To Preamplify or Not

Whitham D. Reeve and Christian Monstein

1. Introduction

A question frequently arises concerning the application of a low noise preamplifier to the Callisto instrument used in the e-CALLISTO solar radio spectrometer network. The e-CALLISTO network has been previous described [Monstein1, 2, 3]. RF preamplifiers go by various names such as low noise amplifier and tower-mounted amplifier (TMA). This article discusses the steps required to determine the solar radio flux levels that may be detected with and without a low noise preamplifier connected to the CALLISTO receiver.

2. Antenna

The same antenna is assumed for both configurations. It is necessary to know the antenna aperture or effective area, $A_{Effective}$. The effective area is proportional to antenna gain and is calculated from

$$A_{Effective} = \frac{\lambda^2}{4 \cdot \pi} \cdot G \text{ m}^2 \qquad (1)$$

where λ is the wavelength in m and G is the antenna gain as a linear ratio. For our calculations we will use a log periodic dipole array antenna with a modest gain of 6 dBi. To convert antenna gain in logarithmic units of dB to a linear ratio, use

$$G = 10^{\frac{G(dB)}{10}} = 10^{\frac{6}{10}} = 4 \qquad (2)$$

Assume the measurements are at 245 MHz, which corresponds to a wavelength of

$$\lambda = \frac{c}{f} = \frac{3 \cdot 10^8}{245 \cdot 10^6} = 1.22 \text{ m} \qquad (3)$$

where c is the speed of light in m/s and f is frequency in Hz. Therefore, the antenna effective area is

$$A_{Effective} = \frac{\lambda^2}{4 \cdot \pi} \cdot G = \frac{1.22^2}{4 \cdot \pi} \cdot 4 = 0.48 \text{ m}^2$$

3. No preamplifier

The antenna in this configuration is connected directly to the receiver RF input through a coaxial cable assumed to have negligible loss (figure 1).

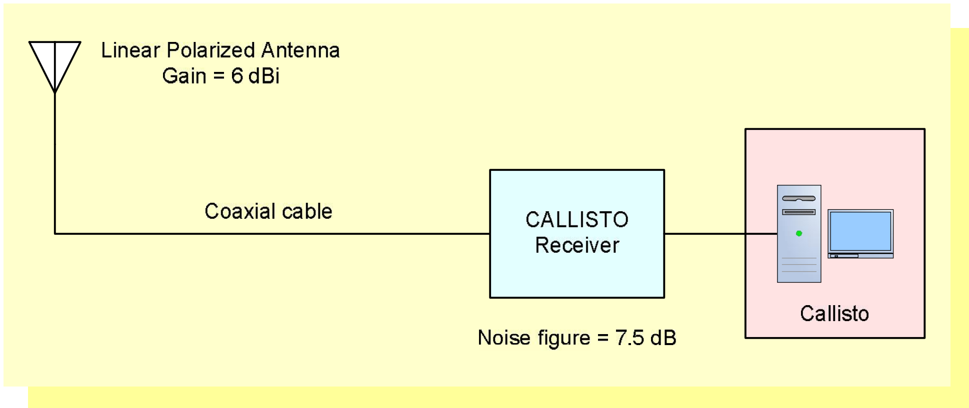

Figure 1 ~ System block diagram for the configuration with no preamplifier. The coaxial cable feedline from the antenna to the receiver is assumed to be short and its effects are not included in the calculations.

First calculate the system noise temperature, T_{Sys}. The system noise temperature is the sum of the sky temperature and the receiver noise temperature in kelvins (K), or

$$T_{Sys} = T_{Sky} + T_{Rx} \tag{4}$$

T_{sky} is estimated to be 300 K at VHF [ITU-R P372.8]. The receiver noise temperature, T_{Rx}, is

$$T_{Rx} = T_0 \cdot \left(10^{\frac{NF}{10}} - 1 \right) \tag{5}$$

where T_0 = 290 K, the reference temperature, and NF is the receiver noise figure in dB. From the block diagram, the receiver noise figure is 7.5 dB. Therefore,

$$T_{Rx} = T_0 \cdot \left(10^{\frac{NF}{10}} - 1 \right) = 290 \cdot \left(10^{\frac{7.5}{10}} - 1 \right) = 1341 \text{ K}$$

