ASEN 6008 - Interplanetary Mission Design
Spring, 2016

Flagship Mission Development

Overall Description

NASA is investigating the possibility of sending a new spacecraft to one of the outer gas giants as a new flagship mission. Europa's sub-surface oceans, Io's volcanoes, Titan's lakes, and Enceladus' geysers are a few examples of features that have been identified in the Jovian and Saturnian systems that have become very compelling scientific targets. No spacecraft has ever entered orbit about Uranus or Neptune; such a mission may uncover features in one of their systems that are equally exciting.

You have been asked to come up with a preliminary design for the interplanetary portion of the mission. The mission will launch no earlier than July 1st, 2015, and you're welcome to explore launch dates out to Dec 31st, 2026. Use your knowledge of the previous Galileo and Cassini missions and interplanetary mission design to develop a suitable trajectory, and then use STK in order to visualize the trajectory. Your report will be in the form of a technical document. Grading will be based on completion of the required elements, any extended work, and overall presentation of your results.

Although a VEEGA is a good starting point for a mission, it is by no means required. You must include at least ***3 (three)*** planetary encounters in your mission. Examples include: VEEGA (1 Venus and 2 Earth encounters), VEMGA (1 Venus, 1 Earth, and 1 Mars encounter), VVVGA (3 Venus encounters), etc. You're welcome to use as many resonant orbits as you need, as many flybys as you need, and as many deep space maneuvers as you need, though try to keep the mission relatively realistic, i.e., keep the total fuel budget and mission duration as low/short as possible – guidelines for Time of Flight, C_3, etc, are listed later in this document. Some potential launch opportunities for various types of trajectories are also provided.

Theoretical Design Suggestions

It is not necessary to do all of the items listed here, but you may find some of these tips helpful when constructing your mission.

- Construct visual aids to help in preliminary mission design. There are different ways to do this. You could construct a series of Pork Chop plots, or you could plot the positions of the planets over time and see where possible flyby itineraries do (and do not) exist.
- Consider different types of resonant orbits, e.g., 2:1, 3:1, 3:2, 5:2, etc. However, consider mission duration when selecting the length of the resonant orbit.
- Consider multi-rev Lambert arcs wisely. While multi-rev arcs may be useful on legs between the inner planets, you probably don't want a multi-rev leg between Jupiter and Neptune.
- Locate reasonable windows of opportunities for each planetary encounter.
  - First locate windows of dates that minimize the Jupiter/Saturn/Uranus/Neptune arrival V_∞ magnitude and the Earth departure V_∞ magnitude (or C_3).

- Using these windows and the Pork Chop Plots, find reasonable planetary flyby windows of opportunity. Locate dates where the V_∞ magnitudes before and after a gravity assist match up. Ensure that the gravity assists do not impact the planet.

- Give some thought to how you will identify a good trajectory to your chosen destination. Consider ways to tell if your route will work or not within a few hours of CPU time. You could try out the "brute force" technique, a black-box MATLAB routine (e.g., fmincon), a genetic algorithm, a hill climbing routine, etc. No matter what, you should have an idea if your chosen route will work pretty quickly.
  - Any technique should start coarse and gradually increase the resolution of the search.
  - The closer $V_{\infty,in}$ and $V_{\infty,out}$ match for each flyby, the smaller your TCMs will likely be. The dates you choose do not need to be integers. Feel free to vary the dates by an hour or two if need be!

STK Implementation

- Typically, students launch from Cape Canaveral, Florida into a LEO parking orbit. If you want to use a different launch site, that's fine, just talk about why and what the consequences are. NOTE: Based on your launch date, RLA, and DLA, you may need to launch someplace other Cape Canaveral.
  - Use a targeter to produce the Injection ΔV as we did in previous Labs.
    - Try to make the launch as realistic as you can make it (i.e., using tangential burns and whatnot), but don't get bogged down in the launch. We're more interested in the interplanetary flight!
- Use *at least one* TCM per segment
  - One may be sufficient, but if you add a second later in a trajectory segment you can often target your B-Plane parameters to tighter tolerance, which may help the downstream maneuvers.
  - The TCM targeter should target the appropriate planet's B-Plane parameters for flybys. TCMs can target various orbital parameters for orbit insertion at the desired final location.
  - Don't add any errors to the TCM (assume they're performed perfectly).
  - If your $V_{\infty,in}$ and $V_{\infty,out}$ values don't match closely from your theoretical analysis, your TCM could possibly be quite large (more like a deep space maneuver than a TCM). You may even have to build a powered flyby – this will be graded poorly unless you give a nice description of the costs and benefits of performing a powered flyby!
- Choose an initial injection orbit at the gas giant and inject into that orbit. The shape/orientation of the injection orbit can be somewhat arbitrary. However, please ensure that the orbit is practical and doesn't require a prohibitively large orbit injection burn (i.e., don't inject into a 300 x 300 km orbit about Jupiter).

