Pre-Lab Reading: Data Science in Radio Astronomy II

Overview of Voyager 1 and Its Signal Characteristics

Voyager 1 is a NASA spacecraft launched on September 5, 1977, as part of the Voyager program to explore the outer planets of the Solar System. It is now the farthest human-made object from Earth, traveling through interstellar space more than 24 billion kilometers (15 billion miles) away. Despite its vast distance, Voyager 1 continues to send signals back to Earth using its X-band radio transmitter operating at 8.4 GHz (8431 MHz).

Voyager 1's signal has several key characteristics:

- Extremely Weak: The transmitted power is only 20 watts, which is about the same as a refrigerator light bulb.
- Narrowband: The signal consists of a strong carrier frequency with telemetry data modulated onto it.
- Doppler-Shifted: Since Voyager 1 is moving relative to Earth, its signal experiences a Doppler shift, meaning its frequency is not exactly 8431 MHz but varies over time.
- Highly Directional: The spacecraft's high-gain antenna must be carefully aimed at Earth to ensure reception.

Voyager 1 provides an excellent real-world analog for a potential SETI (Search for Extraterrestrial Intelligence) signal. Like a hypothetical extraterrestrial transmission, Voyager 1's signal is weak but detectable, requiring advanced signal processing techniques to extract it from background noise. Its Doppler shift mimics what we would expect from a signal originating from an exoplanet, where planetary motion would cause frequency drift. Furthermore, the signal includes a narrowband carrier, which is exactly the type of emission SETI searches prioritize, as it is unlikely to be produced by natural astrophysical processes. While Voyager 1 is a human-made signal, it is now originating from beyond the Solar System, meaning its detection and analysis require similar methods to those used in SETI. By studying Voyager 1, we can apply many of the same techniques used in the search for extraterrestrial intelligence, giving us valuable experience in identifying and characterizing artificial signals from deep space.

IQ Data and Complex Signals

In software-defined radio (SDR), signals are recorded as IQ (In-phase and Quadrature) data, which are complex numbers rather than simple real values. This method allows us to preserve both amplitude and phase information of a signal. A complex signal is represented as:

$$s(t) = I(t) + jQ(t) \tag{1}$$

where I (real part) represents the in-phase component, and Q (imaginary part) represents the quadrature component. By using complex signals, we can:

- Analyze phase shifts in the signal.

- Easily shift frequencies for filtering and processing.
- Improve signal detection by preserving complete information.

Fast Fourier Transform (FFT)

Since Voyager 1's signal is recorded as IQ time-domain data, we must convert it to the frequency domain using the Fast Fourier Transform (FFT). The FFT allows us to analyze which frequencies are present in the signal. In the time domain, Voyager 1's signal looks like random noise. however, in the frequency domain, it appears as a sharp peak at its carrier frequency. An FFT allows us to separate the signal from the noise by converting it into a spectrum. The frequency resolution of an FFT is given by:

$$\Delta f = \frac{f_s}{N} \tag{2}$$

where f_s is the sampling rate (in Hz), and N is the FFT size. A larger FFT size gives better frequency resolution, making it easier to detect narrowband signals like Voyager 1. FFT's can be easily computed using the Numpy function:

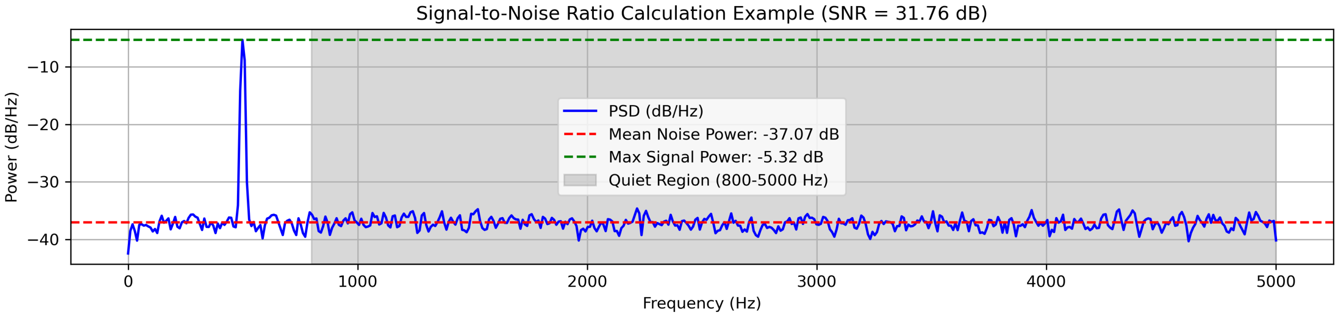
spectrum = np.fft.fftshift(np.fft.fft(signal))

Signal-to-Noise Ratio (SNR)

Voyager 1's signal is very weak, often buried in noise. The Signal-to-Noise Ratio (SNR) quantifies how strong the signal is relative to the noise. A higher SNR makes the signal easier to detect, techniques such as integration (averaging multiple FFTs) can help improve SNR. When working in the logarithmic units of decibels (dB), SNR can be calculated as:

$$SNR = P_{signal} - P_{noise} \tag{3}$$

where P_{signal} is the power of the detected signal, and P_{noise} is the power of the background noise. In order to quantify the power of the noise floor, identify a part of the spectrum where no signal is present and find it's mean value.

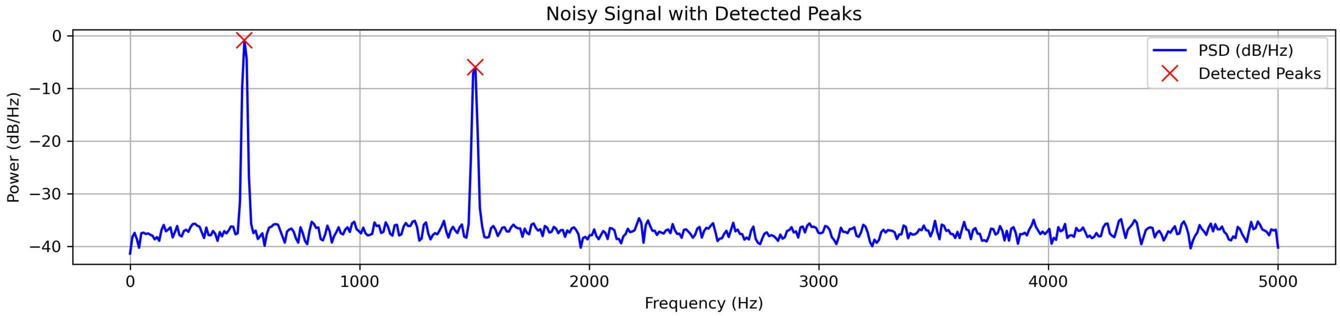


Automated Peak Detection

One of the most important steps in analyzing a signal is detecting peaks in the power spectrum. A peak corresponds to a strong, narrowband signal at a particular frequency. In the case of Voyager 1, the peaks arise from the carrier wave and modulated sidebands of the spacecraft's transmission. In radio astronomy and SETI, peak detection is used to identify narrowband sources that might originate from artificial sources, and to help identify and remove radio frequency interference (RFI) caused by human-made signals.

A peak is defined as a point in the spectrum that is higher than its neighboring points by a certain amount. However, we don't want to detect random noise spikes, so we need to set parameters to filter out insignificant peaks. These parameters are:

- Threshold - The minimum power level a peak must have to be detected.
- Distance - How far apart detected peaks must be to be consider separate.
- Prominence - How much a peak stands out from the surrounding noise.



Automated peak detection is a valuable tool for many different scenarios common in radio astronomy. It allows astronomers to search through large datasets for pulsars, fast radio bursts (FRBs), or to track the Doppler shift of a spacecraft signal over time.