate of the code phase and tracks changes into the future. The signal tracking is at the basis of the overall receiver processing: it allows to decode the navigation message and estimating the pseudorange. The tracking stage can be considered as a two-dimensional (code and carrier) signal replication process. Theory of tracking loops in GNSS receiver is well known and it is reported in many books, as in [8][9][10]. In conventional architectures, the signal at the front end output is generally processed by a coupled loop composed by a Phase Lock Loop (PLL) and a DLL. Generally, GNSS receivers use digital loops, modeled as control systems that can be described by the linear model depicted in Figure 3.

$\xi[k]$ is the parameter to be estimated and represents the phase of the input signal, whereas $\hat{\xi}[k]$ is the estimated phase at the k-th step. Neglecting the noise (i.e.: $n[k]$) a phase error signal $\rho[k] = \xi[k] - \hat{\xi}[k]$ is generated on the basis of a non linear discrimination function, which is also known in the navigation field as S-curve.
Several versions of the DLL discriminator have been proposed in the past [8][9]. The most popular DLL discriminators are non-coherent [9]: they use both the inphase and quadrature channels of the DLL and do not require a parallel carrier phase tracking. On the other hand, the so called coherent Early-minus-Late discriminator uses only the inphase correlator outputs and needs the carrier tracking to be phase-locked to the incoming carrier [9]. GNSS receivers can use different discriminators, but in all cases, for small errors the nonlinear function can be linearized as

$$e[k] = \beta\left(\xi[k] - \hat{\xi}[k]\right) = \beta\rho[k]$$

where β is the slope of the discrimination function around the origin and can be written as:

$$\beta = \frac{dS(\rho)}{d\rho}$$

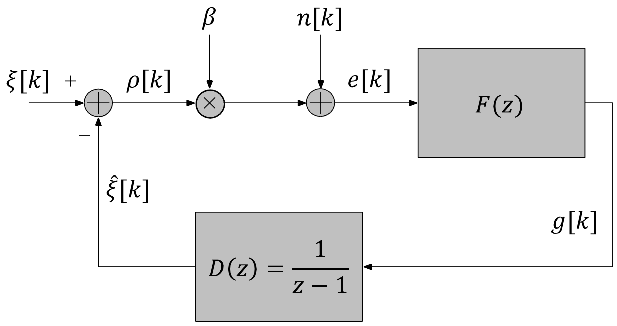

Figure 3 - Linear model for digital tracking loops

Figure 3 reveals that the discriminator output is sent to a digital filter with impulse response equal to $F(z)$, before being numerically integrated in order to get a new estimation of the phase.
The linear model in Figure 3 is the starting point for the derivation of the noise equivalent loop bandwidth and for the whole design of digital tracking loops for GNSS receivers. Nevertheless, the design of robust tracking loops in weak signal conditions is challenging. Several approaches have been proposed in the past to enhance the ability of GPS receivers to track weak, attenuated or corrupted signals [11]. The algorithm presented in this paper acts on the normalization of the DLL discriminator.
In terms of robustness, the code tracking loop performance are evaluated using the jitter standard deviation expressed in meters since directly related to the pseudo-range error. In literature some theoretical expressions are available for both coherent [10] and non coherent architectures [8] [13]. All of them are valid in well-defined contexts. It is important to emphasize that all the theoretical expressions of the jitter standard deviation hold in the linear region of the DLL discriminator function, which is supposed to be normalized with respect to the received signal power. In fact, from the proofs of the theoretical expression of the jitter standard deviations reported in [10] for the coherent case, the S-curve is defined by the equation:

$$S(\rho) = \sqrt{\frac{2}{P_R}}(S_E - S_L)$$

where S_E and S_L are the early and late correlator outputs.
For the non-coherent tracking structure, the expression of the jitter standard deviations reported in [8][13], considers the S-curve defined as:

$$S(\rho) = \frac{2}{P_R}\left(\left|\tilde{S}_E\right|^2 - \left|\tilde{S}_L\right|^2\right)$$

where the terms $\tilde{S}_E$ and $\tilde{S}_L$ are the early and late correlator outputs which account for both the inphase and quadrature phase branches of the DLL.
In practical schemes the received power P_R is not known, and it has to be estimated. This estimation is generally provided at the end of each integration period by the prompt code or properly adding the early and late discriminator outputs. In presence of Additive White Gaussian Noise (AWGN), and applying an ideal carrier wipe-off to the signal at the front end output, the prompt correlators represent an estimate of $P_R/2$, which can be used to normalize the S-curve. It is evident that this estimate tends to worsen when the C/N_0 ratio decreases. A simple but effective way to mitigate the degradation of this estimate is to average a certain number of consecutive values of the prompt correlations. This is the basic concept behind the code tracking loops implemented in the N-Gene software receiver, that improves the signal tracking sensitivity (i.e.: the lowest level at which the receiver reliably tracks at least one satellite [12]) in poor signal conditions, with a negligible increase of the computational burden. The theoretical analysis of this method has been reported in [13].

