Allen Telescope Array

Analog Signal Path Dynamic Range Analysis

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July 29, 2021

Abstract

This document is a work in progress and intends to provide an overview of the power levels throughout the ATA analog signal path. Its assumptions are based on the theoretical component values pulled from data sheets of the components and documentation from the ATA Memo series, all of which are referenced in this document. We use these values to obtain a cascaded signal path model that includes all components, from the Antenna to the analog-to-digital converter. The signal chain is broken into five stages, the Antenna, the Antonio Feed, the Post Amplifier Transceiver (PAX), the RF Conversion Box (RFCB) and the IF Gain Control. All reference to Gain and Bandwidth for components are taken from values in the corresponding datasheets, the system temperature and power output are calculated using the Friis formula. To refine this model, measurements will be required at the various stages in the signal path.

Contents

1 Introduction

This document describes the analog signal path of the Allen Telescope Array from a top level perspective down to the individual components in the signal path. Dynamic range has always been a problematic topic at the ATA, hence this document investigates how much dynamic range is at each individual step throughout the signal path. The top level system diagram is shown in Figure 1, where one can see that the ATA is best divided in five main systems, the Antenna, the Antonio Feed, the Post-Amplifier Transmitter (PAX), the RF-Conversion Box (RFCB), and the IF-Conditioning and DSP backend. This organization is based on the path of a detected signal through the telescope, from the Antenna through the analog electronics to the digital signal processing.

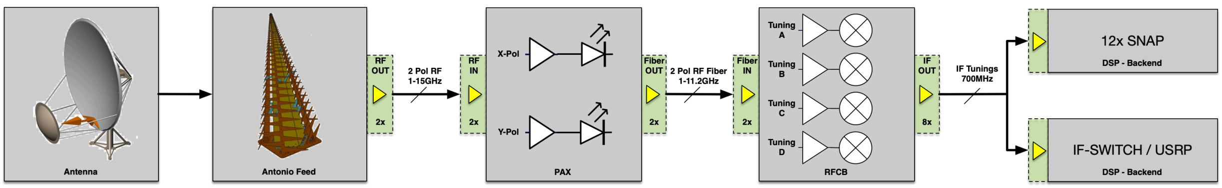

Figure 1: Top level diagram of the ATA analog signal path.

The detailed description of these systems start with the Antonio Feed, in Section 2 where the first active signal components are deployed. The post amplifier fiber transmitter and its sub-systems are described in Section 3. The frequency conversion from RF (0.5 – 11.2 GHz) into the IF frequency (0.1 – 0.8 GHz) and bandwidth reduction is described in Section 4. The IF signal path, described in Section 5, which includes multiple DSP backends focuses on the SNAP based digital signal processing and excludes the IF-Switch and USRP backend. Finally, Section 6 provides an analysis of the cascaded gain through the entire signal path. The analysis is based on the components individual specifications like, gain, bandwidth, loss, compression point as described in the corresponding datasheets.

2 Antonio Feed

The Antonio Feed is a fully cryogenically cooled broadband log-periodic feed. The entire feed structure including the low noise amplifiers are operated at a physical temperature between 70 – 80 K. The feed covers a primary frequency range of 1 – 14 GHz, however due to its intrinsic broadband design it is also receptive to frequencies outside of this range, especially at the lower end. Hence, radio frequency interference in the ISM band around 902 – 928 MHz is also coupled into the signal path. A simplified diagram of the Antonio Feed illustrating the main signal components is shown in Figure 2. This diagram also lists the key parameters of the installed low noise amplifier. The information with reference to gain and bandwidth were taken from the LNA data sheet that can be accessed here [?]. The information with regard to the 1 dB compression point was provided by Low Noise Factory directly.Table 1 gives a more detailed description of the components referenced in Figure 2 and links to the GitHub repository where all data sheets for the LNAs are located.

