Visualizing Europa

Design Research Report

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/ EXECUTIVE SUMMARY

Orbiter missions are complex endeavors that involve collaboration between scientists and engineers of differing domain expertise spread throughout the United States. Disseminating complex domain information such as orbital trajectory, scientific instrument data, and mission planning are tedious tasks given the limitations of today's technologies. Furthermore, conflicts of interest can arise between mission team members in an effort to collect science data for personal academic pursuits.

NASA Jet Propulsion Laboratory has come to us in search of a new ways to visualize orbiter data using immersive technologies to aid scientists and engineers in the upcoming Europa Clipper mission. Set for launch in the 2020s, this mission will investigate the habitability of Jupiter's icy moon, Europa.

After conducting seventeen interviews and assorted research activities with scientists, engineers, domain experts, and mission personnel, our team has identified three promising areas in the Europa Clipper mission that can benefit from design: science data collaboration, instrument scientist and orbital engineer collaboration, and understanding the past, present and future of the mission.

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/ INTRODUCTION

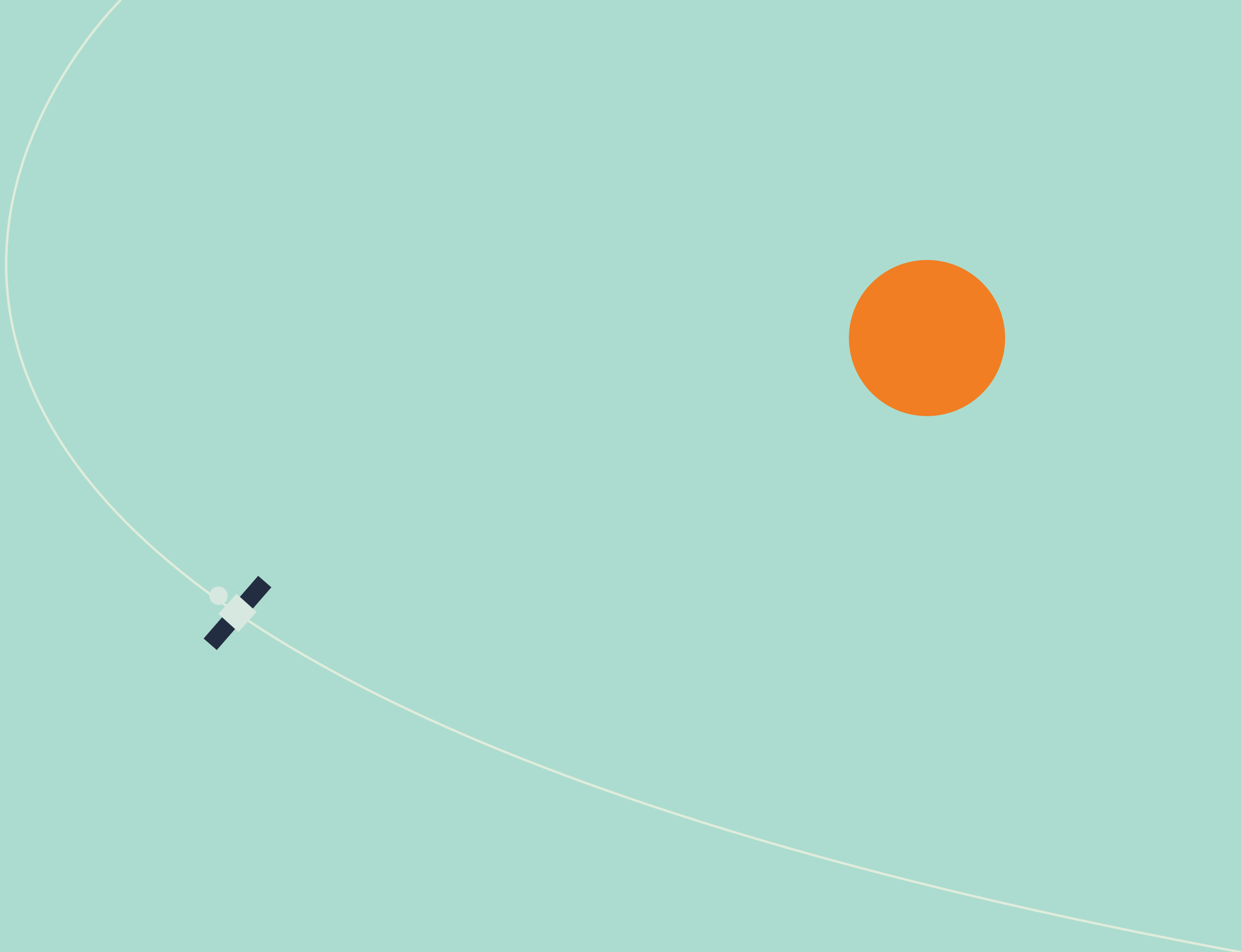
NASA Jet Propulsion Lab (JPL) builds spacecrafts designed to operate in orbit around distant planets and moons hundreds of millions of kilometers away. These orbiters are complex and require operational tools that allow people on Earth to understand orbiter data and command the spacecraft. People looking at orbiter data may be scientists interested in assorted scientific data about the body being orbited or engineers who are more concerned about the health and safety of the spacecraft. Because an orbiter has limited resources such as power and hard drive space, conflicts of interest can often arise between scientists, who want as much scientific data collected as possible, and engineers, who want to keep the orbiter healthy and intact.

JPL has found that using immersive 3D technologies such as augmented reality, virtual reality, and mixed reality holds much promise for increasing capabilities in understanding remote systems and improving mission collaboration as demonstrated by OnSight and ProtoSpace. However, these technologies have yet to be applied to orbiter missions, and JPL is still in the early stages of exploring what is possible.

Our team has been tasked with designing a tool to aid scientists and engineers in the Europa Clipper mission using these immersive 3D technologies. Yet, before an interface is designed and a technology is decided, we must learn from people at JPL, APL, and other participating institutions about the context of orbiter missions, and more specifically, Europa Clipper.

As of now, the Europa Clipper mission is in development by NASA and is comprised of an orbiter that is set for launch in the 2020s. After six years of cruising through space, Europa Clipper will position itself in orbit around Jupiter and will do a series of flybys around the icy moon, Europa. Engineers in the mission will ensure that the structural integrity of the orbiter is sound while scientists will collect and analyze scientific data that is relayed by the orbiter to further understand Europa's habitability: ocean, ice shell, chemistry and geology.

Through a series of research activities, we set out to learn as possible about how scientists and engineers work together in orbiter missions, how data is collected during these missions, and how operations typically happen. We also sought to understand more specifically about the Europa Clipper mission. Our research will not only help designers and engineers develop new orbiter interfaces at NASA JPL for the upcoming Europa Clipper mission, it will also help influence the interface design of future orbiter missions to come.



01 Background

To get acquainted with the complexity of orbiter missions and technology pertaining to our focus area, our team performed extensive secondary research and a competitive analysis.

/ LITERATURE REVIEW

Introduction

Orbiter missions are complex endeavors that require collaboration between a multitude of engineering and science stakeholders to accomplish a set of mission goals [1]. In an attempt to understand the complex nature of these missions and specifically, the Europa Clipper mission, our team has conducted secondary research in the following seven topics areas to aid in the creation of a design research question.

Orbiters

Orbiter spacecraft contain a series of complex subsystems that are controlled by different types of engineering teams on the ground who monitor telemetry, navigation, determination, propulsion, structural integrity, power, and telecommunications [1]. Coordination between all these teams keeps the spacecraft in control and in good operational health.

Scientific Instruments and Clipper

In order to complete the mission's scientific objectives, orbiters house complex scientific instruments that allow scientists to study celestial bodies in detail [1]. Separate science teams are responsible for each of these instruments and the scientific leads for each of these teams are known as PIs (Principal Investigators). Europa Clipper in particular has 9 different scientific instruments: E-THEMIS, MISE, EIS, UVS, REASON, ICEMAG, PIMS, MASPEX and SUDA and nine different PIs spread out across the country [2]. The goal of these instruments is to investigate the moon's degree of habitability by assessing its icy shell, ocean, composition, atmosphere, and geology [3]. However, each PI also has a unique set of scientific goals, in addition to the mission goals, that they would like their instrument to help achieve for their own personal academic research [4, 5].

