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Connecting Science Goals To Payloads for Titan Exploration: A Focus on Geomorphology

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Abstract

Titan's unique and rich geomorphology gives rise to a large number of hypotheses and theories about the origin and development of Saturn's largest moon. For the first time, we present a complete, holistic Science Traceability Matrix (STM) linking high-level scientific objectives, through measurement requirements and specifications, directly to specific instrumentation. This STM serves as a comprehensive guide, consolidating all observation requirements for Titan into a single resource. It highlights how a select number of instruments can address a broad spectrum of scientific questions. Furthermore, the wide-ranging nature of this STM shows the key role connectivity science, where multiple different observations are combined, could play in multi-component missions, such as the proposed Astraeus mission - with an orbiter, aerial flying vehicle and lake submersible - which this work supports. We demonstrate that the step-by-step science-driven approach of an STM is critical to the development of an effective space mission.

We analysed previous missions and proposals, and selected the most relevant instruments and observation techniques to ensure our STM would lead to the capture of high-quality data on Titan's sub-surface, surface, atmosphere and magnetosphere. In this paper, we specifically consider the surface and subsurface processes on Titan which are of key scientific interest, and address geomorphological processes such as cryovolcanoes and hydrocarbon lakes. We analysed existing data from the Cassini-Huygens mission, and proposed methods of further study capable with our selected instruments.

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Keywords:

1. Introduction

1.1. Why Titan?

It is known that Titan, Saturn's largest moon, has unique features: a dense atmosphere and a hydrocarbon cycle similar to the water cycle on Earth. But this is not the only thing that makes Titan one of the most interesting objects for the scientific community. Valuable scientific data obtained during the Cassini-Huygens mission initiated the understanding that Titan is not just an icy moon, but primarily a geologically active object, as evidenced by the variety of landforms traced in radar images obtained by the Cassini orbiter.

Each structure, be it a hydrocarbon river system or a dune field with traces of impact processes, tells the story of the moon's formation, and therefore needs to be studied more thoroughly and comprehensively, both by remote sensing and in-situ [1].

1.2. What are Science Traceability Matricies (STMs)? And why did we choose this method?

The Science Traceability Matrix is a method developed by engineers at NASA's Jet Systems Laboratory specifically for designing complex, multi-level space science missions. If a global and detailed approach to setting scientific goals and objectives and identifying the best methods to achieve them is required, The Science Traceability Matrix (STM) is the most appropriate research method.

When analysing Titan, its atmospheric, surface and subsurface processes need to be considered as a single active system in close relationship to each other, because they ultimately form the appearance of the satellite as we know it. This paper analyses the interaction of Titan's physical and chemical processes as the cause of the moon's rich geomorphology.

1.3. Context

In 2019, using data from the Cassini-Huygens mission, a team from NASA's Jet Propulsion Laboratory and Arizona State University managed to produce the first geologic map of Titan. With this achievement, it became clear that Titan's surface is morphologically sculpted by a rich variety of eolian, pluvial, fluvial, lacustrine, tectonic, impact, and possibly cryovolcanic processes.

2. Environment on Titan

Thanks to the Cassini-Huygens mission, it is known that Titan's surface is rich in various forms of relief. Among the exogenous factors shaping the geomorphology of Titan, we can highlight atmospheric precipitation, atmospheric pressure, impact ("impact with other objects"), aeolian erosion, erosion due to the activity of river systems, lakes and seas, Jupiter's and Sun's influence and possibly cryovolcanic activity.

To better understand Titan's geology and geomorphology, we need to start with its unique atmosphere. The nature of Titan's dense atmosphere, rich in methane, nitrogen and, to a lesser extent, other compounds, ten times denser than Earth's, is not fully understood and has given rise to many debates and theories. The result of ongoing physical and chemical processes in Titan's atmosphere is a specific haze recorded by spacecraft from previous missions. The results of complex energy chemistry processes are condensed and then deposited on the surface of the moon, directly affecting its geology and external appearance.

Similar to Earth, clouds and even entire cyclones form in Titan's atmosphere and fall on Titan as methane rains, forming river systems, enriching high-latitude lakes and seas with hydrocarbons, and creating fluvial erosion of the surface. Hydrocarbon lakes are concentrated mainly at the poles of the moon, prevailing at the north pole. Ligeia Mare, Kraken Mare and Mackay Lacus are among the most notable lakes, thanks to radar photography. Their edges are irregular, which may also indicate the presence of karst processes similar to those that occur on the Earth and and on the rupture of surface layers by deep liquid reservoirs. [2] .

