Orbital Mechanics Project - Megaconstellation Design

ASEN 3200 Orbital Mechanics and Attitude Dynamics
Fall 2021
Assigned November 12, 2021
Due at beginning of lab, December 7 & 9, 2021
This assignment has a total of 100 points and is worth 20% of your final grade

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1 Learning Objectives

- Reinforce fundamental orbital mechanics material, particularly orbit geometry, Kepler's Time of Flight, and J_2 perturbations, then connect them to real commercial uses
- Write a program containing several functions, input files, and generate complex outputs
- Engage in an open-ended team design experience
- Experience in team presentations covering technical material

2 Overview

You are a technical member of a boutique 'new space' company that specializes in constellation design. A fabulously wealthy tech entrepreneur is interested in soliciting concepts for a large spacecraft constellation to provide worldwide ubiquitous internet. You want to win this competition!

2.1 Organization

This project is composed of three parts. Part 1 will involve individual team members each developing their own code to conduct detailed constellation design analyses. . Part 2 will involve team members collectively designing a mega constellation to try and meet multiple objectives articulated by the customer. Part 3 will involve recording a 3-minute pitch video for the customer.

2.2 Resources.

A database of cities is provided on Canvas (the link allows separate download, and also includes the field labels and descriptions). World coastlines are available on Canvas and at the NOAA website.

2.3 Due Dates and Submission

Code for Part 1 will be submitted via GradeScope and will be due before lab on November 30 and December 2 (depending on lab section). Both Part 2 and Part 3 are due before lab on December 7 and 9. Part 2 will be submitted on Canvas, and Part 3 will be submitted via Canvas / YouTube.

3 Project Components

3.1 Part 1: Building Blocks (Individual Assignment)

You will need to write your own code to specify a constellation design, propagate spacecraft, account for J_2 perturbations, and compute line-of-sight from the ground.

Part 1 Rubric [45 points]:

a. [5 points] A function to read a JSON file specifying your constellation design. The JSON specification will be posted on the Canvas assignment page.

b. [10 points] A function to propagate orbit elements with J_2 perturbations and compute the position and velocity vectors in ECI at a given time t.

c. [5 points] A function to compute whether spacecraft j has line of sight to a specified position i in ECEF.

d. [25 points] A main script / simulation to i) read in a JSON constellation design file, ii) propagate the constellation in time for a full mean solar day (30 second time steps), iii) compute the number of spacecraft in line of sight of each city i at each time step, iv) plot a 3D rendering of your constellation orbits and the Earth (with coastlines and cities) at the final time. Functionality will count for 15 points, and style / legibility will count for 10 of the 25 points.

Assumptions

- For line of sight to exist between spacecraft j and city i, the local elevation angle must be at least 15 deg.
- Please assume Keplerian + J_2 dynamics. Note, as an approximation to these dynamics, you can determine the effect of J_2 on the orbit elements first, then use that instantaneous orbit and Kepler's Time of Flight problem to compute an instantaneous $\mathbf{r}(t)$ and $\dot{\mathbf{r}}(t)$.

Because we're using GradeScope to validate your programs, you will be able to submit your code multiple times to verify correction functionality. Note, for GradeScope (or Matlab Autograding) to work, you *must* ensure that your functions match the provided function templates & scaffolds.

Part A is due before lab on November 30 and December 2. Note, you'll be able to start submitting your code via GradeScope for auto-verification starting the week of November 15.

3.2 Part 2: Multi-Objective Design

Now you must take your code building blocks and turn them into something useful! The tech entrepreneur has articulated two things that she cares about: Cost and Value. It is you and your teams job to provide a solution balancing these two objectives.

