Receiver Characteristics

Ambika S.[1], Anaya Dixit[2], Bhargava Ganesh Bhat[3],
Dhairya Kotecha[4], Pranjal Sengupta[5], Saanvi Pande[6]

[1] PSG College of Arts and Science, Coimbatore
[2] Indian Institute of Technology Kharagpur
[3] Poornaprajna College, Udupi
[4] Indian Institute of Technology Roorkee
[5] Indian Association for the Cultivation of Science, Kolkata
[6] Fergusson College, Pune

15th December 2025

1 Introduction

In radio frequency (RF) systems and radio astronomy, the efficient transportation of signals between modules depends on the use of specialized transmission lines, such as coaxial cables, which are modeled as a series of lumped inductors and capacitors. To ensure maximum power transfer and prevent signal degradation, the characteristic impedance of these lines must be precisely matched with both the transmitting and receiving devices. Any impedance mismatch triggers a reflection, where the returning wave superposes with the forward signal to create a frequency-dependent interference pattern known as a standing wave. By measuring the spectral separation between the consecutive peaks or dips of these standing waves, researchers can calculate the time delay and accurately determine the physical distance to a mismatch or the total length of a cable. This phenomenon is also characterized by the voltage-standing-wave-ratio (VSWR), where a value of unity signifies an ideal, reflection-free connection.

2 Theory

2.1 Impedance Matching and Frequency Dependence in a Receiver

In radio-frequency (RF) receivers, signals are carried from one component to another using transmission lines such as coaxial cables. These signals are not simple DC but rapidly oscillating electromagnetic waves. Because of this, how well a signal travels through a cable depends on the signal strength and also on how the cable and connected devices are matched to each other.

2.1.1 What is Impedance and why should it be matched?

Impedance is the RF equivalent of resistance. While resistance describes how a circuit opposes direct current, impedance describes how a circuit opposes alternating signals and depends on both resistance and frequency. Every transmission line has a fixed value called characteristic impedance, which depends on the cable's geometry and dielectric material. For efficient signal transfer, the impedance of the signal source, the transmission line, and the load (receiver input) should all be equal. This condition is called impedance matching. When impedances are matched, maximum power is transferred, and the signal travels smoothly along the cable. If the impedances are not matched, part of the signal is reflected back toward the source. This reflected signal interferes with the forward-traveling signal, producing standing waves along the cable. These standing waves cause the measured signal amplitude to vary with position and frequency, which is undesirable in receiver systems because it distorts the true signal.

2.1.2 Frequency Dependence and Standing Waves

When a reflected wave combines with the incident wave, the resulting signal amplitude depends on the phase difference between the two waves. Since the phase depends on frequency, the measured amplitude varies periodically with frequency. As the frequency is swept, maxima and minima appear in the observed signal. This pattern is the standing wave pattern.

2.1.3 Estimating Wavelength and Cable Length

The separation between consecutive maxima (or minima) in frequency is directly related to the time delay between the forward and reflected signals. This time delay depends on how long it takes for the signal to travel to the reflecting point and back.

If Δf is the frequency separation between two successive maxima (or minima), the round-trip time delay τ is given by:

$$\tau = \frac{1}{\Delta f}$$

The distance to the reflecting point (or the cable length in case of an open end) can then be calculated using:

$$x = \frac{v \times \tau}{2c}$$

where v is the speed of signal propagation in the cable. This speed is usually less than the speed of light and is described by the velocity factor of the cable. Using this method, the physical length of a cable can be estimated from purely frequency-domain measurements.

2.2 Linear region of a Low Noise Amplifier (LNA)

A Low Noise Amplifier (LNA) is one of the most critical components of a receiver. Its purpose is to amplify very weak incoming signals while adding as little noise as possible. The response of an LNA to different input signal amplitudes can be divided into three distinct regions: the noise-dominated region, the linear region, and the non-linear (compression) region.

2.2.1 Very Low Input Amplitude: Noise-Dominated Region

When the input signal amplitude is extremely small, it may be comparable to or even smaller than the internal noise of the amplifier. Every electronic component generates noise due to thermal motion of charge carriers and device physics. In this region, although the LNA is technically amplifying the signal, the output is dominated by noise rather than the actual input signal.

As a result, the output does not increase noticeably with small increases in input amplitude. On a plot of output amplitude versus input amplitude, this region appears as an initial nearly flat or poorly defined section, where a clear straight-line relationship is not observed. This behavior explains why amplification seems ineffective and noisy at very low input levels.

