“Spurious” Analysis of a Wide Bandwidth Undersampled Digitally Heterodyned SFGPR

Giovanni Galiero, Giovanni Alberti
Consortium for Research on Advanced Remote Sensing Systems - CO.RI.S.T.A.
Naples, Italy

Doroteo Adirosi
Thales Alenia Space Italia
Rome, Italy

***Abstract*—A key aspect of a previously proposed undersampled digitally heterodyned stepped frequency GPR is the capability to generate and acquire a large band of frequencies. This is obtained by moving most of the analog domain functionalities of the SFGPR into the digital one. In this paper an analysis of the aliased images generated by the digital frequency generator is performed. Its necessity is dictated by the large bandwidth needed to be generated to achieve high resolution and by the undersampling scheme chosen. The analysis was performed with the aid of different software tools developed ad hoc in a high level language. The key aspects of the analysis and its main results are discussed and illustrated.**

Keywords: SFGPR, undersampling

I. INTRODUCTION

It is well known that the capability of electromagnetic waves to propagate beyond physical discontinuities of the propagation media makes it possible to investigate internal features of dielectric bodies. From this property, an endless number of practical applications have arisen, ranging from medical prospecting to detection of mines, nondestructive testing of industrial items and GPR applications. A Stepped Frequency GPR (SFPGR) is a Ground Penetrating Radar that synthesizes the pulse to be transmitted in the frequency domain instead of time domain [3]. This is achieved by transmitting single tones in successive time intervals. The frequencies of these tones are chosen in the bandwidth of interest with a constant frequency separation (frequency step) starting from an initial frequency. By recording the phase of the echoes received for each step and by employing a suitable inversion algorithm it is possible to reconstruct the equivalent pulse transmitted [3]. In [1] a new architecture of an Undersampled Digitally Heterodyned SFGPR with variable sampling frequency was presented. The idea of this new design started from the technical knowledge and field experience achieved during the design of a SFGPR developed in the framework of the ARCHEO project. It was funded by the Italian Ministry for scientific research and industry, whose main aim is the development of tools to aid archeologists in their field researches [2]. The purpose of this new design was to develop an architecture that could greatly simplify the radio frequency section of a SFGPR still keeping a wide bandwidth generation capability to achieve a high resolution. Two possible choices were possible: homodyne and heterodyne architecture. The latter one was chosen for the reasons recalled in the next section. In an heterodyne SFGPR to simplify the acquisition of the echoes, they are downconverted to a common intermediate frequency, f_{IF} [2]. This is usually achieved by means of another frequency generator whose tone is at f_{IF} Hz away from the transmitted tone. The idea proposed ([1]) started from the purpose to eliminate this second frequency generator by direct acquisition of the echoes received and from the consideration that the bandwidth of the tone transmitted during each step is small (at most few kHz). Undersampling was the optimum choice that allow to solve both the problems: the downconversion of the signal is performed automatically (as result of the sampling process) and the signal is sampled optimally without the need to oversample it (in fact the frequencies of the tones transmitted are in the order of 100 MHz – 400 MHz that would require a sampling frequency of 250 MHz – 1 GHz, well above the few kHz needed to acquire the transmitted bandwidth according to the Nyquist criteria for bandlimited signals). Furthermore, in this case the jitter required for the sampling frequency is much smaller. Once acquired the echoes are digitally downconverted (quadrature downconversion) to determine their phase. Due to the necessity to adapt the undersampling process to the possible various set of parameters chosen for the SFGPR (initial frequency, frequency step, number of step) it may be necessary to modify the sampling frequency on a step by step basis. Such analysis as well as the validity of the idea were successfully demonstrated in [1] with software simulations. In the next section the main characteristics and features of the architecture proposed in [1] are briefly reported.

The digital frequency generator present in the transmitting chain generates the tones to be transmitted and their aliased images. In this paper an analysis of the aliased images is performed. Such analysis is needed for the following reasons: due to the undersampling of the echoes as well as the digital mixing with a digital local oscillator, it is necessary to determine if both the sampled aliased images and the intermodulation products between them and the echoes' intermediate frequency fall outside the useful bandwidth. In order to easily indicate with a single term both disturbing frequencies (aliased images and intermodulation products) the word “spurious” is sometime used in this paper (usually this term is used in literature with a different meaning, for this reason here it is enclosed between “). The analysis is dictated by the large bandwidth needed to be generated to achieve high resolution and it was aid by different software tools developed ad hoc in a high level language (LabView™). The key aspects of the performed analysis as well as its main results are discussed and illustrated.

