

# Week 1 Pre-Lab Reading

## 1 Introduction to Electromagnetic Waves

Electromagnetic waves are fundamental to our understanding of the physical world, encompassing a broad spectrum of energy that spans from radio waves with long wavelengths to gamma rays with extremely short wavelengths. These waves are composed of oscillating electric and magnetic fields that propagate through space at the speed of light, a universal constant denoted by the letter  $c$ . One of the most important features of electromagnetic waves is their ability to travel through a vacuum, making them essential in fields such as telecommunications, medical imaging, and astronomy.

At the heart of electromagnetic waves lies a profound relationship between electric and magnetic fields. When an electric charge accelerates or oscillates, it creates a changing electric field that, in turn, induces a magnetic field perpendicular to it. This interplay of electric and magnetic fields continues as the wave moves forward, forming a self-sustaining wave that can travel across vast distances without a medium. The wave's characteristics, including its wavelength ( $\lambda$ ), frequency ( $f$ ), and amplitude, define its behavior and the type of electromagnetic radiation it represents.

### 1.1 The Electromagnetic Spectrum

The electromagnetic spectrum encompasses a vast range of frequencies, each with distinct properties and applications. At the lowest end are radio waves, used extensively in communication systems like AM/FM radio, TV broadcasting, and wireless networks. Radio astronomy relies heavily on these waves to study cosmic phenomena such as pulsars, galaxies, and the cosmic microwave background radiation. Moving up the spectrum, microwaves find applications in microwave ovens for cooking, satellite communications, and radar systems used in weather forecasting and air traffic control.

Infrared radiation, with wavelengths slightly longer than visible light, plays a crucial role in thermal imaging cameras used in security, night vision goggles, and remote sensing applications like monitoring vegetation health and detecting heat signatures. Visible light, the narrow band of wavelengths visible to the human eye, is fundamental to our perception

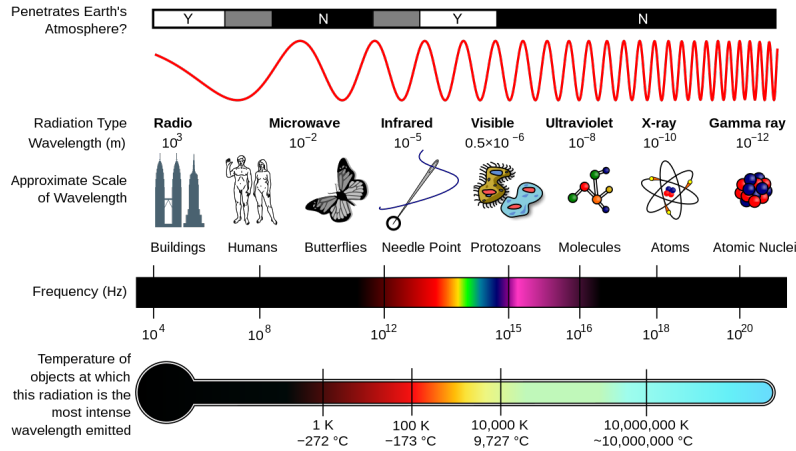


Figure 1: Caption

of the world and is utilized in optical communication systems, photography, and medical imaging technologies like endoscopy and microscopy. Ultraviolet radiation has applications in sterilization processes, forensic investigations, and astronomy for studying hot, energetic objects like young stars.

## 1.2 Frequency and Wavelength

Frequency ( $f$ ) refers to the number of wave cycles passing a fixed point per unit of time, typically measured in Hertz (Hz). Wavelength ( $\lambda$ ) on the other hand, represents the distance between successive wave peaks or troughs and is measured in meters (m). The relationship between frequency and wavelength is governed by the equation  $c = f\lambda$ , where  $c$  is the speed of light in a vacuum (approximately  $3 \times 10^8$  meters per second).