Orbiter Constraints and Europa Clipper

Because orbiters have limited resources such as battery power, communications bandwidth, and data storage, prioritization of scientific data collection is necessary [1]. Furthermore, factors like the orbital path, orbital speed, and radiation can affect instrument health and data collection and transmission times [1]. For Europa Clipper in particular, there's a small window of time where data collection happens given that it is a "flyby" mission [3]. Fortunately, there's a much larger window to relay the data collected back to Earth to free up potential data storage space on the orbiter [3].

Immersive Technologies at NASA

In light of planning complexities in mission operations as demonstrated in Mars Exploration Rover Surface Operations, NASA JPL has investigated the use of new 3D immersive tools such as HoloLens to see whether Mixed Reality (MR) can aid in mission operations [6,7]. Applications designed internally within the NASA Jet Propulsion Lab like OnSight and ProtoSpace provide users with immersive visualizations that facilitate new ways of monitoring complex data to increase efficiency and potentially improve mission collaboration [7]. However, this technology has yet to be applied in the context of orbiter missions.

Effective Data Visualization Techniques

For our project in particular, communicating orbiter health and scientific data collection during the Europa Clipper mission will require an understanding of what makes effective data visualizations. Data journalist David McCandless describes this as a balance between information, story, goal and visual form [8]. Jeffrey Heer, a world-renowned data visualization expert, also describes effective visualizations as something that takes advantage of the innate ability we as human beings to understand geometric shapes and patterns [9]. Our team also looked into Heer's categorization of data visualizations and his critique on common examples that serve specific functions [10]. This exploration has given us frameworks to reference for future design considerations.

Design of 3D Immersive Interfaces

Finally, understanding what 3D immersive technologies exist to create effective visualizations to aid in mission operations and collaboration will be beneficial as well. In light of this, we explored O'Connell's latest text on designing new immersive technologies such as Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) [11]. As he describes, in MR the viewer sees virtual objects that appear real and are accurately mapped into the real world while in AR everything you see is real, with an extra data layer superimposed into your field of view without taking the environment into account [11]. His classification and use cases for different immersive technologies will help our team identify potential correlations in the data we capture to drive our design direction in the future. Our team is aware that using 3D immersive technologies may not create a viable solution; however, being cognisant of their existence is important for determining a future design direction.

Conclusion

In light of this research and our project requirements, our team will be exploring how we might be able to design a visualization to aid scientists and engineers in orbiter mission collaboration. These research findings have enabled us to craft a design research question and a specific set of primary research goals to drive our design process forward around this topic space.

/ COMPETITVE ANAYLSIS

In order to better understand 3D spatial interaction, we conducted a competitive analysis (both quantitative and qualitative) of three applications that either features astronomical exploration or serves the similar target population, namely, Google Earth VR, Galaxy Explorer, and Lunaserv Explorer. Intentionally, we selected applications from different mediums to help inform our design decision and assess the three applications via HTC Vive, Hololens and web browsers separately. Google Earth VR allows the user to view points of interest, geography and topographical information about the Earth. Similarly, Galaxy Explorer hosts a solar system exploration experience in MR that allows the user to explore and interact with the Milky Way Galaxy and all the planets in Solar System. Lunaserv Explorer is a 2D web-based application currently used by NASA scientists to explore a variety of scientific data on different celestial bodies.

In terms of metrics of performance, we selected six tasks that we identified as potential inspirations for our interaction design, which were broad enough to encompass interactions for both 3D(MR/VR) and 2D data visualization tools. The six tasks included: launch the application, navigate the main menu, zoom in and out of celestial bod(ies), navigate to points of interests, learn information about a celestial body, and exit the application. The heuristics we used for each of tasks were inspired by the Nielsen Norman Group, although we adjusted them slightly to better fit the scope of 3D design: feedback, information architecture, user control, consistency, error prevention, intuitiveness, recognition, minimalism, and aesthetics.

All team members have tested the three applications to gain an understanding of the strengths and weaknesses of these tools, and have documented our assessments and takeaways individually to avoid follow-along biases. Later we gathered the insights together to single out the critical findings. Overall, the immersive experience of space exploration confirmed our assumption that 3D technologies could significantly aid in tasks that demand spatial awareness. The key takeaways for each application can be viewed on the next page.

Google Earth VR

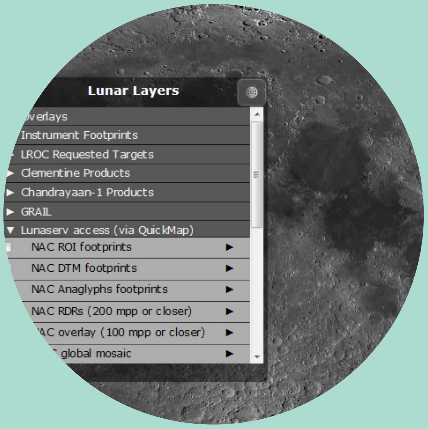
The intuitive interactions, smart use of spatial information architecture (IA) and pleasing aesthetics provided by Google Earth VR constituted great inspirations for our team in determining the flow and hierarchy of visualization for future design.

Type: Virtual Reality

Galaxy Explorer

Despite the stunning visuals and interesting interactions, Galaxy Explorer in MR exposed us to limitations and constraints of using HoloLens that were very informative for us to consider in hand gesture and gaze interaction design.

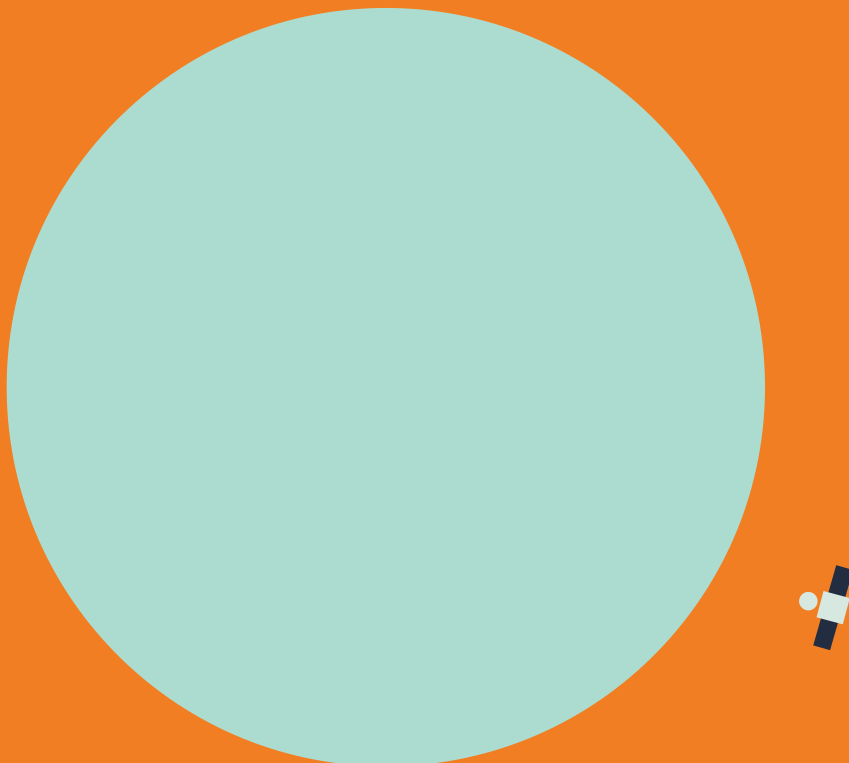
Type: Mixed Reality



Lunaserv Explorer

Although Lunaserv was one of the most widely accepted tools by scientists at JPL, due to its poor performance in basic usability heuristics, our team felt this system was more "what not to do" rather than "what to do" for our design prototype.

Type: Web Application



02 Research

To build empathy and a better understanding of the Europa Clipper mission, we performed a series of design research activities with engineers, scientists, domain experts, and Europa Clipper mission personnel.

Research Question

How might we effectively **visualize** the **Europa Clipper mission** for *scientists* and *engineers* to aid in **mission collaboration?**

/ GOALS

To answer our research question, we created a set of research goals to help us craft our design research activities. These goals also helped us stay focused on our research question.