978-1-4577-0333-1/11/$26.00©2011 IEEE

II. ANALYSED ARCHITECTURE

The SFGPR architecture presented in [1] and analysed in this paper (Fig. 1) is a heterodyned GPR where the quadrature downconversion is performed digitally on the undersampled signals.

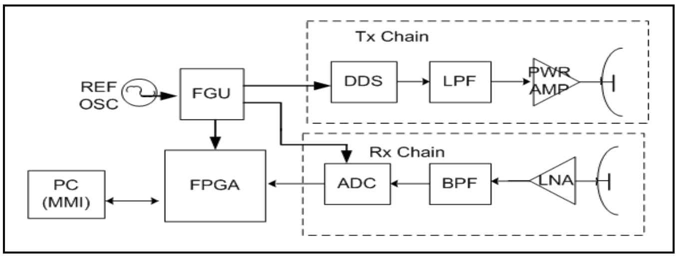

Figure 1. SFGPR architecture analysed in this paper.

This choice allows one to alleviate, not only the problems typical of homodyne GPR related to the flicker noise (in that the frequency of the signal to be sampled is always greater than 0 Hz, i.e. 1 MHz) and to the drift of DC values with the temperature but also the problems related to the quadrature demodulation in that it is performed in the digital domain instead of the analog one by direct acquisition of the IF signal. A brief description of the main blocks is given below:

- **Transmitting Chain** (Tx Chain): the signal to be transmitted is generated by means of a Direct Digital Signal generator (DDS), its output is low pass filtered and amplified prior to be sent to the transmitting antenna. The clock of the DDS is provided by a frequency generation unit.
- **Receiving Chain** (Rx Chain): the signal received by the antenna is amplified by an Low Noise Amplifier (LNA) and provided to a large band ADC; the signal is undersampled with sampling frequencies provided by the FGU. The samples acquired are transferred to an FPGA that performs the quadrature downconversion in the digital domain. The local oscillator of this downconverter is chosen according to the frequency of the transmitted signal and to the planned sampling frequency. Its phase takes into account the possibility of spectral inversion of undersampled signals also.
- **Frequency Generation Unit** (FGU): this unit generates all the frequencies employed in the SFPGR from a very low phase noise master oscillator: DDS and ADC clocks, FPGA reference clock.

The main advantages of the presented architecture are:

- Absence of a synchronism chain, generally used in SFGPR to get a phase reference of the transmitted signal [2].
- Simplified RF front end: both Tx and Rx chains are substantially constituted by an amplifier and a filter; this simplification is allowed by the undersampling of the received echoes.
- Simplified Frequency Generation Unit .
- Substantial reduction of the power consumption and weight due to the great simplification brought in the RF front end.
- Flexible architecture with respect to the possible frequency bands of use. In fact the constraints on which bands to use are mainly due to DDS and ADC 3-dB bandwidths. Nowadays they are present on the market DDSs capable to generate frequencies even in the second and third Nyquist zone as well as ADC with input bandwidth as large as 3 GHz. This allows the employment of the same SFGPR in a large band of investigation frequencies and with very large synthesized bandwidth. This peculiarity of the architecture will be more enhanced in the near future with the advent of integrated circuits with increased input/output bandwidths, as the trend of the last years has indicated.

III. ALIASED IMAGES ANALYSIS

The SFGPR generates frequencies in a large bandwidth. Its main parameters are indicated in Tab. 1 and are derived by the analysis performed in [1]. The sampling frequencies showed in Tab. 1 were chosen to allow digital IF signals to separate at least 500 kHz both from DC and from $f_{s\_ADC}/2$, where f_{s_ADC} is the sampling frequency of the ADC. The overall bandwidth to be generated comprises frequencies from 100 MHz to 415 MHz. Because these should be comprised in the range from DC up to (0.4÷0.46) f_{s_DDS} (sampling frequency of the DDS) and in order to allow an easier design of the anti-aliasing filter at DDS output, the DDS sampling frequencies in the following analysis are 1100 MHz and 1200 MHz.

