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Empowering Satellite Operators with Advanced Visual Data Displays

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Abstract

The rapid expansion of satellite constellations and the increasingly crowded and dynamic space environment have significantly increased the complexity of flight dynamics operations. Traditional systems, which managed only a few satellites, are now insufficient for handling the vast amount of data and operational tasks required for modern satellite fleets. Human cognitive limitations, such as Hick's Law (decision time increases with the number of options and complexity) and Miller's Law (average human's working memory limit of 7-9 items), further complicate this scenario. This research aims to address these challenges through the development of innovative tools and methodologies. The approach involves simplifying data presentation using advanced 2D and 3D visualizations, which integrate external data such as cloud coverage and albedo, enhancing situational awareness and making complex information more accessible. Additionally, customizable dashboards with linked data displays, including 3D views, plots, and Gantt charts, allow operators to analyse various parameters of the satellite system in a coordinated manner, supporting exploratory data analysis and efficient decision-making. Aggregated data analytics facilitate the management of large satellite fleets by enabling the identification of outliers and the creation of actionable dashboards, significantly enhancing operational efficiency and reducing problem resolution time. The integration of these advanced visualization techniques, linked data displays, and aggregated data analytics, combined with automated operations, represents a significant advancement in managing and reducing the complexities of modern satellite constellations. These innovations address human cognitive limitations, enhance mission efficiency, and improve safety, setting a new standard in flight dynamics operations. This comprehensive approach ensures that operators can effectively manage the increasing demands of modern space missions, paving the way for more efficient and safer satellite operations.

Keywords: Constellations, Dashboard, Data

Nomenclature

This section is not numbered. A nomenclature section could be provided when there are mathematical symbols in your paper. Superscripts and subscripts must be listed separately. Nomenclature definitions should not appear again in the text.

Acronyms/Abbreviations

This section is not numbered. Define acronyms and abbreviations that are not standard in this section. Such acronyms and abbreviations that are unavoidable in the abstract must be defined at their first mention there. Ensure consistency of abbreviations throughout the article. Always use the full title followed by the acronym (abbreviation) to be used, e.g., reusable suborbital launch vehicle (RSLV), International Space Station (ISS).

1. Introduction

The space environment is becoming increasingly crowded and dynamic, with new possibilities such as large constellations not previously feasible leading to more complex flight dynamics operations. Traditional systems, which managed only a few satellites, allowed for detailed analysis per satellite. However, these systems are now insufficient for handling the data and operational tasks required for modern satellite fleets. Human cognitive limitations, such as Hick's Law and Miller's Law, further complicate this scenario. This paper discusses the need for innovative tools and methodologies to address these challenges.

2.1 The Challenge of Modern Satellite Fleets

Modern satellite fleets consist of numerous satellites, each generating large volumes of data to be processed. Managing these fleets requires sophisticated systems capable of handling complex operations and data analysis.

Traditional systems, designed for smaller fleets, are unable to cope with the increased demands, leading to inefficiencies and potential errors.

2.2 Human Cognitive Limitations

To align with human cognitive constraints—where decision-making speed decreases with increasing options and complexity, and working memory is limited —the design prioritizes complexity management, cognitive load reduction, and efficient operator interaction with operational insights. This section elaborates on the application of these principles to the proposed visualization approach, building upon its strategic foundation.

This flexible solution adapts to specific mission needs, increasing utility. Besides, the dashboard is part of a full application for Flight Dynamics ensuring seamless workflow and easy access to the automation and computation modules.

Hick's Law states that decision time increases logarithmically with the number of choices and their complexity, while Miller's Law posits that the average person can hold a limited number of items (7 ± 2) in working memory. These constraints can lead to decision fatigue, errors, or delays in a scenario involving real-time satellite monitoring, data management, and mission planning. Below, it is outlined how these considerations are addressed in the dashboard design, building on the previous scenario.

2.2.1 Impact of Cognitive Limitations in This Scenario

Satellite missions generate many —satellite positions, instrument statuses, tracking measurements, observation schedules, scientific outputs, etc... —while requiring operators to make rapid decisions, such as adjusting schedules or responding to anomalies. Without careful design:

- **Hick's Law**: Presenting too many options (e.g., multiple controls for each satellite or complex menus) could slow decision-making, critical during events like natural disasters needing immediate observation.
- **Miller's Law**: Displaying more than 7-9 ungrouped data points (e.g., statuses of 10+ satellites) risks overwhelming memory, leading to missed details or errors in prioritization.

