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VIPRE: A Tool Aiding the Design for Entry Probe Missions

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Abstract

Exploring planetary atmospheres uncovers important information as to how our solar system formed and evolved. While remote sensing is extensively used, some crucial observations require in situ measurements by an atmospheric probe. Given their scientific importance, probe missions to Saturn, Uranus, and Neptune are under consideration for the coming decades. In anticipation of future probe missions, the software tool Visualization of the Impact of PRobe Entry conditions on the science, mission and spacecraft design (VIPRE) was developed as proof-of-concept to facilitate selection of probe entry locations. Currently, there is no analytical way to identify which interplanetary trajectory from thousands of feasible launch opportunities is optimal for a considered mission concept. The search and decision process for that solution is complex and relies on the intuition of mission designers, who focus on a subset of trajectories to make the trade space manageable. The idea of *VIPRE* is (1) to generate a multidimensional data cube showing relevant engineering and science parameters simultaneously for thousands of trajectories, and (2) to visualize the data for all entry sites over the body's envelope. VIPRE lays a foundation to make available the data for browsing in a 3D visualization to identify the best family of solutions for a given mission. This paper introduces the validated and verified core algorithms of VIPRE, published on GitHub Probst. VIPRE serves as a basic framework to be used and extended for different purposes. The paper further presents the motivation for the development and algorithms; it explains the computation and data visualization strategy; and gives a list of suggested functionalities to extend and further develop VIPRE to fully leverage its potential.

Unified Astronomy Thesaurus concepts: Uranus (1751); Solar system gas giant planets (1191); Neptune (1096); Saturn (1426); Landers (901); Space probes (1545); High altitude balloons (738); Atmospheric science (116); Planetary science (1255); Planetary atmospheres (1244); Planetary probes (1252); Ocean planets (1151)

1. Introduction

In the pursuit of deciphering the formation and evolution of our solar system, the exploration of the compositional and dynamical structure of the planets' atmospheres with entry probes plays a crucial role. A probe's measurements provide insight into an atmosphere's deeper composition and dynamical processes not accessible via remote sensing. For example, noble gas abundances hold key information about the origin and possible migration of the planets during the early formation phase (Mousis & Atkinson 2016). To date, Galileo, in 1995, has been the only entry probe to one of the outer planets (namely Jupiter), and Voyager 2 has been the only spacecraft that has visited Uranus (1986) and Neptune (1989). Given their scientific importance, probe missions to Saturn, Uranus, and Neptune are under consideration for the coming decades. Hence, planetary entry probe mission concepts have been discussed in several Planetary Science Decadal Surveys: a probe mission to Saturn has been identified as a New Frontiers mission of highest priority in the current Decadal Survey 2013–2022 National Research Council (2011), and a mission to Uranus and/or Neptune carrying a probe is being considered as a Flagship mission in the 2023–2032 Decadal Survey (Beddingfield et al. 2020; Rymer et al. 2020).

During the development of missions incorporating entry probes, selecting a trajectory to ensure a safe approach and successful probe delivery is a critical element of the mission design. The trajectory has to avoid rings and target the most desirable regions in the atmosphere, while balancing other requirements such as providing an optimal communication geometry between the probe and the relay carrier spacecraft as well as meeting science objectives (Ball et al. 2007; Fletcher et al. 2020). Due to the complexity of the problem, mission concept studies usually focus on the investigation of only a limited number of specific trajectories and probe delivery opportunities, restricting the science to a very small, predefined latitude range, while leaving a huge trade space unexplored (Banfield et al. 2018; Mousis et al. 2014, 2018; Hofstadter et al. 2019).

In order to address this gap, the software package Visualization of the Impact of PRobe Entry conditions on the science, mission and spacecraft design (VIPRE) is being developed to analyze conditions for different trajectories and target bodies. The VIPRE software package consists of the software tools IPED and VAPRE, to compute (IPED) and visualize (VAPRE) the entry conditions for all safe entry opportunities of a planetary entry probe being released from an interplanetary trajectory. VIPRE

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allows a rapid assessment of feasible entry sites by evaluating a large number of arrival trajectories based on their hyperbolic arrival velocities with respect to parameters such as the flight path angle and the relative entry velocity of the probe at the point where the probe enters the atmosphere—which is from here on called the entry interface point. VIPRE is a validated software package as a proof of concept, and a step toward facilitating mission design processes in the future by combining the evaluation of technical feasibility and science value for the investigated scenarios to assess potential entry sites. For reference, for a recent Saturn probe mission study performed at the JPL, three to five trajectories were examined in detail to assess the mission feasibility of each trajectory. VIPRE aims to allow the user to browse through thousands of trajectories to check the resulting mission options with respect to the entry probe site, as well as the impact of the science case on the engineering feasibility.

VIPRE is a validated and verified framework that will allow scientists and engineers to rapidly assess the ability to meet science goals at different latitudes for a large number of approach trajectories, without violating engineering constraints such as the maximum feasible entry velocity. To enable this, VIPRE generates a multidimensional data cube from thousands of trajectories created with the JPL internal trajectory tool STAR by Landau (2018) and makes the data available for browsing in a 3D visualization tool to enable finding the overall best solution for a given mission. The current state of development of VIPRE is available on GitHub[7] (Probst 2021) for institutions to work on and extend to their needs. VIPRE has been validated and verified in peer-review against data created using example trajectories, mission scenarios, and existing tools.

2. Science Input

The objective of the development of VIPRE is to achieve the highest-priority science goals as defined by the science community with respect to a planetary entry probe mission to one of the outer planets, Saturn, Uranus, and Neptune. To better define and understand the science goals and objectives of the community, a science survey was conducted, in which an overview of the atmospheric science fields was created. The survey questions targeted the main characteristics of the atmospheres of Saturn, Uranus, and Neptune as a function of latitude:

Q1: What is your focus of research with respect to the atmosphere of the planet?
Q2: If you could choose, what do you consider to be the most scientifically valuable region for in situ investigation by atmospheric entry probes? Why? Indicate the regions as latitude bands and/or altitude ranges.
Q3: What is the most compelling region for your field of research?
Q4: What are the most important science measurements for a probe targeting the regions you identified? If applicable, indicate the altitude or pressure ranges for those measurements.

The questions target the survey participants' fields of expertise, science focus, as well as their opinion on the scientifically most compelling entry sites for planetary entry probes and why. The questionnaire was distributed among international atmospheric scientists and experts from various institutions having diverse research foci and technical backgrounds. By mapping the science resulting from the survey to the latitude where the science can be observed, it shed light into the size and distribution of the trade space of mission design. The survey was returned by 16 researchers and the results are summarized in so-called "science Maps," as displayed in Figure 1 for Saturn and Figure 2 for Uranus and Neptune. The science maps allocate the relevant science topics and phenomena to the latitude range in which they occur or can be explored. By looking at the results, it becomes clear how important it is for the advancement of science to explore the complete trade space during the initial mission design.

The science maps highlight three science foci represented by overarching fields of science: "Dynamics & Structure" on the left, "Other Phenomena" on the right, and "Origin & Evolution" in the center. The variety of the science fields range from the investigation of mid-latitude storms on Saturn, to the dark spots and vortices in the high latitudes of Neptune, or the observation of auroras on Saturn in the polar region. For the purpose of the mapped representation, it is assumed that the northern and the southern hemispheres are identical and that the overarching topics are equivalent for all of the planets. Hemisphere-specific phenomena such as the North Polar Hexagon on Saturn are marked with an "N" for north or "S" for south, respectively. The survey results for Uranus and Neptune resemble each other and cover very-high-level topics due to the still-limited exploration of the atmospheres and the planets of Uranus and Neptune in general. Therefore, they are shown in a combined representation for both planets.

