

Planning, Simulation, and Assessment of Various Missions from Wallops Flight Facility using Satellite Toolkit (STK)

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Satellite Tool Kit (STK) was used to plan, simulate, analyze, and assess various missions from Wallops Flight Facility. User Interface plug-ins were written to aid in the rapid design of rocket trajectories based on previous missions, and to realize the safety ranges associated with those trajectories. Additional tools were developed for constructing launch debris footprints, visualizing Earth's magnetic field, and exporting dynamic rocket trajectories from STK to Google Earth.

Nomenclature

<i>MPL</i>	=	Mission Planning Lab
<i>WFF</i>	=	Wallops Flight Facility
<i>AGI</i>	=	Analytical Graphics, Inc.
<i>STK</i>	=	Satellite Tool Kit
<i>ISS</i>	=	International Space Station
<i>MDT</i>	=	Missile Design Tool
<i>RAAN</i>	=	Right Ascension of the Ascending Node
<i>AOP</i>	=	Argument of Perigee
<i>TA</i>	=	True Anomaly
<i>UI</i>	=	User Interface
<i>LLA</i>	=	Longitude, Latitude, Altitude
<i>SS</i>	=	Sun-Synchronous
<i>VAFB</i>	=	Vandenberg Air Force Base
<i>PCA</i>	=	Principle Component Analysis
<i>IGRF</i>	=	International Geomagnetic Reference Field

I. Introduction

The Mission Planning Lab (MPL) at NASA's Wallops Flight Facility (WFF) was created to provide a way to simulate, present, and evaluate rocket missions on the Wallops Research Range. The tool of choice for doing so is Analytical Graphics, Inc.'s (AGI) Satellite Tool Kit (STK). This powerful utility makes the planning, visualization, and simulation of rocket missions invaluable. With it, a mission's feasibility can be assessed and variability can be introduced into simulations, all the while presenting an interactive visual rendering of the mission that can be much more easily understood than a series of numbers from RADAR, other ground and air-based sensors, or even older computer programs.

I accomplished many things with STK's versatility. Using it, I designed a set of missions from WFF to rendezvous with the International Space Station (ISS) and another mission from WFF to the Moon. I wrote a plug-in utility to make the variability of rocket trajectory azimuths easier to perform and visualize. In conjunction with another tool created by AGI called Missile Design Tool (MDT), I used STK to assess the feasibility of putting a satellite from WFF in a sun-synchronous orbit aboard a Minotaur I rocket. In some missions, knowing the Earth's magnetic field strength and how it is oriented is important. I wrote a plug-in script to visualize this onboard an orbiting spacecraft. One of the important aspects of Wallops missions is Range Safety, especially if a mission must be terminated shortly after launch. I wrote additional STK tools to visualize a change in hazardous debris area locations when a rocket trajectory's azimuth is changed and to calculate the overall hazard debris "footprint". For users who would like to see near-earth rocket flight paths but do not have STK, the free Google Earth program can

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be used as a simple substitute. I modified an existing tool to export STK trajectory data to a format that can be read by Google Earth and visualized.

This paper assumes the reader has a basic understanding of orbital mechanics.

II. Rendezvous Missions with the International Space Station from WFF

A. Introduction

After launch, in order for one satellite (in this case a shuttle) to rendezvous with another (International Space Station or ISS), the satellites must first be in the same orbit, characterized by the Right Ascension of the Ascending node (RAAN), Inclination, Eccentricity, Argument of Perigee (AOP), and Period orbital parameters. Once in the same orbit as the ISS, the shuttle performs a phasing maneuver at perigee by firing its engines to put it in a different orbit with a particular Period that needs to be determined; the new orbit's perigee is still the same point as in the ISS orbit. After one orbital period, the shuttle returns to perigee, but now the ISS has reached perigee in its own orbit, so both satellites' True Anomaly (TA), or location in orbit, are identical. The shuttle fires its engines once again to return to the same orbit with the ISS. The rendezvous is complete.

