Lecture: Live Observations with the Allen Telescope Array

Objectives

This module introduces students to the fundamentals of radio observations using the Allen Telescope Array (ATA) for live data collection. Students will engage in real-time observations of the 21cm hydrogen emission line from the Milky Way, applying techniques in radio astronomy and data analysis to understand how signals are detected and processed. Through hands-on experience, they will explore the capabilities of radio telescopes and gain insights into the broader field of observational astronomy.

Lecture 1: Introduction to Radio Astronomy

1. **Overview of Radio Astronomy**

   (a) **History of Radio Astronomy**

      i. **Karl Jansky (1930s)** - Considered the "father of radio astronomy", Jansky discovered radio waves emanating from the center of the Milky Way in 1932, opening up a new field of astronomy.

      ii. **Grote Reber (1940s)** - Built the first parabolic radio telescope which let to the mapping of radio sources in the sky, and demonstrated the potential of radio astronomy after Jansky's initial discovery.

      iii. **The 21cm Hydrogen Line (1944-1951)** - The spectral line emitted by the spin-flip transition of neutral Hydrogen, which enabled astronomers to map the structure and rotation of the Milky Way, and provided the first substantial evidence for dark matter.

      iv. **Discovery of Quasars (1963)** - Active galactic nuclei powered by supermassive black holes, which are among the most luminous and distant objects in the universe, expanding our understanding of cosmic evolution.

      v. **Discovery of Pulsars (1967)** - Rapidly rotating neutron stars that emit regular pulses of radiation. First discovered by Jocelyn Bell Burnell, pulsars have become crucial for testing general relativity and studying extreme states of matter.

      vi. **Discovery of the Cosmic Microwave Background Radiation (1965)** - The remnant radiation from the Big Bang, first detected by Arno Penzias and Robert Wilson, provided strong evidence for the Big Bang theory and has become a crucial tool for studying the early universe.

   (b) **Importance of Radio Astronomy**

      i. **Reaching Beyond the Optical Spectrum** - Radio waves allow astronomers to observe phenomena invisible to optical telescopes, such as the cold gas in galaxies and the hidden cores of star-forming regions. Unlike visible light, radio waves can penetrate dust clouds, providing unique insights into star formation and galactic dynamics

ii. **Complementing Other Wavelengths** - Radio observations often complement data from other wavelengths, providing a more complete picture of cosmic events such as supernovae or galaxy mergers.

iii. **Global Collaboration** - Major radio astronomy projects (e.g. ALMA, VLA, SKA) involve international collaboration.

2. **How Radio Telescopes Work**

(a) **The Radio Window** - The Earth's atmosphere is transparent to certain radio wavelengths (roughly 1mm - 10m); this "radio window" allows radio telescope on Earth to observe signals from space with little to no distortion from the atmosphere.

(b) **Key Components**

i. **Parabolic Dish Antennas** - Parabolic dish antennas are used to focus radio waves onto a feed (detector), with different designs being used for various wavelengths of observation. The ATA uses 6.1m (20ft) offset Gregorian style dishes where the focus is located near the bottom on the primary dish.

ii. **Feeds/Detectors** - The feed is positioned at the focus of the dish, where it receives the concentrated radio waves and converts them into electrical signals for further processing. The ATA uses the a custom designed style of log-periodic feed called the "Antonio Feeds", developed in collaboration with Qualcomm co-founder Franklin Antonio, which is cryogenically cooled to 70K (-330°F) and is sensitive between 1-10GHz.

iii. **Amplifiers** - The amplifier boosts the strength of the weak signal captured by the feed, ensuring the signal can be processed without being drowned out by noise. In radio astronomy, where signals from space can be extremely faint, amplification is critical for making the signal strong enough for further analysis.

iv. **Analog to Digital Conversion (ADC)** - The signals from the telescope are carried via fiber cables to the signal processing room (SPR), where they are sampled (measured) and converted into a digital signal, allowing the use of digital signal processing (DSP) techniques to further analyse the signal.

(c) **Challenges of Detecting Faint Signals**

i. **Radio Frequency Interference (RFI)** - RFI from human-made technology sources (e.g. Wi-Fi, cell towers, satellites) is very disruptive to radio astronomy, requiring radio observatories be built in remote and shielded areas. The ATA is built at the Hat Creek Radio Observatory, which is a 90-minute drive from the nearest city, and is surrounded by mountains which helps to shield the observatory from terrestrial interference.

ii. **Noise** - Cosmic noise (e.g. the CMB) and heat from the electronics in the feed and signal path can introduce noise. Cooling the feed and low-noise amplifiers helps reduce thermal noise.

iii. **Sensitivity** - The strength of radio signals from astronomical sources is often in the micro to nano-Jansky range, making them very faint. A radio telescope can be made more sensitive by having a large collecting area (dish size), combining the signals from many dishes (radio telescope array), and using low-noise instrumentation.

