Instructor Lab Manual: Mars Orbiters and the Search for Technosignatures

1 Introduction

The search for extraterrestrial life is guided by two primary strategies: **biosignatures**, which suggest biological activity, and **technosignatures**, which point to advanced technology. Biosignatures are specific chemical or physical indicators that may suggest the presence of life, such as oxygen or methane in a planet's atmosphere that are out of balance with expected natural processes. These signs can also include things like chlorophyll-like pigments, microbial mats, or seasonal variations in atmospheric gases. Technosignatures are signs of technology that could come from intelligent civilizations, including narrowband radio signals, pulsed laser emissions, or atmospheric pollutants like chlorofluorocarbons that don't occur naturally. They may also include large-scale structures, waste heat, or any detectable evidence of artificial systems operating beyond Earth. No such biosignatures or technosignatures have ever been confirmed, but the search is ongoing.

In this lab, you'll focus on one specific type of technosignature: radio signals. Certain kinds of radio emissions, such as narrowband transmissions that appear at a single frequency, or signals that drift in frequency over time due to motion, are difficult to produce through natural processes and may indicate the presence of advanced technology in the universe. SETI researchers use radio telescopes to scan the sky for these unusual signals, searching for patterns that stand out from natural signals or noise. To explore this idea, you'll analyze a real radio signal from the Tianwen-1 Mars orbiter, study its properties using GNU Radio, and learn how to identify the features that make a signal a potential technosignature.

2 Exploring Technosignatures - Signal Classification

SETI researchers can classify radio signals into three broad categories: **technosignatures, natural astronomical signals, and radio frequency interference (RFI)**. This categorization helps determine whether a signal originates from intelligent life, astrophysical processes, or human-made sources. Each class has distinct characteristics that guide how researchers interpret the signal's origin.

Key features like frequency, bandwidth, modulation, repetition, and drift are used to distinguish between these categories. By analyzing these traits, researchers can begin to rule out common sources of interference, recognize natural emissions, or flag signals that may suggest artificial origin.

1. **Technosignatures**: While it's impossible to know what a technosignature would look like, there are some general properties that a genuine technosignature would likely have. The most energy efficient method to broadcast a signal across large interstellar distances is to concentrate all the energy into a very narrow range of frequencies, called a narrowband signal. Due to relative motion between us and the transmitter, the signal would likely exhibit a drift in frequency from the Doppler effect. Moreover, a technosignature would likely lack modulation or have simple, intentional structure, and would not match known natural or human-made signals and may persist or repeat in a way that suggests deliberate transmission.

2. **Natural Astronomical Signals**: Natural signals can arise from a wide range of sources, such as

pulsars, spectral emission lines, or quasars. In general, natural signals are spread across a broad range of frequencies, called a broadband signal, and often appear noisy or irregular. They typically originate from fixed positions in the sky and follow predictable astrophysical behavior.

3. **Radio Frequency Interference (RFI)**: RFI comes from human-made sources like satellites, cell towers, or radar, and can be either narrowband or wideband. These signals often show modulation, strong, persistent power levels, and they typically fall within known communication bands used on Earth. Terrestrial sources of RFI cannot be located in the sky, and will appear no matter which direction the radio telescope is pointed, however RFI from satellites can be sky located, but with non-sidereal motion.

Below are four examples of signals that can be seen with a radio telescope. Each one represents a different kind of source: a natural astronomical signal, radio frequency interference (RFI) from human technology, or a technosignature analog. Carefully examine each signal using the plot and description to determine its most likely origin.

For each signal:

1. **Record your classification:** natural, RFI, or technosignature.
2. **List the key features** you used to make your decision.
3. **Briefly explain your reasoning.** What stood out? Could this signal be mistaken for something else?

Signal A: **Natural: Pulsar B0329+54**

Primary features: broadband, no modulation, no frequency drift, sidereal motion.