and

$$T_{Sys} = T_{Sky} + T_{Rx} = 300 + 1341 = 1641 \text{ K}$$

The power flux density (or, simply, power density) due to system noise temperature is

$$PFD_{Sys} = k \cdot T_{Sys} \tag{6}$$

where k is the Boltzmann constant, $1.38 \cdot 10^{-23}$ W/Hz/K. Based on the system noise temperature determined above, the power flux density at the system noise floor is

$$PFD_{Sys} = k \cdot T_{Sys} = 1.38 \cdot 10^{-23} \cdot 1641 = 2.3 \cdot 10^{-20} \text{ W/Hz}$$

We can express the system noise power flux density in dBm/Hz, as in

$$PFD_{Sys}(dBm/Hz) = 10 \cdot \log\left(\frac{PFD_{sys}}{PFD_{Ref}}\right) = 10 \cdot \log\left(\frac{2.3 \cdot 10^{-20}}{1 \cdot 10^{-3}}\right) = -166.5 \text{ dBm/Hz} \quad (7)$$

The factor $1 \cdot 10^{-3}$ takes into account the 1 mW reference (1000 mW = 1 W). We could have used a 1 W reference, in which case equation (7) becomes

$$PFD_{Sys}(dBW/Hz) = 10 \cdot \log\left(\frac{PFD_{sys}}{PFD_{Ref}}\right) = 10 \cdot \log\left(\frac{2.3 \cdot 10^{-20}}{1}\right) = -196.5 \text{ dBW/Hz} \quad (8)$$

Assume that a solar radio burst can be reliably detected if it is at least 10 dB above the system noise floor. For this situation, the required solar burst power flux density is –196.5 dBW/Hz + 10 dB = –186.5 dBW/Hz. Now, it remains to calculate the solar radio flux that equals this value. For this we convert PFD_{Burst} to linear terms, or

$$PFD_{Burst} = \left(10^{\frac{-186.5}{10}}\right) = 2.2 \cdot 10^{-19} \text{ W/Hz}$$

Next, we calculate the spectral power flux density, S, of the solar radio burst. The spectral flux density is proportional to the power flux density and inversely proportional to antenna effective area, or

$$S = 2 \cdot \frac{PFD_{Burst}}{A_{Effective}} \text{ W/m}^2\text{/Hz} \quad (9)$$

The factor 2 takes into account that a linear polarized antenna receives only 1/2 of the total flux. Using our previous calculations in the equation (9), we obtain

$$S = 2 \cdot \frac{PFD_{Burst}}{A_{Effective}} = 2 \cdot \frac{2.2 \cdot 10^{-19}}{0.48} = 9.3 \cdot 10^{-19} \text{ W/m}^2\text{/Hz}$$

By definition, 1 solar flux unit = 10^{-22} W/m^2/Hz. Therefore, the required spectral flux density in sfu is

$$S = \frac{9.3 \cdot 10^{-19}}{1 \cdot 10^{-22}} = 9328 \text{ sfu} \quad (10)$$

Solar radio bursts this strong are quite rare [Maxwell]. If we could reliably detect radio bursts only 3 dB above system noise, the required flux would be around 2000 sfu. The quiet Sun solar flux at 245 MHz is around 30 to 50 sfu (this varies with the sunspot cycle and measurement location), far below our detection threshold.

4. Low noise tower-mounted amplifier

The antenna in this configuration is connected through a short coaxial cable to the tower-mounted amplifier and the amplifier is connected to the receiver through another coaxial cable (figure 2).