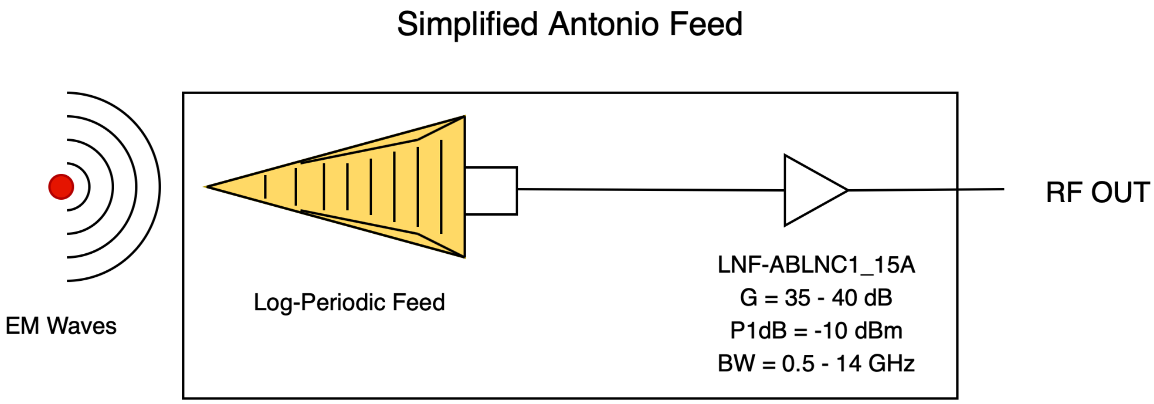

Figure 2: Diagram of the signal components of the Antonio Feed. The log-periodic feed is colored in orange and connected to the differential input low noise amplifier via two 100 Ohm coax cables.

Table 1: Description of signal components used in the Antonio Feed.

Part Number	Description
LNF-ABLNC1_15A	Cryogenic Low Noise Amplifier

To determine the output power of the LNA and its available dynamic range, we first calculate the noise power based on the temperature and the bandwidth of the feed. The noise power produced by the feed looking at a certain temperature T with the bandwidth $\Delta\nu$ is given by

$$P = k_{\mathrm{B}} T \Delta\nu, \tag{1}$$

where k_{B} is the Boltzmann constant. Assuming that our feed has a bandwidth of 15 GHz and detects a cumulative temperature of about 14 K, the noise power is approximately $\mathrm{P}_{\mathrm{ns}} = -85.4\,\mathrm{dBm}$. With a typical gain of about 40 dB the output power of the LNA with no RFI present is approximately $\mathrm{P}_{\mathrm{out}} = -45.4\,\mathrm{dBm}$, which gives us a dynamic range of about roughly 35 dB.

To verify this calculation and to take any stationary RFI into account, we will need to measure the output power of all LNAs with a power meter. Please take into account this point and not that at the end of this document, we will provide an outlook of the next steps that need to be carried out in order to refine this analysis.

3 Post Amplifier Transceiver (PAX)

The Post Amplifier Transceiver is responsible for the analog signal conditioning immediately after the LNA. It biases the signal to an appropriate power level and sends the signal over fiber to the RFCB. The Post Amplifier Module (PAM) consists of a cascade of amplifiers and variable attenuators which allow the gain to be set between 0 dB and 60 dB in order to control the power going into the fibre link and ensure it remains stable. After the cascade of amplifiers and attenuators, the signal is sent to the fiber transmitter and the RF signal is processed by the detector diode.

The detector diode is calibrated and measured so we know the actual power output at this point in the PAM. Figure 3 shows a top level diagram of the PAM from amplification to the fiber transmission module. A more detailed diagram of the cascaded amplifiers and variable attenuators is given in Figure 4.

Table 2 gives a more detailed description of the components referenced in Figure 4 and links to their datasheets. The cascaded system temperature and power at each point in the PAM is given in Figure 7. For the two cascaded attenuators which are at -10.0 and -20.0 dB respectively, the resulting power at the optical transceiver is ~ -9.87 dB. Loss in the Fiber cable between the PAX and RFCB corresponds to approximately 1 K, as expected by the Fiber Tranceiver datasheet.