This relationship means that as the frequency of an electromagnetic wave increases, its wavelength decreases, and vice versa. Higher frequency waves, such as X-rays and gamma rays, have shorter wavelengths and carry more energy per photon compared to lower frequency waves like radio waves. This energy-frequency relationship is crucial in various applications, such as medical imaging (where high-energy X-rays penetrate tissues for diagnostic purposes), telecommunications (where different frequency bands are allocated for specific purposes), and astronomy (where the frequency of radio emissions from celestial objects provides insights into their properties and behaviors). Additionally, frequency and wavelength play roles in determining the propagation characteristics of electromagnetic waves, including their ability to penetrate materials, interact with matter, and exhibit interference and diffraction phenomena.

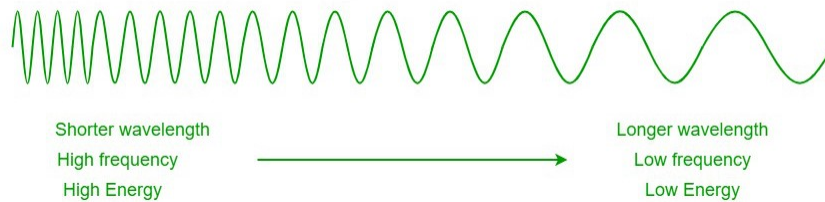


Figure 2: Caption

### 1.3 Amplitude

The amplitude of an electromagnetic wave represents the magnitude of its electric and magnetic field oscillations. It is directly related to the wave's energy, with higher amplitudes corresponding to greater energy levels.

In addition to energy considerations, the amplitude of electromagnetic waves influences other important properties. For example, in communication systems, the amplitude of a wave carries information encoded as variations in its strength. In amplitude modulation (AM) radio, for instance, the audio signal is encoded by varying the amplitude of the carrier wave. Amplitude also affects the wave's intensity, which is crucial in applications such as medical imaging (e.g., MRI) and remote sensing, where the intensity of reflected or emitted waves provides valuable information about the observed object. Furthermore, the amplitude of electromagnetic waves plays a role in determining their interaction with matter, influencing phenomena such as absorption, reflection, and transmission characteristics across different materials and environments.

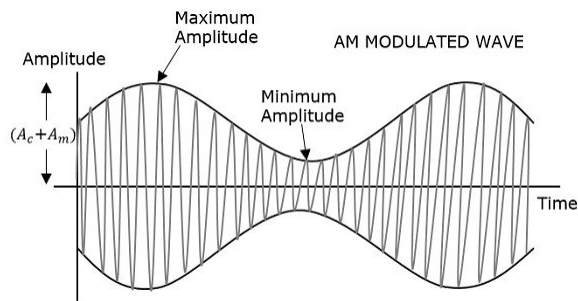


Figure 3: Example of an amplitude modulated electromagnetic wave that can be used to transmit information (AM radio).

## 1.4 Phase

Phase in electromagnetic waves refers to the relative position of the wave's crests and troughs at a specific point in time. It is a critical aspect of wave behavior, influencing phenomena such as interference, coherence, and signal processing. The phase of a wave is often represented in radians or degrees, indicating the fraction of a wave cycle at a given point. When two waves are in phase, their crests and troughs align, resulting in constructive interference and reinforcing the wave's amplitude. Conversely, when two waves are out of phase, with their crests and troughs misaligned, destructive interference occurs, leading to a reduction in amplitude or cancellation of the waves.

Phase in electromagnetic waves holds particular significance in radio astronomy and interferometry, where precise phase measurements are crucial for resolving fine details in celestial objects and achieving high-resolution imaging. In radio astronomy, interferometry techniques combine signals from multiple telescopes to simulate a larger, more powerful telescope called an interferometer. The phase of the signals received by each telescope is carefully synchronized and correlated to create interference patterns that reveal detailed information about astronomical sources. By measuring the phase differences between signals, astronomers can determine the spatial distribution, size, and structures of radio-emitting objects with extraordinary precision.

