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A Galileo E1b,c RF Front-End Optimized for Narrowband Interferers Mitigation

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BIOGRAPHY

Frederic Chastellain received his MSc degree in 2002 from the Swiss Federal Institute of Technology in Lausanne (EPFL). Currently, he is a research assistant at the Institute of Microtechnology (IMT) of the University of Neuchatel, Switzerland, where he is preparing his PhD thesis. His research interests are the design of radio-frequency (RF) circuits and systems for demanding GNSS applications such as multi-frequency front-ends for network synchronization or dual-frequency low-power front-ends.

ABSTRACT

The current Search and Rescue (SAR) service, which is based on the Cospas-Sarsat system, suffers from major limitations such as poor position accuracy, long alert times and high false alarm rate. Two types of distress signals are used, the first 121.5MHz/(up to 100mW) and the second 406MHz/5W, the latter being able to carry digitally encoded identification and position data. The Galileo system will importantly contribute to the improvement of the SAR system. Indeed, the Galileo satellites will include a transponder in order to re-broadcast the 406MHz message, which will allow a better coverage (27 Galileo satellites plus the current seven Cospas-Sarsat satellites) and also a shorter alert time. They will also include a return link message (RLM) in the Galileo E1b open service signal, which will reduce the number of false alarms.

The Galileo system is therefore a great opportunity for the development of a new generation of beacons which will include a Galileo receiver and therefore be able to take advantage of the better coverage provided by the Galileo constellation to provide shorter alert times and of the RLM to reduce the number of false alarms. One of the major issue when designing a Galileo receiver to be operated in a distess beacon is to design a front-end that is sensitive enough to pick the very weak Galileo signals and on the same time rejects the strong distress messages. Indeed, when the beacon is turned on, the Galileo receiver is in cold start conditions and a short amount of time is left to the receiver to get a first fix before any distress message is actually emitted. However, in some cases, the receiver is not able to determine its position sufficiently fast and the front-end therefore has to acquire the satellites in the presence of the distress signals. This paper presents a Galileo radio frequency front-end designed in order to operate in the presence of such signals.

INTRODUCTION

The Search-and-Rescue service

The current search and rescue (SAR) service is based on the Cospas-Sarsat system [1]. It includes two types of satellites: four low-altitude earth orbit satellites (LEOSAR) and three geostationary earth orbit satellites (GEOSAR). Both are complementary in that the GEOSAR provides near instantaneous alerting, beacon identification and position but only over a limited coverage area. The LEOSAR covers the polar regions and computes position from the Doppler information. The Cospas-Sarsat system suffers from limited performances including a non continuous coverage of the earth, non real time alert handling and low position accuracy. Currently, beacons transmit one or both of two types of distress signals, the beacon signal at 406MHz/37dBm and the auxiliary signal at 121.5MHz/(up to 20dBm). Due to the limitations of the 121.5MHz signal and the superior performances of the 406MHz signal, the Cospas-Sarsat will cease satellite processing of the 121.5MHz signal in 2009. The characteristics of the two beacon types are summarized in table 1.

The Galileo system contribution to the search and rescue service (SAR), the SAR/Galileo [2], will greatly improve the SAR service performances. Indeed the Galileo satellite will include a 406MHz transponder to detect alerts from Cospas-Sarsat beacons, broadcast the information to dedicated ground receiving stations also often referred to as local users terminals (MEOLUTS). The MEOLUTS then transmit the distress information to the mission control center (MCC) and the rescue coordination center (RCC) (see figure 1). Galileo will provide near real-time reception of distress messages anywhere on earth, precise location of alerts, increased availability of the space segment (27 medium earth orbit satellites added) and include a return link message (RLM)

	406MHz signal	121.5MHz signal
Signal	Digital (unique ID)	Analog i.e. no data encoded
Signal power	5W pulsed	up to 0.1W continuous
Position accuracy	within 5km (no GPS)	within 20km
Alert time	within 5minutes	within 45minutes
Doppler position ambiguity	Resolved at first pass	Two passes required

Table 1 Comparison of the performance achievable with the 406MHz and 121.5MHz distress signals.

in the E1b signal which will drastically reduce the number of false alarms.

