TARA: Concept Study for an ESA Voyage Titan Exploration Mission

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Abstract: As a study relevant to the ESA's "Voyage 2050" programme, we present an ambitious L-class mission concept aimed at exploring one of the most intriguing bodies in the Solar System – Titan, Saturn's largest moon. Titan is a planet-like moon rich in organic compounds and features complex interactions between its interior, surface, and atmosphere, similar to those seen on Earth. Additionally, Titan is one of the few places in the Solar System with the highest potential for eventual habitability. Despite the groundbreaking discoveries made by the Cassini-Huygens mission, Titan still holds many mysteries that demand further exploration using more advanced technologies and diverse exploration vehicles. Our proposed mission, named TARA (Titan Atmospheric Research Ascendant), aims to conduct both orbital and in situ investigations of Titan, surpassing the scientific and technological achievements of Cassini-Huygens. TARA would provide comprehensive and close-up exploration of Titan over extended periods, utilizing capabilities that were previously unattainable. The mission architecture consists of two primary components: an orbiter equipped with an extensive suite of instruments that would orbit Titan, ideally in a low-eccentricity circular polar orbit, and an ornithopter equipped with a set of in situ exploration elements, both aimed to study Titan's atmospheric dynamics and the evolution of pre-biotic environment. The ideal mission timeline would target an arrival at Titan just before its next northern Spring equinox in 2039, a period of heightened activity for observing Titan's still poorly understood seasonal atmospheric and surface changes. TARA's focus on Titan's northern latitudes would complement NASA's upcoming Dragonfly mission, which is scheduled to explore Titan's equatorial regions in the mid-2030s. Together, these missions would provide comprehensive temporal, spatial, and scientific coverage of this fascinating moon.

Keywords: Titan, Atmosphere, Pre-Biotic Environment, Habitability, Orbiter, Ornithopter, Exploration.

Nomenclature

CHON	Carbon, Hydrogen, Oxygen, Nitrogen
VTOL	Vertical Take-Off and Landing
NASA	National Aeronautics and Space Administration
JPL	Jet Propulsion Laboratory
ESA	European Space Agency
AO	Announcement of Opportunity
PAH	Polycyclic Aromatic Hydrocarbon
HASI	Huygens Atmospheric Structure Instrument
PWA	Permittivity, Wave and Altimeter (package)
TandEM	Titan and Enceladus Mission
TSSM	Titan Saturn System Mission
TAE	Titan Airship Explorer
TiME	Titan Mare Explorer
TALISE	Titan Lake In-situ Sampling Propelled Explorer
AVIATR	Aerial Vehicle for In-situ and Airborne Titan Reconnaissance
JET	Journey to Enceladus and Titan
E^2T	Explorer of Enceladus and Titan
APL	Applied Physics Laboratory
TRL	Technology Readiness Level
JUICE	Jupiter Icy Moons Explorer
UAV	Unmanned Aerial Vehicle
GPS	Global Positioning System
CNES	National Centre for Space Studies
MSSL	Mullard Space Science Laboratory
EAS	Electron Analyser System
TOI	Titan Orbit Insertion
DLS	Descent Landing System
CBE	Current Best Estimate
MEV	Maximum Expected Value
MLI	Multi-Layer Insulation
RHU	Radioisotope Heater Unit
IMU	Inertial Measurement Unit
RCS	Reaction Control System
RTG	Radioisotope Thermoelectric Generator
RWA	Reaction Wheel Assembly
HGA	High Gain Antenna
GTO	Geostationary Transfer Orbit
BOL	Beginning of Life
EOL	End of Life
ESTRACK	European Space Tracking
ECSS	European Cooperation for Space Standardization
COSPAR	Committee on Space Research

1. INTRODUCTION

1.1. Titan and its Significance

Titan, Saturn's largest moon, is an enticing focus for future space missions due to its remarkable similarities to Earth in terms of geological, meteorological, hydrological, and aeronomical characteristics (Lorenz et al., 2005). One of Titan's most striking features is its dense, nitrogen-rich atmosphere, which supports an active meteorological methane cycle influenced by atmospheric and climatic forces. The moon's biosphere is a dynamic ecosystem where interactions among various sub-spheres create aeolian, fluvial, lacustrine, exogenic, and endogenic features and processes, mirroring those found on Earth (Nixon et al., 2018).