3. **Introduction to the Allen Telescope Array (ATA)**

   (a) **Design of the ATA**

      i. **Unique Structure** - The ATA consists of 42 individual radio telescopes, each 6.1m (20ft) in diameter, designed to operate as an interferometer. It is the only radio observatory in the world purpose built for SETI, and it's also used for traditional radio astronomy applications.

      ii. **Phased Array Operation** - The ATA can perform beamforming and correlation, which allows it to focus on specific regions of the sky with enhanced sensitivity, or to scan large areas of the sky.

   (b) **Capabilities of the ATA**

      i. **Wide Frequency Range** - The ATA operates across a broad frequency range, from 1-10GHz, allowing it to detect a variety of signals, from natural phenomena to potential signals from extraterrestrial technology.

      ii. **Simultaneous Observations** - The ATA can observe multiple targets simultaneously, providing a significant advantage in SETI research and in surveying the sky for transient radio signals.

4. **Basic Observation Techniques**

   (a) **Single-Dish Observations** - A single dish radio telescope focuses on a relatively large area of the sky, but at lower resolution and sensitivity than an array of similarly sized telescopes. Single-dish telescopes are often used for sky surveys, detecting bright sources, and creating maps of cosmic radio emissions.

   (b) **Interferometry** - By combining the data from multiple telescopes, interferometry increases the effective aperture size, resulting in higher resolution and sensitivity than a single dish.

      i. **Beamforming** - A type of interferometry that adds the data from multiple telescope to form a focused beam of maximum sensitivity on a specific point on the sky. The beam can be steered electronically without the need to physically move the telescopes, allowing easy on-beam off-beam analysis to determine the source of a signal.

      ii. **Correlation** - Another type of interferometry that computes the cross-correlation of each pair of antennas in the array. The output is a dataset representing the spatial frequencies of the observed source, known as visabilities, which can be used to create a radio image of the sky.

Lecture 1 Discussion Questions

1. How does radio astronomy complement other types of astronomy, such as optical or X-ray astronomy?

   (a) Radio astronomy allows us to observe phenomena that are invisible to optical telescopes, such as cold hydrogen gas, which doesn't emit visible light but does emit radio waves at the 21cm wavelength. While optical telescopes show us the universe in visible light, radio astronomy reveals hidden structures like molecular clouds and galactic magnetic fields. X-ray astronomy, on the other hand, shows high-energy processes like black holes and neutron stars. Each wavelength gives us a different view, and combining them allows astronomers to build a more complete picture of the universe.

2. What are the main characteristics of a signal that might indicate an artificial origin (i.e., from extraterrestrial intelligence), and how would they differ from natural cosmic signals?

   (a) Artificial signals are likely to be narrowband, meaning they occupy a very small range of frequencies, unlike natural cosmic signals, which are typically broadband. A narrowband signal is unlikely to occur naturally and is usually a hallmark of technology. Artificial signals might also exhibit periodicity or modulation, indicating some form of communication. In contrast, natural signals, such as those from pulsars or galaxies, tend to be much broader and noisier.

3. Why are certain parts of the electromagnetic spectrum more accessible to ground-based telescopes, while others are not?

   (a) Earth's atmosphere is transparent to certain wavelengths of the electromagnetic spectrum, particularly visible light and parts of the radio spectrum (roughly from 1mm to 10m). This "radio window" allows ground-based telescopes to detect radio signals from space. However, other wavelengths, such as X-rays and ultraviolet, are blocked by the atmosphere and require space-based telescopes like the Hubble Space Telescope or Chandra X-ray Observatory. The transparency in the radio window is crucial for radio astronomy, enabling observations from Earth-based instruments like the ATA.

Lecture 1 Resources

1. Radio Astronomy and the Allen Telescope Array
2. The History of Radio Astronomy - NRAO
3. Atmospheric Windows Image
4. Optical/Radio Image Slider
5. Cosmic Coloring Compositor
6. ATA General Overview
7. ATA Technical Overview
8. Introduction to Radio Interferometry

Lecture 2: Signal Detection and Processing in Radio Astronomy

1. **Introduction to Signal Processing**

   (a) **What is Signal Processing in Radio Astronomy?** - Signal processing refers to the techniques used to enhance, filter, and analyze the weak radio signals captured by a radio telescope. The goal is to extract meaningful information from the faint signals while minimizing noise and interference.

