

# A Low-Power RF Front-End Architecture for an L1/L2CS GPS Receiver

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## BIOGRAPHIES

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## ABSTRACT

With the apparition of several new civilian signals in the years to come, there will soon be great demand for multi-frequency receivers. As soon as two signals will be available, users will be able to correct the ionospheric error, the main source of error since the SA has been disabled. Multi-frequency receivers will also be able to switch between the current L1 C/A code and the new modernized signals to make

best use of their individual characteristics. As expected, the improvements in performance will be accompanied by an increase in complexity, more noticeably at the RF front-end. In this paper, we discuss the different solutions to realize an RF front-end for a dual-frequency GPS receiver and propose an innovative solution which has a power consumption comparable with that of a single-frequency front-end.

## INTRODUCTION

Probably the next "big thing" in global navigation satellite systems (GNSS) is the integration of positioning applications into everyone's everyday life (or at least into their electronic devices!). The most commonly met GNSS is the US global positioning system (GPS). If current state-of-the-art L1 GPS chipsets are fully integrated, consume almost no power and have a price target below 5\$ [1], there are still two remaining problems preventing the positioning based applications from mass market success. Primarily, the current receivers do hardly track satellites in obstructed environment such as wooded areas or urban canyon. Indoor positioning is even worse, preventing applications such as E911. Secondly, their precision may soon become insufficient for many upcoming applications.

Fortunately, new satellites with modernized signals designed in order to circumvent these problems will be launched in the years to come. The first signal to be available will be the GPS L2 civilian signal (L2CS), which has some long awaited-for new features like improved crosscorrelation or a pilot (no data modulation) signal [2]. Combined with the existing L1 signal, L2CS will also allow the cancelation of the most important error: the ionosphere induced error. It is still difficult to predict if multi-frequency GPS receivers will reach the consumer mass market or will be restricted to high-end applications (scientific projects, survey, timing, ...). It is also possible that future mass market receivers will be single-frequency L2CS receivers, thus benefitting from the L2CS code improved characteristics, allowing, for example, weak signal acquisition or tracking in urban canyon or indoor environments. However, as there will probably not be 24 satellites transmitting L2CS before 2013, an L1/L2CS re-

ceiver may be used as a transitional receiver between L1 and L2CS. In addition, the larger ionospheric error of L2CS (65% worst than that of L1) may prevent single-frequency L2CS receivers from success.

Therefore, an L1/L2CS GPS receiver could be a candidate not only for high-end applications but also for the consumer market and it is important to anticipate the design of low-cost, low-power, compact L1/L2CS receivers. This work concentrates on the RF front-end section of such a receiver. An L1/L2CS RF front-end architecture with a power consumption and chip area comparable with that of an L1 front-end is demonstrated.

This paper is organized as follow: the first section briefly recalls the L1 and L2C signals properties and give a short review of the current multi-frequency front-ends. The second section describes the possible solutions for a low-power dual-frequency front-end and focuses on the proposed solution. The third section presents the simulation results obtained and the fourth section concludes the paper.