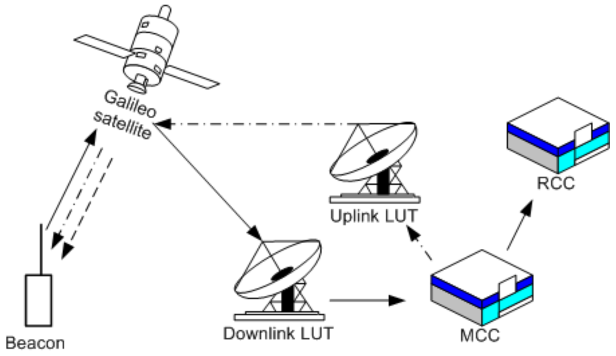

Fig. 1 continuousline : distress message from the beacon broadcasted by the satellite to the LUT, dash-dot line: return link, dashed line: navigation data

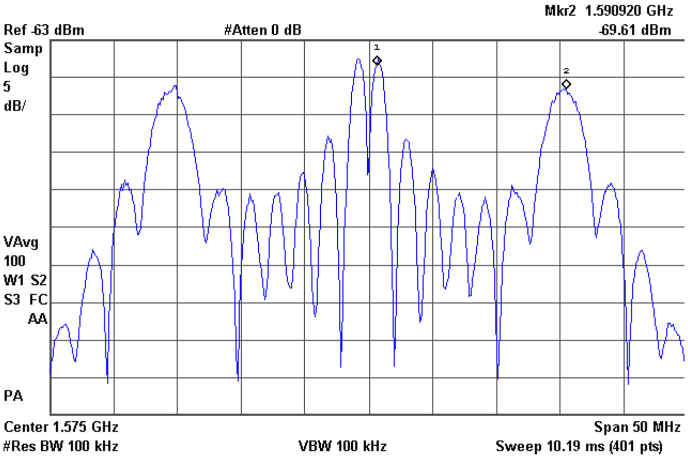

Fig. 2 Galileo E1 signal.

The Galileo E1 signal

This paper uses the same nomenclature as [3], where the three Galileo signals present in the L1 band are called the E1 signals. E1b and E1c are for open service (OS), safety of life (SoL) and commercial service (CS). E1a is for public regulated service (PRS) and is in quadrature with E1b and E1c. The three signals use binary offset carrier (BOC(n, m)) modulation, where the chip rate is equal to n · 1.023MHz and the subcarrier frequency is equal to m · 1.023MHz. Currently E1b and E1c are BOC(1,1) modulated, even though an optimized BOC signal is being considered, and E1a is BOC(15, 2.5) modulated. In figure 2, the spectrum of the E1 signals generated by a Galileo simulator (Spirent GSS7800) and measured with on a spectrum analyzer is represented.

In [3], the combined E1b and E1c (E1b,c) minimum received power is defined as being equal to -127dBm for a 0dBi antenna and an elevation angle equal or larger than 10 degrees. Currently, this power is splitted equally between the data signal, E1b, and the pilot signals, E1c.

The total bandwidth occupied by E1b,c is 24MHz. Due to the limited number of bits available in the distress message, the accuracy of the transmitted position is limited to 120m [**?**]. As a consequence, the system's bandwidth can be reduced without degrading the precision of the position below that broadcasted in the distress message. Furthermore, a smaller bandwidth allows better interference mitigation and a lower cost/power consumption. For GPS L1 C/A mass market receivers, a 2MHz system bandwidth is usually used since most of the PRN energy is located in a single 2MHz lobe centered on L1. For E1b,c, the PRN code is multiplied by a 1.023MHz subcarrier, resulting in the spectrum shown in figure 3). Reducing the system's bandwidth to 4MHz, the two main lobes are kept unfiltered, resulting in a total signal power loss of only 0.6dB. Despite the signal loss, the signal-to-noise ratio (SNR) is actually improved by 7.2dB since the noise is integrated over a 6 times smaller bandwidth. A maximum SNR has been found for an even smaller bandwidth of 2.2MHz, which is explained by the fact that the BOC(1,1) spectrum is not exactly a frequency shift keyed version of the C/A code. Indeed, as seen in figure 3, most of the energy of the two main lobes is located between 1573.42MHz and 1577.42MHz.

