Author(s) Thombre, Sarang; Nurmi, Jari

Title Bandpass-sampling based GNSS sampled data generator - A design perspective

Citation Thombre, Sarang; Nurmi, Jari 2012. Bandpass-Sampling based GNSS sampled data generator - A design perspective. International Conference on Localization and GNSS 2012, (ICL-GNSS), Starnberg, Germany, June 25-27, 2012. International Conference on Localization and GNSS Piscataway, NJ, 1-6.

Year 2012

DOI http://dx.doi.org/10.1109/ICL-GNSS.2012.6253114

Version Post-print

URN http://URN.fi/URN:NBN:fi:tty-201403141128

Bandpass-Sampling based GNSS Sampled Data Generator – A Design Perspective

Sarang Thombre, Jari Nurmi
Department of Computer Systems
Tampere University of Technology (TUT)
Tampere, Finland
{sarang.thombre, jari.nurmi}@tut.fi

Abstract— **This paper presents the design methodology and simulation results of a sampled data generator (SDG) designed to operate over the whole range of Global Navigation Satellite System (GNSS) frequencies (1164MHz to 1615.5MHz). An SDG is actually a radio front-end (RF FE) that generates digital samples at intermediate frequency (IF), which can be recorded and used in the future as test input to a baseband processing unit. The proposed SDG is based on the bandpass-sampling principle and works over combined (but overlapping) frequency bands of all three GNSS constellations (American Global Positioning System (GPS), European Galileo system and the Russian GLONASS system). It is observed that there is currently no commercially available multi-system multi-frequency GNSS SDG. This paper hopes to fill this gap. First, the overall architecture of the proposed SDG is described, followed by the detailed design of each block, namely, the bandpass & bandstop filters, and the frequency planning for the bandpass-sampling analog to digital converter (ADC).**

Keywords-Navigation, bandpass-sampling, sampled data generator

I. INTRODUCTION

The GNSS Receiver Research Group at Tampere University of Technology is engaged in the design and construction of an embedded dual-frequency, dual-system GNSS receiver. One of the challenges faced is the availability of test input. Hardware simulators of GNSS signals are very expensive and hence an alternate solution was needed. One possible solution was to record data samples from a temporarily accessible GNSS simulator. This spawned the idea for constructing a GNSS sampled data generator which would provide at the output a sampled data stream of the GNSS signal input from the simulator. Also, it would be really beneficial if a wideband architecture were used so that most of the GNSS signals could be accommodated.

For some years there has been considerable interest in bandpass-sampling as a means to digitize a wide spectrum of frequencies while keeping the sampling frequency at reasonable levels. In [1], bandpass sampling of a single band of frequencies was considered which evolved to sampling multiple distinct RF bands in [2], [3] and [4]. In [5], bandpass sampling of multiple distinct single-sided (complex) RF bands was accomplished. In all these works, either GPS and GLONASS or GPS and GSM signals were integrated and that too, just L1 band signals in each case. [6] claims to use bandpass sampling and digital filtering for direct conversion of GPS L1 (C/A) and L1/L2 (P(y)) codes into digital intermediate frequency (IF). Therefore, it can be observed that information on using bandpass-sampling to sample the entire GNSS band of frequencies is not yet covered in past literature. Research work has already begun towards this goal and [7] describes the design, construction and results of the low noise amplifier (LNA) to be used in the present SDG.

The layout of the paper is as follows: in Section II the overall block architecture of the SDG and the frequency spectrum of interest have been briefly described. It also presents a summary of the LNA developed in [7]. Then the design and simulation results of the bandpass and bandstop filters are presented in Section III. Section IV presents the frequency planning for the bandpass-sampling ADC. Finally, Section V contains the results of the SDG functional blocks discussed in the earlier sections.

II. BLOCK ARCHITECTURE OF BANDPASS-SAMPLING SDG

The bandpass-sampling architecture works on the principle of down-conversion to a digital IF by direct sampling of the RF signal bandwidth (BW) using intentional, yet non-destructive aliasing. The RF signal from the antenna is filtered (to remove out-of-band noise), amplified and then directly digitized using a high speed ADC. The clock frequency along with proper band-select filters allows selecting the right frequency band to downconvert from the received RF spectrum. After the ADC, either the digital data is stored on a hard-drive or digital filters are employed to separate the IF bands to be demodulated in the baseband processor.

