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Author/Contributor:
Tabatabaei Balaei, Asghar; Akos, Dennis; Dempster, Andrew

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Quantization Degradation of GNSS Signal Quality in the Presence of CW RFI

Asghar Tabatabaei Balaei, Dennis Akos, Andrew G. Dempster

i)

Abstract – In a Digital Matched Filter (DMF) the degradation of signal quality depends on the pre-sampling filter bandwidth and on the number of Analogue to Digital Converter (ADC) bits. Digital matched filters are used in the acquisition of Global Navigation Satellite Systems (GNSS) signals. Automatic Gain Control (AGC) in the GNSS receivers is used to determine the maximum level of quantization by the ADC. In [1], the quantization degradation for different pre sampling bandwidths and ADC bits is analysed in the presence of Additive Gaussian white noise (AGWN). Bandwidths of more than once (or twice) the data bit rate contribute only about 0.4dB (or (0.2dB) to the overall degradation of the DMF. Also 2 bit uniform step quantization with optimum ADC threshold setting is shown to recover most of the digital implementation degradation. In this paper by focusing on pre-sampling filter bandwidth equal to the data bit rate and 2 bit ADC, the effect of quantization on the received GNSS signal quality in the presence of Continuous Wave (CW) radio frequency interference (RFI) is analysed. It is shown that a one bit ADC can have much higher degradation than the 3.5 dB in the AGWN case. It is also shown that the effect of AGC on the quantization degradation has to do with both power and frequency of CW RFI. In the presence of CW RFI, the optimal value for ratio of maximum threshold of ADC to the effective noise RMS is shown to be about 1.35 which is higher than the case when RFI does not exist (0.8).

I. Introduction

GNSS signals are received at a power of nearly 20 dB below the power of the background noise. This makes the receiver vulnerable to radio frequency interference. Despite this extremely low received power, many commercial GNSS receivers use one bit quantization (hard limiting) [2]. This is because of two reasons: i)

i) Unlike some other modulation schemes, the information in the Code Division Multiple Access (CDMA) signal is not in the amplitude. This means that quantization loss is very low and a one bit ADC can contain a high proportion of information. In [1] it is shown that the signal quantization SNR degradation is about 3.5 dB. This degradation with a 2-bit ADC can come down to 1.5 dB.

ii) Using a one bit ADC removes the need of using AGC and this simplifies the hardware.

ii) However, apart from controlling the ADC quantization level, AGC has two other applications in the receivers [3]. It increases the dynamic range and suppresses the pulse interference. In the case of a one-bit ADC, a strong CW RFI can easily capture the receiver because the RFI saturates the front end and keeps the signal away from the zero point from being sampled. In the GNSS receiver, an AGC normally operates with the level of the environmental noise. This makes it the easiest and first component to detect interference as interference affects the level of unwanted signal [4]. In [5], considering the Probability Density Function (PDF) of CW interference, an adaptive approach for determining the level of ADC is introduced to reduce the effect of CW RFI. In that approach, a reduction of 0.6 dB in the degradation was achieved. In this paper, first we try to find out in a two-bit ADC quantization scenario, if the effect of AGC on the degradation depends on power and frequency of CW interference. Then we use the answer to this question (and the characterization of the effect) to make the AGC control the quantization level in a way that minimizes the amount of degradation in the presence of CW RFI. The analyses of this paper are all supported by experiments.

In section II, the problem is described. In section III, the effect of AGC in the presence of CW RFI is examined. In sections IV and V, the quantization errors for different RFI powers and frequencies are respectively analysed. Section VI concludes the paper.

II. Problem Description

AGC is used to normalize the front end output signal level despite variations in input signal power. A typical AGC device operates using a feedback loop whereby the power of the output of a variable gain device (amplifier or attenuator) is sampled and used to adjust the gain of the variable gain device itself. In this way, the output power is maintained at a relatively constant level (Figure 1). The response time of the AGC loop is an important design parameter and is dependent upon the application. Generally the AGC device is adjusted to react fast enough to normalize the overall power but slow enough to maintain the desired information content of the signal.