   (b) **Types of Signal Processing**

      i. **Analog Signal Processing** - Initial stages that involve manipulating the continuous radio frequency (RF) signals before they are converted into digital form for analysis. This stage of processing is crucial because the signals captured by a radio telescope are extremely weak, and the analog processing steps help boost and clean the signal while preserving as much of the original information as possible.

      ii. **Digital Signal Processing (DSP)** - The stage where the analog signals, which have been amplified, filtered, and downconverted, are sampled and converted into a digital format and further manipulated using software algorithms. In radio astronomy, DSP plays a vital role in extracting useful information from signals, performing complex analysis, and improving signal-to-noise ratios.

2. **Sampling and the Nyquist Theorem**

   (a) **Sampling** - the process of converting the analog signal into a series of discrete digital values by measuring the signal at regular intervals. This allows computers to process and store the signal for analysis.

   (b) **Nyquist Sampling Theorem** - The Nyquist theorem states that to accurately capture all the information in a signal, the sampling rate must be at least twice the highest frequency present in the signal. For example, if a radio signal contains frequencies up to 1,000 Hz, it must be sampled at a rate of at least 2,000 samples per second to avoid information loss.

   (c) **Aliasing** - If a signal is undersampled (i.e., sampled below the Nyquist rate), aliasing occurs, causing higher frequencies to appear as lower frequencies in the data, leading to incorrect interpretations of the signal. The included GNU Radio Companion file `Nyquist.grc` can be used to demonstrate this phenomenon.

3. **Fourier Transforms and the Frequency Domain**

   (a) **Time Domain vs. Frequency Domain** - In the time domain, a signal is represented as amplitude over time (e.g., the strength of a radio wave at each moment). In the frequency domain, the signal is represented as amplitude over frequency, showing which frequencies are present in the signal.

   (b) **Fourier Transform** - The Fourier Transform is a mathematical tool that converts a signal from the time domain into the frequency domain. This is especially important in radio astronomy, as most cosmic signals are better analyzed in the frequency domain to identify specific features like the presence of a pulsar or narrowband signals potentially from an extraterrestrial source. A connection to spectroscopy can be made here, as the Fourier transform essentially plays the role of a prism/diffraction grating in optical spectroscopy.

(c) **The Fast Fourier Transform (FFT)** is an algorithm that efficiently computes the Discrete Fourier Transform. It is used in almost all radio astronomy signal processing software, including GNU Radio. The included GNU Radio Companion file `Fourier_Transform.grc` can be used to show how Fourier transforms work.

4. **Tools for Observing with the Allen Telescope Array**

(a) **The Easy ATA GUI (`EAG.py`)** - A simple user interface that allows observers to quickly calibrate and operate an antenna of the ATA. It can be run through the `obs-node1` VNC, once the correct VNC and VPN setting have been set up.

(b) **GNU Radio** - A widely-used open-source toolkit for building and simulating software defined radio (SDR) systems. It offers a range of signal processing blocks that can be linked together to form flowgraphs, making it easy to build custom radio systems. The ATA can output raw data that students can process in GNU Radio. Students can build real-time signal processing pipelines in GNU Radio, visualize signals in the time and frequency domains, and apply filters or transformations as needed. GNU Radio's graphical interface, GNU Radio Companion (GRC), provides a drag-and-drop environment for building radio receivers and processing chains. This makes it accessible to students with minimal programming experience.

Lecture 2 Discussion Questions

1. Why do you think digital signal processing is so important in radio astronomy, especially when compared to traditional analog signal processing? How does DSP change the way we study the universe?

   (a) Digital signal processing (DSP) allows astronomers to analyze large amounts of data quickly and accurately, which is important when dealing with weak signals from space. Traditional analog methods can introduce noise and distortions, while DSP allows for precise filtering, error correction, and real-time adjustments. This enables astronomers to pick out faint signals, such as those from pulsars or potential extraterrestrial sources, in real-time without losing critical information.

2. Why are the signals from space often so weak, and how do you think astronomers overcome the challenges of detecting these faint signals?

   (a) Signals from space are weak because they travel over very large distances, causing the signal to spread out and lose intensity. Additionally, cosmic noise and radio frequency interference (RFI) from Earth-based sources can overwhelm these signals. Astronomers overcome these challenges by using large antennas to collect more radio waves, applying digital filters to remove unwanted noise, and using techniques like signal averaging to enhance weak signals over time.