Fig. 1 shows the block diagram of a bandpass-sampling SDG proposed in this research work. Fig. 2 shows the frequency spectrum over which this SDG is designed to operate. It includes all the GNSS frequency bands and extends from 1164MHz to 1300MHz and again from 1559MHz to 1615.5MHz. Frequencies between 1300MHz and 1559MHz are not interesting to us and this 'empty' band allows for the use of the bandpass-sampling technique.

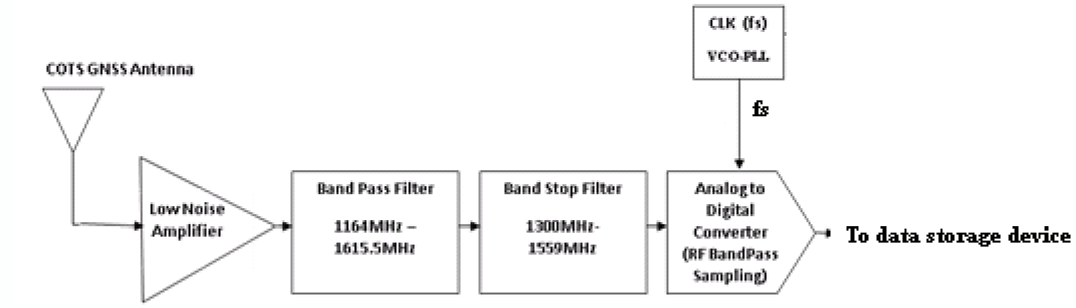


Fig. 1 Block-diagram of the proposed bandpass-Sampling SDG

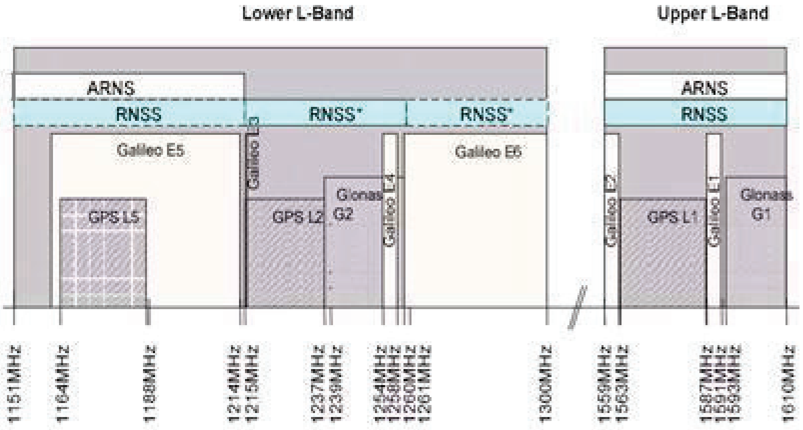


Fig. 2 Frequency spectrum of the proposed SDG [8]

Criteria for optimum sampling frequency according to the Nyquist-Shannon theorem is that it should be at least twice the highest frequency component in the given frequency band [9]. Any frequency lower than this 'Nyquist minimum' will cause aliasing of the frequency band in the digital domain. That is, the frequency band in the digital domain may fold onto itself causing information from two or more distinct channels within the band to interfere when they overlap on one another.

Table 1. Design specifications for bandpass and bandstop filters

Parameter	Bandpass Filter	Bandstop Filter
Topology	Chebyshev	Chebyshev
Filter order	7	7
Pass band ripple	3dB	3dB
Lower cut-off frequency (f_l)	1164MHz	1300MHz
Upper cut-off frequency (f_u)	1615.5MHz	1559MHz
Pass band IL	≤ 3dB	≤ 3dB
Stop band IL	> 3dB	> 3dB
Input impedance	50 Ohm	50 Ohm
Output	50 Ohm	50 Ohm
Return Loss	≥ 15dB	≥ 15dB

However, aliasing is not always destructive. What if there are certain gaps in between the individual channels within the larger RF band? Lower sampling frequency could be used to ensure intentional aliasing that is not destructive to the original information. That is, ensure that the digitized channels fold on the original RF band, but they fall exactly in the spacing in between individual channels, so that the information in any one channel is retained intact.