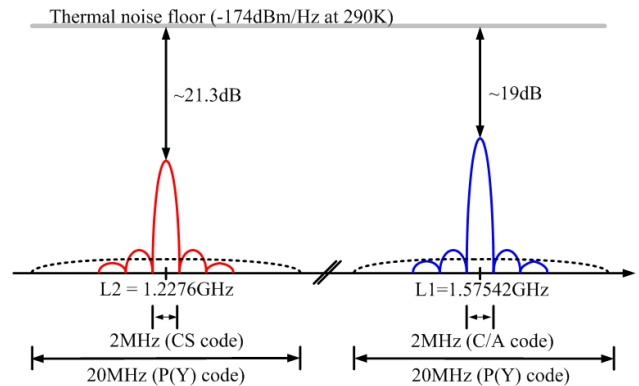
## TECHNICAL BACKGROUND

### The GPS civil signals

The first GPS signal available to civilians was the L1 Coarse Acquisition (C/A) code. It is composed of three parts: the carrier, the pseudo-random noise (PRN) code and the navigation data. The PRN chipping rate is 1.023MHz and the navigation data is transmitted at 50 bits per second. They are combined using modulo-2 addition and then modulated on the L1 carrier using binary phase shift keying (BPSK) modulation [3]. The signal power at the antenna is guaranteed to be at least -130dBm under clear sky conditions (see Fig.1). Most of the signal energy is in its 2.046MHz main lobe. Therefore, if the selectivity filter has a 2MHz 3dB bandwidth, the SNR at the antenna is -19dB. The next GPS civil signal is L2CS. L2CS is in reality a chip-by-chip time division multiplexed (TDM) dual code. The two codes are the moderate code (CM) and the long code (CL), both with a chip rate of 511.5kHz. The power of L2CS as received at the antenna is -133dBm, 2.3dB lower than that of L1 [2]. Since the signal is also spread over 2.046MHz, the SNR at the antenna is -21.3dB. The CM code is 10 times longer than the C/A code and carries 50Hz data. The CL code is 750 times longer than the C/A code and carries no data which enables limitless integration. The L1 code was designed almost 30 years ago when receivers resources were much more limited than nowadays. The L2CS CM code is 10 times longer than the L1 code which is perfectly suited for the computational resources modern receivers have at their disposal.

### Errors

The main factor limiting the precision of today's receivers is the delay introduced by the ionosphere. When two signals with different carriers are available, the ionospheric error can be corrected. The ionosphere-free pseudorange measurement  $\rho^*$  is given in [3] as :



**Fig. 1** L1 C/A and L2CS: both signals are CDMA-like spread by a 1.023MHz PRN code. Note that the PRN code of the military signals has a much higher chipping rate (10.23MHz), spreading the signal over 20MHz.

$$\rho^* = \frac{f_{L1}^2}{(f_{L2}^2 - f_{L1}^2)} \rho_{L1} - \frac{f_{L2}^2}{(f_{L2}^2 - f_{L1}^2)} \rho_{L2} \quad (1)$$

where  $\rho_{L1}$  and  $\rho_{L2}$  are the pseudorange measurements at the L1 and L2 bands, respectively. The errors of a single and dual band receiver are summarized in Table 1, which is based on the values given in the Global Positioning System Standard Positioning Service (SPS) Signal Specification, Second Edition.

Error source	Typical Range Error (m, 1sigma)	
	L1	L1 and L2C
Ionospheric delay	7	0.1
Tropospheric delay	0.2	0.2
Clock and Ephemeris	2.3	2.3
Receiver noise	0.6	0.6
Multipath	1.5	1.5
UERE	7.5	2.8
HDOP	1.5	1.5
Total stand-alone		
Horiz. accuracy (95 %)	22.5	8.5

**Table 1** Error sources for a single and a dual-frequency receiver

### Review of multi-frequency front-end architectures

Today, most the multi-frequency front-ends (MFFE) published have been prototypes realized with discrete components. They can be grouped in two categories: in parallel single frequency front-ends and direct RF sampling front-ends.

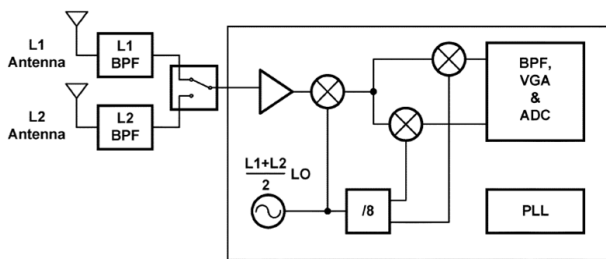
Multiple single-frequency front-ends replicate a single frequency front-end for each added frequency. Usually the design is based on a front-end which has been demonstrated in the past and it is thus a secure way to proceed. However, the problems of harmonics and other intermodulation products present in such a design multiply as the number of mixers and

frequency synthesizers present in a GPS front-end increases [4].

