

Satellite Orbit Simulation to Support Sensor Calibration/Validation

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Introduction

Accurate knowledge of a satellite's position is essential for operating Earth-observing spacecraft and using their measurements for scientific research. Satellite orbit predictions are used to determine where a spacecraft will be located at a given time, identify when it will pass over a particular region, and coordinate observations between multiple satellites. These capabilities are especially important for satellite sensor calibration and validation, where instruments may need to observe the same location under similar conditions. The objectives of this project were to develop a foundational understanding of satellite orbits and orbit prediction, study Two-Line Element sets and the SGP4 propagation model, and evaluate orbital simulation tools for visualization and analysis. The project also investigated the application of the web-based Zerua platform to simulate satellites in the Joint Polar Satellite System, or JPSS, and the COSMIC-2 constellation. Major accomplishments included studying orbital elements, TLEs, and orbit perturbations; examining how perturbations affect prediction accuracy; surveying web-based satellite orbit simulation tools; comparing Zerua with Systems Tool Kit, or STK; and using Zerua to visualize the JPSS and COSMIC-2 satellite missions.

Satellite Orbits

A satellite orbit is the curved path followed by a spacecraft as it moves around Earth or another celestial body. An orbit results from the balance between gravitational acceleration and the satellite's forward velocity. Gravity continuously pulls the spacecraft toward Earth, while its tangential velocity carries it forward. Instead of falling directly to the surface, the satellite continuously falls around Earth. Figure 1 shows the 6 orbits for COSMIC2 satellites.

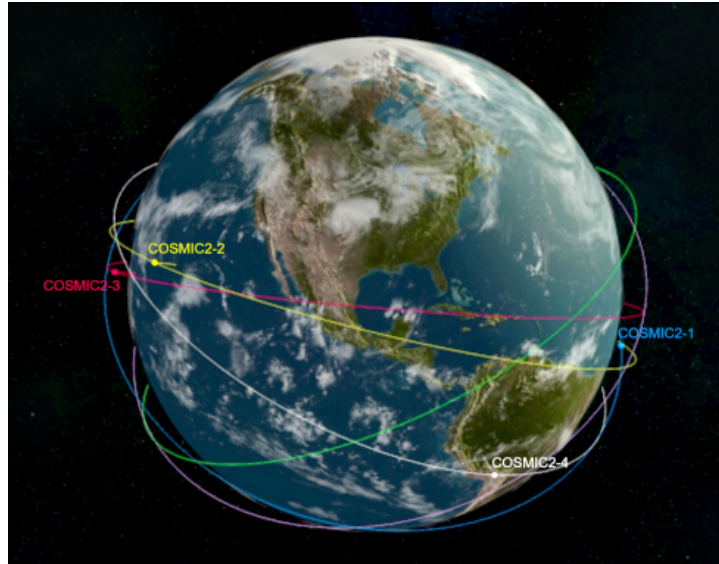


Figure 1: Satellite Orbits with COSMIC2

A satellite's orbit can be described using six classical orbital elements. The semi-major axis represents the size of the orbit, while eccentricity describes its shape. Inclination measures the tilt of the orbital plane relative to Earth's equator. The right ascension of the ascending node defines the orientation of the orbital plane around Earth. The argument of perigee identifies the orientation of the orbit's closest point to Earth, and the true or mean anomaly describes the satellite's position within the orbit at a particular time.

Together, these six parameters provide the information needed to describe the satellite's orbital geometry and location. For operational orbit prediction, the elements are commonly stored with additional information in a standardized format known as a Two-Line Element set.

A Two-Line Element set, or TLE, is a standardized text format that describes a satellite's orbit at a specific reference time called the epoch. TLEs are produced by analyzing observations of satellite motion and estimating the orbital parameters that best represent the spacecraft's trajectory.

