SKA – RRI Bridging

RF Front-End Receiver system for TPM Digital Beamforming Evaluations

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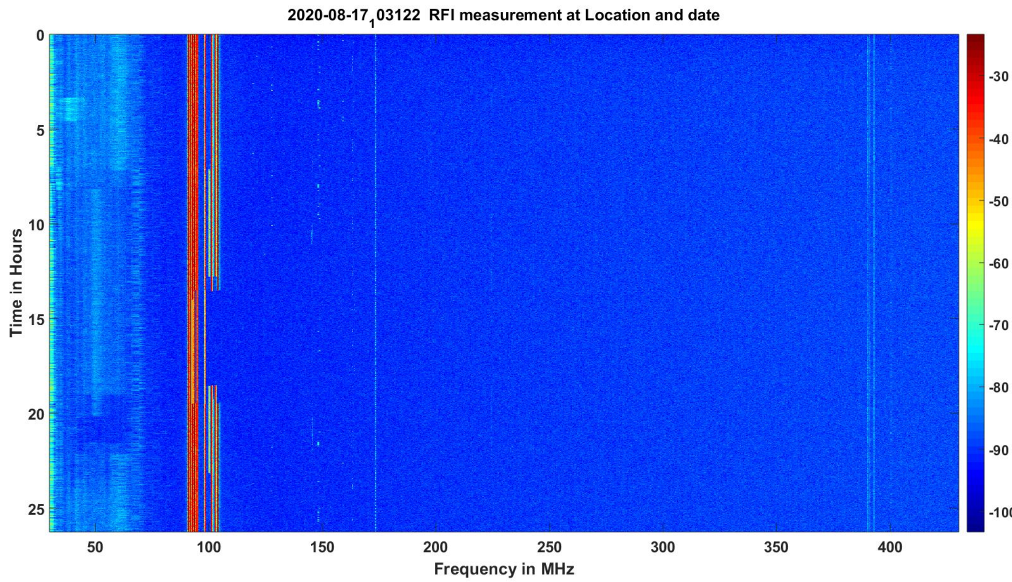
Introduction

The SKA-LOW radio telescope will be a low-frequency aperture array in the frequency range 50-350 MHz composed by around 130,000 antenna elements spread over tens of kilometers and located in Western Australia. Its scientific objectives will prioritize studies of the Epoch of Reionization and pulsar physics. Each single antenna covers full frequency range, digitization process of the received RF signal is technically cumbersome near the antenna, hence it's planned to beamform the 16 antenna RF signals into a single or multiple beams before correlation. Digital beamforming is much more flexible in forming of beams on arbitrary positions on the sky of different bandwidths. Hence the RF signal from the antenna (LNA) is planned to transport to ADC for digital beamforming through an analog conditioning section containing analogue gain and filtering components which shapes the band for successful digitization. In view of this situation, a prototype RF front-end receiver having RFI free bandwidth in the frequency range 185MHz to 355MHz has been built for evaluation of digital boards.

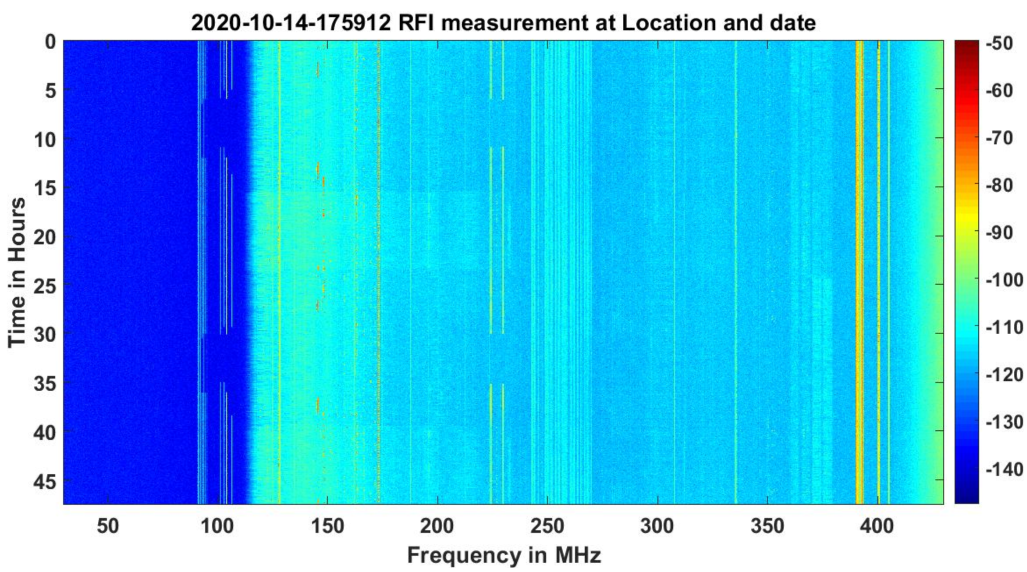
Motivation

To evaluate the digital tile processing modules at RRI, requirement of a high dynamic range low-noise, high bandiwdth front-end receiver system in the frequency range 50-350MHz, which should work in a highly RFI occupaid Bangalore environment. The RFI situation was studied and the analyzed as a separate experiment prior to this activity the requirement of an RF frequency band in the frequency range 50-350MHz reasonably RFI free with required total RF power for ADC digitization



Water fall plot showing the RFI signal strength in the frequency spectrum from 30MHz to 430MHz, including FM band.

(Courtesy : **Internal Technical Report No. : 2, Radio Frequency Interference Measurement at RRI Bangalore, 10 / 02 / 2021)**



Water fall plot showing the RFI signal strength in the frequency spectrum from 110MHz to 430MHz, excluding the FM band.

(Courtesy : **Internal Technical Report No. : 2, Radio Frequency Interference Measurement at RRI Bangalore, 10 / 02 / 2021)**

From the above water fall plots, it's concluded that the preliminary data shows strong 90-110MHz FM band and it's power is -20dBm. An attenuation of greater than 40dB is required to reject FM band for radio astronomical observations. The average RFI power in the frequency range 120MHz to 400MHz is about -85dBm. The frequencies 175MHz and 380MHz are consistently present at all the times. The average RFI total power within the frequency range 120MHz to 400MHz is typically -60dBm From the above plots, it can be inferred that front-end system can be designed for carrying out sky observations in the band from 180MHz to 380MHz with an headroom of 20dB for RFI. This can be ensured by choosing good roll off low-pass and high-pass filters by filtering the FM band, 175MHz and 380MHz frequencies. Hence, we propose to work with this numbers for a possible low frequency receiver system design for use in the campus, may be nearly an octave band from 180MHz to 350MHz.

Implementation

RF Front-End Receiver system :

The proposed front-end receiver system in the frequency range 180MHz to 360MHz composed of two sections. The first section is the RF front-end receiver system which processes the incoming RF signal from the antenna. Then the RF band is transported using optical fiber transmitter for further processing with the second section. The first front-end receiver section was simulated, designed and implemented. The block diagram of the RF front-end receiver section-1 is as shown in the figure 1.

Receiver Section-1

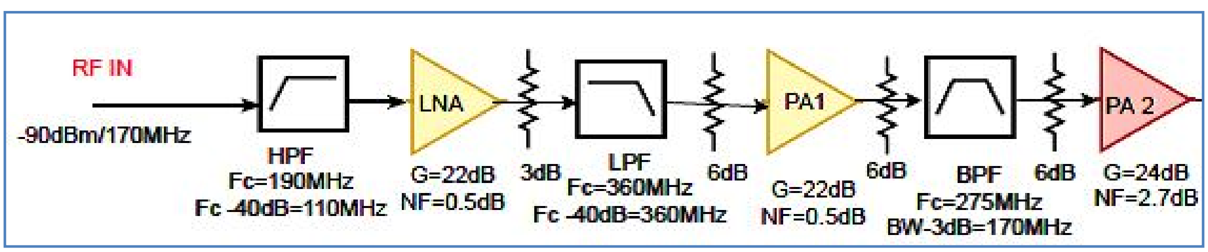


Figure 1. SKA-RRI Bridging RF front-End Receiver system Block diagram

The receiver system consists of a low- noise amplifier, post amplifiers, high roll-off high-pass, low-pass filters and a band-pass filter to reject the RFI signals on either side of the required frequency band ranging from 185MHz to 355MHz.