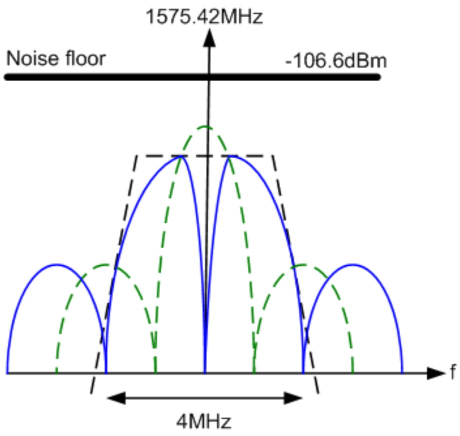

Fig. 3 GPS L1 C/A code (green), Galileo E1b,c (blue) and noise floor for a system's bandwidth of 5.5MHz bandwidth.

Having gained a clear view of the Galileo/SAR context, we now focus on: the definition of the interferers to be considered when operating a Galileo receiver in a distress beacon, the actual design of the front-end, the measurements which have been performed.

INTERFERERS

The received GNSS signals are very weak, usually in the order of -130dBm. The GNSS receivers therefore have to be very sensitive in order to be able to process these signals, which indirectly makes them very sensitive to the potential interferers present in their environment. For this application, three different types of interferers have been identified:

- regulated interferers: interferers any type of GNSS receiver may have to deal with. For this type of interferers, regulation services define the maximum interference level allowed at different frequencies in the form of an interference mask. The mask used for this design is taken from the Galileo test user segment requirements document [4] for rural worst case conditions.
- interferers generated by the receiver itself: includes the local oscillators, clocks as well as any of their harmonics and intermodulation products (IMs).
- interferers generated by the beacon: includes the beacon and auxiliary signals as well as any of their harmonics and IMS. A typical beacon start up protocol is represented in figure 4. In principle, the time t1 before any distress signal is emitted should be sufficient for the Galileo receiver to perform a first position fix. After t1 seconds, the beacons starts to transmit the 406MHz signal during 700ms every 50s. During the remaing 49.3s, the beacon transmits the 121.5MHz signal. Due to external factors such as wrong orientation of the beacon's antenna or perturbation due to immersion in water, the first fix may not be possible during t1. The next position fix has therefore to be performed in the presence of the beacon and auxiliary signals, 20 minutes after the first fix tentative. Therefore, if the receiver is not able to acquire the signal in the presence of the distress signals, the position can't be included in the 406MHz message and the alert time is delayed by at least 20min.

  Simulations have been performed to quantify the impact of the beacon and auxiliary signals on the system in the case no filtering is performed prior to the LNA. A wideband amplifier model from Agilent's Advanced Design System (ADS) was used. The amplifier has been set with a gain of 30dB, an IIP3 of -14dBm and preceded by a low-Q butterworth filter with a maximum rejection of 40dB in order to model the limited bandwidth of the LNA and the filtering due to the antenna. Two harmonic balance (HB) simulations have been run in order to study the impact of the distress signals on the LNA gain. The results are shown in figure 5. We can see that compression occurs for beacon signal levels as low as -15dBm and auxiliary signal levels as low as -5dBm.

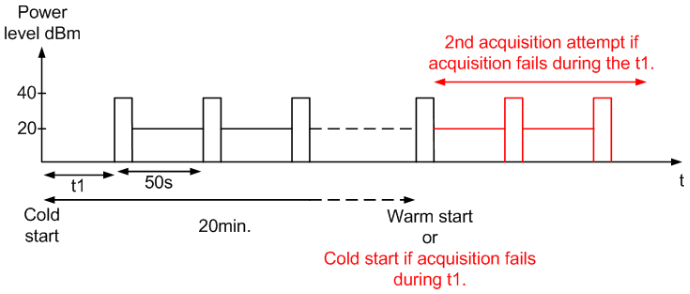

Fig. 4 Typical beacon start-up protocol. t1 is usually larger than the GNSS receiver's TTFF. If acquisition is not possible during t1, a second attempt is made 20minutes later but now in the presence of the beacon signals.