Titan is considered one of the most promising candidates for potential habitability within our solar system. It meets all the essential criteria for supporting life, including a stable substrate, energy sources, organic chemistry, and a liquid solvent (Coustenis et al., 2013). Even though methane makes up only a small percentage of Titan's atmosphere, it plays a crucial role in driving rich organic chemistry, facilitating the formation of CHON (carbon, hydrogen, oxygen, nitrogen) compounds (Israël et al., 2005)(Waite et al., 2007)(Nixon, 2024). This complex organic chemistry is further enriched by the interplay of raining atmospheric compounds, material from dunes, valleys, and volcanoes, combined with the presence of liquids from its subsurface ocean of ammonia-rich water and surface lakes and seas of methane.

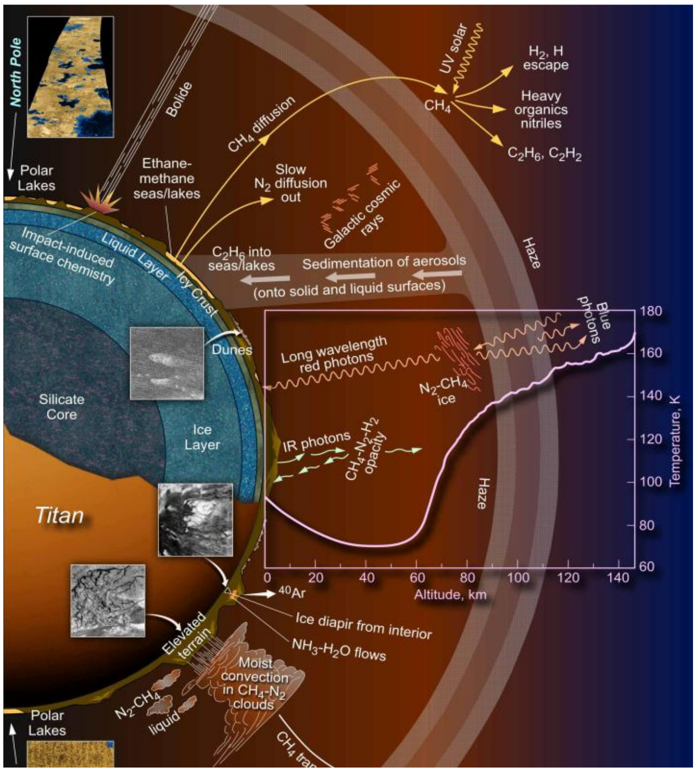

Figure 1: Interplay within Titan's Biosphere (Reh et al., 2009).

Titan thus stands out as a vast natural laboratory for prebiotic chemistry (Raulin et al., 2012), making it an ideal environment to study habitability and the potential diversity of life in the universe (Cockell et al., 2021). Its unique combination of organic material and liquid solvents provides an unparalleled opportunity to explore the processes that could lead to the emergence of life.

1.2. Current Interest in Titan Exploration

Titan has been the prime interest of celestial exploration in the solar system for the past multiple decades. The Cassini-Huygens mission played a pivotal role in our understanding of Titan, as well as ignited a new age of golden interest and exploration of Titan among the space community (Spilker, 2019). Over the last 2 decades, results from the Cassini-Huygens mission have inspired numerous mission concepts aimed towards further exploration and understanding of Titan. Interest in the exploration of Titan is increasing again, largely due to NASA's ambitious Dragonfly mission. Scheduled for launch in 2028 and expected to arrive at Titan in 2034, Dragonfly is a revolutionary project that aims to explore the moon's surface with a robotic rotorcraft (Turtle & Lorenz, 2024). This mission, which has seen significant delays and budget adjustments due to various challenges, including the COVID-19 pandemic and funding constraints, will cost approximately $3.35 billion over its lifecycle.

