Redesign of the Visitor Center Solar Telescope

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1 Introduction

1.1 Purpose

Located behind the Visitor Center at the Very Large Array (VLA) is a radio telescope that converts RF solar energy into a DC voltage through amplification. It was originally constructed in 2013 and is no longer functioning as of June 2023. Weathered components and lack of sufficient documentation to repair the telescope to its original state has warranted a redesign of the entire system to be more appealing to visitors and resistant to wear.

1.2 Scope

This document will describe the design choices made in development of the new solar telescope. Calculations and experiments to support design decisions will be demonstrated along with constraints and requirements.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents may not be directly referenced herein, but may provide necessary context or supporting material.

Ref. No.	Document Title	Rev/Doc. No.
AD01	Desiderata for Solar Observing with the EVLA	EVLAM_70
AD02	EVLA Hardware Modifications in Support of Solar Observing	EVLAM_72

2.2 Reference Documents

The following documents are referenced within this text:

Ref. No.	Document Title	Rev/Doc. No.
RD01	Solar Brightness Temperature and Corresponding Antenna Noise Temperature at Microwave Frequencies	Online
RD02	Antenna Engineering Handbook	DSOC Bookcase
RD03	Tools of Radio Astronomy	Privately Owned
RD04	X-Band System Performance of the Very Large Array	Online
RD05	10-60 GHz G/T Measurements Using the Sun as a Source–A Preliminary Study	Online

3 System Overview

The heart of the telescope is an conical corrugated X-band horn antenna originally used to receive Voyager transmissions at 8.4 GHz; this is to be unchanged in the redesign. Power is supplied through a 15 volt linear DC power supply located inside the visitor center in order to eliminate radio frequency interference (RFI) caused by AC power and switching power supplies.

As the telescope is pointed towards the various objects, RF energy is received by the antenna and amplified. A rectifying circuit converts the RF power into a DC voltage and further amplifies it before outputting to a voltmeter. The DC gain should be adjusted so that as the telescope is pointed directly at the sun, the voltmeter should raise noticeably from its value when pointed at a cold sky[1]. When pointed at the ground or an object, the reading will increase to a maximum due reflections and filling of the antenna sidelobes. This is further explained in Section 5.1.

3.1 Requirements

Being a visitor center attraction, the device should be engaging and appealing to visitors. In order to achieve this, a transparent enclosure will show the electronics and the voltmeter driven by solar energy will provide user feedback. The enclosure of the previous design was made of some sort of polycarbonate material which suffered from yellowing in the sun. Additionally, small computer fans with a mesh screen mounted directly to the enclosure were used to decrease operating temperature but allowed dust to accumulate over the years. In essence, the new design goals are as follows:

(1) Utilizes a transparent enclosure or panel to view electronics, ideally one which will not yellow or fade easily.

(2) Must be dustproof and resilient to accumulation of debris inside the enclosure while still venting heat from electronics.

(3) Electronics must be powered by a fixed DC linear power supply and easily serviceable.

(4) There must be a measurable voltage delta when pointing the telescope at various RF sources.

The first two requirements were fulfilled by Tristen James in designing the enclosure. The following requirements will be discussed in this report.