3. In what everyday situations do you think filtering is used to remove unwanted signals or noise? How is this similar to or different from what radio astronomers do with digital filters?

   (a) Noise-canceling headphones are a common example of filtering in daily life, where unwanted background noise is removed using filters. Similarly, Wi-Fi routers filter out noise from other devices to ensure clear communication. In radio astronomy, filters remove radio frequency interference (RFI) from Earth-based sources, like satellites or cell towers, so astronomers can focus on weak cosmic signals. Both contexts rely on filters to isolate signals of interest.

4. If radio astronomers were to detect a signal that could be from an extraterrestrial civilization, what should the next steps be? Who should decide how to handle that discovery, and how might it affect society?

   (a) If a signal from extraterrestrial intelligence were detected, it would require careful verification to rule out false positives. The scientific community would likely follow established protocols, such as the SETI Post-Detection Protocol, which outlines steps for confirming and reporting the discovery. Handling such a discovery would involve not just scientists, but also governments and global organizations like the UN, as the societal impact could be profound, affecting our views on our place in the universe.

Lecture 2 Resources

1. Digital Signal Processing in Radio Astronomy
2. GNU Radio at the Allen Telescope Array
3. Analog-to-digital converters basics
4. Aliasing - Digital Signals Theory
5. An Interactive Guide To The Fourier Transform
6. Frequency Domain and Fourier Transforms - Princeton

Lecture 3: Observing the 21cm Hydrogen Line

1. **Introduction to the 21cm Hydrogen Line**

   (a) **What is the 21cm Hydrogen Line?**

      i. The 21cm line is a specific radio wavelength emitted by neutral hydrogen atoms due to the **hyperfine transition** of the atom's electron.

      ii. This occurs when the electron and proton inside the hydrogen atom switch from a aligned spin state to an anti-aligned spin state. The energy released in this transition corresponds to the release of a photon with a wavelength of 21cm, or a frequency of about 1420MHz.

      iii. The 21cm line is very important because hydrogen is the most abundant element in the universe, and neutral hydrogen gas is found throughout galaxies, especially in regions far from the influence of stars.

   (b) **Why is it Important in Astronomy?**

   i. The 21cm line allows astronomers to map neutral hydrogen gas, referred to as HI regions, which is often invisible to other wavelengths like optical or X-rays.

   ii. It provides a unique tool for understanding the distribution of gas in galaxies, the structure of the Milky Way, and the large-scale structure of the universe.

   iii. The 21cm line also helps astronomers trace the motion of hydrogen clouds in galaxies, revealing rotational curves and helping identify dark matter distribution by comparing visible mass to gravitational effects.

2. **Historical Context and Key Discoveries**

   (a) **Early Observations**

   i. The 21cm line was first predicted by Dutch astronomer **Hendrik C. van de Hulst** in 1944, who theorized that neutral hydrogen would emit this line due to quantum mechanical transitions.

   ii. It was first observed by **Harold Ewen and Edward Purcell** in 1951 at Harvard. Their observation opened the door to using the 21cm line to study the Milky Way.

   iii. Following this discovery, astronomers **mapped the spiral structure of the Milky Way** using 21cm observations, identifying large clouds of neutral hydrogen throughout the galaxy.

   (b) **Modern 21cm Observations**

   i. Today, 21cm line observations are used in projects like the **Hydrogen Epoch of Reionization Array (HERA)** and the **Canadian Hydrogen Intensity Mapping Experiment (CHIME)** to study the early universe and trace large-scale cosmic structures.

   ii. These observations help astronomers understand the distribution of matter during the early phases of galaxy formation and during the epoch of reionization, when the first stars and galaxies began to form.

3. **Planning Observations with the Allen Telescope Array**

   (a) **The Role of the ATA in Hydrogen Line Observations**

   i. The Allen Telescope Array is capable of observing the 21cm hydrogen line, making it a valuable tool for studying hydrogen distribution within the Milky Way.

   ii. Due to its ability to perform interferometric measurements, the ATA can map hydrogen clouds with higher resolution than single-dish telescopes.

   iii. Students can use the ATA to measure the 21cm line coming from our Milky Way galaxy and measure its rotation.

