Project 1: Satellite Tracking and Orbit Determination

Note: This project will be due **after we have covered all relevant topics in class** (anticipated in early-to-mid October). Don't worry if some parts of the assignment below aren't clear yet – they will make more sense as we discuss orbital mechanics concepts. The goal is to apply what you learn in class to a real satellite's orbit. This handout is designed to guide you through each step with **practical tips, examples, and clear expectations**. The tone is rigorous but we encourage you to be curious and enjoy the process of **becoming an orbital detective**!

Step 1: Choose an Earth-Orbiting Satellite

Select one **active Earth-orbiting satellite** in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), or Geostationary Orbit (GEO) as your subject. This will be the satellite whose orbit you track and analyze throughout the project. The subsequent math will be easier if you choose a satellite with an orbit that is approximately **circular.** This means that the satellite needs an eccentricity very close to 0. Choose a satellite that has sufficient public information about it online.

- **Clearly state your satellite choice** and provide a brief **mission summary**:
- Why did you choose this satellite? Explain what interests you about it (beyond simply "it's famous" or "it takes pictures") – for example, its unique mission, history, or contributions.
- What is the satellite's mission and history? Describe its purpose (science, commercial, military, etc.), when it was launched, and any notable achievements or applications. Be specific rather than giving a generic overview.
- **Include at least one visual (figure/image) with a caption** related to your satellite. This could be the satellite itself, its launch, or an image of what it observes. Make sure to credit the source in the caption. (Do *not* use AI-generated content for this section – use official sources or mission websites for facts and imagery.)
- **Example (for illustration):** If you picked the **Hubble Space Telescope**, you would note it's a famous space telescope launched in 1990, explain that it has provided unprecedented images of the universe, mention its key role in discoveries (like measuring the expansion rate of the universe), and perhaps include an image of Hubble in orbit. You might say you chose it because you're fascinated by astronomy and Hubble's impact on science.

By the end of this step, you should have a **well-defined satellite selection** with a clear motivation and background. This forms the introduction of your report. (Hint: A strong choice will also make subsequent steps easier, e.g. a satellite that passes over your location frequently if you plan to do direct observations.)

Step 2: Data Collection – Observing and Recording the Orbit

In this step, you will **collect observational data** for your chosen satellite. You can gather positional or timing data using **at least one** of the following methods (you are welcome to use more than one to cross-check your data):

- **Tracking software or apps (using TLEs):** Use a satellite tracking app or software that utilizes **Two-Line Element (TLE)** data to predict the satellite's position. Examples: **Heavens Above** (website/app), **Satellite Tracker** (mobile app by Vito Technology), **In The Sky** (website), or similar tools that show where and when the satellite will be visible at your location.
- **Satellite orbit databases:** Retrieve orbital data from databases such as **CelesTrak**, **NORAD/Space-Track**, or NASA websites. These often provide the satellite's orbital elements or tables of pass times for given locations.

Organize and record your data in clear tables and/or plots. At minimum, your raw data should include **timestamps** and corresponding **observations** (such as the satellite's observed position or any measurable quantity like elevation angle). All times should include time zones or UTC and dates. Include units for any measured angles, durations, etc.

Describe your observation method in detail: In your report, explain how you gathered the data and any conditions or assumptions. This should include:

- **Tools and software used:** For example, *"Observations were made using the Satellite Tracker app on an iPhone, and the Heavens Above website for pass predictions."* List any apps, websites, telescopes, or other equipment.
- **Procedure and assumptions:** Describe what you actually did. If you relied on a database or TLE data without visual spotting, state that and note any assumptions (e.g. assuming the TLE corresponds closely to the actual orbit during your observation period).
- **Limitations and conditions:** Note any challenges you faced. Some examples include: weather, horizon obstructions, software precision. Acknowledge these factors as they can affect your data quality.

What You Should Track: In order to get good data, here is the tracking method we recommend. Find the time that your satellite will do a pass near you. Once the satellite is near you, record the azimuth angle, elevation angle, and time. Then, wait for the satellite to pass you again. This step will be easier for satellites with lower periods. Once it passes you again, record the time that the angles match up and the difference between the times will give you your period.