3.2 Architecture

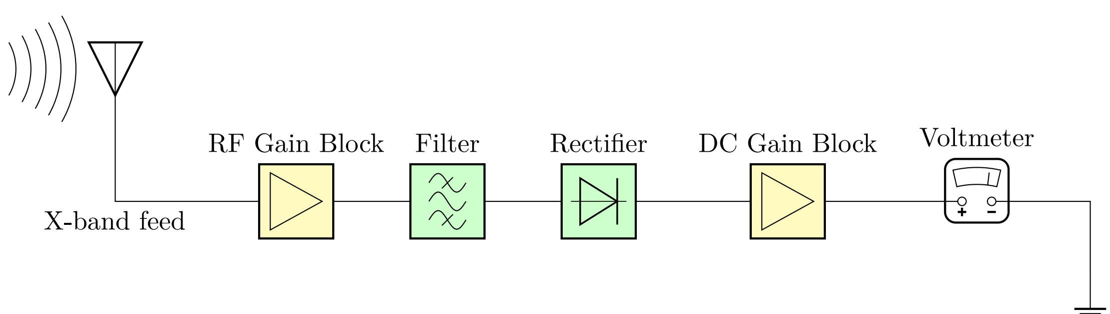

Figure 1: RF signal block diagram

Many of the RF components were either reused from the previous design or gathered at no cost. The RF gain block shown in Fig. 1 and 2 utilizes 3 low noise amplifiers (LNAs) and an attenuator. The first 2 LNAs are Mini-Circuits ZX60-06203ALN+ which provide a combined gain of 41 dB; they are followed by a ZX60-83LN-S+ which provides a mean gain of 15 dB in the filter bandwidth. These amplifiers are followed by an attenuator whose purpose will be described in Section 4. It is important to note that the receiver noise figure is about 2 dB – a higher noise figure could result in an undetectable sun/sky delta.

[1]Cold sky is defined when there are no notable RF emitting objects in the beamwidth. Experimentally, these readings seem to be equivalent to the receiver noise floor.

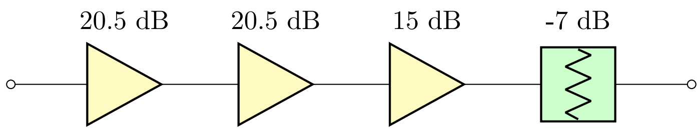

Figure 2: 49 dB RF gain block

The bandpass filter does not have an attached datasheet but it resembles an equiripple filter and measured a 3 dB passband of about 7.8–8.9 GHz.

The rectifier and DC gain block are integrated into a PCB with SMA connectors. The former utilizes an Analog Devices ADL5902, providing a linear-in-decibel output that can be scaled by the choice of resistors on the board or the following gain element. The DC gain block utilizes an LM358 op amp with adjustable gain via potentiometer.

3.3 Power Distribution

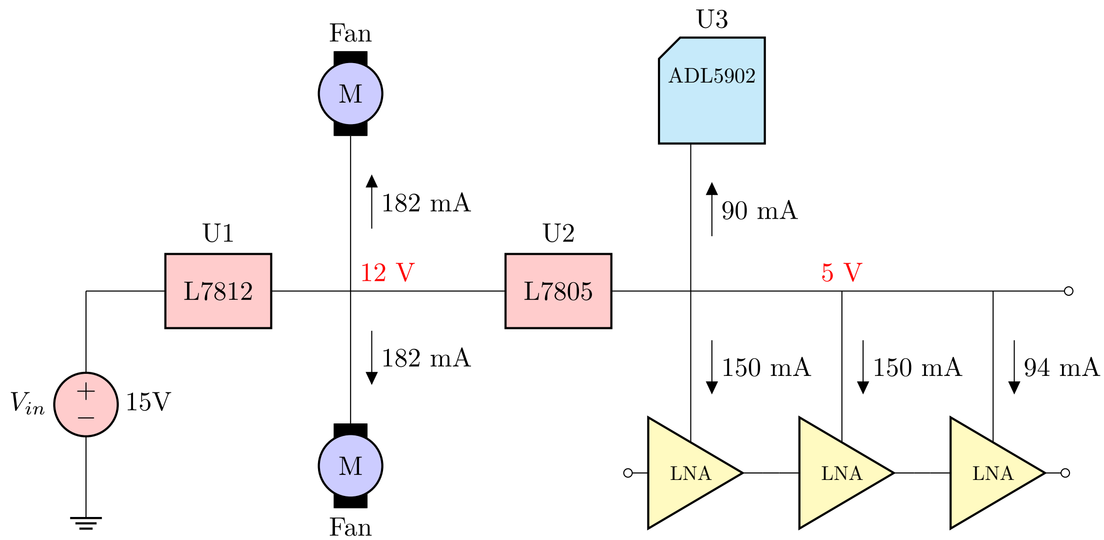

Figure 3: DC power distribution block diagram (Maximum ratings)