Grading

Your grade for the final project will be based on how well you complete the bare minimum requirements and additional elements of your choice. If you complete all of the required (and only the required elements) perfectly, you'll receive a B on your final report. Any additional elements that you choose will boost your grade into the A range.

Required Elements (these are required to earn at least a "B" on your report):

General Report Requirements

- Format:
  - Introduction: Discuss your overall strategy for finding an optimal mission. What were your optimality criteria and how did you go about searching and locating the trajectory? Which planet is your destination? What sort of mission might this be supporting?
  - Body: Be sure to include discussions of your plots, figures, and results. Prove to us that your trajectory works.

- Include any trade-studies you think deserve to be mentioned. Did you try different resonances; did you try different itineraries (i.e., did you try a VVEGA or a VEJGA)? Did you try multi-rev solutions?
- References: Include all references cited.

- Quality and Clarity (e.g., spelling, grammar, style). Don't forget units and even fontsize.
- Completeness

Non-STK Required Elements

- List your itinerary and target destination. We will use this to validate your trajectory! You're welcome to include other details since this may be a good place to put them (such as C_3, radii of periapse, etc). A table summary for each critical event is particularly helpful. It will help you to make sure you've included all the necessary information in the report and it helps us with grading. For instance, Galileo's trajectory would be listed as follows, with any additional information that may be interesting/useful/desirable:

Event	Calendar Date	Julian Date	Information (flyby radius of periapse, φ angle for a resonant orbit, Type I/II/III/IV transfer, B-Plane parameters, etc.)
Launch	October 8, 1989 00:00:00	2447807.5	C_3: km^2/s^2 RLA: deg DLA: deg
Venus Gravity Assist (VGA)	February 10, 1990 00:00:00	2447932.5	R_p: B_T: B_R: V_∞:
Earth Gravity Assist (EGA1)	December 10, 1990 00:00:00	2448235.5	R_p: B_T: B_R: V_∞:
Resonant Orbit			Resonance: 2:1 φ:
Asteroid Gaspra Flyby	October 29, 1991 00:00:00	2448558.5	Flyby radius:
Deep Space Maneuver	XXX	XXX	ΔV: ΔV_x (J2000): ΔV_y (J2000): ΔV_z (J2000):
Earth Gravity Assist (EGA2)	December 9, 1992 12:00:00	2448966.0	R_p: B_T: B_R: V_∞:
Jupiter Arrival (JOI)	March 21, 1996 12:00:00	2450164.0	V_∞: ΔV: Inclination: R_p:

- Pork Chop Plots for all segments (not including resonant orbits).
- At **least** 3 planetary flybys are required. These may be in the form of gravity assists or resonant orbits. When we are grading, we will take into account how complicated your trajectory is and the work that was necessary to produce it. In other words, a more complicated trajectory will likely result in a better grade.

- Resonant orbit plots, i.e., a plot showing the radius of closest approach for each of the two gravity swingbys as functions of the angle φ. Indicate which resonant orbit you chose. If you did not use a resonant orbit, then skip this requirement.
- Chosen Dates. How did you choose these dates?
- C_3 @ Earth, total interplanetary transfer duration, and V_∞ @ Jupiter/Saturn/Uranus/Neptune. Are these realistic given current technology? Take a look at the guidelines for what is achievable/acceptable/desirable for each of these parameters based on your final destination.
- Using the C_3 @ Earth, what is the expected ΔV that must be performed from LEO to get onto the outbound trajectory? Compute this value using patched-conics. Is this maneuver realistic?
- Compute V_∞'s, B-Plane parameters, radius/altitude of closest approach for each gravity assist. What are the values of $\left|V_\infty^{out}\right| - \left|V_\infty^{in}\right|$ for each gravity assist? What are the consequences if this value is non-zero? Did you perform a powered flyby!? Please don't unless you've exhausted all other options. If so, you have to address the costs and benefits of that.
- Are your flyby radii very small? If so, what are the consequences of allowing such a mission to occur? What are the consequences with using the Earth for a gravity assist?
- Orbital elements for the initial orbit about Jupiter/Saturn/Uranus/Neptune:
    - Include at least values for the initial orbit's period, r_a, r_p, and inclination.
    - How did you select your orbit at that gas giant?
- Magnitude of the Jupiter/Saturn/Uranus/Neptune orbit insertion burn (OI ΔV or equivalent), and the magnitude of the B vector. Compute OI ΔV using patched-conics.
- Comparison of the overall performance of this trajectory with a Hohmann transfer, direct transfers, and/or other gravity swingby tours. **You do need to compute at least a Hohmann transfer from Earth to the gas giant**, but you don't need to compute other gravity swingby trajectories. Instead, reference other historical missions, such as Galileo, Voyager 1 & 2, Cassini, New Horizons, etc…

