Instructor Lab Manual: Geostationary Satellites

Introduction

Geostationary satellites orbit at the same rate as Earth's rotation, allowing them to stay fixed in the sky relative to an observer on Earth. This property makes them very useful for communications, weather monitoring, and military applications. In this lab you'll analyze a recorded transmission from one of these satellites, GOES-17 (Geostationary Operational Environmental Satellite), observed at 1.693 GHz by the Allen Telescope Array (ATA). You'll examine the signal's structure and potential modulations schemes to understand how satellite communication works.

To do this, you'll use GNU Radio, an open-source software-defined radio (SDR) platform; installation instructions can be found here: `https://wiki.gnuradio.org/index.php/InstallingGR`. Using GNU Radio, you'll visualize the signals power spectral density (PSD), measure its properties, and explore how geostationary satellites are used for communications. Before starting the lab, please ensure you have downloaded the data file: `GOES-17DATA`.

Orbital Distance of a Geostationary Satellite

In order for a satellite to remain geostationary, i.e. fixed in the sky, it must meet three main requirements:

1. Maintain a circular orbit: Gravity causes objects to orbit in ellipses, with eccentricities ranging from 0 (perfect circle) to 1 (highly elongated). For an orbit with non-zero eccentricity, the speed will change during the course of the orbit. By sustaining an orbit with 0 eccentricity, geostationary satellites can maintain constant orbital distance and speed, ensuring they can stay fixed in the sky.

2. Orbit along the equator (0° inclination): If the satellite's orbit were tilted away from the equator, it would appear to oscillate north and south in the sky throughout the day.

3. Orbit at the same rate as the Earth's rotation: This period is called a sidereal day, the time it takes for Earth to rotate exactly once relative to the background stars, which is about **23 hours 56 minutes and 4 seconds.**

The relationship between orbital period and orbital radius is given by the Newtonian form of Kepler's 3rd law:

$$T^2 = \frac{4\pi^2 r^3}{GM} \tag{1}$$

where T is the orbital period (in seconds), r is the orbital radius[1] (in meters, from the center of mass), G is the gravitational constant ($6.674 \times 10^{-11} \frac{m^3}{kg \cdot s^2}$), and M is the mass of the Earth ($5.972 \times 10^{24} kg$).

[1] Technically r refers to the semi-major axis of the ellipse of the orbit. However, geostationary satellites must maintain a nearly perfect circular orbit so that it's velocity does not vary throughout the orbit, thus this distinction is omitted.

Using Equation 1, find the height above Earth's surface that a satellite must orbit to stay fixed in the sky. Note that the radius of Earth at the equator is about 6.378×10^6 meters, and the value of r is measured to the center of the Earth, so the height above the surface is $r - 6.378 \times 10^6$ meters.

1. Convert orbital period to seconds:

$$T = (23 \text{ hours} \times 60\frac{\text{min}}{\text{hour}} \times 60\frac{\text{sec}}{\text{min}}) + (56\text{min} \times 60\frac{\text{sec}}{\text{min}}) + 4 \text{ sec} = 86,164 \text{ seconds}$$

2. Solve for orbital radius:

$$T^2 = \frac{4\pi^2 r^3}{GM} \rightarrow r = \sqrt[3]{\frac{T^2 GM}{4\pi^2}}$$

3. Plug in values:

$$r = \sqrt[3]{\frac{(86,164)^2(6.674 \times 10^{-11})(5.972 \times 10^{24})}{4\pi^2}} = 42,163,111 \text{ meters}$$

4. Find height above Earth's surface:

$$h = r - r_{Earth} = 42,163,111\text{m} - 6.378 \times 10^6\text{m} = 35,785,111\text{m}$$

Height = 35,785,111 meters

Signal Visualization in GNU Radio

The `GOES-17DATA` file is a raw binary recording of the transmission from the GOES-17 geostationary satellite, observed from the Allen Telescope Array. The signal has been processed and can be visualized using a simple GNU Radio Companion flowgraph. **Open GNU Radio Companion and create a new flowgraph using the button in the upper left of the control panel.** You can add blocks to the workspace by searching for them with the magnifying glass icon on the top control panel and double-clicking; open the properties window by double-clicking on the block. Connect the blocks by selecting the "out" port of one block, then the "in" port of the other block; you should see a black arrow connecting the blocks. **Add the following blocks to your workspace with these modifications, and connect the blocks to match Figure 1.**

- **Sample Rate:** (Change the existing `samp_rate` variable value to 3.84e6)
- **Variable:** (ID: nfft, Value: 2**12)
- **Variable:** (ID: freq, Value: 1693e6)
- **File Source:** (File: your path to the downloaded `GOES-17DATA` file, Output Type: float, Vector Length: nfft)
- **QT GUI Vector Sink:** (Vector Size: nttf, X-Axis Start Value: freq - samp_rate/2, X-Axis Step Value: samp_rate/nfft, X-Axis Label: "Frequency", Y-Axis Label: "Power Spectral Density", X-Axis Units: "Hz", Y-Axis Units: "dB", Grid: Yes, Autoscale: Yes)

Run the flowgraph using the play button on the top control panel, you should see a live plot similar to Figure 2.

