Understanding Orbits using STK

This section will define the Classical Orbital Elements (COE) used to describe an orbit and then use STK to show how changing each orbital element affects the orbit. I recommend the students do the STK exercise to understand how changing COE changes the orbit. I will send the "Answer Key" to Team Directors upon request to Bill Yucuis at stellarxplorers@afa.org.

<u>Classical Orbital Elements</u>: Details can be found in Chapter 5 of the *Understanding Space* textbook.

Hundreds of years ago, Johannes Kepler discovered that the orbits of planets were ellipses, with the Sun at one focus. Satellites which orbit the Earth (or any body) must also be elliptical. Isaac Newton was able to prove mathematically that a satellite must follow the path of a conic section; ellipse, circle (a special type of ellipse), parabola, or hyperbola. Kepler developed a method for describing orbits that allows us to visualize their size, shape, and orientation, as well as the spacecraft's position within the orbit. Because we need six quantities to describe an orbit and a spacecraft's position in the orbit, Kepler defined six orbital elements. We call these the **Classic Orbital Elements (COEs)**. The first two COEs give the size and shape of the orbit, the next three COEs give the orbit's orientation, and the final COE shows where the satellite is located within the orbit. The orbit's orientation is referenced to a 3-dimensional inertial (fixed) coordinate system.

1. **Semi-major Axis (a)**: The semi-major axis gives the **<u>size</u>** of the orbit. On an ellipse, it is half the distance along the major (long) axis.
2. **Eccentricity (e)**: The eccentricity gives the **<u>shape</u>** of the orbit. Each of the four conic section has a different range of eccentricity values.
    a. **Circle**: $e = 0$
    b. **Ellipse**: $0 < e < 1.0$
    c. **Parabola**: $e = 1.0$
    d. **Hyperbola**: $e > 1.0$
3. **Inclination (i)**: For Earth orbits, the fundamental plane is the equatorial plane, so the inclination defines the **<u>tilt</u>** of the orbit plane in relation to the equatorial plane. Inclination values range from 0^0 to 180^0. Several different orbits are defined by the inclination.
    a. **Equatorial Orbit ($e = 0^0$ or 180^0)**: The orbit lies in the equatorial plane.
    b. **Polar Orbit ($e = 90^0$)**: The orbit travels directly over the North and South Poles.
    c. **Direct, or Prograde, Orbit ($0^0 < i < 90^0$)**: The orbit is moving with the Earth's rotation (in an easterly direction).
    d. **Indirect, or Retrograde, Orbit ($90^0 < i < 180^0$):** The orbit is moving opposite the Earth's rotation (in a westerly direction).
4. **Right Ascension of the Ascending Node (Ω), or RAAN**: For Earth orbits, if a satellite is not in an equatorial orbit, the orbit crosses the Equator at two points. The location where it crosses the Equator from south to north is called the Ascending Node. The principal direction in the inertial coordinate system points to the Vernal Equinox direction. The location of the Ascending Node is given in reference to the Vernal Equinox direction and is called the Right Ascension of the Ascending Node (also called

the **swivel**). The values of RAAN are $0^0 < \Omega < 360^0$. There is no value for RAAN if the satellite is in the equatorial plane ($i = 0^0$ or 180^0).

5. **Argument of Perigee (ω)**: On an elliptical orbit around the Earth, the point closest to Earth is called perigee while the furthest point is called apogee. The Argument of Perigee measures the angle, in the orbit plane, between the Ascending Node and Perigee. The values of Argument of Perigee are $0^0 < \Omega < 360^0$. There is no value for Argument of Perigee if the satellite is in the equatorial plane ($i = 0^0$ or 180^0) or in a circular orbit ($i = 0^0$).
6. **True Anomaly (ν)**: For a given orbit, the first five COEs are constants. True Anomaly gives the location of the satellite within the orbit and since the satellite is constantly moving, True Anomaly constantly changes. True Anomaly measures the angle between Perigee and the satellite's location, measured in the direction of motion. The values of True Anomaly are $0^0 < \mathbf{v} < 360^0$. There is no value for True Anomaly if the satellite is in a circular orbit ($i = 0^0$).
7. **Alternate Orbital Elements**: When any of the COEs are not defined, alternate orbital elements must be used. These are described in Chapter 5 of the *Understanding Space* textbook but will not be used during StellarXplorers. The STK software can handle them but you will not need to use them during StellarXplorers.

