Decoding Earth: Signals from Geostationary Orbit

1 Introduction

Orbiting weather satellites are continuously sending information back to Earth to track storms, monitor fires, and study the atmosphere. In our everyday lives, these signals are invisible to us, but with the right tools they can be received and decoded. In this lab, you will use a small radio telescope to receive the transmissions from one of the these satellites and decode it into real-time images of Earth from space. Receiving a signal directly from space is a unique opportunity. Instead of relying on images that have already been processed and shared online, you will build one yourself directly from the raw transmission. This gives you the chance to see how information moves from an orbiting satellite to a ground station, and then is decoded into an image that can be used to study our home planet.

Once you have produced near real-time images of Earth from space, you can think more broadly about what they represent. If you were studying Earth from afar, what clues would you find in these pictures? Clouds and oceans are signs of weather and liquid water. Vegetation shows up in certain spectral bands. Cities and other human structures can sometimes be visible as well. In other words, a single satellite transmission carries evidence of both biology and technology on Earth. The same principles guide the search for life and intelligence on worlds beyond our own.

2 Geostationary Orbit

Satellites can orbit Earth in many different ways, each with their own purpose. Some complete an orbit about every 1.5 hours in Low Earth Orbit (LEO). Satellite higher up in Medium Earth Orbit (MEO), like many GPS satellites, can cover more of Earth's surface. Each type of orbit is chosen for a reason. See Figure 1 in the *Supplementary Materials*.

A geostationary orbit is a very specific case. In this orbit, the satellite appears to stay in the same place in the sky over time, when viewed from the ground. This kind of orbit can cover very large areas of the Earth at once, and simplifies the process of receiving the transmission, as the satellite remains in the same place in the sky. This happens only if the following three conditions are met:

1. The orbital period, the time it takes the satellite to complete one full orbit, must be exactly one sidereal day, the time it takes for Earth to rotate once relative to the background stars. A sidereal day is **23 hours 56 minutes and 4 seconds, or 86,164 seconds.**

2. The path must be circular, keeping the distance and speed constant.

3. The orbit must lie directly above the equator. Any tilt away from the equator would cause the satellite to appear to drift north and south each day.

The altitude needed to achieve this orbit can be found using the Newtonian form of Kepler's third law:

$$P^2 = \frac{4\pi^2 r^3}{GM} \implies r = \sqrt[3]{\frac{P^2 GM}{4\pi^2}} \tag{1}$$

where P is the orbital period in seconds, r is the orbital radius (measured from Earth's center), G is the gravitational constant, and M is the mass of Earth. Subtracting Earth's equatorial radius $R_\oplus$ from r gives the height above the surface of Earth:

$$\text{Height} = r - R_\oplus \tag{2}$$

Quantity	**Symbol**	**Value**
Gravitational constant	G	6.674×10^{-11} m^3 kg^{-1} s^{-2}
Mass of Earth	M	5.972×10^{24} kg
Equatorial radius of Earth	$R_\oplus$	6.378×10^6 m
Orbital period (sidereal day)	P	23 h 56 m 4 s = 86,164 s

Table 1: Constants and values needed to calculate the height of a geostationary orbit.

Using these relationships, calculate the height above Earth's surface a satellite must have to remain geostationary.

Height = _______________ meters

2.1 Optional: Finding the Satellite Azimuth and Elevation

You need two angles to know where to point the dish. **Azimuth** is the compass direction measured clockwise from true north (0° to 360°). **Elevation** is the angle above the horizon (0° at the horizon, 90° overhead). The method below uses a calculator set to degrees and a simple model of geostationary orbit.

Inputs

- Your latitude: ϕ (degrees, north positive)
- Your longitude: λ_o (degrees, east positive, west negative)
- Constant for Earth's radius compared to the geostationary orbit radius: $k = \frac{R_\oplus}{R_{\text{geo}}} \approx 0.1513$

- Satellite longitude: λ_s (degrees, east positive, west negative)
  - ∗ GOES-18: $\lambda_s = 137.2°W = -137.2°$
  - ∗ GOES-19: $\lambda_s = 75.2°W = -75.2°$

Record your latitude (ϕ), longitude (λ_0), and the satellite longitude (λ_s) in degrees.

$$\phi = \_\_\_\_\_\_\_\_°, \quad \lambda_o = \_\_\_\_\_\_\_\_°, \quad \lambda_s = \_\_\_\_\_\_\_\_°$$