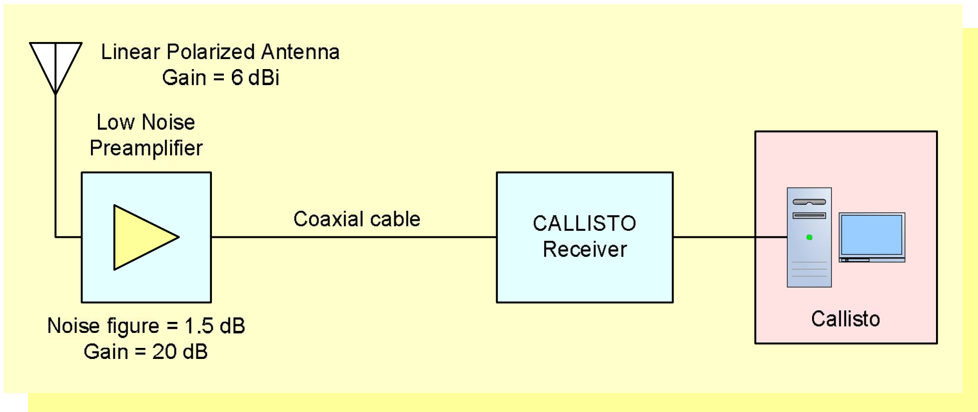

Figure 2 ~ System block diagram for the configuration with a preamplifier. The coaxial cable feedlines from the antenna to the TMA and from TMA to receiver are assumed to be short and their effects are not included in the calculations.

Our analysis follows the same steps previously given. The TMA power gain is 20 dB and is high enough so that the TMA noise figure of 1.5 dB largely determines the system noise figure. Actually, with 20 dB TMA gain the system noise figure is 1.64 dB (figure 3). In the analysis below, we will round this to 1.6 dB.

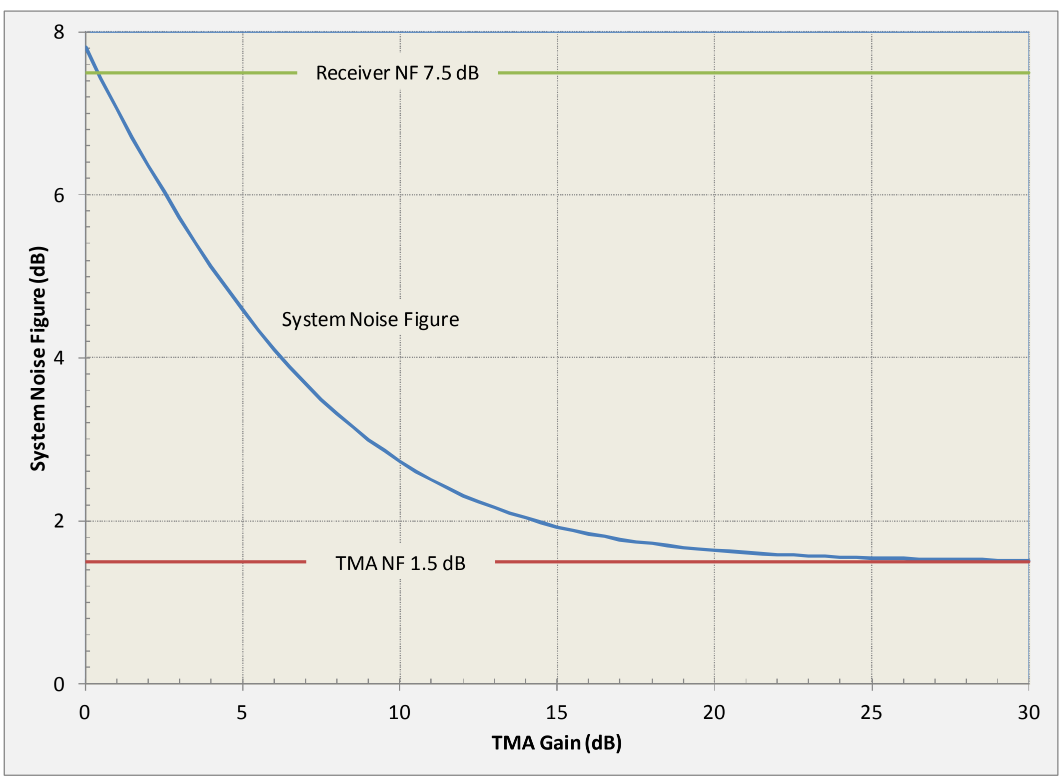

Figure 3 ~ Plot of system noise figure for various TMA gain values. The upper and lower horizontal lines show the receiver and TMA noise figures. As the TMA gain increases it evntually dominates the system noise figure (downward sloping trace).