01 *To uncover how scientists and engineers prioritize orbiter data to inform what would make for a useful visualization.*

Prior to generating a design, we needed to know exactly what kinds of orbiter data scientists and engineers found most important in orbiter missions to perform their job.

02 *To understand the relationship between engineers and scientists in an orbiter mission to inform the context of use.*

NASA JPL informed us that there were conflicts of interest between scientists and engineers in missions. We wanted to learn about the origin of this tension and uncover what their relationships were like in the context of orbiter missions.

03 *To learn about the context of the Europa Clipper mission to allow us to choose an appropriate collaborative technology.*

In order to design useful concept using the right technology, we had to learn about the Europa Clipper mission and the different contexts in which collaboration will happen between mission stakeholders.

/ PARTICIPANTS

Scientists

People conducting scientific research pertaining to the Europa Clipper Mission and other similar orbiter missions.

Engineers

People who maintain the health and safety of spacecraft and rovers on NASA missions.

Domain experts

People who have extensive domain knowledge in aerospace interface design, space operations design, immersive design, and data visualization.

Mission personnel

Personnel at NASA who are not scientists or engineers, but are necessary to successfully conduct a mission.

Additional Notes

The Europa Clipper mission is still in its early stages of development and therefore the official mission team has not yet been formed. We have learned that scientists who have either designed or have done significant research on scientific instruments being implemented on Europa Clipper will likely be on this team. NASA JPL has also informed us that engineers on past and current missions like Mars 2020 will likely join the Europa Clipper mission. Therefore, our research participants could potentially be both experts and direct users of our interface in the future.

/ METHODS

We employed three unique design research to effectively meet our research goals.

01 *Semi-Structured Interviews*

A semi-structured interview is a method in which we prepare a set of questions for a set of hand-selected participants and experts to answer in a semi-structured, conversational way.

02 *Closed Card Sort*

A closed card sort is an activity in which participants sort a collection of cards into predefined categories.

03 *Iterative Diagram*

An iterative diagram is a method used to fill in the blanks of knowledge that your team does not understand in regards to a topic.

/ METHOD 01

Semi-Structured Interviews

Explanation

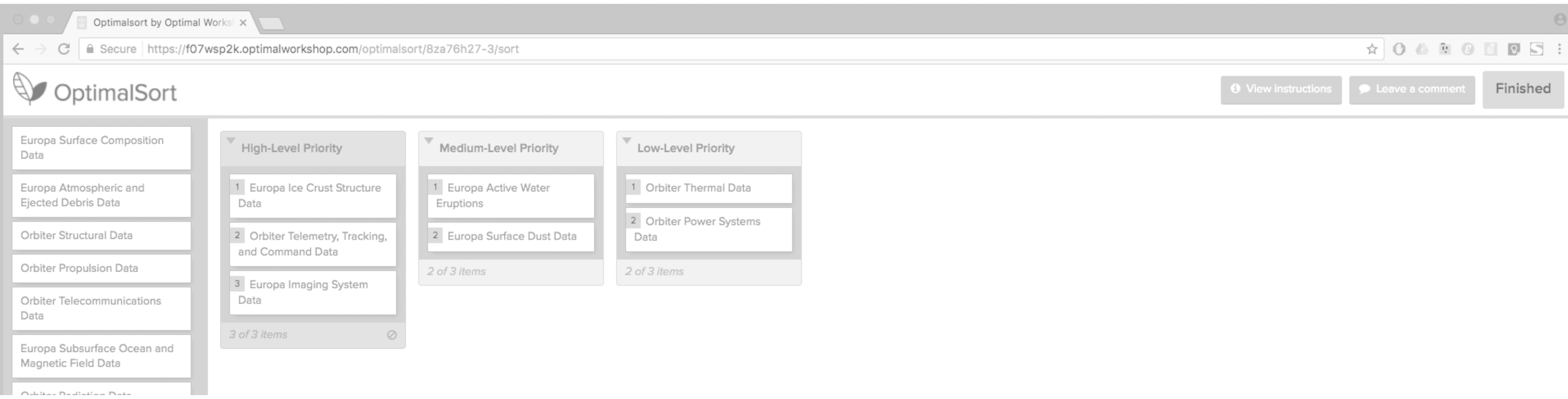
Semi-structured interviews helped our team understand the context in which scientists and engineers collaborate with each other in NASA orbiter missions. Specifically, we learned about their working environment, their relationships, tools, data needs, processes, as well as different scenarios in which collaboration takes place. It also helped us build empathy with those we would be potentially designing for in the future.

Time

Thirty minutes to one hour

Participants

Scientists, Engineers, Domain experts, Mission personnel



Closed Card Sort

Explanation

A remote closed card sort allowed our team to assess how NASA scientists and engineers prioritize different types of orbiter data in three different mission-based scenarios: safe mode, nominal mode, and unexpected discovery. After presenting the participant with a scenario, we asked them to sort cards with different types of orbiter data into high, mid, and low priority categories. However, they were only allowed to place a total of nine cards: three in each category. This was to simulate an orbiter's limited resources in a mission. In each scenario, we asked a series of questions to learn why the participant sorted the way they did and if there was any data or categories we overlooked. The data derived from this activity helped us see if data prioritization in orbiter missions is scenario dependent and whether or not these two groups have a similar mental model of said prioritization.

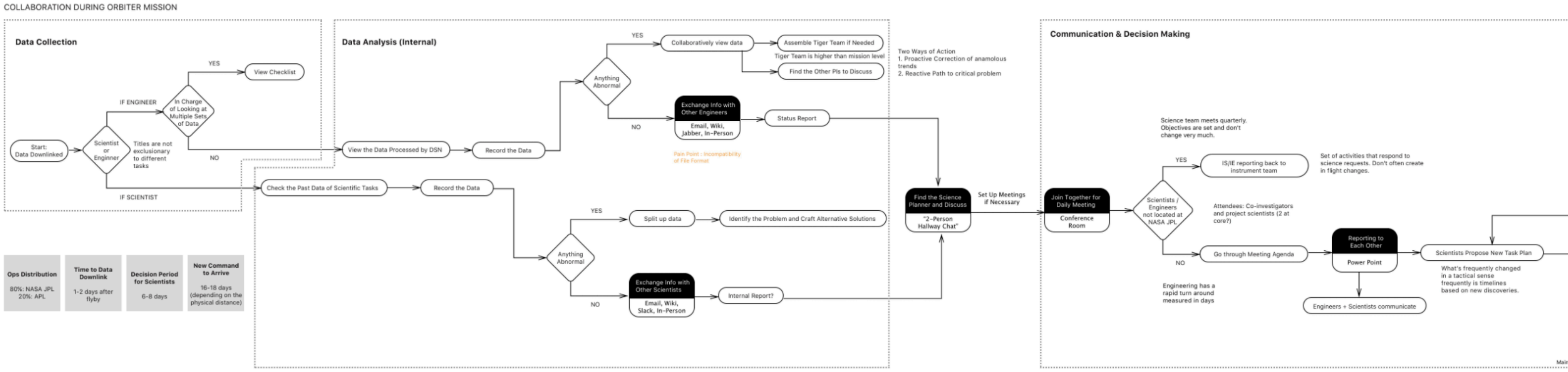
Time

Thirty minutes

Participants

Scientists, Engineers

/ METHOD 03



Iterative Diagram

Explanation

Given the complexity of our problem space, we saw value in presenting NASA engineers and scientists with a visual diagram that was derived from our primary and secondary research findings to allow us to receive ongoing critical feedback of our team's understanding of the collaborative relationship between scientists and engineers. In this method, we presented each participant with a visual diagram that represented our current understanding of how scientists and engineers collaborate in NASA orbiter missions. We then asked participants a series of questions and received critical feedback on our diagram and added additional content to it based on what was shared with the team. Over time, the diagram evolved as we collected more primary research data. This was an effective way of quickly obtaining rapid feedback on our team's mental model of this complex problem space.

Time

Thirty minutes

Participants

Scientists, Engineers, Mission personnel

03 Results

Following our seventeen interviews, four card sorting activities, and five diagramming exercises, our team synthesized our findings into series of insights.

