Design of a GPS and Galileo Multi-Frequency Front-End

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ABSTRACT

GNSS platforms such as the American Global Positioning System (GPS) or the Russian GLONASS system are being continuously updated with new satellites offering new signals, new frequencies and new functionalities. Moreover, new GNSS systems such as the European Union’s Galileo system or the Japan’s Quasi-Zenith Satellite System (QZSS) are currently being developed and planned to be in function within a couple of years. Taking advantage of these new signals requires the use of a multi-frequency Radio-Frequency (RF) Front-End (FE).

In this paper, we highlight the design of such a FE based on a sub-sampling architecture. Indeed, with the technology advances in the Integrated Circuits (IC) industry, and more particularly the availability of GHz bandwidth analog-to-digital converters (ADC), this is one of the most attractive ways to achieve a multi-frequency FE. While a sub-sampling architecture has already been presented in some other publications [1], [2], we present a methodology that takes into account the effects of the filters characteristics and out-of-band noise. As a practical example, we apply our methodology to the design of a multi-frequency RF FE for the simultaneous acquisition of the GPS L1C; L2C; L5, and Galileo E1b,c; E5a,b signals.

INTRODUCTION

Multi-frequency architectures, e.g., the combinations of L1, L2, and L5 bands, have an enormous potential as simple interference multipath and phase ambiguities mitigation means [3], [4]. They can also allow the design of new algorithms to compensate the tropospheric and ionospheric effects and to determine the carrier phase ambiguities in Real Time Kinematic (RTK) applications1.

Table I presents some GPS and Galileo signals of interest, including the recommended receiver bandwidths. Note that some of these signals are already transmitted by existing satellites. For example, the first Galileo prototype satellite that was launched on December 28, 2005, is providing dual frequency E1 (carrier 1575.42 MHz) and either E5 (carrier 1191.795 MHz) or E6 (carrier 1278.75 MHz) signals [5]. Since December 16, 2005, GPS is also providing a second modernized civilian signal (L2C) on L2 frequency (carrier 1227.6 MHz). Furthermore, it is expected that a third civilian signal will be available on L5 (carrier 1176.45 MHz) in 2018 [6], while a fourth civil signal (the modernized L1 signal, L1C) is expected to be available on GPS IIIA satellite in 2014 [7].

![Figure 1. Frequency band occupation of selected GPS and Galileo signals.](image_url)

Figure 1 presents the frequency occupation for the above signals. It can be seen that while the Galileo E1b,c signal is in the same band as the GPS L1C signal, other potential signals of interest, such as L2C or L5, are in other bands located up to several hundreds of MHz from the L1 band. Clearly, acquiring and tracking several signals simultaneously may add a lot of complexity to the receiver. Among the existing receiver topologies, the sub-sampling architecture, which uses the aliasing principle to downconvert the signals near baseband, seems to be the most promising solution due to its flexibility and simplicity of implementation in comparison with heterodyne or digital-IF receivers.

Consequently, this paper focuses on the design of a sub-sampling RF-FE for the simultaneous reception of the GPS L1C; L2C; L5, and Galileo E1b,c; E5a,b signals. Using a sub-sampling approach, the signals of interest can be aliased to

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1RTK describes the differential GNSS procedure whereby code and carrier-phase data corrections are transmitted in real time from a reference receiver to the user’s receiver which calculates carrier differences.
baseband in a non-overlapping way using a carefully chosen sampling frequency close to the Nyquist rate. However, as will be highlighted in this paper, this architecture also requires a careful analysis of its underlying principle, in order to identify its potential weaknesses such as aliasing of out-of-band noise impact on the A-to-D conversion.

This paper is organized as follows. Section I describes the methodology to calculate the minimum sampling frequency for a multi-frequency system front-end. In Section II, we present the calculation of the minimum sampling frequency required to simultaneously receive the GPS and Galileo signals presented in Table I. As the obtained minimum frequency is still relatively high, we then consider the simultaneous acquisition of the same signals but with E5a instead of E5a,b. Then, in Section III, we discuss the practical implementation of the front-end using off the shelf components. Finally, in Section IV, we provide some concluding remarks.