<u>Exploring COE changes in STK</u>

During StellarXplorers, one of the first tasks in determining the best orbit to "observe" a location or area on the Earth's surface. This section will describe how changing each individual COE changes the orbit. Understanding these relationships will give you a better understanding of how to choose the "best" orbit. We will use STK to accomplish this task. We will look at how the ground track (path over the Earth's surface) changes as the COEs change. To begin, it is assumed you know how to use STK to change the Orbital Elements and do an Access Analysis to find the time a satellite (or sensor) "observes" a location on the Earth. There is a You Tube video on the StellarXplorers Website which gives you the basics. Also on the StellarXplorers Website will be an STK .vdf file to download with the starting conditions for this exercise. The beginning conditions are for a satellite in a circular orbit (e = 0) with semi-major axis of 6678.14 km (300 km altitude) and an inclination of 45^0 and Chicago, Illinois as a location. The starting RAAN, Argument of Perigee and True Anomaly will be 0^0. A basic sensor with a 15^0 half-angle cone is installed on the satellite. The STK file analyzes the satellite's operation over a two-week period of November 1-15, 2017.

1. **Changing Semi-major Axis (a)**: We will first change semi-major axis to see how the ground track changes.

    a. Hit Start and watch the satellite move across the Earth.
    b. Change semi-major access to 10000 km and then 20000 km.
    c. What happens to the ground track when increasing semi-major access?
    d. Determine the amount of time the ***satellite*** is in view of Chicago for each value of semi-major axis. Which is greatest?

e. Determine the amount of time the ***sensor*** is in view of Chicago for each value of semi-major axis. Which is greatest?

2. **Changing Inclination (i)**: Return to the initial conditions of a circular orbit (e = 0) with semi-major axis of 6678.14 and an inclination of 45^0

    a. Hit Start and observe the satellite ground track.
    b. Change inclination to 60^0, then 80^0, and then 10^0. These are **direct** orbits.
    c. What happens to the ground track when you only change the inclination?
    d. Determine the amount of time the ***satellite*** is in view of Chicago for each value of inclination. Which is greatest? Least?
    e. Determine the amount of time the ***sensor*** is in view of Chicago for each value of inclination. Which is greatest? Least?
    f. Change inclination to 100^0 and then 120^0. These are **retrograde** orbits.
    g. What happens to the ground track when you only change the inclination?
    h. Determine the amount of time the ***satellite*** is in view of Chicago for each value of inclination. Which is greatest? Least?
    i. Determine the amount of time the ***sensor*** is in view of Chicago for each value of inclination. Which is greatest? Least?

3. **Changing Right Ascension of the Ascending Node (Ω), or RAAN**: Return to the initial conditions of a circular orbit (e = 0) with semi-major axis of 6678.14 and an inclination of 45. RAAN should still be 0^0.

    a. Hit Start and observe the satellite ground track.
    b. Change RAAN to 90^0, 180^0, and then 270^0.
    c. What happens to the ground track when you only change the RAAN?
    d. Determine the amount of time the ***satellite*** is in view of Chicago for each value of RAAN. Which is greatest? Least?
    e. Determine the amount of time the ***sensor*** is in view of Chicago for each value of RAAN. Which is greatest? Least?

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4. **Eccentricity (e)**: We evaluated changes for semi-major axis, inclination, and RAAN for a circular orbit (e = 0). Argument of perigee does not exist for a circular orbit, so we will explore how the ground track changes when only eccentricity change. Return to the initial conditions of a circular orbit (e = 0) with semi-major axis of 6678.14 and an inclination of 45^0 and RAAN of 0^0.

    a. Hit Start and observe the satellite ground track.
    b. We are now going to change how we determine our orbit. Instead of setting semi-major axis and eccentricity, we are going to set the apogee and perigee altitudes. For our circular orbit with a = 6678.14, both altitudes are 300 km.
    c. Keep the perigee altitude at 300 km and change apogee altitude to 500 km, 1000 km, 5000 km, and then 10000.
    d. Determine the values of semi-major axis and eccentricity for each case.
    e. To get a better overall view of what is happening, you need to observe both the ground track (2D view) and orbit (3D view) simultaneously. For these changes, just observe how the ground track and orbit change.

5. **Argument of Perigee (ω):** Return to the initial conditions of an elliptical orbit with apogee altitude of 10000 km and perigee altitude of 300 km, an inclination of 45^0 and RAAN of 0^0. The argument of perigee should still be 0^0 and the eccentricity should now be 0.147533.

    a. Hit Start and observe the satellite ground track.
    b. Change Argument of Perigee to 90^0, 180^0, and then 270^0.
    c. What happens to the ground track when you only change the Argument of Perigee?
    d. Determine the amount of time the ***satellite*** is in view of Chicago for each value of Argument of Perigee. Which is greatest? Least?
    e. Determine the amount of time the ***sensor*** is in view of Chicago for each value of Argument of Perigee. Which is greatest? Least?

6. **Combining all these effects**: The StellarXplorers competition is all about changing the COEs to achieve the best results, based on the scenario given. So here is your first chance to try it. A scenario always has constraints, so for this "scenario", the maximum value for apogee and perigee altitudes is 1000 km. The minimum value for perigee is 300 km.
    a. Determine the amount of time the ***satellite*** is in view of Chicago.
    b. Determine the amount of time the ***sensor*** is in view of Chicago.