HYPERION Memo #2: Calculation of the System Gain Needed at the SNAP ADC Input

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1 Introduction

The following is a detailed calculation of the gain needed to reach a power level of -5.5 dBm at the SNAP (Ver. 2.1.1) ADC input for four frequencies within the science band (50 to 120 MHz). This is necessary in order to obtain ADC rms counts of 12.5 with a Gaussian noise input and a digital gain of 2. This optimal rms value translates to toggling somewhere between 4 and 5 bits on the 8-bit ADC. With a value roughly in between the max and min of toggled bits, we can account for small values that would otherwise not toggle any bits due to quantization and large values (e.g. from RFI) that would saturate the ADC range or be clipped. Since the observing system will be subjected to signals at both ends of this range, this midpoint is advantageous. See memo by Eddie J. Toral (*Reference Data for Nominal SNAP Input Levels* at `https://casper.berkeley.edu/astrobaki/images/4/47/Reference_Data_for_Nominal_SNAP_Input_Levels.pdf`) for tested input power values and their ADC rms counts. See also Donald Backer's 2007 memo, *EoR Experiment - Memo: Quantization with Four Bits*, located at `http://w.astro.berkeley.edu/~dbacker/eor/p011.quant.pdf` for information on the *van Vleck correction* for quantization.

2 Getting the Brightness Temperature and Sky Power

In order to calculate the necessary gain, we must determine the level of the sky power coupled to the antenna at the chosen frequencies. We utilize equation 2 for the brightness temperature at a given frequency from Kara Kundert's memo, *The Relationship Between System Temperature and Sky Beam Coverage* (located at `https://casper.berkeley.edu/astrobaki/images/e/e0/`):

$$T_B(\nu) = T_B(\nu_{150})\left(\frac{\nu}{\nu_{150}}\right)^{-\beta}, \tag{1}$$

where $T_B(\nu_{150}) = 237$ K, $\nu_{150} = 150$ MHz, and $\beta = 2.5$ as defined in the memo. From this, we obtain, for the various frequencies (in MHz):

- $T_B(\nu_{50}) = 3694\text{K}$
- $T_B(\nu_{75}) = 1341\text{K}$
- $T_B(\nu_{100}) = 653.1\text{K}$
- $T_B(\nu_{120}) = 414.0\text{K}$

The brightness temperature is defined as the temperature of a blackbody with an observed specific intensity given by the Rayleigh-Jeans tail (i.e. the low frequency limit) of a blackbody spectrum:

$$I_\nu \approx \frac{2kT_B}{\lambda^2}, \tag{2}$$

where k is Boltzmann's constant and the specific intensity is defined as

$$I_\nu \equiv \frac{dE}{d\nu dA d\Omega dt}, \tag{3}$$

where dE is the energy collected over a bandwidth $d\nu$ with an aperture area dA, solid angle on the sky $d\Omega$, and an exposure time dt.

Equating Equations 2 and 3 and recognizing that dE/dt is the power, P, we can solve for power:

$$P = I_\nu d\nu dA d\Omega \approx \left(\frac{2kT_B}{\lambda^2}\right) d\nu dA d\Omega\ . \tag{4}$$

From electromagnetic theory, we know that

$$d\Omega = \frac{\lambda^2}{dA} \ . \tag{5}$$

This results in the power being independent of aperture area and wavelength, yielding

$$P_\nu \approx 2kT_B(\nu)d\nu \ . \tag{6}$$

Using our bandwidth, $d\nu = 70$ MHz, and the above calculated brightness temperatures, we can obtain the sky power we expect at each frequency. We can then convert this into dBm.

- $P_{50} \approx 7.14016 \times 10^{-9}$ mW $= -81.46292$ dBm
- $P_{75} \approx 2.59203 \times 10^{-9}$ mW $= -85.8636$ dBm
- $P_{100} \approx 1.2624 \times 10^{-9}$ mW $= -88.9881$ dBm
- $P_{120} \approx 8.0022 \times 10^{-10}$ mW $= -90.96788$ dBm

We further assume a 10% return loss since the antenna will not be perfectly efficient. This is a 10dB loss from the sky power, so the power coupled to the antenna at our four test frequencies is

- $P_{50,10\%RL} \approx -91.46292$ dBm
- $P_{75,10\%RL} \approx -95.8636$ dBm
- $P_{100,10\%RL} \approx -98.9881$ dBm
- $P_{120,10\%RL} \approx -100.96788$ dBm

3 Calculating the Gain vs. Loss

Once the sky signal reaches the antenna, it must go through several electrical components which result in either power loss or gain. The degree of loss or gain is frequency dependent as well, so the following (Tables 1 to 4) is a calculation of how much gain is necessary given the current components in the signal chain for each of our test frequencies.

