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ADC bit number and input power needed, in new radio-astronomical applications

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Abstract- For the most part, so far radio astronomy observations have been performed in protected frequency bands, reserved by ITU for scientific purposes. This means that, ideally, only the amplified equivalent system noise is present at the end of the receiver chain (i.e. the ADC input). So, typically, only a few bits are necessary to describe the signal (VLBI signals are digitised with only 2 bits), but today astronomers, in order to get more sensitivity and to boldly observe where no one has observed before, would like to study the radio sky even outside the protected bands. In these cases, a lot of man-made signals, coming both from terrestrial and space radio communication systems, are added to the very weak sky noise. For the first time, radio telescope designers must take in account the problem of the A/D converter dynamic range, since the increase of the total received power could lead the A/D to saturation. Here, a procedure to estimate the required number of bit (resolution and dynamic) and the input power level of an A/D converter, is described and applied to a new radio astronomical system which is under development at the Medicina radio observatory: the BEST project [1].

I. Introduction

At the Medicina observatory the upgrade of the Northern Cross antenna (figure 1) is in progress. The previous version of the Northern Cross receivers worked in a protected 3.9 MHz bandwidth around 408 MHz but, in the new version, the receivers must work in a bandwidth up to 16 MHz. In these conditions, the radio-telescope receives the man-made signals placed in the border of the 16 MHz bandwidth. It is necessary to know the dynamic range of the input signal and its power level in order to design the receiver chain (gain, number of bits, etc.).

II. ADC: bit number and input power evaluation

To evaluate the number of bits needed in an ADC system, the dynamic range of the input signal has to be analyzed. Theoretically a radio telescope should receive only the very weak sky noise, which can be described using only 2 or 3 bits. But, due to the presence of stronger man-made RF signals (only if they fall in a protected frequency band we can call them RFI-Radio Frequency Interference), the raise of the received power has to be taken into account to avoid the saturation of the A/D converter.

Figure 1. The Northern Cross antenna

Figure 2. The 22 mt Medicina RFI monitoring tower

A measurement campaign has to be performed to evaluate the maximum dynamic range of the ADC input signal. This campaign is based on RF measurements with a reference antenna system located on top of a 22 mt Medicina RFI monitoring tower (figure 2). Obviously these are not equal to the antennas of the radio-telescope, but this is the only possible way to estimate the signal power level around the Medicina observatory. In particular, to obtain a worst case estimation of the radio frequency band, a spectrum analyser in max-hold configuration has been connected to 2 Yagi antennas, one for the vertical polarization and one for the horizontal one, while they were rotating continuously to scan all the azimuth directions at an height of 22 mt. A 20 MHz bandwidth around 408 MHz was scanned, obtaining the result shown in figure 3. To consider the overall power contribution of the full bandwidth, all the values detected, in each 30 KHz bandwidth, have been linearly added. The final result (after subtracting the antenna gain, cable loss, amplifier contributions) was:

$$P_{0dBi} = -69.4 \ \ dBm \qquad (1)$$

where the subscript 0dBi indicates that the power level is referred to an isotropic antenna with unitary gain in all directions.
This could be considered a good estimation of the maximum, worst-case[1], RF power that can be received by each BEST-1 and BEST-2 receiver since a mean value of the side lobes, where the RFI are typically received by the antennas, are near 0dBi. The sky contribution should be considered too, but it is negligible in comparison to man-made RF signals.

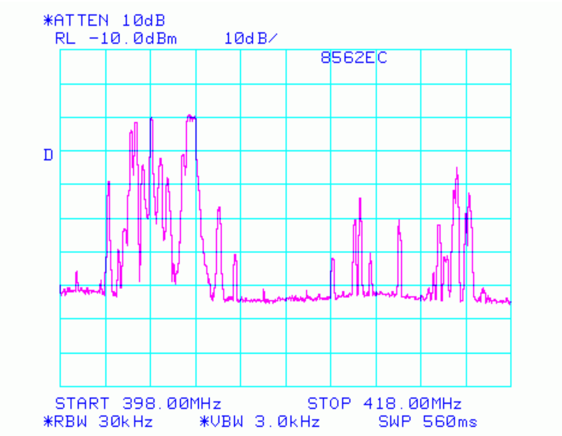

Figure 3. Radio spectrum obtained from the RFI monitoring tower.

