

## Mission Design and Navigation Final Project

Your company "<your first name>'s Rockets and Pizza LLC" has decided that it will enter the market place to compete for the NASA ROSES mission concept to create a Scientist Principal Investigator mission that will explore the upper layers of the ionosphere and part of the South Atlantic Anomaly over the period of 1 week. The mission concept has an overall price cap, with a MD/Nav cost cap set at \$1,000,000 by your project manager. You must create a mission and navigation system design that fits within the cost constraints of the mission. You will present your results to the team in the form of a short white paper highlighting the trade space as you see it. You will investigate several (at least 2) options for your design and explain why the design you came up with is the best one for the team and better than a reasonable alternative(s). Beware- this is a competitive NASA call, which is fundamentally a winner takes all competition. In this case, the winner will receive 5 bonus points. You will be evaluated on 4 criteria: 1) Mission Design (science) objective score, 2) Navigation objective score, and 3) cost realism/growth risk, 4) the quality of your written white paper. The score methodology for Mission Design and Navigation are stated below and each category (MD, Nav) is given half of the total weight (to normalize the scoring by discipline). The 3<sup>rd</sup> category is always a fuzzy criteria- those with designs that cost less but have roughly the same score (a flexible term which includes margins) will ultimately be favored by the review panel. The quality of writing and the ability to communicate the trade space are critical to an effective product and will be important here.

May the best design win!

### Mission Design:

#### 1) Science Objective:

- a. There are 2 science objectives for this project. You must have a **non-zero total for both objectives** to have a valid design.
  - i. **Objective 1:** A sensor that measures particles in the **ionosphere**. It requires:
    1. High latitudes (>70 degrees)
    2. High altitudes (>20,000 km altitude)
    3. Objective Points:
      - a. You gain 1MD-iono objective point for every hour that you are in the region of interest.
  - ii. **Objective 2:** A sensor that measures particles in the **South Atlantic Anomaly**. It requires:
    1. Within a latitude and longitude zone:
      - a. +/- 10 degrees in latitude and longitude
      - b. Altitude does not matter (for this project at least)
    2. Objective Points:
      - a. You gain 5MD-saa objective point for every hour that you are in the region of interest.

#### 2) Mission Operations Objective:

- a. The selected orbit must make ground contact with a ground station at least twice each day.

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- b. You must have 2 ground stations (a primary and a backup).
- c. You may place as many ground stations as you wish, but each one costs money. Ground station costs are discussed in the next section.

### Navigation:

#### 1. Science Objective:

- 1. Determine the **orbital position** precisely to reconstruct the ionosphere from measurements collected during the mission.
  - i. Objective points for the **maximum 3 sigma position error** over the mission time span, **after 2 orbits to converge** your solution:
    - A. 10 Nav-Pos Objective points for 3 sigma < 25 m
    - B. 8 Nav-Pos Objective points for 3 sigma < 50m
    - C. 5 Nav-Pos Objective points for 3 sigma < 200 m
    - D. 3 Nav-Pos Objective points for 3 sigma < 500 m
- 2. Maintain **time knowledge** so that the measurements can be time tagged accurately.
  - i. Objective points for the **maximum 3 sigma time error** over the mission time span:
    - A. 5 Nav-Time Objective points for 3 sigma time < 10 ms
    - B. 4 Nav-Time Objective points for 3 sigma time < 100 ms
    - C. 2 Nav-Time Objective points for 3 sigma time < 1 second

#### 2. Cost:

##### 1. **Ground Station and Navigation System** Costs:

- i. Communications Costs per Station (just for telemetry to satisfy the science objective):
  - A. Continental US and Alaska (no Hawaii) = \$10,000
  - B. Non-US North America, South America, Europe = \$100,000
  - C. Antarctica = \$500,000
- ii. Navigation Service Costs, either A or B:
  - A. Human-in-the-loop: (sum the next 2 sub bullets)
    - a. Analyst time (you want to be paid!): \$100,000
    - b. Additional cost for navigation service:
      - i. Radio-Shack passive system: \$10,000
        - 1. Per station- you need 2 for a TDOA/FDOA pair
      - ii. Amazon Web Services (AWS) ground station usage: \$100,000
      - iii. Deep Space Network (DSN) ground station usage: \$400,000
  - B. Autonomous:
    - a. Flight Qualified GPS Receiver: \$980,000
    - b. Additional cost for system usage – none.
      - i. Assume the receiver has its own navigation filter embedded into the system. You will analyze its expected performance for the trade study, but the procured system would not need your support.