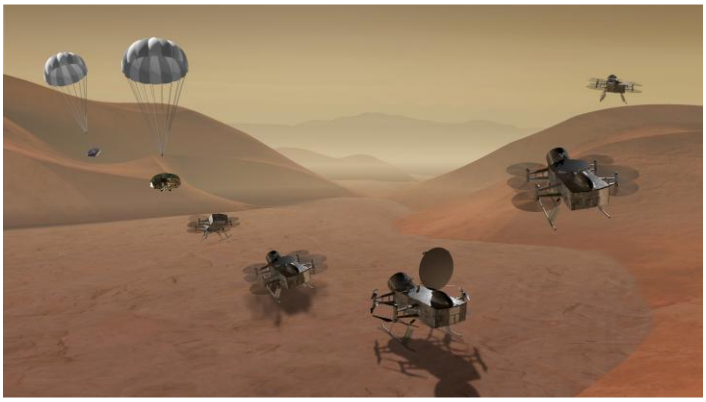

Figure 2: Illustration of Dragonfly Mission (Lorenz et al., 2018).

Dragonfly will be the first multi-rotor aircraft to operate on Titan, conducting the first powered and fully controlled atmospheric flight on any moon. The mission's primary objectives are to study prebiotic chemistry and assess the potential for extraterrestrial habitability (Barnes et al., 2021). Utilizing its vertical takeoff and landing (VTOL) capabilities, Dragonfly will be able to traverse various locations on Titan's surface, enabling extensive exploration and data collection across multiple sites. This innovative approach allows the rotorcraft to cover a wide range of terrains and environments, significantly enhancing the scope and impact of its scientific investigations (Barnes et al., 2021). The mission is managed by the Johns Hopkins Applied Physics Laboratory, with key contributions from several NASA centres and international partners.

Titan's thick atmosphere and stable surface conditions make it an intriguing target for such an innovative exploration approach. This mission is part of NASA's New Frontiers program, which focuses on high-priority solar system exploration. Dragonfly's success could not only enhance our understanding of Titan but also pave the way for future missions employing similar technology on other planetary bodies.

1.3. Opportunity and Need for a Future Mission

After the Cassini-Huygens mission, there is a need to retrospect on the major scientific questions posed at its start and evaluate the advancements made in addressing them. Simultaneously, new significant scientific questions about Titan have arisen from the discoveries made so far post-Cassini-Huygens mission regarding the atmospheric processes, aeolian, fluvial, seas, and lacustrine processes, surface chemistry and geomorphology, interior-surface-atmosphere interactions, and pre-biotic chemistry / habitability on Titan, as discussed in detail in the later sections. Past missions to Titan, such as Pioneer 11, Voyagers 1 and 2, and Cassini-Huygens have set the scene for a new mission to further deeply analyze and monitor the science and mechanisms occurring in Titan's biosphere. In order to completely untangle Titan's complexity, a dedicated M-class or L-class mission to Titan incorporating remote and in-situ elements, equipped with high-resolution measurement instruments with a high degree of accuracy and precision is necessary.

NASA's New Frontiers Program provides opportunities to develop new-generation mission proposals for Titan exploration. The program comprises a series of space exploration missions aimed at deepening our understanding of the Solar System. This initiative focuses on selecting medium-class missions that promise significant scientific discoveries and returns. The New Frontiers Program helps to demonstrate the need for future missions dedicated to solar system exploration.

Figure 3: NASA New Frontiers Program. Credits: NASA Science.

Following several successful planetary missions starting with Giotto, the European Space Agency (ESA) also continues to provide opportunities for planetary missions within their long-term plan "ESA Voyage 2050" for the scientific programme (Favata et al., 2021). The plan focuses on dedicated L-class missions for the top 3 priority themes of "moons of giant planets", "temperate exoplanets or the galactic ecosystem", and "new physical probes of the early Universe" (Favata et al., 2021). The first theme "moons of giant planets" presents a key opportunity for a future mission to the outer Solar System, equipped with advanced instrumentation, aiming to study the correlations between the interiors of ocean-bearing moons and their near-surface environments, alongside identifying possible biosignatures. In 2024, ESA announced the outcome of an expert panel study of missions to the moons of the giant planets (Martin et al., 2024). Titan is one of the target candidates for this theme, alongside Saturn's icy moon Enceladus, and Jupiter's moon Europa (Martin et al., 2024)(Favata et al., 2021).