   (b) Setting Up the Observation

   i. Choosing a Target: The 21cm line is best observed from **HI regions in the Milky Way**, along the galactic plane. The Easy ATA GUI (`EAG.py`) is set to track sources with a galactic latitude of 0°, allowing users to input the desired galactic longitude.

ii. **Galactic Coordinates** are a system used by astronomers to specify the location of objects in the sky relative to the plane of our galaxy, the Milky Way. This coordinate system is centered on the Sun and is aligned with the structure of the Milky Way, making it particularly useful for mapping objects within the galaxy. **Galactic Longitude (l)** measures the angle along the galactic plane, starting from 0° at the direction of the center of the Milky Way (located in the constellation Sagittarius). Galactic longitude ranges from 0° to 360°, wrapping around the plane of the galaxy. **Galactic Latitude** is the angle above or below the galactic plane, which is the imaginary flat disk of the Milky Way. Galactic latitude (b) ranges from +90° (north galactic pole) to -90° (south galactic pole), with 0° lying along the galactic plane.

iii. **Observation Parameters**: The Easy ATA GUI automatically sets the parameters necessary for observing the hydrogen line, including tuning the telescope to the 1420.406MHz hydrogen line, with a bandwidth wide enough to capture Doppler-shifted signals from moving hydrogen clouds.

4. **Data Acquisition and Real-Time Observations**

(a) **Live Data Collection with the ATA**

i. During real-time observations, the ATA collects data from the hydrogen line at 1420 MHz. The data is processed through a digital backend, where it is digitized and filtered to isolate the frequency range of interest.

ii. Using **GNU Radio**, students can visualize the 21cm signal by plotting the data in the frequency domain. The 21cm line appears as a narrow peak at 1420 MHz in the raw data.

iii. Students can adjust their flowgraph to apply bandpass filters around the expected frequency range and use a frequency sink to observe the power spectrum. The signal strength can vary based on the hydrogen cloud's density and distance.

5. **Interpreting Collected Data**

(a) **Understanding Spectral Line Data**

i. Spectral lines can reveal key information about the motion of hydrogen clouds. By measuring the Doppler shift of the 21cm line, students can determine the velocity of hydrogen gas relative to Earth.

ii. For example, hydrogen moving toward Earth will appear blue-shifted (at a slightly higher frequency than 1420 MHz), while hydrogen moving away will be red-shifted (at a lower frequency). This shift allows students to map the rotation of galaxies and calculate the velocity of gas in different regions.

iii. Explain how the Milky Way's rotation curve was measured using 21cm line data, which led to the discovery of flat rotation curves in the outer regions, implying the existence of dark matter.

Lecture 3 Discussion Questions

1. Why is the 21cm hydrogen line particularly valuable for studying the structure of galaxies compared to observations in optical wavelengths?

   (a) The 21cm hydrogen line is valuable because it allows astronomers to observe neutral hydrogen gas, which is often invisible in optical wavelengths due to dust and lack of illumination from stars. The 21cm line penetrates dust and traces the distribution of hydrogen in a galaxy, including its outer regions. This makes it particularly useful for mapping the structure of galaxies, such as their spiral arms, and understanding the dynamics of their rotation. Optical wavelengths, on the other hand, typically show stars and hot gas, giving only a partial view of a galaxy's structure.

2. How does the Doppler shift of the 21cm line help astronomers measure the motion of gas within galaxies?

   (a) The Doppler shift occurs when the frequency of the 21cm line is altered by the motion of hydrogen gas relative to the observer. If the gas is moving toward the observer, the wavelength is blue-shifted (higher frequency); if moving away, it is red-shifted (lower frequency). By measuring these shifts across different regions of a galaxy, astronomers can map the velocity of gas and determine how the galaxy is rotating. This has been key in revealing the flat rotation curves of galaxies, which suggest the presence of dark matter.

3. Why is the 21cm hydrogen line particularly important for studying the early universe, and what is the significance of the Epoch of Reionization in this context?

   (a) The 21cm line is important for studying the early universe because it traces neutral hydrogen, which filled the universe before the first stars and galaxies formed. During the Epoch of Reionization, the first stars and galaxies ionized this hydrogen, marking the end of the "dark ages" of the universe. By observing the redshifted 21cm line from this period, astronomers can map the distribution of hydrogen and study the formation of the first galaxies and large-scale structures. These observations help us understand how the universe transitioned from a neutral state to the highly structured, ionized state we see today.

Lecture 3 Resources

1. The Hydrogen 21cm Line - Hyperphysics
2. Milkyway in 21cm
3. NRAO Essential Radio Astronomy Section 7.8: The HI 21-cm Line
4. Measurement of the Milky Way Rotation
5. Milky Way structure detected with the 21 cm Neutral Hydrogen Emission
6. Mapping Galactic Hydrogen