One alternate option if this is too difficult with your chosen satellite is to find the rate that the true anomaly is changing instead to get angular velocity first. In order to calculate true anomaly, you need right ascension and declination which are from the baycenter of

Earth. We can provide a code to convert your surface measurements to baycenter measurements upon request.

Provide proof of your data collection. Show that you engaged with the observation process. This could include: a screenshot of the app display at the time of observation, a photo of the night sky with an annotation of where the satellite was, or a picture of your notes/timing device. Figures should have captions. These will demonstrate your effort in gathering data.

Guidance for using the "Satellite Tracker" app (one example method):

- The Satellite Tracker app by Vito Technology (Star Walk) has a section listing satellites visible from your location.
- Set up notifications in the app for when the satellite is about to rise or pass overhead. This helps ensure you don't miss it.
- When you get an alert, go outside and use the app's map view to locate the satellite. At the start of the pass, **take a screenshot** of the app's info (it often shows a timer, the current elevation, etc.).
- The app also provides a **list of upcoming pass times** for the next few days. Use this schedule to plan multiple observation sessions. Record data on multiple passes (even across different days) – the more data, the better your analysis will be.
- **Tip:** Collect more data than you think you'll need. Each observation might have uncertainties, so having several passes worth of data allows you to average or choose the best quality data.

Example: A mobile satellite tracking app interface showing an ISS pass prediction. The graph indicates the ISS's elevation angle above the horizon versus time for an upcoming pass (the peak of the curve is when the ISS is highest in the sky). Such data can be recorded and used to estimate orbital period and other parameters.

(Figure: Example of data from a tracking app – here for the International Space Station. The x-axis is time and the y-axis is elevation above the horizon. This kind of plot helps identify when the satellite rises, its maximum elevation, and set time.)

By the end of Step 2, you should have: one or more **tables of raw data** (with columns like Date, Time, Observation details such as "Elev=45° at azimuth 250°""). Also, a clear written description of *how* you obtained the data, with any supporting screenshots/photos as evidence. This will correspond to the "Methods" section of your report, demonstrating a well-documented data collection process.

Step 3: Estimate Basic Orbital Properties (Period and Angular Velocity)

Using your recorded data, you will now **estimate two fundamental orbital properties** of your satellite's orbit: the **orbital period (T)** and the **angular velocity (ω)**.

Orbital Period (T): The orbital period is the time the satellite takes to complete one full orbit around Earth (returning to the same position relative to Earth). We will estimate this from your observation times.

- **Be mindful of units:** If you get T in minutes, you might also convert it to seconds or hours depending on context (e.g., *95 minutes = 1.58 hours = 5700 seconds*). For orbital calculations, seconds are often most convenient.
- **Comment on reliability:** After computing T, include a short discussion of how reliable that estimate is. Did you have only a single pass to go on, or multiple? Did you assume it was the next orbit or could it have been two orbits later? Are you averaging several measurements? For instance, *"Using three different observed intervals between passes, I got periods of 93 min, 96 min, and 91 min. This spread of ~±3% suggests some uncertainty; I'll take the average ~93 min as my period, acknowledging a few-minute possible error."* If you used a TLE to double-check, you might say, *"The published orbital period from TLE data is 95.4 min, which is within 3% of my observation-based estimate – a reasonable match."*

Angular Velocity (ω): Orbital angular velocity is how fast the satellite moves around its orbit, typically measured in radians per second (or degrees per second). For a circular orbit, ω can be treated as constant and related directly to the period.

- **Calculate ω from T:** Use the relationship ω = 2π / T (for one full orbit, 2π radians in T seconds). Give the result in degrees per second and degrees per minute. Show your calculation clearly.
- If your orbit is not perfectly circular (most are slightly elliptical), the instantaneous angular velocity will **vary** along the orbit (faster at perigee, slower at apogee). However, for a first approximation, using the average angular velocity via the period is fine. Note your assumptions in your calculations.

Step 4: Apply Kepler's Laws – Semi-Major Axis and Position Prediction

Now that you have an estimate of the orbital period T, you can explore **Kepler's laws** to learn more about the orbit's size and the satellite's position in its orbit at a given time.