/ INSIGHTS

From affinity diagramming seventeen interviews, conducting four card sorting activities, and creating five iterative diagrams with engineers, scientists, and domain experts, our team generated over ninety themes from over two-hundred codes of data. These themes were distilled into these insights.

01 ***In the face of mission uncertainty, there's conflict between NASA heritage and a need for new tools.***

02 ***Scientists want to collaborate with each other to create knowledge, but are anxious about missing out on a lifetime of academic achievement.***

03 ***Personal academic goals can prevent new scientific discoveries from happening.***

04 ***Although there's consensus that orbiter health and safety are necessary to make science happen, engineers will do everything possible to stretch these limits for the sake of science.***

05 ***Despite the geographic separation, mission stakeholders will go to great lengths to communicate face-to-face for the purpose of mission success.***

06 ***New tools need to support the political nature of collaboration at NASA, and not just the data needs.***

07 ***From piloting spacecraft to verifying scientific discoveries, both engineers and scientists require data redundancy and variety to perform mission tasks.***

08 ***To accommodate expected uncertainty in missions, all personnel and the tools they use have to be flexible and adaptable.***

09 ***There's a communication gap between instrument science teams and spacecraft engineers, so much so that middlemen must relay information back and forth.***

10 ***Given the ramp up, ramp down nature of the flyby missions, tools must accommodate the emotional valence, time pressure, and difference in workload.***

11 ***Scientists seldom know about the intricacies of neighboring scientific instruments and the data they collect in the same mission.***

12 ***There's a strong tension between mission nuances and NASA's desire to create structure in their systems and processes.***

13 ***Mixed reality should only be used if the world needs to be taken into account, while virtual reality should be used for the purposes of immersion in another context.***

/ INSIGHT 01

In the face of mission uncertainty, there's conflict between NASA heritage and a need for new tools.

Explanation

From placing a man on the moon to digging for liquid water on the Martian surface, the systems, tools, and personnel at NASA have a legacy of scientific achievement to live up to. To minimize the inherent risk and uncertainty in missions, there's a tendency to use systems that have a historical track record of success which is known as "heritage." Tools and systems with high heritage have a proven track record of success and are often times reused in future missions to mitigate risk. This tendency makes the creation and adoption of new tools at NASA to be a problematic endeavor. Therefore, designers and developers at NASA must take the extra effort to prove the efficacy of their designs through extensive user testing and simulation with mission stakeholders to build heritage.

Evidence

"No set way of how to operate spacecraft, just rules of thumb."

"There's decades of experience that leads us to doing things in a certain way."

"NASA likes to use instruments that have a lot of 'heritage'."

"AR/VR is associated with the entertainment industry. They could very skeptical."

/ INSIGHT 02

Scientists want to collaborate with each other for the greater good of science, but are anxious about missing out on a lifetime of academic achievement.

Explanation

Planetary scientists, astrobiologists and astronomers spend much of their academic careers studying celestial bodies based on data collected from scientific instruments on NASA spacecraft missions that seldom happen more than twice a century. Often times, academic careers are dependent on the collection of specific data sets during missions, which can lead to future publications and academic achievements. For Europa Clipper, NASA has mandated an open data policy which means that each instrument science team will no longer need to ask permission to access the data sets of other instrument science teams. Although scientists are altruistic about this new open policy change for the sake of scientific discovery, they are also anxious about “getting scooped”, or having their data published in future papers by other scientists in the mission.

Evidence

“People build their entire academic careers around these missions.”

“You are lucky if you see two of these missions in your lifetime.”

“This project has gone to great lengths to make it so that everyone is actually working together.”

“The more open the data is, the more people work on it, the more science is done.”

“[Scientists] realize they are part of something way beyond them.”
“Scientists who are not in the nitty-gritty, they can pluck easy nuggets [from the data] and publish things easier”

/ INSIGHT 03

Personal academic goals can prevent new scientific discoveries from happening.

Explanation

Scientists participating in NASA missions only have one or two chances in their entire academic careers to collect new data from distant worlds and celestial bodies pertaining to their work. Because of their motivation for academic achievement and recognition, missions with multiple instrument science teams such as Europa Clipper are politically charged. Each scientist is motivated to negotiate in favor of their science so that they may contribute to their academic domain. To balance these scientific demands, a project scientist serves as a "science wrangler" on missions and prioritizes the needs of scientists in accordance with a set of mission science goals set by the science teams. However, these in-person negotiations with the project scientist can directly influence the manner in which these science goals are met, which can directly prevent scientific discoveries that fall outside the prioritized list from happening.

Evidence

"Their careers are hanging on it [mission success]."

"You are lucky if you see two of these missions in your lifetime."

"Are their lingering bad feelings from this process [data collection prioritization]? Oh of course."

"Scientists increase margin of data they need, even though they don't need that much."

"Each principal investigator has their own objectives."

/ INSIGHT 04

Although there's consensus that orbiter health and safety are necessary to make science happen, engineers will do everything possible to stretch these limits for the sake of science.

Explanation

NASA goes into space to make scientific discoveries. Although engineers' utmost concern in missions is to ensure the health and safety of the spacecraft are sound, they are cognizant of the importance of making science happen. In nearly every NASA mission to date, engineers have made it a point to create robust spacecraft that survive well beyond their intended lifespan to ensure mission science goals are met. To balance the demands of multiple instrument science teams and mission science goals, engineers will do everything they can to execute maneuvers that lead to the best scientific outcomes. Often times after a spacecraft has achieved its main mission science goals, engineers will perform even more risky maneuvers that may jeopardize the structural integrity of the spacecraft to help scientists make new discoveries.

Evidence

"Level 1 science goals need to be solved to call the mission a success."

"If we don't know where the orbiter is pointing, science data is garbage."

"The engineers will take things into consideration, will carefully consider all the pros and cons, will create unique and innovative solutions for these things, and generally figure out some way to make this thing work."

"Once level 1 science goals are met, bonus science can be done."

/ INSIGHT 05

Despite the geographic separation, mission stakeholders will go to great lengths to communicate face-to-face for the purpose of mission success.

Explanation

Even though instrument science and engineering teams are spread all throughout the United States, they understand the value of face-to-face communication and will make it a point to meet in-person as often as possible. Participants in previous NASA missions spoke very highly of these types of interactions and described how they help everyone focus and achieve a sense of mission comradery. Current collaborative practices at NASA employ this type of interaction given its overwhelming favorability and historical success. From weekly instrument science team meetings to massive one hundred fifty people project science group meetings, teams will make an effort to make face-to-face happen in missions.

Evidence

"Science team is pretty spread out, mostly at Universities"

"When science folks are collocated, it makes a huge difference."

"Information travels face-to-face. That information is the most valuable."

"They want to bond because they need each other... so they get more data alignment."

"The outer planets missions seem to all have a hallway chat philosophy."

"Science group meetings an opportunity for science groups to get together and synergize."

/ INSIGHT 06

From piloting spacecraft to verifying scientific discoveries, both engineers and scientists require data redundancy and variety to perform mission tasks.

Explanation

From navigating through the uncertain environment that is space to identifying instrument nuances to creating ground-breaking scientific knowledge, data redundancy is necessary at NASA.
Given the high-stakes nature of these missions, NASA understands that it has an organizational responsibility to citizens of the United States and the entire scientific community to be thorough and redundant in the analysis and dissemination of data. After all, success and failure in missions can determine future mission funding and public perception. As a result, scientists and engineers in missions are trained to analyze data from multiple sources to validate their findings and prove that their decision making process is sound.

Evidence

"Important to keep repeating the same data over and over just to verify the measurement is real."

"I wanted to get pictures because they are very important for navigation and attitudinal control"

"Using the instruments together gets you better objectives than used alone."

/ INSIGHT 07

To accommodate expected uncertainty in missions, all personnel and the tools they use have to be flexible and adaptable.

Explanation

NASA missions are inherently uncertain. Often times mission teams will not know about the mission environment until a spacecraft reaches its intended destination. Unknown factors such as radiation, scientific instrument performance and unprecedented scientific events like the erupting water plumes change the mission plan, schedule, and timeline. Mission stakeholders understand and expect mission uncertainty, therefore the processes and systems in place at NASA must account for the ever changing nature of missions. They must be both flexible and adaptable to these situations.