Direct-RF sampling front-ends use aliasing to down-convert the different signals present at the antenna. If the sampling frequency  $f_s$  is chosen carefully, all the bands can be down converted simultaneously to reasonable IF frequencies and no overlapping occurs. In [5], an L1 C/A and L2 P(Y) direct-RF sampling front-end has been designed. In the case where no overlapping is allowed between signals, the lowest sampling frequency  $f_s$  is 99.23MHz and 30 seconds of data represent approximately 3GSamples of data!

### A POTENTIAL ARCHITECTURE FOR LOW-POWER DUAL-FREQUENCY GPS FRONT-ENDS

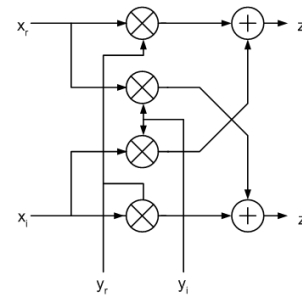
When a receiver is designed to process two frequencies, there's another opportunity though. Indeed, a mixer doesn't "differentiate" its lower and upper sidebands, which is the reason for the well known image frequency problem. Now, with a single mixer and frequency synthesizer, two signals can be downconverted to a common intermediate frequency (IF) if they are taken image one of each other or equivalently if the local oscillator (LO) is chosen right in between the two signals. From a power consumption point of view, this is attractive since a single mixer and frequency synthesizer are required. This also solves the image frequency problem since no strong interferer should be present at L1 or L2. The image frequency rejection is therefore reduced to the rejection of the noise present in the GPS bands. This solution presents several limitations though. The first is due to the fact that the information required to separate the two signals is lost after they have been downconverted to their first IF. As a consequence, this architecture doesn't allow simultaneous acquisition of both signals (with a single front-end). Indeed the front-end must be either duplicated for dual-frequency operation, or preceded by a selectable filter to select the wanted band for single band operation (see Fig.2) [6].



**Fig. 2** L1/L2C front-end with the LO at  $(L1+L2)/2 = 1401.51\text{MHz}$ . When only one signal is required at a time, the front-end can be preceded by a switch to select the wanted band.

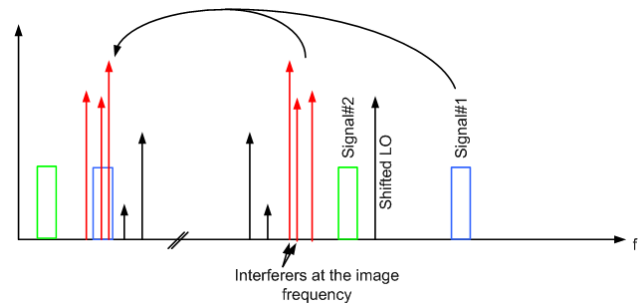
One of the solutions to the aforementioned problem is to replace the first mixer by a quadrature mixer. This way, the signals are multiplied twice, once with a sine and once with a cosine, and all the information necessary to separate the two signals is conserved. Unlike in low-IF front-ends, the signal

cannot be filtered with an analog complex filter in order to reject L1's image since it has been replaced by a valid signal: L2CS. As a consequence, a real filter is used instead and a second quadrature mixing stage is necessary. When two quadrature mixers are required, the architecture becomes more complex since it involves the multiplication of two complex signals (see Fig.3) [7]. Since the lowest achievable IF frequency is 173.91MHz, A/D conversion can't be performed at IF and all these operations must take place in the analog domain, increasing power consumption dramatically.