1.1 High-Pass Filter

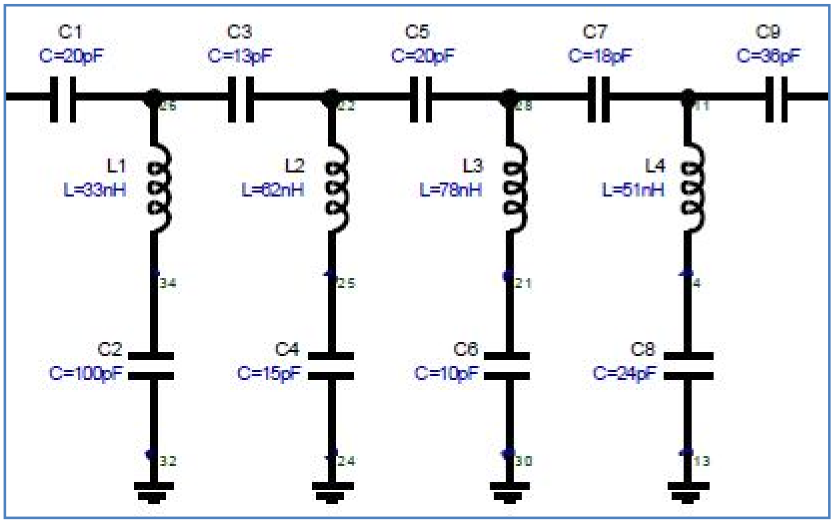


Figure 2. Circuit diagram of the 185MHz High-Pass Filter

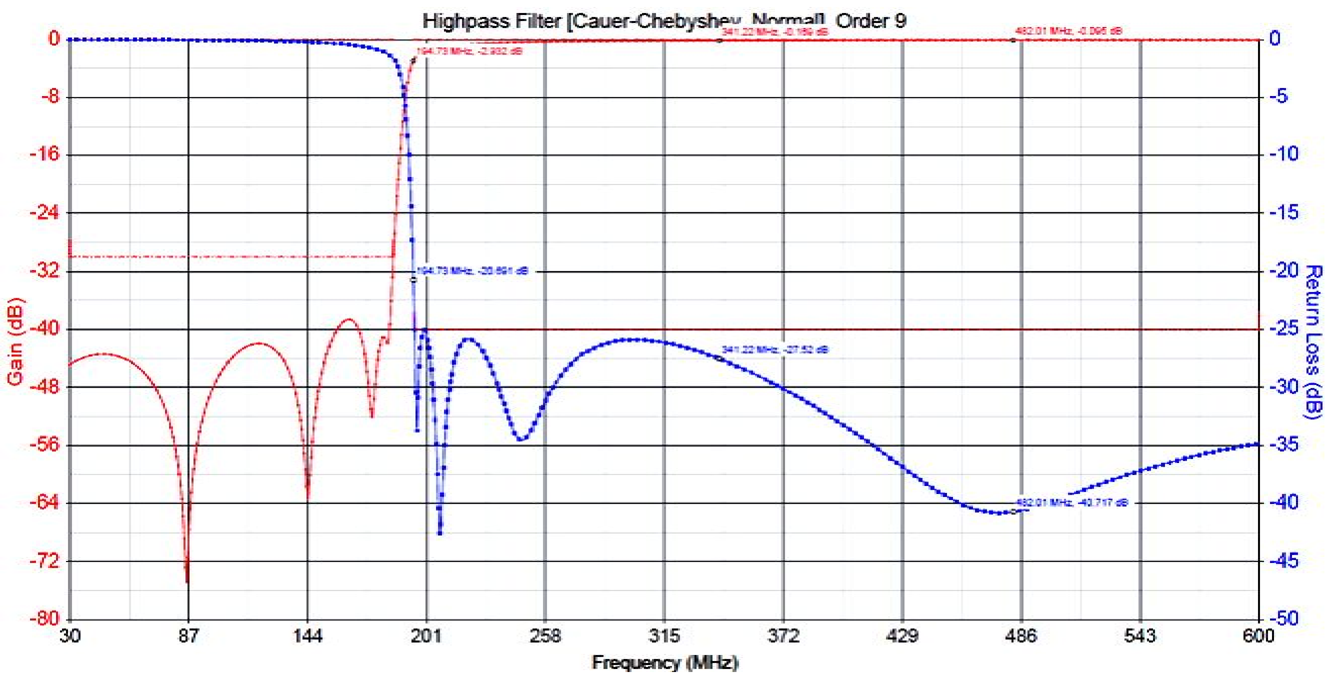


Figure 2a. Simulated S21 and S11 response of the High-Pass Filter

The high- pass filter is the first section of the front-end receiver system designed to have 3dB cut-off frequency at 185MHz. It is a 9th order minimum inductance topology filter. The filter is designed with cauer chebyshev characteristics with 40db stop band attenuation and 0.1 db ripple in the pass band. Since inductors are usually larger, more expensive due to their higher quality factor is incorporated as the first choice. The filter is tuned and optimized for minimum insertion loss over the pass band frequency range 185-500MHz, so that the noise figure of the entire system is least affected. The 3dB cut-off frequency of the filter is tuned at 185MHz with reasonably good VSWR of 1.4:1 over the band. The simulated S21 and return loss S11 response is as shown in figure 2. The detailed circuit diagram with component specifications is shown in the annexure.

Measured Frequency Response of the 185MHz High-pass filter

Figure 2b. Measured S21 (Transmission) and S11 (Rreturn Loss) response of the tuned and implemented Hih-Pass Filter.

The high-pass filter is implemented with designed components having high Q values. The 3dB lower cut-off frequency is achieved at 185MHz. The stop band attenuation of better than 35dB upto 110MHz, so that the RFI frequencies upto 180MHz along with the strong FM signals are rejected by 30dB attenuation. The insertion loss in the pass band is about 0.8dB. The measured frequency response of the implemented high-pass filter is as shown in figure 2a.