But this is not the only way of atmospheric influence on the formation of Titan's relief. Atmospheric pressure at the surface is 1.5 times higher than at the Earth, which also probably contributes to the formation of flat relief forms, and does not favour the development of sharply pronounced relief forms, as for example on the Earth or Mars. With the radar imaging of Titan's surface, it was possible to establish that the average height difference is no more than 2 km, and mountain systems do not exceed 3 km in height. Thus, Titan owes its flatness to a combination of denudation by winds, intense precipitation and increased atmospheric pressure [1].

The abundance of methane precipitation forms a fluid cycle similar to Earth's. This means that pluvial processes have a great influence on Titan's appearance. Extensive river systems cut through Titan's icy surface, facilitating the transport of debris material composed of dust and ice. Probably the products of such processes were recorded by the Huygens landing platform during its grand landing on the surface of the icy moon - the image clearly shows pelletized debris of different sizes 10–15 cm in diameter, likely composed of water ice with impurities[3].

Evidence of active geologic processes is also indicated by the absence of many traces of impact craters in comparison with others moons of Saturn, which could simply denuded and eroded over time. It is believed that to date only four structures on the surface of Titan can be identified as impact craters, among them a structure called Sinlap, which is where NASA plans to launch the Dragonfly mission in July 2028.

One of the most debated subjects in the scientific community regarding Titan is the presence of cryovolcanism on the moon. In discussing the existence of cryovolcanism on Titan, scientists rely on data obtained from synthetic aperture radar (SAR) during four targeted flybys of Titan by Cassini: on October 26, 2004 (referred to as Ta), on February 15, 2005 (T3), on September 7, 2005 (T7), and October 28, 2005 (T8). The presence of cryovolcanism is a compelling theory about the methane cycle. Since methane is photodissociated in Titan's atmosphere and forms ethane[1], the replenishment of methane is thought to be accomplished by means of either large bodies of surface liquids (not found so far) or from an internal reservoir by cryovolcanism. One of the most likely places where traces of cryovolcanism are present is a structure or even an entire radial flow trace field called Ganesa Macula. The rounded central shape is considered to have a depression about 20 km in diameter, which may be a crater or a cryovolcanic caldera. Flow traces can be observed for 91 km around the caldera, which may indicate prolonged outpourings of material to the surface. The absence of impact traces may indicate that the sediments are relatively young [4].

2.1. Influence of the atmosphere on Titan's geomorphology

There are about 300 moons in the Solar System, and Titan is the only moon with a dense atmosphere. Titan's atmosphere is 50 % denser than the atmosphere of the Earth and is rich in nitrogen and methane. This unique atmospheric composition is central to shaping the moon's diverse geomorphology [5, 2, 6]. The Cassini-Huygens Spacecraft's onboard sensors provided various insights into the composition of Titan's atmosphere, revealing crucial keys to the formation of Titan's distinctive landforms. The most extensive geologic units on Titan are plains (61%), dunes (19%), hummocky unit (15%), and the lake unit (2.2%) based on the images taken by Synthetic Aperture Radar [4].

The thick atmosphere facilitates a methane cycle akin to Earth's hydrological cycle, where methane evaporates, forms clouds, and precipitates as rain [7, 8]. This process drives the formation of river channels, lakes, and seas, particularly in Titan's polar regions, contributing to ongoing fluvial erosion [3, 9]. Additionally, complex organic molecules formed in the upper atmosphere descend as aerosols, depositing on the surface and contributing to the extensive plains and dune fields observed across Titan [8, 5].

Moreover, the high surface pressure, combined with Titan's low gravity, influences the formation of broad, flat landscapes rather than sharp, rugged terrain [9]. Aeolian processes, driven by the dense atmosphere, continuously shape the vast dune fields near the equator [9, 6]. Importantly, Titan's atmosphere also plays a role in preserving surface features. The thick haze and atmospheric shielding protect the surface from micrometeorite impacts and cosmic radiation, which on bodies like the Moon or Mars, contribute significantly to surface weathering and erosion [5, 2]. As a result, Titan's surface is less frequently disturbed by external forces, allowing ancient and modern geomorphological features to coexist and providing valuable insights into its long-term surface evolution [6, 3].