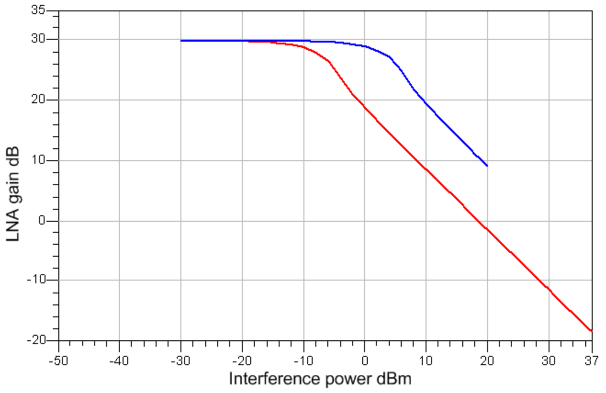

Fig. 5 LNA gain vs (top blue) 121.5MHz distress signal, (bottom red) 406MHz distress signal

In figure 6, the HB simulation is run with fixed distress signals levels (beacon signal at 37dBm and auxiliary signal at 20dBm) in order to display the spectrum of the signal at the output of the LNA. As we can see, the 13th harmonic of the auxiliary signal at 1579.5MHz is several tenth of dBs stronger than the actual signal. When the beacon signal is turned on, the gain compression is even more important, resulting in a complete loss of the signal.

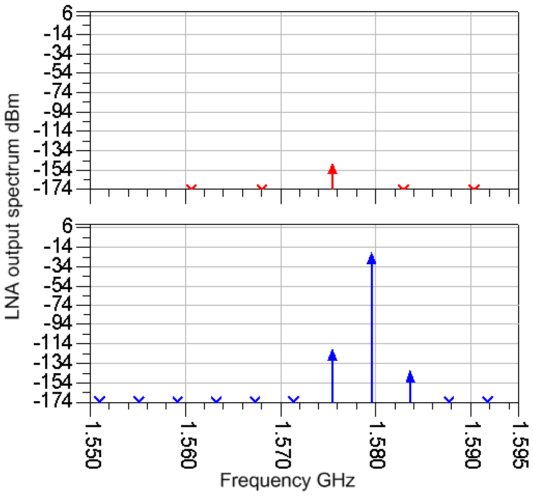

Fig. 6 Spectrum at the output of the LNA when (bottom blue) 121.5MHz auxiliary signal on, (top red)406MHz beacon signal on.

FRONT-END DESIGN

Among the solutions available to mitigate the interferers created by the distress messages, it has been chosen to place a bandpass filter in front of the LNA in order to reduce the beacon and auxiliary signals power before they actually reach the LNA input. Other solutions such as pulse blanking and insertion of notch filters is not possible due to the (almost) continuously emitted 121.5MHz signal and to the number of signals/harmonics/IMS. The bandpass filter also reduces the front-end's susceptibility to the two other types of interferers described in the previous paragraph.
Recalling Friis formula, one can see that the filter's severely degrades the system's NF if the filter's insertion loss (IL) is not minimized.

$$NF_{system} = 10log(IL_{filter} + \frac{F_{LNA} - 1}{G_{filter}} + ...) \tag{1}$$

Based on the requirement for the system's NF to be below 3dB, a SAW filter with a worst case IL of 1.6dB has been chosen in order to achieve a 2.84dB NF. A SAW filter model from the ADS system library has been used for simulations. Based on the filter's datasheet, the SAW maximum rejection has been set to 28dB for simulations. Combined with the limited bandwidth of the LNA and antenna, 68dB of attenuation is performed at 121.5MHz and 406MHz. The harmonic balance simulations results, including the SAW filter, are shown in figure 7 and 8.