**Fig. 3** Realization of the multiplication of two complex signals.

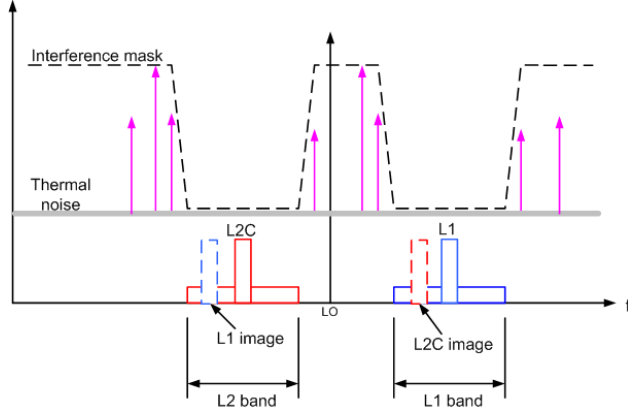
To avoid the superposition of L1 and L2CS at IF without using complex processing, the first LO can also be shifted from 1401.51MHz. In most wireless standards this wouldn't be possible since strong interferers may be present in the frequency spectrum surrounding the band of interest: in Fig.4, the LO has been shifted from the center position so that signal#1 and signal#2 don't overlap at IF. Unfortunately, the new image of signal#1 now falls in an uncontrolled part of the spectrum where potentially strong interferers can be present.



**Fig. 4** For most wireless standards, it is not possible to shift the LO frequency since the new image may contain strong interferers.

For GPS, we can take advantage of a quite different situation. Due the weak power of the received signals, the interference mask in the GPS bands has been set much lower than in most other bands. As a consequence, we can consider that the GPS bands are dominated by thermal noise and don't contain any strong interferer. Also, the GPS civil bands only occupy 2MHz of the 20MHz allocated to the GPS military bands. Consequently, the LO can be shifted while keeping the images in the GPS bands (see Fig.5), which limits the im-

age rejection requirements to the rejection of the noise at the image frequency. In [8], a similar principle has been used within the GPS L1 band. In this case, the image rejection requirements have been demonstrated to be only 10dB.



**Fig. 5** When the LO shift is sufficiently small, the images fall into the 20MHz GPS P(Y) bands. The image is therefore limited to the thermal noise present in the GPS bands.

To downconvert the two signals to baseband, we use a slightly modified Weaver architecture [9]. As in the traditional Weaver demodulator, L2CS is selected and L1 rejected by subtracting the output of the I and Q paths. L1 can also be selected and L2CS rejected if an additional path is created where the output of the I and Q paths is added (see Fig.6). Since the two second IFs are different for L1 and L2CS, a supplementary set of digital mixers is required and the Weaver architecture is modified as shown in Fig.7.

In a dual-frequency GPS receiver were both signals are images one of each other, each signal sees unfiltered noise at its image frequency (see Fig.8(b)(2)). The SNR at the output of the RF mixer is therefore 3dB lower than at its input (see Fig.8(b)(3)). In our case, L1 and L2CS are not image of each other and therefore, depending on the RF filters bandwidth and on the LO shift, the image noise is rejected (see Fig.8(c)(2)). For a better filtering of the image noise, the LO frequency should be shifted as much as possible.

The constraints for the LO shift are summarized in the following set of equations:

$$f_{shift} > \frac{BW_{L1C/A} + BW_{L2CS}}{4} \quad (2)$$

$$f_{shift} < \frac{\frac{BW_{L2P(Y)}}{2} - \frac{BW_{L1C/A}}{2}}{2} \quad (3)$$

$$f_{shift} < \frac{\frac{BW_{L1P(Y)}}{2} - \frac{BW_{L2CS}}{2}}{2} \quad (4)$$

$$f_{shift} > 3dBbw_{L1} \quad (5)$$

$$f_{shift} > 3dBbw_{L2} \quad (6)$$

where  $BW_i$  is the bandwidth of the signal  $i$  and  $3dBbw_i$  is the 3dB bandwidth of the filters centered at  $i$ .

The maximal shift, given by (3) and (4), is 4.615MHz. It also satisfies (2) and relaxes the RF filters requirements The

resulting LO are 1396.89MHz and 1406.12MHz.