As revealed with the survey results and the science maps, the distribution of atmospheric and other phenomena across the latitude range of the planets shows that the whole latitude range of a planet is worth to be considered as a potential entry site of interest. Hence, we divided the southern and northern hemispheres into four potential entry zones of interest, applicable for all three planets:

(1) An equatorial region (latitudes less than 15°);
(2) a mid-latitude region (15°–45°);
(3) a high-latitude region (45° and 75°); and
(4) a polar region (latitudes greater than 75°).

Those four latitude ranges represent an example for entry interface zones that could be used for a trade-off analysis performed using VIPRE. However, the main takeaway from the survey for this research is that it shows how important it is for the advancement of science to explore the complete trade space of mission scenarios instead of focusing on a particular solution early on. The presented framework of VIPRE lays the foundation for the extension of current capabilities of mission designers at the same time that it allows a greater involvement of scientists in the early decision-making process by making important information available in an easy-to-grasp manner.

3. Engineering Input

In order to provide a framework that makes relevant information for a selection of an entry site available, the engineering data computation is needed as input. The mission concept evaluated from an engineering perspective for that purpose is a planetary entry probe mission with direct entry. The parameters investigated are chosen based on their impact on

[7] Under the account @planetaryprobst.

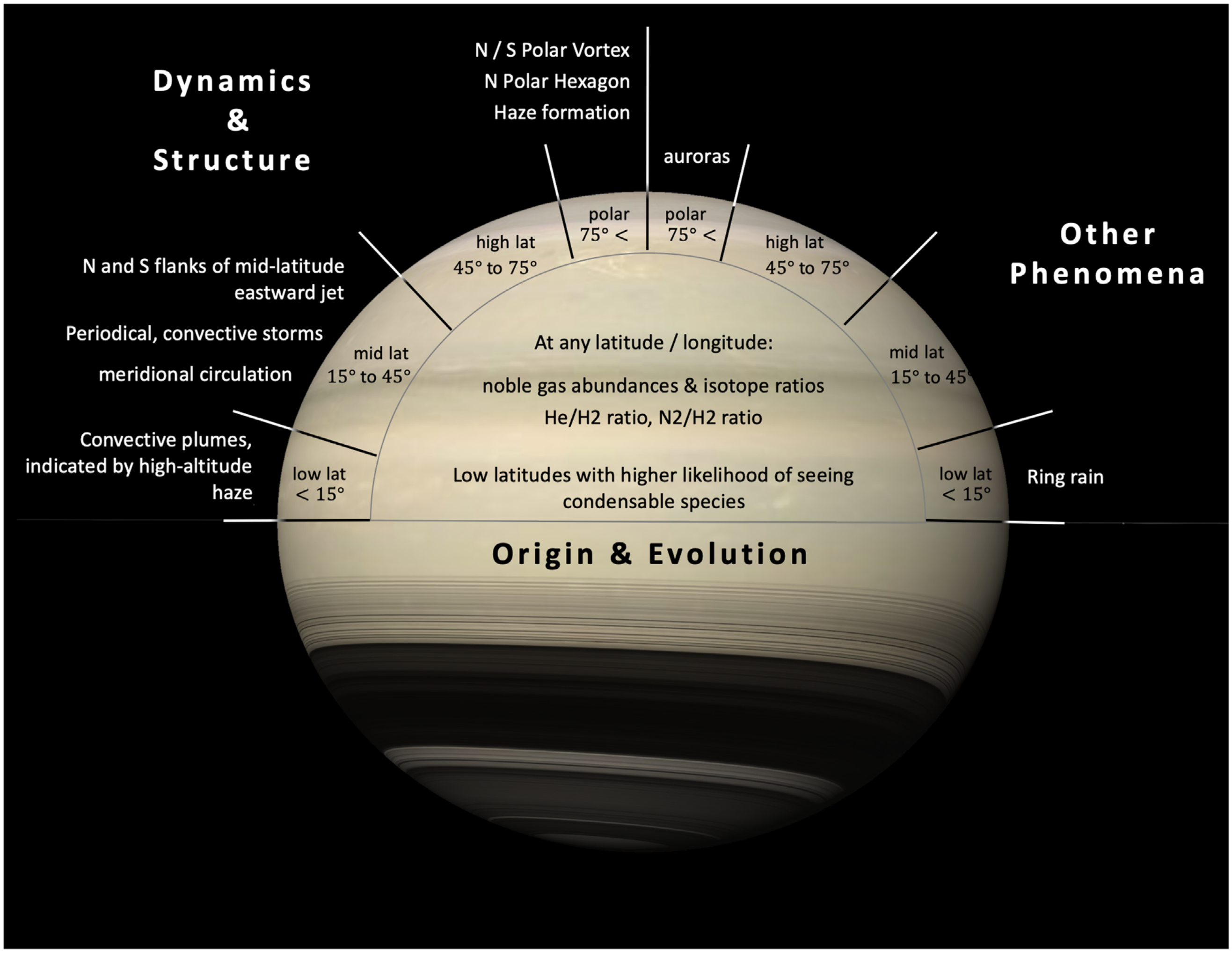

Figure 1. Science map for Saturn. The compelling atmospheric science highlights are organized in three overarching fields: "Dynamics & Structure" on the left, "Other Phenomena" on the right, and "Origin & Evolution" in the center. Adapted from Probst et al. (2020).

the mission success and mission feasibility. For implementation purposes, the mission concept is divided into two phases, the interplanetary phase and the approach phase, separated by the event of the probe release. The two phases are sketched in Figure 3.

The interplanetary phase is characterized by the cruise of the composite spacecraft (carrier+probe) from launch to the arrival at the planetary system. The parameters that drive the trajectory are the launch opportunities available in a certain launch window, and the characteristics of each trajectory such as the time of flight (ToF), the postlaunch, Δv, the (composite) spacecraft mass upon arrival, $m_{S/C,arr}$, and the hyperbolic arrival velocity, v_{∞}.

The approach phase follows the probe separation and is defined by the probe and the carrier spacecraft being on separate trajectories. The *probe trajectory* is a continuation of the interplanetary trajectory, which sets the entry conditions—including the entry interface point—of the probe. The relevant design parameters that define the probe entry are the atmospheric-relative velocity of the probe at entry, $v_{rel,entry}$, and the flight path angle at entry, FPA_{entry}. Both parameters vary over the course of the trajectory, and are therefore subject to the definition of the entry interface point, which is translated into the entry interface altitude above an atmospheric pressure of 1 bar. Hence, the latter has been chosen as one of the input variables for the development of VIPRE. The *carrier spacecraft* diverts from the direct entry trajectory to a fly-by trajectory by applying an orbital-deflection maneuver, Δv_{ODM}. The carrier trajectory after the maneuver is a trade-off between an adequate communication time slot and data rate during the operational phase of the probe as well as the orbital-deflection maneuver, Δv_{ODM}, and a potential subsequent orbit insertion maneuver, Δv_{OI}.