1.2 Low-Noise Amplifier section

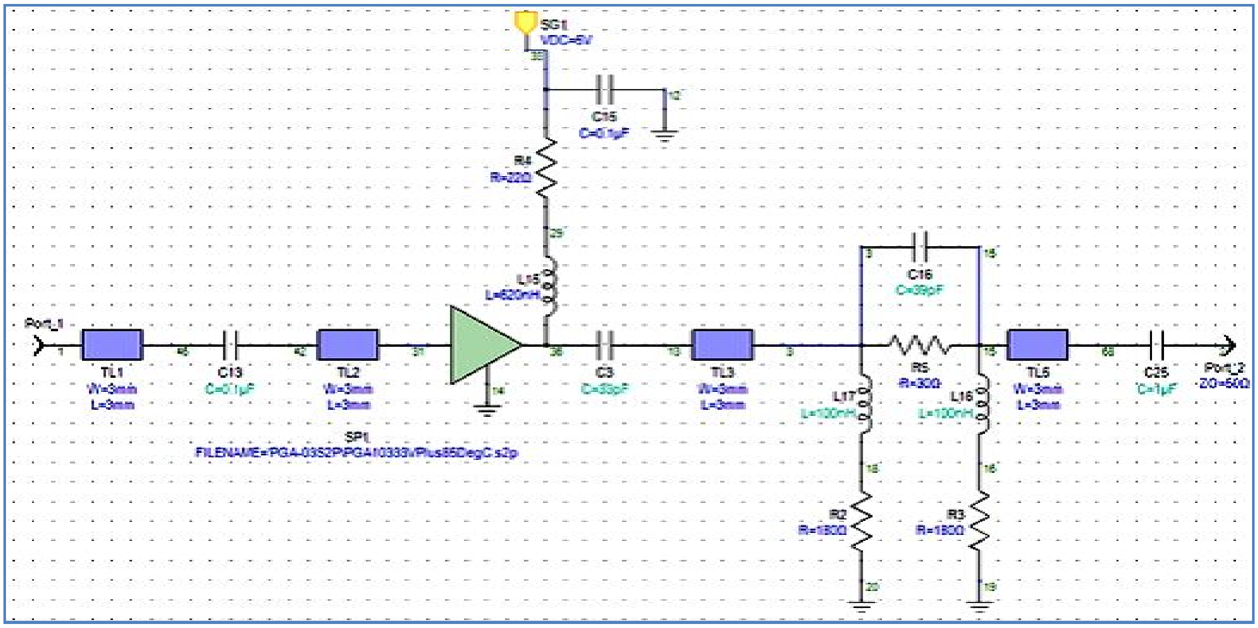


Figure 3. Schematic diagram of the Low-Noise amplifier with gain compensation circuit

The low-noise amplifier is a high dynamic range monolithic microwave integrated (mmic) amplifier PGA-103+, having gain of 20dB and the noise figure of 0.5dB in the frequency range from 120MHz to 400Mhz. The coupling capacitors is chosen is such a way that the RF signals from as low as 50MHz to 400MHz are amplified and passed by the amplifier. To equialize the droop in the gain over the frequency range from 120MHz to 400MHz, a gain compensation circuit is incorporated. This circuit, the higher gain at the lower frequencies is equialized to lower gain at higher frequencies which is about 20dB, so that the gain is reasonably maintained flat in the frequency range 120MHz to 400MHz. The circuit diagram of the low-noise amplifier with gain compensation circuit is as shown in figure 3. The simulated frequency response is as shown in figure 3a.

To achieve high dynamic range and low noise figure as per the data sheet of the amplifier, the device voltage and current consumed by the amplifier are set as follows :

Vdd -- +3.3V, Idd --- 70mA.

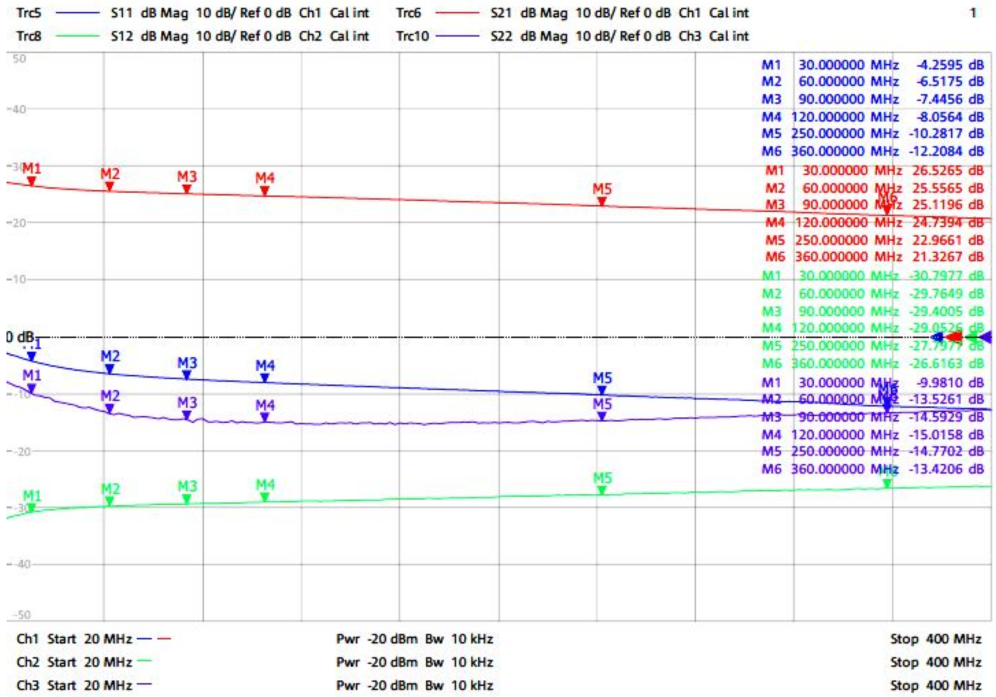


Figure 3a. Simulated S21,S11,S22,S12 frequency response of PGA-103 Low-Noise Amplifier.

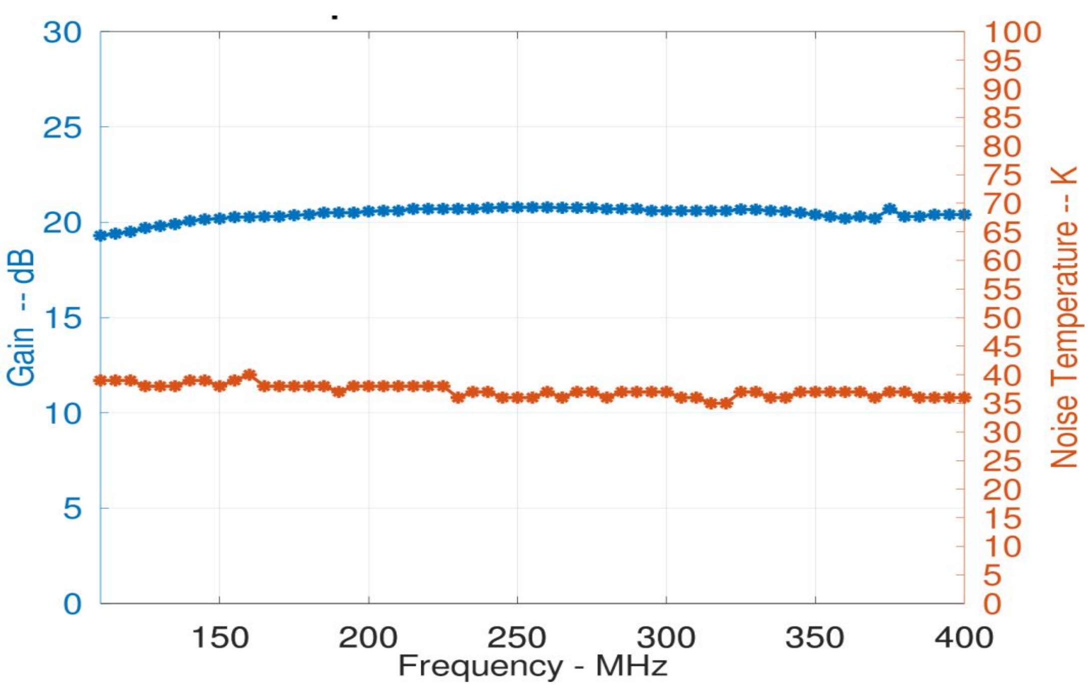


Figure 3b . Measured Gain and Noise Temperature of the implemented Low-Noise Amplifier.

The measured frequency response of the implemented low-noise amplifier section is as shown in figure 3b. It is observed from the plot that, the gain is flat about 20dB-21dB and 0.5dB (35K) noise figure is achieved in the required frequency range from 185MHz to 400MHz.