STK Visualization Required Elements

- General discussion of STK's capabilities and uses (and possibly where it isn't useful…).
- Plots of the inner trajectory and the overall trajectory, as seen from above the ecliptic and from a tilted side angle (4 plots).
- Screen-capture of the Jupiter/Saturn/Uranus/Neptune arrival and the initial orbit.
- Discuss how you implemented TCMs in STK.
    - Include the TCM ΔV values and dates in your report.
    - How did you pick the dates for your TCMs?
    - Discuss what could be done to reduce these ΔVs.

Additional Elements (Those that will push your report into the "A" range)

You certainly don't have to complete all of these; but the better you do in this section, the better your grade will be. Note: Some of these additional elements are more time-consuming and challenging than others. Take this into account when writing your project. Doing six very easy elements may not boost your grade as high as doing four more challenging elements (and describing them well in the report!) Keep in mind that a more complicated trajectory (i.e., more than 3 flybys) may be more impressive than a less complicated one.

- Discuss how you constructed (or would construct better) the launch sequence and how that impacts the mission. Consider the implications of where/when you launch and your launch window.

- How many days in a row can you launch? What are the implications of launching several days late?
- Ground track plot (2D map of Earth's surface) of the first week of the mission.
    - Include the DSN facilities in the ground track plot.
- Plot showing which DSN facility has access to the spacecraft during the mission.
- Include plots of the position and velocity magnitudes wrt the Sun for the full mission.
- Include plots of the spacecraft's energy with respect to the Sun during the interplanetary trajectory. Indicate where gravity flybys occurred. If possible, include a plot that was produced in Matlab using simple 2-body equations and compare it with a plot that was produced in STK using the full ephemeris of the solar system.
- Include plots of the position magnitude wrt the Earth for the full mission (impacts communication, anything else?)
- Design a more complicated mission at Jupiter/Saturn/Uranus/Neptune (i.e., more than just inserting into a simple conic orbit the planet). This could include plane changes to study different regions of the planet, targeting certain moons as part of a tour, etc. There are many things that can be covered here: how, when, and where to perform maneuvers, computing the magnitudes of the maneuvers either in STK or in Matlab using 2-body motion, etc.
- Include a plot of the Earth-Spacecraft-Sun angle during the mission. Does it ever go below 5°? 1°? What are the consequences of that happening?
- Implement more than one TCM per segment. Include discussions of how you placed and constructed each TCM. What are the magnitudes and what is the overall effect of adding in multiple TCMs? How does the addition of multiple TCMs per segment affect the overall mission and what factors should be considered for the addition of TMCs?
- Discuss any Planetary Quarantine issues with your trajectory. How would you mitigate them? Did you mitigate them in any way?
- Include pictures of each gravity swingby, centered on the host planet. Include pictures of each gravity swingby and the Jupiter/Saturn/Uranus/Neptune Orbit Insertion as observed from the Earth.
- What are the eclipse durations during each gravity swingby? That is, what is the duration that the spacecraft is in the planet's shadow? What is the duration that the spacecraft is out of view of the Earth?
- Ground track plot of the final few hours before the JOI/SOI/UOI/NOI maneuver, as viewed from Earth. Which DSN facility has access to this maneuver?
- Can you tweak the trajectory so that the JOI/SOI/UOI/NOI maneuver is over Goldstone, CA? Or even better, over Goldstone AND another DSN facility? If so, how would you do it? (Did you do it!?)
- Anything else that is interesting and/or useful for the interplanetary mission design.