I. METHODOLOGY TO CALCULATE THE MINIMUM SAMPLING FREQUENCY

The subsampling process consists in aliasing an input frequency of interest near base band where it becomes the output frequency. A visual representation of the aliasing principle for two signals is shown in Figure 2 using triangles of width $f_s$.

In this figure, the input frequencies have been represented on the horizontal axis and the output frequencies on the vertical axis. The triangles are used to map the input frequencies to the output frequencies.

A mathematical description of the process is given by the following expression [12].

$$f_0 = |f_i - \frac{n f_s}{2}|$$ (1)

and

$$f_s > 2BW$$ (2)

Where $f_s$ is the sampling frequency and $n$ ($n = 1, 2, 3, ...$) is the number of times that $BW$ fits the input frequency $f_i$.

There are two main issues that may cause a SNR degradation due to the aliasing process. The first one results from the position of the signal within its triangle: each input signal should be positioned in a triangle, either in the right or left side, but not in the middle, to avoid that part of the signal folds over itself. The second issue arises when there is more than one signal to be received at the same time: the selection of $f_s$ and $n$ must then be made so as to avoid the superposition in the output frequencies of the different signals. In this case, the minimum candidate sampling frequency, $f_{s,\text{min}}$ is the direct relation between Nyquist theorem and the addition of all the signal bandwidths. The relation for the case when $m$ signals are received is shown in (3).

$$f_{s,\text{min}} = 2\sum_{i=1}^{m}(BW_i)$$ (3)

The calculation of any solution for $n$ is defined as the ratio between the highest frequency component of interest $f_{hl}$ and the $\sum(BW)$, as shown in (4).

$$n = \frac{f_{hl}}{m \sum(BW_i)}$$ (4)

Considering the noise and filtering effects, $f_s$ should guarantee no overlaps for each of the $m$ aliased signals as mentioned. To understand the effect of the noise, consider that there is only one signal to be aliased with a certain sampling frequency $f_s$. The input frequency is then aliased. Nevertheless, the noise in each triangle is also aliased. If the noise is considered to have a constant amplitude level over the whole frequency spectrum of interest and no filtering process is performed prior to the aliasing, the SNR at the output of the ADC can be expressed as the ratio of the input signal power divided by $n$ times the noise power as in (5).

$$\frac{S_{out}}{N_{out}} = \frac{S_{in}}{nN}$$ (5)

It is therefore necessary to filter the signal prior to the analog-to-digital conversion. The signal at the input of the ADC, filtered by an ideal filter with an attenuation $A$ is shown in Figure 3.

When the aliasing process is applied, the attenuated noise $N/A$ is $n-1$ times aliased as shown in Figure 4.

Then the total noise of the sampled signal can be written as:

$$N_{out} = N + \frac{(n - 1)N}{A}$$ (6)

Equation (5) can be rewritten to express the SNR degradation due to aliasing as a function of $n$ and $A$. Then, $SNR_{out}$ is given by

$$SNR_{out} = \frac{S_{in}}{N} \frac{1}{1 + \frac{(n-1)N}{A}}$$ (7)
Considering this last equation, the degradation of the system can be defined as the ratio of $SNR_{out}$ with $SNR_{in}$ analogy to the definition of the Noise Factor:

$$F = \frac{1}{1 + \frac{(n-1)}{A}} \quad (9)$$

Knowing $n$ and selecting $1/F$, the required attenuation $A$ can be computed. For a given filter, this attenuation corresponds to a bandwidth called here $BW_A$. In this bandwidth, the noise is attenuated less than A dB (Figure 5). As the filters are not ideal, they have limited rejection responses and non zero insertion losses. As a consequence, the front-end must be designed with these limitations in mind in order to satisfy the requirements. The total filter attenuation at a given frequency depends on the number of filters that are implemented, and the $BW_A$ bandwidth will be reduced if the number of filters is increased to achieve higher selectivity. This bandwidth should not overlap with any of the aliased signals in order not to degrade the SNR by more than the selected degradation. As a consequence, for each signal, $BW_A$ now replaces the actual signal bandwidth in our computation of the sampling frequency. The minimum sampling frequency is now, based on Nyquist criteria,

$$f_{s_{\text{min}}} = 2 \sum_{i=1}^{m} (BW_{Ai})$$ \quad (10)