		Epoch (year/day of year)						
1	43013U	17073A	26176.10726413	.00000032	00000+0	36252-4	0	9991
2	43013	98.7772	115.4995	0000552	131.6706	228.4517	14.19513092445594	
	ID	INC	RAAN	ECC	AOP	TA	MM	

Figure 2: Two-Line Element Example

A TLE contains two lines of orbital information. The first line includes information such as the satellite identification number, the epoch, and terms related to orbital drag. The epoch identifies

the specific date and time at which the TLE is valid. It is commonly expressed using the last two digits of the year followed by the fractional day of the year.

The second line contains the satellite identification number and several orbital elements, including inclination, right ascension of the ascending node, eccentricity, argument of perigee, mean anomaly, and mean motion. Mean anomaly describes the satellite's position within its orbit at the epoch, while mean motion represents the number of revolutions the satellite completes per day. The line also includes the orbit or revolution number.

A TLE is not a complete record of the satellite's future motion. Instead, it provides a snapshot of the orbit at one point in time. A propagation model must be used with the TLE to estimate the spacecraft's position and velocity before or after the epoch.

Orbit Perturbations

An idealized Keplerian orbit assumes that a satellite is affected only by the gravitational attraction of a perfectly spherical Earth. Actual satellite motion is more complicated. Orbit perturbations are deviations from the ideal orbit caused by additional forces acting on the spacecraft.

One important perturbation is Earth's nonspherical gravity. Earth is not a perfect sphere, and its uneven mass distribution causes variations in the gravitational field. Atmospheric drag also affects satellites in low Earth orbit by slowing them and gradually reducing their orbital altitude. Other perturbations include solar radiation pressure, Earth and ocean tides, the gravitational attraction of the Sun and Moon, and spacecraft maneuvers or attitude changes. Although some of these accelerations are small, their effects can accumulate over time.

Because satellite orbits continuously change as a result of perturbations, TLE data also change over time. Updated TLEs are generated to represent the satellite's more recent orbital state and maintain the accuracy of future predictions.

Importance of Orbit Perturbations

Understanding orbit perturbations is necessary because small errors in orbital acceleration can eventually produce large errors in predicted position. As prediction time increases, the difference between a simplified orbit and the satellite's actual trajectory can grow.

If perturbations are ignored, the predicted orbit may no longer accurately represent the spacecraft's real location (Figure 3). This can lead to errors when determining ground tracks, estimating satellite overpass times, or coordinating observations between different spacecraft. Accurate orbit prediction is also important for evaluating possible conjunctions with other satellites or orbital debris.

The orbit-prediction process therefore involves more than calculating motion under ideal gravity. An initial orbit is modified by perturbing forces, producing a changing trajectory. New

observations are then used to create an updated TLE, which supports more accurate future predictions.

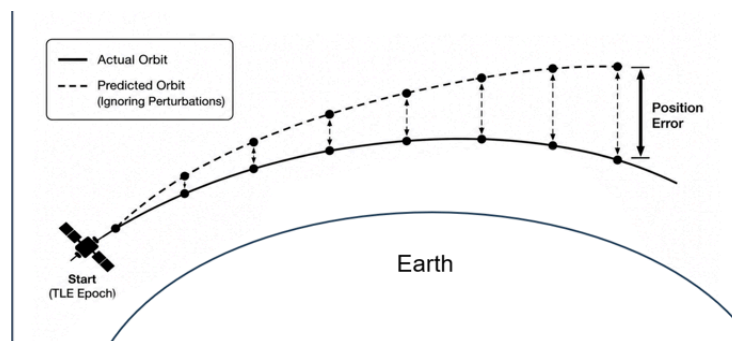


Figure 3: Position error grows over time when orbital perturbations are ignored. The dashed line represents the predicted orbit, while the solid line represents the actual orbit. The increasing separation between the two trajectories illustrates the growth of prediction error with time from the TLE epoch.

SGP4 Orbit Propagation

The Simplified General Perturbations 4 model, commonly known as SGP4, is the standard orbit propagation model used with TLE data. A TLE supplies the satellite's orbital state at its epoch, and SGP4 uses this information to estimate the satellite's position and velocity at another time. SGP4 models the effects of Earth's gravity and several important orbital perturbations. The model propagates the orbital elements forward or backward from the TLE epoch and generates a predicted satellite trajectory.