These limitations complicate the dashboard's goal of providing comprehensive yet actionable insights, necessitating a design that minimizes cognitive load while maintaining functionality.

2.2.2 Design Strategies to Address Hick's Law

Hick's Law suggests that reducing the number and complexity of choices speeds up decision-making. In the dashboard context, this translates to simplifying interactions and prioritizing clarity:

1. **Minimize Visible Options and Reduce Visual Noise**:
   a. Limit the number of actions available at any given time. For example, instead of showing all possible satellite data, use a context-sensitive approach where only relevant options appear based on the selected satellites or task (e.g., "Schedule Observation" for an idle satellite).
   b. Use progressive disclosure: Hide advanced settings or less-used features in collapsible menus, dedicated views or secondary panels, revealing them only when needed. This reduces the initial decision set, limiting access to these more detailed views after an initial assessment. This requires that the initial view contains meaningful information about any potential issue that needs attention.
   c. Toolbars for interactive items such as Gantt charts or plots are hidden by default, being only activated when the user is actively working on that item. This is implemented that as the cursor is in the item area the toolbar is displayed allowing to selected actions such as zoom in-out, zoom mode, etc... This reduces the quantity of information displayed in the whole dashboard allowing the operators to focus on the data analysis and decision making.
2. **Prioritize Time-Sensitive Tasks**:
   a. Highlight critical actions with prominent placement or color (e.g., a red "Alert" display for anomalies), ensuring operators can act quickly without sifting through options. This aligns with Hick's emphasis on reducing decision time in high-stakes scenarios.
3. **Simplify Navigation**:
   a. Use a flat, intuitive menu structure rather than deep hierarchies. For example, a top-level navigation bar with "Satellites," "Data," and "Planning" avoids overwhelming users with nested submenus, keeping choices manageable.

2.2.3 Design Strategies to Address Miller's Law

Miller's Law highlights the working memory limit of 7 ± 2 items, requiring the dashboard to present information in digestible chunks to avoid overload:

1. **Chunk Information into Groups**:
   a. Group related data into clusters of limited items. For instance, instead of listing all satellite statuses individually in a constellation of 20, categorize them into orbit planes with each group showing up to 7 entries before expanding into a detailed view.
   b. On a map, cluster satellite icons by region or orbit plane, displaying summary stats (e.g., "5 satellites over Europe") rather than individual markers unless zoomed in.
2. **Use Summaries and Hierarchies**:
   a. Provide high-level summaries to reduce the number of items processed at once. A dashboard overview might show "Total Satellites: 15, Operational: 12, Issues: 3," allowing operators to grasp the mission status within memory limits before diving into details.
   b. Implement a drill-down approach: Some items like status lists provide a summary (e.g., "Issues: 3") for each element of higher hierarchy groups such as a satellite collocation group, while allowing to expand the group and then each satellite for more details. keeping initial cognitive load low but allowing detailed exploration of the data.
3. **Leverage Visual Cues**:
   a. Use icons, colors, or shapes to encode information, reducing reliance on text-based memory. For example, green circles for operational satellites and red triangles for failures allow quick recognition without counting or reading multiple labels. Also, symbols allow colorblind operators to assess the system status, improving accessibility.

1. **Intuitive Layout and Visual Hierarchy**:
   a. Arrange elements logically and in a consistent way (e.g., satellite status on the left, data visualization in the center, controls on the right) to match operator workflows, reducing the mental effort to locate information when switching contexts. Familiar patterns lower the learning curve and decision complexity.
   b. Emphasize important data with size, color, or position (e.g., bold alerts at the top), guiding attention without overwhelming the user with options or details. Always considering color contrast and variations to maximize the application accessibility.
2. **Feedback and Confirmation**:
   a. Provide immediate feedback for actions (e.g., "Observation Scheduled" popup) to confirm decisions, reducing uncertainty and the need to remember prior steps, aligning with memory limits.
   b. Avoid overloading with simultaneous notifications; queue or prioritize alerts (e.g., 5-7 at a time) to stay within Miller's range.
3. **Training and Familiarity**:
   a. Design with consistency (e.g., same icons across sections) to leverage long-term memory, bypassing working memory limits over time. Tooltips or a guided onboarding mode can initially simplify complex options, easing the transition for new users.