Formulas (calculator in degrees)

$\Delta\lambda$ is how far east or west the satellite is from your longitude. If $\Delta\lambda$ is positive the satellite is east of you. If it is negative the satellite is west of you.

$$\Delta\lambda = \lambda_s - \lambda_o \tag{3}$$

$$\Delta\lambda = \_\_\_\_\_\_\_\_°,$$

The ratio u accounts for Earth's radius compared to the geostationary orbit radius.

$$u = \cos\phi\,\cos\Delta\lambda \tag{4}$$

$$u = \_\_\_\_\_\_\_\_\_\_$$

Azimuth is measured clockwise from north, so the subtraction from 180° shifts the reference from "south" to the usual compass bearing. Elevation uses the ratio u and the constant k. If you get a negative azimuth, add 360° to bring it into $[0°, 360°)$. Record Az and El to the nearest 0.1°.

$$\text{Azimuth} = 180° \; - \; \arctan\left(\frac{\tan\Delta\lambda}{\sin\phi}\right) \tag{5}$$

$$\text{Elevation} = \arctan\left(\frac{u-k}{\sqrt{1-u^2}}\right) \tag{6}$$

$$\text{Elevation} = \_\_\_\_\_\_\_\_\_\_°, \quad \text{Azimuth} = \_\_\_\_\_\_\_\_\_\_°$$

3 Setting up SatDump

Before pointing the dish, you need to make sure the software-defined radio and decoding software are working correctly. SatDump is an open-source program that can control your SDR, tune to the satellite's frequency, and decode the data stream into images. In this section, you will install SatDump, connect the SDR, and verify that it's ready to receive.

The easiest way to get SatDump is to download the pre-built version from the official website:

`https://www.satdump.org/download/` or see Section 3 in the *Supplementary Materials* for a clickable link.

- Download the Installer file appropriate for your operating system.
- Run the `.exe` installer file.
- Follow the on-screen installation steps and complete the install using the default settings.

Once SatDump is installed, open the application and follow the steps below. Unless otherwise specified, used the default settings.

1. Plug in the SDR into a USB port on your laptop.
2. Open the SatDump application and navigate to the `Recorder` tab in the upper left.
3. In the `Device` section, expand the drop down menu and select `RTL-SDR (NESDR SMArTee XTR)`. If this option does not appear, make sure the SDR is plugged in and select the refresh button.
4. Enter `2.4 Msps` for the `Samplerate`.
5. Select the `Start` button. You should see a live spectrum appear in the plot on the right. If the spectrum does not appear, unplug the SDR and repeat steps 1-4.
6. Expand the `Processing` tree; search for and select `GOES-R HRIT` in the `Search pipelines` entry.
7. Expand the `Freq` drop down menu and select `HRIT`, this will automatically tune the SDR to the downlink frequency of 1694.1 MHz.

Once the above steps are completed and working correctly, you're ready to move on to setting up the dish.

4 Setting up the Dish

To receive images from GOES, you will set up a small radio dish with a feed, low-noise amplifier, coaxial cable, and software-defined radio. Each part plays an important role in capturing the weak signal that travels from geostationary orbit to your receiver. In this section, you will assemble the hardware, point the dish towards the satellite, and verify that the signal path is working correctly before moving on to decoding the transmission.

What each component does

The system has five main parts, see Figure 2 in the *Supplementary Materials*:

1. **Dish/Antenna:** Collects the weak signal from the satellite and focuses it onto the feed.

2. **Feed:** Sits at the focus and converts the radio waves into an electrical signal.

3. **Low-Noise Amplifier (LNA):** Amplifies the weak signal without adding noise.

4. **Coaxial cable:** Carries the signal between the feed, LNA, and SDR.

5. **Software-Defined Radio (SDR):** Measures the incoming signal and converts it to a digital format using an Analog-to-Digital Converter (ADC) that can be read by software.

Choosing a Site

Pick a location outside with a clear view towards the Azimuth and Elevation you found in Section 2.1. The satellite may be low on the horizon, so obstacles like trees, walls, or buildings can block the signal. Use a planetarium app with compass capabilities to locate the position of the satellite in the sky.

Assemble the Receiver System

1. **Mount the dish.** Set the tripod so it's level.

2. **Connect the LNA.** Carefully thread the `IN` port of the LNA into the short coaxial cable from the dish, be careful not to over-tighten. Thread the `OUT` port of the LNA into one end of the long coaxial cable.