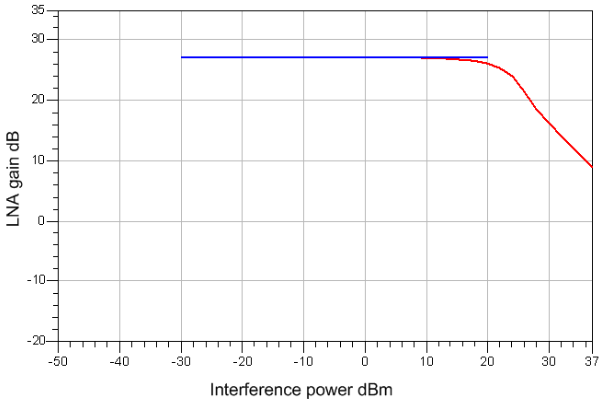

Fig. 7 LNA gain vs (top blue) 121.5MHz interferer, (bottom red) 406MHz interferer when a SAW filter is inserted between the antenna and the LNA

When the auxiliary signal is emitted, the LNA gain compression is now smaller than 1dB. When the beacon signal is transmitted, the signal is still compressed by approximately 18dB. However, since the spectrum is now free of any inband interferer, in particular the 1579.5MHz harmonic, the gain compression can be compensated by the variable gain amplifier (VGA).

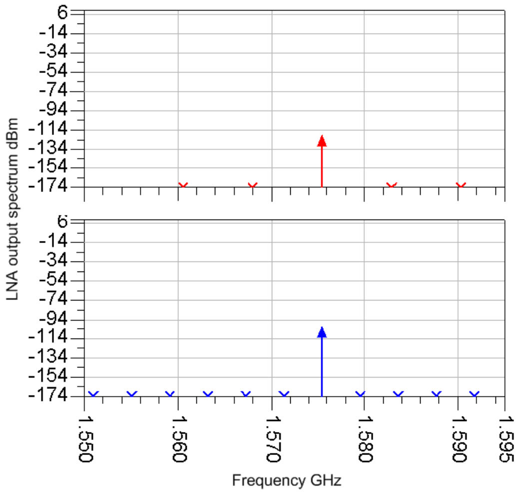

Fig. 8 Spectrum at the output of the LNA when: (bottom blue) 121.5MHz auxiliary signal on, (top red)406MHz beacon signal on .

After the LNA, the signal is filtered a second time and it is then downconverted to a first intermediate frequency (IF). The E1b,c and distress signals levels up to second saw filter output as well as the inband and outband gain (G_i and G_o) of the different components involved are summarized in table 2 where the letters A, B, C, D and E refer to specific test points defined in figure 9.

The choice for the first IF is a compromise between a low frequency to relax the IF filter performances and a high fre-

	A	Ant.	B	RF SAW1	C	LNA	D	RF SAW2	E
G_i dB		0.0		−1.6		27.0		−2.6	
G_o dB		−20.0		−28.0		−20.0		−40.0	
$E1_{b,c}$ dBm	−130.0		−130.0		−131.6		−104.6		−105.2
Beac. dBm	37.0		17.0		−11.0		−31.0		−71.0
Aux. dBm	20.0		0.0		−28.0		−48.0		−88.0

Table 2 Inband and outband gain as well as E1b,c ,beacon and auxiliary signals levels up to the second RF SAW filter.

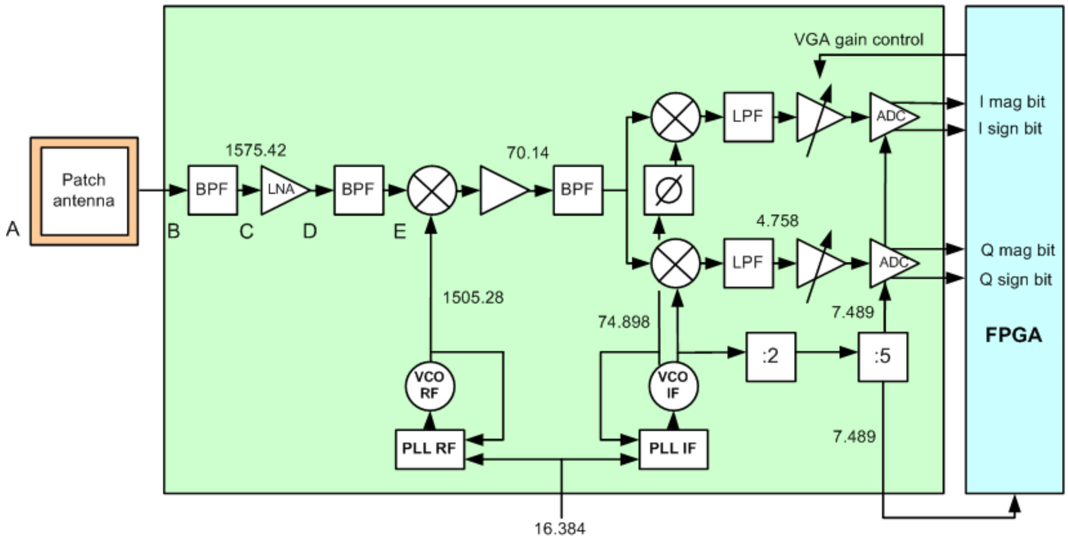

Fig. 9 Frequency plan configuration for dual lobe acquisition.