Required Values

Use the following values for your project:

Gravitational Parameters	**km^3/s^2**
Sun	$1.32712440 \times 10^{11}$
Earth	3.98600433×10^{5}
Venus	3.24858599×10^{5}
Mars	4.28283100×10^{4}
Jupiter	1.26686534×10^{8}
Saturn	3.79395000×10^{7}
Uranus	5.79396566×10^{6}
Neptune	6.83509920×10^{6}
Planetary Radii	**km**
Venus	6051.8
Earth	6378.14

Mars	3396.19
Jupiter	71,492
Saturn	60,268
Uranus	25,559
Neptune	24,764
AU	$1.49597870691 \times 10^8$ km

Interplanetary Transfer Guidelines

You may target your transfer to arrive at Jupiter, Saturn, Uranus, or Neptune. If you have your heart set on Pluto (even though it's not a planet!) or Mercury, see me. It is more challenging to try to reach these destinations. Over the last several years, we have spent some time locating trajectories to J/S/U/N so we can provide you with a general idea of when you can launch. We don't have a library of trajectories for Mercury or Pluto, so it may be very challenging to find a mission itinerary.

Be sure you know before you go: getting a trajectory to Uranus or Neptune is harder than getting one to Jupiter. As such, points will be awarded the further out you go. If you're aiming for Neptune, you may consider building a VEEGA to Jupiter as a backup in case you don't get a working trajectory. If you try and fail, but you find something interesting, it's great to write about it in your final report.

You may launch anytime from 7/1/2015 to 12/31/2026. Your interplanetary trajectory must fit into the requirements listed in the following table. The requirements are more relaxed the further out you go – keep that in mind. However, we will look more favorably on missions that try to minimize these parameters.

	Jupiter	**Saturn**	**Uranus**	**Neptune**
Time of Flight (years)	< 10	< 15	< 20	< 25
C_3 (km^2/s^2)	< 18	< 25	< 35	< 40
Arrival V_∞ (km/s)	< 6	< 10	< 14	< 18
Total Deep Space ΔV (km/s) or the *total* ΔV_∞ of all flybys (Not including STK's TCMs).	< 0.3	< 0.5	< 1.0	< 1.5

There is often a balance between each of these parameters. If you find a trajectory that you love that breaks one of these guidelines, describe why you like it and the consequences of breaking the guideline. Note that in order to insert into orbit, you really want an arrival V_∞ to be as low as possible; it is very possible to get a mission to Neptune with an arrival V_∞ of 4 km/s, but the transfer durations are often 30+ years.

Here are some places to start searching. We've successfully generated trajectories to all of these planets – feel free to ask us for more information about these options if you want to pursue them. MR denotes a multi-rev solution on one of the trajectory legs.

Destination: Jupiter

VEEJ: Launches in 2016, 2017, 2018 (MR), 2020, 2025 (MR).

VVEJ: Launch in 2108.

VVEEJ: Launch in 2018. Two resonant orbits (VV and EE)

VVEEJ: Launch in 2021. Tricky (but cool!) trajectory. VV leg is NOT a resonant orbit. Has 1 multi-rev leg.

VEMEJ: Launch 2023

VEEMJ: Launch 2026
Plenty of others! Try a VVVGA or a VEVEGA, or spell out your favorite word (VAVAVOOM GA)?

Destination: Saturn
VEES: Launch 2016 (MR), 2025
VEEJS: Launch Late 2016, 2020
VEEMJS: Launch 2026 (MR)
Others?
Destination: Uranus
VEESU: Launch 2023 (MR)
VEEMJU: Launch 2026
VEEJSU: Launch 2015.
VMEESU: Launch in 2023

Destination: Neptune
VEEJN: Launch in 2023.
VEEMJN: Launch 2026 (MR)
VEEJSN: Launch in 2015.

Other options for Saturn, Uranus and Neptune that we haven't found surely exist. New itineraries you find that meet the criteria listed in the table will boost your project grade.

Due Dates

- Apr. 7, 2016: Initial Pork Chop Plots are due, including a 1st guess for your interplanetary trajectory. Turn in the plots and your initial dates for Launch, GAs, resonant orbits/phi values (if applicable), and Jupiter/Saturn/Uranus/Neptune Arrival. These dates may change as you continue to refine your search. We just want to verify that you have a valid working trajectory based on C_3, V-infinity differences, periapsis passages, etc. 100 points. Due at 5:00 p.m. Late policy: 10% per day.
- Apr. 14, 2016: The final dates for your trajectory are due. No plots are necessary, just a simple table. Theoretically these values shouldn't change too much from the first set of dates that you submit. The dates should just be refined for smaller V-infinity differences, lower C_3, etc. 50 points. Due at 5:00 p.m. Late policy: 10% per day.
- Apr. 28, 2016: Your final write-up is due. Due at 5:00 p.m. Late Policy: 10% per day.