1.3 Low-Pass Filter

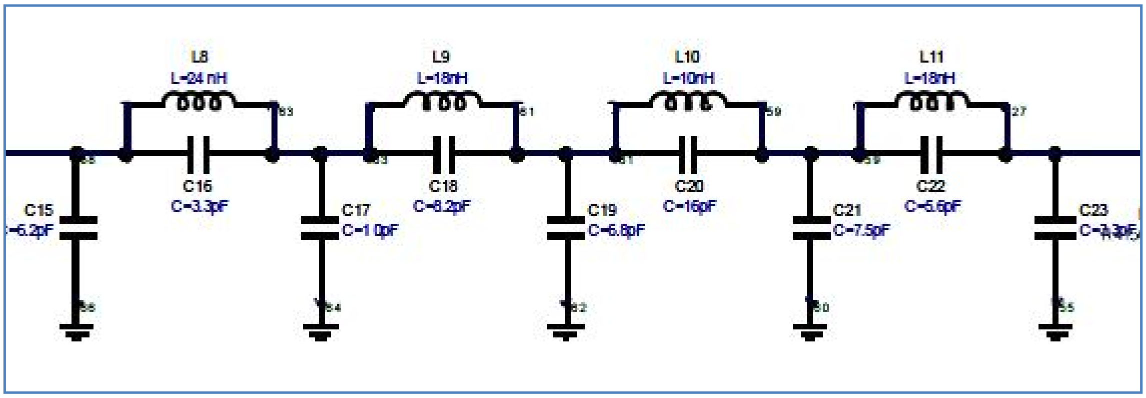


Figure 4. Circuit diagram of the 185MHz High-Pass Filter

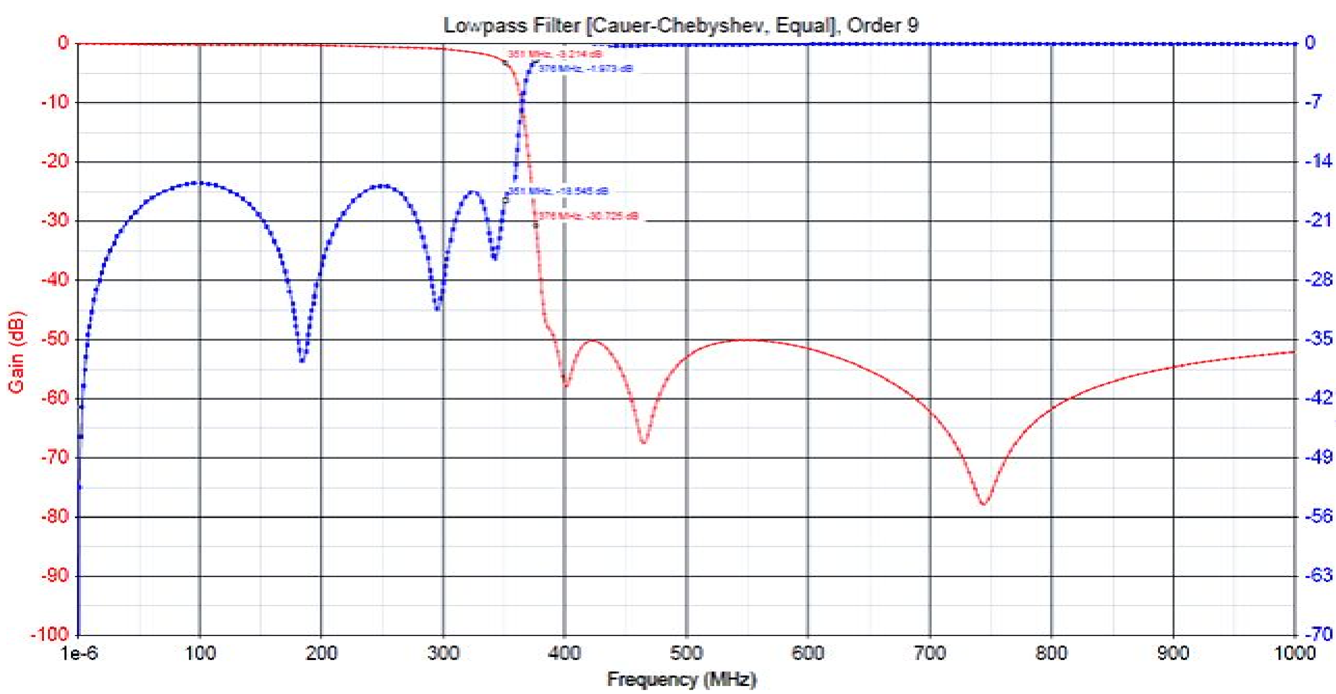


Figure 4a. Simulated Frequency response S21 and S11 response of the Low-Pass Filter

The Low- pass filter section of the front-end receiver system is designed to have 3dB cut-off frequency at 355MHz. It is a 9th order minimum inductance topology filter. The filter is designed with cauer chebyshev characteristics with 40db stop band attenuation and 0.1 db ripple in the pass band. Since inductors are usually larger, more expensive due to their higher quality factor is incorporated as the first choice. The filter is tuned and optimized for minimum insertion loss over the pass band frequency range DC-355MHz, so that the noise figure of the entire system is least affected. The 3dB cut-off frequency of the filter is tuned at 350MHz with reasonably good VSWR of 1.4:1 over the band. The simulated S21 and return loss S11 response is as shown in figure 4a. The detailed circuit diagram with component specifications is shown in the annexure.

Figure 4b.   Measured Frequency S21 and S11 Response of the implemented Low-pass filter

The measured response of the implemented low-pass filter is as shown in figure 4b. The achieved higher frequency -3dB cut-off is at 355MHz with expected insertion loss and return loss of about 0.5dB and 15dB respectively in the pass band frequency upto 350MHz. The rejection of the higher frequencies above 360MHz stop-band is about better than 40dB level.