To evaluate the ADC dynamic range, the minimum input power has to be calculated: this is the cold sky temperature (i.e. the temperature of an area of the sky far from the galactic plane where there are no radio sources) plus the equivalent system noise referred to the antenna terminals. The theoretical antenna noise temperature T_A for BEST-1, when the antenna is pointed to the zenith, is [2]:

$$\mathrm{T_A} = 35K \,@\, 408\, MHz \qquad (2)$$

Considering [2] and [3], T_{SYS} is:

$$T_{\mathrm{SYS}} = 86.2K \qquad (3)$$

Therefore, the equivalent system input noise power P_{SYS} for a B = 16 MHz bandwidth (as in the BEST project) is:

$$P_{sys} = 10\log_{10}\left(\frac{kT_{sys}B}{1\cdot 10^{-3}}\right) = -107.2\ dBm \qquad (4)$$

[1] The N/S focal lines are at an height of about 5 *mt* above ground, so they have a shorter radio horizon than the RFI monitoring system. In the BEST-3 system, some receivers will be placed on the E/W focal line, at about 30 *mt* above ground, higher than the antennas of the RFI monitoring tower. So the situation could be worse (i.e. P_{0dBi} could be higher than -69.4*dBm*).

where k is the Boltzmann constant. The maximum dynamic range, P_d, results:

$$P_d = P_{0dBi} - P_{sys} = -69.4 - (-107.2) = 37.8 \ \ dB \tag{5}$$

In order to evaluate the number of bits needed to describe this power dynamic, since an ADC converts voltage into bits and not power into bits, we need a relationship between the power and the voltage at the input of the AD converter. If we consider the simplest possible situation, where there is only a monochromatic tone at the input of the ADC, we can easily find the relationship (considering a 50 Ω matched system):

$$P = 30 + 10\log_{10}\left[\frac{V_P^2}{2R}\right] = 30 + 20\log_{10}\left[\frac{V_P}{100}\right] \tag{6}$$

where V_P is the voltage peak value, expressed in Volt, and the power P is expressed in dBm. From this equation we obtain also that if the voltage is doubled ($2V_P$), there is a 6dB of power increase ($20 \cdot \log_{10}2=6$). So, each bit corresponds to an increment of the input signal of, respectively, 3dB in voltage and 6dB in power. If we divide the dynamic range P_d by 6, we can obtain the required ADC number of bits to sustain such dynamic. But the previous relationships are rigorous only in that simple situation: if we look at figure 3, we can see that a real RF scenario can be very different from a single CW tone. In that situation a simple closed form to express the relationship between the input power and the input voltage (and so the number of bits) does not exist. And even if it is still true that each more significant bit corresponds to a doubling of the instantaneous input voltage, not necessarily each bit corresponds to a 6dB of input power increase. We can say: the more RF scenario is dominated by a single strong signal, the more accurate the previous relationships are. That said, for a first attempt we consider the relationships valid also for the BEST system RF scenario, so:

$$N_d = \frac{P_d}{6} = 6.3\,bit \tag{7}$$

The integer value greater than N_d is 7. Considering 3 bits to describe the radio astronomical signal, the final number of bits is:

$$N_{bit} = \lceil N_d \rceil + 3 = 7 + 3 = 10\ bit \tag{8}$$

In our case the chosen ADC is the AD6645 from Analog Devices, which presents 14 bits and a peak-to-peak input voltage $V_{PP\text{-}IN}$ = 2.2V. From the datasheet, the effective number of bits (ENOB) is 12 at 100 MSPS (sampling frequency in the BEST project[2]), so the device sensibility (minimum detectable input signal voltage variation) $V_{PP\text{-}LSB}$ results:

$$V_{PP-LSB} = \frac{V_{PP-IN}}{2^{12}} = \frac{2.2}{2^{12}} = 537\mu V \tag{9}$$