In this development stage of VIPRE, the implementation covers the interplanetary phase and the probe trajectory of the approach phase after probe release. This enables the evaluation of the driving parameters of the probe entry conditions based on the input of a target body, an interplanetary trajectory data set in a specified launch window, and the entry altitude at which the probe's atmospheric entry begins.

4. VIPRE: Visualization of the Impact of PRobe Entry Conditions on the Science, Mission and Spacecraft Design

The implementation of the VIPRE tool is based on two software tools, each explained in detail in the following sections: (1) IPED, the computation of the parameters and entry conditions for a given interplanetary trajectory data set is described in Section 4.1; and (2) VAPRE, the visualization of the computed data in Section 4.2.

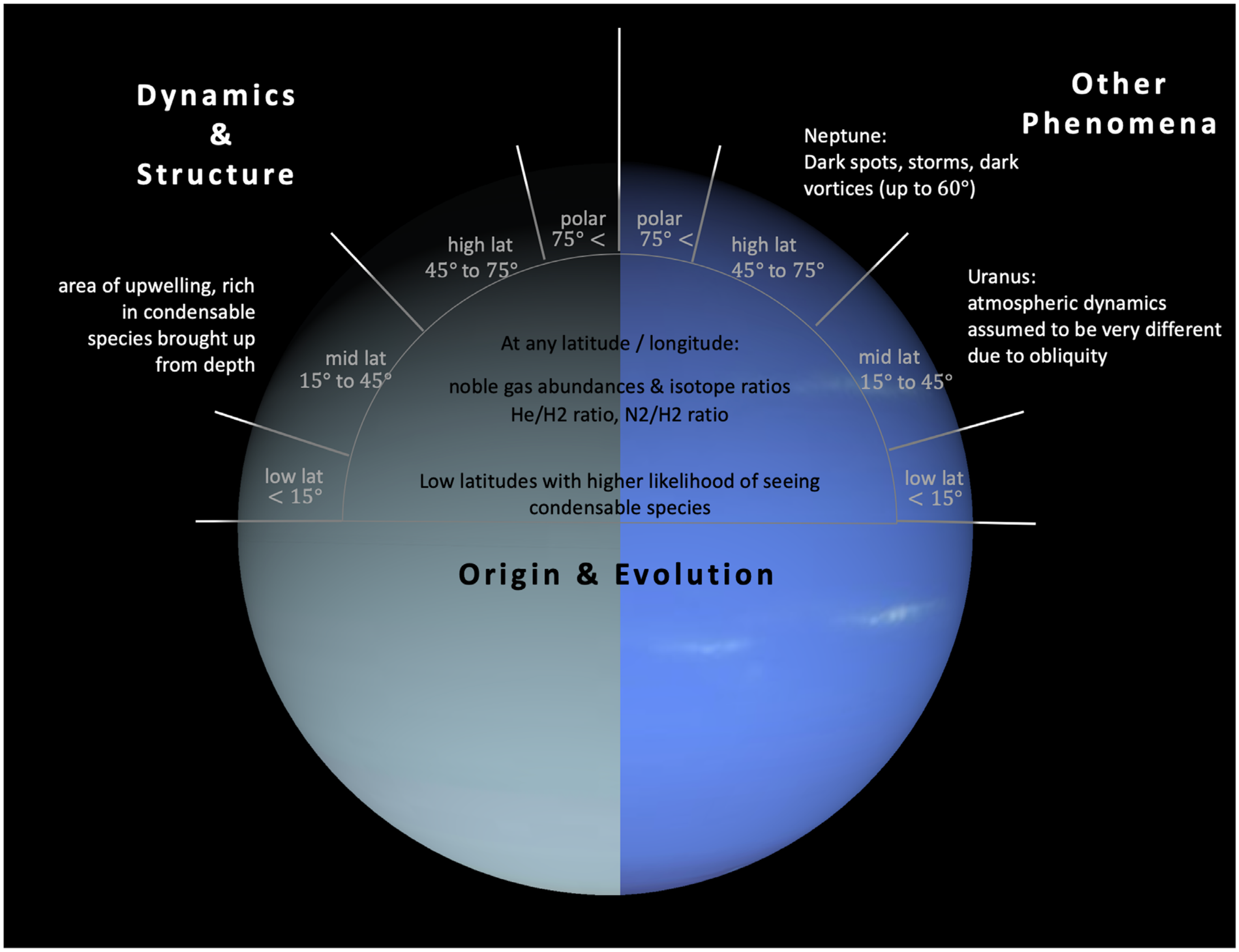

Figure 2. Combined science map for Uranus and Neptune. The compelling atmospheric science highlights are organized in three overarching fields: "Dynamics & Structure" on the left, "Other Phenomena" on the right, and "Origin & Evolution" in the center. Adapted from Probst et al. (2020).

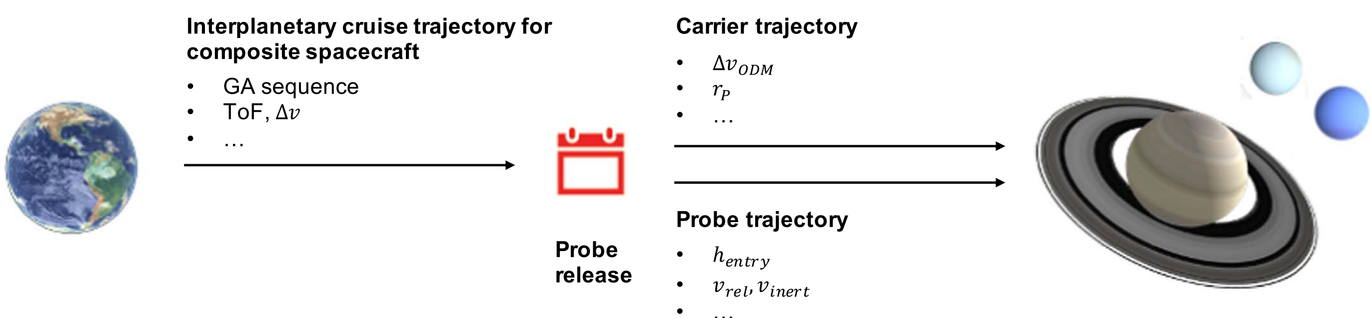

Figure 3. Sketch visualizing the interplanetary phase and the approach phase. The phases are separated by the probe release, symbolized by a calendar event.

The logic and main algorithms of the computation are explained in this section. The published release of VIPRE represents the validated core software that allows further development by users according to their needs. Ideas for future developments are listed in Section 5.

4.1. IPED: Generation of the Entry Conditions

IPED stands for the Impact of the location of the Planetary Entry probe on spacecraft and mission Design, and computes the entry conditions for all safe, direct entry opportunities of a planetary entry probe being released on a interplanetary trajectory. The generation of the physical entry conditions is realized using a combination of Python (Van Rossum & Drake 2009), Matlab (The Mathworks Inc 2019), and the JPL NAIF SPICE toolkit for Matlab (MICE; Acton 1996; Acton et al. 2018). A flow chart of the program is sketched in Figure 4, and the following description follows the steps indicated in the figure.

