FLYBY AND RENDEZVOUS MISSION ANALYSIS FOR INTERSTELLAR OBJECTS: 'OUMUAMUA & BORISOV

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INTRODUCTION

The first known interstellar object to visit our solar system, 1I/2017 U1 'Oumuamua, was discovered on Oct. 19, 2017, by the University of Hawaii's Pan-STARRS1 telescope, funded by NASA's Near-Earth Object Observations (NEOO) Program, which finds and tracks asteroids and comets in Earth's neighborhood.[1] The discovery of 'Oumuamua was a surprise and a puzzle to the scientific community, as the physical properties of the solar system object were impossible to reconcile with solar system objects. After this miraculous discovery, another object determined to originate beyond our solar system was discovered by Gennady Borisov on August 30, 2019.[2] Colloquially known as "Borisov", after the Crimean amateur astronomer, the comet was found to have a high hyperbolic excess velocity of 32 km/s. An artist's rendition of each of the objects' shapes can be seen in Figure 1. While only two of these "alien" visitors have been detected thus far, we continue to search for the passage of new interstellar objects through efforts such as the James Webb Space Telescope (JWST) and other astronomical efforts. Learning more about their composition and origin aims to provide invaluable insight and knowledge of our universe and the bodies that live beyond our observable horizon.

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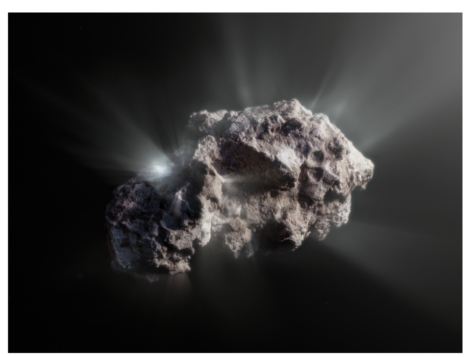
(a) Comet 1I/2017 U1/'Oumuamua

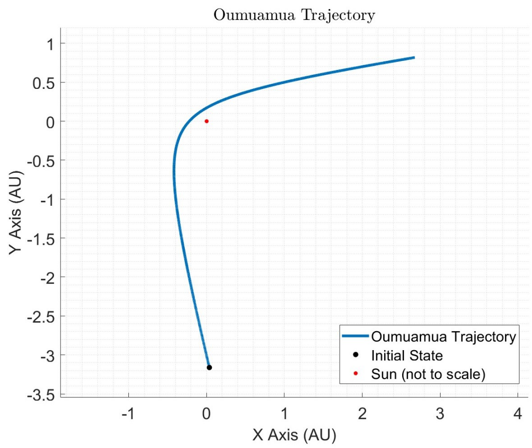


(b) Comet 2I/Borisov

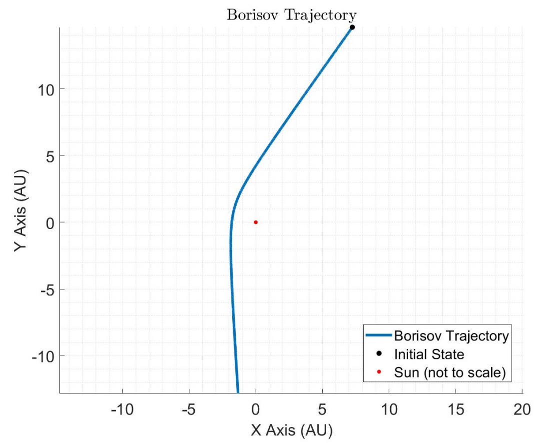
Figure 1: An artists' renditions of the two observed interstellar objects 'Oumuamua[3] and Borisov[4]

Problem Statement

For this homework assignment, we were tasked with creating pork chop plots for flyby and rendezvous missions to interstellar comets 'Oumuamua and Borisov. The first step of the process was to write a universal variable propagator to obtain the state of a body, given some initial conditions and time, under Keplerian dynamics. Using the formulation detailed in Curtis,[5] a MATLAB code was implemented to perform these calculations and propagate the states of 'Oumuamua and Borisov detailing their hyperbolic trajectories, with respect to the Sun, seen in Figure 2. The orbital elements of each respective body can be seen in Table 1. It is easy to see, from their eccentricity values ($e > 1$) and semimajor axis values ($a < 0$) that these objects are on hyperbolic trajectories with respect to the sun, and therefore not bound to our solar system.