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- iii. Example: a human-in-the-loop navigation system with a laydown of 1 AWS station in the US and 1 in Europe would cost \$100K (analyst time) + [\$10K (telemetry, US) + \$100K (AWS nav package)] + [\$100K (telemetry, Europe) + \$100K (AWS nav package)] = \$410K

### 2. Clock Costs:

- i. VTCXO = free
- ii. OCXO = \$10,000
- iii. Rubidium = \$500,000
- iv. Cesium = \$1,000,000

### 3. Performance:

#### 1. Navigation System Performances:

- i. Radio-Shack passive system (requires 2 stations and both must see the satellite): 5 m 1 sigma TDOA and 0.25 m/s 1 sigma FDOA
  - A. Sigma TDOA position = 5 m, divide by c to get the time sigma
  - B. Sigma FDOA = 0.00833 Hz and has a  $f_0=10\text{MHz}$ , (corresponds to 0.25 m/s Doppler shift)
- ii. AWS ground station: 15 meters 1-sigma ideal range
- iii. DSN ground station: 1 meter 1-sigma ideal range
- iv. Flight Qualified GPS Receiver: (Nav sols) 5-meter 1-sigma in X/Y/Z
  - A. Only works below an altitude of 20,000 km (approximate GPS constellation altitude)

#### 2. Disturbance:

- i. Position & Velocity: for simplicity we will assume a process noise sigma of  $1e-8$ , with Q diagonal.
- ii. Clock error parameters (don't use the third clock state):

Clock Type	$\sigma_1$	$\sigma_2$	$\sigma_3$
VCTCXO	2.24e-11	4.44e-10	0
OCXO	1.12e-11	7.04e-11	0
Rubidium	2.24e-12	5.06e-13	0
Cesium	1e-10	2.81e-14	0

### Solution Notes:

- 1. This is an individual assignment.
- 2. You will be provided numerous pieces of code, including a template for the navigation analysis (it uses the \*.mat file described below for an interface), but some of them will have sections that you need to complete. These sections have been designated with "???". In particular you will need to complete the following:
  - a. An orbital to Cartesian function.
  - b. Elevation masks in measurement models. Basically, if the satellite is below the horizon, then a ground station cannot see it. You will need to create the function "computeElevation.m" which takes 2 position vectors and computes the local elevation at the instrument location.

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- c. Measurement matching in the Kalman filter. The measurement IDs that you haven't used yet will be critical here, as you will not always see measurements that you expect, and you want to only process the right residuals.
3. Do not modify the initial state generation sent into the filter (it should have a small error that corresponds to the initial covariance).
3. Do not change the times step of 100 seconds.
4. Use an Extended Kalman filter for this project.
5. You may mix different measurement methods, but it is on you to write a filter that can handle the heterogeneous system and match up the measurements.
6. If you use numerical derivative, then be aware that in rare instances the small finite step size could cause a measurement to drop below an elevation mask and thus the measurement will not be generated. This could cause an error. You may need to reduce the step size more than normal to prevent this.
7. Clocks:
  - a. I recommend simulating the clock independently from the navigation filter. I tried to break it out into a separate step to save time and complication. I recommend a linear covariance analysis (see Module 12).
  - b. Assume the clock error resets to an error of 10 ns in phase and 1e-7 Hz in frequency 1 sigma when in contact with a ground station (ranging or TDOA/FDOA), or when the GPS receiver is below the altitude limit.
8. When placing your plots into your whitepaper, be sure that you can see the relevant information clearly.
9. Numerous pieces of code will be provided.

### Recap of the Problem:

- Mission Design Objective Score composed of: 1) MD-iono points, and 2) MD-saa points
  - You must have non-zero values for both objectives.
- Navigation Objective Score composed of: 1) Nav-Pos points, 2) Nav-Time points
- Constraints: 1) \$1,000,000 cost cap, 2) Ground Station Placement Options
- Flexible trade space: 1) Cost, 2) Margins, 3) Written communication skills

### Submission:

1. Set your random number generator before the truth-model simulation to 1 (e.g., `rng(1)`).
2. Provide the initial state vector (position and velocity in the inertial frame)
  - a.  $x = [r', v']'$
3. Provide your selection of navigation sensors in one structure ("navSensors")
  - a. If ground stations, then:
    - i. Provide all locations in latitude and longitude [degrees]
      1. Define a matrix field in "navSensors" called "GndStats"
    - ii. Provide the station type (AWS, DSN, or RadioShack TDOA+FDOA)
      1. Define a string field in "navSensors" called "statType"
        - a. `navSensors.stateType = 'AWS'`

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- b. navSensors.stateType = 'DSN'
    - c. navSensors.stateType = 'RadioShack'
  - b. If GPS receiver, then:
    - i. Define a string field in "navSensors" called "statType":
      - 1. navSensors.stateType = 'GPS'
- 4. Provide your oscillator selection.
  - a. Define a string variable called "clock" and select one of the following clock types:
    - i. clock = 'VCTCXO'
    - ii. clock = 'OCXO'
    - iii. clock = 'Rubidium'
    - iv. clock = 'Cesium'