Thus, according to the theory of bandpass-sampling, the sampling frequency can be lower than Nyquist criteria and yet (by careful frequency planning) not cause destructive aliasing. The minimum sampling frequency can now be the twice of the bandwidth to be sampled instead of twice of the highest frequency component. Thus, the resulting sampling rate can be significantly reduced. The sampled band is then replicated at every harmonic multiple of the sampling frequency.

The first stage of the proposed SDG is the low noise amplifier. The LNA has already been designed, simulated and implemented on PCB. Its results have been published in [7]. Designed to be unconditionally stable with gain of over 18dB and noise figure of 2dB over a considerable bandwidth of about 450MHz, the achieved results conformed quite well to the specifications. Final implementation results include a gain of 18.5dB at the centre frequency with a nominal variation of ±1.3dB over the desired bandwidth. The noise figure obtained is 2.18dB and the amplifier stability range extends from 0Hz to 9GHz. Very high degree of linearity is achieved with output 1dB compression at +13dB and output third order intercept at +23dB.

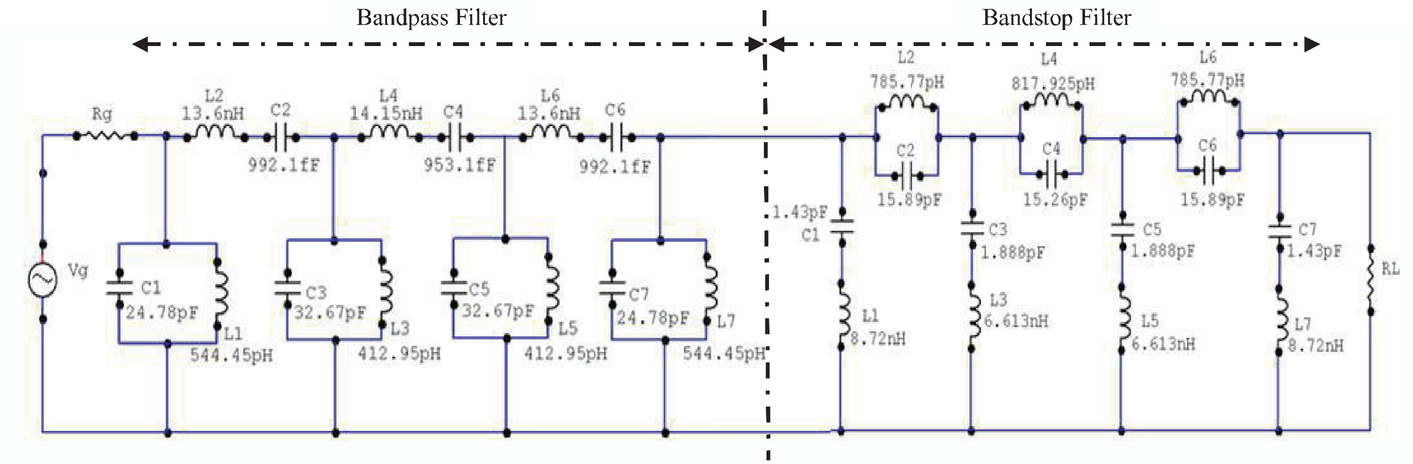


Fig. 3 Final schematic of the cascade of seventh order bandpass and bandstop filters

III. FILTER DESIGN

GNSS frequency bands extend from 1164MHz to 1300MHz and from 1559MHz to 1615.5MHz. Hence to isolate these two bands, it needs one RF bandpass filter (1164MHz to 1615.5MHz) followed by an RF bandstop filter (1300MHz to 1559MHz). To prove the concept, these two filters were designed as seventh-order LC Chebyshev filters.