Considering 3 bits to describe the radio astronomical signal (8 quantization levels), the peak-to-peak voltage excursion $V_{PP\text{-}N}$ (N=noise) is:

$$V_{PP-N} = 2^3 \cdot V_{PP-LSB} = 8 \cdot 537 \cdot 10^{-6} = 4.3\,mV \tag{10}$$

The effective voltage (V_{RMS}), computed in a radio astronomical band, is [4]:

$$V_{RMS} = \frac{V_{PP-N}/2}{\sqrt{20}} = \frac{4.3 \cdot 10^{-3}/2}{\sqrt{20}} = 0.48mV \tag{11}$$

Considering the ADC driven by a 50 Ω input impedance buffer, the ADC input power level P_{IN} needed is:

[2] The Northern Cross antenna works at 408 MHz, but the signal is down converted to 30 MHz before the ADC. Therefore, in the IF stage (intermediate frequency), the bandwidth is 16 MHz centred at 30 MHz (from 22 to 38 MHz) and we can sampling at 100 MSPS.

$$P_{IN} = 30 + 10 \cdot \log\left(\frac{V_{RMS}^2}{|Z_{input}|}\right) = 30 + 10 \cdot \log\left(\frac{(0.48 \cdot 10^{-3})^2}{50}\right) = -53\ dBm \qquad (12)$$

This power value is important to calculate the total gain of the receiver chain.

III. Measure of the effective number of bit and Input Power

The measurement bank was composed of a spectrum analyser, a power meter and a logic analyser program; in order to acquire the same signal coming from the antenna, it was split in 3 ways. The A/D converter is the AD6645 evaluation board from Analog Devices. We made a Labview program (working in a PC) in order to synchronize all the instruments and to acquire the data. The logic analyser ran in another PC, where we also installed a configuration software for the ADC evaluation board. Through the spectrum analyser we monitored the sky FFT scenario and the spectrum power. This last datum was compared with the output of the power meter in order to check it. Through the logic analyser we monitored the bits variations. A picture of the measurement bank is shown in figure 4. This measurement phase lasted for a few weeks to achieve data observing in all directions.

