

I’LL HAVE THE PORTER: INTERACTIVELY VISUALIZING THE RESULTS OF STATISTICAL MANEUVER ANALYSIS

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Mission design and navigation relies on statistical maneuver analysis and Monte Carlo simulations when evaluating candidate mission trajectories. Engineers must analyze large quantities of data to optimize mission safety and propellant margins, but currently rely on static text files and dense PDF slide decks to review simulation results. This approach is time-intensive, non-interactive, and difficult to share or coordinate with other mission designers. To improve this process, we present Porter: a web-based interactive mission analysis tool. This work describes Porter’s user-centered design process, its processing pipeline for importing and processing LAMBIC simulation data, core interactive features, and preliminary user feedback.

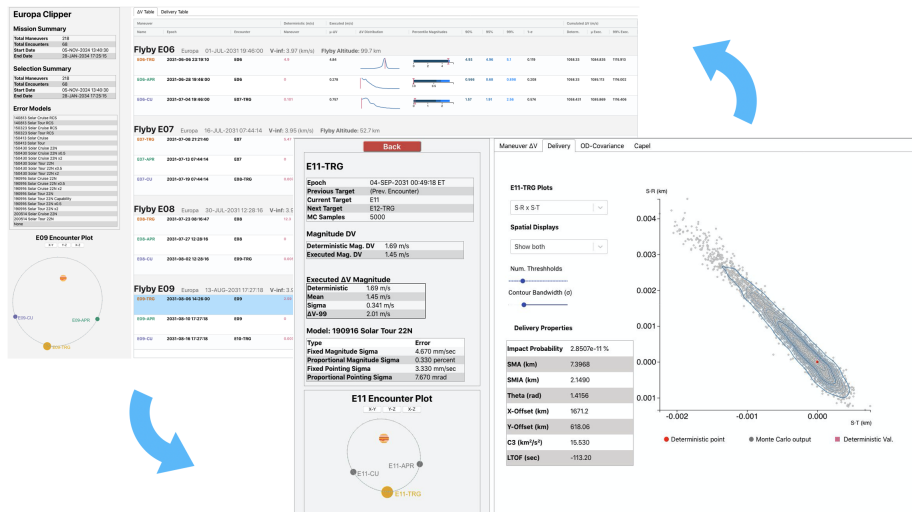


Figure 1. Porter supports analysts to interactively load and review Monte Carlo aggregate statistics (background) and maneuver-specific detail data (foreground).

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INTRODUCTION

Statistical maneuver analysis is essential to the overall mission design and navigation process. Deterministic maneuvers are placed by mission designers to build a reference trajectory. However, execution errors, uncertainties in celestial ephemerides and the spacecraft state, as well as orbit determination errors all warrant the need for statistical maneuvers along the trajectory. Their placement and magnitudes are critical to the trajectory itself and subsequent mission requirements and so extensive analysis is conducted to optimally place these maneuvers. A Monte Carlo simulation of maneuver executions and their subsequent delivery and ΔV statistics are beneficial to evaluate the required propellant for the mission and trajectory sensitivity. These simulations generate large sets of data which can be difficult to navigate without an intuitive interface to assist analysts in uncovering important trends. In this paper we outline the development and discuss the core features of Porter, a software tool designed to make accessing and interpreting Monte Carlo based maneuver simulation data more visual, convenient, and informative.

Porter supplements existing analysis strategies with interactive visualization techniques to make reviewing simulation data familiar and productive for maneuver designers. Researching existing analysis practices showed that users were often cognitively burdened by the large sets of data created from the Monte Carlo simulations. Some trajectories, like those used for tour missions, can have hundreds of maneuvers making their data sets very difficult to study. This leads to a greater dependence on aggregate statistics, which can give an incomplete assessment of the underlying sample distribution.¹ Porter aims to unify the high level maneuver analysis needs regardless of the flight project by displaying additional data that is commonly accessed when reviewing simulation data.

In this paper, we will discuss existing pain points in assessing large Monte Carlo data sets for maneuver simulations, the extended functionality goals for an interface, how the Porter interface addresses these goals through its design, and how it was received in initial user testing feedback interviews from members of the Mission Design and Navigation (MDNav) section at NASA Jet Propulsion Laboratory (JPL). Porter is designed to be a mission-agnostic visual interface tool and compatible with multiple flight projects, allowing users to intuitively explore Monte Carlo generated maneuver simulation results and subsequent related data.

BACKGROUND ON MANEUVER ANALYSIS

After designing a baseline trajectory and its corresponding deterministic maneuvers, analysts must assess trajectory robustness toward various error sources, including dynamical mismodeling to maneuver execution and orbit determination errors. Statistical maneuvers are commonly introduced to the trajectory at key points in order to provide options for flight path control and error correction. Finding the most suitable locations for such maneuvers is an integral aspect of trajectory planning wherein designers must balance propellant consumption, tracking schedules, analysis turn-around time, and other operational considerations. Maneuver and navigation plans are validated through the use of Monte Carlo analysis simulating a variety of error sources and outputting large quantities of data. JPL maneuver design teams use the Linear Analysis of Maneuvers with Bounds and Inequality Constraints (LAMBIC) package to perform these Monte Carlo analysis tasks which is interfaced through Mission Analysis, Operations, and Navigation Toolkit Environment (Monte). Execution errors injected into the Monte Carlo simulation are determined based off the Gates model. In this section, we summarize the LAMBIC tool set, current visualization techniques of simulation data, and the flight project datasets that were employed in testing Porter to ensure compatibility.

Monte

Monte is widely utilized at JPL's Mission Design and Navigation section and is routinely updated. This object oriented Python-based library is capable of robust force modeling, numerical integration, mission analysis tasks, and supports optimization routines for their data input and output (IO). Generated data objects can be saved in the proprietary Binary Object Archive (BOA) file type with some examples including: ephemeris files, spacecraft geometry, frame definitions, and any Monte object.² A convenience with using Monte is its ability to import multiple BOA files into memory, thus negating the need to open and close files when writing analysis scripts. The scripting layer of Monte enables users to include Monte library functions into Python scripts (which are saved as .mpy Monte Python files). The toolkit currently contains methods for accessing LAMBIC data in output BOA files, thus making it a convenient platform to develop Porter's processing functions from. MDNav users at JPL are familiar with Monte making Porter easily expandable and maintainable.

LAMBIC

LAMBIC is used for the Monte Carlo analysis of maneuver executions and their subsequent delivery properties. It operates by linearizing the dynamics relative to a baseline trajectory then propagating samples across the mission timeline using the state transition matrix.³ Each maneuver is designed with a specific aimpoint, or target. This varies from a spherical coordinate set, Cartesian position or velocity states, B-plane targeting, or a custom defined frame and epoch. Maneuvers can act in chains to reduce the total ΔV across the set to an aimpoint. Errors are introduced based on state uncertainty, orbit determination knowledge, and maneuver execution while corrective maneuvers are computed and propagated forward to simulate potential end-to-end missions.⁴ Outputs range from propellant consumption to targeting errors for tens of thousands to millions of sample trajectories. By default, this multitude of individual samples is summarized and reported out as text files representing a few key statistics, for example: ΔV_{99} (the 99th percentile of ΔV required) and impact probabilities for close approaches with celestial bodies. Covariance matrices, means, and Gaussian assumed standard deviation error ellipse properties are generated and reported in the resulting text files.

