Voyager 2 Orbital Trajectory: The Study of Humankind's Largest Step Into The Stars

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Abstract

This paper describes the mission overview of Voyager 2 and a detailed analysis of its orbital trajectories. Voyager 2 left Earth through an injection maneuver, which was followed by four gravity assists to study all planets post-mars, while minimizing ΔV. This detailed analysis encompassed a direct model of the actual trajectory, done in AGI's STK. This model produced relatively close position points to that of the actual trajectory, with percent error values varying from 0% to 30.29% with an average error of 8.5%. The largest percent errors occurred at three planets; these planets were Jupiter, Saturn, and Neptune, with 30.29%, 21.77%, and 19.14%, respectively. These large discrepancies were due to assumptions made with the trajectory model not taking into account perturbations. Saturn and Jupiter have exceptionally large moons, which directly caused shifts in Voyager 2's trajectory due to their spheres of influence being so large. However, with Neptune it was found that the large percent error was due to Voyager 2's trajectory being exceptionally close to Triton, Neptune's largest moon, in comparison to any other celestial body. Triton being a relatively small moon caused a massive perturbation despite its size. Overall, the model provided a substantial replication of Voyager 2's trajectory through, and then after leaving, our solar system.

I. Introduction

Launched in 1977 by NASA, the Voyager missions are space probes designed to explore the outer Solar System and beyond. Specifically, with the Voyager 2 mission, the main focus is on studying Jupiter and Saturn, their moons, rings, and magnetic fields. Voyager 2 then went on to explore Uranus and Neptune, and analyze the heliosphere region. Similar to its twin, Voyager 1, the probes have deepened our understanding of the Solar System and have traveled farther than any other man-made spacecrafts; the spacecrafts are now billions of miles outside the heliopause. In this report, the group outlines a brief history and overview of the mission overview. Additionally, the attitude and orbital control systems (ACOS), on-board instrumentation, and orbital trajectory of the spacecraft will be discussed. The appendix contains all MATLAB scripts and further information.

II. Mission Overview

Voyager 2 launched from Cape Canaveral, Florida in 1977. From this location, its first destination was Jupiter. Voyager 2 would perform an injection maneuver to enter Jupiter's sphere of influence (SOI) on July 9th, 1979. After entering Jupiter's SOI, it would then perform a flyby where it studied Jupiter's various moons, as well as Jupiter's magnetic field. Leaving the viewing flyby of Jupiter, Voyager 2 entered into another viewing flyby, but with a focus about Saturn on August 25th, 1981. Voyager 2 was tasked in performing nearly the same tasks as Jupiter, but with a higher focus on studying Saturn's rings; The primary focus was on the ring's composition. Voyager 2 weaved its way through the solar system viewing all of the gas and ice giants until it reached its final send-off into deep space Voyager 2 after doing a flyby of Neptune on August 25, 1989. Both

Voyager missions utilized these flybys as gravity assists to continue gaining and decreasing orbital speed to have enough time to study all of the planets. Voyager 2's last gravity assist allowed for the spacecraft to fly below the sun's orbital plane; This orbital trajectory provided a hyperbolic orbit that would put it on course to leave the sun's SOI. Figure 1 below displays a timeline of the Voyager 2 mission inside the solar system.

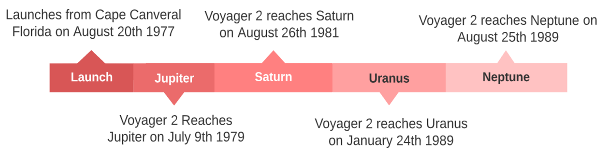

Figure 1: Voyager 2 Mission [1]

III. Attitude and Orbital Control System (ACOS)

Voyager 2 is a 721.9 kg spacecraft that was designed and manufactured by the Jet Propulsion Lab (JPL) in Pasadena, California [2]. The spacecraft can be seen below in Figure 2 below.