(a) 'Oumuamua Trajectory from 2017-Jan-01 to 2017-Dec-31



(b) 'Borisov Trajectory from 2017-Jan-01 to 2019-Dec-31

Figure 2: Hyperbolic trajectories of the two interstellar objects, propagated with two-body dynamics, with respect to the Sun

	a (AU)	e (rad)	i (rad)	ω (rad)	Ω (rad)	f (rad)
'Oumuamua	-1.274	1.201	2.142	0.429	4.222	3.868
Borisov	-0.851	3.359	0.768	5.380	3.648	4.534

Table 1: Keplerian orbital elements of the two interstellar objects

Lambert Solver

In order to generate the Delta-V (ΔV) approximations for the mission analysis, a Lambert solver (derived from Curtis[6]) was used to compute the terminal velocity vectors, resulting in feasible impulsive trajectories between the departure and arrival positions. Departure dates for the 'Oumuamua mission range from 2017-Jan-01 to 2017-Dec-31, with arrival dates ranging from 2017-Aug-01 to 2019-Dec-31. Similarly, Departure dates for the Borisov mission range from 2017-Jan-01 to 2020-Jul-31, with arrival dates ranging from 2019-Jun-01 to 2022-Jan-31. Prograde and retrograde transfers are then computed between the departure and arrival states and compared for their respective $\Delta V s$. The lower $\Delta V s$ for each combination of departure and arrival dates is then saved for further analysis.

An intermediate step in the Lambert solver requires finding the roots of the $F(z)$ function to solve for the universal anomaly required for the transfer. Curtis describes how a trivial initial guess of $z = 0$ can be used to warm start the newton method used to compute the root of the $F(z)$ function. However, often times this initial guess was too far away from the root to converge to a solution. An alternative method implemented in the solver, introduced by Curtis, is to evaluate the $F(z)$ function for a range of z values. A more appropriate initial guess can then be obtained by choosing a value close to where $F(z)$ crosses the x-axis (see Figure 3).

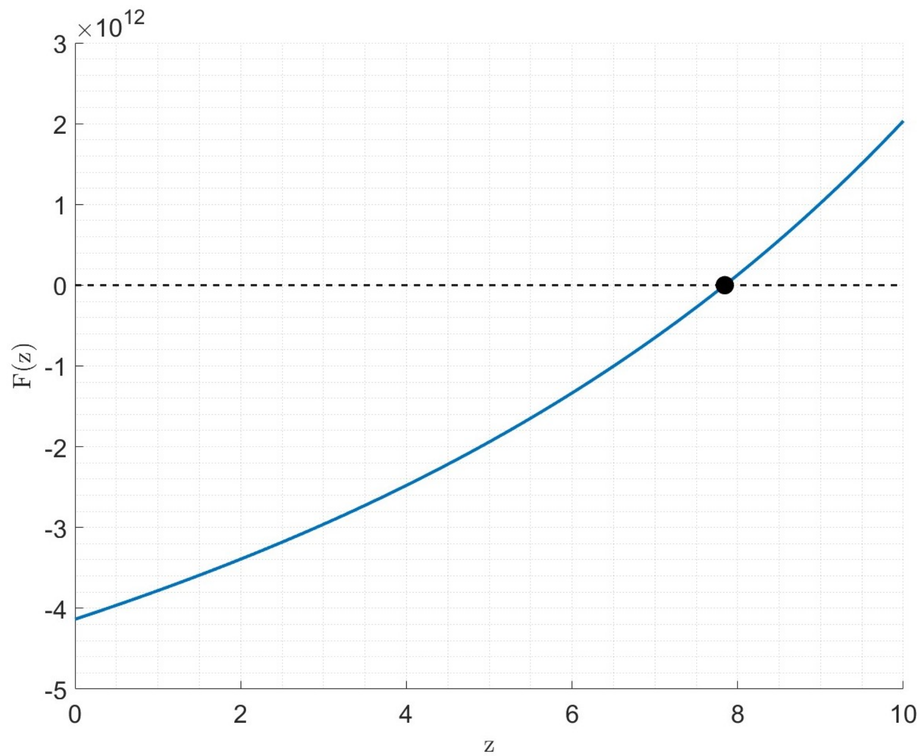


Figure 3: $F(z)$ evaluated from $z \in [0, 10]$

RESULTS

Using our Lambert solver to compute the terminal velocity vectors of our feasible transfers, we then compute the ΔV required for a given departure and arrival date. Finally we create Pork Chop Plots to visualize a heat map depicting the ΔV requirements to depart at different times of the year with varying times of flight (TOF). The results for the 'Oumuamua flyby and rendezvous missions can be seen in Figures 4 and 5. Similarly, the mission analysis for the Borisov missions can be seen in Figures 6 and 7. Notably, the plots were restricted to ΔV values below 20 km/s for the flyby missions and below 50 km/s (60 km/s for Borisov) for the rendezvous missions.

