Week 4 Lab: Interferometry

1 Introduction

In this week's lab, you will delve into the world of radio interferometry, a powerful technique used in radio astronomy to combine signals from multiple telescopes and extract detailed information about astronomical sources. By constructing a flowgraph in GNU Radio, you will simulate the process of combining signals from multiple telescopes to create an interferometric array. Through this exercise, you will understand how interferometry enhances the sensitivity of radio telescopes, enabling astronomers to study astronomical sources with unprecedented detail.

To begin your exploration, we've provided a starting point with variables and a simulated astronomical source. This initial setup is designed to save you time and allow you to dive into the heart of interferometry. Your task will be to build upon this foundation, creating the simulated receivers and blocks necessary for performing interferometry.

2 Creating the GRC Flowgraph

Note: all blocks in your flowgraph should use the complex data type (blue port).

1. Download the `Interferometry.grc` file and open it in GNU Radio Companion.

   This file will be your starting point for creating the rest of the flowgraph. It contains a simulated broadband signal from an astronomical source, as well as the variables that you will adjust while the flowgraph is running.

2. Search for the **Virtual Source** block and add two blocks to your workspace.

   (a) Change the stream ID to "*astro_signal*" to match the ID of the Virtual Sink block.

   These blocks will connect to the Virtual Sink block and receive data from the simulated astronomical source, acting as the simulated antenna feed. Virtual Sink and Source blocks are an easy way to connect sections of a flowgraph.

3. Add two **Note** blocks next to the Virtual Source blocks to indicate which antenna each is being simulated. Label them "Antenna 1" and "Antenna 2".

4. Add two **Channel Model** blocks to your workspace and connect them with the Virtual Source blocks. Make the following modifications:

   (a) **Antenna 1:** Noise Voltage: 1, Frequency Offset: 0, Epsilon: 1, Taps: 1, Seed: 1.

   (b) **Antenna 2:** Noise Voltage: 1, Frequency Offset: 0, Epsilon: 1, Taps: 1, Seed: 2.

   These blocks will simulated the effects of the electronics present in the antennas which introduce noise into the signal. Here, the noise is generated using a random number generator, which does not actually produce truly random numbers, but uses a complicated algorithm to produce numbers based on a seed number. Entering different seeds for each antenna ensures that the noise is independent for each antenna, as they would be for a real antenna.

5. Add a **Delay** block and connect it only to the "Antenna 1" Channel Model block.

   (a) In the properties, enter "delay_diff" in the Delay section.

   Because the signals from separate antennas in an array have different distances to travel, they must be precisely delayed to ensure that the signals are in phase when they arrive to the signal processing computers. This block will allow you to see what happens if the signal path length is not properly accounted for when combining the signals for interferometry.

6. Place an **Add** block in your workspace. Connect it to the Channel Model block for antenna 1, and the Delay block for antenna 2.

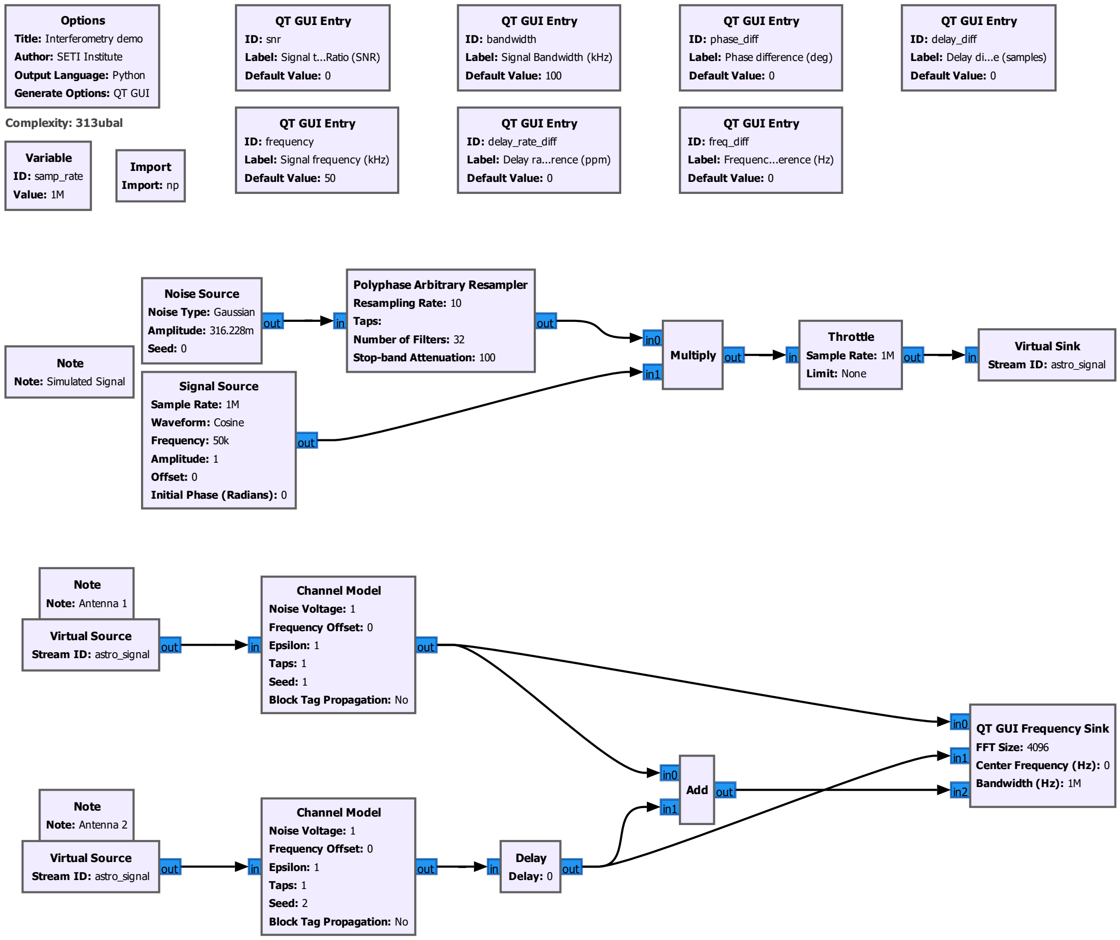
7. Add a **QT GUI Freqeuncy Sink** block and make the following modifications:

   (a) **General:** FFT Size: 4096, Center Frequency: 0, Bandwidth: samp_rate, Number of Inputs: 3

   (b) **Config:** Line 1 Label: Antenna 1, Line 1 Color: Blue, Line 2 Label: Antenna 2, Line 2 Color: Red, Line 3 Label: Interferometry, Line 3 Color: Green

   Make the following connections: Channel Model block from antenna 1 to the `in0` port, Delay block from antenna 2 to the `in1` port, Add block to the `in2` port.

8. Your flowgraph is now completed! It should look like this:



3 Experiments with Interferometry

3.1 Signal to Noise Ratio (SNR)

When the signals from the antennas are in phase, they add together constructively, leading to an increase in the combined signal's strength. If the signals are out of phase, they can partially or completely cancel each other out, resulting in a weaker combined signal. Noise is typically random and uncorrelated between antennas. When the signals from the antennas are combined, the noise adds up incoherently. This means that the noise power increases as the square root of the number of antennas (assuming uncorrelated noise sources), which is known as the square root of N scaling.

The combined signal strength can increase significantly due to constructive interference, especially for sources that are strong and spatially coherent across the antennas' fields of view. The noise also increases with the addition of signals from multiple antennas. However, the increase in noise power is slower compared to the increase in signal power. This is because the noise adds up incoherently, leading to an SNR improvement that scales with the square root of the number of antennas. As a result of the signal strength increasing more than the noise power, the overall SNR improves when signals from two or more antennas are combined. This is a key advantage of interferometry, as it allows for better detection and analysis of weak astronomical signals against background noise.

Measure the relative gain (hover your mouse on the graph) of each of the following:

1. Antenna 1-2 Noise: ______________________________
2. Antenna 1-2 Signal: ______________________________
3. Antenna 1-2 SNR: ______________________________
4. Interferometry Noise: ______________________________
5. Interferometry Signal: ______________________________
6. Interferometry SNR: ______________________________

How much did the SNR increase when the signals are added together? Is this consistent with what you expect?

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3.2 Phase

The key to interferometry is adding the signals together in phase. Constructive interference (in-phase interference) leads to a stronger combined signal, enhancing the (SNR) and improving the visibility of astronomical features. Destructive interference (out-of-phase interference) can weaken or cancel out the combined signal, reducing the SNR and making it harder to detect or analyze astronomical sources. What will happen if the signals are added with a phase difference of 90°? How about 180°? Write your prediction below, and then enter these phase difference values and compute the SNR for each scenario.

Prediction: ____

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Observation: ____

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3.3 Frequency

Combining signals with the same frequency is essential for achieving constructive interference. Coherent addition leads to constructive interference, enhancing the signal strength and improving the SNR in interferometric observations. What will happen if there is a frequency offset in the combined signals? Write your prediction below, then change the frequency difference to 0.1 Hz and observe the results. What is the relationship between the frequency difference and the period you see in the combined signal?

Prediction: ____

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Observation: ____

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3.4 Delay

The antennas in an array will receive the signal from an astronomical source at slightly different time due to the light travel time difference. The antennas are also connected to the signal processing room via cables, usually optical fibers. Because each antenna is a different distance from the signal processing room, and the cables connecting them have varying lengths, the signals must be precisely delayed to ensure they arrive at the signal processing room at the same time and thus will add constructively. The process of beamforming will also adjust these delays to form the beam of maximum sensitivity towards the desired direction in the sky.

In your flowgraph, change the signal bandwidth to 700 kHz. What will happen if the delay factor is not properly accounted for? Do you expect this will affect all frequencies equally? Write your prediction below, then change the delay rate difference to 1 part per million (ppm) and observe the results. This is what you expected? Can you explain what's happening to the combined signal?

Prediction: ____

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Observation: ____

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