## Frequency plan

Frequency planning is quite a complex task since, in addition to the usual constraints met in the design of an RF front-end, the LO is limited by the constraints (2)-(6). In the frame of this work a 10MHz reference was imposed. The first LO is either 1397.5MHz or 1405.5MHz. The second LO, is obtained by dividing the first LO by 8. The resulting frequency plans are summarized in Table 2. With the first LO at 1405.5MHz, the two signals do not overlap neither at the first neither at the second IF. The sampling frequency  $f_s = 14.64$ MHz is obtained by dividing the 2nd LO by 24.

LO1	L1 IF1	L2C IF1	LO2	L1 IF2	L2C IF2
1397.50	177.92	169.9	174.69	3.23	4.79
1405.50	169.90	177.90	175.68	5.76	2.21

**Table 2** Frequency plan propositions

## Power consumption

Table 3 summarizes the current state-of-the-art GPS low-power front-ends. Even though the proposed dual-frequency front-end has not been integrated yet, it is similar to that in [6]. The only difference is the LO which, instead of being 1401.51MHz as in [6], has been chosen at 1405.5MHz in order to allow simultaneous downconversion of L1 and L2CS. As a consequence, one can expect a similar power consumption in the order of 19mW for the proposed dual-frequency GPS front-end.

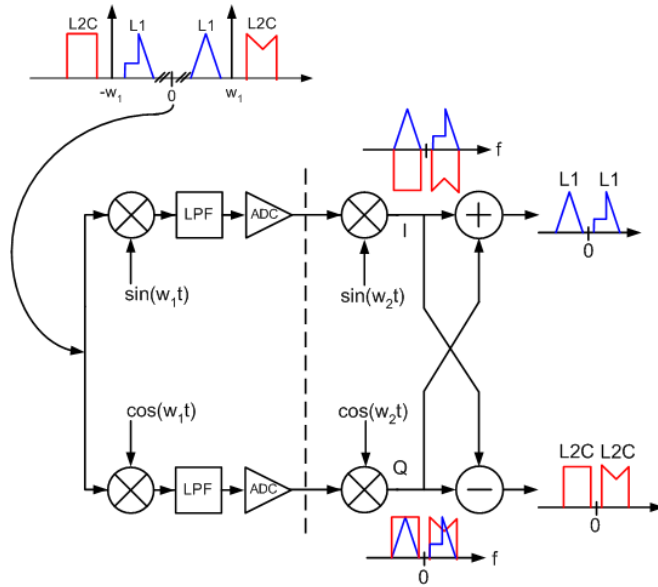
Author	Band	Power cons.	LNA	Tech.	Year	Ref.
Behbahani	L1	27mW	Ext.	CMOS 0.35um	2002	[10]
Gramegna	L1	28mW	Int.	CMOS 0.18um	2004	[11]
Kadoyama	L1	24mW	Int.	CMOS 0.18um	2004	[12]
Nemerix	L1	17mW	Int.	SiGe	2005	[13]
Jinho	L1 or L2	19mW	Ext.	CMOS 0.18um	2005	[6]