This region is important in receiver design because it defines the minimum detectable signal. The role of an LNA is to minimize this noise contribution so that weak astronomical or communication signals can rise above the noise floor.

2.2.2 Linear Amplification Region

As the input signal amplitude increases beyond the noise floor, the LNA enters its linear operating region. In this region, the output signal amplitude is directly proportional to the input amplitude. This produces a straight-line relationship between input and output, indicating constant gain.

In the linear region:

- The amplifier gain remains constant
- The waveform shape is preserved

- No additional frequencies are generated

This is the desired mode of operation for receiver systems. During the experiment, moderate input amplitudes showed this clear linear response, confirming that the LNA was operating correctly and without distortion.

2.2.3 High Input Amplitude: Non-Linear and Saturation Region

When the input signal amplitude is increased further, the LNA begins to leave the linear region. This happens because the active devices inside the amplifier (such as transistors) have physical limits on voltage swing and current handling.
In this non-linear region:

- The output amplitude no longer increases proportionally with input
- Gain begins to decrease (gain compression)
- Waveform distortion occurs

At sufficiently high input levels, the amplifier reaches saturation, where further increases in input amplitude produce little or no increase in output amplitude. Non-linear behavior also leads to the generation of unwanted harmonics and inter-modulation products, which can interfere with nearby frequency channels and degrade receiver performance.

3 Observations and Calculations

3.1 Data Acquisition

RMS Input–Output Log Table (CSV)

3.2 Tabular Column

Tabulation for Maxima

Sn.no	l_th (m)	f_1 (MHz)	f_2 (MHz)	Velocity Factor	l_exp (m)	Error
1	20.4	9.717	5.428	0.66	21.282	1.391
2	36.4	8.394	2.784	0.66	35.6505	-0.7495
3	46.6	8.506	2.167	0.66	46.663	0.063
4	57(approx)	8.856	1.741	0.66	56.239	-0.75075

Tabulation for Minima

Sn.no	l_th (m)	f_1 (MHz)	f_2 (MHz)	Velocity Factor	l_exp (m)	Error
1	20.4	7.209	2.395	0.66	20.773	0.373
2	36.4	9.711	1.372	0.66	35.986	-0.414
3	46.6	9.644	3.161	0.66	46.270	-0.33
4	57(approx)	8.856	1.741	0.66	56.526	-0.474

Calculation of Effective Length of the Cable

The effective length of the cable is determined from the frequency separation of successive maxima (or minima) in the standing wave pattern. For two successive maxima occurring at frequencies f_1 and f_2, the round-trip time delay τ is given by,

$$|f_1 - f_2| = \frac{1}{\tau}$$

The signal propagates through the cable with a velocity,

$$v_{\text{cable}} = 0.66\,c \approx 2 \times 10^8 \text{ m s}^{-1}$$

The time delay τ is related to the effective length x of the cable by,

$$\tau = \frac{2x}{v_{\text{cable}}}$$

Combining the above relations, the effective length of the cable is obtained as,

$$x = \frac{v_{\text{cable}}}{2|f_1 - f_2|}$$

Substituting $v_{\text{cable}} = 2 \times 10^8$ m s^{-1} and expressing frequency in MHz, the effective length becomes,

$$\boxed{x = \frac{100}{|f_1 - f_2|} \text{ m}}$$

Thus, the effective length of the cable is calculated from the frequency separation of successive maxima or minima.

First cable (Length: 20.4)
Max values:

$$f_1 = 9.717, \quad f_2 = 5.428$$

$$\frac{100}{|9.717 - 5.428|} = 21.791 \text{ m}$$

Min values:

$$f_1 = 7.209, \quad f_2 = 2.395$$

$$\frac{100}{|7.209 - 2.395|} = 20.773 \text{ m}$$

Second Cable (Length: 36.4)
Max values:

$$f_1 = 8.394, \quad f_2 = 5.594, \quad f_3 = 2.784$$

$$\frac{100}{|8.394 - 5.594|} = 35.714 \text{ m}$$

$$\frac{100}{|5.594 - 2.784|} = 35.587 \text{ m}$$

Min values:

$$f_1 = 9.711, \quad f_2 = 6.875, \quad f_3 = 4.090, \quad f_4 = 1.372$$

$$\frac{100}{|9.711 - 6.875|} = 35.261 \text{ m}$$

$$\frac{100}{|6.875 - 4.090|} = 35.907 \text{ m}$$

$$\frac{100}{|4.090 - 1.372|} = 36.792 \text{ m}$$

Third Cable (Length: 46.6)
Max values:

$$f_1 = 8.506, \quad f_2 = 6.392, \quad f_3 = 4.255, \quad f_4 = 2.167$$

$$\frac{100}{|8.506 - 6.392|} = 47.304 \text{ m}$$

$$\frac{100}{|6.392 - 4.255|} = 46.794 \text{ m}$$

$$\frac{100}{|4.255 - 2.167|} = 45.892 \text{ m}$$

Min values:

$$f_1 = 9.644, \quad f_2 = 7.497, \quad f_3 = 5.366, \quad f_4 = 3.161$$

$$\frac{100}{|9.644 - 7.497|} = 46.533 \text{ m}$$

$$\frac{100}{|7.497 - 5.366|} = 46.926 \text{ m}$$

$$\frac{100}{|5.366 - 3.161|} = 45.351 \text{ m}$$

Fourth Cable (Length: 57(approx))
Max values:

$$f_1 = 8.856, \quad f_2 = 7.083, \quad f_3 = 5.247, \quad f_4 = 3.494, \quad f_5 = 1.741$$

$$\frac{100}{|8.856 - 7.083|} = 56.401 \text{ m}$$

$$\frac{100}{|7.083 - 5.247|} = 54.466 \text{ m}$$

$$\frac{100}{|5.247 - 3.494|} = 57.045 \text{ m}$$

$$\frac{100}{|3.494 - 1.741|} = 57.045 \text{ m}$$

Min values:

$$f_1 = 9.682, \quad f_2 = 7.885, \quad f_3 = 6.116, \quad f_4 = 4.359, \quad f_5 = 2.605$$

$$\frac{100}{|9.682 - 7.885|} = 55.648 \text{ m}$$

$$\frac{100}{|7.885 - 6.116|} = 56.529 \text{ m}$$

$$\frac{100}{|6.116 - 4.359|} = 56.915 \text{ m}$$

$$\frac{100}{|4.359 - 2.605|} = 57.012 \text{ m}$$

3.3 Calculation for loss in the cable

The maximum voltage V_{max} and minimum voltage V_{min} correspond to the voltages measured at standing wave maxima and minima respectively. The loss factor is given by,

$$\alpha = \frac{V_{\text{max}} - V_{\text{min}}}{V_{\text{max}} + V_{\text{min}}}$$

The loss per unit length of the cable is then given by,

$$\alpha_{\text{per unit length}} = \frac{\alpha}{2x}$$

Loss in the First cable:

$$\alpha = \frac{48.7 - 4.6}{48.7 + 4.6} = 0.827$$

$$\alpha_{\text{per unit length}} = \frac{0.827}{2 \times 21.0275} = 19.664 \times 10^{-3}\ \text{m}^{-1}$$

Loss in the Second cable:

$$\alpha = \frac{41.8 - 8.3}{41.8 + 8.3} = 0.636$$

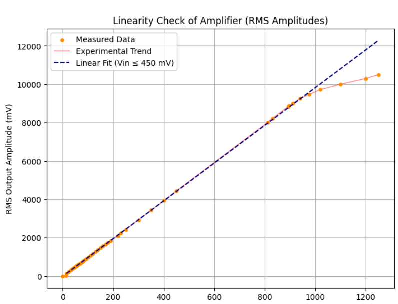
$$\alpha_{\text{per unit length}} = \frac{0.636}{2 \times 35.8182} = 8.878 \times 10^{-3}\ \text{m}^{-1}$$

Loss in the Third cable:

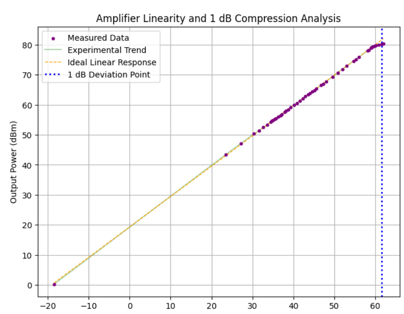
$$\alpha = \frac{39.8 - 10.8}{39.8 + 10.8} = 0.573$$

$$\alpha_{\text{per unit length}} = \frac{0.573}{2 \times 46.4665} = 6.6165 \times 10^{-3}\ \text{m}^{-1}$$

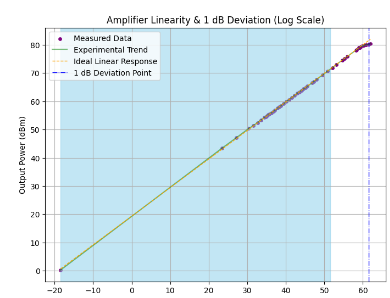
3.4 Data Plot



Linearity Check of Amplitude



Amplifier Linearity and 1 dB Compression Analysis



Operating Region

Operating Range

Figure 1: Characteristics of the amplifier.

