AE4898 - Space Debris Tracking and Mitigation - Homework Assignment 3

This assignment continues 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 combine and extend your previous conjunction analysis by working with a group of your peers to evaluate the risk across a small catalog of simulated resident space objects (RSOs). You will identify High Interest Events (HIEs) per your own criteria, develop an appropriately tuned filter to process measurements, and define tasks for a simulated ground-based sensor to collect measurements to refine your 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 code and data required for this assignment, which can be retrieved from the course github repository:
`https://github.com/tudat-team/space-debris-2024/assignment3`

No template is provided for this assignment, you must write your own well-formatted report adhering to the guidelines in this document.

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 is recommended. 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.

(1) $\boxed{\textbf{40 points}}$ In this question you will combine the outcomes of your individual analyses to evaluate the risk of collision across a small catalog of simulated RSOs.

(a) $\boxed{\text{10 points}}$ Compare your choices for how to evaluate collision risk, what information to include in the CDM, and what criteria you will apply to identify HIEs, recommend collision avoidance maneuvers, and evaluate the efficacy of such maneuvers. Define your final choices for these items as a group and provide justification based on your previous analysis and/or reference to literature.

(b) $\boxed{\text{20 points}}$ Apply your analysis across the given space object catalog. Perform conjunction screening for a period of 48 hours from the initial epoch provided. Generate CDMs, identify HIEs, and present your risk analysis to the O/O per your stated criteria. You should assume the following:

- The object catalog contains estimated mean state and covariance parameters for all O/O assets, as well as a set of resident space objects (RSOs). These should be considered to have unknown errors relative to the true object states.
- State errors for all objects in the catalog are Gaussian distributed at the initial time. Errors are consistent with the provided covariances, i.e., you can assume the true state is most likely within 3-σ of the estimated state.
- Objects are modeled as spheres, with physical parameters such as mass and area provided in the catalog. You should consider these parameters to be true.
- The acceleration model includes the following forces, which you can consider to be complete and true for the purpose of this assignment.

Table 1: Question 1 Acceleration Models

Earth Gravity Field	Spherical Harmonics (8,8)
Third Bodies	Sun, Moon
Aerodynamic Drag	Included (cannonball)
Solar Radiation Pressure	Included (cannonball)

(c) $\boxed{\text{10 points}}$ Provide a detailed description of the methodology used to perform each step of your analysis, at a level of detail sufficient to reproduce your results. Include mathematical formulations for the calculation of metrics used and citation to literature as appropriate. Justify your chosen method(s) and include a discussion of whether your approach would be appropriate to scale to a catalog of 40,000 objects.

(2) $\boxed{\textbf{25 points}}$ Develop a procedure and recommended values to apply State Noise Compensation (SNC), also known as Process Noise, for the Unscented Kalman Filter (UKF). **Groups of 3 people are only required to complete Parts (a) and (c)**.

(a) $\boxed{\text{10 points}}$ In the first test case, the acceleration model used in the filter will exactly match that used to generate the truth and measurement data. In particular, only conservative forces are applied, as summarized in Table 2.

Table 2: Question 2(a) Acceleration Models

Acceleration	Truth Model	Filter Model
Earth Gravity Field	Spherical Harmonics (8,8)	Spherical Harmonics (8,8)
Third Bodies	Sun, Moon	Sun, Moon
Aerodynamic Drag	Not included	Not included
Solar Radiation Pressure	Not included	Not included

Measurements are simulated for both a radar and optical sensor located in Delft, using location parameters in Table 3. Measurements have been corrupted by Gaussian noise with the characteristics as provided in Question 3. In order to simplify the analysis and maintain a regular cadence of measurement data for all cases, no constraints are applied to the sensor, i.e., measurements can be collected when the object is below the horizon, in eclipse, or otherwise exceeding sensor constraints.

Table 3: Delft Location Parameters

Geodetic Latitude [deg]	52.00667
Geodetic Longitude [deg]	4.35556
Geodetic Height [meters]	0.0

Develop a procedure to adjust the SNC covariance to process the measurements using the UKF. State your final selection with justification. You must include, at minimum, a plot of your position errors with 3-σ covariance bounds in the Radial-Intrack-Crosstrack (RIC) coordinate frame, as well as a plot of post-fit measurement residuals using your selected SNC parameters. You may include any additional plots or tables at your discretion.

(i) $\boxed{\text{5 points}}$ Present your analysis and discussion for the 3D radar measurements.

(ii) $\boxed{\text{5 points}}$ Present your analysis and discussion for the 2D optical measurements.

(b) $\boxed{\text{10 points}}$ [**Groups of 4 only**] Repeat your analysis from Part (a) to tune the process noise parameters in the case that the acceleration model used in the filter does not match that used to generate the truth and measurement data. In particular, non-conservative forces in the truth model should be excluded from the filter acceleration model, and instead compensated for with the use of SNC.

Note that for low orbits (below 1000 km), the unmodeled acceleration will be aerodynamic drag, while for high orbits (above 1000 km), the unmodeled acceleration is solar radiation pressure, as detailed in Table 4.