4. N-GENE SOFTWARE RECEIVER

The solutions presented in this paper were intensively analyzed during the design of the N-Gene software receiver, which is one of the major output of the Innovation and Research on GALileo (IRGAL) project. The implementation of a software radio receiver is particularly important for the development of future multi frequency receivers and for the validation of innovative GNSS algorithms.
Software radio is a promising technology that generates interest in the receiver industry for some applications and provides a useful simulation and testing environment.
N-Gene offers enhanced characteristics with respect to other existing GNSS software receivers. N-Gene processes the sample stream, at the Analogue-to-Digital Converter (ADC) output, quantized over 8 bits, with the ability of processing more than 12 channels in real time. N-Gene receives the GPS Coarse Acquisition (C/A) code on L1 and tracks live GIOVE-A and GIOVE-B signals transmitted on the E1 band. The receiver guarantees an improved positioning accuracy through the use of differential correction broadcasted by the Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay System (EGNOS) systems. A Universal Serial Bus (USB) connection toward the RF front end makes the receiver particularly versatile. The receiver works either with low cost front ends, representing the analog signal with few bits per samples at a low rate (e.g.: see for example front ends based on the Nemerix NJ1006A [5]), or with front end prototypes, characterized by higher sampling frequency and a digitization over 8 bits. The 8-bits quantization becomes fundamental in case a fine resolution representation of the signal is needed, as in the implementation of innovative interference mitigation (see for example [6]).

5. RESULTS

Suggested strategies for acquisition and tracking have been implemented in the N-Gene software receiver. This implementation is compatible with elaboration of real time signals sampled from an antenna, proving the reduced computational burden of proposed algorithms as presented by the authors in [14]. Also performance analysis has been performed through the use of N-Gene: in this case the receiver has been fed with an input signal generated by a simulator and read from a file, in order to accurately determine parameters of the analysis.

It is particularly interesting to compare the detection rate versus the Carrier to Noise Power spectral density (C/N_0) given a fixed false detection rate of the classical method and the one implementing the AC. Figure 4 shows the case where a signal sampled at 16.3676 MHz is processed using a classical approach (red curve) and the case with complexity reduction (blue curve). Due to the reduction of complexity deriving by the AC (that for this specific case of sampling frequency it is of about 22 times) the saving in terms of operation is used to perform a statistical improvement. The results is quite interesting because simply adopting an M over N Bernoulli test, the AC fast acquisition methods outperforms of about 4 dBHz the classical fast acquisition and still the number of operations to be executed is significantly lower than the multiplications necessary for the fast acquisition based on a full FFT.

In order to better investigate the new tracking strategy both the traditional implementation of tracking and the proposed one have been tested on the N-Gene receiver, where a tracking system composed by a second order Costas PLL and a coherent DLL has been included. These two solutions have been examined with different values of Early-Late spacing. Moreover, several data sets of the raw samples of the generated signal at the IF output were simulated at different values of C/N_0.

In this analysis the integration time was equal to 10 ms, while the bandwidths of the PLL and DLL were set to 10 Hz and 5 Hz, respectively.

Figure 5 summarizes the major results of this analysis and shows the tracking jitter with respect to the C/N_0 in a range of [18-36] dBHz. Solid lines are for Early-Late spacing d_s=0.2 chip, and dotted lines for d_s=1 chip.

The lines with diamond markers represent the theoretical tracking jitter for a coherent Early minus Late Power (normalized with $|\tilde{S}_E|^2 + |\tilde{S}_L|^2$). Since this type of discriminator is usually implemented in GPS receivers, this curve serves as reference.

The circle markers lines represent the measured tracking jitter for the mentioned Early minus Late Power discriminator normalized with the instantaneous prompt (i.e.: estimate of $P_R/2$), whereas the square markers lines are related to the results obtained using the enhanced normalization.

When d_s is equal to 1 chip, a good match between the theoretical and the simulated results for the classical approach can be seen when the C/N_0 is higher than 28 dBHz (26 dBHz for d_s=0.2 chip), while for C/N_0 in the range of 18-28 dBHz (18-26 dBHz for d_s=0.2 chip), the measured tracking jitter does not follow the theoretical trend. In this case, due to the increased noise power, the DLL does not work in the linear region of the S-curve and the formula used to plot the theoretical tracking jitter is no longer valid to represent the DLL operations.