1.4 Band-Pass Filter

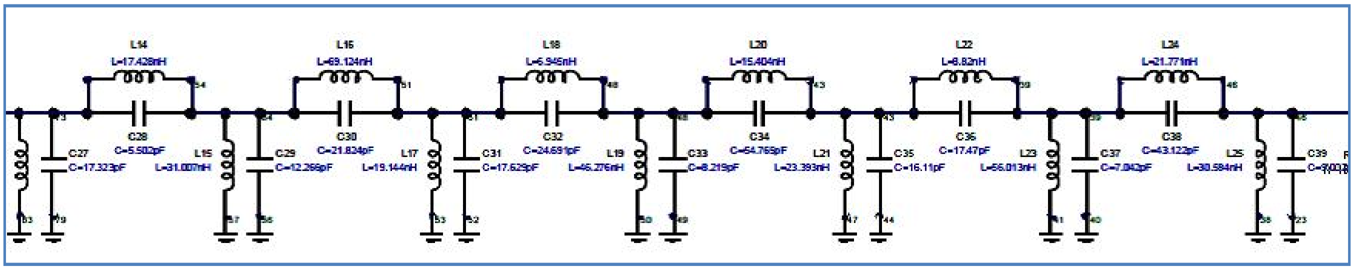


Figure 5. Band-Pass Filter circuit diagram

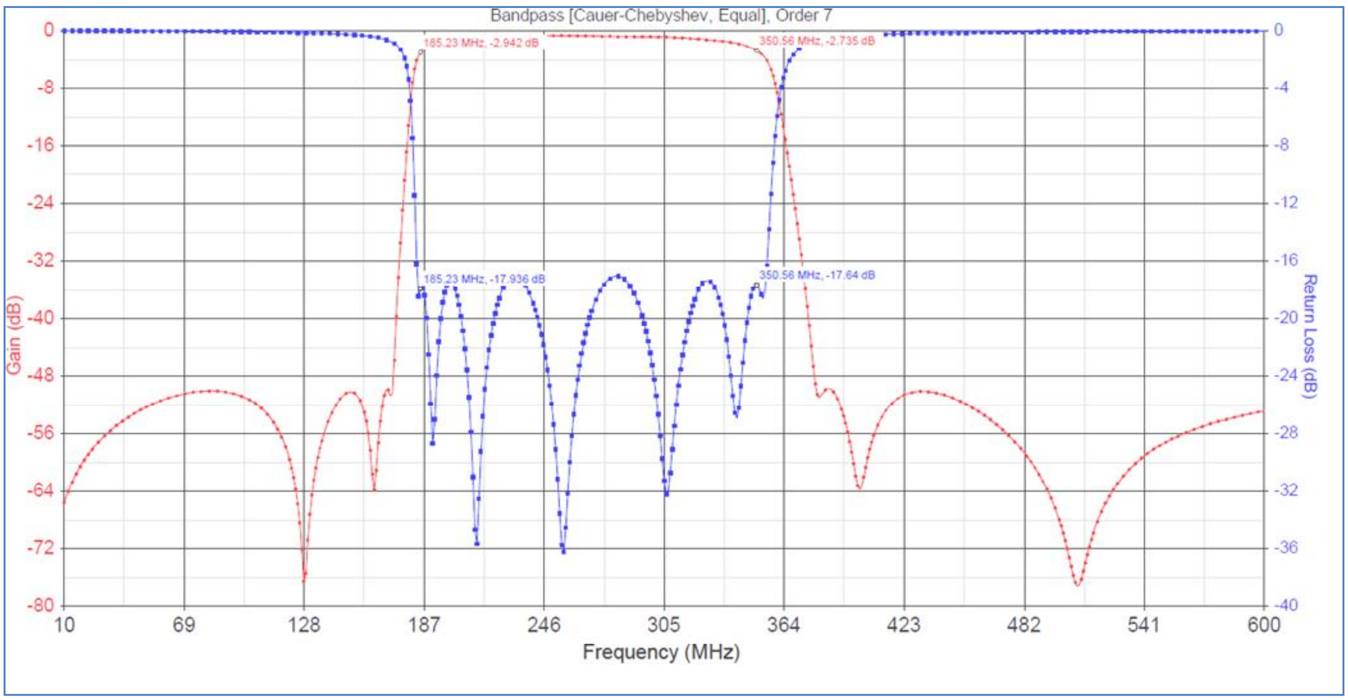


Figure 5a. Simulated Frequency response S21 and S11 response of the Band-Pass Filter

The band- pass filter plays as one of the major role in the receiver system.. It is 7^{th} order chebyschev topology cauer type filter and is designed to have lower -3dB cut-off frequency at 185MHz and upeer -3dB cut-ff frequency at 355MHz. The pass-band frequency bandwidth is around 170MHz with better than 40db stop band attenuation on either side of the pass-band freuqncy range.. The filter is tuned and optimized for minimum insertion loss over the pass band frequency range 185-335MHz, so that the noise figure of the entire system is least affected. The simulated S21 and return loss S11 response is as shown in figure 5a.

1.5 Post Amplifiers

The post amplifiers are employed in the RF chain to meet the required signal frequency band channel power for further digitization. Amplifiers are built using high dynamic range linear amplifier GALI-74+ mmic chip, having gain of 24dB in the passband range with noise figure of 2.7dB.