Table 1 presents the design specifications for the two filters. The design methodology adopted was as follows: first, the seventh-order low pass Chebyshev filter was designed. Next, transformation from low pass to bandpass or bandstop filter was performed using the principle of component transformations. Fig. 3 shows the final schematic of the cascade of the seventh-order bandstop and bandpass filters. The results in graphical format are presented in the Section V.

IV. FREQUENCY PLANNING FOR BANDPASS SAMPLING

Frequency planning was carried out based on the theory presented in [1], [2], [3], [4], [5], [6], [10], [11], and [12]. For a set of two real distinct frequency bands (as in the case of the proposed SDG), appropriate sampling frequency can be computed based on the simultaneous fulfillment of certain conditions. It is possible to prepare a Matlab program to compute all those sampling frequency values which satisfy all these requirements simultaneously. The requirements are given in (1)-(8):

BW of interest (BWoI) = band 1 + band 2

= (1300MHz – 1164MHz) + (1615.5MHz – 1559MHz)

= 192.5MHz (1)

Center frequency of band 1 (f_{c1}) = 1232MHz (2)

Center frequency of band 2 (f_{c2}) = 1587.25MHz (3)

Minimum sampling frequency (f_{smin}) = 2* BWoI (4)

$$\mathrm{IF} = f_{IFi} \begin{cases} = \mathrm{Rem}\left(\frac{f_{ci}}{f_s}\right) & \text{if } \mathrm{Int}\left[\frac{f_{ci}}{\frac{f_s}{2}}\right] = \text{even} \\ = f_s - \mathrm{Rem}\left(\frac{f_{ci}}{f_s}\right) & \text{if } \mathrm{Int}\left[\frac{f_{ci}}{\frac{f_s}{2}}\right] = \text{odd} \end{cases} \quad (5)$$

$$f_{IFi} > \frac{BWi}{2} \quad (6)$$

$$f_{IFi} < \frac{f_{s-BWi}}{2} \quad (7)$$

$$|\, f_{IF1} - f_{IF2} | \geq \frac{BW_1 - BW_2}{2} \quad (8)$$

Where: Int[x] = largest integer smaller than x (or simply, rounding off to the nearest lower integer)
i = the frequency band number

A Matlab program was written to find out possible values of sampling frequency and intermediate frequencies. These computations are applicable for sampling real GNSS signals. If the GNSS signals are converted into complex/analytic by using Hilbert transformer and then sampled, the sampling frequency requirement is further relaxed. Fig. 4 shows the frequency spectrum of two complex signals with all important frequency points marked on the diagram.

(9)-(12) give the criteria that must be simultaneously satisfied by the sampling frequency in case of complex GNSS signals [5].

$$n_1 \leq \mathrm{Int}\left[\frac{f_{c1}}{B_1 + B_2}\right] \quad (9)$$

$$\mathrm{Int}\left[\frac{n_1 * f_{c2}}{f_{c1}}\right] \leq n_2 \leq \mathrm{Int}\left[n_1 * \left(\frac{f_{c2}}{f_{c1}}\right) + \frac{f_{c2}}{f_{c1}}\right] \quad (10)$$

$$\frac{f_{H2} - f_{L1}}{n_2 - n_1 + 1} \leq f_s \leq \frac{f_{L2} - f_{H1}}{n_2 - n_1} \quad (11)$$

$$\frac{f_{H2} - f_{L1}}{n_2 - n_1} \leq f_s \leq \frac{f_{L2} - f_{H1}}{n_2 - n_1 - 1} \quad (12)$$

(11) should be used if the position of the resulting sampled bands should be as shown in Fig. 5. While if their positions should be as in Fig. 6, then (12) should be used. The solid frequency band denotes spectra of original signal and the dashed frequency band denotes a replica after sampling the original band.