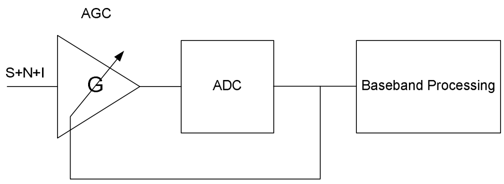

Figure 1 Block diagram of AGC and ADC inside the receiver

In GNSS receivers, the AGC controls the ADC quantization level. If L is considered as the highest threshold level of the ADC and σ is the standard deviation of the noise (RMS noise level), it is shown in [1] that $\frac{L}{\sigma}$ plays a significant role in the quantization degradation. Including the precorrelation filtering effect, this degradation can be as low as 1.2 dB. The loss caused with 1 bit quantization in Gaussian noise is 1.96 dB. However that number is only true for the infinite bandwidth/infinite sample rate case. In Figure 2 the signal power to noise power ratio for three different cases are shown. In this experiment, 3 second of GPS PRN1 (satellite number 1) signal which also includes noise is passed through the acquisition stage of the software receiver. The vertical axis in this figure shows the ratio of i) cross correlation between the received signal and the receiver replica of the signal and ii) the variance of the noise after the cross correlation (SNR). The horizontal axis is the ratio of the maximum threshold of the ADC to RMS noise level ($\frac{L}{\sigma}$).

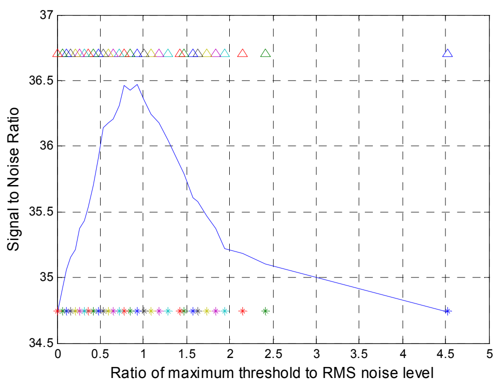

Figure 2 Quantization degradation for analogue (^), one-bit (*) and two bit (-) ADC for a particular signal and noise level

In this experiment, the ratio ($\frac{L}{\sigma}$) varies between 0.001 and 0.99. In the receiver, the percentage of samples having the highest level in the ADC is used to determine the gain of the AGC and Figure 3 shows the relationship between the ratio ($\frac{L}{\sigma}$) and this percentage.

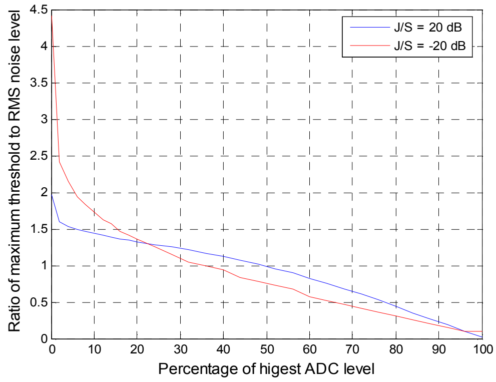

Figure 3 Relationship between $\frac{L}{\sigma}$ and percentage of highest AGC level

III. AGC in the Presence of CW Interference

To better understand how AGC reacts in the presence of CW RFI, the effect of the RFI Probability Density Function (PDF) on the PDF of the effective noise (noise and interference) is examined.

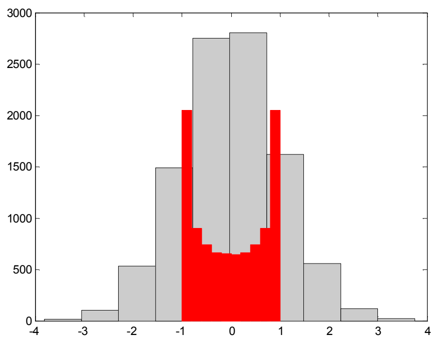

Figure 4 Histogram of Gaussian noise (grey) and CW RFI (red)

In [3] it is explained that the probability density of a CW signal amplitude is:

$$P(x) = \frac{1}{\pi\sqrt{1-x^2}}$$

Figure 4 shows the histogram of the analogue samples of CW interference and Gaussian noise separately and Figure 5 shows the histogram of the jamming plus noise when the power of jamming is four times the power of noise.