Reasoning: The signal is broadband and shows highly regular, periodic pulses with no modulation or Doppler drift. Its sidereal motion confirms it's a fixed astronomical source. These characteristics are well established features of pulsars and don't resemble any artificial or Earth-based transmissions.

Signal B: **Technosignature Analog: Tianwen-1 Mars Orbiter**

Primary features: strong narrowband signal, modulation, frequency drift, sidereal motion.

Reasoning: The narrowband features and symmetric sidebands indicate intentional transmission with modulation, clear signs of an artificial origin. The presence of Doppler drift shows the transmitter is in motion relative to the observer, ruling out fixed terrestrial sources. Its sidereal motion confirms the signal is extraterrestrial, consistent with a technosignature.

Signal C: **Natural: Milky Way 21cm Hydrogen line**

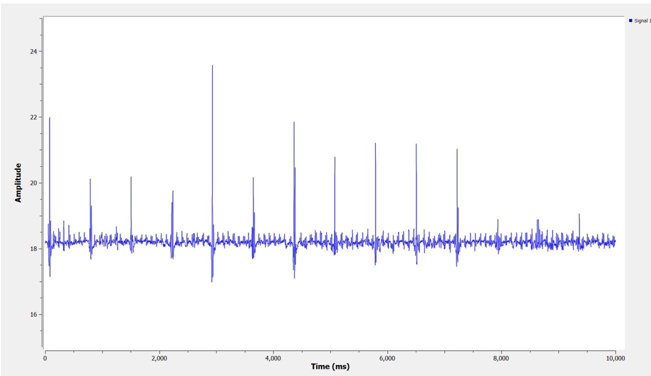
Primary features: moderate bandwidth, alignment with known natural emission from hydrogen, direction dependent signal strength and spectral structure.

Reasoning: The frequency is approximately 1420 MHz, matching well known natural emission from neutral hydrogen. The lack of clear modulation or Doppler drift does not resemble an artificial signal. The signal strength and spectral structure vary with sky position (the signal is strongest along the galactic plane), suggesting a natural astronomical origin.

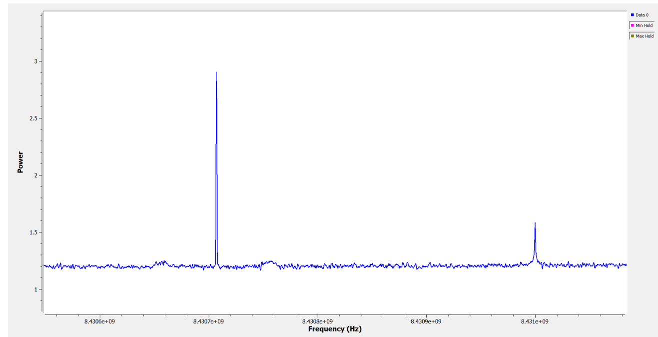
Signal D: **RFI: GOES-17 Geostationary Satellite**

Primary features: strong and persistent signal, narrowband spectral features, modulation, no frequency drift, non-sidereal motion.

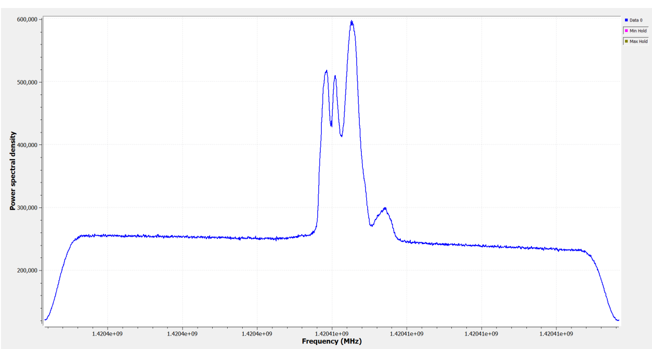
Reasoning: The signal has both narrowband and modulated broadband features, suggesting artificial origin. However, the signal exhibits non-sidereal motion and no Doppler drift, signs of a human-made transmitter in Earth orbit, specifically a geostationary orbit.