quency to relax the image frequency rejection requirement. Since no IF SAW filter has been designed specifically for the Galileo E1b,c signals yet, a standard frequency of 70MHz has been chosen. It has the advantage that for the same center frequency, several filters bandwidths are available, which allows to easily reconfigure the front-end in order to perform, for example, BOC(1,1) single sidelobe acquisition. When choosing the bandwidth, the group delay introduced by the IF filter is also an important parameter. As a result, among the existing bandwidths available, 5MHz has been chosen. The IF can then also be slightly shifted from 70MHz and a higher PLL comparison frequency can be used, which reduces the frequency synthesizer phase noise contribution. The SNR degradation due to the wider bandwidth is less than 1dB.
The signal is then downconverted by a quadrature mixer to a second IF of 4.758MHz. The second IF has been chosen in order to:

- maximize the image rejection.
- minimize the 1/f noise contribution.
- minimize the sampling clock.

The IF signal is then filtered by a lowpass multi feedback (MFB) 4th order butterworth filter. The filter's 3dB bandwidth is 7.2MHz and the maximum group delay variation in the signal band (2.758MHz to 6.758MHz) is 27.5ns. The 45dB variable gain amplifier (VGA) is digitally controlled by the FPGA where the baseband acquisition and tracking channels are implemented, in order to optimize the use of the 2 bits ADC full scale range. The sampling frequency and FPGA clock, 7.489MHZ, is derived from the second LO. The complete frequency plan is shown in figure 9.

The front-end minimum IP3 is computed from the interference mask. The first SAW filter has been chosen primarily for its low IL. As a consequence, it is also not very selective. In the inband region of the mask, the allowed interference level is below the noise floor. In the outband region, the allowed interference level is higher but the filter's attenuation is sufficient to prevent any intermodulation product stronger than the noise floor to fall inband. Therefore the only critical region of the mask is the transition between inband and outband, where the allowed interferer level increases faster than the filter's attenuation. Summing the mask and the filter's transfer functions, the strongest component has been determined and used to compute the required minimum IP3. The linearity requirements are relaxed after the IF filtering stage due to its narrower bandwidth.

FRONT-END REALIZATION

The front-end has been implemented on a four layer printed board circuit (PCB). The analog and digital sections have separate ground planes. Additionally, the RF, IF, baseband and frequency synthesizers are all isolated by ground rings.

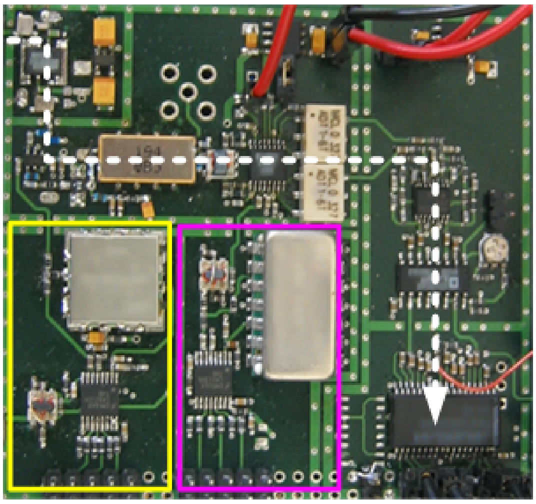

Fig. 10 Picture of the first front-end prototype. Signal path (white line:), RF frequency synthesizer (yellow rectangle), IF frequency synthesizer (pink rectangle)

MEASUREMENTS

The following set of measurements has been realized on the first prototype of the front-end. The major difference with the second prototype is the VGA which is not controlled digitally but with a gain control voltage. The two VGAs have the same gain ranges though.