This particular Period of the phasing orbit depends on the ISS's TA with respect to the shuttle. If the ISS is behind the shuttle, it must "catch up", and the time it takes to do so will be the Period of the phasing maneuver. This is illustrated in Figure 1. The idea is for the ISS to make at least one full orbit in order to arrive at the shuttle's initial location at the beginning of the phasing maneuver. The change in TA is 360 degrees plus the difference between the satellites' TA, so the time it takes the ISS to traverse this change in TA needs to be the orbital Period of the shuttle's phasing orbit. That way, when the shuttle finishes a single orbit and returns to its starting position, the ISS is there too. Of course the ISS does not have to orbit just once during the phasing maneuver, but it can orbit an integer number of times, n , with a change in TA of $n * 360$ degrees plus the satellites' TA difference. Thus, the phasing orbit Period depends on n .

Similarly, if the ISS is ahead of the shuttle, the shuttle must "catch up", and can either move into a phasing orbit with a smaller Period (the ISS orbits less than once during this time), or an orbit with a larger Period (the ISS orbits more than once, but less than an integer multiple of times n).

B. Using STK to Design a Rendezvous Trajectory

STK has a plug-in called Astrogator, which is a "solving" utility for determining orbit parameters, positions, velocities, and other useful information from both boundary and initial conditions specified by the mission. The ISS is constrained by its orbital parameters, and the launch facility is constrained at WFF. The shuttle's launch range is also constrained by its fuel. The following trajectory design method can be used for any desired launch date in which the ISS's orbital plane is within the shuttle's range. If the orbital plane is not in range, additional maneuvers will be necessary to put the shuttle in it.

C. Trajectory Design Method

The first step is to match the ISS's orbital Inclination and RAAN. Targeting these two orbital parameters will put the shuttle into the same orbital plane as the ISS. Launching from WFF, Astrogator solves for the launch azimuth and required delta-V (change in velocity due to controlled rocket engine burns) to put the shuttle into the ISS orbital plane. The resulting orbit is not the same as the ISS's orbit however, as the extra delta-V has made the shuttle orbit slightly more elliptical than the ISS orbit.

Upon reaching perigee, the point of closest approach to Earth, the shuttle is slowed down enough to enter an orbit of the same Eccentricity ("elliptical-ness") and period as the ISS. Astrogator can perform the necessary calculations for the delta-V required to do this. Once this is done, Astrogator gives us the AOP and TA of both the shuttle and the ISS at this specific moment in time. From these, it can be determined how far ahead or behind the shuttle is with respect to the ISS, and thus the orbital Period of the phasing maneuver can be computed. Note that an assumption is made: the Eccentricity of the orbit is so close to zero that the AOPs of the two orbits can be treated as identical and thus factored into their respective satellites' TAs in order to determine the overall difference in TA between the satellites.

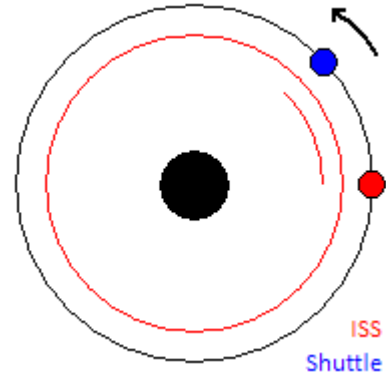


Figure 1. Phasing Maneuver. *The ISS must "catch up" to the shuttle.*

After obtaining this phasing orbit period constraint, Astrogator solves for the delta-V's necessary to enter and exit the phasing orbit. When the simulation is compiled and run, the rendezvous can be confirmed visually.

III. Mission from WFF to the Moon

There are Moon missions from Kennedy Space Center in Florida readily available as STK Astrogator scenarios². The logistics of how it works is beyond the scope of this paper (it could be a paper of its own) and will not be described. Sufficed to say, simply substituting Kennedy Space Center for WFF, making the launch azimuth variable and adding an intermediate delta-V for targeting the appropriate orbit inclination, a trajectory to the Moon can be calculated. While not the most efficient trajectory, it allows for a rough idea of what one would look like and shows that it can be done from WFF. An image is available in the Appendix, Figure 6.

IV. STK User Interface Plug-ins

A. Introduction

The newest version of STK, STK 9, supports User Interface (UI) plug-ins written in Microsoft's Visual Basic .NET or C#. Earlier versions of STK allowed for plug-ins written in HTML web pages using VBScript or JScript, but required one to open STK's built-in HTML viewer, navigate to the plug-in page, and fill in text fields, check boxes, or click on buttons. UI plug-ins allow for right-click context menus and custom toolbar buttons, often much quicker and easier to use.