(a) Semi-Major Axis via Kepler's Third Law: Kepler's Third Law relates the orbital period to the size of the orbit. For an object orbiting Earth (assuming a two-body system and a relatively small eccentricity for simplicity), the law can be written as:

$$T^2 = \frac{4\pi^2}{\mu} a^3,$$

where α is the **semi-major axis** of the orbit (essentially the orbit's "average" radius), and μ is Earth's standard gravitational parameter.

From this formula, we can solve for the semi-major axis α:

$$a^3 = \frac{\mu T^2}{4\pi^2},$$

so

$$a = \left(\frac{\mu T^2}{4\pi^2}\right)^{1/3}.$$

This is directly derived from Kepler's third law. Now plug in your satellite's period **T** (in seconds) to compute α in kilometers:

- State any assumptions
- Comment on units and accuracy

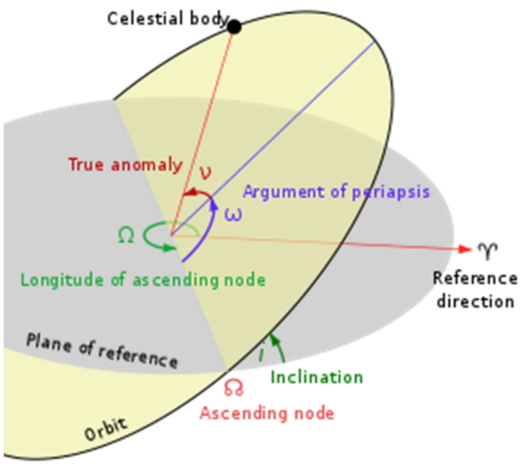
(b) Satellite Position Prediction using Kepler's Equation: Now we will **predict the satellite's position along its orbit at a future (or specific) time**. This involves a concept called **mean anomaly** and **Kepler's Equation**.

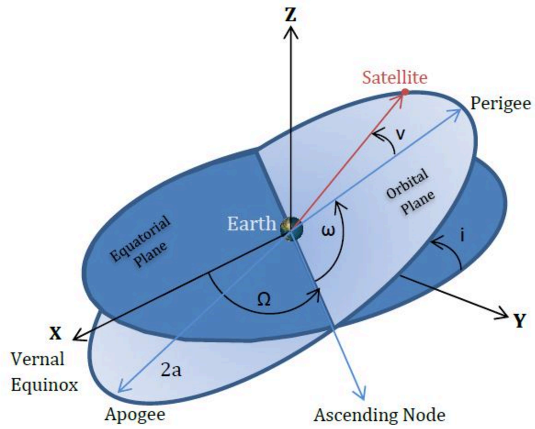
- **Choose a reference time:** Pick a moment as a reference (for example, the time of one of your observations when the satellite was at a known position like directly above you or rising on the horizon). Let's call that time t_0.
- **Compute the mean anomaly (M) at a later time:** Let's say you want to predict where the satellite will be after a time Δt (e.g., 10 minutes after your reference observation, or during a pass two days later). The *mean anomaly* M is basically how far the satellite *would have traveled* on average around the orbit (in radians) since t_0 if it moved at constant speed.

$$M = E - esinE.$$

Step 5: Determination of Additional Orbital Elements (Orbital Parameters)

Calculate additional orbital parameters. The six orbital parameters are i, Ω, ω, a, e, and θ. Explain what each orbital element means as you calculate it. Since we are using circular orbits only, true anomaly = mean anomaly.





Explain what each element means: As you introduce each orbital element in your discussion, briefly define it (as done above). For example, don't just say "inclination = 45°" – say "inclination = 45°, which means the orbit plane is tilted 45° relative to Earth's equator, so the satellite goes as far north/south as 45° latitude."

Compare all calculations against numbers from published data. Include your source(s).