2.2. *Influence of the lakes on Titan's geomorphology*

Titan's lakes and seas are predominantly located in its polar regions, particularly in the north, and are composed primarily of liquid methane and ethane [7, 8, 10]. These bodies of liquid are a direct consequence of Titan's methane cycle, which functions similarly to Earth's hydrological cycle [8, 10]. The formation and evolution of these lakes and seas are central to understanding the geomorphology of Titan [11].

The interaction between Titan's dense atmosphere and its surface results in the accumulation of methane in low-lying areas, where it can persist as liquid under Titan's cold temperatures [11, 8]. Over time, precipitation from methane rain, combined with surface runoff, fills depressions and creates lakes [7, 10]. The presence of such stable bodies of liquid on Titan's surface is unique in the Solar System, except for Earth [2].

Furthermore, the distribution and morphology of these lakes provide insights into the subsurface structure and the potential for cryovolcanism [11, 6]. Some lakes appear to be connected to subsurface reservoirs, indicating that liquid methane might percolate through porous ice or even that there might be some geothermal activity driving the movement of these liquids [8, 5]. The boundaries of the lakes, often sharply defined, suggest that Titan's surface material is relatively impermeable, potentially due to a layer of organic material formed by atmospheric deposition [8, 6].

In addition to the surface processes, the lakes also play a role in the geomorphological shaping of their surroundings. Methane and ethane, in liquid form, can dissolve and transport surface materials, contributing to the erosion of nearby terrain and the formation of river valleys that feed into the lakes [2, 8]. This process leads to the continuous reshaping of Titan's surface, highlighting the active and evolving nature of its geomorphology [3, 10].

The study of Titan's lakes, therefore, not only provides a window into the moon's current climate and weather patterns but also offers clues about the geological history of Titan and the complex interplay between its surface and atmosphere [6, 5].

2.3. *Influence of the magnetosphere on Titan's geomorphology*

Titan's magnetosphere affects its surface by influencing the behaviour of charged particles that interact with it. Such interactions can lead to surface erosion and the formation of distinctive geological features.

To understand this impact, we must explore how electrons, ions, and anions within Titan's magnetosphere and ionosphere contribute to these changes. These charged particles are integral to plasma dynamics and can be lost through processes such as magnetic reconnection and collisions. Their interactions with Titan's atmosphere drive surface erosion, shape geological features, and transfer energy to the lower atmosphere. This energy transfer further influences the moon's surface by heating the lower atmosphere and altering its chemical composition [12].

These charged particles—electrons, ions, and anions—in Titan's plasma interact with the atmosphere, transferring energy. Each type of particle influences internal processes in distinct ways.

Electrons play a key role in ionising atmospheric gases, which facilitates the formation of Titan's ionosphere. They transfer energy to the lower atmosphere through collisions with neutral particles and other heavier charged particles. As electrons are lost through processes such as magnetic reconnection and collisions with ions or neutral particles, they influence the plasma density and energy distribution, ultimately affecting how energy is transferred downward [13].

In Titan's vicinity, common positive ions include H^+ (protons), H_2^+ (molecular hydrogen ions), and N^+ (nitrogen ions). Titan shows a dominance of H_2CN^+ and $C_2H_5^+$ in the upper ionosphere. These ions transport energy from the ionosphere to the lower atmosphere through interactions with atmospheric gases, playing a crucial role in heating the lower atmosphere. Their movement and energy transfer are essential for atmospheric dynamics. Ions are lost through processes such as magnetic reconnection, collisions, and escape to space, which impacts the ionosphere's density and overall energy balance [14].

Anions help maintain charge neutrality in the plasma and contribute to overall plasma stability. In Titan's ionosphere, common anions include C_2^- (carbon-based anions) and N_2^- (nitrogen anions). They interact with ions and neutral particles, affecting energy transfer processes. The loss of anions through collisions and connection processes with positive ions influences the ionosphere's chemical composition and plasma behaviour, impacting how energy is distributed throughout Titan's atmosphere [15].

Delving into Titan's internal plasma processes by analysing the density, energy, velocity, loss mechanisms, types, and masses of electrons, ions, and anions will help answer broader questions about atmospheric energy transfer and its impacts from the ionosphere to Titan's surface. Understanding these factors is crucial for outlining the Titan's geological impacts and overall geomorphology.

3. The Comprehensive Science Traceability Matrix

3.1. Methodology

The initial step in constructing the STM involves the precise definition of science goals, derived from the broader scientific questions and knowledge gaps. Each goal is written with measurable outcomes in mind, allowing for direct traceability between the measurements, and the instruments which will carry out the observations.