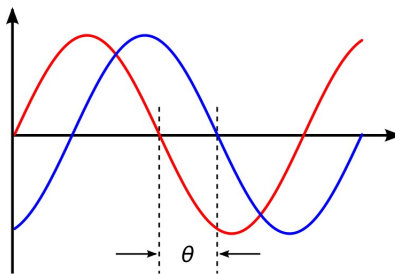


Figure 4: Caption

## 1.5 Propagation

Electromagnetic waves propagate as transverse waves, meaning that the oscillations of the electric ( $\mathbf{E}$ ) and magnetic ( $\mathbf{B}$ ) fields occur perpendicular to the direction of wave travel. This transverse nature is a fundamental characteristic of electromagnetic waves and is distinct from longitudinal waves, where oscillations occur parallel to the direction of propagation. As an electromagnetic wave travels through space, the electric field oscillates in one plane (e.g., up and down), while the magnetic field oscillates in a plane perpendicular to the electric field (e.g., side to side). This perpendicular oscillation pattern enables electromagnetic waves to propagate freely through vacuum and various media, including

air, water, and solids.

The behavior of the electric and magnetic fields during electromagnetic wave propagation is governed by Maxwell's equations, which describe the interactions between electric charges, electric fields, magnetic fields, and currents. These equations illustrate how a changing electric field induces a magnetic field, and vice versa, leading to the self-propagation of electromagnetic waves. During propagation, the electric and magnetic fields are in phase with each other, meaning that their peaks and troughs align. This phase relationship ensures that the wave maintains its transverse nature and carries energy efficiently across space. The combined oscillations of the  $\mathbf{E}$  and  $\mathbf{B}$  fields create a wavefront that moves outward from the source, with the direction of propagation perpendicular to both the electric and magnetic field vectors.

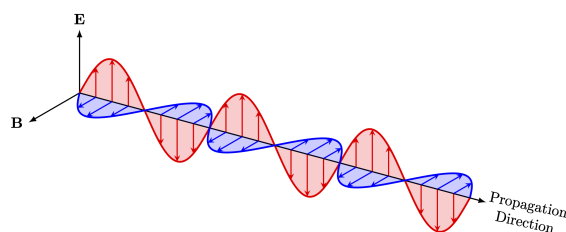


Figure 5: Caption

## 1.6 Applications of Radio Waves

Radio waves play a pivotal role in astronomy, offering unique insights into celestial objects and phenomena. Radio telescopes detect emissions from sources like stars, galaxies, pulsars, and cosmic background radiation, providing valuable data for studying cosmic evolution and structure. Radio interferometry, combining signals from multiple telescopes, enables high-resolution imaging and precise measurements of astronomical objects.

In technology, radio waves support wireless communication networks, satellite communications, and GPS navigation systems. Everyday applications include Wi-Fi routers, Bluetooth devices, and RFID technology used in contactless payment systems and inventory management. The versatility of radio waves extends to medical applications like MRI imaging and industrial applications such as radar sensing and remote sensing for environmental monitoring. Overall, radio waves contribute significantly to our understanding of the universe and enhance our daily lives through diverse technological applications.

## 2 Software Defined Radio (SDR) Overview

Traditional radio systems rely on hardware components, such as analog circuits and dedicated modules, to perform signal processing and modulation tasks. These systems are designed for specific frequency bands and modulation schemes, requiring hardware reconfiguration or replacement to adapt to new standards or frequencies. In contrast, software-defined radio (SDR) revolutionizes radio communication by shifting the signal processing functions from hardware to software. SDR systems use general-purpose processors, such as CPUs and digital signal processors (DSPs), along with software algorithms to implement modulation, demodulation, filtering, and other radio functions. This flexibility allows SDR devices to support multiple frequency bands, modulation schemes, and protocols through software updates or reprogramming, without the need for hardware modifications.

The applications of SDR span across various domains, from telecommunications and wireless networks to scientific research and radio astronomy. In telecommunications, SDR enables dynamic spectrum access, where devices can adaptively use available frequency bands based on real-time conditions. This flexibility optimizes spectrum utilization and enhances communication reliability and efficiency. In wireless networks, SDR technology supports cognitive radio systems, which intelligently sense and utilize unused spectrum to improve network capacity and performance.