B. Rocket Trajectory Azimuth Variability

1. Introduction

The observed rocket trajectories from previous missions are often used in STK when planning and visualizing new missions utilizing the same rockets. It is often the case that the exact azimuth of the trajectory is not useful due to various factors, such as having different goals or targets in the new mission, so being able to vary it quickly and easily is quite helpful for exploring new or potential trajectories.

The rocket trajectories gathered are described by sets of four data points: time, longitude, latitude, and altitude (LLA). These series of LLA points can be put into an Ephemeris file, something STK can read and associate with a Launch Vehicle for simulations. Originally, the method of choice for changing the launch azimuth in MPL was to manually extract, rotate, and re-insert the LLA points into the Ephemeris file. This time consuming process requires one to leave STK to perform the rotation and, upon coming back to it, re-load Ephemeris data. An STK UI Plug-in would simplify this process and would not require the user to leave STK.

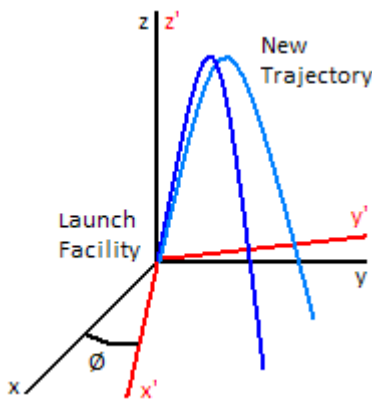


Figure 2. Trajectory Azimuth Rotation. The axis of rotation is normal to Earth's surface.

2. Algorithm

The process for rotating the launch azimuth by a given angle is a straight-forward coordinate rotation about the axis normal to the Earth's surface at the point of rotation (the Launch Facility) as seen in Figure 2. This coordinate system is known as the Topocentric Coordinate System in STK. By converting the LLA points into this coordinate system (in Cartesian x, y, and z), feeding the data to MATLAB to perform the coordinate rotation in the background, and re-converting the output points back to LLA for an Ephemeris file, the resulting trajectory can be reloaded and immediately presented to the user.

The relationship between Figure 2's (x', y', z') and (x, y, z) coordinates rotated about the z axis by angle \emptyset is as follows:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos \emptyset & \sin \emptyset & 0 \\ -\sin \emptyset & \cos \emptyset & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (1)$$

² <http://www.astrogatorsguild.com>

3. Implementation

The UI plug-in was written in Visual Basic .NET. It adds a “Rotate Azimuth” context menu to STK Objects. The user is prompted for a Launch Vehicle whose trajectory is to be rotated, a Launch Facility to rotate the trajectory azimuth about, and the angle in degrees to rotate the azimuth. After performing the rotation as described in the above algorithm, the newly rotated trajectory is reloaded and displayed to the user. The angles for any subsequent rotations are rotated with respect to the new trajectory, not the old one, as one would expect.

C. Hazard Area Changes

1. Introduction

The premises for this STK UI Plug-in are nearly identical to the Rocket Trajectory Azimuth Rotator. Depending on the rocket trajectory’s azimuth, the hazard areas rotate along with it. Hazard areas are characterized by an STK AreaTarget, bounded by STK Target points, and an STK LineTarget to visually serve as the AreaTarget boundary.

2. Algorithm

The Topocentric Coordinate System is not available for STK Targets, LineTargets, and AreaTargets, the objects used to represent hazard areas. As a result, a new method of obtaining a coordinate system to rotate the Targets in is required. Each type of Target has its point or points represented by a longitude and latitude (LLA). These LLA points are relative to a coordinate system centered at the Earth’s surface with the x axis going through the Equator and Prime Meridian and the z axis going through the North Pole. This algorithm moves the x axis to the launch pad’s LLA, and simply remaps the LLA points of the Targets relative to the pad to create the desired coordinate system (in two dimensions since there is no altitude). Now instead of rotating about the z axis, the points are rotated about the x axis:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \emptyset & -\sin \emptyset \\ 0 & \sin \emptyset & \cos \emptyset \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (2)$$

3. Implementation

Like the Rocket Trajectory Azimuth Rotator, this UI plug-in was written in VB .NET and behaves in much the same way. However, the user is prompted for the hazard area to rotate, the STK Target to rotate about (typically the launch pad), and the number of degrees of rotation instead.