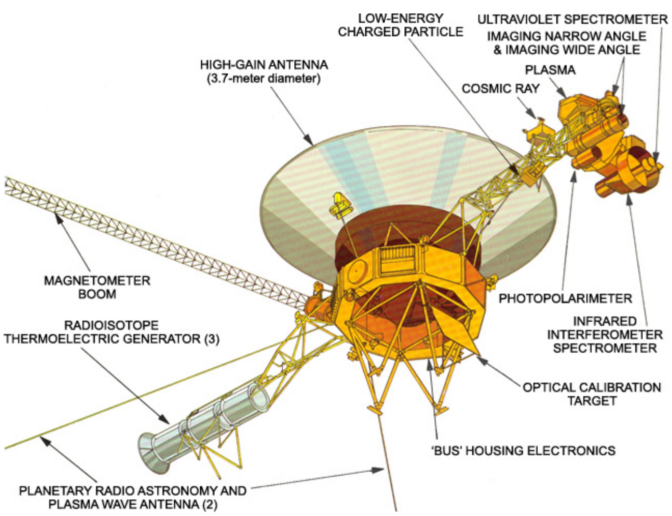

Figure 2: Voyager 2 With Labeled Instrumentation [3]

On-board Voyager 2 utilizes a three-axis stability system that can use either gyroscopic stabilizer (gyro) or celestial attitude control [1]. This stability system is used to keep a high-gain antenna pointed towards Earth and to position a visible-light camera, with multiple filters, to capture images of planets, moons, and other celestial objects. For attitude control and small delta-v adjustments, Voyager 2 had 16 small monopropellant thrusters on-board which utilize hydrazine as the propellant [2]. Of these 16 thrusters, 4 are used for trajectory corrections, 4 are used for yaw corrections, 4 are used for pitch corrections, and 4 for roll control. When launched, Voyager 2 was equipped with a single titanium tank containing 210 lbs of hydrazine which is expected to last until 2034 [2]. All of these systems constantly work together to keep Voyager 2 correctly positioned.

IV. Instruments Onboard Voyager 2

Voyager 2 is equipped with multiple instruments that are still studying the cosmos today. Voyager 2 is powered by three radioisotope thermoelectric generators. These generators use decaying Plutonium-238 which results in the release of particles that heat up the thermoelectric converter [8]. These three generators power all the systems onboard Voyager 2. Voyager 2 captured pictures of moons and eventually images of the whole solar system once it was placed on its final trajectory out of the solar system. The visible-light camera had 8 filters that could be used. These filters used different resolutions and lens angles in order to capture desired images [6]. Voyager 2's high gain antenna allows the transmission of images, collected data, and overall spacecraft health back to Earth. On-board is an Infrared Interferometer Spectrometer and Radiometer, which measures the temperature of a planet along with the different particles that appear in a planet's atmosphere. There are also several other devices that can measure different spectrums of light to determine what types of light and particles are present at certain points in space [6]. All of this equipment has been essential for the collection of data along Voyager 2's flight path.

V. Orbital Trajectory

There is one major difference between the Voyager missions. Unlike Voyager 1, Voyager 2 continued flybys of all of the endo planets. However, both made stops at Jupiter and Saturn. The first maneuver Voyager 2 performed was an injection maneuver into Jupiter's SOI. This needed to be perfectly timed to avoid any perturbations from Mars, and minimize use of the on-board ACOS. Once reaching Jupiter, Voyager 2 was able to capture images of all of Jupiter's moons, including 4 new moons that were never previously discovered [2]. During this flyby, Voyager 2 was able to capture 17,000 new images of Jupiter and its surrounding moons. After completing its flyby of Jupiter, Voyager, and capture readings of Jupiter's magnetic field. Voyager 2 used a gravity assist maneuver to reach Saturn [2]. While conducting its flyby of Saturn, Voyager 2 was able to capture images of Saturn, seven of Saturn's moons, and images of Saturn's rings, studying the ring's particles, and giving a better understanding of the ice and rock that are within [2]. Once again using a gravity assist maneuver, Voyager 2 was directed towards Uranus. Once reaching Uranus, Voyager 2 became the first man made spacecraft to pass Uranus. With only a 5 hour window Voyager 2 discovered ten new moons and two new rings around Uranus, bringing a whole new understanding of the planet. For the spacecraft's final orbital adjustment, a gravity assist positioned the spacecraft into a hyperbolic orbit about Neptune. Once reaching Neptune, Voyager 2 was able to complete a flyby that was only 2,980 miles above the clouds of Neptune, which was the closest flyby that Voyager 2 completed on its interplanetary mission [2]. Similarly to Uranus, this currently is the closest humankind has been to either ice giant. Given the spacecraft's close orbit, images were captured of six new moons and four more rings that surround the planet. The full trajectory of Voyager 2 can be seen below in Figure 3.