Gates Model

The Gates model is used when running LAMBIC to apply maneuver execution errors. It consists of four sets of independent errors: fixed and proportional errors for the ΔV magnitude and direction. Directional errors are generated uniformly and all errors are Gaussian.^{4,5} Each maneuver in the LAMBIC simulation can have its own Gates model properties which are defined in an input Monte object. For example, the execution error properties can vary for different engines and at different phases of the mission. Accordingly, having access to the Gates model inputs when analyzing output data from LAMBIC is beneficial to give further context to the execution errors and subsequent deliveries in the results.

The B-plane for Delivery Visualization

For hyperbolic trajectories, propagated samples are commonly mapped to the B-plane (Body Plane).⁶ This in itself is a visualization technique that maneuver analysts employ by the use of a dispersion ellipse, assuming a Gaussian distribution for the LAMBIC outputs. Figure 2 is an example of a hyperbolic reference trajectory and its associated B-plane, which shows position relative to the flyby body. Trajectory errors, which are propagated Monte Carlo samples can be characterized

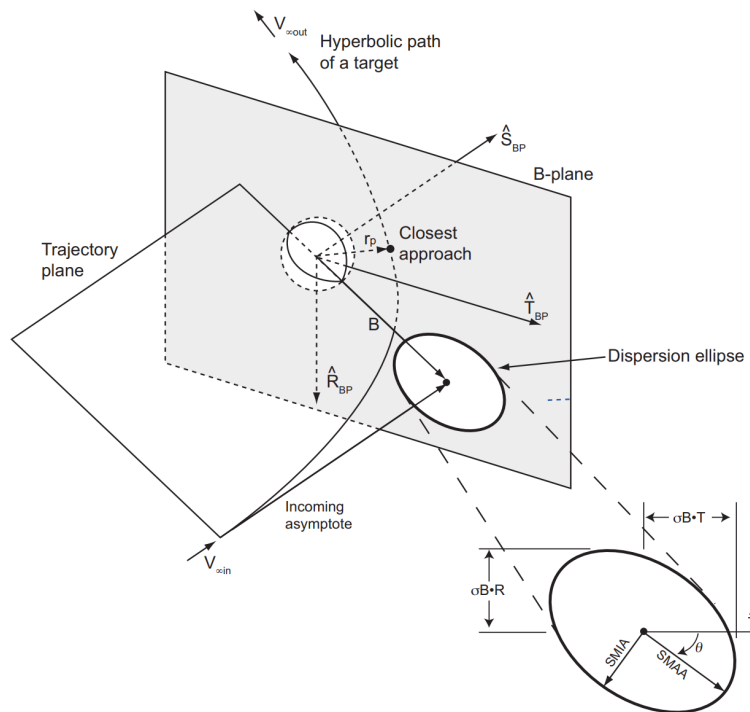


Figure 2. The B-plane with a delivery dispersion ellipse.⁷ Assuming a Gaussian distribution of the Monte Carlo samples, a standard deviation (σ) ellipses can be generated. The \hat{B} is the reference B-plane vector.

by a standard deviation (σ) dispersion ellipse as show in the figure. The SMAA is the semi-major axis, the SMIA is the semi-minor axis, and the ellipse is rotated about θ which is the orientation measured clockwise from the \hat{T} axis of the B-plane. Each sample has a slightly different state compared to the reference so the linearized flight time (LTOF), or rectilinear time-to-go to the center of the body, is also used to characterize these differences with respect to the reference LTOF. Alternatively, a distribution plot of $S \cdot R \times S \cdot T$ can be used to visualize the out of plane components with respect to the reference flyby B-plane. The capture and impact radii can also be represented in the B-plane giving the size of the dispersion ellipses and probability of impact statistics further context. For mid-course maneuver dispersion ellipses that target the same encounter body, the progression in the delivery can be investigated to meet navigational requirements in this visualization. It is important to note that the close approach radius and the B-plane vector, as seen in the figure, do not coincide. This would only be the case if the gravity of the body were removed.

CAPEL Plot Visual

For a hyperbolic reference trajectory, the Capability Ellipse (CAPEL) analysis yields insight into optimal maneuver placement. CAPEL is a method to evaluate how the resulting variations of miss parameters, or gradients, change as a function of a unitary ΔV applied at any time along the approach hyperbola.⁸ This is created by a sphere of new velocity states at some time preceding the flyby, and the resulting variations in the flyby target miss parameters, such as \vec{B} and the LTOF, can be calculated.⁸ Studying these gradients uncovers trends in the sensitivity of the trajectory, thus yielding optimal locations for maneuver placement. Figure 3 is an example CAPEL plot of the $B \cdot R$ and $B \cdot T$ gradients for the flyby named "E12". Placing a maneuver shortly before the

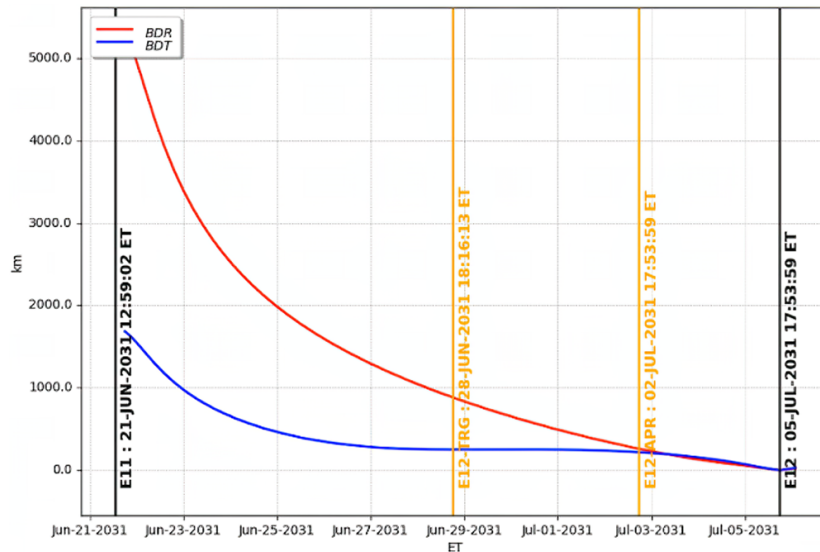


Figure 3. Example of a CAPEL plot showing the $B \cdot R$ and $B \cdot T$ gradients as a function of time till the next flyby (E12). Maneuvers are shown as yellow lines in the plot and flyby encounters are black.

flyby yields the smallest change in the B-plane gradient and therefore can be used for slight aimpoint corrections. Variations in the LTOF, ellipse geometry, and B-plane gradients are commonly assessed when determining optimal maneuver locations.

Mission Datasets

At JPL, LAMBIC is utilized for numerous flight projects. Through Porter's development, we routinely tested mission datasets from Europa Clipper, Juno, and Double Asteroid Redirection Test (DART). Each mission contains unique results, uses varying sets of input parameters, and can help gauge the multi-flight project capability of Porter. However, we primarily focused our testing on different simulations for Europa Clipper as it is a lengthy mission incorporating: an interplanetary and tour⁹ portion using several Gates models, different targeting strategies like a Cartesian state or B-plane parameters, different optimization strategies for chains of maneuvers, and a large quantity of maneuvers. The spacecraft is modeled in LAMBIC with a main engine and a reaction control system both having different Gates model properties in the interplanetary segment as well as during the tour.⁴ Including a Jovian orbital insertion and subsequent high ΔV maneuvers (on the order of several hundred m/s) along with tour course corrections (often less than 1 m/s) can help to stress the visual design and ensure the interface is capable of displaying a wide variety of maneuver data without losing details or the sense of scale. Europa Clipper's tour portion follows maneuver placement strategies employed during the Cassini mission¹⁰ which include resonant orbits with respect to the Jovian moons and a set of deterministic and statistical maneuvers per flyby encounter.⁴ Figure 4 illustrates the maneuver sequence applied to Europa Clipper's tour. Near apojove, a deterministic trajectory shaping maneuver (TRG) targeting the next flyby's aimpoint B-plane $B \cdot R$, $B \cdot T$, and LTOF values is conducted. If required, one or two statistical approach maneuvers (APR) refine the course several days prior to the flyby with the same aimpoint. Post-flyby, a cleanup maneuver (CU) is performed targeting the Cartesian state, either position or velocity, of the next TRG maneuver.⁴ Backup maneuver opportunities are available between these locations, however were not modeled