Evidence

"Schedule is completely scratched when something interesting has been found."

"...may change the priorities of science based on what we discover and that's a big deal"

"Fundamentally we don't know what the environment is like - the radiation at least."

/ INSIGHT 08

New tools need to support the political nature of collaboration at NASA, and not just the data needs.

Explanation

NASA missions are politically charged in both a microscopic and macroscopic sense. Scientists' academic careers are dependent on the successful collection of data that is collected from instruments on NASA spacecraft. These personal motivations fuel intense political negotiation and debate that directly affects the success of the mission. Additionally, on an organizational level, mission leads must represent the best interest of NASA and ensure the most important science goals are met to maintain the respect of the current political administration and United States citizens for future funding. As a result, mission stakeholders have unique political motivations that cannot be ignored or disregarded. Apart from providing mission stakeholders with the right data, tools need to account for the political motivations that drive different types of collaborative actions that happen in missions.

Evidence

"This is a good way to start a fight."

"[Fear of] getting scooped."

"Scientists who are not in the nitty-gritty, they can pluck easy nuggets [from the data] and publish things easier"

/ INSIGHT 09

There's a communication gap between instrument science teams and spacecraft engineers, so much so that middlemen must relay information back and forth.

Explanation

Given the geographic separation and vast array of domain expertise in missions, it is difficult for instrument science teams and spacecraft engineers at NASA to directly communicate with one another. To facilitate effective communication between the two groups, NASA employs instrument scientists (IS) and instrument engineers (IE). These individuals serve as the middlemen between instrument science teams and spacecraft engineers; they communicate demands, requirements, and relevant domain expertise to ensure mission success. The presence of these middlemen demonstrates that communication between instrument science teams and spacecraft engineers requires immense effort.

Evidence

"IS makes sure nothing falls through the cracks and identifies any miscommunications."

"IE makes sure information flows from one group to another."

"[IEs] know a lot more than we should, and we should not share everything with [the instrument teams]."

/ INSIGHT 10

Given the ramp up, ramp down nature of the flyby missions, tools must accommodate the emotional valence, time pressure, and difference in workload.

Explanation

Flyby missions like Europa Clipper are complicated in that they have long orbits with very short, critical periods of data collection. Unlike other orbiter missions, the high radiation environment around Europa gives the orbiter's hardware a limited lifespan, making each window of data collection imperative to achieve all desired scientific goals. Given this unique high-stakes context, tools must be designed in such a way to help mission stakeholders mitigate the stress and time pressure of each flyby.

Evidence

"There is a ramp up and ramp down period"

"There's more pressure with the first couple flybys because of more unknowns."

"A lot of things change from flyby to flyby."

"Once you're in the Europa environment, you're working against the clock"

"When making quick decisions, people need to trust each other"

"Shorter orbital periods crush everything together"

/ INSIGHT 11

Scientists seldom understand the intricacies of all scientific instruments in the payload and the data they collect in the same mission.

Explanation

Instrument scientists often have radically different domain expertise that do not share many commonalities. Yet, these differing expertises are necessary to collect to right data to validate ground-breaking scientific breakthroughs such as the discovery of life on other worlds. Despite all being in the same spacecraft's payload, instrument scientists often do not know about the intricacies of other scientific instruments and the data they collect in the mission. To make matters more complicated, these scientists often use their own tools to analyze their data, making their accumulated knowledge even more inaccessible to other instrument science teams.

Evidence

"The spacecraft is a big entity that has different teams working on different parts."

"Why do I need something that I can build myself?"

"I don't know what EIS [Europa Imaging System] does, but I assume it relates it relates to the level 1 science goal"

"So I don't recall all the level 1 science goals off the top of my head, but I know the ones that relate to my science."

/ INSIGHT 12

There's a strong tension between mission nuances and NASA's desire to create structure in their systems and processes.

Explanation

Every mission is different and comes with a set of nuances. These nuances are formed from mission-specific environmental challenges, team dynamics and even spacecraft configurations. As NASA attempts to create more structured and model-based systems and processes throughout their organization to facilitate better collaboration among mission stakeholders, they are constantly held back by the intricacies and systematic entropy caused by mission nuances. Mission nuances often force stakeholders to create their own tools and systems that conflict with NASA's desire for mission uniformity and structure. This poses a problem for NASA when it comes to re-purposing prior tools, systems and processes for future missions.

Evidence

"This project has gone to great lengths to make it so that everyone is actually working with each other."

"Each mission is its own. Different people and different technologies and different managers."

"Keeping internal temperature is very important"

"Our biggest problem is collaboration because most people here build their own tools"

"[Instrument] Principal Investigators are from different institutions."

"Need to figure out our visualization tools"

/ INSIGHT 13

Mixed reality should only be used if the world needs to be taken into account, while virtual reality should be used for the purposes of immersion in another context.

Explanation

Mixed reality is an immersive technology that is meant to be used for shared spatial awareness between users and face-to-face interactions. Therefore, should an interface not require users to participate with other nearby users or their immediate local environment, there should be no reason to employ it. The world would create unnecessary distractions that impede a user from performing tasks in immersive contexts. In contrast, virtual reality should be used for the purposes of escaping the world to an entirely new context.

Evidence

"Mixed reality let's you walk around"

"Protospace [Mixed reality application] users saw ability to discuss and problem solve unlike before."

"Virtual reality is like a 'dream machine' and is about 'escaping the world'."

/ GENERATIVE ARTIFACTS

As a part of our synthesis process, our team generated four unique research artifacts. These helped create meaningful visualizations of the data we collected from our research activities.

01 *Orbital Map*

This visualization maps out all relevant information pertaining to how the Europa Clipper orbiter will operate during each flyby.

02 *Journey Map*

This user journey map outlines how data collection, analysis, decision making, and execution will happen in Phase E of the Europa Clipper mission.

03 *Personnel Map*

The personnel map illustrates where mission teams are located and what their communications channels are between each other.

04 *Card Sort Chart*

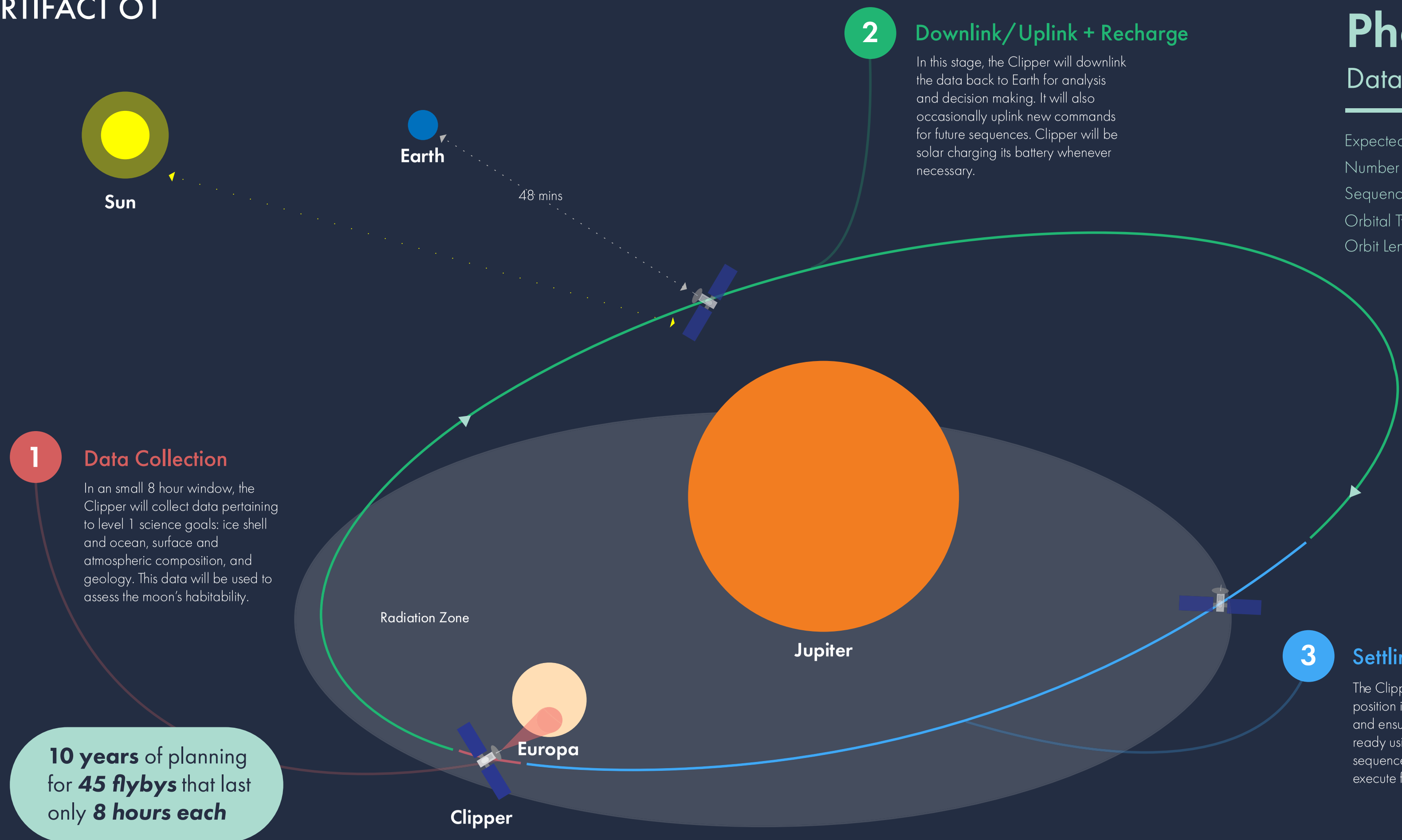
This chart summarizes our card sort findings and how data is prioritized in different orbiter scenarios.