3. Solutions

3.1 Advanced Visualizations

We simplify data presentation using advanced 2D and 3D visualizations. These visual tools integrate external data such as cloud coverage, albedo, and other GIS information affecting satellite operations. This enhances situational awareness and makes complex information more accessible and understandable. For example, in an Earth observation mission, advanced visualizations help operators better understand imaging acquisition by displaying relevant data in an intuitive manner.

3.2 Customizable Dashboards

We implement customizable dashboards with linked data displays, such as 3D views, plots, and Gantt charts. These dashboards allow operators to analyse various parameters of the satellite system in a coordinated manner. This integration supports exploratory data analysis, helping operators understand the relationships between several factors and make informed decisions efficiently. For instance, in relocation missions, customizable dashboards enable operators to monitor and plan satellite movements effectively.

3.3 Aggregated Data Analytics

We use aggregated data to manage large satellite fleets effectively. Aggregation, dynamic cross-filtering, and selection of data facilitate the identification of outliers and the creation of actionable dashboards. These dashboards help operators quickly identify and address the root causes of issues, significantly enhancing operational efficiency and reducing the time required for problem resolution. By applying these tools together, operators gain a comprehensive view of the satellite constellation, improving control and situational awareness.

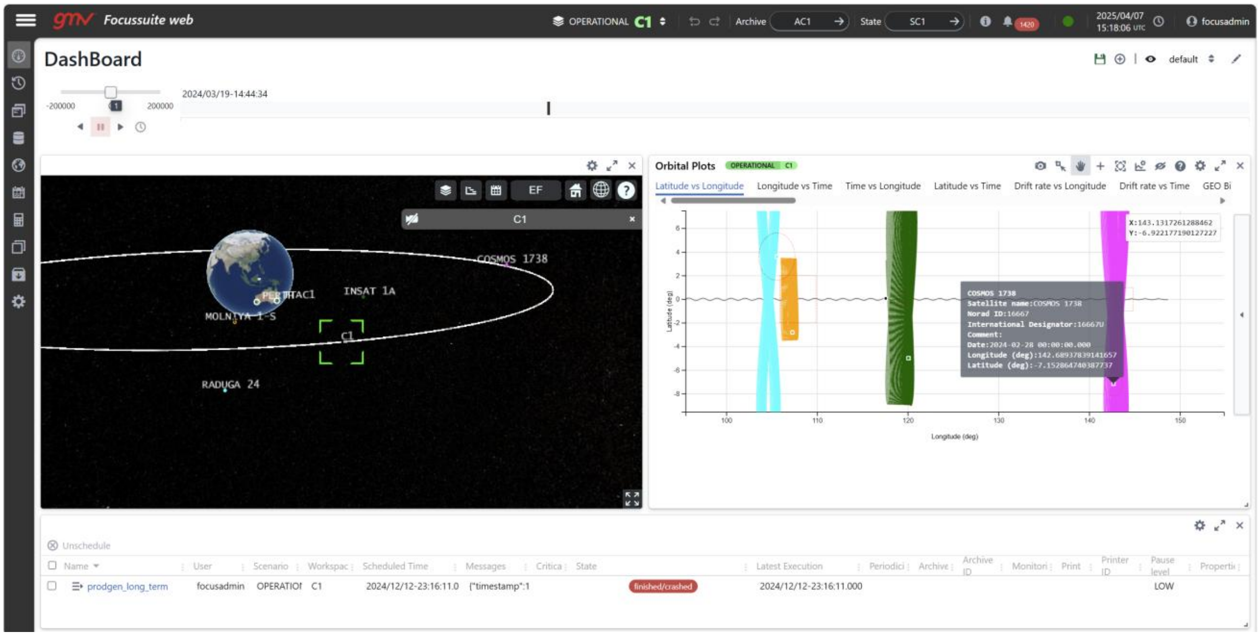

Fig. 1. ***Focussuite*** Dashboard

4. Uses cases

4.1 Earth Observation

Earth observation missions develop in a dynamic environment requiring clear, cohesive presentation to support operational situational awareness. This section describes an approach integrating advanced 2D and 3D visualizations, sensor views, and a Gantt chart into a customizable dashboard, allowing operators to combine views—such as a side-by-side display of sensor data with albedo and cloud data—for a unified analysis. Sensor views provide real-time instrument insights, while the Gantt chart highlights imaging opportunities, maneuvers and data links, streamlining planning and tracking. The primary objectives are to enhance situational awareness, simplify complex operational insights, and enable rapid, accurate decisions, such as imaging acquisition tasks. This method has proven effective in optimizing operator workflows within Earth observation missions.