- **Eccentricity (e):** We assumed e = 0 and chose mostly circular orbits, but let's do a calculation to find the actual eccentricity. If you have information on the satellite's **apogee and perigee** (highest and lowest orbital distances from Earth's center or altitudes above Earth's surface), you can calculate e by:

$$e = \frac{r_a - r_p}{r_a + r_p},$$

  where r_a and r_p are the apogee and perigee distances (from Earth's center). You can get r_a and r_p either from data provided in your app or from a TLE online such as *In the Sky*. How circular is your orbit?
- **Inclination (i):** Find the inclination of your satellite and include it in your report. Explain what different values of inclination might mean for a satellite.
- **Other elements (Ω, ω):** These are harder to get without more advanced observations:
- **RAAN (Ω):** If you have orbital tracking data over a few days, you might notice the **longitude of the ascending node** shifting due to Earth's precession (J2 effect). Without computations, you probably won't determine Ω from just a few ground sightings, and that's okay. However, you can retrieve RAAN from a TLE (it's one of the numbers listed). It's usually given in degrees (0–360). Report it for completeness.
- **Argument of perigee (ω) & True anomaly (θ) at epoch:** For nearly circular orbits, these values are not very meaningful. Explain why. Explain what the relationship between mean anomaly and true anomaly is for a circular orbit. What is the expression for mean anomaly? Do you have enough information to determine the mean anomaly?

Step 6: Error Analysis

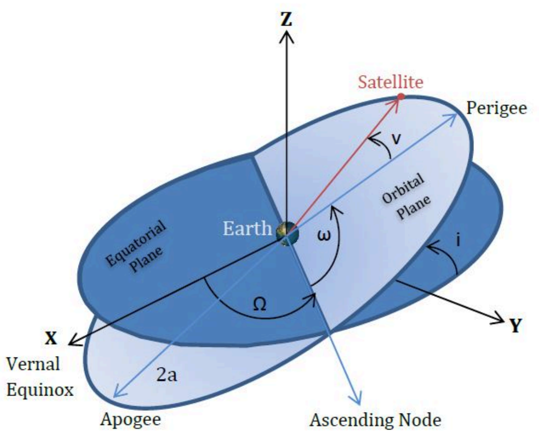
Identify sources of error, quantify your error, discuss the significance, and suggest improvements.

Step 7: Conclusion

Include a summary of your experiment and results. Write a one-paragraph reflection about what you learned and how you found the project.

Step 8: Visualization

Draw (by hand or using a computer program like Google Drawings) a visualization of your satellite's orbit using as much information as you can from the data you collected. Include measurements. Try to make it similar to the below image, with information specific to your satellite:



Report Format and Submission Guidelines

Throughout the report, **include figures and tables** where appropriate, with proper labels and captions. **Clarity and conciseness** are important – write in complete sentences, avoid bullet points.

Citations: If you use any external information (orbital elements from a site, definitions from textbook, etc.), cite them in a bibliography or as footnotes.

Grading Rubric (100 points total)

1. **Satellite Selection & Mission Summary (10 pts)**
    a. Clear statement of chosen satellite (name, type, orbit) – **2 pts**

    b. Explanation of why it’s interesting – **3 pts**
    c. Mission/history summary – **5 pts**

2. **Data Collection & Documentation (20 pts)**
    a. Raw data tables included – **5 pts**
    b. Plots/graphs of observations – **5 pts**
    c. Description of method – **5 pts**
    d. Evidence of original effort – **5 pts**

3. **Estimation of Orbital Properties (15 pts)**
    a. Orbital period correctly calculated – **5 pts**
    b. Angular velocity correctly calculated – **5 pts**
    c. Critical comment on reliability – **5 pts**

4. **Application of Kepler’s Laws (15 pts)**
    a. Semi-major axis (a) calculated via Kepler’s Third Law – **5 pts**
    b. Satellite position prediction using Kepler’s Equation – **5 pts**
    c. Comparison with actual observation or database – **5 pts**

5. **Determination of Orbital Elements (15 pts)**
    a. At least one additional orbital element calculated – **5 pts**
    b. Plots of parameter(s) over multiple days – **5 pts**
    c. Discussion of observed changes – **5 pts**

6. **Error Analysis (10 pts)**
    a. Identification of multiple error sources – **5 pts**
    b. Suggestions for improvement – **5 pts**

7. **Comparison to Published Data (10 pts)**
    a. Official orbital elements researched and cited – **5 pts**
    b. Comparison and reflection – **5 pts**

8. **Report Quality & Reflection (5 pts)**
    a. Organization and clarity of writing – **3 pts**
    b. Reflection on learning – **2 pts**