The STM process takes the following steps:

- **Science question:** This is a broad scientific question which outlines a theme a mission will address.
- **Scientific objective:** These should be questions which need to be answered in order to contribute to answering the broader science question.
- **Observational tasks:** These are the actual observations which need to be performed by the spacecraft.

The STM process is shown in Figure 1. It can be seen how the multiple connections between the *Observational Task* layer and the *Measurement Requirement* layer can be useful in strengthening the case for particular observations if they are capable of answering multiple observational tasks, and likewise when multiple observation tasks can be performed by a single measurement requirement. This allows weights to be assigned to the various layers, and then for the optimal number of measurements to be performed to answer the overarching science question. This optimisation also extends to the selection of instrumentation, allowing for an understanding of the effectiveness of the possible instruments and the optimal smallest number needed to answer the overarching science questions.

While the quantitative refinement of mass, power, and telemetry budgets is possible this way, there is also a large degree of qualitative analysis performed by scientists, where a degree of judgment and consensus is required. In this paper, this analysis was performed by the Conex Research science team, with every key area from geomorphology, atmosphere, lakes, and magnetosphere assigned to a responsible party with the most in-depth knowledge, but where the consensus of the entire team was required before optimisation took place.

3.2. Results

The Science Traceability Matrix (STM) approach reveals the broad scientific value of each instrument across multiple observational tasks, highlighting the versatility of the mission payload. By connecting instruments to a wide array of scientific goals, we are able to see how individual tools can serve multiple disciplines.

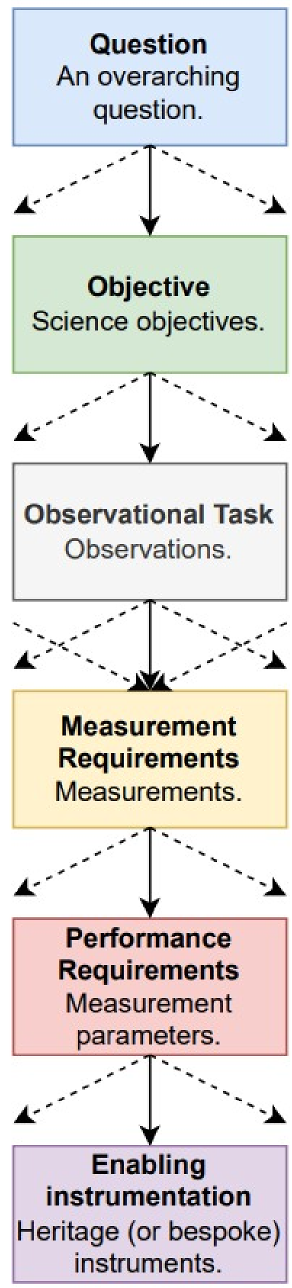

Figure 1. Graphic showing the STM process.

For example, Europa Clipper/REASON (Ground-Penetrating Radar) offers insights into both surface and subsurface structures. While it was originally included to explore Titan's crust and interior, REASON also helps to determine whether Titan's lakes are connected to subsurface reservoirs and identify the composition of various surface features, making it essential for studying Titan's lakes and cryovolcanic features. This cross-functional capability underscores the importance of subsurface radar in linking geomorphology with hydrological and atmospheric science.

The UCLSat/INMS (Mass Spectrometer) is another critical instrument. Initially intended to study the composition of Titan's atmosphere, the INMS also helps uncover interactions between the atmosphere and magnetosphere, and contributes to understanding prebiotic chemical processes. This makes it valuable across atmospheric chemistry, planetary magnetism, and astrobiology, illustrating how a single instrument can bridge multiple scientific domains.

BepiColumbo/MERTIS (Thermal Emission Spectrometer) expands our understanding of Titan by measuring surface temperatures, which not only informs the moon's heat budget but also helps investigate potential outgassing and surface plumes. Additionally, MERTIS contributes to studying the composition of Titan's terrain and lakes, connecting surface heat dynamics to geomorphological and atmospheric science.

The STM method is essential for making these interconnections visible and actionable. By systematically linking scientific objectives to specific measurements and instruments, the STM demonstrates how tools originally intended for a specific task—such as seismology or atmospheric chemistry—can serve a wide range of scientific disciplines. This approach helps optimise mission planning by ensuring that each instrument is used to its fullest capacity, while also highlighting areas where multiple instruments might provide complementary data.