The dashboard uses 2D and 3D visualizations not just for aesthetic appeal but as functional tools to convey complex operational data—satellite positions, imaging opportunities, and environmental factors—affecting Earth observation. This integration aims to make data accessible, but without cognitive considerations, it risks overwhelming operators with too many options or details, slowing decisions (Hick's Law) or exceeding memory capacity (Miller's Law). The goal is to refine this approach to optimize usability.

4.1.1 Simplifying Data Presentation

The dashboard combines 2D and 3D visualizations, sensor views, and a Gantt chart into a flexible interface where operators can arrange and integrate multiple data perspectives. A 2D map displays satellite positions and imaging targets with cloud coverage overlays, using color gradients (e.g., blue for clouds, green for clear zones) to indicate observation potential for each imaging opportunity which are also displayed on the map as colored polygons. A 3D model visualizes orbits and fields of view, defaulting to a basic path view with optional albedo or GIS layers. Sensor views present live instrument outputs—e.g., camera feeds or spectral data—while the Gantt chart shows imaging opportunities and data links (e.g., "Image Download: 10:00-10:15"). Operators can combine these elements, such as placing a sensor feed side to side with albedo and cloud data, to directly compare imaging conditions.

Rather than presenting an extensive array of over 10 data overlays, the interface preselects critical layers (e.g., cloud coverage for imaging) by default, relegating additional options to a collapsible menu.

4.1.2 Enhancing Situational Awareness

Weather forecast data is provided by a dedicated backend service using updated data which is fed into the dashboard in real-time. The source of the data can be varied from open datasets to paid services with better resolutions depending on the requirements of the mission. Also, other customized GIS data can be displayed on the map for a more tailored assessment.

By integrating external data, sensor outputs, and scheduling into combinable views, the dashboard provides a comprehensive, real-time operational perspective. Cloud coverage on the 2D map reflects weather impacts, while the 3D view incorporates albedo to show image quality variations. Sensor views display current instrument outputs (e.g., a camera’s live frame), and the Gantt chart lists imaging opportunities (e.g., "Clear Pass: 09:30-09:45") with data links (e.g., "Ground Station Link: 10:00"). Operators can configure side-by-side views—e.g., a sensor feed next to albedo and cloud overlays—enabling direct assessment of how environmental factors affect imaging. Interactive controls—such as "Zoom" in 3D, "Switch Feed" in sensor views, or "Expand" in the Gantt chart—are embedded across views, with summary stats (e.g., "Clear Targets: 5, Sensors Active: 3") offering a quick mission snapshot.

The Gantt chart’s clear display of imaging opportunities and data links, combined with other views, ensures planning and tracking remain intuitive and efficient. The interface aligns with operator workflows through a customizable, logical layout.

4.2 Satellite relocation

Satellite operations in geostationary orbits require flexible interfaces that adapt to diverse operational demands while providing coordinated insights into system dynamics. This section presents an approach using customizable dashboards with linked data displays—comprising 3D views, plots, and Gantt charts—to facilitate exploratory data analysis and efficient decision-making. The primary objectives are to enable operators to analyze relationships between satellite parameters, such as orbit, health, and scheduling, and to streamline monitoring and planning tasks, particularly for relocation missions.

4.2.1 Enabling Customizable Dashboards

To support varied operator needs, the dashboard provides a modular, user-configurable interface. Operators can arrange panels—e.g., a 3D orbit view, a plot of system metrics, or a Gantt chart for scheduling—through a drag-and-drop system tailored to specific workflows.

One of the options available is to align all the items in the dashboard view with a common timeline control. This integration allows to evaluate the evolution of the relocation parameters along the time.

Although the modularity of the systems allows the operator to add and remove the items in the dashboard view, there are some core elements for the relocation. The following elements were considered important to integrate in the view and synchronize to have a clear assessment of the relocation process:

- 3D view of the orbit with all the involved satellites and ground stations displayed. This view is also used to show the links between satellite and ground stations. The view can switch into a 2D mode.
- 2D latitude – longitude plot showing in a clear way the relocation path alongside all the satellites present during the process. Some satellites can display their collocation boxes to have an easy assessment of potential incursions and interferences during the evolution of the relocation.
- Azimuth Elevation plots display the visibility of the satellite from the selected stations relevant to the relocation, where the satellite position is marked for the given time as a highlighted point in the plotted orbit segment. For each satellite RF hinder boxes are also displayed in real-time in order to foresee any interference between satellites.
- Gantt chart displaying in a synchronized manner the relevant events associated with the relocation such as maneuvers, eclipses, etc...
- Events Feed: show the active elements at a given time, giving more details about them