Measurements of the standalone front-end

The measured system's NF is 2.92dB which is 0.08dB above the expected value of 2.84dB and 0.08dB better than the NF specified in the requirements. The gain has been measured between the front-end's input and the output of a selection of its key circuits, in order to verify that each circuit was working properly. As we can see in table 3, the total gain up to the VGA input is 1.5dB below the expected gain.

	RF SAW 2	RF mixer	IF SAW	IQ mixer	LPF
$G_{sim.}$ dB	22.8	34.8	55.8	67.8	66.8
$G_{meas.}$ dB	25.4	37.3	52.1	66.2	65.3
Δ dB	2.6	2.5	−3.7	−1.6	− 1.5

Table 3 Simulated and measured gain between the input and the output of a selection of key circuits of the front-end

In figure 11, the theoretical and measured VGA gains are represented versus the gain control voltage. When more gain is required, the VGA gain range can be shifted from (-14dB to + 34dB) to (+0dB to +48dB) resulting in the upper trace in figure 11.

The frequency synthesizers phase noise measurements are summarized in table 4.

Measurements of the front-end integrated with the receiver platform.

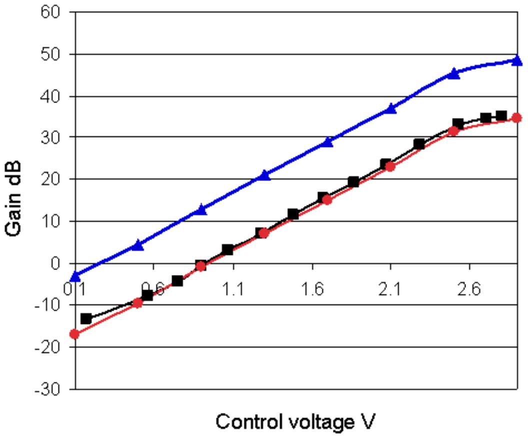

Fig. 11 Expected (circles) and measured (squares) VGA gain versus control voltage, shifted gain range (triangles)

	Phase noise dBc/Hz @		
	1kHz	10kHz	100kHz
RF freq. synth. dB	−78.5	−77.8	−106.8
IF freq. synth. dB	−84	−87.4	−101.3

Table 4 RF and IF frequency synthesizer phase noise measurement.

The measured IF spectrum when the front-end is integrated in the complete development platform (see [5] for a detailed description), is shown in figure 12. Beside the sampling frequency component at 7.498MHz, no digital interference is apparent on the spectrum and the noise outside of the signal band is efficiently filtered by the IF and baseband filters.

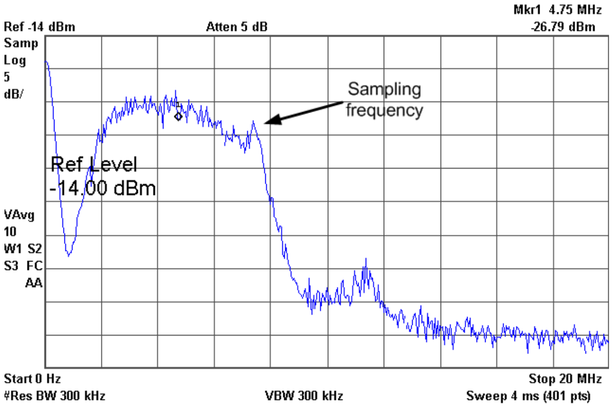

Fig. 12 IF spectrum measured on the complete developement platform.

A series of tests has then been performed with the GSS7800 Galileo simulator in order to validate the front-end and the platform's correlators. Acquisition and tracking was successful, with a average measured C/N$_0$ 0.8dB higher than the expected theoretical value. For the next measurement, a 121.55MHz and a 406MHz continuous wave (CW) signals have been alternatively injected directly in the front-end and the spectrum measured at the output of the second SAW filter. The three traces in figure 13 represent the cases where: no distress signal, the 121.5MHz/20dBm signal, the 406MHz/37dBm signal are emitted. In order to account for the GPS antenna attenuation at 121.5MHz and 406MHz, an attenuator has been placed between the CW generator and the front-end's input. As we can see in figure 13, no interferer, harmonic of intermodulation product actually falls in-band (1572.67MHz-1578.17MHz) but the noise floor is increased by up to 25dB when the 406MHz signal is emitted.