V. Assessing the Feasibility of Sun-Synchronous Orbit from WFF with a Minotaur I

A. Introduction

Some of the planned missions being addressed in the MPL involve the launching of small satellites into sun-synchronous (SS) orbits 900 kilometers above the Earth aboard a Minotaur I rocket. One of the questions raised is how massive of a payload can be taken to this orbit. Orbital Sciences, the company that makes the Minotaur I, provides a data sheet³ for its rocket, which has, among other things, graphs of payload mass versus orbit-insertion altitude at various orbital inclinations for the Kodiak Island, Vandenberg AFB (VAFB), Wallops Flight Facility, and Cape Canaveral launch sites. (The first two are on the United States West Coast; the latter two are on the East Coast.) Unfortunately, the curve for a SS orbit is not available for the East Coast launch facilities, only the West Coast ones, as the data sheet hints that missions from the East Coast requiring orbital inclinations higher than 55 degrees should be “evaluated on a case-by-case basis”. SS orbits require an orbital inclination of 99.3 degrees, so the maximum payload mass is unknown and must be calculated.

B. Modeling a Minotaur I Rocket

In Orbital Science’s data sheet for the multi-stage Minotaur I, the names of the rocket motors used in each of the stages as well as experimental data for a 700 kilometer SS orbit launch from VAFB is provided. AGI’s Missile Design Tool (MDT) allows for the design and modeling of multi-stage missiles, so it was used to create the stages of the Minotaur I using existing motor data⁴.

After creating the rocket model, an identical simulation to the VAFB launch should yield comparable results. Only then can the results from a simulated WFF launch be considered plausible. MDT can mimic a rocket trajectory

³ http://www.orbital.com/NewsInfo/Publications/Minotaur_Guide.pdf

⁴ <http://www.astronautix.com/>

by changing the missile’s pitch over time (“pitch profile”) from 90 degrees (vertical) at launch. After putting the VAFB trajectory data into STK, the rocket’s pitch profile was generated and results fed to MDT for analysis.

The VAFB launch simulation of the model Minotaur I yielded a 1.6% error in orbital velocity and 6.2% error in orbital altitude compared to the actual launch. While not terribly accurate, reasonable payload mass estimates can be made.

C. Simulation Results

In order to determine the maximum payload mass that could be put into a 900 kilometer altitude SS orbit, some simplifying assumptions had to be made: 1) Altitude depends only on payload mass; 2) Zero pitch profile (rocket trajectory is straight up). The basic process was to vary the payload mass in the simulation until the maximum altitude reached is 900 kilometers. Applying some fundamental orbital mechanics shows that an orbit of this altitude requires an orbital velocity of 7.50 kilometers per second, so the simulation’s maximum velocity must be greater than or equal to this value.

Instead of using the 6.2% error in altitude, a more conservative 3% error was used, yielding a maximum payload mass of 250 kilograms with a maximum velocity of 7.96 ± 0.13 kilometers per second. Because the maximum velocity exceeds the orbital velocity, some of that velocity can be used for pitching the rocket onto an orbital path (recall the zero pitch profile assumption), but a more in-depth study would be required to see if this is sufficient.

The West Coast launch site graphs give the maximum payload mass to be around 275 kilograms from both sites. Therefore our 250 kilogram estimate appears reasonable.

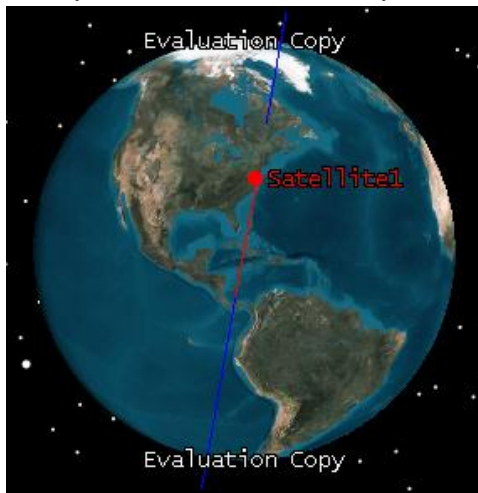


Figure 3. A Sun-Synchronous Orbit Trajectory Launched from Wallops.