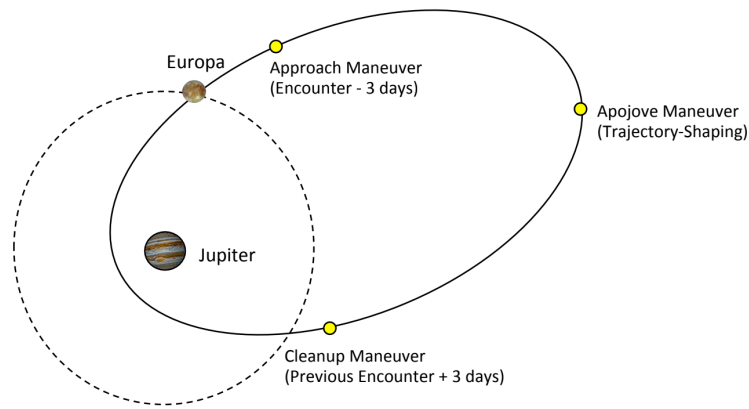


Figure 4. Europa Clipper’s tour maneuver strategy.⁴ The shaping, approach, and cleanup maneuver strategy is used for flybys of the Galilean moons.

simultaneously in the LAMBIC simulation.

MOTIVATION FOR PORTER

When prototyping maneuvers for a trajectory using LAMBIC, maneuver designers rely heavily on aggregate statistics to evaluate the feasibility of candidate trajectories. At this step, simulation outliers or inconsistencies can indicate problematic maneuvers or flybys, and should quickly be identified. For example, analysts search for maneuvers that grow too large in ΔV_{99} or significantly deviate from aimpoint and present too high of an impact risk. When discovered, designers seek an appropriate remedy, such as increased tracking, changing maneuver timing, or adding additional burns. However, finding outliers can be difficult when analyzing large, static data sets. Identifying the best corrective action usually requires both expert intuition as well as trial and error.

Access to the aggregate LAMBIC output data is currently accomplished by using Monte’s BOA Dump feature which exports results to dense text tables. These text files contains various result data: 99th percentile ΔV (ΔV_{99}), the B-Plane delivery 1- σ ellipse geometry, the Cartesian or Spherical means for the delivery, covariance matrices, and other generated statistics. For simulations involving many maneuvers, these text files can be several thousand lines long, making even high-level analysis quite difficult. Once this is completed, designers closely review individual result sets in the aggregate statistics text file. Means and standard deviations can inform how well data distributions fit the Gaussian assumption, but can obscure more fine-grained distribution characteristics¹ that is essential for evaluating true trajectory robustness. Consequently, mission analysts create their own tools for reviewing and sharing simulation results, and commonly include custom Monte scripts to generate static plots of sample data. In maneuver strategy meetings, several-hundred page slide decks containing static images of distributions and dense result tables are shared with other analysts. This current analytic workflow is slow, cumbersome to review, and inefficient from having to source data from different locations.

Porter addresses these shortcomings by providing a conversion layer between the raw simulation output and mission analysts’ exploratory data analysis workflows, and incorporates these common exploratory analysis tasks within an interactive web-based tool. We improve the visualization and data presentation techniques related to maneuver design by creating a multi-flight project friendly interface that groups commonly accessed data and reduces the cognitive burden for reviewing Monte

Carlo samples. This allows for a more streamlined analysis process, and simplified sharing with other analysts. Porter's interactive environment also supplements analyst's capabilities with additional Monte visual analysis prototypes¹¹ and further supports maneuver designers to more conveniently and effectively work with Monte LAMBIC output and supplemental data. The following sections describe how Porter processes and organizes LAMBIC simulation data for interactive analysis.

PORTER CONSTRUCTION

The Porter environment consists of a Python back-end to convert Monte LAMBIC simulation output to a generalized format, an Express.js API for hosting content, and a React.js front-end to load and explore mission data. Porter is designed from the bottom-up to be used with multiple flight projects and simulations, as well as automatically handling all native LAMBIC data types and result sets. The following sections outline how Porter processes and organizes LAMBIC output files into a JSON format, serves this data through an API, and supports browser-based visual review and analysis.

Processing Monte Data

Figure 5 shows the flow of data from post-simulation LAMBIC results to the inputs for the Porter server API and React.js interface. Tracing the flow of data, a completed LAMBIC simulation yields an outputs directory folder containing specifically formatted BOAs and a Python pickle (.pkl) results overview file. The results pickle file compiles the aggregate statistics into accessible Monte objects making it a useful file for data extraction. There are several BOAs that store the Monte Carlo samples for the maneuvers including: pre and post maneuver execution offsets at the target as well as the ΔV information. In addition to the LAMBIC outputs, this processing step also integrates several supplemental files to generate the necessary output data contents. Ephemeris BOA or SPICE BSP files are necessary for Porter's trajectory visualization. Each flight project has a lockfile BOA that defines constants, frames, and other essential information.¹¹ This lockfile is a required input if the flight project does not import Monte's default frame definitions and constants. This workflow also illustrates a standalone bulk processing script that additionally writes the converted JSON files to multiple sheets in a Microsoft Excel file, plus PNG image files for individual maneuver delivery and CAPEL plot figures. This functionality was added in response to user requests for standalone bulk processing and data exports, and currently exists separately from Porter's front-end interface.

Porter's data processing script is called via a terminal window, but it can be cumbersome to have to define input file paths and settings in a user entered command. Therefore, a wrapper script named "porterstart.mpy" is included that is able to read a configuration JSON file containing the LAMBIC outputs directory, ephemeris files, and lockfile locations. Users can set custom analysis start and stop periods, toggle flags, and define certain output parameters like the trajectory visual frame and center body in this file as well. The JSON's key names are defined in the Porter users' manual enabling the user to set specific conditions for their analysis as well as specify where the required BOA and pickle files are located. For example, if the user is only interested in the tour portion of the entire trajectory, they can add in a start and end date key/value pair into the JSON defined by the manual. Other key/value pairs for the configuration JSON include: solar conjunction assessment angles, defining a custom frame and center body, step sizes, and more. The Porter Processing scripts are designed to copy the required inputs to a temporary directory located in the Porter directory for data extraction. This ensures operation both server-side or locally and that any modifications do not