/ ARTIFACT 01

Phase E

Data Collection

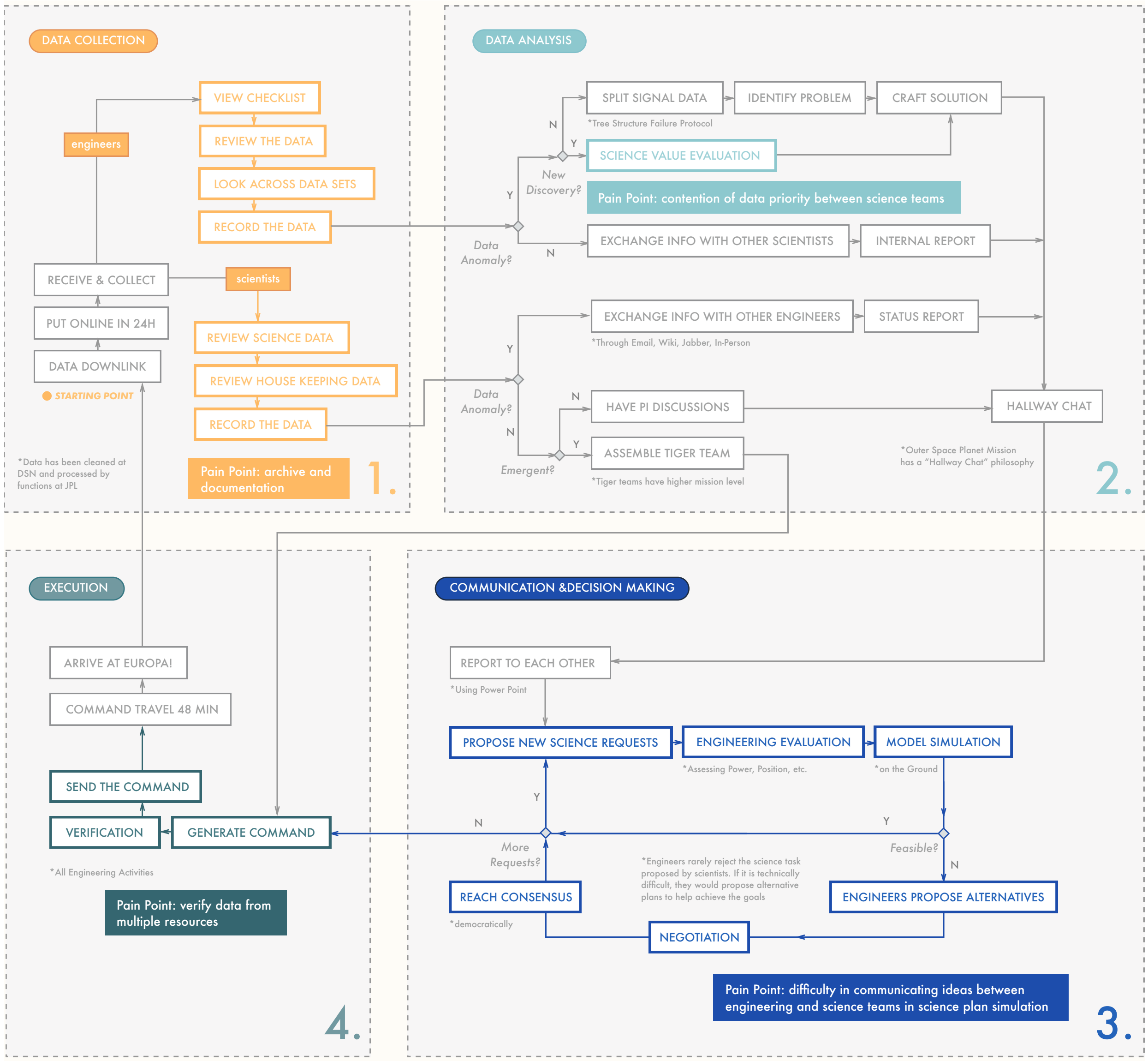
Expected Arrival **2026**
Number of Flybys **45+**
Sequences **1-4 months**
Orbital Type **Low Altitude**
Orbit Length **14 days**



Orbital Map

This map demonstrates how the Clipper orbiter will operate when it begins its orbit around Jupiter in Phase E of the Europa Clipper mission. Each orbit will be comprised of three maneuvers: data collection, up-linking and down-linking data while recharging with the solar array, and finally settling, or preparing the instruments for the next flyby. This diagram illustrates the high stakes nature of the mission given the small eight hour window of data collection.

/ ARTIFACT O2



***Instrument Engineers (IE) and Instrument Scientists (IS) will relay information throughout the mission between teams at JPL and instrument teams at third party institutions.**

Journey Map

This journey map illustrates the flow of data collaboration on an orbiter mission at NASA. It is derived from the iterative diagramming activity in our user research, which allowed us to identify key interaction moments, pain points and potential focus areas to move forward on.

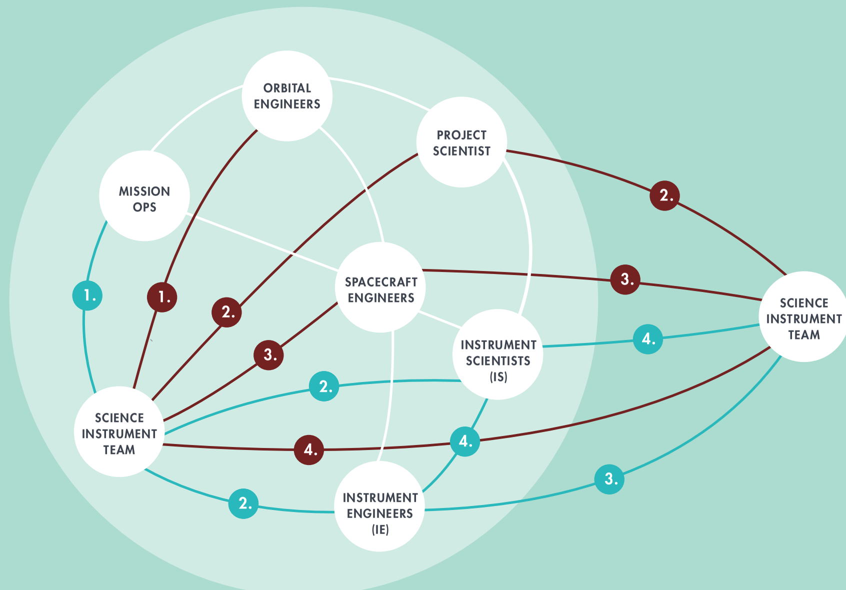
/ ARTIFACT O3

LEGEND

- Good relationship not needing more explanation
- Good relationship
- Pain points
- No lines - unknown relationship

1. "Engineers do not make scientific decisions"
2. Being located at JPL, not as crucial to be informed by IE and IS
3. "[IE + IS] are invaluable communication tools"
4. IS + IE work closely for their science instrument team

1. Scientists have high trust and faith in orbital engineers but there may be a communication gap. "'No' is usually not an answer."
2. Science Instrument Team seeks Project Scientist's attention to get what they want
3. Identified lack of regular communication between spacecraft engineers and science instrument team, but not an alarming pain point
4. Fear of "getting scooped" engendered mistrust between science teams. The lack of communication and understanding of how different science instruments work will also hinder science findings.