D. Launch Trajectories

The Minotaur I data sheet cautions that satellite launches from WFF to orbital inclinations higher than 55 degrees “may experience reduced performance due to overflight and ground impact concerns that may require non-standard trajectory maneuvers”. This can easily be seen in Figure 3 when modeling the launch trajectory for the 99.3 degree SS orbit in STK. The only other alternative I see is launching for a smaller degree inclination and performing a plane-changing maneuver to put the satellite in the correctly inclined SS orbit. The plane changing maneuver requires a certain delta-V, and consequently a certain amount of fuel. This relationship is represented by the so-called “Rocket Equation”:

$$\Delta V = I_{sp} g_0 \ln \frac{m_0}{m_0 - \Delta m} \quad (3)$$

I_{sp} is the specific impulse of the rocket motor being fired to produce the delta-V, g_0 is the local acceleration of gravity, and m_0 is the initial mass of the spacecraft, fuel and all.

By launching for the recommended 55 degree inclination, a 44.3 degree plane changing maneuver is needed. Using Astrogator to calculate the maneuver’s required delta-V and then solving the rocket equation for the necessary amount of fuel gave an amount that was greater than the onboard capacity of the 4th stage of the Minotaur I rocket. This leads me to believe that a SS launch using such a rocket from WFF is not possible, regardless of the mass of the payload.

VI. Calculating Debris “Footprints”

A. Introduction

Sometimes missions must be terminated shortly after launch. One reason might be that the rocket’s trajectory deviated too much from the “safe” path. In such cases the resulting debris field creates many hazard areas where the debris impacts the Earth’s surface or ocean. These are represented in STK as elliptic AreaTargets. The debris “footprint” is defined as the area that contains all of the individual hazard areas; it is also an elliptic AreaTarget. The shape and orientation of this footprint varies from mission to mission and must be calculated.

B. Algorithm

The technique of Principle Component Analysis (PCA) will be used to determine the debris footprint ellipse. For a two-dimensional data set, there are two principle components: the first accounting for as much variability as possible in a determined direction, the second accounting for the remaining variability. When representing these components in two dimensions, they are orthogonal to each other. Since the shape of any ellipse is characterized by its orthogonal semi-major and semi-minor axes, the principle components of the data set will be the debris footprint ellipse axes. This can be seen in Figure 4.

The Covariance Method⁵ for PCA was performed in MATLAB and summarized here:

1. Calculate the centroid of the hazard areas.
2. Calculate the positions of the hazard areas with respect to the centroid (deviations from the mean).
3. Calculate the covariance matrix of data points.
4. Calculate the two eigenvalues and two eigenvectors of the covariance matrix.
5. Sort the columns of the eigenvector matrix in order of decreasing eigenvalue.

The semi-major and semi-minor axes are the maximum and minimum, respectively, of the square root of the eigenvalues (recall that variance is sigma squared). The orientation of the ellipse is characterized by the arctangent of either of the two eigenvectors, taking into account of trigonometric quadrant ambiguities.

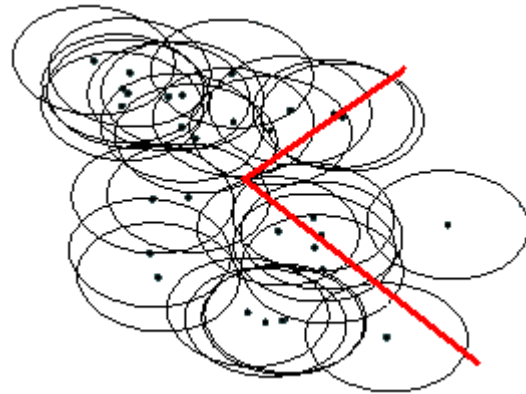


Figure 4. Hazard Areas in STK. *The red lines represent the principle components of variability in two dimensions.*

VII. Visualizing Earth's Magnetic Field



Figure 5. Magnetic Field Vector. *The units of the field strength are micro-Tesla (μT).*

Some missions require the knowledge of the Earth's magnetic field strength and orientation. While STK does not provide this information at this time, it can be obtained from the National Oceanographic and Atmospheric Administration (NOAA). It is called the International Geomagnetic Reference Field (IGRF) and is provided along with a computer program⁶ to calculate the field strength and orientation at a given location in the Earth's atmosphere on a given date.

STK's Vector Geometry Tool allows for the creation of custom Vectors whose components are determined by running a user-created script. This allows the representation of vectors that change over time. I used the IGRF to create a Visual Basic Script (VBScript) that receives positional information from a spacecraft in STK, computes the magnetic field strength and orientation at that position, and outputs the result as a vector back to STK. As the satellite orbits the Earth, this script is called again and again, and the displayed vector can be visualized over time.