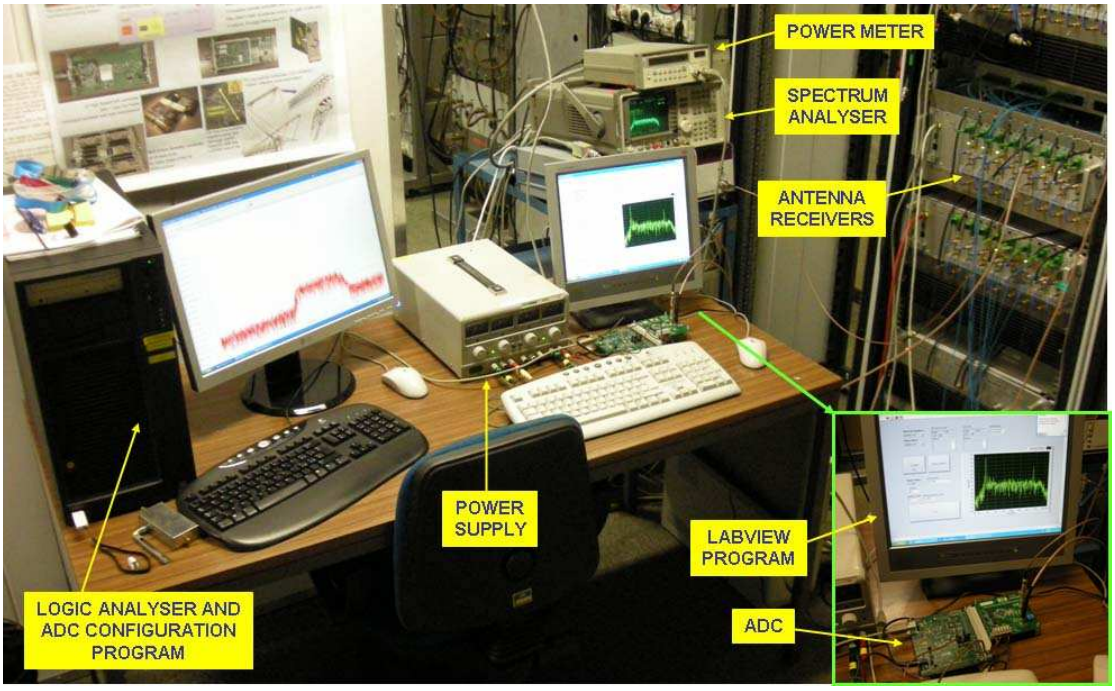

Figure 4. The measurement bank.

Using a 14 bit ADC (sampling rate = 100 MSPS) the number of bits describing the noise system was evaluated disconnecting the antenna from the receiver chain: 3 bits of variation were noted (8 counts). Of course, the minimum ADC input power of the radio-astronomical signal must exceed the noise system. In order to calibrate the measure bank, we connected a very narrow band filter (1.7 MHz) at the end of the analogue receiver chain. In this case, we had no man-made signal inside the band (protected band) and we observed 11 counts (3.46 bits): this is our noise floor. Since the Northern Cross radio-telescope bandwidth is 16 MHz, we calculated the power increase (ΔP) due to the band widening from 1.7 MHz ($B_{1.7}$) to 16 MHz (B_{16}):

$$\Delta P = 10\log_{10}(kTB_{16}) - 10\log_{10}(kTB_{1.7}) = 10\log\frac{B_{16}}{B_{1.7}} = 10\log\frac{16}{1.7} = 9.74\,dB \qquad (13)$$

We also have to consider that the 1.7 MHz filter has an attenuation of 5.57 dB, therefore, when we dismount the filter, we will have an increase of the power due to the elimination of the filter attenuation. In order to calibrate the system, we adjusted the step attenuators (placed on the analogue receiver board) in order to compensate the filter loss. Considering (7) we can say that ΔP=9.74 dB corresponds to 1.62 bits. Adding that value to the bits of the noise floor (3.46 bits), we have 5.08 bits of variation, equivalent to -42.9dBm: that it is the power of 16MHz bandwidth without interferences. After this calibration phase, we were ready to measure the number of bits variation due to the interferences. Inside the 16 MHz bandwidth we observed a lot of man-made signals, especially radio relay stations (figure 5).