Figure 4: ESA Voyage 2050 Science Programme. Credits: ESA Science and Technology.

We suggest that there is a strong need for a future mission to Titan since Titan is an excellent candidate for future solar system exploration, which would have a high scientific return.

2. LITERATURE STUDY OF TITAN

2.1. Current Science about Titan

Based on the scientific and technological accomplishments of the Cassini-Huygens and previous legacy missions to Titan and the Saturnian system, an overview of the current knowledge about various spheres of Titan are listed as follows:

2.1.1. Upper Atmosphere: Magnetospheric Interactions, Physical / Chemical Processes:

The Cassini mission made a crucial discovery by detecting complex negative ions, positive ions, and neutrals, with negative ion masses up to 13,800 amu/q, at altitudes over 870 km (Coates et al., 2007)(Coates et al., 2009)(Shebanits et al., 2016)(Haythornthwaite et al., 2021). This finding revealed that Titan's upper atmosphere, starting above 870 km, involves complex chemistry between ions and neutral particles (Vuitton et al., 2007), leading to the formation of nanoparticles at higher altitudes than previously thought (Lavvas et al., 2013). Additionally, between 500 and 1000 km, aerosol seed particles grow through coagulation and chemical reactions (García Muñoz et al., 2018) as they descend. Although Cassini's pioneering measurements were somewhat limited, they revealed density profiles of various significant hydrocarbons and nitriles, effects of aerosol extinction, and the potential presence of polycyclic aromatic hydrocarbons (PAHs) (Coates et al., 2007)(Delitsky & McKay, 2010).

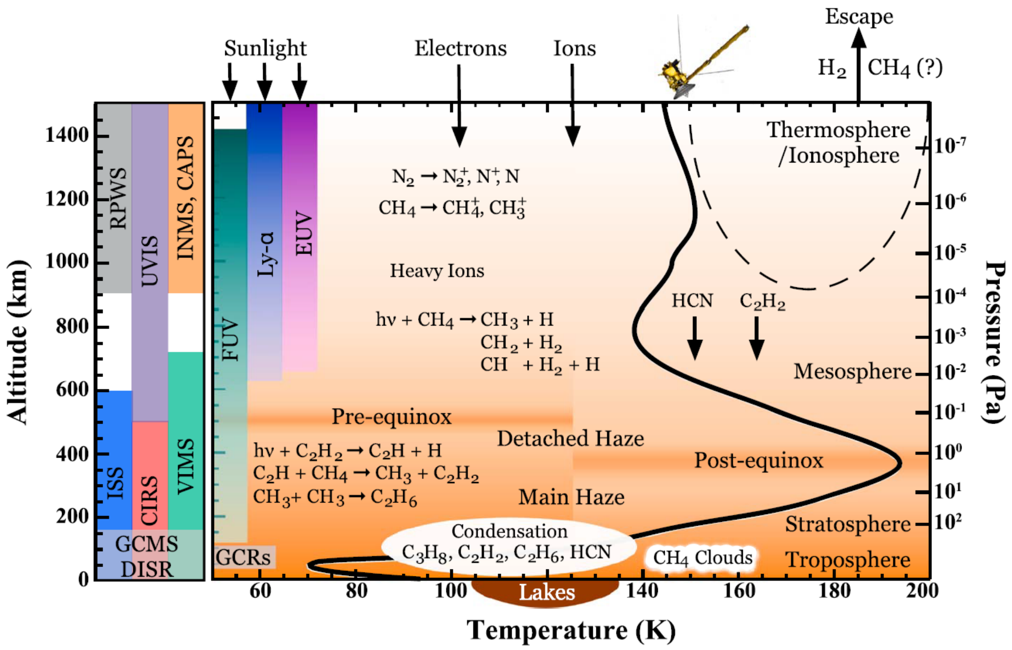

Figure 5: Overall Profile of Titan's Atmosphere (Hörst, 2017).