Thus, the procedure for obtaining a range of valid sampling

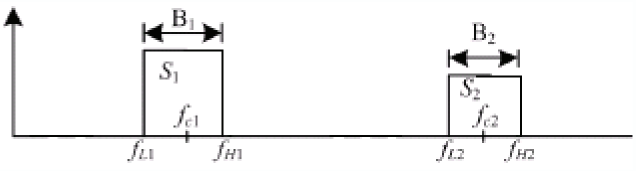


Fig. 4 Frequency spectrum of two complex RF signal bands

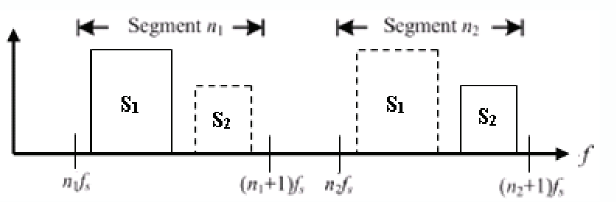


Fig. 5 First possibility of arranging the sampled and original bands

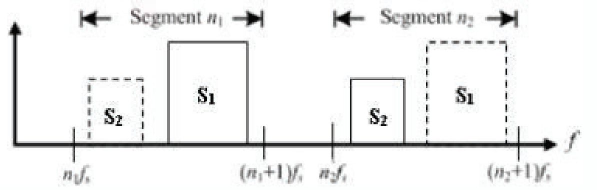


Fig. 6 Second possibility of arranging the sampled and original bands

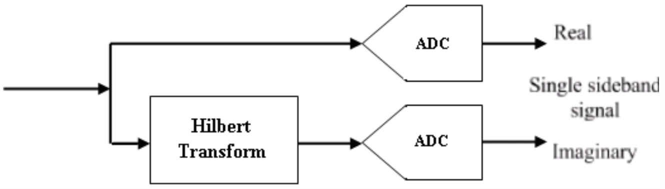


Fig. 7 Block diagram of complex bandpass-sampling

frequencies for two complex RF signals is: first, choose an appropriate n_1 using (9); next, choose an appropriate n_2 using (10), and last, using (11) or (12) compute the range of sampling frequencies. (13) gives the new position of the sampled IF band when complex GNSS signals are considered [5].

$$f_c^m = m*f_s + \text{rem}(f_c, f_s) \qquad (m = 0, \pm1, \pm2, \pm3\ldots\ldots) \qquad (13)$$

Where: f_c^m = Center frequency of the m^{th} replica of the sampled band

rem(f_c, f_s) = Remainder from the ratio of f_c and f_s

In general, the desired bands can be down-converted using a much lower minimum sampling frequency in case of complex bandpass sampling than real bandpass sampling. Also, the choice of valid sampling frequencies is much narrower in case of real sampling and even a slight deviation from calculated sampling frequency may cause harmful aliasing [5]. However, in case of complex sampling, because there are two signal streams (Inphase & Quadrature), the ADC would need to be replicated in both the signal branches, as shown in Fig. 7.

The limitation due to this additional hardware requirement outweighs the advantage of a relaxed sampling frequency, and hence, using real bandpass sampling is more beneficial. Finally, if this spectrum is passed through a suitable low pass IF filter, it is possible to extract the desired bands downconverted to baseband. This describes the concept of frequency translation by bandpass sampling.

V. RESULTS

Fig. 9 shows the results for the cascade of the bandpass and bandstop filters. Together the two filters effectively isolate the desired GNSS frequency bands (1164MHz to 1300MHz and 1559MHz to 1615.5MHz). The phase response shows that the cascade is stable at all frequencies since the gain never exceeds 0dB. The group delay, however, is quite high (around 30nsec) close to the cut-off frequencies and the effect of this group delay on later stages of GNSS signal processing is yet to be determined.

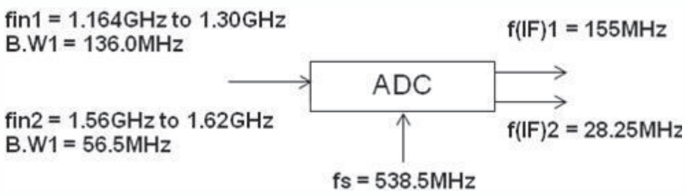


Fig.8 Most convenient sampling frequency and resultant intermediate frequencies.