Based on the mission scenario defined by the destination planet and the atmospheric entry altitude of the probe, a given

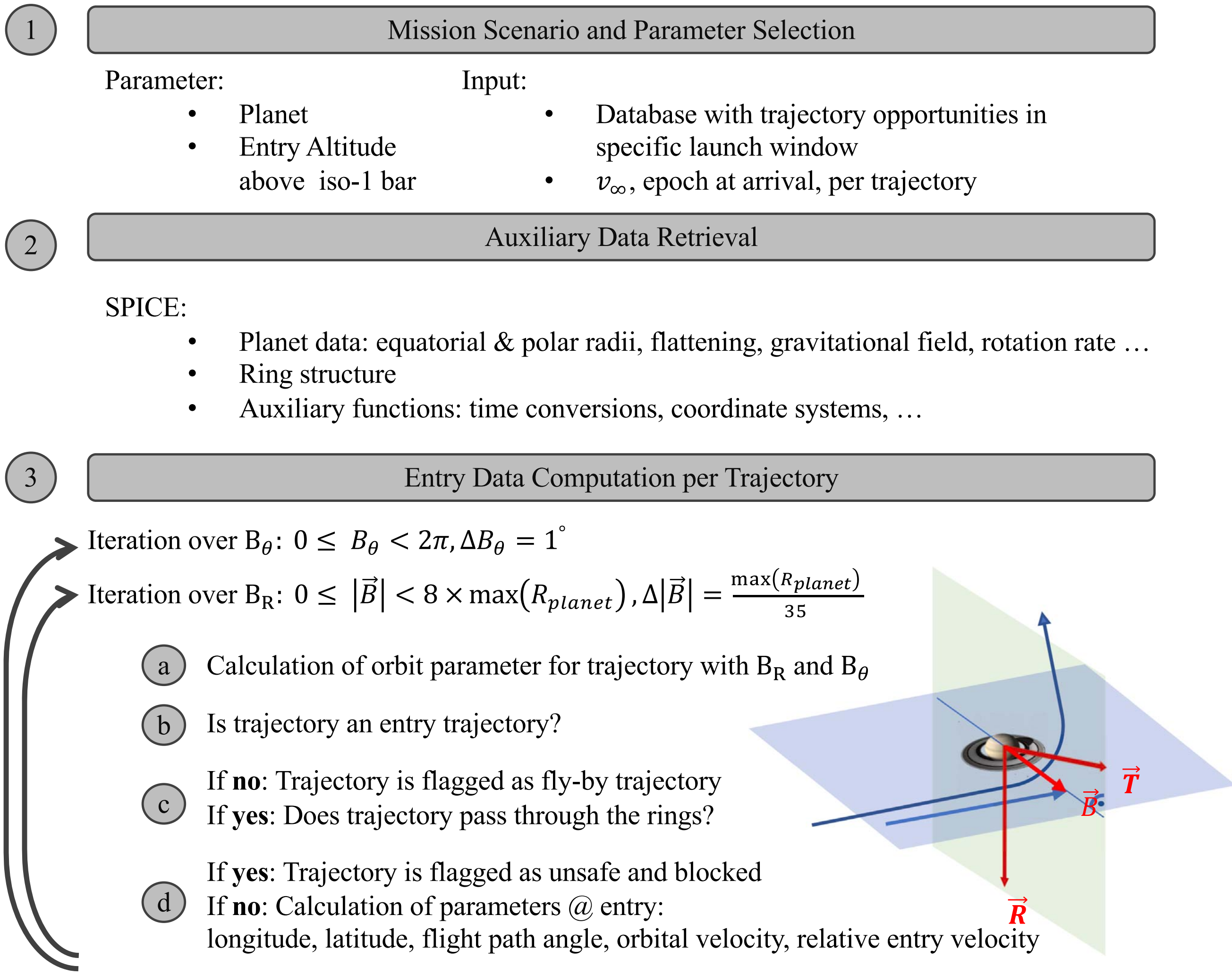

Figure 4. Flow chart sketching the logic of the entry data generation. After the (1) parameter and trajectory data set input and the (2) retrieval of the auxiliary data, the (3) entry data computation per trajectory is explained.

data set of interplanetary trajectories for a specific launch window (step 1) as well as auxiliary data (step 2) is loaded. The interplanetary trajectory data set (step 1) was computed with the JPL internal software tool STAR by Landau (2018) for a given launch window and a maximum ToF. The auxiliary data (step 2) includes information such as the physical characteristics of the planet (polar and equatorial radii, gravitational parameter, etc.) and the structure of the rings, if any. Using the loaded input, the values of the entry parameters are computed based on an iteration over the geometry of the B vector, $\boldsymbol{B}$ (step 3), by changing the magnitude, $|\boldsymbol{B}|$, and the angle, θ, of $\boldsymbol{B}$ for each of the trajectories in the data set. The iteration over the geometry of $\boldsymbol{B}$ allows the exploration of all entry interface points accessible with this interplanetary trajectory without changing the postlaunch Δv notably. The geometry of the B plane and the B vector, $\boldsymbol{B}$, as used in step 3 is explained in more detail in the next paragraph and illustrated in Figure 5.

Using the hyperbolic arrival velocity vector, $\boldsymbol{v}_\infty$, of the incoming trajectory, the B plane is established. The B plane is the plane that is perpendicular to the trajectory plane and includes the focus of the trajectory, which is the center of the main gravitational body, here represented by Saturn. The B vector, $\boldsymbol{B}$, spans along the intersection line of the trajectory and the B plane, starting on the center of the planet, to the point where the incoming asymptote pierces the B plane. $\boldsymbol{B}$ is defined by the unit vectors $\hat{R}$ and $\hat{T}$, which define the B plane, and the angle θ.

The unit vectors $\hat{R}$ and $\hat{T}$ are described as

$$\hat{T} = \frac{\hat{S} \times \hat{N}}{|\hat{S} \times \hat{N}|}, \tag{1}$$

$$\hat{R} = \hat{S} \times \hat{T}, \tag{2}$$

with $\hat{S}$ being the unit vector of the incoming asymptote of the trajectory, and $\hat{N}$ the orbit normal. Further, θ is defined by

$$\theta = \sin^{-1}\left(\frac{|\boldsymbol{B} \cdot \hat{R}|}{|\boldsymbol{B}|}\right) = \cos^{-1}\left(\frac{|\boldsymbol{B} \cdot \hat{T}|}{|\boldsymbol{B}|}\right). \tag{3}$$

$\boldsymbol{B}$ is sketched in the lower-right corner of Figure 5. By rotating the B vector around the planet's center and varying its length, all accessible entry interface point locations for this particular arrival trajectory are explored, including retrograde arrival trajectories. To avoid confusion, the interplanetary arrival trajectory is called the parent trajectory, while the trajectory variations created by the variation of $\boldsymbol{B}$ are called the offspring trajectories.