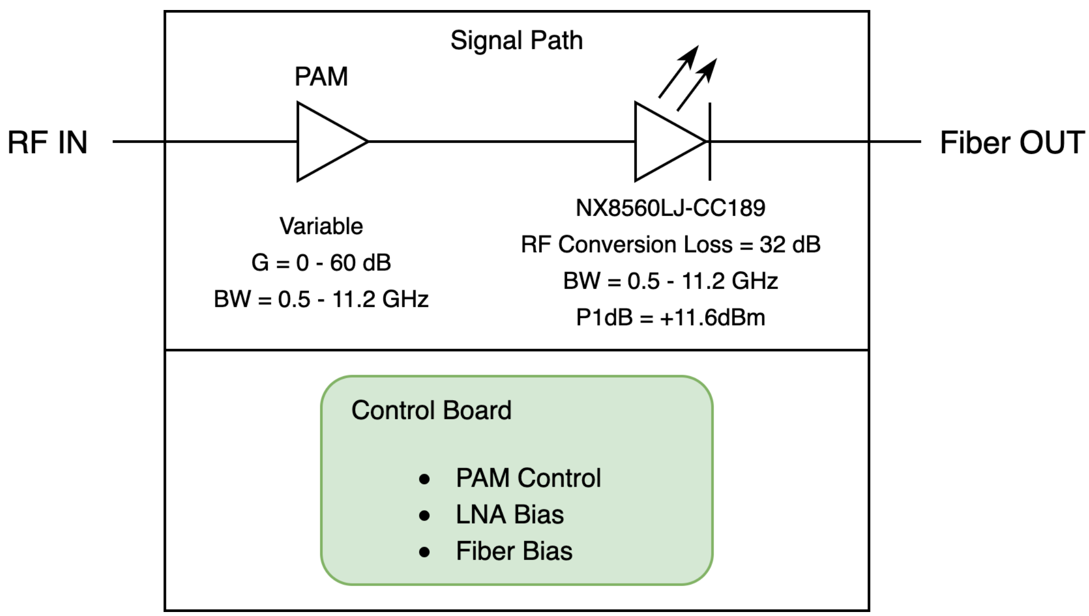

Figure 3: Top level diagram of the post-amplifier fiber transmission module. The three main components in the PAX are the PAM module, the optical fiber transmitter, and the control board.

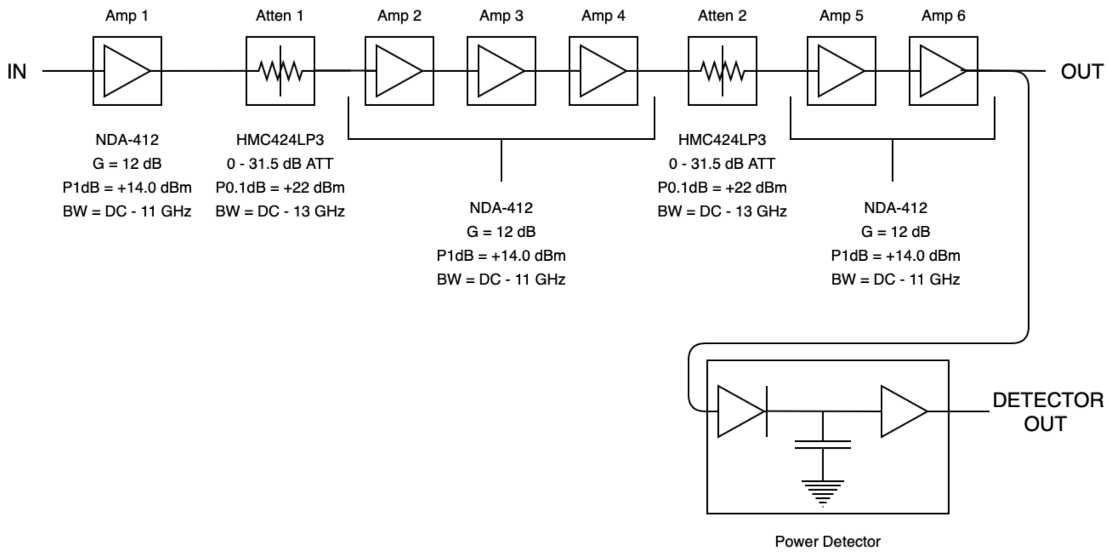

Figure 4: Schematic of the post amplifier module displaying the individual signal components and their specifications.

Table 2: Description of signal components used in the PAX.

Part Number	Description
NDA-412	Linear Amplifier
HMC424LP3	Variable Attenuator
NX8560LJ-CC189	Fiber Transmitter

4 RF Conversion Box (RFCB)

The RF converter takes the analog optical fiber signal from each antenna as input and produces four independent analog IF outputs with a bandwidth of about 700 MHz. Each of the four IF tunings (A-D) has a dedicated variable local oscillator that allows the selection of any frequency band within the primary RF band of 0.5 – 11.2 GHz and down converts it to a center frequency of 450 MHz. There are 42 RF conversion boxes installed in the signal processing room, each of which takes two inputs X-pol and Y-pol of a single antenna.