Moreover, the STM fosters collaboration between scientists working in traditionally separate fields. For instance, geophysicists studying Titan's crust can collaborate with atmospheric scientists investigating how interior processes affect atmospheric outgassing or how surface features interact with weather patterns, and these connections are guided to those most beneficial by the STM. This cross-disciplinary approach helps researchers from different backgrounds discover new insights that might not have been realised through discipline-specific research.

Finally, the STM process encourages the exploration of potential synergies between instruments, allowing the mission team to prioritise observations that serve multiple objectives. This not only makes the mission more efficient but also amplifies the overall scientific return by leveraging the full potential of the payload.

4. Mission Architecture

4.1. System Architecture

Astraeus features four spacecraft systems split into two orbital segments and two lander segments as shown in Figure 2. An Entry Module is included for protection of the lander segments until operation on the surface of Titan. The Main Orbital Spacecraft (MOS) serves as the mission's hub, orbiting Titan and conducting detailed observations of its terrain and magnetosphere. Additionally, a fleet of 3U CubeSats called Mites is designated for atmospheric analysis, deployed annually to study the atmospheric conditions. The mission also includes the Mayfly, an unmanned aerial vehicle for atmospheric and surface exploration, and the Manta, an underwater vehicle tasked with investigating Titan's hydrocarbon lakes. These elements collaborate constructively, with MOS acting as a communication relay between Earth and the mission's components.

The operation of the Astraeus mission is multifaceted: The MOS orbits Titan, mapping its surface and studying its magnetosphere, while simultaneously facilitating communication. The Mites probe the atmosphere, analysing its composition and dynamics. On Titan's surface and beneath its lakes, the Mayfly and Manta explore respectively, with the Mayfly examining the atmosphere and surface, and the Manta delving into the hydrocarbon lakes to analyse their composition. This multi-platform approach aims to provide a comprehensive understanding of Titan geomorphology by combining orbital, atmospheric, and surface exploration.

4.1.1. Main Orbital Spacecraft

The Main Orbital Spacecraft (MOS) is the central component of the Astraeus mission which has to ensure successful transport and deployment of the lander segments, and also facilitate scientific experiments. It is equipped with a deployable high gain antenna to ensure robust communication with the Earth. Certain atmospheric and surface phenomenon can only be studied from orbit where continuous monitoring of a broad area is possible. To meet these needs MOS is designed to orbit Titan, serving as a critical platform for high altitude experiments and surface mapping.

MOS hosts the CubeSats called Mites, which are deployed from an altitude of 1400km into a low decay-rate orbit to study Titan's atmospheric composition with varying altitude. MOS will also deploy the entry module once it is in the desired orbit around Titan. The entry module protects Mayfly and Manta during it's journey through the atmosphere of Titan to reach the surface.

After MOS has released the entry module, it will remain in its orbit and collect magnetometer data, operate a synthetic aperture radar as shown in Figure 3, enabling detailed mapping of the surface of Titan, and release the

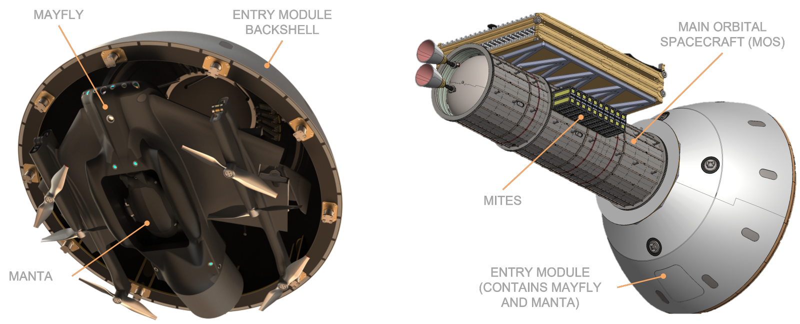

Figure 2. The Astraeus system architecture.

Mites at the rate of approximately one per Earth year. Additionally, the lander segments, once deployed, can communicate directly with Earth, reducing dependency on the MOS.