As part of the effort to make the telescope more modern and visually appealing, the protoboard on the previous design was replaced with a PCB that contains the voltage regulators, the RF power detector IC, and dual noninverting op amps. The 15 volt supply is dropped to 12 volts and 5 volts via linear regulators, each of which powers different components. Figure 3 shows the maximum current draw of each component to ensure that the system does not exceed the 1.5 amp rating of the L78XX chips.

4 Tuning System Gain

Figure 4 shows the voltage-power curve of the ADL5902-EVALZ[2] at the telescope's operating frequency. Pointing the telescope at a high temperature object will produce an input power higher than pointing it at

[2] Resistor values were changed on the evaluation board to achieve 86.3 mV/dB slope: R6 = 1180Ω and R2 = 2000Ω

the cold sky; this dynamic range is represented by the dotted lines and filled section of the curve[3]. Adding attenuation or RF gain will shift this area to the left or right respectively. Adding DC gain will increase the slope of this curve and vice versa. Ideally, the RF gain should be adjusted such that the low end is roughly

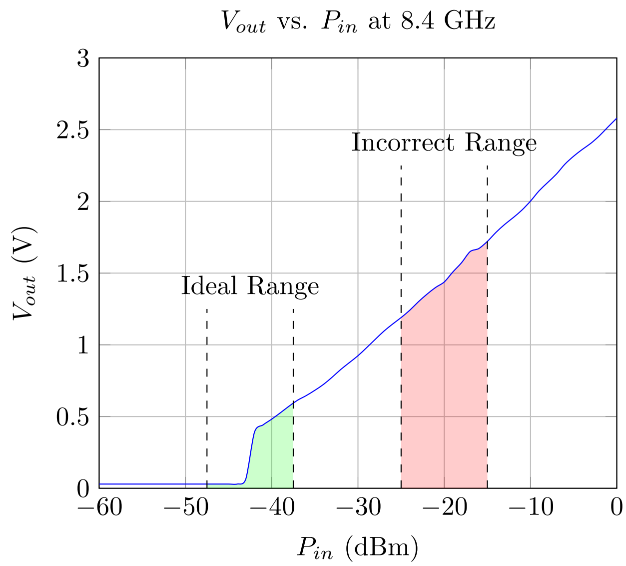

Figure 4: Output voltage of the ADL5902-EVALZ as a function of input power.

0 volts whereas the the high end is scaled to 3 volts by the DC gain block. In this case, amplification from the DC gain block will have negligible effect on the low end. If, for some reason, granular attenuation is not possible, the DC gain will cause the nonzero low end to increase above 0 volts. A simple solution is presented in Fig. 5 where the negative terminal of the voltmeter can be set to reference a nonzero voltage. In reality, the sensitivity of the receiver will prevent a perfect 0 to 3 volt scaling at all times. Thus, in order

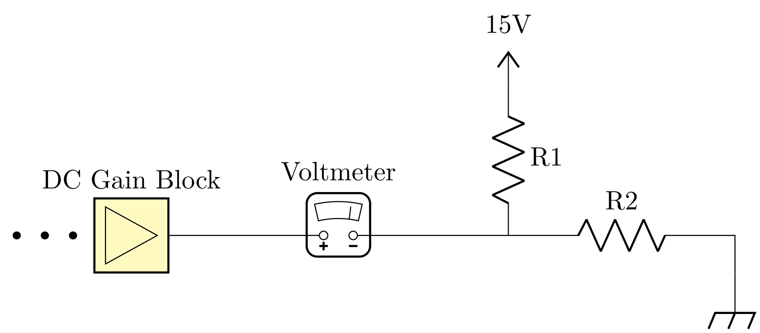

Figure 5: Optional output scaling circuit.

to ensure some amount of voltmeter deflection occurs despite environmental changes, a practical range around 0.5–2.5 volts may be desired.