(i) $\boxed{\text{5 points}}$ Present your analysis and discussion for the 3D radar measurements.

(ii) $\boxed{\text{5 points}}$ Present your analysis and discussion for the 2D optical measurements.

Table 4: Question 2(b) Acceleration Models

Acceleration	Truth (Below 1000 km)	Truth (Above 1000 km)	Filter (All cases)
Earth Gravity Field	Sph Harm (8,8)	Sph Harm (8,8)	Sph Harm (8,8)
Third Bodies	Sun, Moon	Sun, Moon	Sun, Moon
Aerodynamic Drag	Included (cannonball)	Not included	Not included
Solar Radiation Pressure	Not included	Included (cannonball)	Not included

(c) $\boxed{\text{5 points}}$ Summarize your findings by answering the following questions.

(i) Are state errors consistent with the covariance? Is the RMS of measurement residuals at the expected value? If not, why?

(ii) Do certain measurements dominate the solution in certain cases? If so, why?

(iii) What are the main similarities and differences between the radar and optical results, and why?

(iv) **Groups of 4 only** Did you observe any difference in results for Parts (a) and (b)? Why or why not?

(3) $\boxed{\textbf{25 points}}$ Select a ground-based sensor and tasking strategy to gather information on the RSO catalog. There are two options available, radar and passive optical telescope, with the constraints and characteristics provided in the table below. Note that optical sensors are constrained to operate at night, which is defined as the period during which the sun is below $-12°$ elevation, corresponding to nautical twilight. **Groups of 3 people are only required to complete Parts (a) and (b)**

Table 5: Sensor Characteristics

	Radar	Optical Telescope
Field of View (FOV)	10°x10°	4°x4°
Elevation Mask	5°	15°
Maximum Range	5000 km	N/A
Measurement Types	Range, Az, El (ρ, az, el)	Topo RA/DEC (α_T, δ_T)
Measurement Noise	$\sigma_\rho = 10$ m	$\sigma_{\alpha/\delta} = 1''$
	$\sigma_{az/el} = 0.1°$	
Day/Night Operation	Either	Night only (nautical twilight)
Weather Conditions	Any	Clear skies

(a) $\boxed{\text{5 points}}$ State which sensor you are using and provide a location, using geodetic latitude, longitude, and height. Justify your selection across all factors you deem relevant, e.g. considering the visibility of RSOs, measurement quality, operating limitations, light and radio noise pollution, weather conditions, atmospheric seeing, accessibility for power, data, and maintenance, etc. This justification may be qualitative or quantitative, derived from your own analysis or reference to literature or existing SSA sensor networks.

(b) $\boxed{\text{10 points}}$ During the 24 hour period beginning 2024-03-21 12:00:00 UTC, you are allowed to define 10 tasks for the sensor. Tasks which are well-defined to meet sensor constraints will be used to simulate measurements that you can use to refine the estimated RSO catalog and improve your conjunction analysis for Assignment 4. In the case that a task does not meet sensor constraints, measurements will not be provided for that task.

A task is defined by specifying the NORAD ID of the object, as well as the start time of the task. A task lasts a maximum of five minutes, and observations are made once every 10 seconds during the task. If the object is visible for less than five minutes, observations will be provided from the start time until it is no longer in view.

Develop a method to ensure the objects you schedule for observation will meet the defined constraints of your sensor. Provide a detailed description of this methodology in your report, including mathematical formulations and citation to literature as appropriate.

Provide a table summarizing your sensor tasks (NORAD ID and UTC start time) and justify your selection of objects and times. Supplemental to your report, provide a sensor tasking file in JSON format, using the code provided to generate the tasking file.

(c) $\boxed{\text{10 points}}$ [**Groups of 4 only**] Develop a sensor tasking strategy to search for objects not currently in the RSO catalog. Notionally, when the sensor is not tasked to observe specific objects as you define in Part (b), it would execute this search. It is not necessary to produce a sensor tasking file for search tasks, but the description should be at a sufficient level of detail to implement it, including figures, flowcharts, or other means of visualizing and describing the method. In particular, you should address the following information:

(i) Does the sensor maintain a fixed pointing direction (in inertial or topocentric coordinates) or does it scan through different pointing directions?

(ii) Define the pointing direction(s) in Az/El or RA/DEC, and the cadence at which they are scanned, if appropriate.

(iii) Justify your search strategy with reference to the provided RSO catalog, public catalogs such as the TLE database, and literature, with specific consideration of implications for the O/O asset.

(4) $\boxed{\textbf{10 points}}$ 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, bibliography, and sensor tasking file 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.
- The sensor tasking file must be provided in the format specified in Q3. **FAILURE TO COMPLY WITH THE TASKING FILE FORMAT DEFINITION MAY DELAY YOUR ABILITY TO START WORK ON ASSIGNMENT 4**.
- Hint: Ensure that the information you want to convey can be properly read from your plots.