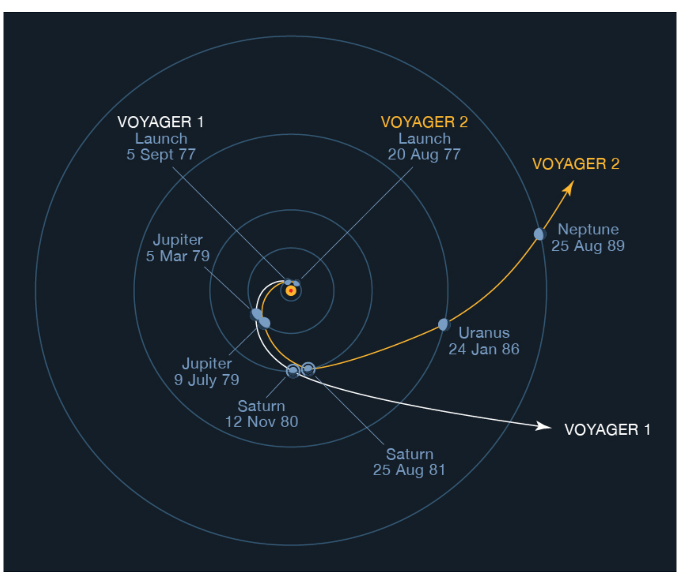

Figure 3: Voyager 2 Path [3]

Voyager reached interstellar space in December of 2018 and will continue its journey until it ultimately runs out of power. Voyager 2 has shut down all but five instruments in order to save power but continues to send data back to Earth. The five remaining instruments consist of the high gain antenna, the magnetometer, the low energy charged particle instrument, hydrazine thrusters, and the optical calibration target [5]. Scientists and engineers at NASA will continue shutting down instruments as needed to preserve Voyager's power. Voyager 2 will continue to travel into interstellar space and complete its mission, which will provide scientists with more new knowledge of deep space.

To recreate the path followed by Voyager 2, data from NASA's website was plotted in a 3D plot in MATLAB. Also plotted in MATLAB were the orbits of Jupiter, Saturn, Uranus, and Neptune. These orbits and the trajectory of Voyager 2 can be seen in Figure 4.

