AE4898 - Space Debris Tracking and Mitigation - Homework Assignment 4

This assignment concludes your analysis of space debris risks and mitigation measures in support of an Owner/Operator (O/O) space asset. In particular, in this assignment, you will process additional measurements to characterize RSO parameters, detect and reconstruct maneuvers, initialize new orbit estimates and refine your collision risk assessment.

Throughout the assignments, emphasis is placed on producing useful analysis products, well-informed recommendations, and careful justification of the tools and settings used. In other words, you must convince the O/O that your analysis and recommendations are fundamentally sound.

This homework assignment is a **group** one. Collaboration with other groups is allowed, but each group must write their own unique code and report. The deadline for all assignments is communicated through Brightspace, and submission of the reports is also done through Brightspace. For late submissions, 1 point (out of the total of 10) will be subtracted per day, noting that part of a day counts as a full day. So, when handing in the report x days late, $\lceil x \rceil$ points will be deducted.

We have provided a set of data required for this assignment, which can be retrieved from the `assignment4` directory in the course github repository:
`https://github.com/tudat-team/space-debris-2024`

No template is provided for this assignment, you must write your own well-formatted report adhering to the guidelines in this document. The use of generative AI tools is allowed, but you must include an appendix specifying exactly where and how they were used, per the stated policy on Brightspace.

Even though this assignment is a group assignment, each student must have a distinct individual technical and reporting contribution. For each sub-question, it must be indicated who worked on it, distinguishing between technical and reporting contributions where relevant. In case multiple people worked on one question, percentages of the total contribution, and a brief description of contributions, must be provided. Subquestions may be broken down further into tasks at your discretion, but it is recommended to do so. Each individual must have at least one subquestion/task for which they are the responsible engineer and conduct more than 50% of the technical work. All contributions must be clearly stated in a table, per subquestion and/or task, included at the end of the report. The individual and group grades of this and the next assignment combined will count for 50% of the final assignment grade.

Note: in case of doubt about any personal contributions and/or the spent hours, we may invite you for a personal interview where you can explain the work you have done, before giving you the grade for the course.

For each of the following questions, a set of measurement data are provided for you to analyze. You are welcome to use any estimation technique(s), and to supplement the provided data with measurements generated from your tasking requests in Assignment 3 if relevant. Groups of 3 people, select two questions from the set of {Q1, Q2, Q3} to complete, i.e., you may skip one of the first three questions.

(1) $\boxed{\textbf{20 points}}$ A colleague has informed you that the physical parameters of one of the catalog objects have been mismodeled, i.e., default assumptions about shape, area, mass, drag and/or reflectivity coefficients are in some way incorrect. They have collected some additional data to help you characterize the object, noting that the provided measurement file contains the possibly erroneous default state parameters.

  (a) $\boxed{\text{10 points}}$ Develop an appropriate method to characterize the physical parameters of the object. Describe the approach in sufficient detail to reproduce your method, including mathematical formulation and figures as appropriate. Justify your approach.

  (b) $\boxed{\text{10 points}}$ Identify which physical parameters have been mismodeled relative to the assumptions stated in Assignment 3. Provide your best estimate(s) for the physical model of the RSO. If possible, quantify the uncertainty associated with your estimated physical model parameters. Furthermore, estimate the state and uncertainty of the RSO, producing at minimum the following outputs:

  - State the best estimate shape, area, mass, drag, and reflectivity coefficient of the object, including uncertainties where possible.
  - State all parameter settings used in the estimator.
  - Plot the post-fit residuals and compute the RMS.
  - Plot the 3-σ covariance bounds of position in the Radial/Intrack/Crosstrack coordinate frame.
  - Use this model and best orbit state estimate for analysis in Q4.

(2) $\boxed{\textbf{20 points}}$ The same colleague informs you that one of the catalog objects appears to have performed an impulsive maneuver between 2024-03-21 12:00 and 2024-03-22 12:00 UTC and has provided additional data to help you investigate.

  (a) $\boxed{\text{10 points}}$ Develop an appropriate method to determine the time and $\Delta \boldsymbol{v}$ imparted by the maneuver. You may assume the maneuver is impulsive, obeying the Tsiolkovsky rocket equation, with a thruster of specific impulse $I_{sp} = 220$ seconds. Describe the approach in sufficient detail to reproduce your method, including mathematical formulation and figures as appropriate. Justify your approach.