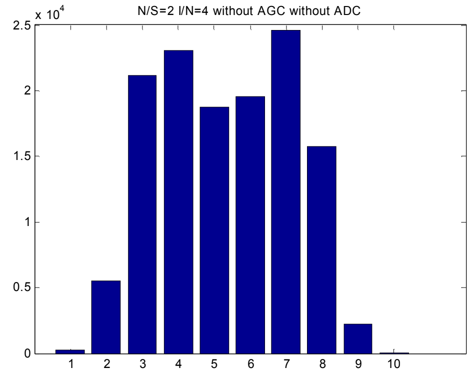

Figure 5 Histogram of noise plus CW interference interference power 4 times that of noise

When the above signal passes through the AGC with a ratio of maximum threshold to RMS noise level of one, then the histogram of the signal after passing through the ADC is shown in Figure 6.

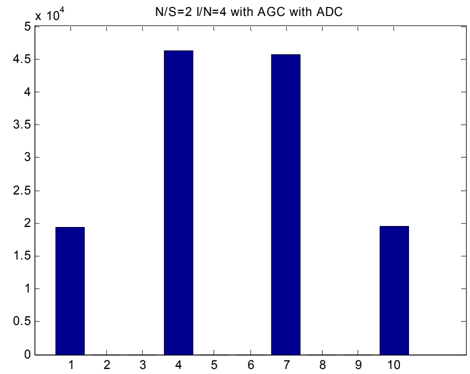

Figure 6 Histogram of noise plus CW RFI after the AGC and 2-bit ADC with 30% highest level sample rate

As was mentioned earlier, the AGC gain is determined on the basis of the percentage of the highest ADC level samples. The relationship between this percentage and "$\frac{L}{\sigma}$" is shown in Figure 3. The relationship between the variance of interference and variance of "interference plus noise" is shown in Figure 7. By using these two relationships, for a particular RFI power and particular "$\frac{L}{\sigma}$", it is possible to evaluate the "percentage of samples at the highest ADC level" to be used to determine the optimum AGC gain. In the next two sections, the aim is to analyse if the optimum "$\frac{L}{\sigma}$" for which we have minimum quantization degradation changes with power and frequency of the RFI and the nature of this change.

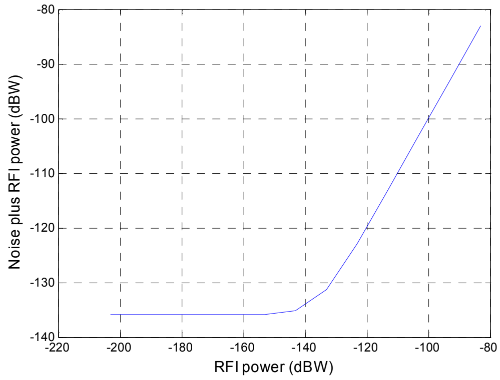

Figure 7 Variance of noise plus RFI w.r.t. RFI power

IV. Quantization Error for Different RFI Power

In this section, the aim is to answer the following question. Does the effect of AGC on the quantization degradation depend on power of CW interference? To answer this question the same experiment which was explained in section II is conducted for a number of different jamming to noise power ratios. The frequency of the RFI is chosen to be 500 Hz away from the Intermediate Frequency (IF) of the signal. Jamming to noise ratios of -30 to +20 dB were examined. Figure 8 shows the results.