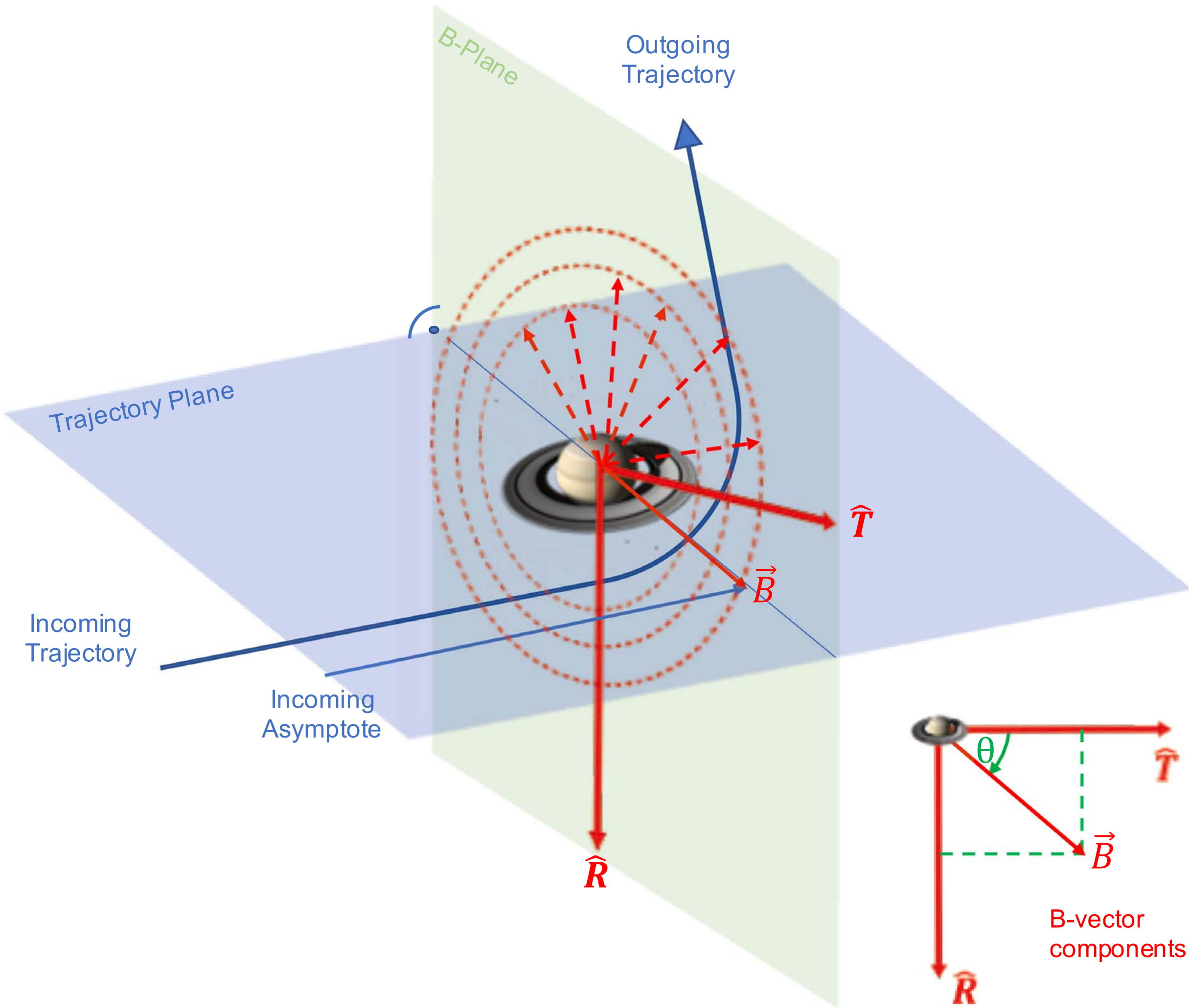

Figure 5. Illustration of the B-plane geometry on the example of Saturn. The B plane (vertical) is perpendicular to the plane of the interplanetary trajectory (horizontal), with the gravitational body in the center. The B plane is defined by the unit vectors $\hat{R}$ and $\hat{T}$. The B vector, $\boldsymbol{B}$, spans from the center of the planet to the point where the incoming asymptote pierces the B plane. By varying the angle, θ, and the length of $\boldsymbol{B}$, the trajectory trade space for one interplanetary, hyperbolic arrival trajectory can be explored, sketched as dashed arrows and concentric dashed circles.

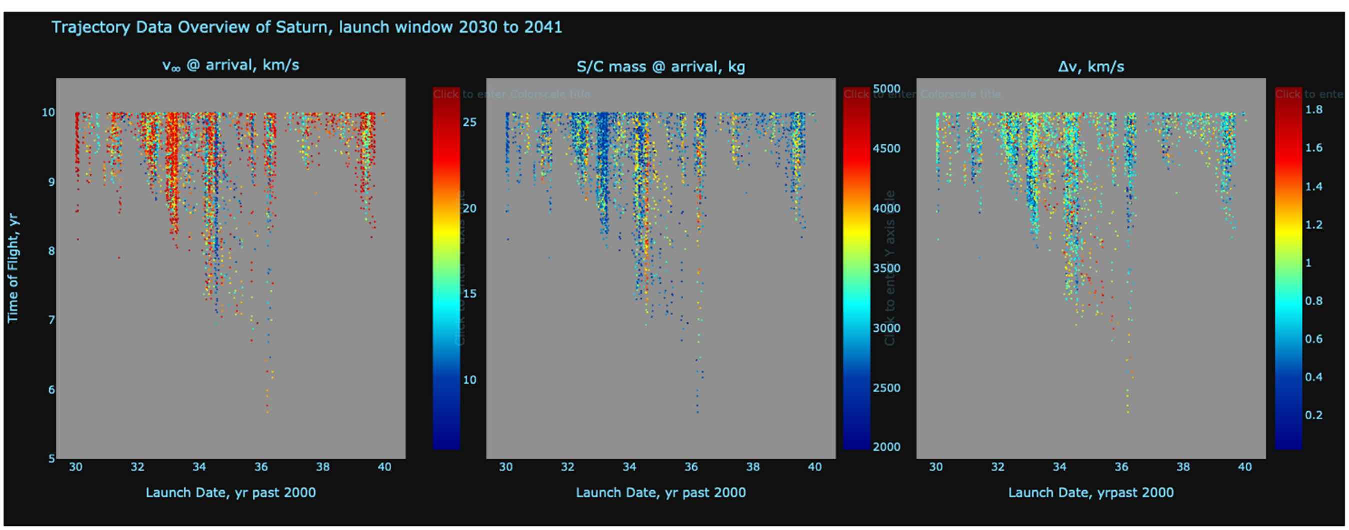

Figure 6. Screenshot of the parent trajectory overview visualization of the trajectory data set that has been used to generate the entry data set. It shows each launch opportunity plotted for the time of flight over the launch date, color-coded in the characteristics hyperbolic arrival velocity, spacecraft mass at arrival, and postlaunch Δv for transfer (from left to right). The color scale ranges from dark blue (low values) to dark red (high values). For better readability, each diagram can be found in bigger scale in the Appendix, Figures 8–10. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