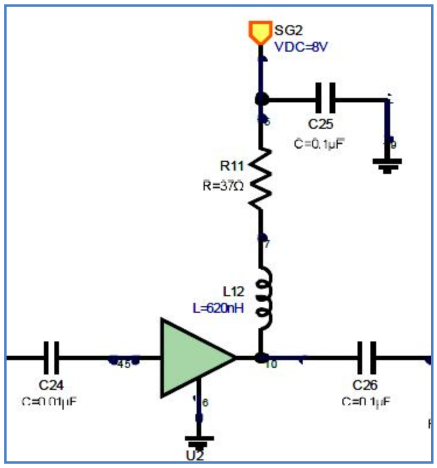


Figure 6. Circuit diagram of the GALI-74+ Post-Amplifier

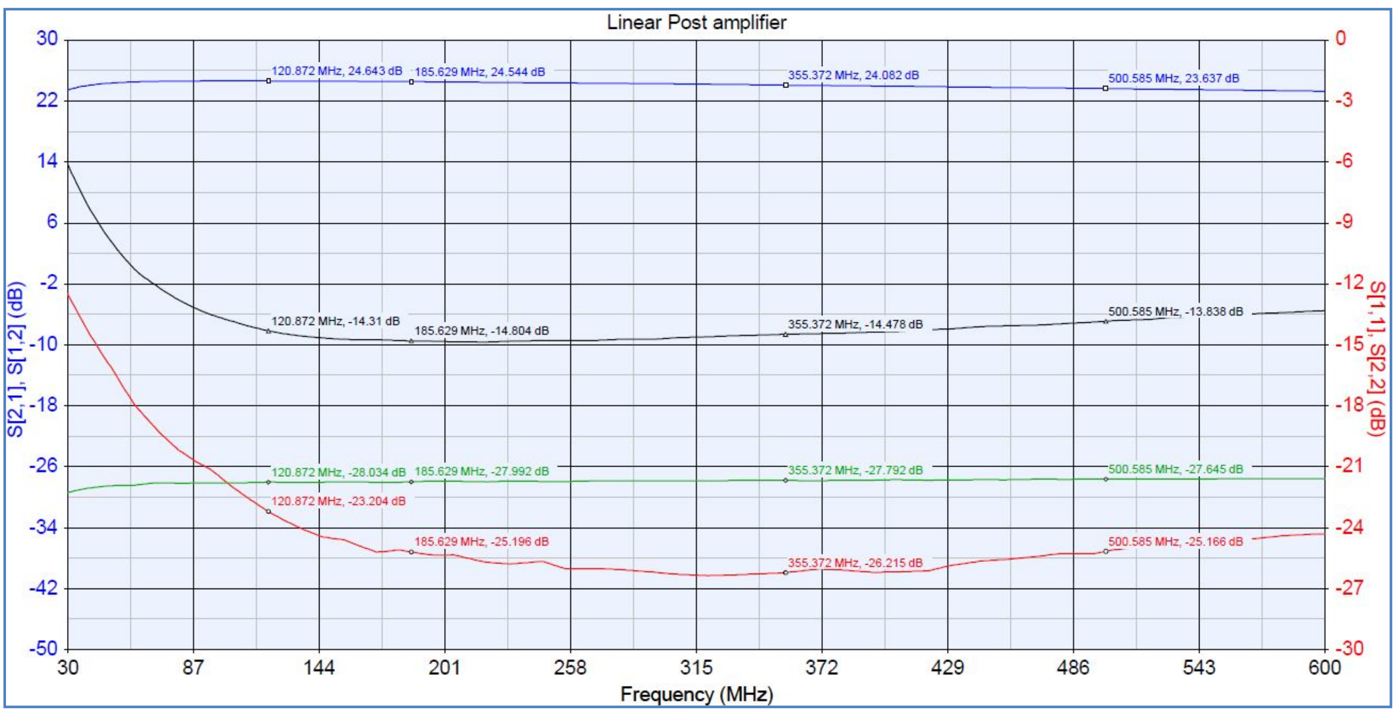


Figure 6a. Simulated frequency response of the post-amplifier

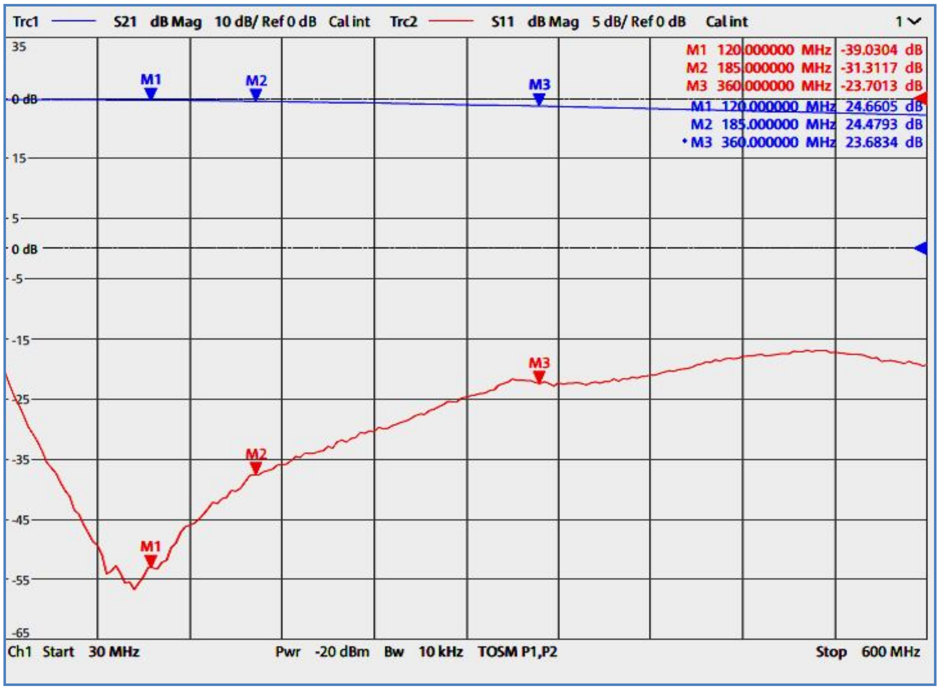


Figure 6a. Measured frequency response S21 and S11 of the GALI-74+ post-amplifier

From the measured plot, it is observed that the gain S21 of the pre-amplifier is around 24dB over the frequency from 30MHz to 400MHz and the return loss S11 is better than 20dB.

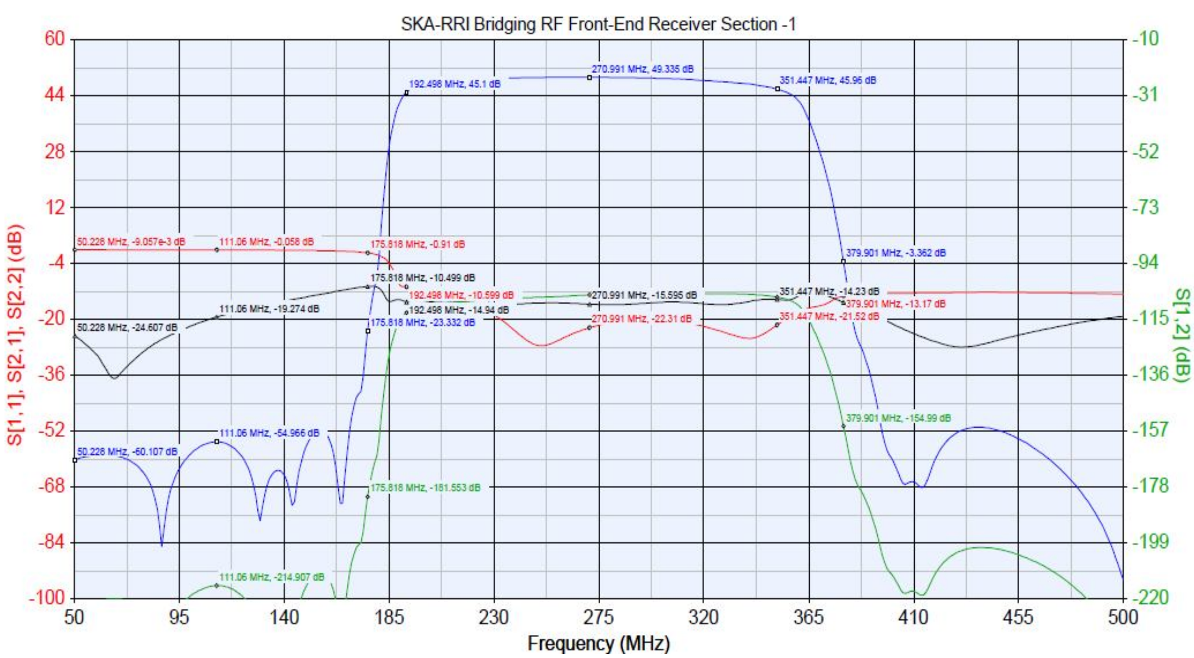


Figure 7. Simulated Frequency response S21 and S11 response of the complete Front-End Receiver Circuit

2. Front-End Receiver Section-1 Implementation

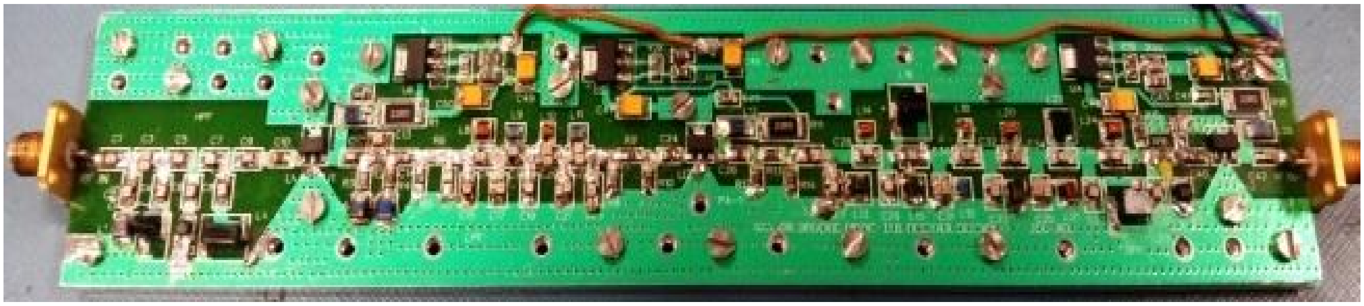


Figure 8. Implemented SKA-RRI Front-End Receiver section

The complete front-end receiver with all the amplifiers. Analog conditioning and attenuators as per the design flow has been implemented on a single FR4 glass epoxy laminate as shown in figure 8.. Two SMA RF connectors are soldered, one for feeding RF signal Input and another for RF output. The low-noise amplifier PGA-103+ post RF amplifiers GALI-74+ are biased with dedicated individual regulators and resistors to derive the appropriate Vdd device voltage for it's proper operation.