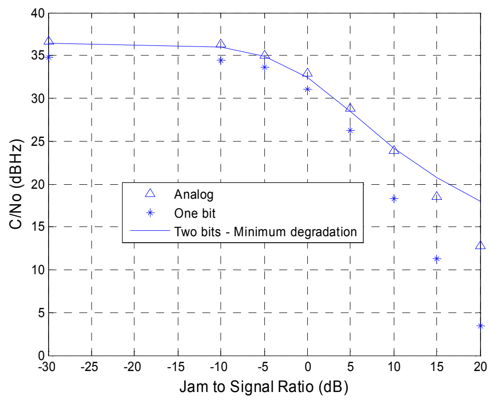

Figure 8 C/No for the three cases of analogue (i.e. no quantization), one bit and 2-bit ADC for different J/S

The fact that C/No decreases with the increase of jamming power is obvious [3]. However Figure 8 also shows that for higher power RFI, with a 2-bit ADC one can achieve higher C/No than for an unquantized signal. Further investigation must be pursued in order to explain this phenomenon. As a particular case, the C/No for J/N 20 dB and frequency 500 Hz away from the IF is shown in Figure 9 for different "$\frac{L}{\sigma}$".

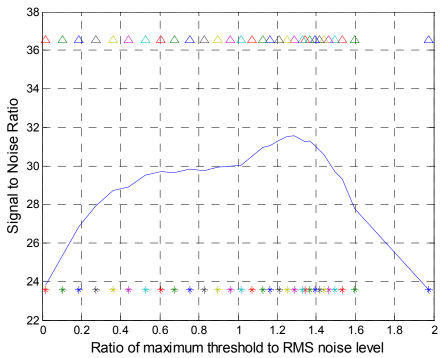

Figure 9 C/No for J/N 20 dB for different "$\frac{L}{\sigma}$" and three cases of analogue (^), one-bit (*) and 2 bit (-)

It is clear from this figure that the optimum "$\frac{L}{\sigma}$" (about 1.3) has moved compared to Figure 2 in which there is no RFI (about 1.0). The quantization degradation for the case of one-bit ADC for the Gaussian white noise is about 2 dB. Figure 9 shows that this degradation in the presence of CW RFI is much higher (12 dB).

V. Quantization Error for Different RFI Frequencies

In [6, 8], a closed formula is derived for the carrier to noise ratio after the correlation in GNSS receivers. It is shown in that paper that if the CW RFI frequency changes there are troughs in the C/No if the Doppler frequency of that satellite signal and also the RFI power are assumed to be constant. In this section of the paper the following question is to be answered. Does the effect of AGC on the quantization degradation depend on the frequency of CW interference? To answer this question, two experiments are conducted. In the first experiment, 20 minutes of GPS PRN1 signal with fixed Doppler frequency is added to noise and interference of which frequency changes by 3.5 kHz. In three different scenarios this signal is passed through the Kai Borre software receiver [7]. In the scenario where the analogue (simulated here by full Matlab floating point) signal is fed to the receiver, the C/No has its highest value. If the signal is digitized and no AGC is used obviously the C/No has the lowest value. The important point to notice in this experiment is the fact that the difference between C/No for the two cases of with and without AGC changes with RFI frequency as in Figure 10.

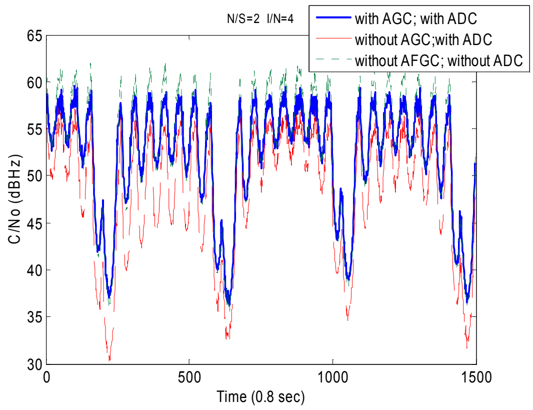

Figure 10 C/No of GPS PRN 1 for different scenarios

In another experiment, similar to the experiment of section II, the RFI frequency is chosen to be 1000 Hz away from the IF frequency with J/N 20 dB. The difference between this experiment and experiment of Figure 9 is in the RFI frequency. It clearly shows a much higher drop in the C/No for all the three cases of analogue, one-bit and two-bit ADC. The other thing which is noticeable in this figure is the fact that where $\frac{L}{\sigma}$ is about 1.35, the signal degradation is even lower than that of the analogue case (and thus the C/No is higher).