4.2.2 Application to Relocation Missions

For relocation missions, the dashboard supports both monitoring and planning activities. During monitoring, a 3D view shows current satellite positions alongside a plot of fuel levels and a Gantt chart tracking relocation progress, providing a real-time operational overview. For planning, operators can adjust a Gantt chart timeline, with the 3D view updating to preview the new orbit and the plot reflecting fuel consumption, ensuring coordinated modifications. Analysis is facilitated by filtering the 3D view for satellites requiring relocation, assessing their health in plots, and refining schedules in the Gantt chart, integrating spatial, system, and temporal data into a cohesive workflow.

4.3 Constellations

Managing large satellite fleets in Earth observation missions demands tools that simplify oversight of large quantity of data elements while enabling rapid identification and resolution of operational issues. This section outlines an approach integrating aggregated data, dynamic cross-filtering, and data exploration within a dashboard framework to enhance operational efficiency and situational awareness. Applied to constellations with potentially hundreds or thousands of satellites, these tools enable the monitoring and planning of satellite operations by providing operators with clear, actionable insights. The primary objectives are to streamline fleet management, reduce problem resolution time, and ensure operator-friendly control over complex systems.

4.3.1 Aggregated Data for Simplified Oversight

To manage large fleets effectively, aggregated data is employed to distil complex satellite information into concise, high-level summaries. The dashboard can present metrics such as the number of operational, malfunctioning, or offline satellites (e.g., "Operational: 45, Issues: 5, Offline: 2") as a primary interface element in the form of cards. Satellites are grouped by operational parameters—such as orbit plane —to provide a snapshot without requiring operators to process individual data points. These aggregates update in real time, reflecting the constellation's current state and enabling rapid assessment of fleet-wide conditions.

Some Elements of the dashboard are designed to provide aggregate data while allowing a more detailed exploration. One of such elements are groupable tables that show for each group an overview of warning and errors. This reduced and clear information display allows operator to easily and quickly identify problems in any of the groups without the need to review each satellite which could be infeasible when operating hundreds of satellites. But identifying problems in a group is not enough to make a proper assessment so the operator has the capability to easily expand the group information to explore and identify the underlying causes in a focused manner. Issues are prioritized by severity (e.g., "Critical: 2, Warning: 3"), ensuring urgent problems are identified easily and receive prompt attention, optimizing response times across the fleet.

Alongside the groupable tables, other elements such as the Gantt chart also implement this mechanism to reduce the necessary cognitive load of the operator but allowing data to be explored and assessed with detail. Groups can be hierarchical for example satellite groups, then grouped satellite events.

4.3.2 Dynamic Cross-Filtering for Relational Analysis

Dynamic cross-filtering enhances exploratory analysis by linking dashboard components, allowing operators to isolate specific subsets of the fleet based on multiple parameters. For instance, selecting a specific group of satellites from a status summary filters a geospatial map to display only affected satellites' locations while simultaneously updating a trend chart to show their orbit parameters over time. Operators can apply compound filters—e.g., "Offline" and "Polar Orbit"—to narrow the view across all displays, with a single-click reset option restoring the full fleet perspective. This interconnected filtering mechanism ensures swift identification of relationships between operational factors.

For more insight and in order to keep the data displayed within a limited set of items operators can navigate by clicking on some elements into dedicated dashboard views with more dedicated insights about the selected item, e.g. by click on a card that shows a warning about a satellite manoeuvre the operator will be displayed a view focused on the manoeuvre and orbit parameters related to that satellite in order to allow a more focused review and situational awareness.

These features allow the constellation operators to have a clear yet simple overview of the system while having the capability to investigate deeper details without an overwhelming quantity of data that might lead to analysis paralysis. Moving to more focused data in an exploratory process allows proper analysis of the situation and provides the operator the required understanding of the system to act accordingly.

6. Conclusions

The integration of advanced visualization techniques, linked data displays, and aggregated data analytics, combined with automated operations, represents a significant advancement in managing and reducing the complexities of modern satellite operations. These innovations address human cognitive limitations, enhance mission efficiency, and improve safety. Our comprehensive approach ensures that operators can effectively manage the increasing demands of modern space missions, paving the way for more efficient and safer satellite operations.