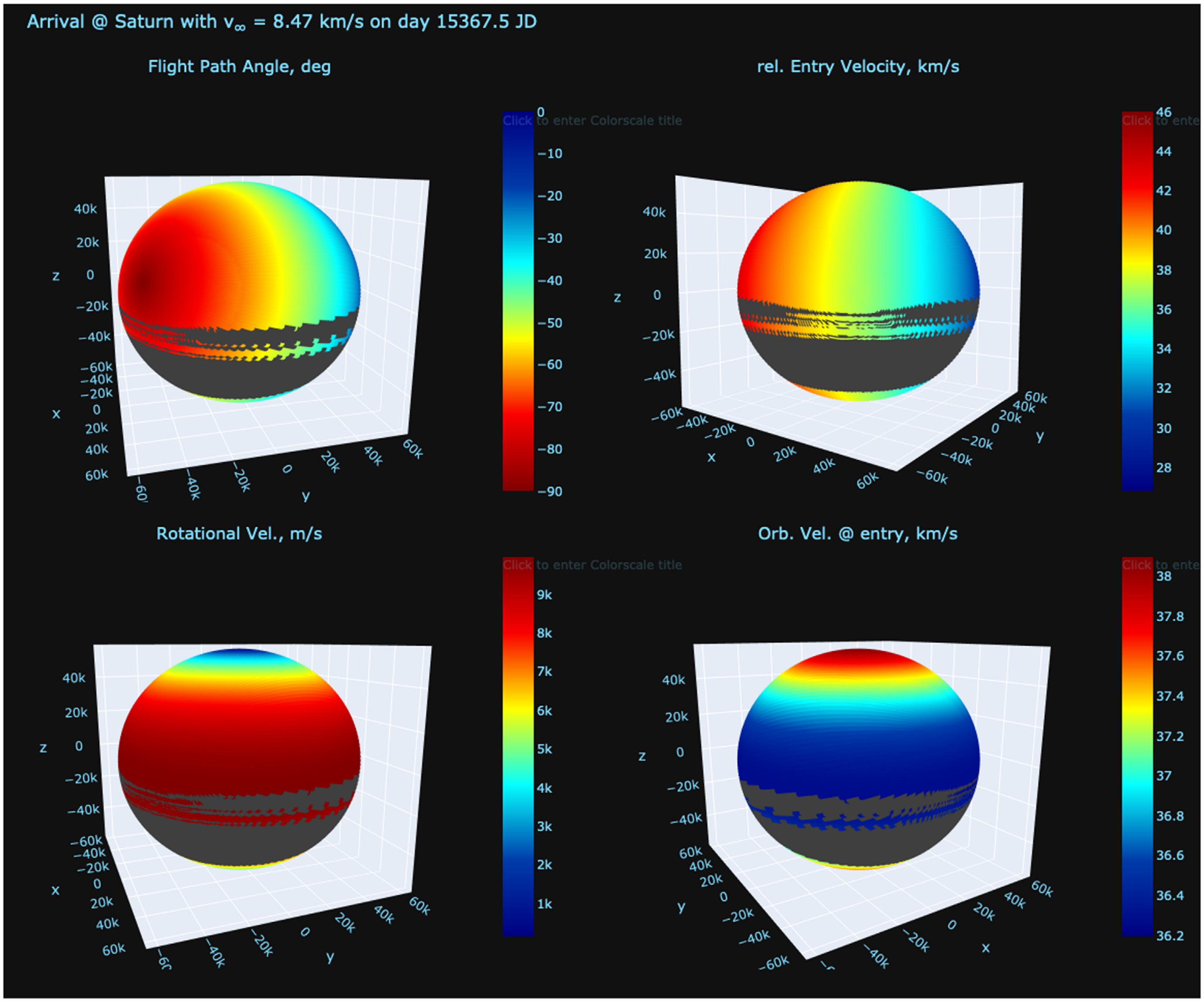

Figure 7. 3D visualization of the entry conditions for an example arrival trajectory at Saturn. Each globe shows how a different parameter changes over the different latitudes and longitudes. Changes of the respective parameters are indicated by a dark red to dark blue color scale. Nonaccessible entry regions are colored in gray, in this case caused by ring blockages. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Each combination of $|\boldsymbol{B}|$ and θ yield one offspring trajectory, and for each offspring trajectory the orbit parameters are calculated. Two checkpoints are implemented. (a) It is checked if the parent trajectory is an entry trajectory or a fly-by trajectory, using the chosen entry altitude and the ellipsoidal shape of the body as a reference; any probe fly-by trajectory will be discarded and not further considered. (b) Each offspring trajectory is checked for ring avoidance; if the probe entry trajectory does not cross the rings, the parameters at atmospheric entry are calculated, such as the longitude and latitude of the entry location, the flight path angle, the orbital velocity and the relative entry velocity of the probe. For each offspring trajectory, the data is saved in a text file for future processing, visualization, and further analysis. In order to check if the trajectory does or does not cross the rings, the trajectory states are compared to the ring structure in the ring plane. If the position vector crosses in an area that is considered part of the ring structure at any point in time, the trajectory is flagged as unsafe. In this stage of the design, we are neither considering any gravitational influence other than the central planet on the trajectories nor discarding trajectories based on collisions with satellites such as moons, as both points are deemed not critical in the first order of the mission process.

4.2. VAPRE: Data Visualization

VAPRE stands for the Visualization of Atmospheric PRobe Entry conditions for different bodies and trajectories, and is the visualization of the 3D data cube generated with IPED. The visualization feature has been implemented in order to faciliate scientists and engineers with a rapid evaluation and interpretation of the data generated. The visualization is based on Dash Python (Plotly Technologies Inc. 2015), a framework for creating web applications. It enables us to build dashboards that run on a web browser and are therefore easily accessible to a wide range of users, including the general public. VAPRE consists of two parts: the *trajectory overview,* representing the interplanetary phase, and the *entry conditions,* representing the approach phase. Their functionalities are described in the following two paragraphs.

The trajectory overview. The trajectory overview gives the user the option to select the combination of input parameters *planet* and *entry altitude* based on the available data sets and thereby to define the mission scenario. VAPRE then loads the parent trajectory data set based on the selected mission scenario entry data. The parent trajectory data set is displayed by plotting the ToF over the launch date, color-coding characteristics such as the spacecraft mass at arrival at the destination planet, or the postlaunch transfer, Δv, for each trajectory. A screenshot of the trajectory overview visualization is shown in Figure 6. For better readibility, each of the subfigures of Figure 6 are displayed separately in the Appendix in Figures 8–10.

The tool also allows the user to filter important variables for the value range that is relevant to them. Variables include the launch date, the ToF, the hyperbolic arrival velocity of the trajectories displayed, or the spacecraft mass at arrival at the destination planet. This way, the user can focus on the most relevant (parent) trajectories for their scenario. By clicking on a trajectory in the overview plot, the details about the selected interplanetary parent trajectory are displayed in a concise form and include additional information, such as the gravity assist sequence and the C_3.

The entry conditions. By selecting an altitude and a parent trajectory, the entry condition data of the selected parent trajectory is loaded into the tool. It is displayed as a 3D visualization of the change of the entry parameters across the planet's globe for each of the offspring trajectories, by color-coding the entry location in the parameter value on the envelope of the planet at entry altitude above the 1 bar radius of the planet, as shown in Figure 7 for an example arrival at Saturn. Each globe shows the variation of a different parameter for all accessible latitudes and longitudes. Changes of the respective parameters are indicated by a dark red to dark blue color scale. Blocked locations because of the planet's individual ring structure are shown in dark gray; nonaccessible regions because of the direction of the hyperbolic arrival velocity of the parent trajectory are not plotted. Parameters projected on the globes include the entry flight path angle, the relative entry velocity, the rotational velocity of the planet, and the orbital velocity of the probe at entry, as seen in Figure 7. Each figure can be modified and rotated, depending on the user's interest, and conceptually demonstrates how to enable a complete assessment of the available trade space by visualization.

5. Summary and Future Work

The significance and potential of VIPRE lies in its future impact on the mission design process. VIPRE will facilitate browsing for an optimal mission option because it will enable the rapid assessment of a large number of approach trajectories, determining which meet the science objectives without violating the engineering constraints of a planetary entry probe. The engineering constraints currently implemented target the atmospheric entry dynamics and aid, among others, the design of the thermal protection system of the planetary entry probe. VIPRE represents a basic and validated framework that sets the foundation for an immediate evaluation of the value of different science cases versus the technical feasibility for a planetary entry probe. The current release allows the mission concept assessment with respect to the parameters of the entry flight path angle and the atmospheric entry velocity. The potential and convincing features of VIPRE is that it is easy to use, hands-on, and extendable for various target bodies and other mission elements and scenarios. The tool framework is set up to be flexible and easy to extend, by implementing more functionalities to enable a more detailed and complete mission evaluation, or by expanding to other mission scenarios.