TABLE I. SFPGR FREQUENCY GENERATION MAIN PARAMETERS

PARAMETER	VALUE
F_Start	100 MHz
Step Frequency	15 MHz
Number of Steps	21
Sampling Frequencies	40 MHz / 58 MHz 42 MHz/ 58 MHz

TABLE II. SFPGR ALTERNATIVE VALUES FOR FREQUENCY GENERATION MAIN PARAMETERS

PARAMETER	VALUE
F_Start	100 MHz
Step Frequency	14 MHz
Number of Steps	21
Sampling Frequencies	40 MHz / 58 MHz 44 MHz / 58 MHz

The main characteristics of the anti-aliasing LPF are that its 3-dB bandwidth is between 0.46 f_{s_DDS} and 0.5 f_{s_DDS} and the end of transition bandwidth is between f_{s_DDS} and 2 f_{s_DDS}. The order of this filter must be chosen according to the target SNR of the SFGPR. As already assumed in [1], the target SNR is 40 dB. Assuming a 5th order filter and one octave for the transition bandwidth (worst case condition) the guaranteed attenuation is 30 dB. By taking into account that the first lateral lobe of the sinc at DDS output is attenuated at least 13 dB, the overall guaranteed attenuation for frequencies falling in the second lobe is 43dB. Due to the large bandwidth of frequencies to be transmitted many of the aliased images generated during the synthesis may fall in the useful IF band. An analysis must be performed to assess if the chosen frequency plan (tab. 1) achieves the desidered objectives.

For the above mentioned reasons the following worst case scenarios are assumed in the analysis: the aliased images taken into account are $f_{s\_DDS} - f_i$, $f_{s\_DDS} + f_i$, $2f_{s\_DDS} - f_i$ where f_i indicates the generic step frequency. To simplify the analysis, the images previously mentioned are assumed to have all the same amplitude (worst case condition).

To perform the aliased images analysis two software tools were developed: a Frequency&Images Planner and a software simulator of the postprocessing performed in the digital receiver of the SFGPR. The aim of the first software tool is to determine if the values chosen for the set of parameters determining the behaviour of the SFGPR in the frequency domain are acceptable. If this would not be the result for all or some of the step frequencies it is possible to tune the values of some or all the parameters (e.g. sampling frequency of ADC/DDS, step frequency, number of steps) to find the right combinations of values. The steps to be followed are:

a) by means of the FrequencyPlanner software tool [1] initial values for the above mentioned set of parameters are chosen. By taking into account the need to have the resulting f_{IF} $B_{IF}/2$ Hz away both from DC and from $f_{s\_ADC}/2$;

b) the output f_{IF} generated in the previous step are used by the Frequency&Images Planner software tool that automatically determines and reports if the "spurious" frequencies fall outside the prohibited band (determined in the following). In case it is impossible to achieve this objective it is possible to modify some parameters (e.g. f_{s_ADC} of involved steps, f_{s_DDS}, step frequency and so on) in order to evaluate the effects of these changes;

c) if the value of some of the step frequencies have been changed in the previous step it is necessary to perform the step a) again.

The process just described is a "brute force" trial and error process to be repeated until a good set of values is found.