The general process begins with a TLE, which is entered into the SGP4 model. The model then calculates the predicted orbit, position, and velocity over the selected time interval. Prediction errors generally increase as the propagation time moves farther from the epoch because the satellite's actual orbit continues to change. For this reason, updated TLEs are required regularly to maintain prediction accuracy.

One application of accurate propagation is predicting simultaneous nadir overpasses. A simultaneous nadir overpass occurs when two satellites observe approximately the same Earth location at nearly the same time. These events can be used for intersatellite sensor calibration because measurements from one satellite can be compared with observations from another under similar geographic and temporal conditions. The example below shows a 1-second SNO between NOAA-16 and Terra near the North Pole on 21 March 2003, when their nadir locations were separated by about 3 km. Such events are useful for intersatellite sensor calibration because measurements from the two instruments can be directly compared, helping evaluate relative calibration differences and measurement consistency (Cao et al., 2004).

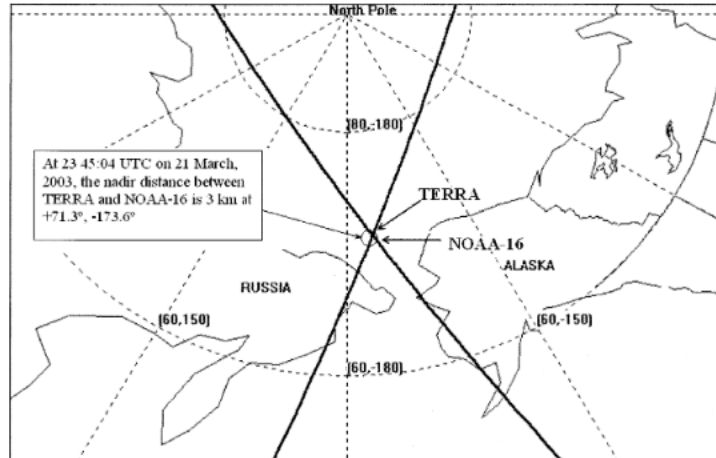


FIG. 1. Simultaneous (1 s) nadir overpass (SNO) between NOAA-16 and Terra.

Figure 4: Example of a Simultaneous Nadir Overpass (SNO) between NOAA-16 and Terra (adapted from Cao et al., 2004).

Orbit Simulation and Visualization tools

Orbit simulation tools allow users to enter satellite data, propagate trajectories, display three-dimensional orbits, calculate ground tracks, and perform mission analysis. Two tools examined during this project were STK and Zerua.

STK is a widely used aerospace analysis platform that provides high-fidelity orbit modeling and many advanced analysis tools. It includes strong reporting and export capabilities and can support complex satellite missions. However, STK has a relatively steep learning curve. It requires installation, and some advanced capabilities require paid access (Ansys, 2026). Its large number of features may also be excessive for users who only need basic orbit propagation or visualization.

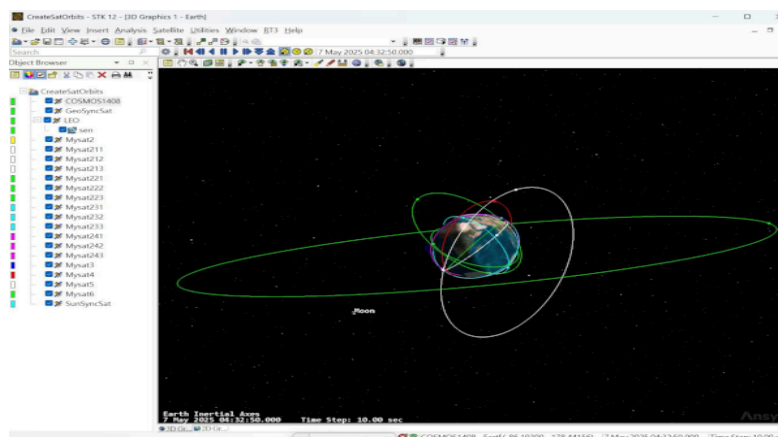


Figure 5: STK tool

Zerua is a web-based orbital visualization tool that is easier to learn and use. It runs directly on a web browser, provides fast three-dimensional orbit visualization, and allows relatively simple TLE input (Zerua Tech, 2026). It is suitable for introductory analysis and rapidly displaying satellite trajectories.