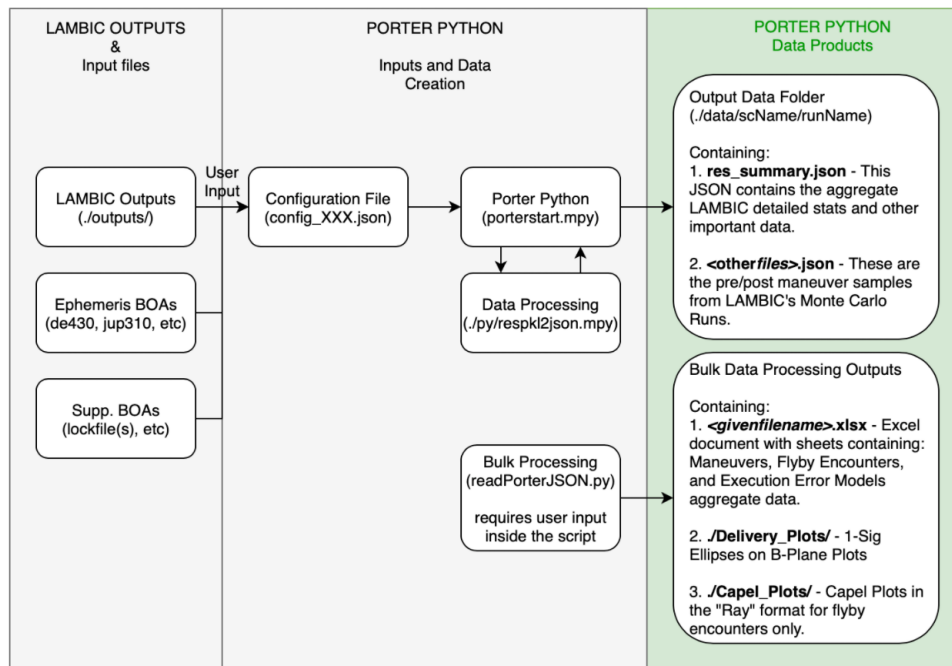


Figure 5. Flow of data inputs and products for Porter Processing data extraction scripts.

affect the main flight project files.

Due to the customizable nature of LAMBIC and different uses for flight projects, varying sets of results can be present in the outputs. This led to the creation of the "respkl2json.mpy" script, containing a comprehensive set of Python functions from the Monte library, that search for required results and handle cases where certain data is not found. The script receives the user settings from the wrapper and unpacks the BOA and results pickle file into memory. It uses the settings to call sub-functions designed to handle specific result sets per maneuver or encounter, with error checking and handling along the way. If the process is unable to find results or encounters an error, the user is alerted in the terminal window with the exact point of failure for diagnosis. The completed output from the script is passed back to the wrapper to be exported to a master results summary JSON and additional JSONs containing the individual Monte Carlo samples and CAPEL points. Output products are formatted specifically to be read by the React.js front-end for to be displayed. Figure 6 details the outermost level of keys and some sub-keys present in a Europa Clipper results summary JSON. At the top of the JSON header information is provided such as the spacecraft name, number of samples used per maneuver, discarded samples, and the number of maneuvers. A list of all the maneuver names are also included along with the various Gates execution error models defined in the simulation. The "State Data" key contains the trajectory from the defined start/end date pairs in the step size. Note that if users do not specify this information, Porter will automatically find the analysis start and end dates and use a default step size. The "Maneuvers" key makes up the bulk of the JSON as it includes all the aggregate data blocks for each maneuver shown in the "Included Blocks". Monte Carlo samples are not included in this file, but a sub-key/value pair exists within this section that points to the separate JSON file. The same concept is applied for the CAPEL data in the "Encounters" section, and additional flyby information is also provided there.

Simulation outputs can quickly grow to several hundred or hundreds of megabytes for longer

missions. To avoid transferring and storing the entire mission in memory, we divide the converted JSON output data into smaller files that can be requested as needed. This helps reduce overhead and improves interface responsiveness. Porter’s back-end includes an application programming interface (API) that allows analysts to dynamically load mission data through the Porter interface. In its prototype state, the Porter API is a locally-hosted server that organizes simulation data by mission name, simulation name, and maneuver.

For example, an analyst working on Simulation-Output-1 from the Europa-Clipper mission can access all data related to the E11-TRG maneuver at the <PorterServerAddress>/data/Europa-Clipper/Simulation-Output-1/E11-TRG API endpoint. The Porter interface utilizes this API format to request specific data on-demand to reduce browser memory loads during use.

```
./data/Europa_Clipper/20fb20/res_summary.json
{
  "Body": "Europa Clipper",
  "Number of Samples": 5000,
  "Number of Discarded Samples": 0,
  "Number of Random Seeds": 8435,
  "Number of Total Burns": 218,
  "Number of Included Burns": 218,
  "Included Burn Names" : [...],
  "Execution Error Models" : [...],
  "Output Units" : [...],
  "State Data" : [
    "Solar Conjunctions" : {...},
    "Traj States" : {...}],
  "Maneuvers" : [...],
  "Encounters" : [...],
  "Included Blocks" : [
    "Info",
    "Impact Probability",
    "Design Aimpoint",
    "Delivery",
    "Next-Encounter Design Aimpoint",
    "Next-Encounter Delivery",
    "Next-Encounter Miss",
    "Miss",
    "Commanded Delta-v Magnitude",
    "Commanded Delta-v (Spherical)",
    "Commanded Delta-v",
    "Executed Delta-v Magnitude",
    "Executed Delta-v (Spherical)",
    "Executed Delta-v",
    "Execution Error Magnitude",
    "Execution Error (Spherical)",
    "Execution Error",
    "OD Covariance"]
}
```

Figure 6. Key structure in the primary results summary JSON file. This example is specific to a Europa Clipper test case, but the keys will be identical for other flight projects.

Designing Porter

We designed Porter’s interface in close collaboration with JPL maneuver analysts and trajectory engineers to assist their simulation analysis workflows. Using methods informed by user-centered design,¹² participatory design,¹³ and presumptive design,¹⁴ we conducted various user interviews, design critiques, and a creativity workshop¹⁵ to help characterize analysis workflows and validate candidate designs for the Porter interface. We translated these qualitative outcomes into an organi-



Figure 7. Workshop participants collaboratively define, group, and rank design criteria.

zational design that groups commonly accessed data and supplements analysts' existing techniques to leverage their experience and familiarity. The following sections describe these activities, their results, and how it has informed Porter's design and organization.

Creativity Workshop Creativity workshops are an adaptation of creative problem-solving and software requirements workshops, and used as a part of visualization design research. These workshops accelerate problem characterization and task analysis by engaging participants with brainstorming and analysis activities to help us more quickly generate a wide-range of design goals, compared to other research methods.^{15,16}

We conducted a 2-hour creativity workshop with 12 JPL MDNav engineers, including orbit determination specialists, trajectory analysts, and maneuver designers. We conducted this workshop early in Porter's design cycle to elicit people's simulation analysis priorities and pain points during their day-to-day tasks. These data were captured on sticky notes and discussed with the group to establish a shared understanding of individual goals and meanings (Figure 7). Afterwards, all participants collaboratively grouped these goals into core workshop themes and ranked them by selecting their top three thematic priorities (Table 1).

The resulting theme categories reflect a diverse range of analytic goals from the workshop group. Follow-on discussion reminded everyone of the workshop's overarching visualization- and design-focus, and led participants to collectively prioritize more interactive and exploratory workflows. The numerical and computational themes at the bottom of Table 1 remain important aspects of their work, but are outside the scope of work for this design project.

The results of this exercise emphasized the need for simplified data review sharing tools. Workshop discussions also surfaced three engineering workflows within this top-voted theme: (1) Interactively exploring high-level summary statistics, (2) drilling-down to visualize Monte Carlo simulation data, and (3) comparing different simulation outputs between various simulation conditions. The available data and design timeline led us to focus on the first two workflows, leaving between-

Table 1. Creativity workshop themes. Design priorities ordered by participant votes.