  (b) $\boxed{\text{10 points}}$ Provide your best estimate of the maneuver time and $\Delta \boldsymbol{v}$ (magnitude and direction). If possible, quantify the uncertainty associated with your estimated maneuver parameters. Furthermore, estimate the state and uncertainty of the RSO, producing at minimum the following outputs:

  - State the maneuver time in UTC. You may state a single time or a window of possible times.
  - State the maneuver $\Delta \boldsymbol{v}$ magnitude and direction, with uncertainties if possible.
  - State all parameter settings used in the estimator.
  - Plot the post-fit residuals and compute the RMS.
  - Plot the 3-σ covariance bounds of position in the Radial/Intrack/Crosstrack coordinate frame.
  - Use this model and best orbit state estimate for analysis in Q4.

(3) $\boxed{\textbf{20 points}}$ A new RSO has been detected and a sparse set of measurement data have been generated to perform an initial orbit determination. Note that the measurement file contains an empty dictionary for the unknown state parameters.

(a) $\boxed{\text{10 points}}$ Develop an appropriate method to estimate the Keplerian orbital elements and Cartesian state of the newly discovered object, as well as a quantification of the associated uncertainty in inertial Cartesian coordinates. Describe the approach in sufficient detail to reproduce your method, including mathematical formulation and figures as appropriate. If the method requires assumptions regarding physical parameters of the RSO, provide the selected values. Justify your approach.

(b) $\boxed{\text{10 points}}$ Provide your best estimate of the RSO. Quantify the uncertainty in your estimate. Does the RSO merit further analysis as a potential hazard to the O/O asset? Justify your response. Produce at minimum the following outputs:

- State the Keplerian orbital elements corresponding to the first measurement time.
- Provide any physical parameters assumed or estimated for the RSO.
- Use this model and best orbit state estimate for analysis in Q4.

(4) $\boxed{\textbf{30 points}}$ Process measurement data and perform a final collision risk assessment.

(a) $\boxed{\text{10 points}}$ Using the method of your choice, process the measurements generated by your sensor tasking scheme for all objects from Assignment 3. Produce a table with RMS residuals for each object. For a representative object, plot the 3-σ covariance bounds of position in the Radial/Intrack/Crosstrack coordinate frame. Do the results indicate the estimator has produced a good solution for each object? Justify your response.

(b) $\boxed{\text{10 points}}$ Produce your final risk assessment for the O/O using the refined catalog estimates. Highlight any changes, either in applied criteria or results, from your findings in Assignment 3. What is the reason for these changes? At minimum, include the following:

- Conjunction Data Messages (CDMs) for all identified High Interest Events (HIEs).
- A clear recommendation for each HIE whether a collision avoidance maneuver is required, with justification.

(c) $\boxed{\text{10 points}}$ Reflect on the performance of your sensor and measurement collection. Did the measurements generated improve your catalog estimates and help to refine your conjunction metrics? If so, quantify the improvement relative to the propagated state and uncertainty from Assignment 3. If you were to iterate on the sensor selection and tasks, would you do anything differently to improve the performance?

(5) $\boxed{\textbf{10 points}}$ Reporting technique: present your findings in a concise and efficient manner.

- The report must not exceed 30 (content) pages in length, including figures, tables, equations and appendices. Use no more than 15 pages for text. The cover page and bibliography are not included in the page count.
- On the front page: include a link to your GitHub repository containing the code that you used for this assignment, and the individual hours you spent
- Add a table at the end of the report with a clear breakdown of individual technical and reporting contributions to the report. **REPORTS THAT DO NOT HAVE SUCH A TABLE WILL NOT BE GRADED**
- All margins should be at least 2 cm (on A4 page size).
- The minimum font size is 10pt.

- Readability of the report is an important element for the grading. Figures that are not readable are assumed to be absent from the analysis.
- Discuss all figures and tables in your report: observe, analyze, conclude.
- **Hint: Ensure that the information you want to convey can be properly read from your plots.**