The goal is to avoid the presence of aliased images and intermodulation products in the useful band after the digital quadrature demodulation. The first step is to identify the prohibited band for "spurious" signals. After the digital mixing there is a low pass filter around DC. It is possible to demonstrate that the prohibited band is centered around f_{IF} and large B_{IF_Att}, where f_{IF} is the frequency of the intermediate signal resulting from the direct undersampling of the i-th step frequency f_i and B_{IF_Att} is the end of the transition bandwidth of the digital LPF following the mixer and it is the first frequency for which the required attenuation is guaranteed. The following considerations hold. The frequencies to be considered are those comprised in the range $0 \div f_{s\_ADC}/2$; the frequencies in the range $f_{s\_ADC}/2 \div f_{s\_ADC}$ represent the negative ones with f_{s_ADC} representing DC. The result is demonstrated by dividing this frequency interval in smaller ones, each large $f_{s\_ADC}/8$. $f_{spurious}$ is the frequency resulting by the undersampling of the generic aliased image generated with f_i. Let us consider the following case: f_{IF} fall in the frequency range $\frac{3}{8} f_{s\_ADC} \div \frac{1}{2} f_{s\_ADC}$. For each aliased image $f_{spurious}$ the intermodulation products (due to the digital mixing) to be taken into account are $f_{spurious} + f_{IF}$ and $f_{spurious} - f_{IF}$. If $f_{spurious} - f_{IF}$ is outside the range $f_{IF} \pm B_{IF\_Att}/2$ the resulting frequency fall outside the useful band B_{IF_Att} (by difference). The frequency $f_{spurious} + f_{IF}$ may remain below $f_{s\_ADC}/2$ or it may go beyond it depending on the values of $f_{spurious}$ and f_{IF}. Our goal is to obtain a resulting frequency distant from DC more than $B_{IF\_Att}/2$. If it remains positive the goal is achieved by definition. If it becomes negative it must be considered that the resulting frequency must be below $f_{s\_ADC}/2$ by more than $B_{IF\_Att}/2$ (this is equivalent to say that the resulting frequency is folded back and that it must be greater than DC by more than $B_{IF\_Att}/2$). The goal is achieved if $f_{spurious} + f_{IF}$ is outside the range $f_{IF} \pm B_{IF\_Att}/2$. The case just described is the worst case. A similar demonstration can be applied to the other f_{IF} ranges.

In the GUI of the Frequency&Images Planner software tool it is possible to see, in particular, the resulting f_{IF} frequencies with the limits of the prohibited band together with the "spurious" frequencies. For sake of clarity in the lower right corner of the GUI the "spurious" frequencies falling inside the prohibited band are shown.

We now show the results obtained with the software simulator. It uses the data generated by the Frequency&Images Planner tool and allows us to simulate the aliased images and choose which ones. The inversion algorithm used to synthesize targets is the modified Walton described in detail in [3].

IV. SIMULATION RESULTS

We show the effects that the "spurious" have on the detectability of targets. Many simulations were performed with different combinations of the parameters mentioned above (see Tab. 1). Most were obtained by simulating two targets with the same relative amplitude and at a "temporal distance" of, respectively, 7 ns and 12 ns. The characteristics of the digital LPF considered for the simulations are: Elliptic Filter type of 4th order; CutOff Freq 500 kHz; in band ripple 0.5dB and out of band attenuation 40dB.

Fig.2-A shows the results obtained with the software simulator in the following two cases: simulation performed without taking into account any "spurious" signal and by considering all of them (digitally low pass filtered; f_{s_DDS} considered is 1100 MHz). It is evident that two lines match perfectly so that the characteristics chosen for the LPF are sufficient to filter efficiently the out of band "spurious" frequencies. This figure constitutes a reference with which to perform comparisons in the cases following. In all the simulations' results presented hereafter the first line of the graphs is the same as the first one just showed and only the descriptions related to the second line will be reported.

In order to remark the importance of the digital filtering in fig.2-B we show the simulations results obtained by considering all spurious frequencies and by avoiding to perform the digital LPF. The figure shows that one of the targets is slightly distorted. All the spurious frequencies taken into account in this simulation were out of the prohibited band described in previous paragraph and more evident distortions would be shown if in-band spurious would be taken into account. This figure shows the importance of low pass filtering of the spurious frequencies in the digital domain in order to avoid distortions. Fig. 2-C and Fig. 2-D show the effects of in-band spurious frequencies which cannot be filtered out; both figures show distortions of both targets.

To show the effects that few in band spurious frequencies can have on the targets' location other simulations were performed with a different set of parameters. The values considered for these simulations are reported in Tab. 2. Fig. 3-A and fig. 3-B show, respectively, the reference graphs, in the same simulation hypothesis as the ones considered for fig. 2-A, and a comparison among the reference targets and those obtained with one and with three in-band spurious frequencies. While the plot for 1 in band spurious presents only a slight distortion with respect to the reference line, the plot for 3 ones

is more distorted than the previous.

With the aim to underline the effects that in band spurious frequencies can have on targets' location, simulations were performed with the set of parameters reported in Tab. 1.