Workshop Theme	Theme Description	Votes
Accessing and sharing data	Reduce effort to find, process, and share simulation output	8
Delta-V minimization	Understand and compare ΔV_{99} totals and distributions	7
Maneuver placement	Optimize statistical maneuver placement to improve delivery, reduce ΔV	7
Sensitivity studies	Review parameter variation, distribution over a simulation	6
Probability of impact	Review and reduce the probability of impact	4
Numerical sensitivity	Access LAMBIC’s convergence properties	3
Computational time	Improve underlying algorithms’ performance and runtime	0
Reference trajectory design	Design, revise spacecraft trajectories	0
Ops. Analysis	Ability to reoptimize parts of the LAMBIC simulation given operational O.D. data	0
Non-linear solvers	Create improved algorithms to deal with non-linear trajectory characteristics	0

simulation comparisons for future work.

Sketching and iterating Porter’s interface design proceeded remotely due to the COVID-19 pandemic. Authors created numerous digital mock-ups and shared these high-fidelity prototypes through online whiteboard and collaborative design websites, including MURAL* and inversion†. These tools helped maintain the participatory design process by enabling us to collect feedback on candidate designs while people worked from home.

Building on themes and workflows discussed during the creativity workshop, we used existing analyst charts and tables as inspiration for our organizational layouts. Starting with familiar workflows would help to both reduce end-user confusion and improve buy-in with any revised designs. As we unpacked LAMBIC simulation data, frequent meetings with authors and analysts helped establish the most relevant variables to include for reviewing both high-level statistical data and low-level Monte Carlo distributions.

Informed by user interviews and creativity workshop feedback, we used analysts’ predominant workflows to group commonly accessed data into overview- and detail-level views to provide a visual summary for ΔV and Delivery data (Figure 8). This approach prioritizes showing analysts mission summary data to more quickly determine whether a simulated trajectory meets engineering criteria. Incorporating previously distributed data into a centralized interface lets analysts to more conveniently perform their exploratory analysis tasks. Adding visual styling and supplementing previously static tables with interactive, analytic filters further improve maneuver evaluation and assist in discovering outliers.

Porter Interface: Interactive Visual Elements

The Porter interface organizes data according to the “overview first, details on demand” visualization mantra.¹⁷ When loading data, Porter presents a mission-wide summary to the analyst. This goal of this view is to help facilitate an interactive and holistic visual review of LAMBIC’s

*www.mural.co

†www.invisionapp.com

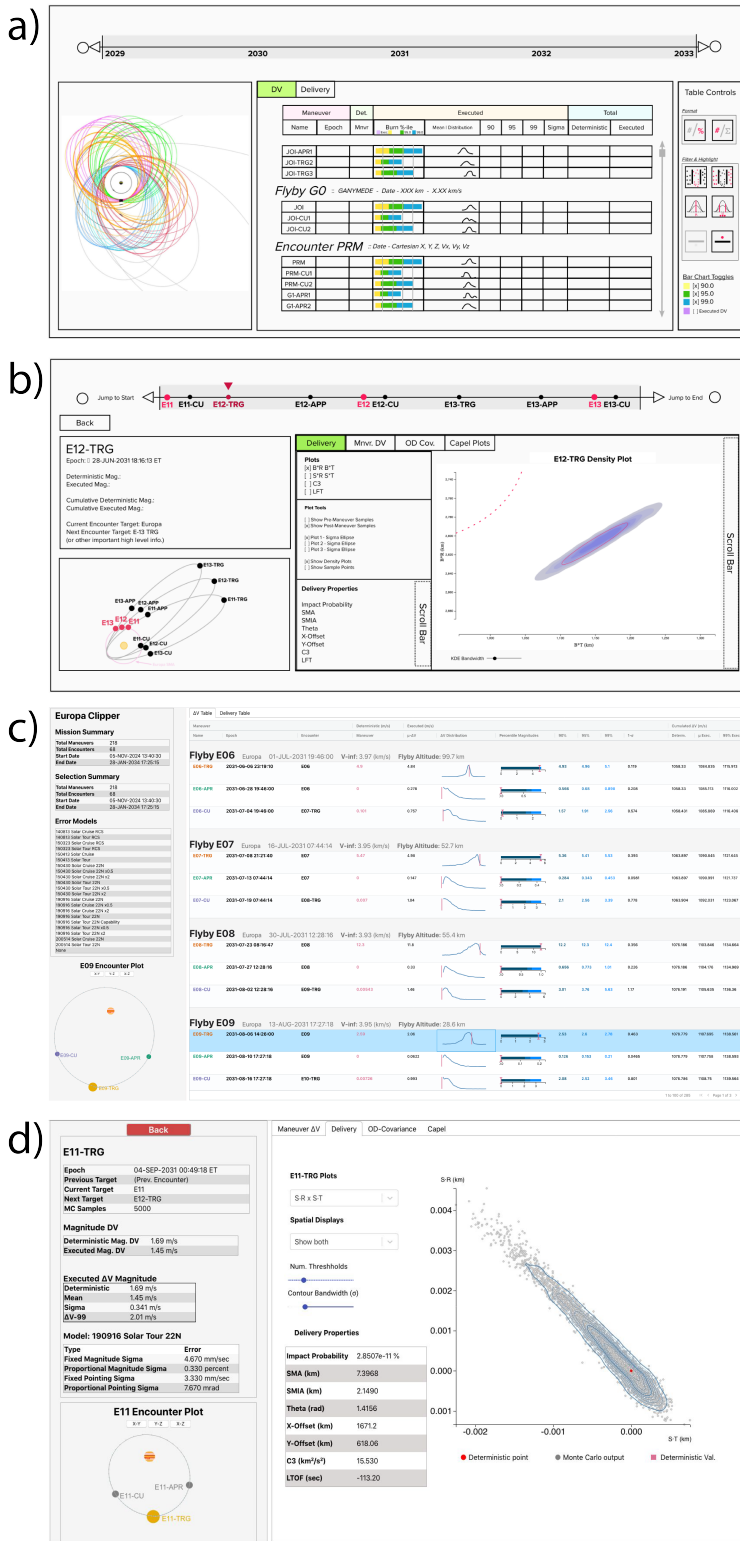


Figure 8. Porter design sketches (a,b) and prototype interface (c,d). Mission data is organized to flow from a high-level mission overview (a,c) to more detailed maneuver-specific views (b,d). Views (a) and (c) show the mission ΔV statistical summary data table, while (b) and (d) show detailed maneuver delivery data.