VIII. Visualizing Trajectories with Google Earth

STK has developed a tool⁷ for exporting STK data to Google Earth's KML format. While a vehicle trajectory path can be visualized, the entire path is shown, so there is no way to see a Launch Vehicle's propagation along the path over time. By querying STK for the time associated with each of the trajectory's data points and wrapping it in KML "TimeStamp" tags, an animation is created by Google Earth upon importing the trajectory and can be played.

IX. Conclusion

In conclusion I used tools like STK and MDT to plan, simulate, visualize, and assess various missions from WFF like an ISS rendezvous, a trajectory to the moon, and a launch into SS orbit. I also wrote tools for STK to make

⁵ http://en.wikipedia.org/wiki/Principal_component_analysis#Computing_PCA_using_the_Covariance_Method

⁶ <http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html>

⁷ <http://www.agi.com/solutions/specializedAreas/virtualGlobes/utilities/index.cfm>

mission planning and visualization easier, as well as contributing to other tools for range safety. Finally I enabled the simple visualization of rocket trajectory flight paths in Google Earth for clients without STK.

Appendix

A. Additional Figures

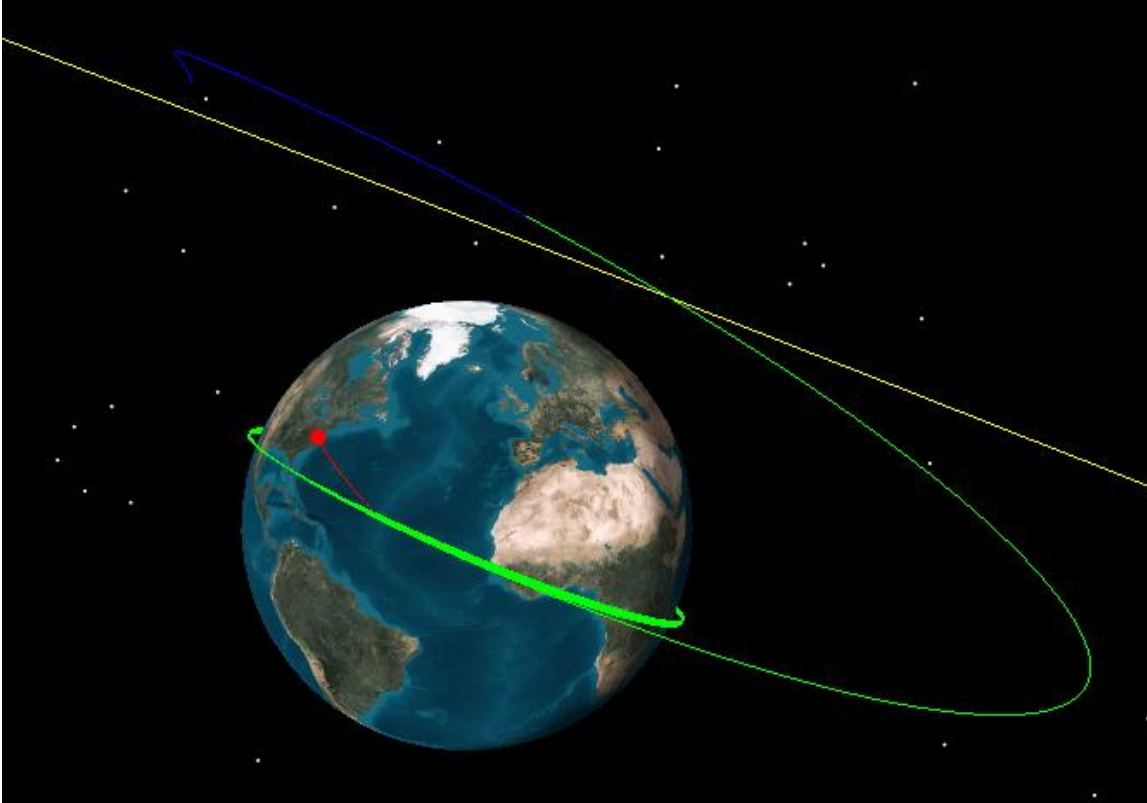


Figure 6. Moon Trajectory. *An example trajectory from WSF to the Moon.*

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