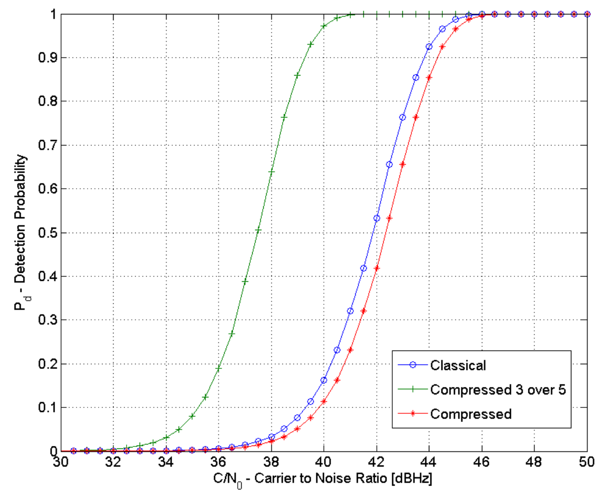

Figure 4 - Detection comparison among the classical acquisition technique, the compressed version, and the compressed version with the M over N tries enhancement (false detection rate 10^{-6})

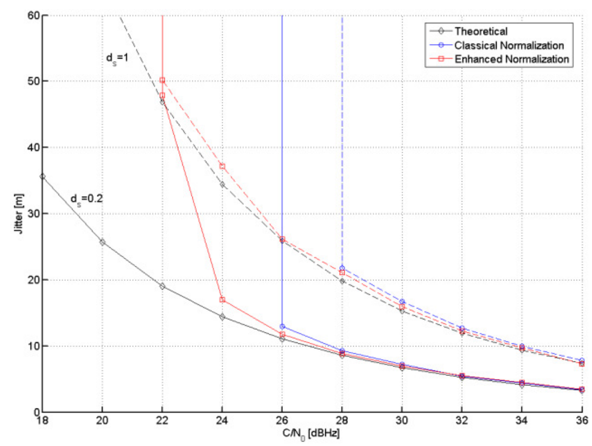

Figure 5 - Code tracking jitter for the GPS C/A code signal for different DLL discriminators, considering a tracking architecture composed by a PLL and a coherent DLL.

When the enhanced approach is considered, the moving average filter is proved to be useful to extend the code tracking region between 22 and 28 dBHz when d_s = 1 chip (22-26 dBHz when d_s = 0.2 chip). In this range, the S-curve is normalized with the result of the averaged of the previous 10 values of the prompt correlation. This helps the DLL to work in the linear region. It is possible to state that with a minimal increase of the complexity, the code tracking is more robust and the tracking sensitivity is reduced of approximately 5 dBHz. Note that for high C/N_0, the new method behaves as the coherent DLL, normalized with the instantaneous prompt (square and circle–marker curves are almost superimposed).

6. CONCLUSION

This paper presented an efficient signal acquisition and a robust method for GNSS code tracking. Both the algorithms are an appropriate solution for software implementations. The paper demonstrates the performance improvements with respect to standard algorithms, with a negligible increment of the computational burden.

The signal acquisition combines the AC operation with the fast acquisition technique. This allows for computing the FFT over shorter signal blocks, improving the computation speed. Results have been presented for the detection probability with respect to the C/N_0. Results demonstrated that if this algorithm is used with a M over N (3/5) Bernoulli test, it outperforms the classical fast acquisition methods of about 4 dBHz, still saving in the total computational load.

The paper presents also a robust method for code tracking. The design of code tracking loops is based on the definition of the discriminator function. If this function becomes sensible to the fluctuations of the early, prompt and late correlations, due to a degradation of their estimates, also the loop characteristics (noise equivalent bandwidth, pole position, etc.) change. In order to keep the discriminator function as close as possible to its noise-free definition, a method to make the evaluation of the S-curve more stable has been proposed. Such a method normalizes the S-curve, with the estimate of the received signal power, which is obtained averaging a set of previous prompt correlations. The paper reports the results obtained in simulation, measuring the code tracking jitter with respect to the C/N_0. These results confirm that the proposed strategy improves the robustness of the signal tracking, mainly in weak signals environments (i.e.: C/N_0 approximately in the range of 22 – 28 dBHz).

Both the algorithms for signal acquisition and tracking presented in the paper have been successfully implemented in the real time N-Gene software receiver.

7. ACKNOWLEDGMENT

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