The system diagram illustrating one polarisation and one tuning of an RFCB is shown in Figure 5, where the RF signal is received through the optical link on the left-hand side and directed to the IF signal conditioning on the right-hand side. The boxes in the diagram indicate the physical groupings of components within the RFCB. The fiber detection module consists of the fiber detector diode, which converts the entire band back to RF and is followed by a number of signal components that amplify, divide, and filter the signal. The output of this module is then connected to four identical signal chains, one of which is drawn in the diagram. The connection between the modules and individual components use semi-ridged coaxial cables which make it possible to measure power levels at these distinct points in the signal path.

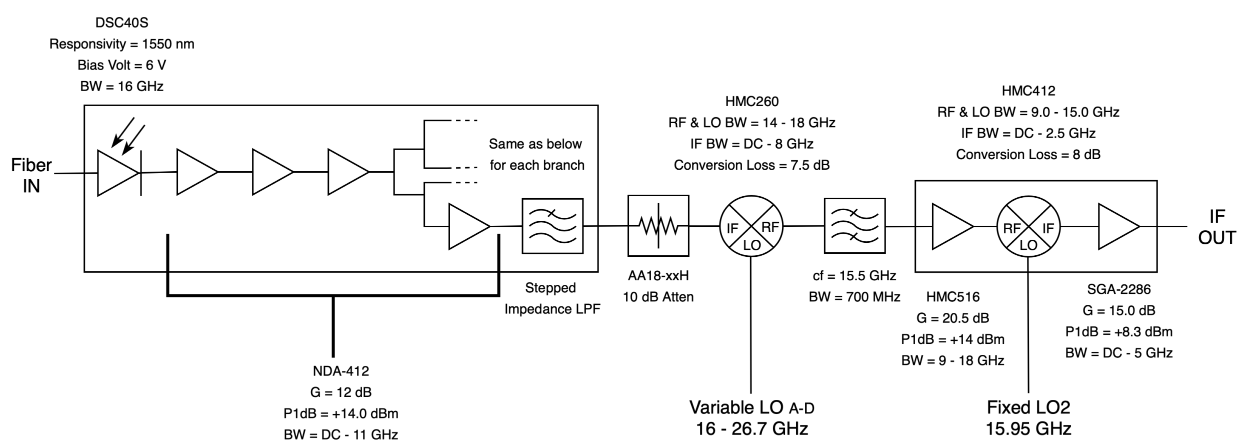

Figure 5: Schematic of the RF conversion box displaying the individual signal components and their specifications.

Based on the information from ATA Memo 54 [?], we know that the RF conversion loss of the fiber link including the transmitter, fiber cable to the signal processing room, and detector diode is about -35 dB. With an ideal power setting in the PAX box, the input power into the fiber link is approximately -10 dBm, which computes to an input RF power level into the RFCB detector module of ≈ -45 dBm. The signal is then amplified by a cascade of amplifiers, knowing their nominal gain we can estimate that the highest power level in the path occurs at the last amplifier with a value of about -3 dBm. The P1dB compression point for the amplifiers used is +14 dBm, which leaves us with a dynamic range of about 17 dB. Continuing along the signal path, the power is reduced by a fixed 10 dB attenuator and is then up converted in frequency, where the band defining filter reduces the entire RF band to 700 MHz. At this stage in the signal path, the power level is reduced to approximately

-37 dBm. The final component in the RFCB is a module which consists of an RF amplifier, mixer, and IF amplifier. This module down converts the 700 MHz pass band to IF with a center frequency of 450 MHz. Taking into account the conversion loss, band reduction, and gain of the individual components, the output power of the RFCB is about -10 dBm.

All RFCBs located in the signal processing room have been tested with a known input signal. The testing included an IF band pass measurement and a total IF power measurement for all polarizations and tunings. The measurement document is currently in preparation and will be available under following link [**?**]. The first look at the total power measurement results indicates that the IF output power ranges from 0 – -10 dBm for intact RFCBs.

Table 3 gives a more detailed description of the components referenced in Figure 5 and links to the individual data sheet. Finally, the detailed power level and dynamic range analysis for all components in the RFCB signal path is presented in Section 6.