Part 2 Rubric [30 points] You must write a team report (PDF, 12pt Times New Roman, single-spaced, 1-in margins) capturing the following elements:

a. [5 points] Cover Page and Executive summary (< 100 words) describing your constellation design, salient features, and performance on objectives O1 and O2. This should be its own, separate page (that's why it's called a cover page!)

b. [15 points] 4 page description of i) your design constraints, ii) your design objectives, iii) your design approach, iv) your final solution, and v) supporting evidence as to why your solution is the best!

c. [5 points] In an appendix, plot and discuss the i) time series of the number of spacecraft (weighted by population) in view of the cities at any given time between t_0 and t_f, and ii) a 3D plot of the Earth and constellation orbits at the final time.

d. [5 points] In an appendix, a 1-page block diagram of your integrated code *and* a 1-page description of how it works.

e. Please include a QR code link to your Constellation Pitch video (Part 3) on your project report Cover Page (Part 2)! There are a wide variety of free QR code generators - you pick![1]

Assumptions. There are two objectives we will attempt to optimize:

O1 Cost. Each spacecraft and each launch vehicle costs a certain amount of money (identified in the table below), and naturally, we wish to minimize how much money is necessary to launch the constellation.

O2 Value. Your customers live in cities, and your value provided to them will be measured by the time-averaged number of spacecraft per million people

$$J_v = \sum_{i=1}^{N_c} \left[\frac{p_{c,i}}{(t_f - t_0)} \int_{t_0}^{t_f} N_{sc,los,i}(t) dt \right] \tag{1}$$

Where N_c are the number of cities each indexed by i, $p_{c,i}$ is the population of city i, t_0 and t_f are the start and stop times of the performance period, and $N_{sc,los,i}(t)$ is the number of spacecraft in the line of sight of city i at time t.[2]

You will not be able to simultaneously maximize both of these measures, so you'll need to make some hard design decisions! Said differently, there is no single correct solution![3]

[1] No doubt, these will be fun to put on your resume, if you want!

[2] Hint: You can check whether spacecraft j has line of sight to city i by checking a dot product inequality in either the ECI or ECEF frames.

[3] However, there exists a family of solutions that trade performance in one objective for performance in another. This type of solution is called a Pareto Surface, which is composed of individual non-dominated points. Emphatically, you only need to find a point that you believe is on the Pareto surface - not the entire family!

Further, you must abide by the following orbit constraints for all spacecraft within your constellation: $R_e + 350\text{km} \leq r_p \leq r_a \leq R_e + 1100\text{km}$. Please ignore drag for the purposes of this assignment. Finally, please ensure your spacecraft don't collide with one another!

Finally, the minimum constellation size is 100 spacecraft spread over 3 different orbit planes[4].

Table 1: Constellation Element Costs

Element	Cost ($M)	Notes
Launch Vehicle	100	Can carry up to 50 spacecraft to an orbit; you will need multiple launch vehicles to launch to different orbit planes
Spacecraft	5	Assume spacecraft can maneuver to spread themselves out as desired in terms of true anomaly, but they can't change other orbit elements!

[4] I **strongly** recommend that, when designing your constellation, you randomly select a set of 100-400 cities so that your simulation runs faster! You can add the full city list back in when you generate your final results.

3.3 Part 3: Constellation Pitch.

You and your team will record a 3-minute pitch for your planned design (posted on YouTube; doesn't have to be a public video). Note, you can record videos with video capture and slides using Zoom. The presentations will be reviewed in lab during the Tu/Th sections on December 7, 9. We will watch all of the pitches for each group and vote for the best pitch at the end of the lab!

Part 3 Rubric [25 points] Your 3-minute YouTube Constellation Pitch should include:

a. A work-appropriate unique 'company' name so we can vote for you!

b. [5 points] A 15-second summary of your design and the performance measures you have achieved

c. [15 points] Verbal and graphical description of your design process, including i) how you chose candidate orbit planes and orbits, ii) how you chose the number of launches and spacecraft per launch, and iii) how do you know that your solution is the best?

d. [5 points] An animation of your constellation design over the full simulation period (runtime should be no more than 30 seconds).

e. For full credit, each team member must be speaking for at least 45 seconds in the video.