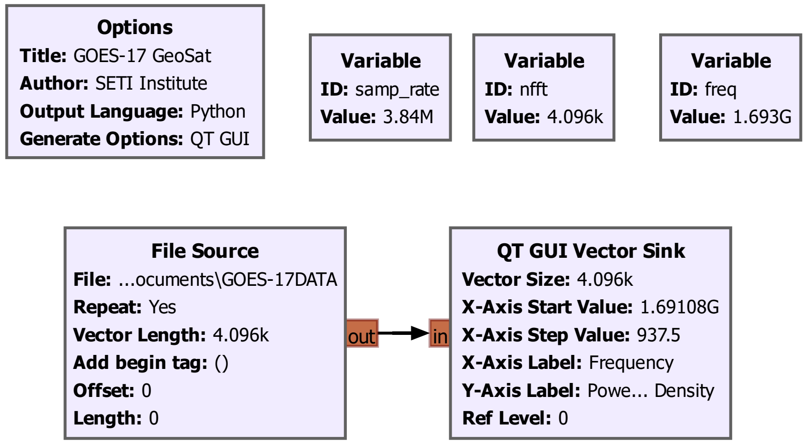

Figure 1: GNU Radio Companion flowgraph for visualizing the GOES-17 transmission.

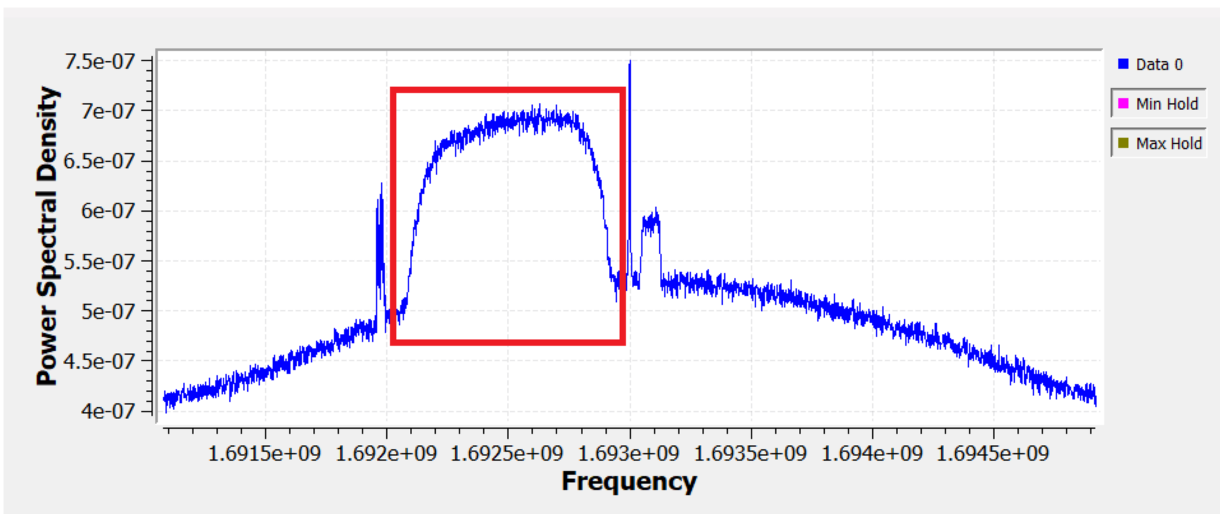

Figure 2: GNU Radio Companion plot of the GOES-17 transmission.

Bandwidth and Symbol Rate

The rate at which data can be transmitted, called the symbol rate R_s (measured in symbols per second), depends on both the modulation scheme and the signal bandwidth. The purpose of modulation is to efficiently transmit bits, the basic units of information, with different modulation schemes encoding varying numbers of bits per symbol. The relationship between symbol rate, bandwidth, and bits per symbol for common modulation types used in satellite communication is shown in Table 1.

To determine the data rate of the GOES-17 transmission, first measure the bandwidth of one of the modulated sidebands. **In your GRC plot, zoom in on the boxed region shown in Figure 2 by dragging a box around the area.** The cursor will display the frequency at it's location on the plot. Using this, **measure and record the approximate frequencies of the beginning and end of the modulated section of the spectrum to at least 5 significant figures.** The bandwidth (BW) is the difference between the upper and lower frequencies:

Modulation	Symbol Rate/Bandwidth	Bits per Symbol (k)
BPSK	$R_s \approx BW$	1
QPSK	$R_s \approx BW$	2
8-PSK	$R_s \approx BW$	3
16-QAM	$R_s \approx 2\,BW$	4
64-QAM	$R_s \approx 3\,BW$	6

Table 1: Summary of modulation properties.