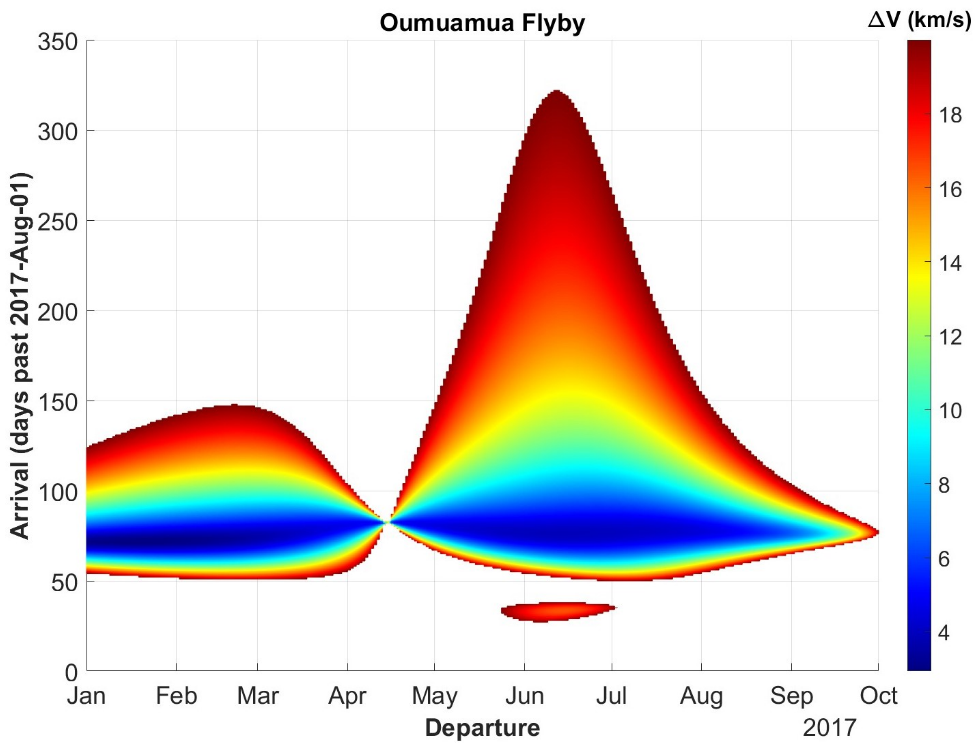


Figure 4: ’Oumuamua Flyby ΔV

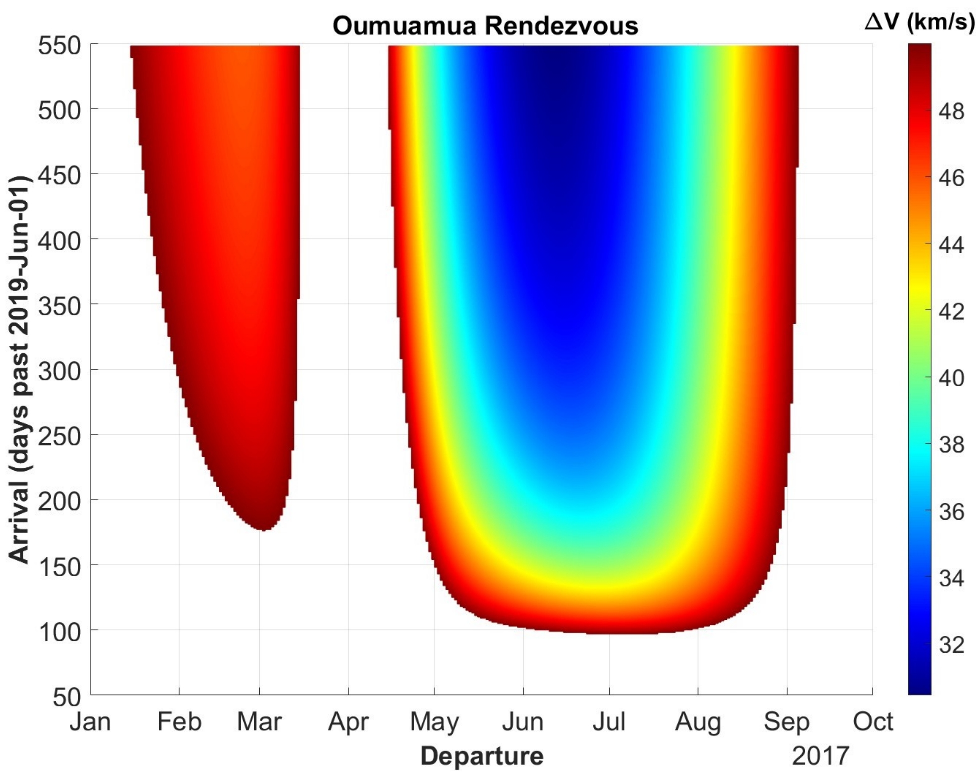


Figure 5: ’Oumuamua Rendezvous ΔV

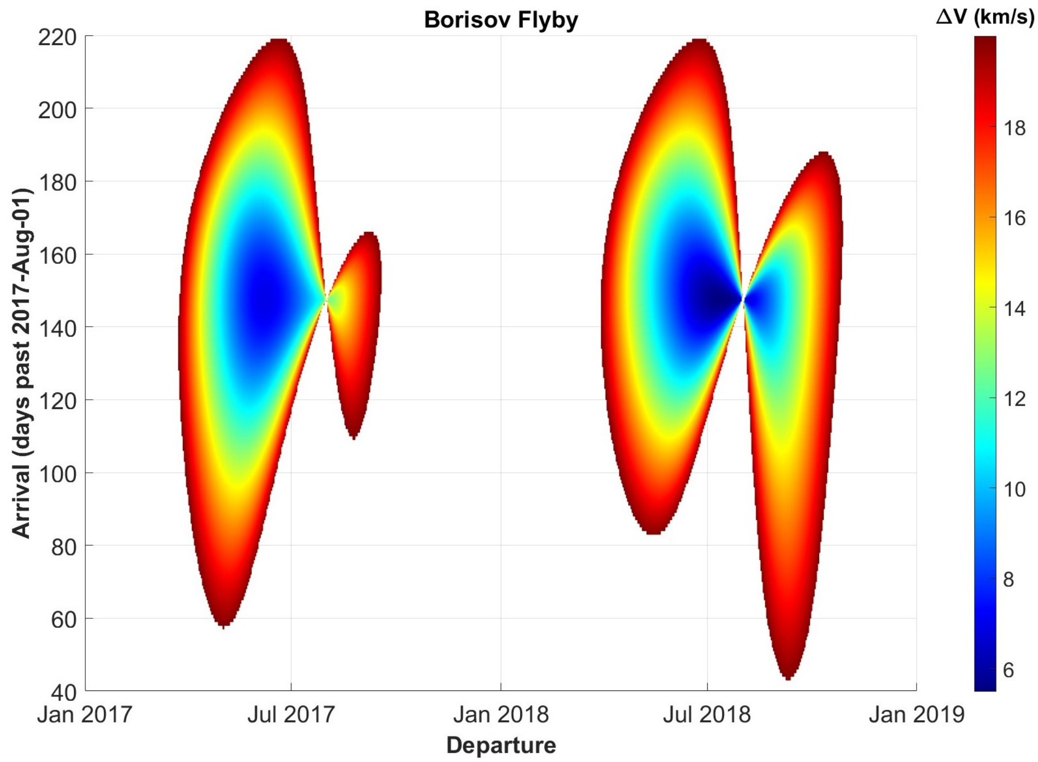


Figure 6: Borisov Flyby ΔV

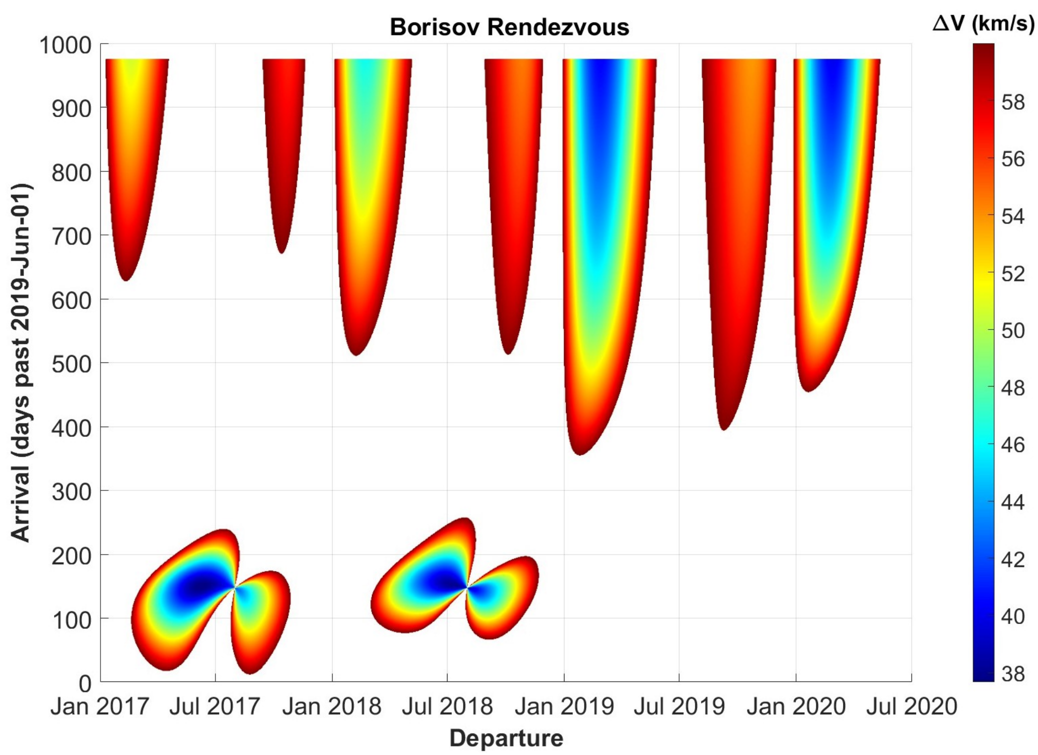


Figure 7: Borisov Rendezvous ΔV

DISCUSSION

Pork chop plots provide valuable visual tools for mission designers to analyze the potential options in the preliminary mission design phase. The results produced for the 'Oumuamua and Borisov missions allow us to analyze the feasibility of certain mission scenarios. Trying to determine which mission scenario is more feasible is not so black-and-white as it may initially appear. If the main consideration is choosing a mission that minimizes the fuel required, then our results would point to the 'Oumuamua flyby case, departing around 2017-Feb and arriving around 2017-Oct. This would be a good option if we simply want to pass the object to image it and perform other astronomical calculations. However, considering we have only observed two of these objects in our solar system so far, we may want to take the time (and spend the additional fuel) to design a more complex rendezvous mission that allows us to land on the comet to obtain a sample. This, of course, would be a much more complicated mission than