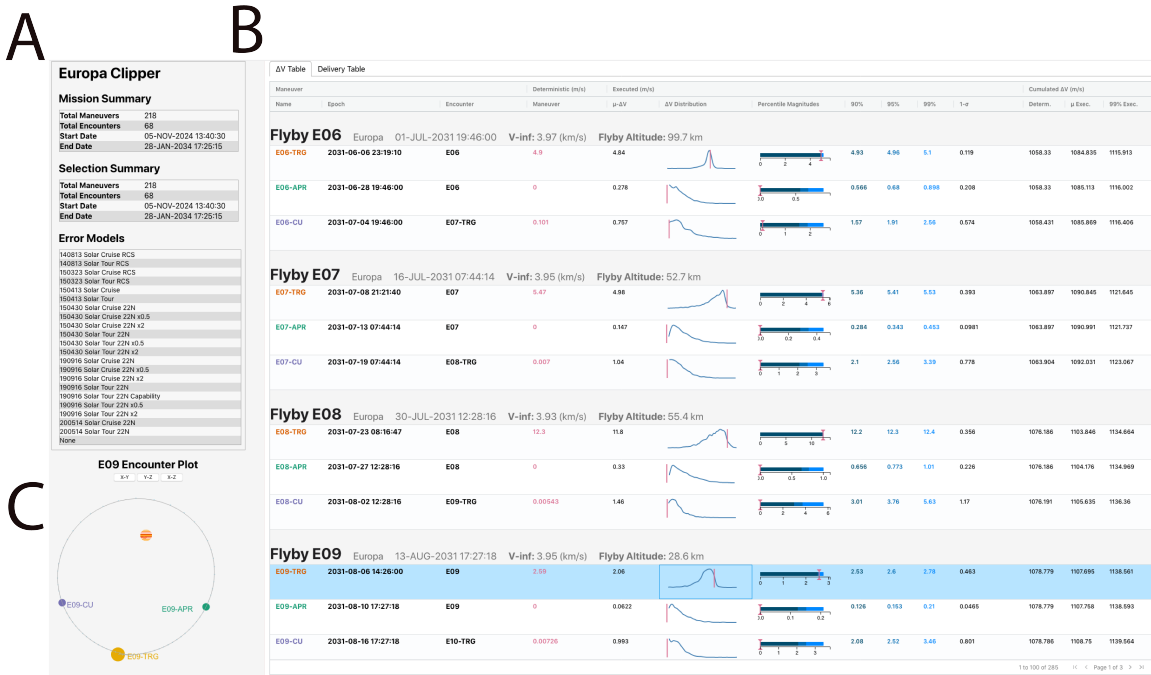


Figure 9. Mission overview page showing the A) summary panel, B) maneuver table, and C) Encounter plot

output over the total simulation date range (Figure 9). The mission overview page consists of an interactive summary table with the ability to transition between reviewing mission-level data and maneuver-specific details by double clicking on individual maneuver rows in the summary table.

Porter was developed in conjunction with the Europa Clipper mission, and loads this data by default. While Porter has successfully tested Juno and DART mission data, loading alternate missions remains the focus of future work.

Mission Overview Page The mission overview page (Figure 9) provides analysts with a visual and interactive review through a high-level summary of various mission data. This summary view is divided across multiple sections: a mission-wide *summary panel* (A), maneuver and encounter properties in a *maneuver table* (B), and various maneuvers' spatial distribution about the central body for each flyby encounter in *Encounter Plot* (C).

The left summary panel outlines the total number of maneuvers and encounters over the mission date range, as well as those within any filtered subset. This panel also outlines each of the error models used in the specific simulation so analysts can know which models inform the simulation output.

The interactive maneuver table (Figure 9-B) utilizes the React.js ag-Grid library* to provide a highly customizable interface for arranging, filtering, sorting, and styling various mission data. Individual cells or text can be shaded according to mission rules (e.g. *flag maneuvers with impact probabilities over 0.01*), or to visually style similar maneuvers types (e.g. Targeting, Approach, and Clean Up maneuvers within the summary table and encounter plot). These changes replace the static text files analysts are accustomed to working with and enable them to more easily review data

*<https://www.ag-grid.com/>

Maneuver		Deterministic (m/s)		Executed (m/s)		Percentile Magnitudes					Cumulated ΔV (m/s)		
Name	Epoch	Encounter	Maneuver	μ - ΔV	ΔV Distribution	90%	95%	99%	1- σ	Determ.	μ Exec.	99% Exec.	
Flyby E06 Europa 01-JUL-2031 19:46:00 V-inf: 3.97 (km/s) Flyby Altitude: 99.7 km													
E06-TRG	2031-06-06 23:19:10	E06	4.9	4.84			4.93	4.96	5.1	0.119	1058.33	1084.835	1115.913
E06-APR	2031-06-28 19:46:00	E06	0	0.278			0.566	0.68	0.898	0.208	1058.33	1085.113	1116.002
E06-CU	2031-07-04 19:46:00	E07-TRG	0.101	0.757			1.57	1.91	2.56	0.574	1058.431	1085.869	1116.406

Maneuver		Impact		Delivery Properties					Ellipse Plot		
Name	Epoch	Probability (%)	Gaussian	SMA (km)	SMIA (km)	Theta (rad)	X-offset (km)	Y-offset (km)	Mean Vx	Mean Vy	Mean Vz
Flyby E11 Europa 11-SEP-2031 03:26:10 V-inf: 3.94 (km/s) Flyby Altitude: 26.5 km											
E11-TRG	2031-09-04 00:49:18	0.000	TBD	7.397	2.149	1.416	1671.160	618.065			
E11-APR	2031-09-08 03:26:10	0.000	TBD	0.952	0.587	0.482	1671.160	618.065			
E11-CU	2031-09-14 03:26:10	--	--	806.028	96.519	141.567	-0.000	0.001	0.001		

Figure 10. The maneuver summary table provides mission-level statistical summaries on mean, deterministic, and executed ΔV information (top) and Delivery table information outlining impact- and delivery-related information (bottom) per maneuver.

and discover outliers.

The maneuver table chronologically lists mission maneuvers and divides their associated properties into the ΔV and Delivery tabs (Figure 10). Both summary tables include maneuver names, epochs, flyby body encounter if applicable, and maneuver type groups. For Europa Clipper, these groupings include the previously discussed: Approach (APR), Clean-Up (CU), and Targeting (TRG) maneuvers that comprise of the majority of the tour. Relevant flyby information such as the close-approach altitude, V_∞ , and epoch are also listed in this view to support analysts to simultaneously review information alongside the reference trajectory parameters. Incorporating various sparkline plots¹⁸ into the summary tables let analysts quickly review ΔV distribution with respect to the deterministic ΔV , and evaluate 1- σ delivery ellipse shape. While analysts can probe this information in the detailed view, having easy-to-review and integrated visualizations in the summary tables eases the cognitive workload.

The ΔV tab outlines various statistical values for each maneuver. This table outlines the maneuver's deterministic and executed mean ΔV , plus the 90th, 95th, and 99th percentiles. It also indicates the cumulative deterministic, mean executed, and 99th percentile Executed ΔV cumulated through that point in the mission, which analysts use to assess trajectory feasibility. The two central columns' sparklines plots help analysts quickly evaluate quantitative summary statistics by visualizing the underlying Monte Carlo distribution for the executed mean ΔV statistics (left), and a bar chart representation of the 90th, 95th, and 99th percentile magnitude values (right). Both visualizations overlay the maneuver's deterministic values to help analysts more quickly identify ill-performing or outlier maneuvers. In particular, the executed ΔV distribution line plots allow analysts to visually check whether simulation results are normally distributed, something previously not available in earlier analysis tools. This embedded chart can immediately communicate which maneuvers and encounters require a closer inspection by visually scanning for abnormal distribu-