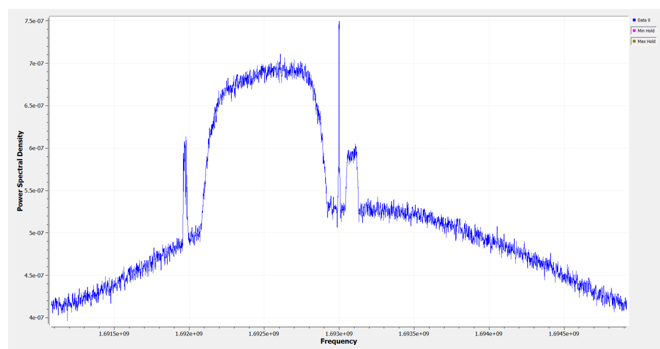
(a) **Signal A**: A time-series plot showing repeating, broadband pulses with a very precise period. The signal is consistent over time, shows no frequency drift or modulation, and can be localized to a position in the sky with sidereal motion.



(b) **Signal B**: A spectrum showing two distinct narrowband features. The stronger of the two has weak symmetric sidebands and exhibits clear Doppler drift over time, while the second narrowband feature shows some modulation. On short timescales, the signal moves across the sky with sidereal motion.



(c) **Signal C**: Spectrum showing a medium bandwidth signal with internal spectral structure. The signal strength and shape vary depending on the direction of observation, and it is centered near 1420 MHz, a frequency commonly associated with neutral hydrogen in the galaxy.



(d) **Signal D**: A strong, persistent signal confined to a small frequency band, showing no frequency drift over time. The signal remains fixed in both frequency and sky position during the observation, but exhibits non-sidereal motion.

Figure 1: Time-series and spectral plots of different signal types.

3 Analyzing the Tianwen-1 Mars Orbiter Signal

In this section, you'll analyze a real radio signal from Tianwen-1, a Chinese spacecraft orbiting Mars, which transmits a continuous narrowband signal to Earth. The spacecraft transmits this unmodulated continuous wave signal for Doppler tracking. By measuring the precise frequency of the received signal and how it shifts over time due to the Doppler effect, ground stations can determine the spacecraft's velocity and refine its trajectory. The Tianwen-1 signal shares many characteristics we might expect from a potential signature, making it a good real-world analog. These features include:

- **Narrowband Carrier:** The Tianwen-1 signal is extremely narrow in frequency, a hallmark of energy-efficient artificial transmissions, similar to how a beacon might behave.
- **Modulated Sidebands:** The low-power, symmetric, modulated sidebands are used to transmit information over large distances.
- **Doppler Drift:** The signal shifts in frequency over time due to relative motion, just as a technosignature from a distant planetary system would.
- **Persistent:** It is continuous and detectable throughout the observation, matching the expectations for an intentional, artificial source.
- **Sky-Localized Motion:** The signal tracks to a specific location in the sky and exhibits non-sidereal motion, as expected for a spacecraft within our solar system. Unlike Tianwen-1, which moves with non-sidereal motion, an interstellar technosignature would likely appear to move with sidereal motion, fixed relative to the background stars.

To explore the signal, you'll use GNU Radio, an open source toolkit that allows you to build signal processing flowgraphs. **Open GNU Radio Companion and create a new flowgraph** using the button on the far left of the top control panel. Using the search tool (magnifying glass icon in the control panel), search for and **add the following blocks to your workspace**. Once you've added a block to your workspace, double-click to **open the properties window and make the modifications below.**

- Edit the existing `samp_rate` variable.
  - Value: `2.84e6`
- **Variable**
  - ID: `nfft`
  - Value: `2**13`
- **Variable**
  - ID: `freq`
  - Value: `8431e6`
- **File Source**
  - File: your path to the downloaded `Tianwen_DATA` file
  - Output Type: `float`
  - Repeat: `Yes`
  - Vector Length: `nfft`