[3]The range has been enlarged for the purpose of demonstration. The true range is much smaller (Section 5.1)

4.1 Installation Notes

Figure 2 shows 49 dB of RF gain; this was determined to be functional with the antenna and log-detector via testing, however, $\pm$1 dB of attenuation may work if the DC gain block is scaled correctly. Exact numbers are not shown for DC gain because slight variations in cable loss and component accuracy make it difficult to calculate. The easiest way to determine DC gain is simply to measure the voltage readings at the receiver output and adjust accordingly.

5 Calculating Receiver Input Power

The first step to determine RF gain will be to find the power delta as the antenna is pointed at the sun from a cold sky; note that this may vary daily and annually depending on solar cycle[RD01, Fig. 2]. This calculation also assumes that solar flux density is constant across the entire frequency range of the receiver. This is a limitation of available information on solar flux density; in practice, it generally increases with frequency[RD05]. Instantaneous channel power received by the antenna from a celestial source in watts, in an additive white Gaussian noise (AWGN) channel, P_R, is defined by Eq. 1[RD02, eq. (41-2)]

$$\begin{aligned} P_R &= P_{sun} + P_{noise} \\ P_R &= SA_e\Delta f + k_B T\Delta f \end{aligned} \tag{1}$$

where: S is the source flux density in W m^{-2} Hz^{-1},
A_e is the effective aperture area in m^2
Δf is the receiver bandwidth in Hz,
k_B is the Boltzmann constant in J K^{-1}, and
T is the system noise temperature in K.

To simplify calculations, we will focus on power spectral density (PSD) defined as $P(f)$ in W/Hz, ignoring the receiver bandwidth for now. Additionally, it is safe to assume that $P_R = P_{noise}$ when the antenna is pointed at a cold sky.

$$\begin{aligned} P_R(f) &= P_{sun}(f) + P_{noise}(f) \\ &= SA_e + k_B T \end{aligned} \tag{2}$$

Effective aperture at a fixed wavelength λ can be calculated using measurements of the antenna as shown in Eq. 3[RD02, pg. (15-27)][RD03, eq. (5.58)]

$$\begin{aligned} A_e &= \frac{\lambda^2}{4\pi}G \\ &= \frac{\pi d^2}{4}\eta_a \end{aligned} \tag{3}$$

where: G is linear antenna gain,
d is the diameter of the circular horn at the aperture, and
η_a is the unitless aperture efficiency.

An ideal horn antenna has an η_a of 0.522. The calculations for this design will use an approximate value of 0.5[4]. The antenna diameter at the opening measures 34 cm, resulting in an effective area of 0.0454 m^2 or -13.4 dB m^2.

[4]The x-band horn measured an estimated aperture efficiency of 0.62$\pm$0.03 but only when mounted to the VLA dish[RD04]. This design will assume the antenna to be a standard horn antenna.

Values for solar flux density S must be found within the operating frequency. Ho *et al.*[RD01] measured mean, minimum, and maximum values for solar flux density at 2800 MHz and 8800 MHz but only numbers for the former are shown in the text. However, they claim that solar flux density at 8800 MHz are higher by a factor of 2.17 on average, thus, the mean, minimum, and maximum values at 2800 MHz can be multiplied by 2.17 to achieve approximate values for S. Additionally, solar brightness temperature shown in [RD01, Fig. 5] can be used to calculate solar flux density via [RD01, eq. (2)]. The former method shows higher dynamic range and is shown in Table 1 in solar flux units[5].

	S_{min}	S_{μ}	S_{max}
2.8 GHz	70 SFU	150 SFU	280 SFU
8.8 GHz	152 SFU	326 SFU	608 SFU

Table 1: Solar Flux Density S at 8.8 GHz extrapolated by multiplying S in [RD01] at 2.8 GHz by a factor of 2.17.