Personnel Map

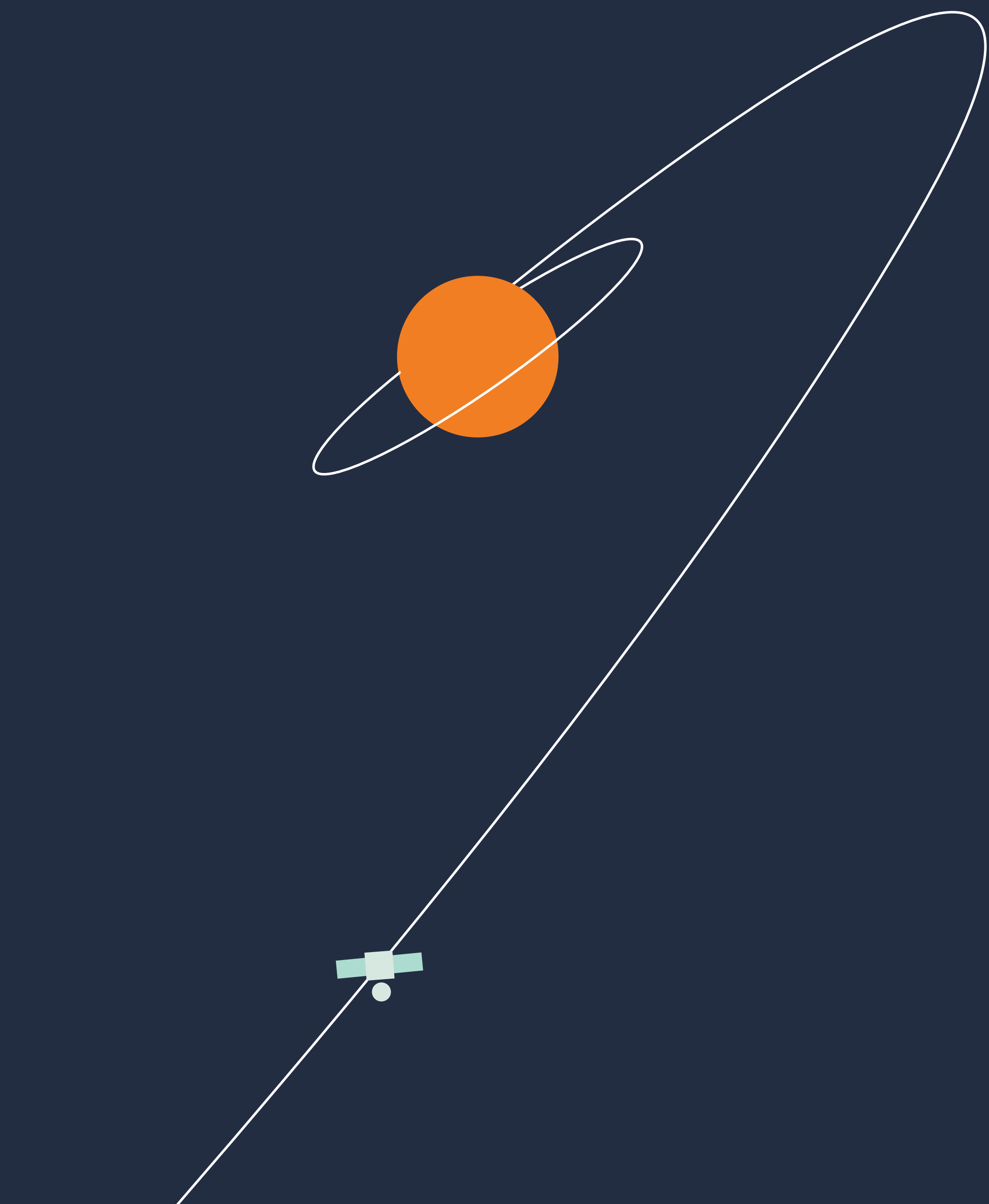
The personnel map summarizes our team's research on the inter-relationships of the Europa Clipper mission from a sociological lens. It shows where teams are located (engineering and science teams inside JPL and science teams outside of JPL) and how each cluster relates and feels about one another. Throughout our research, we have identified both positive and negative aspects of these relationships which would in no doubt affect how they collaborate with one another during the mission.

/ ARTIFACT O4

	Safe Mode Scenario 01	Nominal Mode Scenario 02	New Discovery Scenario 03
Insight	**Everyone knows protocols exist for when the spacecraft goes into safe mode.**	**Scientists do not necessarily know much about other scientist's instruments, and what they can collect.**	**People willingly throw the previous plan out in service of the level 1 science goals despite the amount of effort that went into the previous plan.**
Evidence	"When you're in safe mode, there's a protocol." "Want to know power, to know if the spacecraft will survive."	"I do not recall all the level 1 on the top of my head. But I know the one related to my science." "I don't know what EIS does, but I assume it relates to the level 1 science goals"	"The schedule is completely thrown out." "Can we go back?"
Highest Priority Data	Orbiter Telemetry, Tracking and Command Data Orbiter Power Data Orbiter Attitude Determination and Control Data	Europa Active Water Eruptions Europa Subsurface Ocean and Magnetic Field Data	Orbiter Telecommunications Europa Imaging System Europa Erupting Plumes and Exosphere Data Europa Active Water Eruptions

Card Sort Chart

The card sort helped us answer our first research goal: how scientists and engineers prioritize data at NASA. We found that overall, how people prioritize depends on the context of the data usage, and the personal agendas of the individual users. However, institutional structures can also come into play with what information people will seek out from the orbiter.



04 Discussion

Using our insights, we created a set of design principles and identified three focus areas in which scientists and engineers can benefit from design in the Europa Clipper mission.

/ PRINCIPLES

From our insights, our team crafted a set of design principles that are representative of our primary and secondary findings. They will be used to inform the direction of our design going forward.

01 *Embrace NASA's heritage*

02 *Acknowledge the politics*

03 *Socially translucent*

04 *Time sensitive*

05 *Emotionally aware*

06 *Just Redundant Enough*

07 *Adaptable and flexible*

08 *Immersive where it counts*

/PRINCIPLE 01

Embrace NASA's heritage

NASA has a rich history of pushing the limits of mankind. At the same time, tools, instruments, and systems at NASA have to build what's known as "heritage" by withstanding the trials and uncertainties of missions. The more heritage something has, the more it can be trusted in a mission environment. Therefore, we must not only embrace NASA's drive to push the envelope of what's possible, but we must also prove the utility and robustness of our design through extensive testing and simulation.

/PRINCIPLE 02

Acknowledges the politics

Politics will happen in NASA missions no matter what as a result of personal and organizational motivations. Therefore, the design must acknowledge these political motivations and tensions in an effort to improve collaboration between mission stakeholders.

/PRINCIPLE 03

Socially translucent

In an effort to improve mission transparency among stakeholders to facilitate better communication and collaboration, the design must make system actions and activities clearly visible among all teams to instill trust and empathy.

/PRINCIPLE 04

Time sensitive

Flyby missions, particularly ones with harsh irradiated environments like Europa Clipper make every orbit precious. Furthermore, Jovian missions embody a "hallway chat philosophy" at JPL that represents a fast, transient exchange of information between mission collaborators. Because of this, the design must be cognizant the limited time in the mission and take quick, time-sensitive, face-to-face interactions into account.