- **QT GUI Vector Sink**
  - Vector Size: `nfft`
  - X-Axis Start Value: `freq - samp_rate/2`
  - X-Axis Step Value: `samp_rate/nfft`
  - X-Axis Label: `"Frequency (Hz)"`
  - Y-Axis Label: `"Power"`
  - Autoscale: `No`
  - Y min: `0.5`
  - Y max: `3.5`

These blocks can be connected to create a flowgraph; connect the blocks by first selecting the **out** port of one block, then the **in** port of the other. Organize and **connect the blocks as shown in Figure 2**. The connecting arrows should be black; if they're red then there's a mismatch between the data types being used in each block. If this happens, double check the data type of each block, they should all have orange ports indicating the `float` data type.

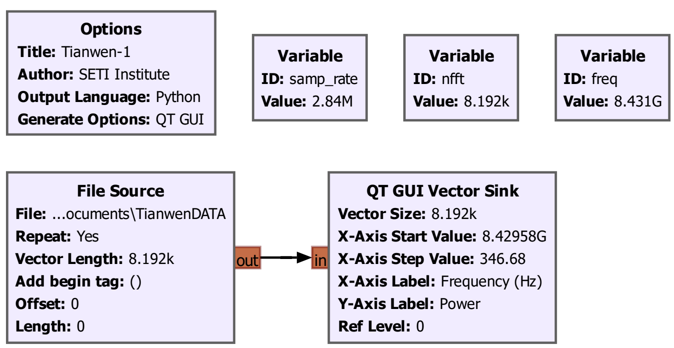


Figure 2: GNU Radio Companion flowgraph for visualizing the signal from Tianwen-1.

Run the flowgraph using the play button on the toolbar, you should see a plot similar to Figure 3. Zoom in on the plot by dragging a box around the region of interest.

3.1 Identify Spectral Features

As you examine the spectrum plot in GNU Radio, look for distinct peaks or features that stand out from the background noise. These may include narrowband spikes, broader modulated signals, or signals with sidebands. Hover your cursor over the plot to view the frequency at the current location. For each spectral feature, measure and record the following:

- Approximate center frequency (MHz).
- Approximate bandwidth (kHz): Bandwidth $= f_{upper} - f_{lower}$

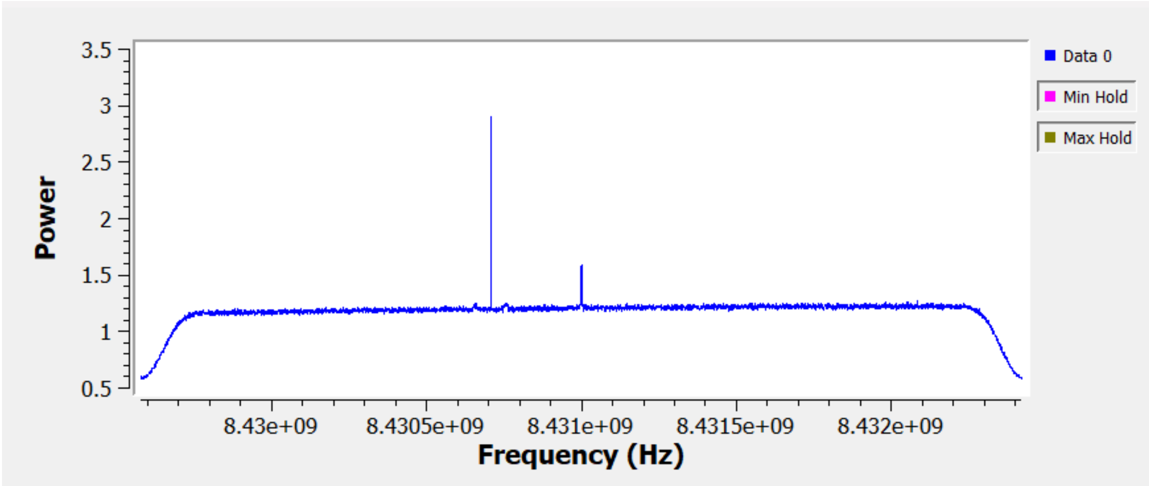


Figure 3: Spectrum plot of the signal from Tianwen-1.