**Table 3** State-of-the-art GPS front-ends review

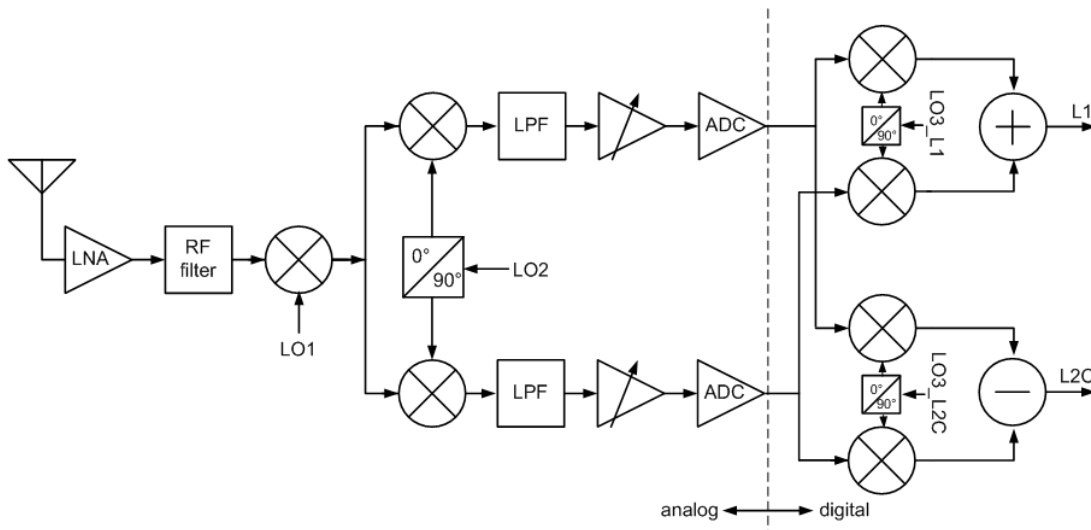
## SIMULATION RESULTS

To double check the frequency plan, the front-end has been simulated with Agilent's Advanced Design System (ADS).

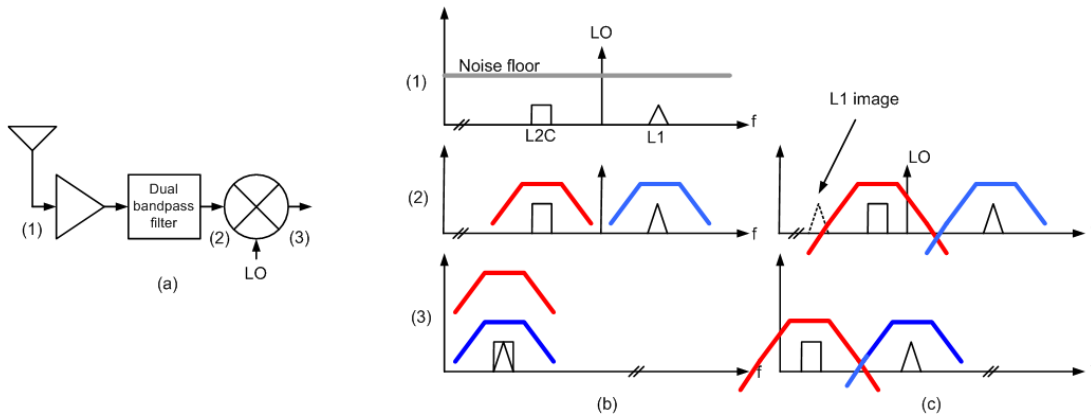
A simulation was ran to help quantify the RF filters requirements. A fixed LO frequency of 1405.5MHz was used while the filters Q factor was swept. The schematic used for simulation is equivalent to that in Fig.8(a). The amplifier and the mixer are parametered in order to have no impact on the NF. The Q factor of the L1 and L2C filters is then varied in order to see its impact on the NF. Fig.9 shows the system single sideband (SSB) NF versus the L1 filters Q. For an L1 filter Q factor higher than 235 and an L2C filter Q factor higher than 185, the NF is degraded by only 0.1dB. The Weaver stage is not included in the simulation. It has been demonstrated that, despite coarse quantization, it effectively rejects the image noise as it would with any other signal or interferer at the image frequency, leading to an SNR improvement of 3dB as compared to that at the output of the I and Q paths [8].



**Fig. 6** Weaver architecture used to select the correct band



**Fig. 7** The resulting front-end based on an heterodyne architecture with the LO shifted from 1401.51MHz.



**Fig. 8** Problem of the noise at the image frequency when (a) a simplified representation of the components involved in the image noise problem, (b) L1 and L2CS are image one of each other (the first LO is 1401.51MHz), (c) the LO is shifted from 1401.51MHz.