Ideas to further extend the basic framework of VIPRE—and leverage its full potential—include the following.

1. Visualization of a range of entry conditions for a chosen subset of parent trajectories.
2. Visualization of the trajectory data sets as pork-chop plots.[8]
3. Filtering for specific parameter ranges for a (sub)set of parent trajectories.
4. Assessment of carrier trajectories to find an optimal trajectory combination for the probe and carrier, evaluating parameters such as distance and angular separation between the two spacecraft, including a communication analysis.
5. Evaluation of science objectives by assigning a factor of urgency or importance to each objective, and assigning those factors to latitudes and up to what level that objective can be achieved. This way, specific latitudes can be ranked for their science value with respect to specific science objectives.
6. Targeting of specific atmospheric features (fixed longitude/latitude) by implementing a time dependency.
7. Evaluation of the entry dynamics and thermal loads.
8. Switching between coordinate systems of the plotted data.
9. Evaluation of different mission scenarios such as lander, entry probes, or balloons, including multielement missions with release from orbit, and including more planets and other objects such as moons.

The code of VIPRE is available on GitHub under the account @planetaryprobst (Probst 2021) for the general public or other institutions to use and extend to their needs.

The authors want to thank Damon Landau for his support with the trajectory computations using STAR, as well as emirror-de for their extensive support in the web development of the visualization tool VAPRE of the software package VIPRE.

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Software: Matlab (The Mathworks Inc. 2019), Python 3 (Van Rossum & Drake 2009), NAIF/MICE (Acton 1996; Acton et al. 2018), STAR (Landau 2018).

Appendix

For better readibility and detail, this appendix contains the subfigures of Figure 6 in separate Figures 8–10. Each of Figures 8–10 shows the available launch opportunities with the Time of Flight (in years) over the Launch Date (in years past 2000), color coded in a different parameter. Figure 8 highlights the hyperbolic arrival velocity (in km/s), Figure 9 the S/C mass at arrival (in kg), and Figure 10 the Δv for the interplantary cruise (in km/s).

[8] In orbital mechanics, a pork-chop plot is a chart that shows contours of equal characteristic energy (C_3) against combinations of launch date and arrival date for a particular interplanetary launch opportunity.

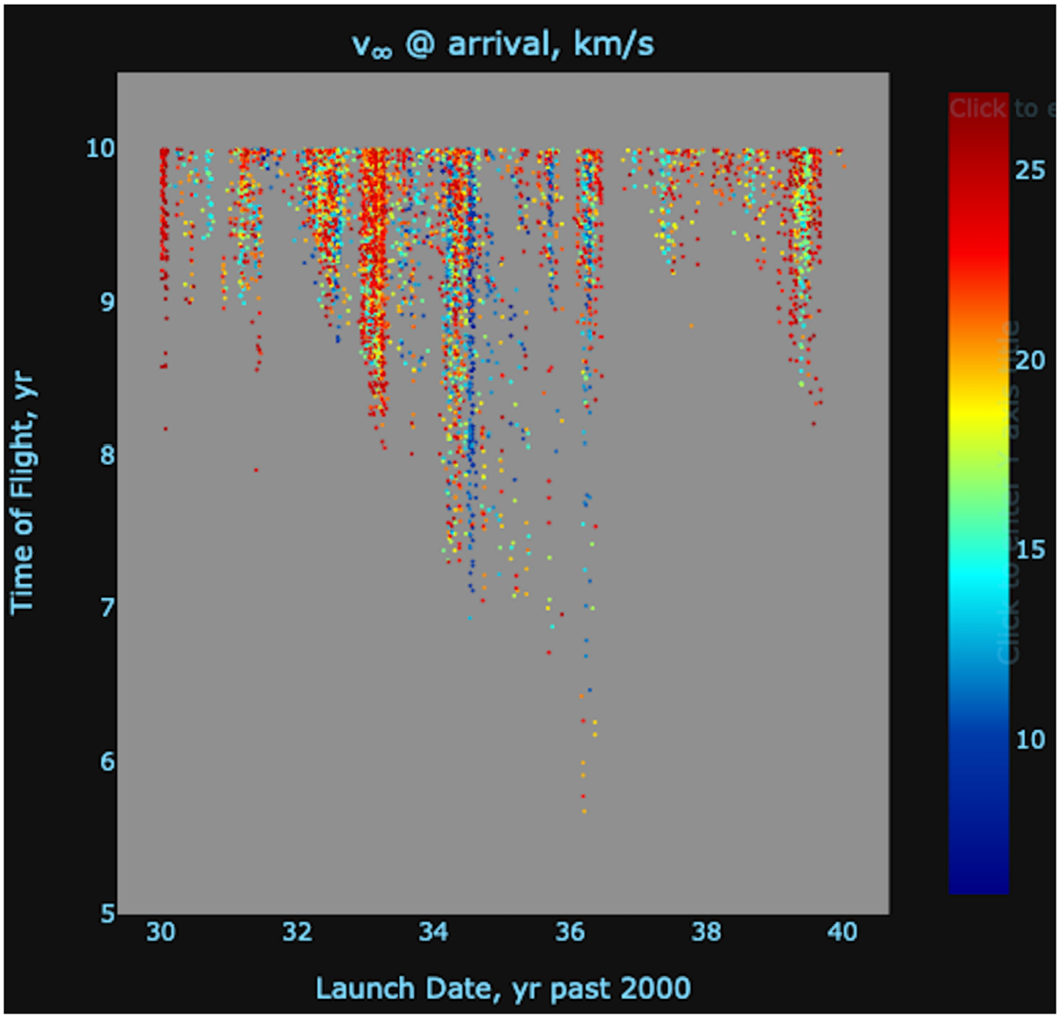

Figure 8. Screenshot of the parent trajectory overview visualization of the trajectory data set that has been used to generate the entry data set. It shows each launch opportunity plotted for the time of flight over the launch date, color-coded here in the values of the hyperbolic arrival velocity. The color scale ranges from dark blue (low values) to dark red (high values).