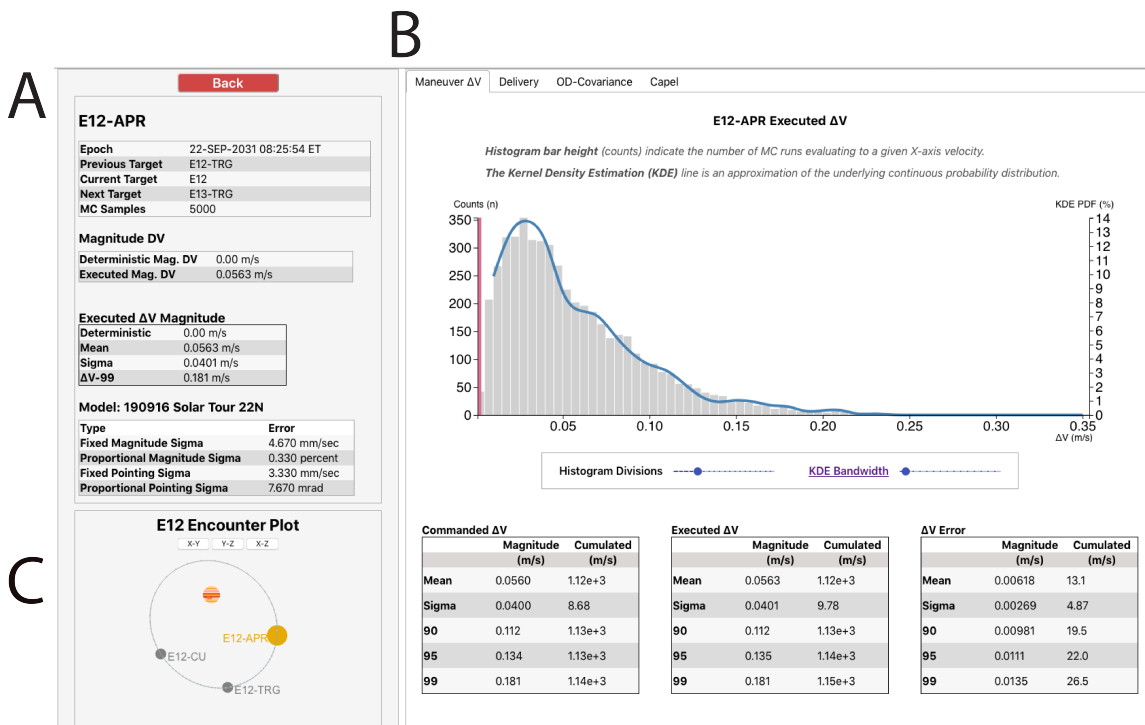


Figure 11. The maneuver detail page displays various maneuver-specific summary data (A), statistic (B) and spatial (C) properties.

tions.

The delivery table (Figure 10, bottom) presents B-plane and Cartesian information by interleaving two color-coded datasets to improve data density and legibility. B-plane data (in black) corresponds to the top header labels, and relate to the craft's impact probability with the flyby body as well as various error ellipse properties: semi-major and semi-minor axes, ellipse orientation (theta), and center point (x- and y- offsets). Maneuvers exceeding mission-specific impact probability thresholds will automatically be styled red to draw analysts' attention for closer review. The last column includes a representative graphic for that maneuver's error ellipse, as well as the orbiting bodies impact and capture radii to additionally indicate maneuvers with a greater likelihood for impact. Cartesian data (in blue) corresponds to the craft's Cartesian state, and outlines the mean Cartesian position and velocities.

Mousing over the table rows will update the encounter plot (Figure 9-C) to plot and highlight the spatial distribution of the specific encounter and hovered maneuver. The analyst can double-click any maneuver on the mission summary page to load more detailed maneuver information (Figure 11).

Maneuver Detail Page The Maneuver detail page (Figure 11) shares the same layout to the summary page and includes a summary panel to outline maneuver-specific data (A), a tabbed display panel to explore various maneuver properties (B), and an identical encounter plot, with the specific maneuver highlighted for context (C). The maneuver summary panel provides high-level maneuver information such as the maneuver epoch, previous, current, and next targets, the maneuver's executed and deterministic magnitude ΔV values, plus the specific error model and error characteristics

for the selected maneuver.

Like the previous pages' summary tables, maneuver property tabs (Figure 11-B) organize detailed maneuver information related to maneuver ΔV and Delivery*. The Maneuver ΔV tab provides an interactive histogram and kernel density estimation line to further investigate the Monte Carlo distribution that shapes the executed ΔV values, as well as more detailed columns on the Commanded, Executed and residual ΔV errors.

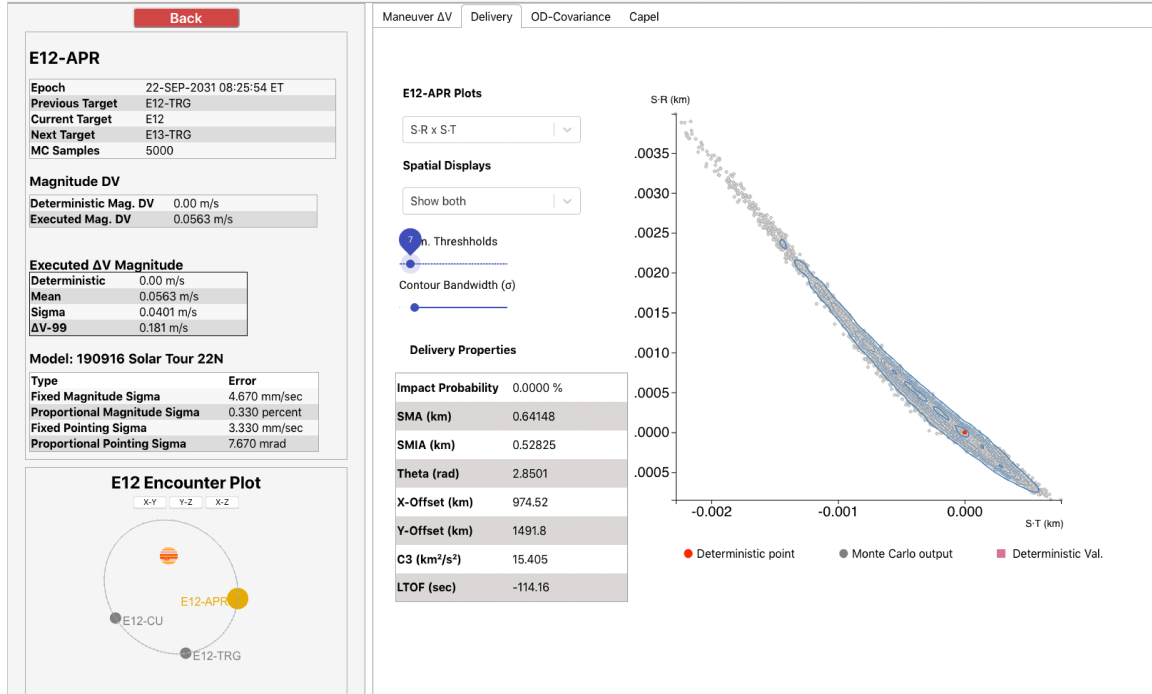


Figure 12. Delivery panel data for the E12 Approach Maneuver. This plot shows the $S \cdot R \times S \cdot T$ Monte Carlo distribution from 5,000 simulated trajectories (deterministic value overlaid as red dot). While the standard statistical summary would report a numeric average and standard deviation for these simulated points, it would fail to communicate its non-uniform distribution or clustered pockets of points within the Monte Carlo distribution outcomes.

The Delivery Panel (Figure 12) provides an interactive plot window. Here, the user can visualize the Monte Carlo distribution data as a scatter plot ($B \cdot R \times B \cdot T$, and $S \cdot R \times S \cdot T$), or histogram (LTOF and C3). Each plot also their respective deterministic value as a reference point. $B \cdot R \times B \cdot T$, and $S \cdot R \times S \cdot T$ plots can optionally be overlaid with density contours to indicate the underlying distribution of Monte Carlo results to improve data legibility in cases of over-plotting. Analysts can refer to these views to review and extract more information than standard statistical summaries would provide.