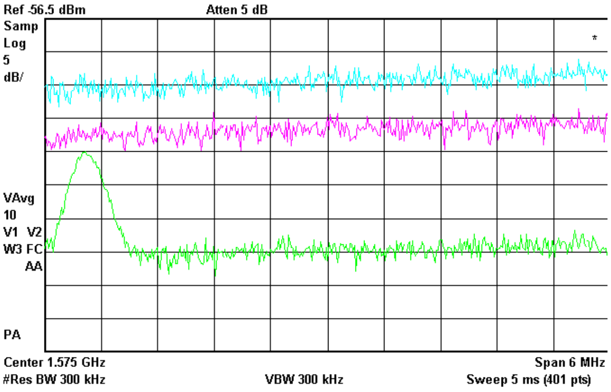

Fig. 13 Spectrum measured at the output of the second RF SAW filter when: (bottom green) no distress signal is emitted, (middle pink) 121.5MHz signal is emitted, (top blue) 406MHz signal is emitted.

Combining the signal and the distress signals with a 3dB power combiner, it has been determined that the receiver could still acquire the signal for 121.55MHz levels below +9dBm, resulting in a C/N_0 of 41.5dBm/Hz, and for 406MHz levels below +4dBm, resulting in a C/N_0 of 39.4dBm/Hz.

For the next measurement, a beacon modified for testing purposes has been used: the 121.5MHz signal has been shifted to 121.55MHz in order not to be processed as a distess signal and the identification data included in the 406MHz signal identifies the beacon as a test beacon. The beacon antenna has been placed beside the front-end input. It should be noted that the front-end prototype was not shielded, which gave the opportunity for the distress signals to couple in the front-end at sensitive points such as after the IF SAW filter. Figure 14 shows the measurement results: the green traces shows the IF spectrum measured at the output of the VGA when no interferer is transmitted, the yellow when the 121.55MHz signal is transmitted and the pink when the 406MHz signal is transmitted. As we can see, the front-end seems to be insensitive to the 121.5MHz distress signal. The emission of the 406MHz distress signal results in a strong component at 3.9MHz and a gain reduction of 15dB (the VGA control voltage being set to a fixed value).

CONCLUSIONS

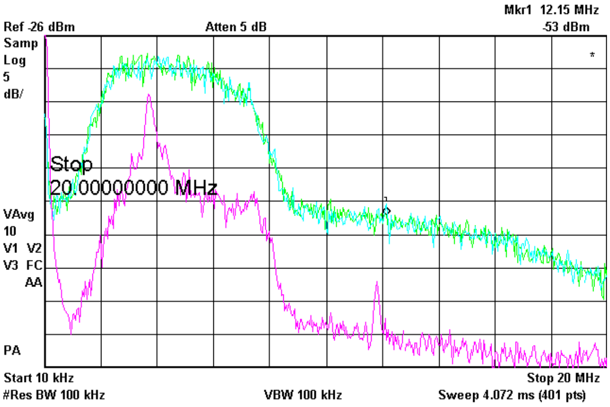

Fig. 14 Spectrum measured at the output of the VGA with (top green) no distress signal emitted, (top blue) 121.5MHz signal emitted, (bottom pink) 406MHz signal emitted.

A Galileo front-end to process the E1b,c signals in the presence of strong interferers emitted by a distress beacon has been designed. We have seen during the measurement phase that the front-end rejects the distress signals efficiently, making it possible to acquire the Galileo E1b,c signal in the presence of a 121.55MHz CW signal of +9dBm or a 406MHz CW signal of +4dBm, when these signals are directly injected in the front-end. Proceeding to similar tests with a real beacon, we have seen that the front-end is insensitive to the 121.55MHz distress signal and that the 406MHz distress signal leads to a 15dB gain loss. We could also verify that when the receiver was in tracking mode, the lock was not lost during emission of the distress beacons. As a consequence the level of the signals, when directly injected in the front-end seems to be much higher than the level of the distress signals actually coupling from the beacon antenna in to the receiver.

ACKNOWLEDGEMENTS

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