4 Results

The loss per unit length of the first, second, and third cables is $1.97 \times 10^{-2}\,\text{m}^{-1}$, $8.88 \times 10^{-3}\,\text{m}^{-1}$, and $6.62 \times 10^{-3}\,\text{m}^{-1}$, respectively.

The maximum linear operating limit is chosen 10 dB below the 1 dB deviation point to ensure operation well within the linear regime, since nonlinear distortion grows rapidly near compression. In our experiment, 1 dB deviation occurs at : Input Power = 61.583 dBm Input RMS Voltage = 1200.0 mV

The amplifier begins to deviate from linearity at an input power of approximately 62 dBm. For linear operation, the maximum recommended input is about 10 dBm lower. Hence , we take the voltage at approximately 52dBm to be our maximum safe opertaing input. At 52 dBm , Input Voltage = 400 mV

The dynamic range is approximately -28 dBm to 52dBm , which is 70dBm.

The noise temperature of the system is estimated.

$$P = k\,T\,\Delta\nu \tag{1}$$

where P is the measured noise power, $k = 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$ is the Boltzmann constant, T is the effective system noise temperature, and $\Delta\nu$ is the effective bandwidth.

The effective bandwidth is determined from the full width at half maximum (FWHM) of the observed noise spectrum using the oscilloscope trigger function. The measured bandwidth is

$$\Delta\nu_{\mathrm{FWHM}} \approx 2 \text{ MHz}. \tag{2}$$

For an observed output RMS voltage of 1.03 mV and a system gain of 10, the corresponding ideal input RMS voltage is

$$V_{\mathrm{rms}} = 0.103 \text{ mV} = 1.03 \times 10^{-4}\,\mathrm{V}. \tag{3}$$

The noise power is calculated from the RMS voltage using

$$P = \frac{V_{\mathrm{rms}}^2}{R}, \tag{4}$$

where the input resistance is $R = 1$ MΩ. Substituting values,

$$P = \frac{(1.03 \times 10^{-4})^2}{1.0 \times 10^6} = 1.06 \times 10^{-14}\,\mathrm{W}. \tag{5}$$

Substituting the measured power and FWHM bandwidth into the radiometer equation, the system noise temperature is

$$T = \frac{P}{k\,\Delta\nu_{\mathrm{FWHM}}} = \frac{1.06 \times 10^{-14}}{(1.38 \times 10^{-23})(2.0 \times 10^6)} \approx 3.84 \times 10^2\,\mathrm{K}. \tag{6}$$

Hence, the effective noise temperature of the system is

$$\boxed{T \approx 384 \text{ K}}. \tag{7}$$

5 Interpretation

Standing wave formation in the cable

In the cable, the waves are being reflected at the open end (infinite impedance), and hence, standing waves are being formed. By using the relation between the difference between two successive frequencies where the two consecutive maxima (or consecutive minima) occur, we calculate the length of the cable and measure the error in the length of the cable.

Response of the Amplifier with Input Voltage

The amplifier shows the linearity (ideal) as expected for a certain range of input voltages, where the Output Voltage = Gain × Input Voltage and the gain remains constant throughout this range. However, beyond this range, the amplifier starts getting saturated and is unable to provide the required output and the deviation from ideality starts increasing with increase in voltage i.e., the gain keeps on falling down. Below the lower level, a very low input voltage was simulated by disconnecting the input cable, but that still results in a non-zero output voltage, which lets us probe the output noise of the Amplifier, thus getting its Input Noise too as a Noise Temperature of the Amplifier.

6 Acknowledgements

We would like to express our sincere gratitude to Mr. Jameer Manur, Dr. Prakash Arumugaswamy and Dr. Avinash Deshpande for helping us get valuable insights in this particular experiment. We also thank IUCAA and the entire organizing committee of RAWS 2025 for their support and providing us with the opportunity to perform this experiment.

7 Contributions

Introduction - Saanvi Pande[6]
Theory - Dhairya Kotecha[4]
Observations - Ambika S[1]
Data Analysis, Plotting - Anaya Atul Dixit[2], Bhargava Ganesh Bhat[3] and Pranjal Sengupta[5]
Results - Anaya Atul Dixit[2]
Interpretation - Pranjal Sengupta[5]

8 References

Manual, Pozar, D.M., Microwave Engineering, 4th Edition, Wiley, Impedance Matching, Cripps, S. C., *RF Amplifier Design*, 2nd Edition, Artech House, Chatgpt