/PRINCIPLE 05

Emotionally aware

Flyby missions are high-stakes endeavors that require ample planning to get all necessary scientific data to call the mission a success. Because each flyby can provide a wealth of scientific data, this can cause immense pressure on mission stakeholders. The design must recognize the emotional valence of these types of missions in order to help users perform the right tasks in the right contexts.

/PRINCIPLE 06

Just redundant enough

From diagnosing problems with spacecraft to proving the existence of life on other worlds, redundancy is necessary at NASA given the high-stakes nature of missions. Therefore, the design must take this fact into account and provide redundant data in all appropriate contexts, but only when necessary.

/PRINCIPLE 07

Adaptable and flexible

NASA missions are inherently uncertain. Despite rigorous planning efforts, many missions often change. The design must easily accommodate the expected uncertainty of orbiter missions and a constantly changing mission plan, schedule and timeline.

/PRINCIPLE 08

Immersive where it counts

Some things just work better in 2D. Furthermore, many new immersive devices have a wide range of hardware and software constraints that impede intuitive 3D interactions. Because of this, the design should only employ 3D immersive environments when necessary.

/ OPPORTUNITIES

After looking through our insights, principles, and generative research artifacts, we identified three promising areas that we believe design can aid in mission collaboration for Europa Clipper.

01 *Science data collaboration*

NASA has made a significant push to get scientists to share their data with each other during missions. However, scientists remain hesitant about sharing data with each other, which poses an interesting design challenge.

02 *Instrument scientist and orbital engineer collaboration*

Communicating complex concepts between instrument scientists and engineers can benefit from new tools that can render quick simulations for planning and explanatory purposes.

03 *Understanding the past, present, and future of the mission*

Being able to communicate the position of the orbiter in a temporal context could greatly improve collaboration between teams.

/ OPPORTUNITY 01

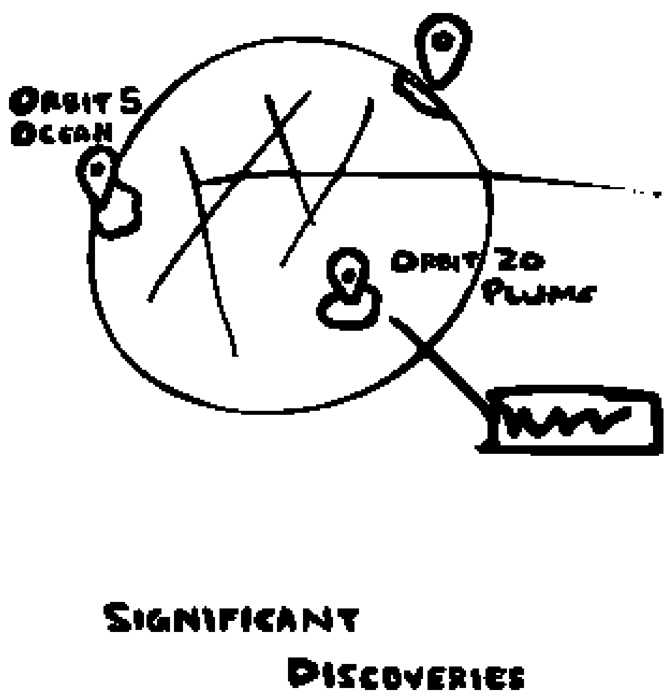
Science data collaboration

The Clipper features a payload of nine scientific instruments to help achieve mission science goals. Each instrument has its own science team that individually holds specific intentions and critical academic goals in the mission. The relativity of distinct data sets necessitates collaboration between science groups, which has witnessed issues of social translucency. Acknowledging the politics and the attempts to encourage data sharing, we are interested in pursuing solutions to bolster data collaboration between science groups.

Potential Concept

After the spacecraft reaches Europa, many interesting discoveries worthy of investigation will likely arise that are more relevant to some instrument groups than others. However, other scientists will want to examine the data to determine usefulness to their research.

Due to the fear of getting "scooped" on a discovery, this concept would establish more social translucence by displaying how many, and who exactly is viewing an instrument group's data. At the same time, it would immersively display which parts of the data other people are interested in and may potentially want to publish.



/ OPPORTUNITY 02

Instrument scientist and orbital engineer collaboration

Scientists and engineers are constantly collaborating in orbiter missions, especially when it comes to planning science tasks. Engineers strive to assist scientists in achieving science goals by simulating the proposals and crafting alternative solutions to the conundrums. However, engineers find it difficult to communicate and report the orbital simulation results back to scientists, which constitutes a potential problem space for our design.

Potential Concept

This concept was inspired by hallway chat discussions that happen during outer planets missions. From what we have learned, mission planners can have trouble conveying highly technical ideas to others that are not already steeped in their work. Part of this is that the data, and by extension the knowledge, is rooted in data that does not comfortably fit on a piece of paper or computer screen.

By providing a tool that creates an easier way of rapidly prototyping complex space-related information like orbital trajectories between communities of experts within the Clipper mission, people can come to decision quicker and more effortlessly.

/ OPPORTUNITY 03

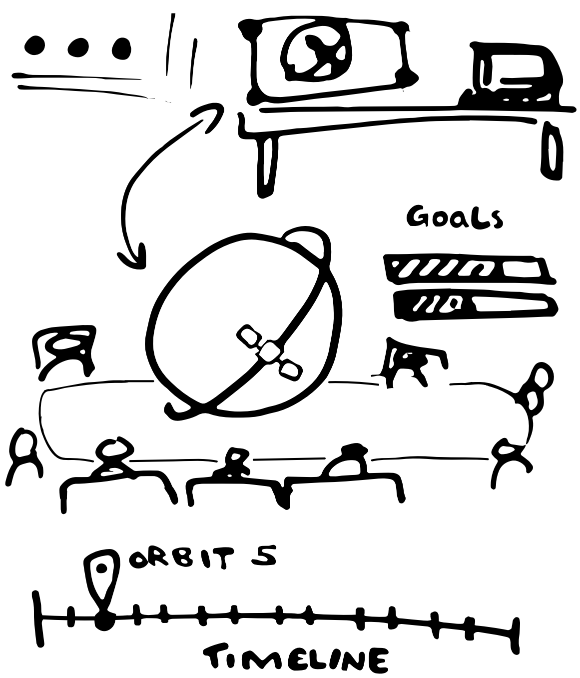
Understanding the past, present and future of the mission

Having observed the efforts of both science and engineering teams at JPL to document and make sense of the current state of the mission in 2D forms, we have identified opportunities in helping them better contextualize and visualize the state of the mission. In particular, during Phase E, team members need a means of quickly getting up to speed on what has happened, what is currently happening, and what will happen to the orbiter given its trajectory. Showing a unified visualization of the orbiter in conjunction will science goals could provide a handy means of reference and conversation for all team members, especially for those who are remotely located.

Potential Concept

Much of the data that a NASA mission generates is inherently associated with points in time. Each mission currently carefully archives this information to be used in mission simulations and future publications.

We identified the pain point of exploring this vast trove of data and making sense of it. This concept would leverage the inherent temporal nature of the data, and allow people to immersively explore the mission past, present, and future. Furthermore, within each time point, people could explore all the data collected at that point in time, and make sense of it more naturally.



/ NEXT STEPS

We are just starting to move into the next phase of refining and leveraging our design principles for ideation. Currently we have mapped out three major areas that could use improvement at NASA: data collaboration between scientists, collaboration between instrument scientists and engineers, and visualizing data from the past, present, and future. We will explore and evaluate each to determine which one will yield the richest design opportunities.

Regarding our principles, they are largely established. However, we will continue to refine them as we learn new information. Ideation and prototyping may reveal a principle to be unworkable or unclear, or we may need to augment one in some way. Additionally, we expect to add a few more in light of the tool we choose to develop our final concept with. Each device is nuanced in the interactions that it allows, and the experience it provides. We will need to provide ourselves constraints to ensure we design effectively.

Lastly, we will be familiarizing ourselves as quickly as we can with 3D and immersive experience prototyping methods. We will initially start with low fidelity methods such as card board and paper prototypes. But we will eventually move to more high fidelity prototypes, which will require skill and finesse to execute.

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