To find the solution for $f_s$, $f_{s_{\text{min}}}$ should be increased until there is no overlap between the aliased $BW_A$s, following the steps:
1.- Find $n_{\text{max}}$ applying (10) into (4)
2.- Find optimum $f_s$, decreasing $n$ from its maximum value from step 1, until finding a non-overlap solution with the out-of-band noise $BW_A$
3.- If necessary, allow some overlaps between the $BW_A$ (but not the $BW$) or allow a greater degradation $(1/F)$ in order to further decrease $f_s$, or select a different $BW_A$ and its corresponding attenuation $A$.

II. APPLICATION OF THE METHODOLOGY FOR THE SELECTED GPS AND GALILEO SIGNALS

Applying the step one of our methodology to the signals in Table I leads to a $f_{s_{\text{min}}} = 155 MHz$ and $n_{\text{max}} = 20$. Following the step two and considering the filters bandwidths $BW_A$, we find a required attenuation of 14dB for a degradation of $\frac{1}{F} = 0.933$. After the iteration process to avoid overlaps (developed in an Excel spread sheet), the optimum $f_s$ we obtained for a 0.3dB degradation was 512MHz, leading to no overlaps between the signals and the $BW_A$s’ bandwidths. Unfortunately, 512MHz is a relatively high sampling frequency for most of the current data transfer and storage systems.

In order to minimize $f_s$ (step three), we increased the degradation level while still not allowing overlaps between the signals’ bandwidths and the $BW_A$. We obtained $f_s = 227MHz$ by increasing the degradation from 0.3dB to 1.9dB.

Since 227MHz is still a relatively high sampling frequency, the next step was to consider the acquisition of the same signals, but with E5a instead of E5ab, i.e., for the acquisition of GPS L1C; L2C; L5; and Galileo E1b,c; E5a.

For this scenario, after some iterations in step two, the optimum sampling frequency was $f_s = 222MHz$ and $n = 5$.

The results are depicted in Figure 6. The required attenuation was 19.34dB for a $\frac{1}{F} = 0.933$. This solution does not have
overlaps and represents the best one at this point. However, further minimizing the optimum \( f_s \) by allowing some overlaps between the \( BW_A \) bandwidths (step three), the result was a sampling frequency of \( f_s = 158.8\,MHz \) with an attenuation \( A \)

\[
\text{of 21dB keeping constant the degradation definition of 0.3dB.}
\]

Interestingly, one of the first overlap issue occurs for the \( BW_A \) bandwidth of L5. However, since it is the noise part of L5’s \( BW_A \) that does cross the limit between the left and right triangle, it has no impact on the L5’s SNR. As a second drawback, the lower bandwidth limit of L1 is very near DC and may be subject to degradation by the flicker noise.

At this point there is one solution at 222MHz and an alternative solution of 158MHz. We will now focus on these solutions to analyze the noise, gain and linearity budget.

If these solutions would have considered ideal filters, the optimum sampling frequencies would have been lower and no optimizations due to the out-of-band noise bandwidths could be implemented. Nevertheless the solutions would not consider the degradations when real filters are implemented.

III. RF-FE IMPLEMENTATION

A. Noise and Gain Budgets

The GNSS signals are received with a very low power in the order of -130dBm. The total noise power is defined by:

\[
\text{noise}(N) = -174dBm + 10\log(\Delta f)
\]

Where \( \Delta f \) is the bandwidth defined in Table I. The noise power is -99dBm for L1, -108dBm for L2, -101dBm for L5 and E5\(_a\) and -97dBm for E5\(_{a,b}\). It is evident that the noise is greater than the signal, nevertheless the signal is embedded in the noise. Then the candidate to be processed is the noise, otherwise the signal amplification would saturate the ADC by the noise presence until the end of the amplification.