we are simplifying it to in this assignment, but we don't know when the next of these objects may pass through our solar system. Collecting a sample and returning it back to Earth to study the composition of the object, could provide invaluable insight into the origin of the objects and how they may have formed.

If we had to choose between the Borisov and 'Oumuamua missions, my choice would be to perform a rendezvous sample return mission to 'Oumuamua. The reason for choosing 'Oumuamua, in this case, is simply due to the fact that the object made a closer approach to the nominal orbit of the Earth. Intuitively, and through the results of our pork chop plots, we can reason that a mission to 'Oumuamua would result in lower ΔV requirements and less TOF to perform the mission. A shorter TOF to get to the comet and return back to the Earth for a sample return mission would allow scientists to begin analyzing the composition of the object far sooner than in the Borisov case. Additionally, the approximate shape of 'Oumuamua is quite odd and puzzled scientists regarding how it may have formed. Personally, I believe that there would be more to gain from learning about 'Oumuamua and the TOF, and fuel requirements would result in a more favorable mission scenario.

Ultimately, there is no black-and-white answer as to what the perfect mission parameters would be. However, utilizing visual tools such as the pork chop plots created in this assignment helps provide valuable insight into options that can be considered, alongside all of the additional constraints and mission requirements.

GITHUB

Please find the code related to this assignment at the following link to my GitHub repository: https://github.com/brianpatrick3/Advanced-Orbital-Mechanics. In order to run the code properly, please do the following:

- Navigate to: *Advanced-Orbital-Mechanics/Homework1/bin/* and run the "*setup.m*" script
- Next, in the same folder, run the "*startup.m* script"
- To generate the pork chop plots, run the "*missionDesign.m*" script
- NOTE: The mission design file has two variables at the top of the code, labeled "**asteroid**" and "**transferType**". You can adjust the string for the asteroid to either "**Oumuamua**" or "**Borisov**", and the string for transferType between "**prograde**" or "**retrograde**" to simulate different transfers

REFERENCES

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[6] Howard D. Curtis. Chapter 5 - preliminary orbit determination. In Howard D. Curtis, editor, *Orbital Mechanics for Engineering Students (Third Edition)*, pages 239–298. Butterworth-Heinemann, Boston, third edition edition, 2014.