The "temporal distances" considered are 8 ns and 11 ns. As shown in fig. 3 the effects are more evident than the slight distortion reported in fig. 2-C and fig. 2-D; only one target appears instead of two.

The simulations results showed point out the importance to plan in advance not only the step frequencies to be generated together with the ADC sampling frequencies to be employed for each one of them, but also the DDS sampling frequency in order to avoid distortions of the targets to be detected. This can be achieved by following the trial and error process described in the previous paragraph with the aid of the mentioned software tools. The employment of these tools is fundamental in that they allow one to easily tune the entire set of parameters characterising the SFGPR by simply looking at the resulting f_{IF} and $f_{spurious}$ and by checking if the last ones can be filtered out in the digital domain of the described receiver.

Furthermore it is possible to choose and to tune the characteristics of the digital LPF in order to minimize both the postprocessing time and step duration. It is possible to evaluate the effects that the chosen LPF has on the whole SFGPR by means of the simulator software tool.

The values showed in tab. 1, with 40/58 MHz for the f_{s_ADC}, constitute the intial set of value for the trial and error process. After the analysis performed, the set of values to be taken into account for future development of the presented SFGPR are still the ones showed in table 1 but with 44/58 MHz for the f_{s_ADC}.

V. CONCLUSIONS

This paper presented the aliased images analysis of a new SFGPR architecture. The necessity of the analysis performed was due to the wide bandwidth needed to be generated to achieve high resolution and to the undersampling scheme chosen. The intrisic advantages achievable by moving GPR complexities from the analog domain into the digital one have the side effect to potentially "move" aliased images into the useful intermediate frequency band if a suitable frequency plan is not performed in advance. The analysis has shown that a successful result is achievable with the aid of ad hoc software tools and that the characteristics of the filtering to be performed both in the analog domain (anti-aliasing LPF at DDS output) and in the digital one (LPF at the quadrature downconversion output) are easily achievable: results have shown that the digital transition bandwidth can be increased from 0.5MHz to 1.5MHz.