Loss/Gain Mechanism	Loss/Gain	Running total for power
Coupled Power		-91.46292 dBm
Loss through balun + discretes	-0.5 dB	-91.96292 dBm
LNA amplifier (TQP3M9018)	+23 dB	-68.96292 dBm
LMR-240 cable loss (6ft cable + connectors)	-0.122 dB	-69.08492 dBm
BIAS-T (MC ZFBT-4R2G-FT+)	typ. -0.2 dB	-69.28492 dBm
Filters (insertion loss): 2 stages of LP (MC SLP-90+) and 2 stages of HP (MC SHP-50+)	1st LP: -0.20 dB (interpolated) 1st HP: -0.5 dB (rough) 2nd LP: -0.20 dB (interpolated) 2nd HP: -0.5 dB (rough)	-70.68492 dBm
Amplifiers (TBD)	+65.65492 dB	-5.03 dBm
LMR-400 50ft cable + connector	-0.47 dB	-5.5 dBm

Table 1: Gain vs. Loss calculation for 50 MHz.

Loss/Gain Mechanism	Loss/Gain	Running total for power
Coupled Power		-95.8636 dBm
Loss through balun + discretes	-0.5 dB	-96.3636 dBm
LNA amplifier (TQP3M9018)	+23.2 dB	-73.1636 dBm
LMR-240 cable loss (6ft cable + connectors)	-0.166 dB	-73.3296 dBm
BIAS-T (MC ZFBT-4R2G-FT+)	typ. -0.2 dB	-73.5296 dBm
Filters (insertion loss): 2 stages of LP (MC SLP-90+) and 2 stages of HP (MC SHP-50+)	1st LP: -0.39 dB (interpolated) 1st HP: -0.5 dB (rough) 2nd LP: -0.39 dB (interpolated) 2nd HP: -0.5 dB (rough)	-75.3096 dBm
Amplifiers (TBD)	+70.3996 dB	-4.91 dBm
LMR-400 50ft cable + connector	-0.59 dB	-5.5 dBm

Table 2: Gain vs. Loss calculation for 75 MHz.

Loss/Gain Mechanism	Loss/Gain	Running total for power
Coupled Power		-98.9881 dBm
Loss through balun + discretes	-0.5 dB	-99.4881 dBm
LNA amplifier (TQP3M9018)	+23.2 dB	-76.2881 dBm
LMR-240 cable loss (6ft cable + connectors)	-0.19 dB	-76.4781 dBm
BIAS-T (MC ZFBT-4R2G-FT+)	typ. -0.2 dB	-76.6781 dBm
Filters (insertion loss): 2 stages of LP (MC SLP-90+) and 2 stages of HP (MC SHP-50+)	1st LP: -0.57 dB (interpolated) 1st HP: -0.26 dB 2nd LP: -0.57 dB (interpolated) 2nd HP: -0.26 dB	-78.3381 dBm
Amplifiers (TBD)	+73.4781 dB	-4.86 dBm
LMR-400 50ft cable + connector	-0.64 dB	-5.5 dBm

Table 3: Gain vs. Loss calculation for 100 MHz.

Loss/Gain Mechanism	Loss/Gain	Running total for power
Coupled Power		-100.96788 dBm
Loss through balun + discretes	-0.5 dB	-101.46788 dBm
LNA amplifier (TQP3M9018)	+23 dB	-78.46788 dBm
LMR-240 cable loss (6ft cable + connectors)	-0.202 dB	-78.66988 dBm
BIAS-T (MC ZFBT-4R2G-FT+)	typ. -0.2 dB	-78.86988 dBm
Filters (insertion loss): 2 stages of LP (MC SLP-90+) and 2 stages of HP (MC SHP-50+)	1st LP: -2.30 dB 1st HP: -0.26 dB 2nd LP: -2.30 dB 2nd HP: -0.26 dB	-83.98988 dBm
Amplifiers (TBD)	+79.22988 dB	-4.76 dBm
LMR-400 50ft cable + connector	-0.74 dB	-5.5 dBm

Table 4: Gain vs. Loss calculation for 120 MHz.

From the above calculations, we have, for the chosen frequencies within the science band, the gain needed to reach -5.5 dBm at the ADC input point:

- $G_{50} = +65.65492$ dB
- $G_{75} = +70.3996$ dB
- $G_{100} = +73.4781$ dB
- $G_{120} = +79.22988$ dB

This range of gains will be obtained via a series of connectorized amplifiers near the filter stages.