DESIGN CHALLENGES

Apart from conducting design work remotely due to COVID-19, collaborating with highly trained professionals in highly specialized domains posed a number of unique challenges. Working within a dynamic and lean engineering environment makes it very difficult to get time with end-users, and

*OD-Covariance and CAPEL tabs are shown, but left for future work

engineering feedback may only highlight how customized certain workflows are. There may be no singular overarching design satisfying everyone's goals, and attempting to create such a tool can lead to significant scope-creep or fractured design efforts. From a design perspective, it is important to be aware of these common pitfalls¹⁹ and avoid premature optimization or overly broad usability goals.²⁰

Astrodynamics data processing and analysis has led to fairly specialized workflows, making engineers wary of new or untested tools or techniques. This professional caution affects how engineers and designers approach proposed solutions, and one senior JPL designer summarizes this interaction as, "... *engineers have a **strong** bias toward stable UI's. Anything new they hate immediately, and if it's done any way differently than it has been done before, it's terrible.*"

This motivated our approach to build on existing methods and interfaces rather than propose new or drastic departures from existing workflows. However, separate rounds of engineering design presentations returned little feedback on organizational approaches or design choices. Even when presented with familiar groupings and presentation techniques, it was hard for engineers to weigh in on usability or usefulness from viewing design sketches without being able to engage with them. This is partially due to a lack of design vocabulary and experience, and partially from the inherent difficulty of critiquing a tool or technique without engaging it directly. To overcome this, we applied a presumptive design methodology¹⁴ to "*build the wrong thing first*" and prioritize rapid prototyping to collect positive and negative user feedback to inform the next iteration.

The Porter prototype was built over a two month sprint and presented for observational hands-on evaluation.

USER FEEDBACK AND EVALUATION

Porter was developed in close collaboration with end-users and designers to inform its organizational structure. We conducted five hour-long observational interviews with volunteer maneuver analysts to collect feedback on Porter's layout and feature set, as well as solicit additional features for future development and prototype iterations.

Observational Interviews

Five volunteer analysts (P1 - P5) from JPL's MDNav group completed an hour-long semi-structured observational interview over WebEx to use and critique the Porter interface. All participants were familiar with or actively used LAMBIC simulation data as part of their analysis work, and two of the volunteers had also participated in the previous creativity workshop (P1, P4). The other three participants (P2, P3, P5) were new to Porter and the design project.

Participants spent the first half hour freely exploring the interface while two interviewers captured audio and screen recordings of how they interacted with Porter. Study participants were free to ask questions about anything they saw or interacted with in Porter while interviewers refrained from suggesting or leading them to any part of the interface. The second half hour involved a co-design activity in Google Slides. Participants were shown screenshots of the Porter interface and encouraged to mark-up and critique the various views, interactivity mechanisms, or overall organizational structure based on their own goals and workflows.

Both researchers collected and shared notes after each interview, and one researcher combined

all interview notes into separate AirTable* bases to track participant feedback and feature requests.

User Feedback Participant interviews yielded 35 positive reactions, 25 pain-points, and 90 feature requests. Porter garnered unanimously positive feedback for its simplicity (**P3**: “*This is much easier than scanning through a text file*”), convenience (**P2**: “*I really like the information being in one place so I don’t have to keep hopping back and forth between different documents*”), and overall workflow improvements (**P1**: “*Good to see the ΔV distributions and overview tables, previously this was much more difficult*”, **P5**: “*Just this on its own is already an improvement [...] it’s very easy to share*”). Porter’s pain points primarily dealt with the learning curve from using a new tool for the first time. These difficulties stemmed from misunderstanding specific plots or visual encodings, such as the Maneuver ΔV bar charts and kernel density estimation overlays, due to inadequate on-screen instructions for explaining these views and their data. Most participants commented how more time with the tool would improve their familiarity, and all felt Porter’s organizational design was intuitive and reflected the ways they thought of the data.

Participants’ feature requests focused on improving or extending different interface elements, along with integrating more mission data to incorporate it as part of their existing analysis workflow (**P4**: “*Do you know what you’re going to put in the OD Covariance tab? [...] it would also be nice to export pics for meetings.*”). We summarize these requests in the following future work section.

Future Work

Evaluation feedback and developer goals outline several follow-on projects to improve Porter’s back- and front-end capabilities.

Back-end Improvements In its current prototype state, Porter is deployed as a locally-hosted web application. This client-side operation requires analysts to manually download and run the back- and front-end code to process and visualize their data. Porter’s long term project goals require a more permanent and centralized home within the MDNav network infrastructure to support on-demand LAMBIC output conversion, individual user accounts, and group workspaces to easily share simulation analyses and visualizations.

Porter is built to work with Europa Clipper mission data and has also successfully loaded other missions including DART and Juno. Extending Porter with more diverse LAMBIC-designed flight projects will help expand its user base and build toward a mission-agnostic visual analysis tool for LAMBIC-generated simulation data.

Front-end Improvements User evaluations provide a first step toward identifying various interface improvements and future design efforts to ensure Porter will serve analysts’ needs. Preliminary user feedback requests extending the detailed maneuver views to include additional flight information, such as CAPEL plots and maneuver orbit determination covariance data. Porter’s tabular design allows these self-contained views to be independently designed and prototyped, which would require dedicated design project for each of these views. More broadly, bringing Porter out of its prototype stages require continued user testing and targeted design studies as each of its individual views mature.

Early project constraints prioritized Porter’s design to focus on supporting analysts with exploring single simulation outputs. As we unpacked LAMBIC’s BOA files and data formats, we worked with analysts to interleave its high-level summary data with low level Monte Carlo distributions

*www.airtable.com

to design an intuitive exploratory visual analytics interface. This leaves the third design goal for between-simulation comparisons as a separate project. This design effort will require its own design studies to characterize engineering workflows and interface elements that can assist users with this comparative analysis process.

We hope Porter's positive reception and initial successes motivate continued interest for developing this tool. Integrating Porter within MDNav design and operations workflows will help to secure more users and opportunities to develop additional capabilities over time.

CONCLUSION

In this work, we have described the motivation, design process, and preliminary implementation for Porter, a visually interactive tool for the statistical analysis of spacecraft maneuvers. Porter focuses on the intuitive presentation of and interaction with the results of a Monte Carlo analysis conducted via JPL's Monte LAMBIC toolkit. LAMBIC outputs are first converted to JSON format and partitioned into smaller data files that are then called as needed by the Porter server. Porter's front end is a browser-based presentation of the mission and per-maneuver summary data in tabular format; interactive clicks enable users to navigate to breakout panels that provide more detailed information about maneuvers and their associated target states. In addition to summary text, Porter presents the distribution of samples in the Monte Carlo run as histograms (e.g., executed ΔV or linearized time of flight) or as 2D plots (scatter or contour plots of B-plane or S-plane targets). Users can control aspects of the plots such as the number of histogram bins or the contour levels on the B-plane plots, enabling analysts to quickly query the Monte Carlo results, for example to test the assumption of Gaussian results for a given maneuver. Taken in total, the interactive visualization capabilities of Porter enable mission designers and navigators to gain a richer understanding of the operational characteristics of a given trajectory, set of deterministic burns, and navigation plan, both for individual maneuvers and across a full mission timeline.

Porter was developed as a collaboration between trajectory analysts and user design (UX) experts, combining astrodynamics domain knowledge with proven methods for improving human-computer interaction and analysis of large datasets. We interviewed a variety of trajectory analysts before the initial prototyping of Porter, hosted a design workshop, and conducted a series of user tests of the Porter interface to solicit feedback and generate ideas for future implementation. This process was iterative, with several cycles of eliciting information from maneuver design experts, prototyping visualization elements and interactions, and testing the newly developed capabilities with domain specialists. Porter has been met with enthusiasm and positive comments from the interviewed astrodynamists and a prioritized set of follow-on enhancements has been generated based on their feedback. The common theme of all the comments has been that Porter's visual interface is intuitive, offers greater insight into the results of statistical maneuver analysis, and would be a welcome addition to the Monte software suite.

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