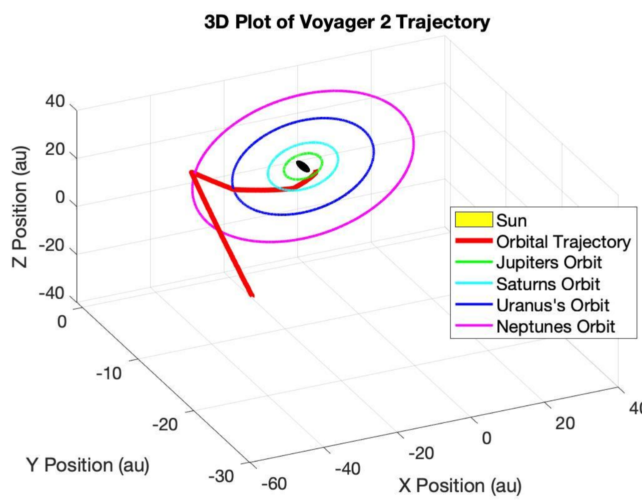

Figure 4: 3D Plot of Voyager 2's Trajectory

In Figure 4, the final trajectory of Voyager 2 can be seen. This trajectory, which comes after it encounters Neptune, is the rough trajectory of Voyager 2 today. The data plotted in Figure 4 is only the real data of Voyager 2's path up to the year 2000. This was done to improve the view of Voyager 2's path between the planets. As shown in Figure 4, Voyager 2's trajectory takes an immediate dip after passing Neptune. This is due to the spacecraft using the gravity assist as a way to drop below the sun's orbital plane, thus leaving the solar system.

VI. STK Model

An STK model was created to replicate Voyager 2's travels from earth and out of the solar system. This model can be found below in Figure 5 below.

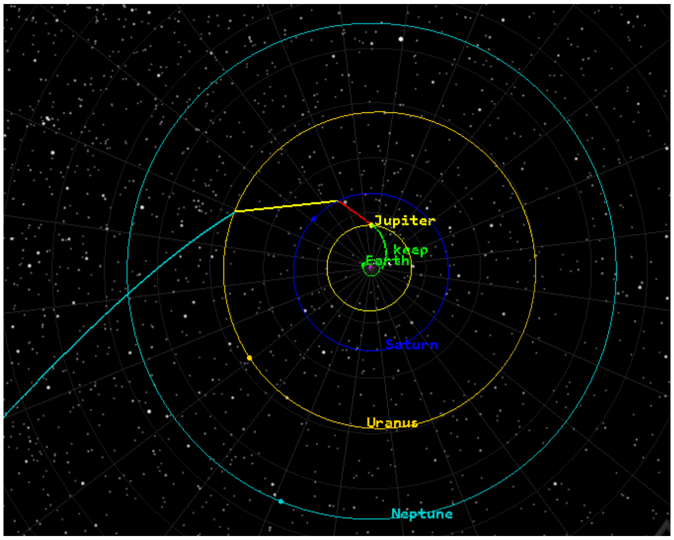

Figure 5: Voyager 2 STK Model

From this model, values such as ΔV and positioning were calculated. Discrepancies in this model could include errors in the data built into STK as well as human error inputting maneuvers and assumptions.

A. *STK Method and Approach*

To construct the STK model, each relevant planet was inserted into the model using the data from Ephemeris Source DE 430 [10]. This was selected since the data built into STK did not date back to the timeline of the Voyager 2 mission. The path off the satellite was made by using the astrogator feature found in the properties of the satellite. The segment in Voyager's journey where it travels from Earth to Jupiter, STK's Lambert's solver was used by defining the initial and final body, where an automatic mission control sequence (MCS) was constructed. From there, a path for each planet was made by inserting each maneuver with its parameters into the mission control panel of the satellite's properties, after that of its previous segment, where each path and transition can be seen as a separate color in Figure 5. The data observed from the STK was the cartesian coordinates of each planet where Voyager 2 would intercept that planet depending on time of flight and position. Assumptions in the STK model included no perturbations performed, as well as the data built into STK concerning planetary position was correct.

VII. Model Comparisons and Results

After each method was performed, all the results between STK and real data were compared. All of the actual data was accessed on one of NASA's websites, which provides trajectory data for multiple spacecraft [1]. Table 1 below displays the values found from each method.

Table 1

Comparison Between Position Data

	STK[1]	Real Data	Error
Earth			
x	0.846743	0.86	1.54%
y	-0.508147	-0.54	5.89%
z	0.0	0.0	0.00%
Jupiter			
x	-3.574486	-3.90	8.34%
y	4.70351	3.61	30.29%
z	0.02028	0.07	7.1%
Saturn			
x	-8.32691	-9.33	10.75%
y	-2.73949	-2.99	8.37%
z	0.3129	0.40	21.77%
Uranus			
x	-3.83233	-3.74	2.46%
y	-17.7742	-18.74	5.15%
z	0.0292	-0.03	2.37%
Neptune			
x	6.07	5.92	2.53%
y	-30.12	-29.62	1.69%
z	0.56	0.47	19.14%

From Table 1 above, it can be concluded that the STK model is accurate since most error values are within an acceptable tolerance of <10%.