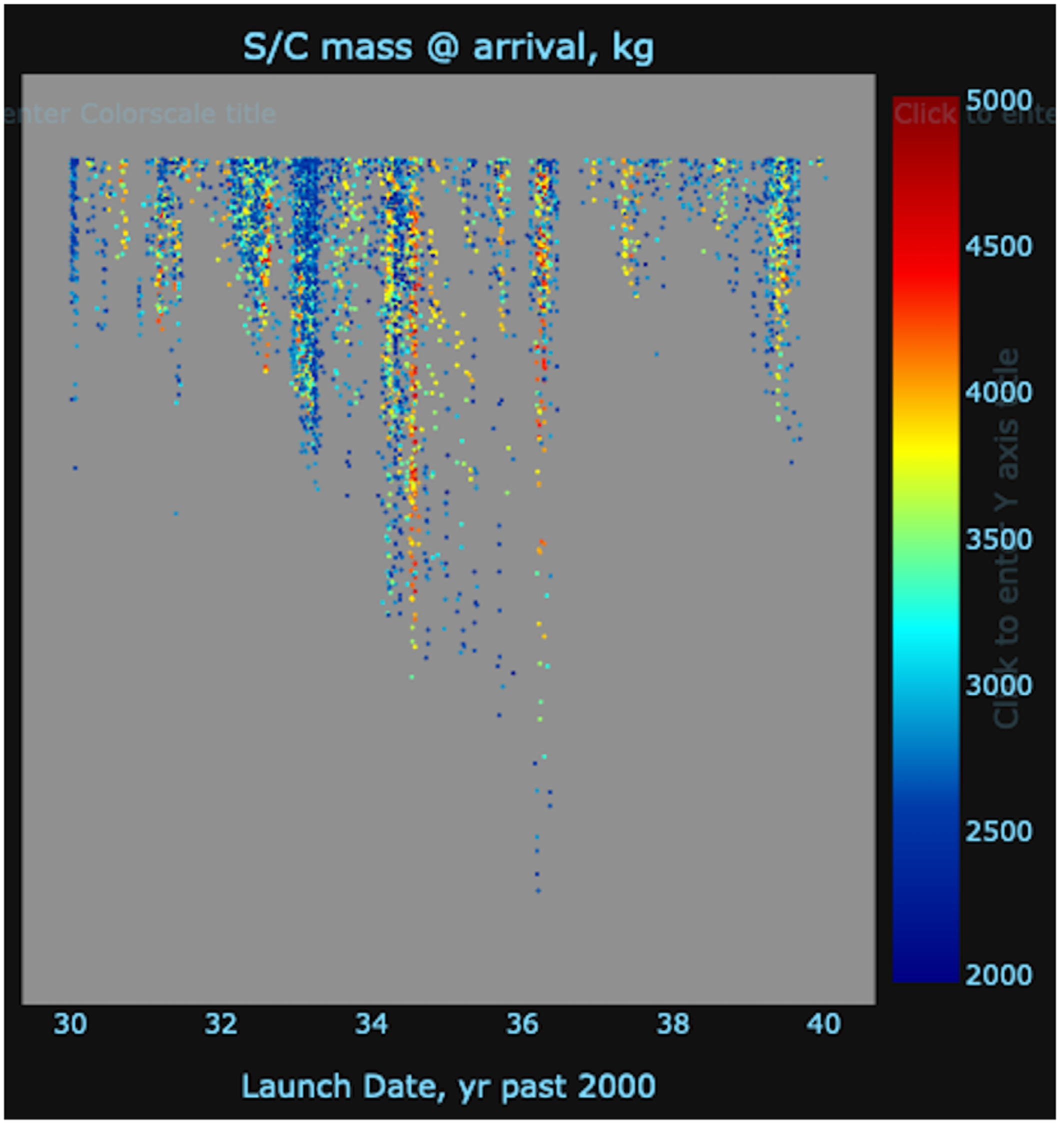

Figure 9. Screenshot of the parent trajectory overview visualization of the trajectory data set that has been used to generate the entry data set. It shows each launch opportunity plotted for the time of flight over the launch date, color-coded here in the values of the spacecraft mass at arrival. The color scale ranges from dark blue (low values) to dark red (high values).

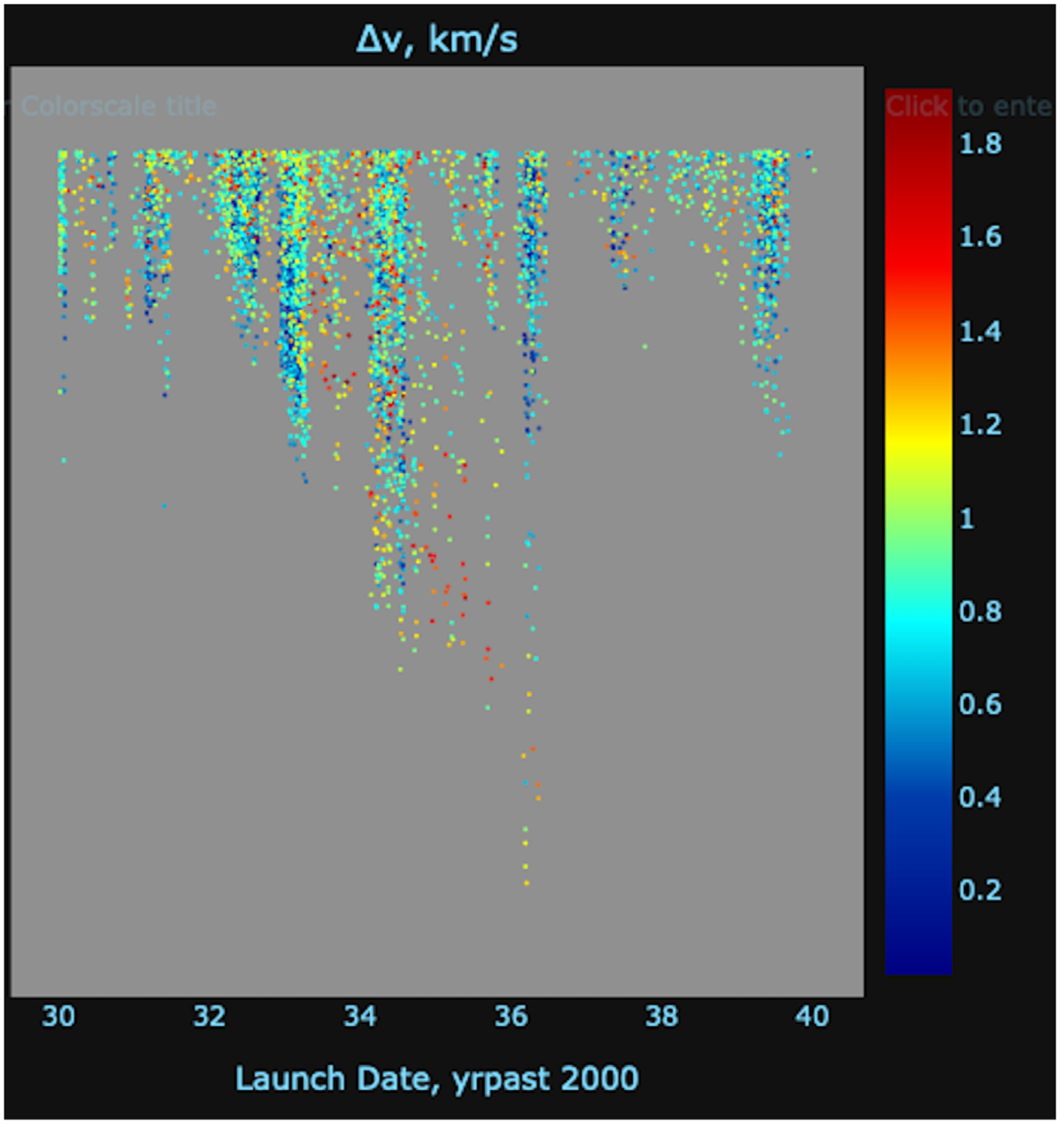

Figure 10. Screenshot of the parent trajectory overview visualization of the trajectory data set that has been used to generate the entry data set. It shows each launch opportunity plotted for the time of flight over the launch date, color-coded here in the values of the postlaunch Δv for transfer (from left to right). The color scale ranges from dark blue (low values) to dark red (high values).

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