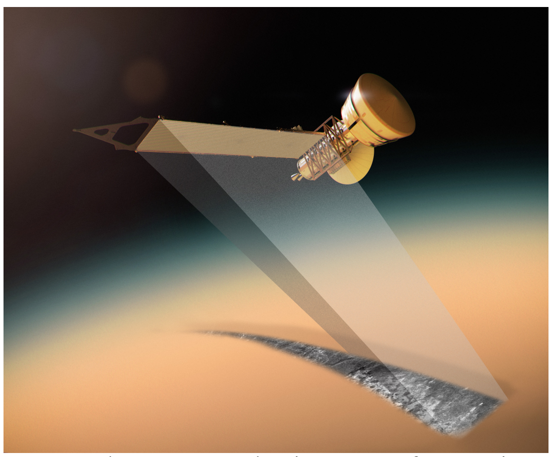

Figure 3. The MOS conducting a Interferometric Synthetic Aperture Radar (InSAR) experiment.

4.1.2. *Mites*

The Mites are a fleet of 3U CubeSats designed to measure Titan's atmospheric composition at varying altitudes over a 10-year mission, capturing data during all seasonal sessions. Each Mite is equipped with an Ion and Neutral Mass Spectrometer (INMS) to continuously gather atmospheric data. There are 14 RTG-powered CubeSats in total, each with a lifespan of 18 months, and two are deployed every 12 months.

In addition to atmospheric data collection,the Mites will also record composition data during re-entry into Titan's atmosphere. Based on a trade study, the Mechanical Inflatable Entry Capsule re-entry system was selected to ensure a safe landing on Titan's surface. The system is expected to reduce the re-entry velocity from 1424.15 m/s to 5 m/s, enabling a soft landing while preventing the dispersion of radioactive material from the onboard RTG power generator.

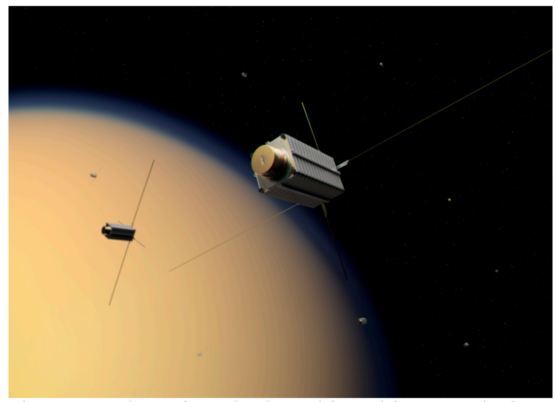

Figure 4. The Mites deployed in orbit around Titan.

4.1.3. *Entry Module*

The entry module is a vessel for atmospheric entry for Mayfly and Manta. After being released from the MOS, the entry module is decelerated until it achieves subsonic speeds to allow for parachute deployment. During this coast phase, the entry module passes over the cryovolcano, Ganesa Macula. An INMS onboard the entry module shall measure the heavy anion concentration in the atmosphere directly above Ganesa Macula allowing for characterisation of the cryovolcano ejecta. After surveying the cryovolcano, Mayfly is turned on and separates from the entry module and enters a vertical hover before transitioning into a glide as shown in Figure 5.

4.1.4. *Mayfly*

Mayfly is a hybrid uncrewed aerial vehicle (UAV) which observes Titan during atmospheric flight. This allows for measurement of Titan's surface and atmosphere at a great resolution that can be compared to orbital observations collected by the MOS and Mites.

The hybrid configuration allows Mayfly to efficiently travel long distance in horizontal flight and maintain a hover in vertical flight. Over an 18 month period, Mayfly is capable of exploring the Titan's northern hemisphere by visiting sites of interest. This begins with Ligeia Mare followed by Kraken Mare, Mackay Lacus and Ganesa


Figure 5. Mayfly in a glide within Titan's upper atmosphere once separated from the entry module.

Macula before the cycle repeats. The variation in terrain does not limit Mayfly which shall be capable of VTOL on solid ground and lakes whilst also being able to maintain a hover over craters, steep gradients and cryovolcanoes.

4.1.5. *Manta*

Manta is a remote operated vehicle (ROV) tasked with exploring Titan's lakes and seas. It is stored onboard Mayfly and deployed during lake landings. As Mayfly floats on the surface of a lake, Manta descends into the depths of the hydrocarbon seas. Manta is equipped with a visible light and near-infrared camera, modelled using Perseverance Rover's Mastcam-Z, to capture images from within the lake.

Datalink, power and control are all provided to all of Manta's subsystems by Mayfly via an umbilical cord that connects both vehicles. The inclusion of an umbilical cord reduces the mass and power requirements of the power and command & data handling subsystems onboard Manta to a minimal value. This is advantageous as the total mass of the ROV decreases which has a multiplier effect where the total mission mass also decreases. Additionally, Titan's lakes expose Manta to cryogenic temperatures, pressures of up to 4 bar and a mix of short-chain hydrocarbons. Therefore, a share of the residual mass and power budget can be allocated to the following subsystems:

- **Structural:** Manta require a structure that can adequately operate at environmental conditions found in Titan's lakes.