Table 3: Description of signal components used in the RFCB.

Part Number	Description
NDA-412	Linear Amplifier
HMC424LP3	Variable Attenuator
DSC40S	Fiber Detector Diode
AA18-xxH	10 dB Fixed Attenuator
HMC260	Passive Double Balanced Mixer
HMC516	SMT PHEMT Low Noise Amplifier
HMC412	Passive Double Balanced Mixer
SGA-2286	IF Amplifier

5 IF Gain Control

The task of the IF gain control is to set the power level going into the analog to digital converter to a specific value. The control system reads out the ADC RMS values recorded by the SNAP board and compares them to a predefined target value. It then changes the attenuation accordingly until the required RMS value has been reached. The installed attenuators have a resolution of 0.5 dB, thereby allowing to set the power level within that quantisation. Currently the specified input power into the ADC is set to -18 dBm.

Figure 6, shows the IF signal path for the SNAP based DSP backend. Coming from the RFCB outputs all channels are first power leveled with fixed attenuators to about -20 dBm. After that the signal goes through the IF gain control, where it is amplified and then set to the correct power level using the step attenuator.

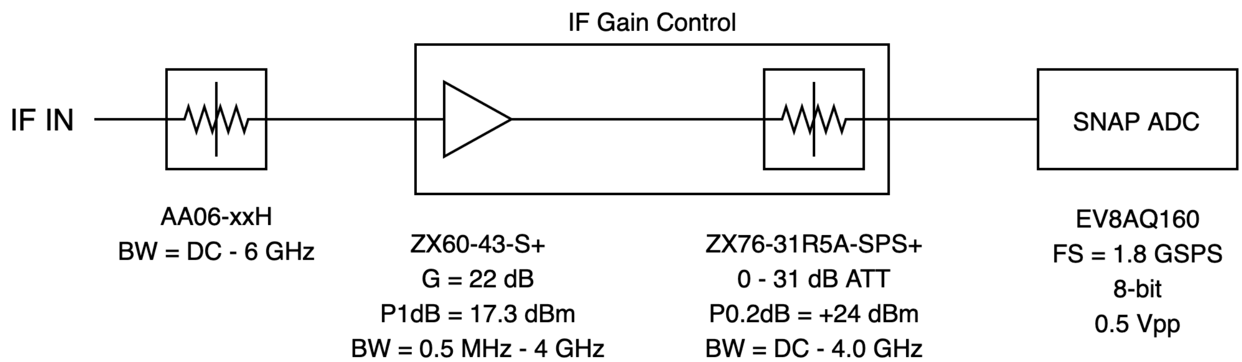

Figure 6: Schematic of the IF signal path when connected to the output of the RFCB. The signal is approximately leveled to -20 dBm using a fixed attenuator and then connected to the IF-Gain Module, which consists of an amplifier and a variable step attenuator. After that the signal is digitized by the 5G-ADC of the SNAP DSP unit.

Table 4 gives a more detailed description of the components referenced in Figure 6 and links to the individual data sheets.

Table 4: Description of signal components used in the IF Gain Control.

Part Number	Description
AA06-xxH	Fixed Attenuator
ZX60-43-S+	Linear Amplifier
ZX76-31R5A-SPS+	Variable Attenuator
EV8AQ160	Analog to Digital Converter

6 Cascade Analysis

This section provides an analysis of the entire ATA analog signal path. This is done by combining the individual systems, Antonio Feed, PAX, RFCB, and IF gain control on a single component level basis. In the previous sections we went over each system individually and identified the installed components and their properties. We now take all of these components and combine them in a cascaded chain. The chain is based on the *Friis* formula for cascaded amplification stages which is given by

$$T_{\mathrm{sys}} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + ... + \frac{T_{\mathrm{i}}}{G_1 G_2 ... G_{\mathrm{i}-1}}, \tag{2}$$

where T_{i} and G_{i} represent the noise temperature and gain of the individual component in the receiver chain [**?**]. Lossy components with $G_{\mathrm{i}} < 1$ contribute to a noise temperature, T_{i} which is given by

$$T_{\mathrm{i}} = (1 - G_{\mathrm{i}})\, T_{\mathrm{p}}, \tag{3}$$

where T_{p} is the physical temperature of the device e.g. cable, connector, splitter, etc. Note, that this equation does not take into account noise contributions caused by reflections between components. To take this effect into account, please see [**?**] which provides a detailed analysis of reflection losses in a similar system. However, for well-matched components with individual return losses of $S_{11} \lesssim -20\,\mathrm{dB}$ these effects are negligible.