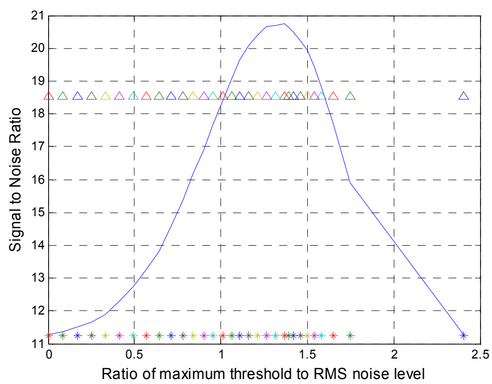

Figure 11 C/No for J/N + 20 dB for different "$\frac{L}{\sigma}$" and three cases of analogue (^), one-bit (*) and 2 bit (-)

Now that it is known that the effect of AGC on the quantization degradation does depend on frequency and power of CW interference, the next step is to characterize this effect. In Figure 12, the optimum "$\frac{L}{\sigma}$" for two different RFI frequencies, 500 and 1000 Hz away from the IF frequency (one in line and one far from the PRN code spectral line), and J/N levels of from -30 dB to +20 dB are shown. It is possible to say from this figure that jamming power starts to affect the AGC/ADC when it is 5-10 dB below the noise. For RFI power higher than the noise power (positive J/N), the optimum "$\frac{L}{\sigma}$" is higher than that of negative J/N and has some value between 1.1 and 1.4.

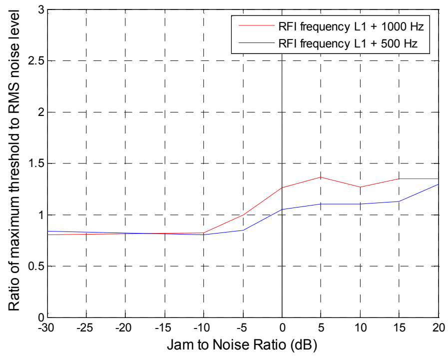

Figure 12 The optimum "$\frac{L}{\sigma}$" for different RFI power and frequency

VI. Summary and Future Work

It was shown in this paper that the quantization degradation of a CDMA signal increases significantly in the presence of CW interference. The quantization degradation for the case of one-bit ADC for the Gaussian white noise is about 2 dB. It was shown that this degradation in the presence of CW RFI is much higher (12 dB).

It was also shown that the ratio of maximum ADC threshold to RMS noise level, in which the quantization degradation is minimum, grows with jamming to signal ratio. This value when interference does not exist is 0.8. For a jamming to signal ratio of 20 dB, it is shown that this optimal ratio is 1.4. In the experiments it is possible to observe that with this specific ratio, the quantization for some RFI frequencies actually adds to the signal to noise ratio of the received signal compared to the case where there is no quantization. Further work must be done to explain this phenomenon.

References

[1] Chang, H., "Presampling filtering, sampling and quantization effects on the digital matched filter performance, *Proceedings of the international Telemetering Conference, (San Diego, CA),* 1982, pp. 889-915.

[2] Parkinson, B.W., Spilker J.J. (1996a) Global positioning system: Theory and Applications Volume I, *American Institute of Aeronautics and Astronautics, Inc.*

[3] Kaplan E. (2005) Understanding GPS: Principles and Applications, *Artech House.*

[4] Ward, P. (2007) What's going on? RFI situational awareness *inside GNSS* 2007

[5] Amoroso, F. (1983) Adaptive A/D Converter to Suppress CW Interference in DSPN Speard-Spectrum Communications. *IEEE Transaction on Communications*

[6] Tabatabaei Balaei, A., Dempster, G.A., Lo Presti, L., (2007a) Characterization of the effects of CW and pulse CW interference on the GPS signal quality *Accepted for publication in IEEE Transaction on Aerospace and Electronic systems* March

[7] Borre, K., Akos, D.M. Bertelsen, N. (2007) A Software-Defined GPS and Galileo Receiver. A Single-Frequency Approach.

[8] Tabatabaei Balaei, A., Motella, B., Dempster, G.A., (2007d) A Preventative Approach to Mitigating CW Interference in GPS Receivers *accepted for publication in GPS Solution* October