- **Thermal management:** All subsystems would benefit from the addition of a decentralised thermal management system via heat wires. This provides control of thermal gradients within Manta and between the internal and external environment.

- **Propulsion & attitude control:** Modern ROVs typically use a drivetrain that feature electric motors to rotate marine propellers. As Manta ventures deeper into Titan's lakes, the length of the umbilical cord increases resulting in a greater drag area. Equipping Manta with more powerful motors combats this drag force at the cost of additional mass and power consumption.


Figure 6. Manta submerged in Kraken Mare during subsea exploration.

4.2. *Concept of Operations*

Astraeus begins its journey to Titan with a launch window opening in late 2037 and closing in late 2038. The timeline of major phases shown in Figure 7 details the scenario with the longest duration to arrive at Titan. The spacecraft stack follows an EJS trajectory during Transfer 1 expending over 7 km/s on its way to Saturn. No more than 6 years after launch, Astraeus is captured in an orbit around Saturn. This arrival in the Saturnian system enables Astraeus to characterise Titan during the Spring-Summer equinox: a period of Titan's seasonal calendar not previously observed.

Science Phase 1 is a period three months spent measuring the electromagnetic field strength around Saturn to provide a baseline for comparison with future measurements. Astraeus departs its orbit around Saturn to commence Transfer 2 to Titan. This phase ends once captured around the moon. A second phase of orbital science begins with the release of the first two Mites CubeSats and observations of Titan's surface and atmosphere via the MOS.

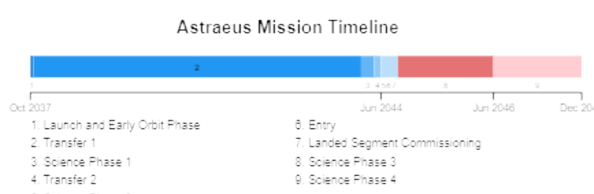

Figure 7. The Astraeus mission timeline.

The banks of Kraken Mare are selected as the primary landing site. This must be balanced with a low-speed pass over Ganesa Macula within Titan's atmosphere. These requirements determine the descent profile of the Entry Module. Refinements are made to the profile using data gathered from the MOS during the first and second science phases. During Science Phase 2, entry of the lander vehicles through Titan;s atmosphere begins. Once through the hypersonics and supersonic regimes of the entry, a parachute is deployed and the heat shield is jettisoned at approximately 60 km from the surface. The entire lander segment passes over Ganesa Macula to gather initial data on its composition by measuring the anions that linger in the atmosphere from plumes.

Titan Entry enters its terminal phase once Mayfly is turned on, unfolded and decoupled from the Entry Module. Mayfly begins a long glide to Kraken Mare which culminates in a vertical landing on solid ground near Titan's largest lake. A bout of commissioning on land, on the surface of the lakes and submerged within the lakes begins to verify that Mayfly and Manta are operational. This includes, but is not limited to, hovers over solid ground and the surface of the lakes, landing tests on included ground and the surface of the lakes, Manta deployment and submersible commissioning.

Science Phase 3 commences in June 2044 where total connectivity science across the four platforms can be conducted. 18-months are spent by the MOS, Mites, Mayfly and Manta to gather data in order to fulfil the science objectives outlined in the STM. The time period was selected specifically to enable repeat measurements for all science objectives that aid in answering "Is Titan geomorphologically active?" which requires a maximum time period of 12 months between measurements. Therefore, there is sufficient time budget within the operational schedule.

Future science phases will also follow this 18-month cycles. As the mission matures in age, the proportion of data collection to fulfil science objectives in the STM will decrease. Additionally, new sites of interest will likely emerge which the Astraeus Mission Architecture is capable of exploring. Therefore, it is anticipated that STM data collection will be balanced with this new connectivity science (NCS) data collection throughout Science Phase 4. With each new phase, the proportion of NCS shall increase until an equilibrium is reached that satisfies both legacy and emergent science objectives within the limits of the Astraeus mission architecture.