The result of this analysis is shown in Figure 7. The blue boxes on the left-hand side indicate to which system the components in the cascade belong to. Starting from the Antenna / Feed we assume an initial receiver bandwidth of 15 GHz. The individual segments in the *Component* column are color coded, red indicates amplifier and purple indicates attenuators. The location in the signal path where the gain can be adjusted, either by fixed or variable attenuators are color coded green in the *Gain dB* column. The power level at each state of the signal path as well as the available dynamic range based on the individual components 1dB compression point are marked orange in the *Power at this stage (dBm)* and *Available Dynamic Range (dB)* columns.

Based on this analysis we reduced the PAM output power set point from the original -3 dBm to -10 dBm which leaves us with about 20 dB of dynamic range for the fiber link. Moreover, this analysis also indicates that compression in the RFCB is possible and likely under certain conditions. To improve the accuracy of this model, we now need to measure the power level at different locations in the ATA signal path for a number of antennas.

Finally, Table 5 gives a more detailed description of the components referenced in Figure 7 and links to the individual data sheet.

	Component	Gain dB	Gain Linear	Physical temp (K)	Gain temp (K)	Running Gain (dB)	Power at this stage (dBm)	(P1dB)	Dynamic Range (dB)	Tsys (K)
Antenna /Feed	CMB	**0.000**	1.000	2.7	0	0	-92.53	-	-	2.700
	Atmosphere	**-0.060**	0.986	220.0	0	-0.060	-89.30	-	-	5.761
	Dish	**-0.020**	0.995	290.0	0	-0.080	-88.40	-	-	7.118
	Mirror	**-0.020**	0.995	290.0	0	-0.100	-87.66	-	-	8.481
	Radome	**0.000**	1.000	290.0	0	-0.100	-87.66	-	-	8.481
	Feed	**-0.040**	0.991	80.0	0	-0.140	-87.32	-	-	9.239
	Link-Capacitor	**-0.300**	0.933	80.0	0	-0.440	-85.48	-	-	15.148
	Cable1	**-0.100**	0.977	80.0	0	-0.540	-85.02	-	-	17.210
	LNA	**38.000**	6309.573	0.0	**20**	37.460	-43.38	-10.00	33.38	39.858
	SS cable	**-1.500**	0.708	80.0	0	35.960	-44.87	-	-	39.864
	Feedthu SMA	**-0.100**	0.977	290.0	0	35.860	-44.97	-	-	39.865
	SS cable	**-2.000**	0.631	290.0	0	33.860	-46.97	-	-	39.909
PAX	Bandwith red. 12/15 GHz	**-1.000**	0.794	0.0	0	32.860	-47.97	-	-	39.909
	NDA-412	**12.000**	15.849	0.0	**630**	44.860	-35.93	14.00	49.93	40.235
	Filter	**-4.000**	0.398	0.0	0	40.860	-39.93	-	-	40.235
	HMC424	-10.000	0.100	0.0	0	30.860	-49.93	22.00	71.93	40.235
	NDA-412	**12.000**	15.849	0.0	**630**	42.860	-37.88	14.00	51.88	40.752
	NDA-412	**12.000**	15.849	0.0	**630**	54.860	-25.88	14.00	39.88	40.785
	NDA-412	**12.000**	15.849	0.0	**630**	66.860	-13.88	14.00	27.88	40.787
	HMC424	-20.000	0.010	0.0	0	46.860	-33.88	22.00	55.88	40.787
	NDA-412	**12.000**	15.849	0.0	**630**	58.860	-21.87	14.00	35.87	40.800
	NDA-412	**12.000**	15.849	0.0	**630**	70.860	-9.87	14.00	23.87	40.801
	PAM output cable to OTX	**0.000**	1.000	0.0	0	70.860	-9.87	-	-	40.801
	NX8560LJ-CC189	**0.000**	1.000	0.0	0	70.860	-9.87	11.60	21.47	40.801
	Fiber cable	**-35.000**	0.000	290.0	**7284180**	35.860	-44.80	-	-	41.474
RFCB	DSC-40S	**0.000**	1.000	0.0	0	35.860	-44.80	-	-	41.474
	NDA-412	**12.000**	15.849	0.0	**630**	47.860	-32.79	14.00	46.79	41.637
	NDA-412	**12.000**	15.849	0.0	**630**	59.860	-20.78	14.00	34.78	41.647
	NDA-412	**12.000**	15.849	0.0	**630**	71.860	-8.78	14.00	22.78	41.648
	4-way Wilkinson Divider	**-6.000**	0.251	290.0	0	65.860	-14.78	-	-	41.648
	NDA-412	**12.000**	15.849	0.0	**630**	77.860	-2.78	14.00	16.78	41.648
	Stepped Impedance Filter	**-1.000**	0.794	290.0	0	76.860	-3.78	-	-	41.648
	Fixed Attenuator	**-10.000**	0.100	290.0	0	66.860	-13.78	-	-	41.648
	HMC260	**-7.500**	0.178	290.0	0	59.360	-21.28	12.00	33.28	41.649
	BPF 700MHz	**-3.500**	0.447	290.0	0	55.860	-24.78	-	-	41.649
	Bandwith red. 0.7/12 GHz	**-12.300**	0.059	0.0	0	43.560	-37.08	-	-	41.649
	HMC516	**20.500**	112.202	0.0	**170**	64.060	-16.58	14.00	30.58	41.656
	HMC412	**-8.000**	0.158	290.0	0	56.060	-24.58	11.50	36.08	41.657
	SGA-2286	**15.000**	31.623	0.0	**360**	71.060	-9.58	8.30	17.88	41.658
	RFCB output cable	**-0.100**	0.977	290.0	0	70.960	-9.68	-	-	41.658
IF	LMR-240 25ft	**-1.500**	0.708	290.0	0	69.460	-11.18	-	-	41.658
	AA06-xxH	-10.000	0.100	0.0	0	59.460	-21.18	-	-	41.658
	ZX60-43-S+	**22.000**	158.489	0.0	**715**	81.460	0.82	17.30	16.48	41.659
	ZX76-31R5A-SPS+	-19.000	0.013	290.0	0	62.460	-18.18	22.00	40.18	41.659
	AFX-CA-141-xx	**-0.100**	0.977	290.0	0	62.360	-18.28	-	-	41.659
	EVA8AQ160 ADC	**-0.050**	0.989	290.0	0	62.310	-18.33	0.00	18.33	41.659