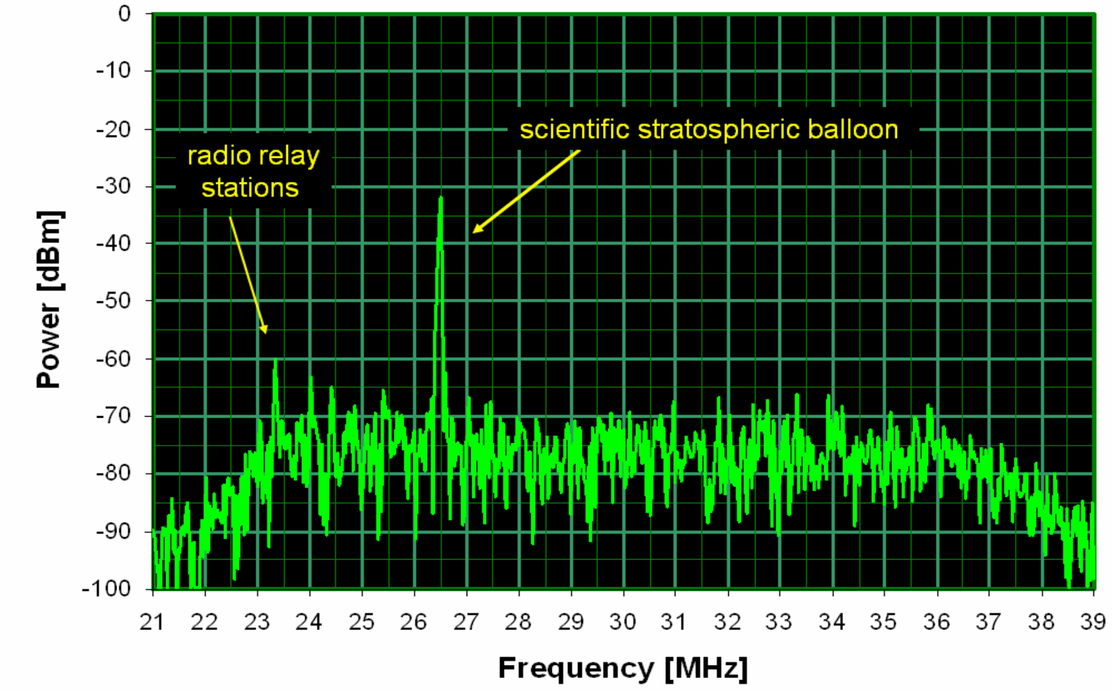

Figure 5. Power spectrum at the ADC input.

Sometimes, near the Medicina radio-telescope, a scientific stratospheric balloon is launched. The interference contribution coming from the balloon is variable and depends on its position, due to the wind direction. So, it is not easy to understand its effective interference power. During a measurement, the interference contribution from the scientific stratospheric balloon was very high: it has to be considered as a very strong source. Using a logic analyser, the maximum value of the measured counts was 259 (8.02 bits) equivalent to -25.2dBm. Since we started with 5.08 bits, the maximum bits variation (due only to the interference contribution) is 3 bits (8.02-5.08=2.94 bits). The power value measured with the spectrum analyser was -27.58dBm. If we apply (7) we obtain a contribution of 2.55 bits of variation, very near to the value of the number of bits measured with the logic analyser. We can say that the previously relationships is a good method to value the ADC resolution when there is a strong source higher than any other man-made signal.

III. Conclusions

A complete new receiver chain was built and installed on the Northern Cross radio-telescope. For the first time the system bandwidth has been intentionally broadened besides the limit of the reserved band, in order to test new techniques and algorithms to reject unwanted RF signals in radio astronomical applications. A receiver design procedure to estimate the requested dynamic range to the A/D converter and its needed input power has been studied, applied and finally compared with the actual receiver chain. In the adopted procedure (8) above described, 7 bits due to the interferences have been estimated, so a 10 bit A/D converter seemed necessary, considering 3 bits for the radio astronomical signal. From the measures we performed on the actual receiver chain, only 3 bits seem to be necessary to sustain the man-made radio signals in the BEST bandwidth, so the total number of bits required is 6. Following these considerations, an 8 bit A/D converter could work properly, so we decided to try also a different acquisition system with fewer bits.
We attribute the difference between the estimated bit number and the measured one to the different antenna systems: Yagi antennas pointed towards the horizon and working in the max-hold mode versus a half wavelength dipole focal line inside a North-South cylindrical reflector pointed towards the sky.

We have concluded that our estimation procedure was conservative, but applicable to radio astronomical observations. Further investigations should be performed to reduce the difference between the estimated and the actual requested number of bits. However we noted that when the spectrum analyser in connected directly to the radio telescope (and not to a separate monitoring tower) the procedure to value the requested ADC number of bits seem to be a good estimation.

References

[1] S. Montebugnoli, G. Bianchi, C. Bortolotti, A. Cattani, A. Cremonini, A. Maccaferri, F. Perini, M. Roma, J. Roda, P. Zacchiroli, "Italian SKA test bed based on cylindrical antennas", *Astronomische Nachrichten*, Volume 327, Issue 5-6 (p 624-625), May 11th 2006.

[2] P. Bolli, F. Perini, S. Montebugnoli, G. Pelosi, "Description of a rigorous procedure to evaluate the antenna temperature and its application to BEST-1", *IRA Technical Report N° 377/05*, December 15th 2005, http://www.ira.inaf.it/ska/Documenti/IRA%20Documents/TechRep_IRA_%20377_05.pdf

[3] Parbhu D. Patel, "Antenna Concepts Consideration for SKA", *Draft*, September 2005.

[4] L. Calandrino, M. Chiani, *Lezioni di comunicazioni elettriche,* Pitagora Editrice, Bologna, 2006.