5. Conclusion

This paper summarizes the data, with a focus on geomorphology-related science objectives, obtained during three years of intensive work on the project. Thanks to the integrated STM approach developed by NASA engineers and scientific data from previous missions such as Cassini-Huygens and Voyager, the Conex team was able to develop a custom mission profile to Titan, a moon of Saturn, with appropriate scientific goals and objectives.

Based on 15 objectives, 57 observational tasks, 91 measurement requirements, and 31 actual spaceflight missions, we were able to select instruments for investigations both in orbit of the moon and on its surface, during the flyby over a potential area of cryovolcanism development, and even while diving into Titan's hydrocarbon reservoirs. Now a completed theoretical proposal called Astraeus, we invite engineers and space manufacturing representatives to collaborate and discuss our work.

Acknowledgements

We would like to thank the engineers, scientists and young professionals who have invested their time and energy in working on this exciting journey to the Saturn system and its largest moon, Titan. The Conex Research team is the real example of international cooperation for the advancement of science and space exploration. We thank each and every member of the team for their invaluable contributions to the project, it is an honour and a pleasure to work with you shoulder to shoulder across geographical and political boundaries.

References

[1] R. M.C. Lopes et al. "Distribution and interplay of geologic processes on Titan from Cassini radar data". In: *Icarus* 205 (2 Feb. 2010), pp. 540–558. DOI: 10.1016/j.icarus.2009.08.010.

[2] S.D.B. Graves et al. "Rain and hail can reach the surface of Titan". eng. In: *Planetary and space science* 56.3 (2008), pp. 346–357. ISSN: 0032-0633. DOI: 10.1016/j.pss.2007.11.001.

[3] L. A. Soderblom et al. "Topography and geomorphology of the Huygens landing site on Titan". In: *Planetary and Space Science* 55 (2007), pp. 2015–2044. DOI: 10.1016/j.pss.2007.04.015.

[4] R. M.C. Lopes et al. *A global geomorphologic map of Saturn's moon Titan*. Mar. 2020. DOI: 10.1038/s41550-019-0917-6.

[5] H. B. Niemann et al. "The abundances of constituents of Titan's atmosphere from the GCMS instrument on the Huygens probe". In: *Nature* 438 (2005), pp. 779–784. DOI: 10.1038/nature04122.

[6] J. I. Lunine et al. "Titan's diverse landscapes as evidenced by Cassini RADAR's third and fourth looks at Titan". In: *Icarus* 195 (2008), pp. 415–433. DOI: 10.1016/j.icarus.2007.12.022.

[7] E. R. Stofan et al. "The lakes of Titan". In: *Nature* 445 (2007), pp. 61–64. DOI: 10.1038/nature05438.

[8] G. Mitri et al. "Hydrocarbon lakes on Titan". In: *Icarus* 186 (2007), pp. 385–394. DOI: 10.1016/j.icarus.2006.09.004.

[9] R. D. Lorenz et al. "The sand seas of Titan: Cassini RADAR observations of longitudinal dunes". In: *Science* 312 (2006), pp. 724–727. DOI: 10.1126/science.1123257.

[10] M. Mastrogiuseppe et al. "Bathymetry and composition of Titan's Ontario Lacus derived from Monte Carlo-based waveform inversion of Cassini RADAR altimetry data". In: *Icarus* 300 (2018), pp. 203–209. DOI: 10.1016/j.icarus.2017.09.009.

[11] R. M. C. Lopes et al. "Cryovolcanic features on Titan's surface as revealed by the Cassini Titan Radar Mapper". In: *Icarus* 186 (2007), pp. 395–412. DOI: 10.1016/j.icarus.2006.09.006.

[12] I. P. Robertson et al. "Structure of Titan's ionosphere: Model comparisons with Cassini data". In: *Planetary and Space Science* 57 (14-15 July 2009), pp. 1834–1846. DOI: 10.1016/j.pss.2009.07.011.

[13] L. Gan, C. N. Keller, and T. E. Cravens. "Electrons in the ionosphere of Titan". In: *Journal of Geophysical Research* 97.A8 (1992), p. 12137. DOI: 10.1029/92ja00300.

[14] A. J. Coates et al. "Recent Results from Titan's Ionosphere". In: *Space Science Reviews* 162 (1-4 June 2011), pp. 85–111. DOI: 10.1007/s11214-011-9826-4.

[15] R. T. Desai et al. "Carbon Chain Anions and the Growth of Complex Organic Molecules in Titan's Ionosphere". In: *The Astrophysical Journal* 844.2 (2017), p. L18. DOI: 10.3847/2041-8213/aa7851.