3. **Plug in the SDR.** Thread the SDR into the other end of the coaxial cable. Plug the SDR into a USB 3.0 port on your laptop.

5 Signal Acquisition and Image Generation

Now that the software and hardware are both setup, the last step is to point the dish at the satellite and acquire the signal.

- Use a planetarium phone app to locate the position of the satellite in the sky. The dish will need to be pointed to within a few degrees of the satellite, otherwise the signal will not be strong enough to generate an image. With the satellite position selected and the compass mode activated, place the phone at the back of the dish and move it to the approximate location of the satellite.

- Increase the LNA Gain to approximately 75% of the maximum.

- Adjust the FFT Max and FFT Min so the the signal is clear and within the frame. See Figure 3 in the *Supplementary Materials* for an example.

Fine-Tune the Pointing

At the bottom of the processing screen, there are three windows to pay attention to.

1. On the bottom left of the screen, you'll see a live graph showing the **BPSK Demodulation**. This is how the program turns the raw radio signal into a digital data stream. BPSK (Binary Phase-Shift Keying) is a simple form of modulation; the satellite shifts the phase of the radio wave between two possible values representing a binary digit, 0 or 1. The graph in SatDump is a real-time view of

these received binary digits, with points in two distinct clusters on the left and right. One cluster corresponds to a binary 0, the other to 1. When the dish is well aligned and the signal is strong, the clusters appear tight and separate. If the pointing is not well aligned or the signal is noisy, the clusters may blur together.

2. Once SatDump has locked onto the BPSK signal, the software still needs to clean up errors and reorganize the raw stream of bits into usable packets. Two windows help you see this process: Viterbi and Deframer.

   (a) **Viterbi:** Radio signals traveling thousands of kilometers from space will inevitably pick up noise and distortions. To protect the data, the GOES satellites add error correcting codes before transmitting. The Viterbi algorithm is a mathematical method that uses these codes to fill in the most likely original bit sequence, even if some of the bits were corrupted during transmission. When the dish is well aligned, the software will display `State:SYNCED`, followed by the Bit Error Rate (BER). In order to decode an image, Viterbi must be synced with a BER <0.05.

   (b) **Deframer:** After the error correction, the bits still arrive as a continuous stream with no obvious start or end. The job of the deframer is to recognize patterns that mark the beginning of each frame of data. One the frames are identified, SatDump can reassemble them into files and images. In the Deframer window, you'll see counters showing frames being detected and processed; a steady increase means the pipeline is working correctly and image files will soon appear in your output folder.

Use these three windows to fine-tune the alignment and ensure that the demodulation is working correctly. Once the dish is pointed to the approximate location of the satellite, slowly move the dish side-to-side and up-to-down until:

1. The BPSK Demodulator shows two distinct clusters and an SNR of at least 3 dB.

2. Viterbi displays `State:SYNCED` with a BER <0.05.

3. Deframer displays `State:SYNCED`

Once the signal is locked, the GOES HRIT Data Decoder window on the bottom right will display `Status: Receiving` and will display a preview of the full disk images as they're being built. The Freq value shown under Signal refers to the small offset of the demodulated baseband signal from the expected center frequency. This offset arises from oscillator inaccuracies or Doppler shift, and is automatically corrected by the demodulator during carrier recovery. Record the following information displayed next to the BPSK Demodulator window:

Freq = ________Hz, SNR (dB) = ________, Peak SNR (dB) = ________

6 Detecting Life and Technology from Space

6.1 Observing Earth from Orbit

You have now produced your own images of Earth from geostationary orbit. Unlike weather maps found online, these images came directly from your receiver and dish. Satellites like GOES produce more than one kind of image, capturing different bands, or wavelengths of light. Each band highlights a different property of Earth's surface or atmosphere. By comparing these bands, you can start to see how scientists use remote sensing to study Earth.

Visible / False Color

The visible or false color band is closest to what your eyes would see from space. False color images are made by combining information from several different spectral bands and assigning them red, green, and blue so that features like vegetation, land, water, and clouds are easier to distinguish.

Longwave Infrared

In the infrared longwave band, GOES images are shown with an inverted grayscale so colder features like high cloud tops appear bright, and warmer features appear dark, even though physically, warmer objects emit more infrared light. Unlike visible light, infrared light does not depend on sunlight; warm objects on the surface of Earth and in the atmosphere give off their own heat (infrared), which can be detected at any time of the day.