Figure 7: Excel sheet, showing the cascaded Tsys / Gain of the ATA analog signal chain. The points in the signal chain where the gain can be adjusted, either by fixed or variable attenuators are marked green in the *Gain dB* column. The running power level at each state of the signal chain as well as the available dynamic range based on the components 1dB compression point are marked orange in the *Power at this stage (dBm)* and *Available Dynamic Range (dB)* columns.

Table 5: Description of signal components used in the ATA signal path.

Part Number	Bandwidth	Compression Point	Description
LNF-ABLNC1_15A	0.5 – 14 GHz	P1dB = -10 dBm	Cryogenic Low Noise Amplifier
NDA-412	DC – 11 GHz	P1dB = +14.0 dBm	Linear Amplifier
HMC424LP3	DC – 13 GHz	P1dB = +22 dBm	Variable Attenuator
NX8560LJ-CC189	0.5 – 11.2 GHz	P1dB = +11.6 dBm	Fiber Transmitter
DSC40S	16 GHz		Fiber Detector Diode
AA18-xxH			10 dB Fixed Attenuator
HMC260	RF = 14 – 18 GHz		Passive Double Balanced Mixer
	IF = DC – 8 GHz		
HMC516	9 – 16 GHz	P1dB = +14 dBm	SMT PHEMT Low Noise Amplifier
HMC412	RF = DC – 2.5 GHz		Passive Double Balanced Mixer
	IF= DC – 2.5 GHz		
SGA-2286	DC – 5 GHz		IF Amplifier
AA06-xxH	DC – 6 GHz		Fixed Attenuator
ZX60-43-S+	0.5 MHz – 4 GHz	P1dB = 17.3 dBm	Linear Amplifier
ZX76-31R5A-SPS+	DC – 4.0 GHz	P0.2dB = +24 dBm	Variable Attenuator
EV8AQ160			Analog to Digital Converter