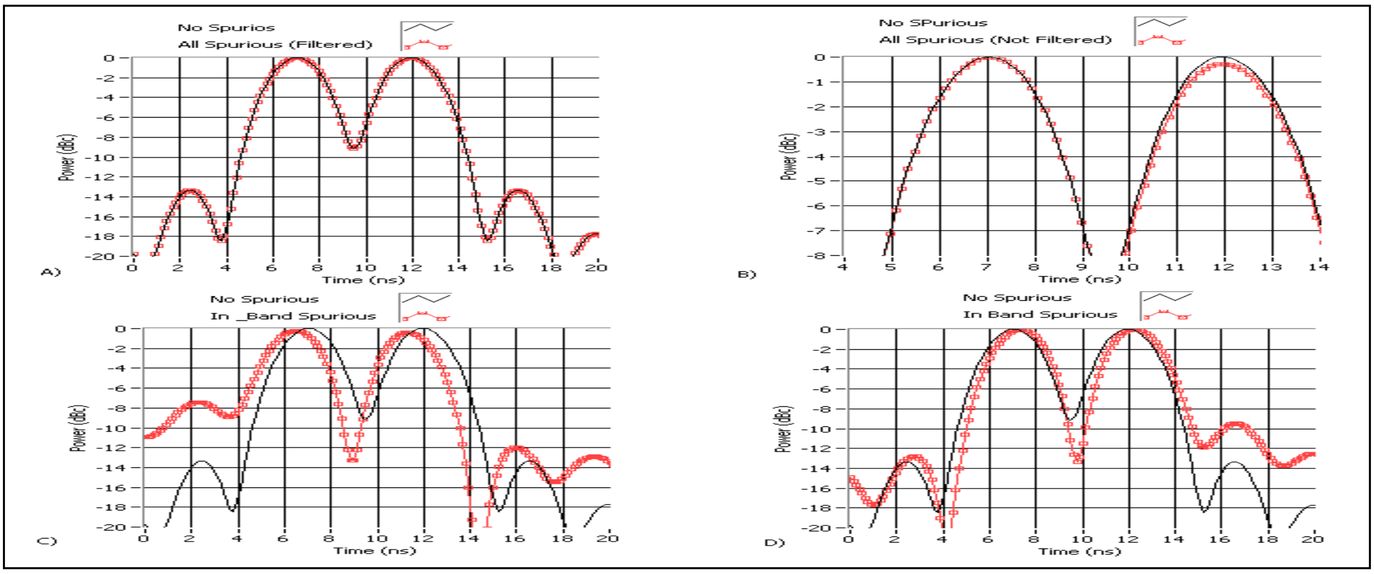

Figure 2. Simulation Results: A) Simulated Targets without taking into account any spurious frequency (reference line) and by filtering all of them; B) Reference Line and all out of band spurious frequencies without filtering; C) Reference Line and in band spurious frequencies (f_{s_DDS} =1200 MHz); D) Reference Line and in band spurious frequencies (f_{s_DDS} =1100 MHz)

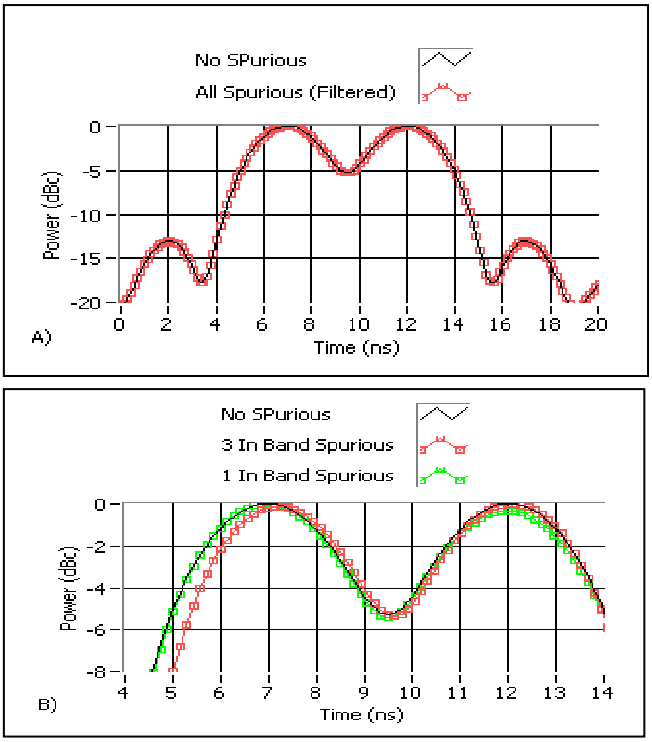

Figure 3. Simulation Results with new set of parameters: A) Simulated Targets without taking into account any spurious frequency (reference line) and by filtering all of them; B) Reference Line and 1 and 3 in band spurious signals.

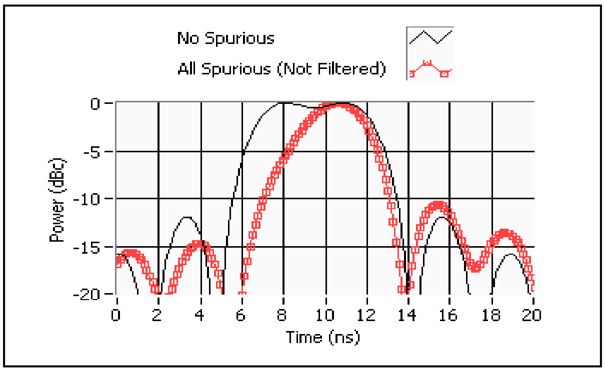

Figure 4. Simulation Results: Simulated Targets without taking into account any spurious frequency (reference line) and by not filtering all of them with two very close targets

REFERENCES

[1] G. Galiero, D. Adirosi, G. Alberti, □Undersampled digitally heterodyned SFGPR with variable sampling frequency□, in Proceedings of Progress in Electromagnetic Research Symposium (PIERS 2011), Marrakesh, Morocco, March 2011, in press.

[2] G. Alberti, L. Ciofaniello, G. Galiero, R. Persico, M. Sacchettino, “An Italian experience on stepped frequency GPR”, in Proceedings of Progress in Electromagnetic Research Symposium (PIERS 2004), PISA, Italy, March 2004.

[3] D.J. Daniels, Surface Penetrating Radar, The institution of Electrical Engineers : London, 1996. London ,1996.