Tropospheric Water Vapor

Water vapor absorbs and emits strongly in certain parts of the infrared spectrum, which allows satellites to track moisture in the atmosphere even when there are no visible clouds. Bright areas indicate regions with more moisture, while darker areas show drier air. Different water vapor bands highlight different altitudes in the atmosphere, such as the mid-troposphere or upper-troposphere.

Use your images in each band to answer the questions below.

1. In the visible image, find one land feature such as a coastline, mountain range, or desert. Can you still recognize this feature in the infrared image?

2. Find a storm system in the visible image. How does it appear in infrared? What does the brightness tell you about the temperature of the clouds?

3. In the water vapor image, find a bright moist region. Does this same area show up as cloudy in visible or infrared, or does the water vapor image reveal moisture that other bands miss?

6.2 Biosignatures on Earth

From orbit, one of the clearest signs of life on Earth is large scale photosynthesis. On land, plants become more or less "green" with the seasons as leaves grow and die back. In the oceans, phytoplankton blooms grow and shrink as nutrients, sunlight, and temperatures change. These patterns repeat in time and follow climate zones, which are difficult to explain without biology.

Open the interactive *Global Biosphere* visualization using the link provided in the *Supplementary Materials*. This interactive visualization, created by NASA's Goddard Space Flight Center Scientific Visualization Studio, combines five years of data from the GeoEye-1 satellite and SeaWiFS instrument on the OrbView-2 satellite. It displays two primary layers: Land Vegetation (NDVI) and Ocean Chlorophyll Concentration. NDVI, or normalized difference vegetation index, tracks photosynthesis activity on land using red and near-infrared bands. Ocean Chlorophyll is estimated by measuring reflectivity in green and blue bands, and is used as a proxy for the abundance of phytoplankton.

Explore the interactive visualization, rotating the Earth to look at different regions of interest, and answer the following questions.

1. Choose one mid-latitude land region (about halfway between the equator and the poles, e.g. U.S. Midwest, Central Europe, etc.). In which season/month is NDVI at it's maximum? When is it at it's minimum? Then choose a nearby tropical region (close to the equator). Does this tropical region change as much over the year as the mid-latitudes? Explain using what you observe along the timeline.

2. Pick a coastline where a continent meets an adjacent ocean. When does the land region reach peak NDVI? When does the nearby ocean show a chlorophyll peak? Do these peaks occur at the same time or at different times in the year? Why is this?

3. Choose a high-latitude (near the poles) coastline. In which month do NDVI or chlorophyll values first appear after the snow/sea-ice clears? Identify one change following this that indicates biological activity (e.g. a steady NDVI increase on land or a narrow chlorophyll band along the retreating ice edge)?

4. Imagine you only had this kind of year long, planet wide information for a distant planet. List two specific features that would make you confident the signal is caused by life, and one feature you would check to rule out a non-biological explanation.

6.3 Technosignatures on Earth

In addition to signs of biology, Earth also shows clear signs of technology when viewed from space. These are called technosignatures. Unlike natural features, technosignatures are created by intelligent life. On Earth, they include things like radio transmissions, city lights, agriculture, and satellites. If we were studying a distant planet, a technosignature would be strong evidence for advanced life.

Lights at Night

Open the *GOES Image Viewer* using the link the *Supplementary Materials* to look at a recent timelapse of images from the GOES satellites. Play the animation and pause when the night side of Earth is visible. Use these images to answer the following questions.

1. Identity one large region that is brightly lit at night. Which features make it clear that these are cities and not natural sources of light?

2. Imagine observing Earth from light-years away. Could these lights be visible? What challenges would an alien astronomer face in detecting them?

Human Land Use

Humans have reshaped Earth's landscapes at large scales, and those changes leave distinct geometric patterns that can be seen from space. Open the *Earth Observatory Agricultural Patterns* using the link in the *Supplementary Materials*. Use these images to answer the following questions.

1. Choose two different images from the gallery. For each image, identify the primary human made pattern (e.g. squares, circles, lines, etc.).

2. Using only the geometric evidence visible in these images, give one reason a distant observer might infer the presence of technology on Earth, and one limitation that could make the conclusion uncertain.

In this lab, you've explored both biological and technological signals that make Earth stand out as a living world. From seasonal vegetation cycles to city light, these patterns show how life and intelligence can be detected from orbit. The same methods guide SETI research as we search for biosignatures and technosignatures on distant planets, asking whether other worlds might reveal signs of life and technology as clearly as our own.