Moreover, SDR plays a vital role in radio astronomy by facilitating the development of advanced radio telescopes and interferometric arrays. SDR-based radio telescopes offer enhanced flexibility in frequency tuning, signal processing, and data analysis, allowing astronomers to study cosmic phenomena with higher precision and sensitivity. Additionally, SDR enables the implementation of sophisticated signal processing techniques for interference mitigation, wideband signal capture, and digital beamforming in radio astronomy observations.

### 2.1 Components of an SDR System

- **The antenna** is the first component of an SDR system, responsible for capturing radio frequency (RF) signals. It converts electromagnetic waves into electrical signals, which are then processed by the rest of the SDR components. Antennas come in various designs optimized for different frequency ranges and directional characteristics, allowing SDR systems to receive signals from specific sources or regions.
- **Radio frequency (RF) hardware** includes components such as filters, amplifiers, and mixers, collectively known as the RF front end. These components work together to condition and manipulate the incoming RF signals. Filters remove unwanted frequencies and noise, amplifiers boost signal strength, and mixers convert frequencies to intermediate frequencies (IF) for easier processing by digital circuits.

- **An analog-to-digital converter (ADC)** converts the analog RF signals from the RF front end into digital signals that can be processed by digital circuits and software. It samples the analog signal at a specified rate (sampling frequency) and quantizes each sample into digital values.
- **The digital front end** processes the digitized RF signals from the ADC. It includes components such as digital filters, downconverters, and demodulators. Digital filters remove unwanted noise and interference, downconverters convert signals to baseband or intermediate frequencies, and demodulators extract information or modulate signals for transmission.
- **Baseband processors** handle signal processing tasks at the baseband level, including modulation, demodulation, encoding, decoding, and error correction. They use digital signal processing (DSP) algorithms to manipulate and analyze the baseband signals, preparing them for further processing or transmission.
- **Software** is a crucial component of an SDR system, providing the user interface, control functionalities, signal processing algorithms, and networking capabilities. SDR software allows users to configure SDR parameters, select operating modes, visualize signals, analyze data, and develop custom applications. Popular SDR software tools include GNU Radio, MATLAB/Simulink, and proprietary SDR platforms, offering a range of features for SDR development and experimentation

### 3 GNU Radio

GNU Radio is an open-source software toolkit that provides a framework for building software-defined radio (SDR) systems. Developed by a community of radio enthusiasts, engineers, and researchers, GNU Radio offers a flexible and powerful platform for designing and implementing radio communication systems using software and general-purpose hardware. At its core, GNU Radio leverages digital signal processing (DSP) techniques to process and manipulate radio frequency (RF) signals in real time, enabling a wide range of applications in telecommunications, wireless networking, radio astronomy, and scientific research.

One of the key strengths of GNU Radio lies in its modularity and extensibility. Users can create custom signal processing blocks called "gr\_blocks" using Python or C++, allowing for the development of complex signal processing pipelines tailored to specific requirements. These blocks can perform tasks such as modulation, demodulation, filtering, signal generation, and data analysis. Additionally, GNU Radio supports various hardware platforms, including universal software radio peripherals (USRPs), HackRF, RTL-SDR dongles, and other SDR devices, making it accessible to a diverse range of users and applications.

Instructions for installing GNU Radio and GRC can be found on the GNU Radio wiki page

or at the following link: [Installing GR](#).

### **3.1 Creating Flowgraphs in GRC**

GNU Radio Companion (GRC) is a graphical interface that sits on top of the normal GNU Radio programming environment in Python. GRC translates the flowgraph we create in the GUI canvas into a Python script, so when we execute a flowgraph, we are really running a Python program. For more information about using GRC, follow the tutorial at the following link to the GNU Radio Wiki web page: [Guided Tour GRC](#)

Once you have GNU Radio and GRC installed, we suggest you work through the following tutorials to familiarize yourself with the process of making flowgraphs:

- [Python Variables in GRC](#)
- [Variables in Flowgraphs](#)
- [Runtime Updating Variables](#)
- [Signal Data Types](#)
- [Converting Data Types](#)