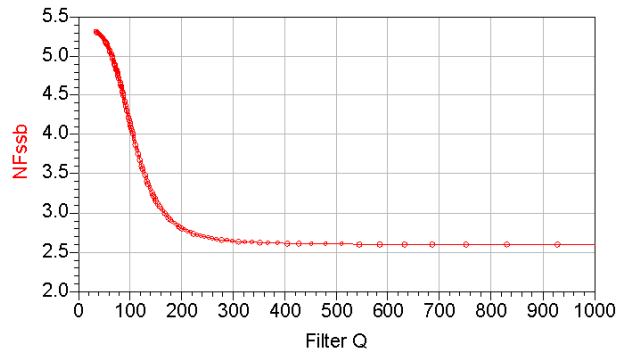


Fig. 9 SSB NF versus dual bandpass filter Q factor.

The system level models have been used for the front-end circuits (LNA, mixer, ...). The models parameters have been entered to fit typical performance of current CMOS integrated circuits. A wideband LNA with a gain of 18dB and a NF of 2dB, a mixer with a gain 12dB and a NF of 15dB are used. The Harmonic Simulator (HB) engine is used to check the spectrum at each stage of the front-end. The harmonics of the LOs up to the ninth order and intermodulation products up to the fifth order have been considered. The most important points to check are the NF and the spectrum at each stage of the front-end. As we can see in Table 4, L1 is downconverted to 5.7675MHz and the single sideband (SSB) NF is 3.214dB. L2C is downconverted to 2.2125MHz and the SSB NF is 3.525.

Band	2nd IF	$NF_{SSB}$	$NF_{DSB}$
L1	2.21MHz	3.52dB	2.22dB
L2C	5.76MHz	3.21dB	2.23dB

Table 4 System NF for L1 and L2C

In Fig.10 and Fig.11, the frequency spectrum at the output of the RF mixer and of the I path IF mixer is represented. We can see that it is free from any undesirable component.

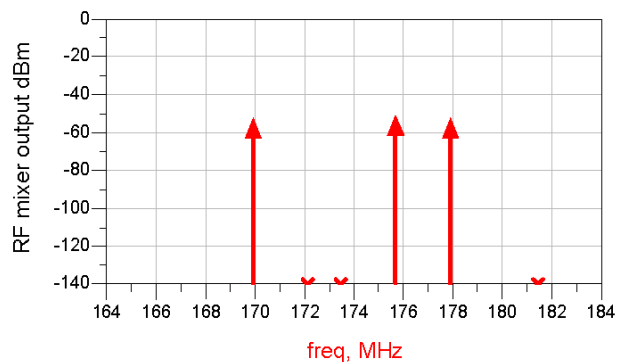


Fig. 10 Spectrum a the RF mixer output

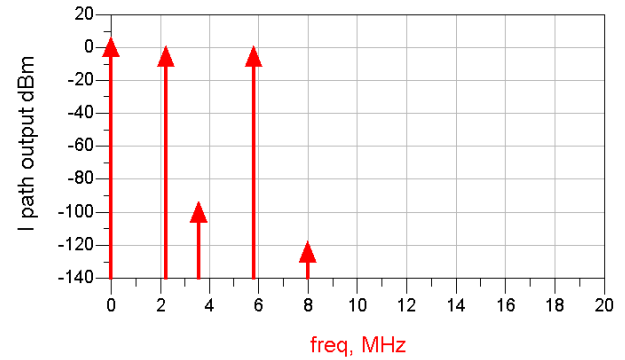


Fig. 11 Spectrum at the output of the I path IF mixer

## CONCLUSIONS

A low-power dual-frequency front-end architecture based on the classical heterodyne architecture has been proposed. Due to the nature of the GPS signals, the civil signals images can be chosen in the P(Y) bands. It is therefore not mandatory to take the LO frequency at  $(L1+L2)/2$  and the two signals can be simultaneously downconverted to baseband with the equivalent of a single-frequency heterodyne front-end. A very similar front-end, implemented in CMOS 0.18um, has been presented in [6] and has a power consumption 19-mW. A similar power consumption should therefore be achievable for the architecture presented in this paper.

## ACKNOWLEDGMENTS

This authors would like to acknowledge all the members who have directly or indirectly participated to this project.

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