- Likely purpose: Based on the appearance of the signal (e.g. narrow or wide, presence of sidebands...), write your hypothesis about what this spectral feature might represent. Is it likely used for telemetry, Doppler tracking, communication, or some other purpose?

Table 1: Spectral Feature Analysis

Feature #	Approx. Frequency (MHz)	Approx. Bandwidth (kHz)	Likely Purpose
1	8430.70	0	Doppler Tracking
2	8430.65	20	Communication
3	8430.75	20	Communication
4	8431.00	10	Telemetry

4 Designing a Technosignature

Now that you've explored how SETI researchers classify different radio signal types, you'll apply this knowledge to design a technosignature meant for detection by other technologically advanced life in the universe. This is not just a creative exercise, it's a chance to reflect on what makes a signal detectable, distinguishable, and intentional.

Answer the following questions to help guide your signal design.

There are many possible answers in this activity. The main thing to check is that the answers for each section are consistent with each other. For example, if the purpose of the signal is communication, then it should have moderate or broad bandwidth, and some type of modulation.

1. **What is the purpose of your signal?**

   ☐ Beacon (announce presence)

☐ Communication (transmit information)

☐ Other: ___________________________

Explain: Why would this signal be sent? What is it trying to achieve?

____

____

____

2. **Will your signal be transmitted directionally (towards a specific location) or omnidirectionally (equally in all directions)?**

   ☐ Directional

   ☐ Omnidirectional

   ☐ Other: ___________________________

   Explain: Why did you choose this approach? What are the trade-offs in terms of energy, detectability, range, etc?

   ____

   ____

   ____

3. **What frequency will your signal use?**

   Choose a frequency. Would it be near a natural spectral line, far from human RFI bands, etc?

   Center Frequency: _____________________

   Explain: Why did you choose this frequency? How does your choice impact the detectability of your signal?

4. **What bandwidth will your signal have?**

   ☐ Narrowband

   ☐ Moderate

   ☐ Broadband

   Explain: Why did you choose this bandwidth? How does it affect detectability and information content?

   ____

   ____

   ____

5. **Will your signal be modulated? If so, how?**

   ☐ No modulation

☐ Amplitude modulation (AM)

☐ Frequency modulation (FM)

☐ Pulses

☐ Digital modulation

☐ Other: ___________________________

Explain: Why did you choose this type of modulation? How does it affect detectability and the ability to transmit information?

____

____

____

6. **What feature makes your signal stand out?**

   Explain: What unique features help your signal to stand out from a natural astronomical sources, noise, or RFI?

   ____

   ____

   ____

Using Figures 4 and 5, draw what the technosignature would look like as a spectrum and as a time-series.