2. Front-End Receiver Section-1 Characterization

2.1 S – Parameters Measurements

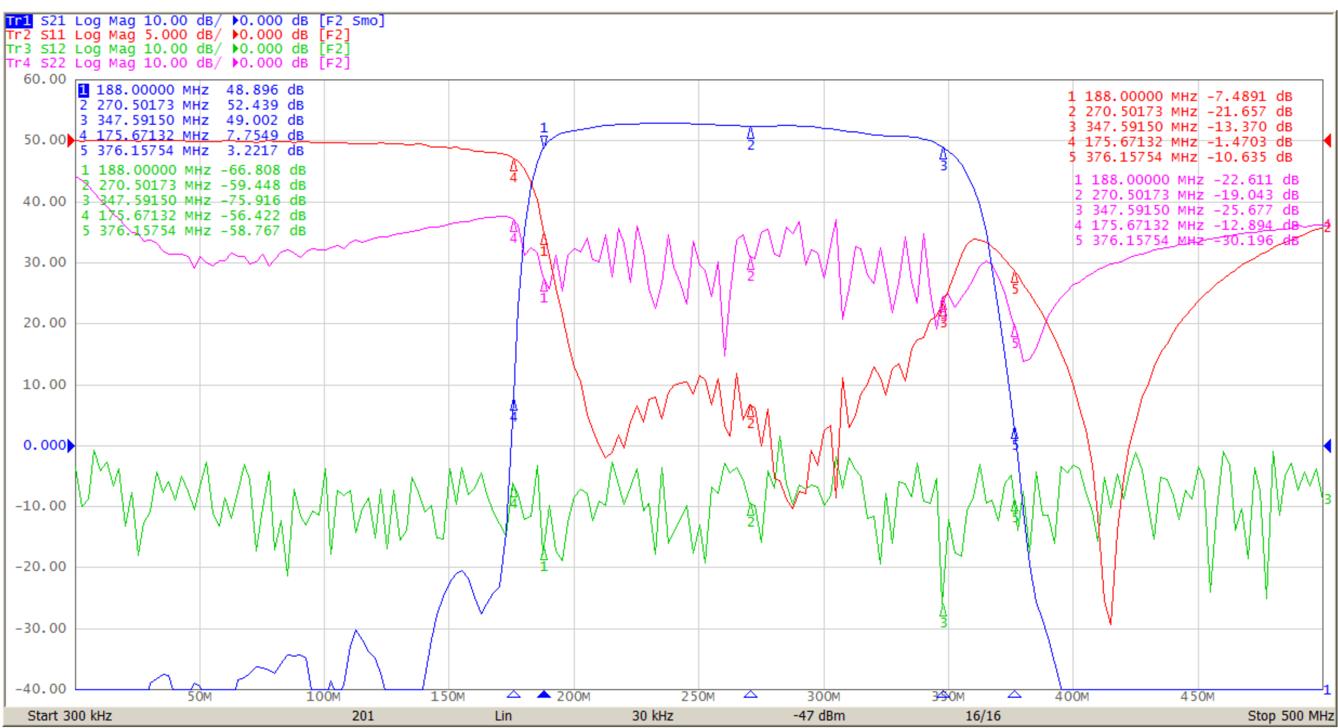


Figure 9. Measured S-Parameters of the Front-End Receiver section-1 (S21, S11, S12 & S22)

The characterization of the front-end receiver has been done using Vector network analyzer. The frequency response of it is as shown in figure. The operating pass-band 3dB frequency bandwidth is around 170MHz centered around 270MHz. The system gain S21 of the receiver system is around 53dB with a flatness variation of +/- 1.5dB. The achieved S11 input and output return loss S22 is better than -12dB and -20dB respectively. The 30dB Bandwidth is around 191 MHz and 50dB bandwidth is around 200MHz. The rejection at 165MHz and below is better than 43dB level, so that the RFI including FM frequencies are suppressed by greater than 60dB. On the other side of the band, the high frequency rejection above 360MHz higher than 50dB is achieved as shown in figure 9.

2.2 Noise Figure Measurement of the Front-End Receiver system

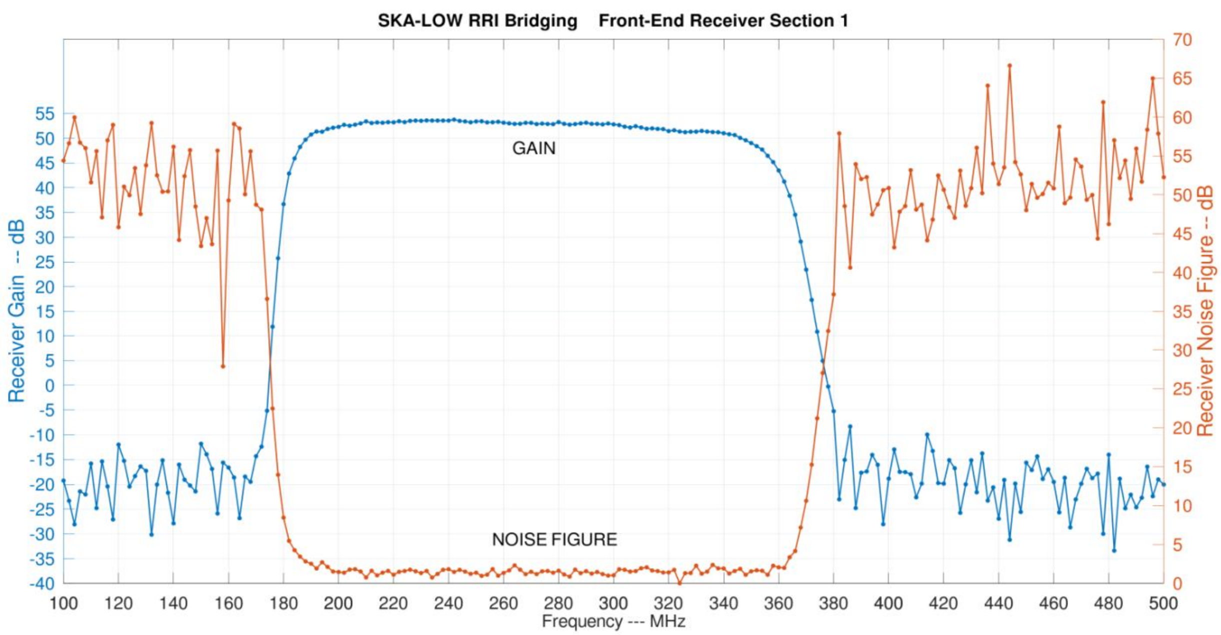


Figure 10. Measured Gain and Noise Figure plot of the front-end receiver section-1

The gain and noise figure measurements were carried out using Hp Noise figure analyzer in the designed frequency range from 180MHz to 360MHz.   The noise figure is almost consistently 1.3dB over the full range of frequency band as shown in figure 10.

<u>Noise Floor</u>

In general Receiver Noise floor dBm = 10* $\log_{10}$ (k × To × 1000) + NF dB + 10 $\log_{10}$ BW

In this Receiver case the Noise figure is 1.35 dB and the Bandwidth is = 165 MHz, To = 300K

So the Rx Noise floor (dBm) =

$10 * \log10(1.38\times10^{-23} \times 300 \text{ x } 1\times10^{3}) + 1.35\text{dB} + 10* \log(165\times10^{6}) = -90.65$ dBm.

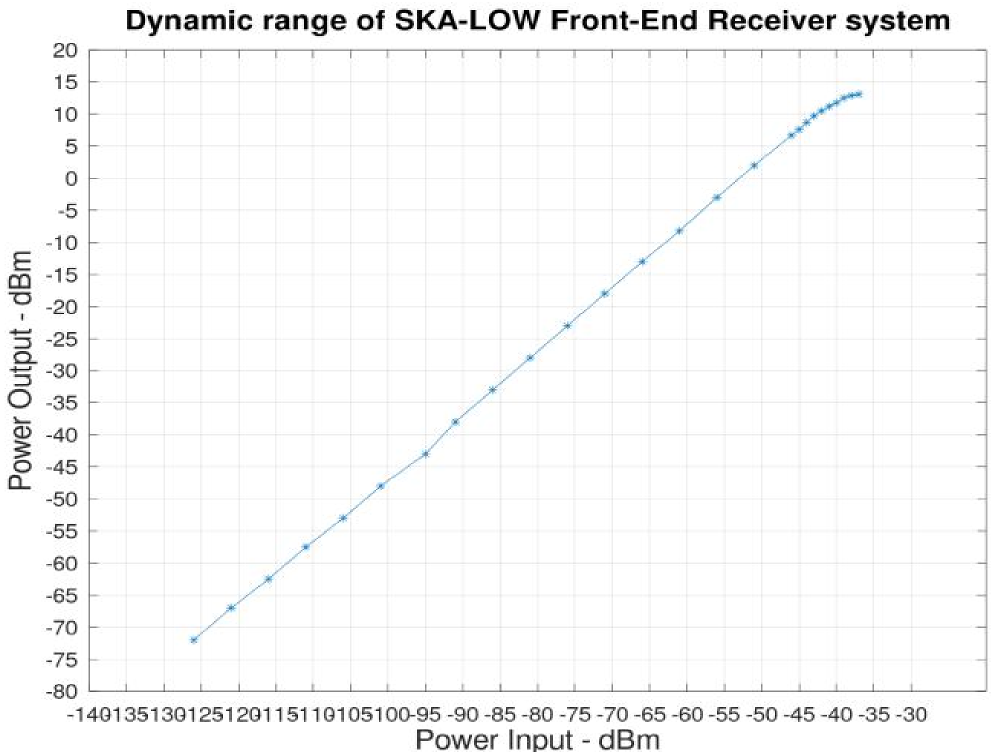


Figure 11. Measured dynamic range of the of the RF front-end Receiver system section-1

Dynamic Range means capability of the Receiver can operate over wide range of input power levels. Receiver's Output starts to saturate if the Input is above the range, and other direction the noise dominates.