With values for S and A_e found, we can now calculate $P_{sun}(f)$ with equation 2 to be -181.6 dBm/Hz at S_{min}. A problem arises when comparing this to the thermal noise PSD of -174 dBm/Hz at 300 K; because the power received by the sun is below the noise floor, the increase in P_R due to P_{sun} will be very small compared to P_{noise}.

The nominal 7.6 dB difference between the $P_{noise}(f)$ and $P_{sun}(f)$ means that pointing the antenna at the sun will raise the antenna output power by a mere 0.7 dB at minimum. If a receiver noise figure of 2 dB is to be assumed, this output power delta ΔP decreases to 0.45 dB[6].

$$\begin{aligned}\Delta P &= \left[\frac{P_R(f)}{P_{noise}(f)}\right]_{dB} \\ &= \left[\frac{P_{sun}(f) + P_{noise}(f)}{P_{noise}(f)}\right]_{dB} \\ &= 10\,\text{log}_{10}\left(1 + 10^{-0.76-0.2}\right) \\ &= 0.452\ \text{dB}\end{aligned}$$

5.1 Antenna Power Measurements

In order to confirm these calculations, the antenna was connected to an Anritsu MS2720T/720 spectrum analyzer and pointed at various targets.

[5] One solar flux unit (SFU) is equal to 10^{-22} W m^{-2} Hz^{-1}.

[6] Δ is typically used to denote a difference of linear terms. Here it is being used to denote a difference in logarithmic terms which translates to a linear ratio.

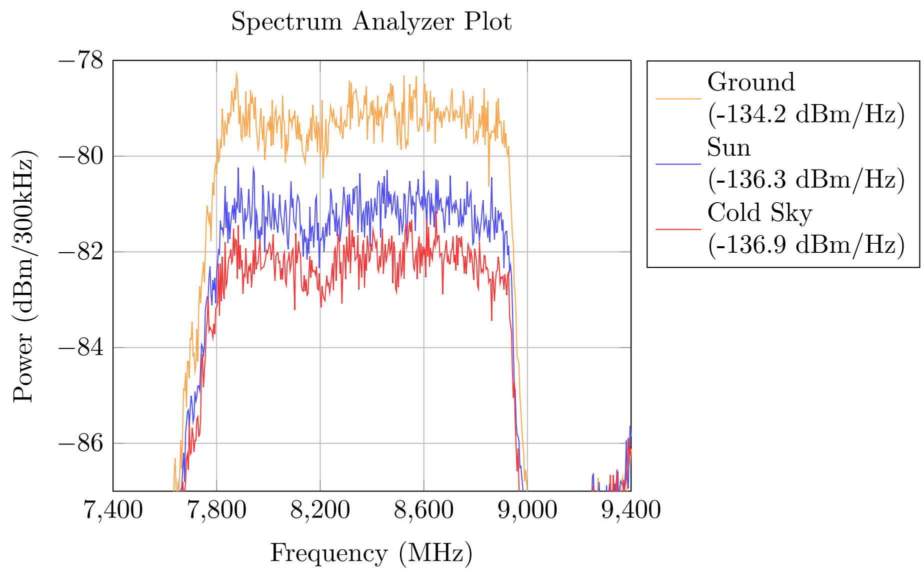

Figure 6: Signal trace with 41 dB of gain from two ZX60-06203ALN+ LNAs.

Mean channel power measurements on the Anritsu from 7.95 to 8.85 GHz show a 2.7 dB ground/sky delta and a 0.6 dB sun/sky delta. It is difficult to calculate the RF power received from the ground prior to measurement, however, the sun/sky delta is well within range of expected values.

5.2 Final Thoughts

These measurements and the preceding calculations were the basis for design decisions in Section 3.2. It's possible other architectures would operate more favorably but further testing is required. Some ideas to increase sun/sky dynamic range would be to sum the two polarized feeds from the antenna via combiner or to create dual-channel rectifier and combine the outputs via summing op-amp, however, these remain as hypotheses at the time.