$$BW = f_{upper} - f_{lower} \tag{2}$$

f_{upper} =1692.1 MHz

f_{lower} =1692.9 MHz

BW = 0.8 MHz

Now that you've measured the bandwidth of the modulated sideband, you can use this to calculate the data rate (R_b) for different modulation schemes. As previously discussed, the data rate (R_b) depends both on the relationship between symbol rate (R_s) to bandwidth, as well as the number of bits per symbol (k), quantified in Equation 3. **Using Equation 3 and Table 1, calculate the data rate for each type of modulation scheme; express your answer in Megabits per second (Mbps), where 1 Mbps = 1,000,000 bps.**

$$R_b = R_s \times k \tag{3}$$

Modulation	Data Rate R_b (Mbps)
BPSK	$R_b = (1 \times 0.8) \times 1 = 0.8$
QPSK	$R_b = (1 \times 0.8) \times 2 = 1.6$
8-PSK	$R_b = (1 \times 0.8) \times 3 = 2.4$
16-QAM	$R_b = (2 \times 0.8) \times 4 = 6.4$
64-QAM	$R_b = (3 \times 0.8) \times 6 = 14.4$

Table 2: Data Rate Calculation Table

Global Communication Example

Suppose you want to send your favorite movie, which has a file size of 5 Megabytes (8-bits per byte), to a friend who is on the other side of the world. This can be accomplished by using a geostationary satellite relay, with the following signal path: You → Satellite 1 → Satellite 2 → Your Friend. Assume the distance from the ground to the satellite, and vice versa, is the height you found in Part 1, and the distance between the satellites is 7.3×10^7 meters (you can verify this with some trigonometry, assuming a 3-satellite constellation such as that in the pre-lab reading).

Radio signals, such as those used in satellite communication, travel at the speed of light (c), which is about 300,000,000 meters/second. The time it takes light to travel a distance d is:

$$t = \frac{d}{c} \tag{4}$$

Using Equation 4 and the data rate you found above (assume 64-QAM modulation), calculate the total time it will take to transmit and receive the file, accounting both for bit rate and light travel time.

1. Light travel time from the ground to satellite 1, and satellite 2 to the ground:

$$t_1 = \frac{35,785,111 \text{ m}}{300,000,000 \text{ m/s}} = 0.119 \text{ seconds}$$

2. Light travel time from satellite 1 to satellite 2:

$$t_2 = \frac{7.3 \times 10^7 \text{ m}}{300,000,000 \text{ m/s}} = 0.243 \text{ seconds}$$

3. Total light travel time:

$$t_{\text{Travel}} = 0.119 + 0.243 + 0.119 = 0.482 \text{ seconds}$$

4. Convert file size from Megabytes (MB) to Megabits (Mb):

$$5 \text{ MB} \times 8 \text{ Mb/MB} = 40 \text{ Mb}$$

5. Calculate transmission time:

$$t_{\text{Transmission}} = \frac{\text{File Size}}{\text{Data Rate}} = \frac{40 \text{ Mb}}{14.4 \text{ Mbps}} = 2.777 \text{ seconds}$$

6. Find the total time:

$$t_{\text{Total}} = t_{\text{Travel}} + t_{\text{Transmission}} = 0.482 \text{ seconds} + 2.777 \text{ seconds} = 3.259 \text{ seconds}$$

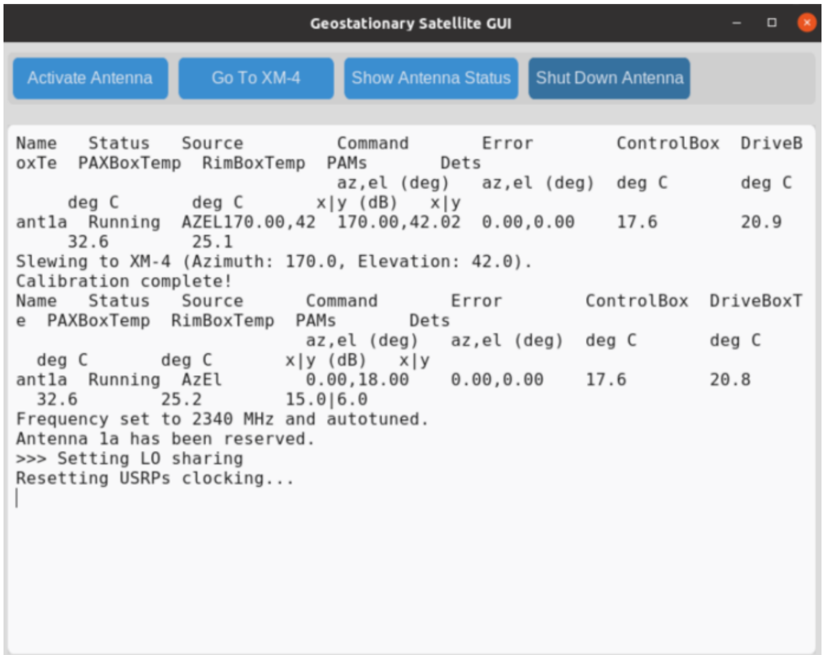

Figure 3: The Graphical User Interface you will use to observe GOES-17 with the Allen Telescope Array.

Live Observation

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 GeoSatGUI.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 `GeoSat_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 GOES-17` button. The telescope will begin slewing to the azimuth and elevation of GOES-17. 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 (Azimuth=170°, Elevation=42°).

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's finished.