The front-end receiver was fed with two CW tones separated by 1MHz resolution power combined and measured the dynamic range by increasing the power amplitude linearly. The dynamic range plot is as shown in figure 11 and it is accessed around 80dB. The output Intercept point (OIP3) is calculated as +30dBm.

So here the Measured Rx P1dB point is --- +13 dBm and the measured Dynamic Range is around 80dB..

2.3 Housing of the implemented Front-End Receiver System

Figure 12. Photograph of the SKA-RRI bridging RF Front-End Receiver system Section-1

FR4 Printed Circuit Board size → L X W → 205mm X 40mm.

Aluminium Tube diameter size → 50mm

Tube length with End Caps → 220mm

The aluminium tube serves as an RFI shielding house, where in the strong FM band signals are almost suppressed by 50 – 60dB level, and unwanted spurious frequencies due to inter modulation distorsion are avoided, as per the spectrum analyzer measurements done in the filed as shown in the plots below in the figure 12.

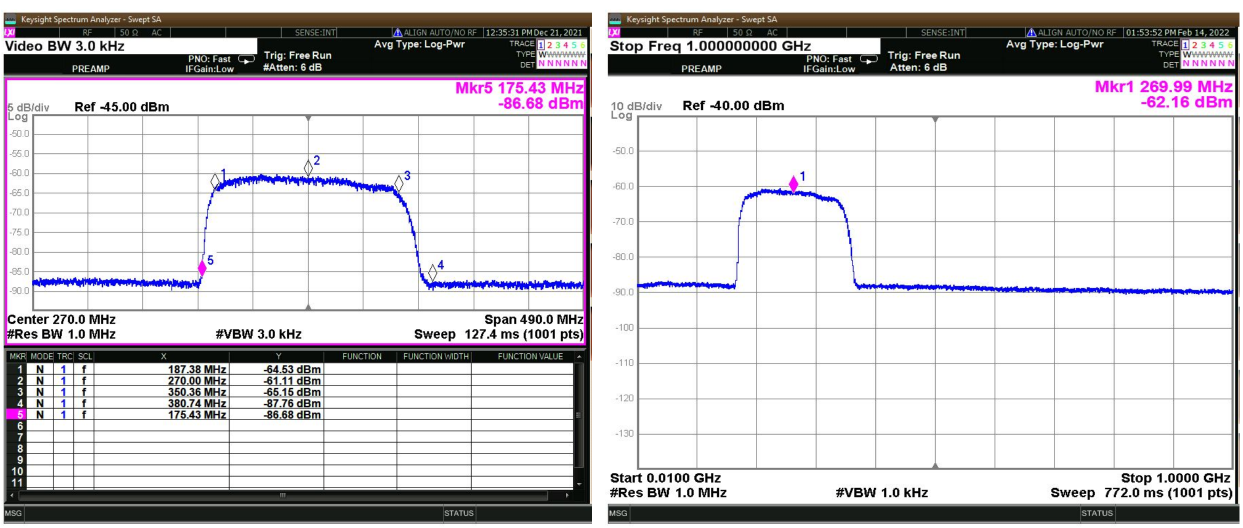


Figure 13. Front-End Receiver 165MHz frequency band spectrum measurements.

The total channel power measured in the frequency bandwidth of 165MHz is around -38dBm.

Evaluation of the Implemented Front-End Receiver system section-1 in the Field

Figure 14. Testing view of the Front-end receiver system with LPDA on EEG Terrace

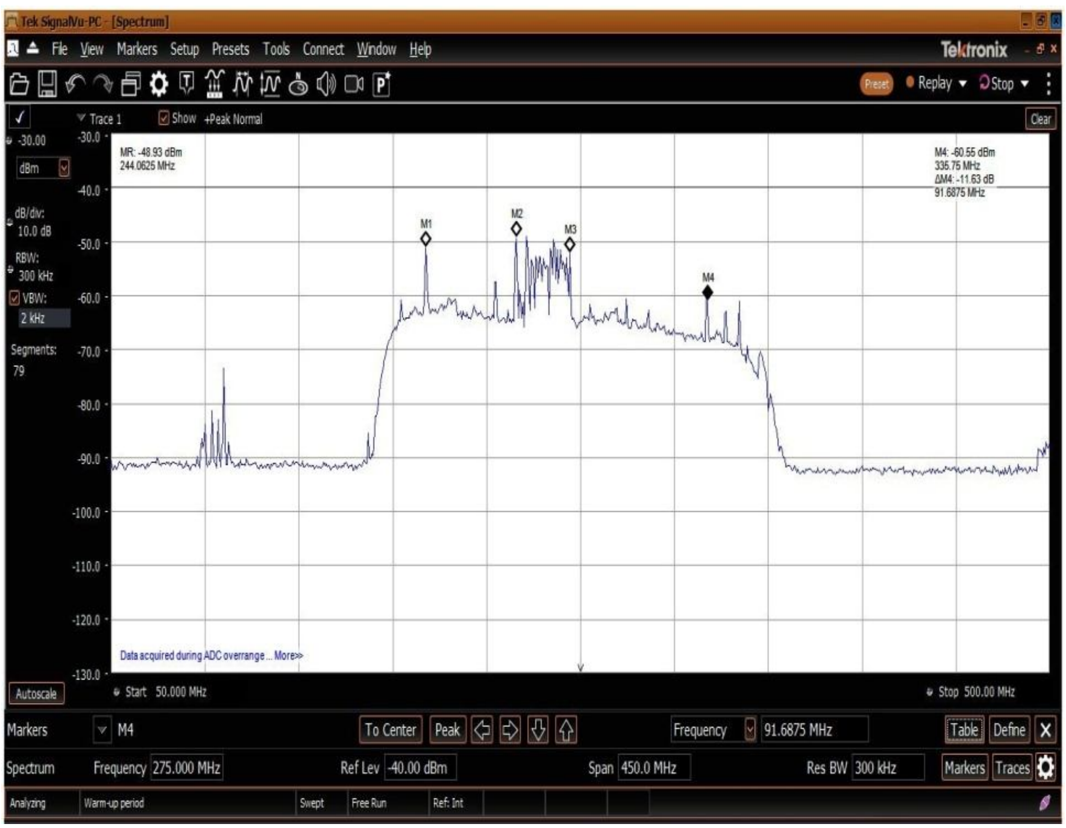


Figure 15. The 165MHz RF band spectrum measured on EEG terrace

It’s observed from the RF spectrum that RFI signals below 180MHZ are suppressed by 50 dB.

Considering strong RFI within the band as CW tones, their total output power in the order of -40 dBm, and measured OIP3 of +30dBm, the 3rd order IMD distorsion can be computed using the equation

OIP3 = P_{OUT} + $\Delta P/2$, where ΔP is the difference in dB between carrier frequency to the 3rd order frequencies, Pout is the currently operating output power of the recever

So ΔP will be ~140dB below the fundamental RFI frequency.

The allowable head room with which the Rx can handle of around 40dB.

3. Conclusions

Accomodated two front-end Receiver boards in a single tube housing for dual polarization observations at RRI Bangalore.

The implemented RF Front-end receiver section-1 has been interfaced with the fiber interface.

Progressing towards implementing 120MHz-360MHz, 240MHz bandwidth front-end receiver section-1, for use at Gauribidanur field station.

Implementing the receiver section-2 under progress.

Acknowledgements

We thank Ibrahim and his colleagues from basement workshop in supporting in making the alumimum shielded tubes for accommodating the front-end receiver PBCs.