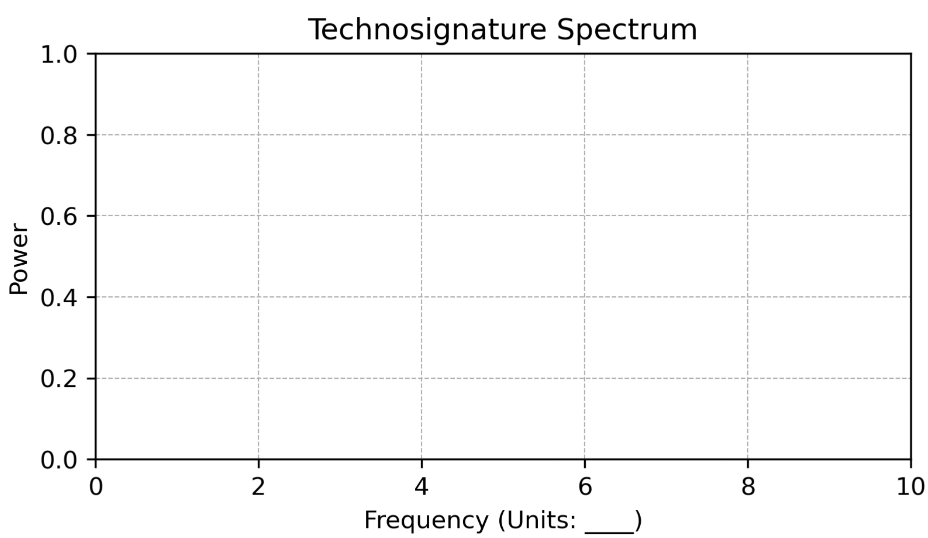


Figure 4: Spectrum of your designed technosignature.

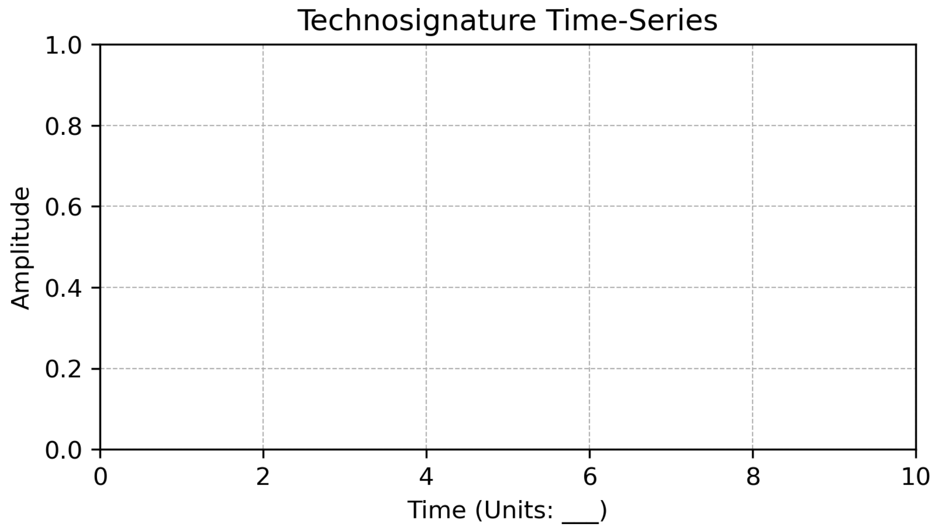


Figure 5: Time-series of your designed technosignature.

5 Optional: Observing Tianwen-1 with the Allen Telescope Array

1. In the gnuradio VNC, right click on the desktop and select `Open Terminal`

2. Navigate to the correct directory with `cd ATA-Control-GUI`

3. Open the GUI with `python MarsGUI.py`

4. Select the `Activate Antenna` button. This will take about 75 seconds, and will automatically calibrate the telescope for this observation. When the process is finished, text will print in the terminal, including "Calibration Complete". At this point, data will beginning streaming into the `Tianwen_Receive.grc` GNU Radio Companion flowgraph. Run the flowgraph using the play button on the top control panel to see the live data.

5. Select `Go To Mars` button. The telescope will begin slewing to the right ascension and declination of Mars. Monitor both the live camera feed of the telescope and the data stream; note any changes in the spectrum as the telescope moves across the sky.

6. If you want to confirm the telescope pointing or other details, select the `Show Antenna Status` button, ensure the telescope is pointing to the correct location.

7. When you are finished with the observation, select the `Shut Down Antenna`. This will stop data streaming, and put the telescope back in the park position. Monitor the live camera feed to ensure the telescope parks correctly, the terminal will display "Antenna 1a has been parked!" when it is finished.