[1] All values for position for both STK and Real Data are given in terms of au

The values outside of this 10% are highly likely to be off due to unaccounted for perturbations. This high likelihood is primarily due to the various large moons, or clusters of moons, that the gas and ice giants have in orbit. The highest percent difference of the planets come from Jupiter, Saturn, and Neptune. Jupiter and Saturn house Ganymede (⌀ 5268.2 km)[2] [11] and Titan (⌀ 5149.4 km) [12], respectively. Both of which are larger, than the size of Pluto (⌀ 2376.7 km) [13]. These masses have a definite influence on the flybys of Voyager 2, which would now open the discussion of Neptune. Neptune has a moon smaller than that of the earth, Triton, which at first glance seemed like it would not produce the same amount of acceleration due to its size. However, Triton was the closest encounter Voyager 2 had within a planet's SOI [1]. Voyager 2 came within 40,000 km to Triton, which was the last object the spacecraft studied before finishing Neptune's gravity assist [14]. Due to gravitational accelerations having an inverse square relationship with distance between bodies, this close encounter would provide a massive acceleration onto Voyager 2. Thus, explaining the difference in what was found between the team's STK results and that of the real data.

VIII. Conclusion

After replicating Voyager 2's orbit trajectory using STK, it was determined that the models were fairly accurate when compared to the actual trajectory of Voyager 2. Using STK's astrogator tool, Voyager 2's orbit trajectory was created as shown above in Figure 5. All of the planets that Voyager 2 interacted with were mapped, and the approximate paths between each flyby were created. By using STK, the group was able to get a clear and interactive orbit trajectory of Voyager 2 which was also able to provide ΔV and positional coordinates. When comparing these coordinates to NASA's actual coordinates of Voyager 2, it was determined that the STK model was relatively accurate. When comparing coordinates, percent error values varied from 0% to 30.29% with an average error of 8.5%. Overall the STK model is considered to be an accurate representation of Voyager 2's orbit trajectory.

[2] ⌀ is used to represent a measure of diameter

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List of Contributions

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- Document Editor
- Orbital Trajectory Research
- Abstract

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- Document Editor
- STK Modeling
- Mission Overview

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- Document Editor
- AOCS Research
- Real Values Research

Appendix

A. MATLAB Plotting Script

```
% Orbital Mechanics Project
M = readmatrix('OD.txt'); % get orbit data
x = M(:,4);   % pull out data into columns
y = M(:,5);
z = M(:,3);
X = 0;  % suns center in graph.
Y = 0;
Z = 0;
[X,Y,Z] = sphere;   % plot sun
k = 0:.001:(2*pi);  % Create jupiter's orbit
e = 5.2*cos(k);
f = 5.2*sin(k);
g = zeros(1,6284);
v = 9.54*cos(k);    % create saturn's orbit
c = 9.54*sin(k);
s = 19.22*cos(k);   % create uranus's orbit
a = 19.22*sin(k);
r = 30.06*cos(k);   % create neptune's orbit
q = 30.06*sin(k);
surf(X,Y,Z)   % plot sun
hold on
plot3(x,y,z,'linewidth',4,'color','r')  % plot orbit trajectory
xlabel('X Position (au)','FontSize',16)
ylabel('Y Position (au)','FontSize',16)
zlabel('Z Position (au)','FontSize',16)
title('3D Plot of Voyager 2 Trajectory','FontSize',16)
grid on
plot3(e,g,f,'color','g');   % plot jupiters orbit
plot3(v,g,c,'color','r');   % plot saturns orbit
plot3(s,g,a,'color','b');   % plot uranus orbit
plot3(r,g,q,'color','m');   % plot neptune orbit
```