Fig. 8 shows the most convenient values for the sampling frequency and the resulting IF for the two input bands of interest. The required sampling frequency is over 500MHz, which would be stretching the limits of state-of-art ADCs. The implementation of such an ADC is currently under research in the GNSS Receiver Research Group of Tampere University of Technology.

CONCLUSION

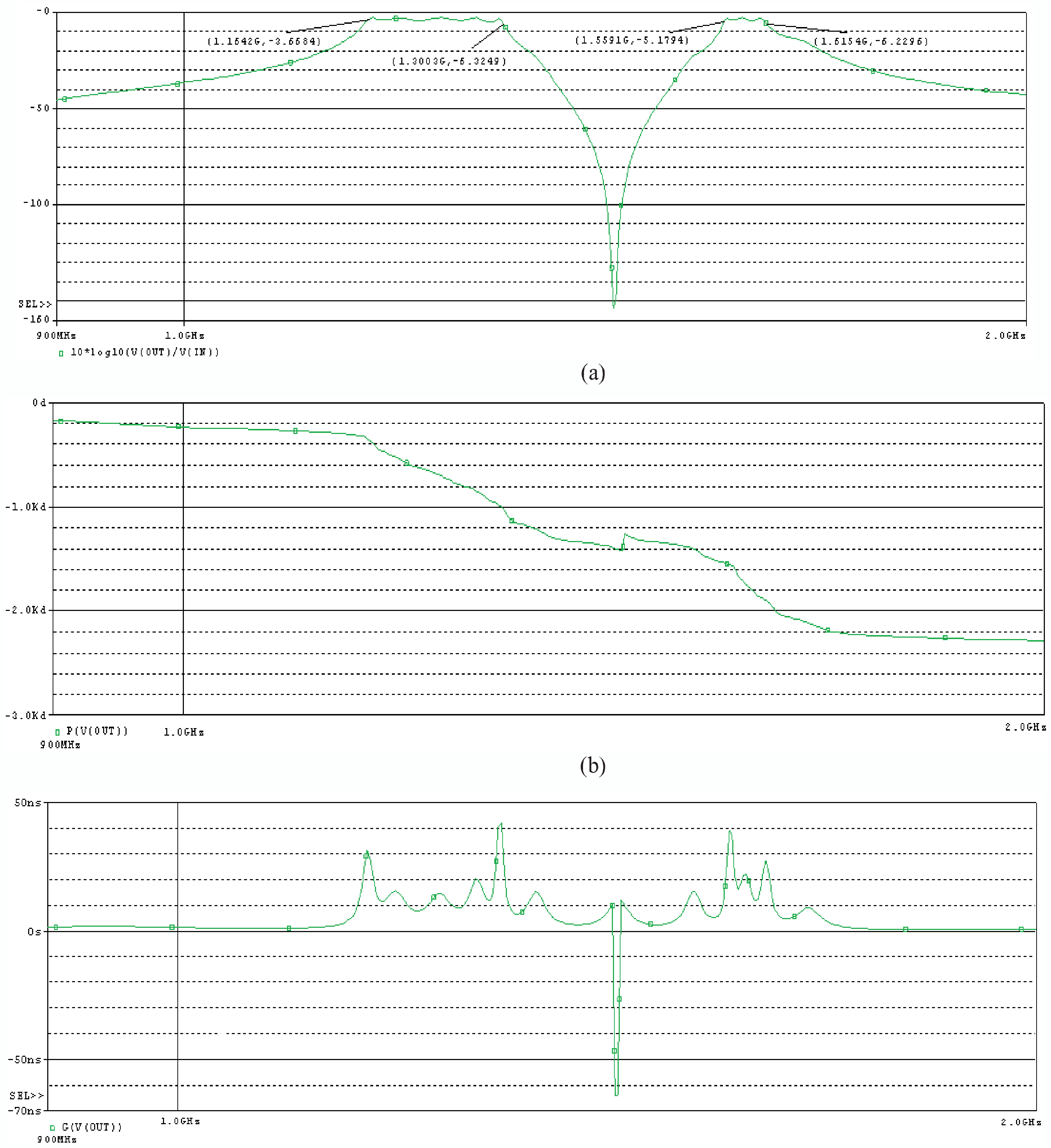
This paper presented an architectural design of a bandpass-sampling based sampled data generator for GNSS applications. After the successful implementation of the LNA, the next logical step was the design and simulation of the filter stage and frequency planning for the bandpass-sampling ADC. By incorporating the theoretical criteria for bandpass-sampling frequency into software, this process is automated for all possible input signal conditions. Both, real and complex sampling is considered. Due to obvious advantage in resource utilization of real bandpass-sampling, its complex equivalent is not considered further. For real sampling, the optimum sampling frequency was computed to be 538.5MHz and the resulting digital intermediate frequencies were 28.25MHz and 155MHz. In spite of the numerous advantages of the direct bandpass-sampling architecture, there are a number of challenges, such as SNR degradation due to Jitter, noise aliasing and quantization or high power consumption and subsequent heating of the ADC due to the extremely large sampling frequency requirement. The effect of these nonlinearities on the final digitized output has yet to be quantified and can be a subject of further research along with possible solutions to mitigate their effects, possibly by efficient digital signal processing of the digitized intermediate frequency signals.