For the preamplifier configuration, the system noise temperature is the sum of the sky noise temperature and the TMA noise temperature in kelvins (K), or

$$T_{Sys} = T_{Sky} + T_{TMA} \tag{11}$$

The TMA noise temperature, T_{TMA}, is

$$T_{TMA} = T_0 \cdot \left(10^{\frac{NF}{10}} - 1 \right) = 290 \cdot \left(10^{\frac{1.6}{10}} - 1 \right) = 129 \text{ K} \tag{12}$$

and

$$T_{Sys} = T_{Sky} + T_{TMA} = 300 + 129 = 429 \text{ K}$$

Based on the system noise temperature, the power flux density at the system noise floor is

$$PFD_{Sys} = k \cdot T_{Sys} = 1.38 \cdot 10^{-23} \cdot 429 = 5.9 \cdot 10^{-21} \text{ W/Hz} \tag{13}$$

The system noise power flux density in dBm/Hz is

$$PFD_{Sys}(dBm / Hz) = 10 \cdot \log\left(\frac{PFD_{sys}}{PFD_{\mathrm{Re}f}} \right) = 10 \cdot \log\left(\frac{5.9 \cdot 10^{-21}}{1 \cdot 10^{-3}} \right) = -172.3 \text{ dBm/Hz} \tag{14}$$

If we use a 1 W reference, the power flux density is

$$PFD_{Sys}(dBW / Hz) = 10 \cdot \log\left(\frac{PFD_{sys}}{PFD_{\mathrm{Re}f}} \right) = 10 \cdot \log\left(\frac{5.9 \cdot 10^{-21}}{1} \right) = -202.3 \text{ dBW/Hz} \tag{15}$$

For a 10 dB detection threshold, the required solar burst power flux density is –202.3 dBW/Hz + 10 dB = –192.3 dBW/Hz. In linear terms

$$PFD_{Burst} = \left(10^{\frac{-192.3}{10}} \right) = 5.9 \cdot 10^{-20} \text{ W/Hz}$$

The required spectral power flux density of the solar radio burst is

$$S = 2 \cdot \frac{PFD_{Burst}}{A_{Effective}} = 2 \cdot \frac{5.9 \cdot 10^{-20}}{0.48} = 2.5 \cdot 10^{-19} \text{ W/m}^2\text{/Hz}$$

Converting this to solar flux units gives

$$S = \frac{2.5 \cdot 10^{-19}}{1 \cdot 10^{-22}} = 2500 \text{ sfu}$$

The tower-mounted amplifier improves our solar radio burst detection by a factor of about 4.

5. Coaxial cable losses

The calculations given above assume negligible coaxial feedline losses. For calculations associated with real systems, we would need to take these into account. Where a tower-mounted amplifier is used, it should be located as close to the antenna as possible to minimize the cable length from the antenna. The feedline between the antenna and TMA degrades system noise figure in proportion to its loss. For example, 1 dB of cable loss from the antenna to the TMA increases the system noise figure by 1 dB. The combination of 1 dB additional noise figure with a 1dB loss noticeably degrades the total sensitivity of the radio telescope. In the TMA configuration above, the system noise figure would be 2.5 dB instead of 1.5 dB. The cable from the TMA to the receiver has little effect on the system noise figure if the TMA gain is sufficiently high, but its loss should be minimized to the extent possible so that it does not compromise system gain.

6. Conclusions

Without a low noise preamplifier the smallest solar radio burst that may be detected is a little more than 9400 sfu. With a preamplifier, this falls to about 2500 sfu. Experience has shown that the Callisto is capable of detecting less powerful bursts. It could be that our assumptions on detection threshold and antenna gains are too restrictive.

In professional radio observatories, the low noise amplifiers generally are cooled to lower their noise figures. However, in the VHF range there is no need to cool down the preamplifier to get lower noise figure because the sky noise is always higher. For receivers that operate above 1 GHz, where the sky noise is only a few kelvins, it makes sense to cool down the preamplifier. For solar burst observations within the Callisto receiver band (45 MHz - 870 MHz), a low noise preamplifier is a must; otherwise the science output will be very low.

7. References and further reading

[ITU-R P372.8] RECOMMENDATION ITU-R P.372-8, Radio noise, International Telecommunication Union – Radiocommunication Sector, 2003

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