The signal, received from the wideband antenna is first amplified with a wideband Low Noise Amplifier (LNA). Due to the different frequency response of the filters and different signal levels, it is necessary to create a path optimized for each signal to be acquired. The signal is therefore splitted in three independent branches. Each branch is composed of several amplifiers, filters and a Variable Gain Amplifier (VGA). The VGA guarantees that the amplified signals make full use of the ADC’s full scale range (FSR). The three signals are then recombined and A-to-D converted. In each branch, the goal is to amplify the noise (and embedded signal) up to the full scale range of the ADC. Considering the sampling frequency range from 158MHz to 222MHz, the 8 bits, and 2.2GHz bandwidth, MAX106 ADC from Maxim has been chosen. The optimum input voltage peak-to-peak (\( V_{pp} \)) requirements of the ADC is in the range of 0.475 and 0.525 Volts. The second step was to identify the amplifiers and the number of amplification stages per branch. The goal is to play with the gain distribution in each branch in order to realize a good compromise between noise and linearity. For the first amplification step, it was necessary to implement a LNA with high gain.

B. Simulation Results

The Radio Frequency design requires special care when the amplification module is being designed, and particularly since the goal is to amplify a signal input of around -1000dBm to 0dBm. For this reason, the amplifiers design and the decoupling interfaces are two of the most important issues to solve in order to avoid undesired oscillations.

The amplifiers used and tested in our laboratory were the “ERA-3-SM” from Minicircuits. These amplifiers have some advantages like they are internally matched to 50 Ohms; they are unconditionally stable and they have a NF of 2.8dB. To decouple the amplifiers, some attenuators have been used.

The amplifiers have been tested in three different carrier frequencies that correspond to the L1, L2 and L5 bands. The gain response was different for each one, for this reason a VGA has been placed in each path; the lowest gain obtained was for L2 and the maximum amplification was for L5. The number of amplifiers and the VGA’s gain has been defined to reach the optimum voltage for the ADC that is 500mVpp (-2dBm). After system level simulations using ADS2008 and the laboratory experimental tests, the number of amplification layers illustrated in Figure 7 has been selected. As an example,
**Table II**

**FINAL DESIGN VALUES**

<table>
<thead>
<tr>
<th>Band</th>
<th>Final Power(dBm)</th>
<th>IIP3(dBm)</th>
<th>NF(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>−3.0</td>
<td>−69.45</td>
<td>2.86</td>
</tr>
<tr>
<td>L2</td>
<td>−2.1</td>
<td>−77.95</td>
<td>2.84</td>
</tr>
<tr>
<td>L5</td>
<td>−2.1</td>
<td>−71.30</td>
<td>2.83</td>
</tr>
</tbody>
</table>

**IV. CONCLUSIONS**

This paper presents a novel approach for the design of multi-frequency front-ends based on the sub-sampling architecture including more than two signals, see Table III. In particular, we discussed how to take into account the filter characteristics (insertion loss, bandwidth and attenuation characteristics).

This analysis leads to a minimization of the sampling frequency, allowing some overlaps within the out-of-band noise region between the aliased signals. This approach minimizes the storage rate that normally is a bottleneck for the software radio receivers.

**Table III**

**SAMPLING FREQUENCY COMPARISON**

<table>
<thead>
<tr>
<th>Signal</th>
<th>$f_s$ (MHz)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 and L2</td>
<td>99</td>
<td>[1]</td>
</tr>
<tr>
<td>L1, E5a and E5b</td>
<td>110</td>
<td>[2]</td>
</tr>
<tr>
<td>L1, L2 and E5a</td>
<td>158</td>
<td>[This Work]</td>
</tr>
<tr>
<td>L1, L2, E5a and E5b</td>
<td>227</td>
<td>[This work]</td>
</tr>
</tbody>
</table>

**REFERENCES**