REFERENCES

[1] R. G. Vaughan, N. L. Scott, & D. R. White, "The Theory of Bandpass Sampling", IEEE Transactions on Signal Processing. Vol. 39, No. 9. September 1991

[2] D. M. Akos, M. Stockmaster, J. B. Y. Tsui, & J. Caschera, "Direct Bandpass Sampling of Multiple Distinct RF Signals", IEEE Transactions on Communications, Vol. 47, No. 7, July 1999

[3] N. Wong & Tung-Sang Ng, "An Efficient Algorithm for Downconverting Multiple Bandpass Signals Using Bandpass Sampling", IEEE International Conference on Communications Proceedings, Helsinki, Finland, June 2001, v. 3, p. 910-914



(a)

(b)

(c)

Fig. 9 Bandpass – bandstop cascade filter results: (a) Amplitude response (b) Phase response (c) Group delay response

[4] Ching-Hsiang Tseng & Sun-Chung Chou, "Direct Downconversion of Multiband RF Signals Using Bandpass Sampling", IEEE Transactions on Wireless Communications, Vol. 5, No. 1, January 2006

[5] Jie-Cherng Liu, "Bandpass Sampling of Multiple Single Sideband RF Signals", ISCCSP 2008, Malta, 12-14 March 2008

[6] M. L. Psiaki, S. P. Powell, H. Jung, & P. M. Kintner, "Design and Practical Implementation of Multifrequency RF Front Ends Using Direct RF Sampling", IEEE Transactions on Microwave Theory and Techniques, Vol. 53, No. 10, October 2005

[7] S. Thombre, H. Hurskainen, J. Nurmi, "Wideband, High Gain, High Linearity, Low Noise Amplifier for GNSS Frequencies with

Compensation for Low Frequency Instability", Proceedings of the 5th Advanced Satellite Multimedia Systems (ASMS) Conference, September 2010 in Cagliari, Italy.

[8] GALILEO (2005). "Mission High Level Definition (HLD) (2002), European Commission Communication Document", W. Doc. 2002/05 - Version 3, 23. September 2002. Available at: http://www.galileoju.com, http://www.esa.int/esaNA/index.html.

[9] C. Shannon, "Communication in the Presence of Noise", Proceedings of the IRE, January 1949

[10] Yi-Ran Sun, "Generalized Bandpass Sampling Receivers for Software Defined Radio", Doctoral Dissertation, Royal Institute of Technology, Stockholm 2006

[11] M. L. Psiaki, D. M. Akos, J. Thor, "A Comparison of Direct RF Sampling and Down-Convert & Sampling GNSS Receiver Architectures", ION GPS/GNSS 2003, 9-12 September 2003, USA

[12] A. Latiri, L. Joet, P. Desgreys, P. Loumeau, "A Reconfigurable RF Sampling Receiver For Multistandard Applications", Académie Des Sciences, 2006