However, Zerua offers fewer advanced analysis capabilities than STK. Its orbit modeling is less detailed, it has more limited propagation options, and it does not provide direct animation export. Therefore, Zerua is useful for accessible visualization and initial investigation, while STK is more suitable for detailed professional mission analysis.

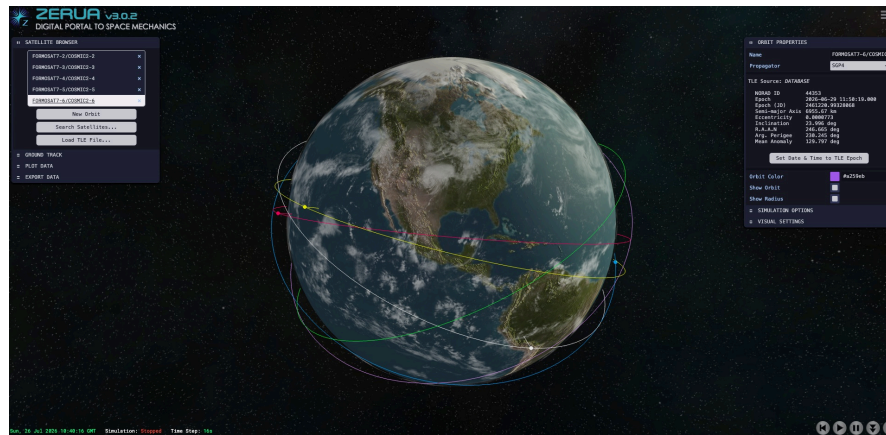


Figure 6: Zerua tool

Application to JPSS and COSMIC2

The project applied orbital simulation tools to the JPSS and the COSMIC-2 satellites. (Figure 7) These polar-orbiting environmental satellites travel around Earth and collect observations used for weather, climate, and environmental monitoring. Visualizing their orbits helps demonstrate their similar orbital configurations and provides context for identifying ground tracks, overpasses, and opportunities for coordinated observations.



Figure 7. On the left side: S-NPP, NOAA-20, NOAA-21 satellite. On the right side: COSMIC2

The COSMIC-2 constellation includes six spacecraft:

- FORMOSAT-7/COSMIC-2-1

- FORMOSAT-7/COSMIC-2-2
- FORMOSAT-7/COSMIC-2-3
- FORMOSAT-7/COSMIC-2-4
- FORMOSAT-7/COSMIC-2-5
- FORMOSAT-7/COSMIC-2-6

Simulating the full constellation shows how multiple satellites can be distributed around Earth to collect observations across different geographic regions. Visualizing JPSS and COSMIC-2 satellites together also demonstrates how orbit simulation tools can be used to study relationships between individual spacecraft and larger satellite constellations.

Conclusion

This project developed an introductory understanding of satellite orbits, TLE data, orbit perturbations, and orbital propagation. The six orbital elements provide a mathematical description of an orbit, while a TLE records the estimated orbital state of a satellite at a specific epoch. The SGP4 propagation model uses the TLE to predict the satellite's future position and velocity while accounting for major perturbing effects.

The investigation also demonstrated that orbit prediction accuracy depends on both the propagation model and the age of the orbital data. Because perturbations continuously modify satellite trajectories, updated TLEs are necessary for maintaining reliable predictions.

Finally, the comparison between STK and Zerua showed that different orbital tools serve different purposes. STK provides advanced, high-fidelity analysis, while Zerua offers accessible and efficient web-based visualization. Using Zerua to simulate JPSS and COSMIC-2 satellites demonstrated how orbit-prediction tools can support satellite visualization, overpass analysis, and sensor calibration and validation activities.

Reference

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