2.1.2. Middle Atmosphere: Circulation, Haze Distribution:

Titan's middle atmosphere, located above 80 kilometers, acts as a transitional zone linking the dynamic region where molecules and aerosols form in the upper atmosphere to the troposphere (Lora et al., 2015). The concentration of photochemical products from the upper atmosphere rises with altitude, significantly influenced by global dynamics. During winter, Titan experiences the development of a polar vortex, featuring high-speed zonal winds that isolate the air within from the surrounding atmosphere. These vortices are notably rich in photochemically generated species, especially during specific seasonal periods (Mathé et al., 2020)(Teanby et al., 2017). Aerosols are crucial in this balance, affecting the stratospheric temperature through both heating and cooling mechanisms (Bézard et al., 2018).

2.1.3. Lower Atmosphere: Methane Cycle, Weather:

The lower 80 kilometers of Titan's atmosphere, which includes the deep stratosphere and troposphere, remains largely uncharted territory, aside from observations of cloud activity and data from the Huygens probe. This region is intriguing due to the surface-atmosphere interactions at the boundary layer within the lowest 2 kilometers, driven by convection processes. Aerosols play a significant role below 100 kilometres, serving as nuclei for condensation. Titan's conditions support a methane-based hydrological cycle in its lower atmosphere, analogous to Earth's water cycle but with methane instead (Hayes et al., 2018a). The precise proportions and vertical distributions of methane and its photochemical byproducts are not well understood (Niemann et al., 2005)(Niemann et al., 2010a). Understanding these proportions is essential for comprehending cloud formation and the methane cycle in Titan's lower atmosphere.

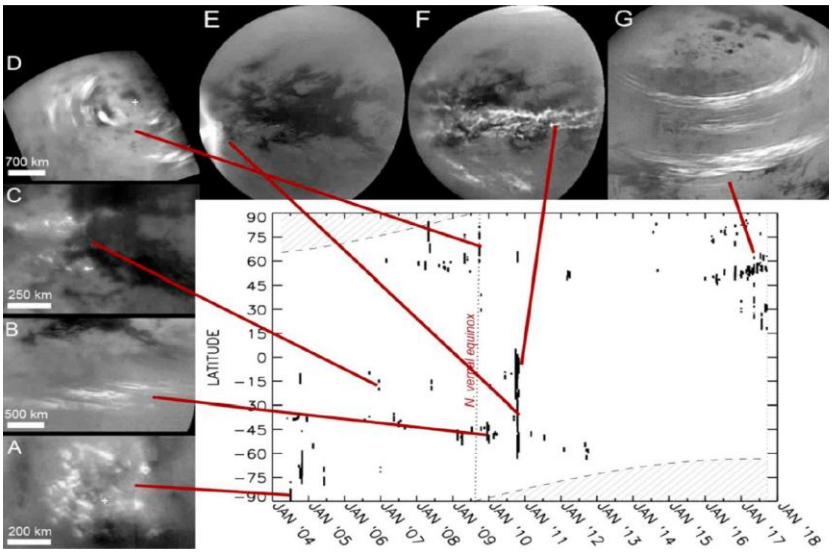

Figure 6: Cloud images of Titan from Cassini / ISS (Turtle et al., 2018).

2.1.4. Aeolian Features and Processes:

Observations from the Cassini spacecraft have revealed that dunes are the predominant wind-shaped features on Titan, Saturn's moon. Their distribution varies with latitude, indicating different climatic conditions. These dunes provide important insights into Titan's sedimentary and climatic history, especially in tropical regions (Schoenfeld et al., 2021). The widespread and consistent presence of these dunes suggests a long-standing history of wind-driven sand formation and transport on Titan (Radebaugh, 2013). Additionally, these dunes are among the darkest features seen in infrared by Cassini, exhibiting a low albedo and a red spectrum, which indicates they are composed of smooth, homogeneous organic material (Brossier et al., 2018)(Barnes et al., 2008). This points to the dunes being a significant carbon reservoir on Titan, with the sand likely originating from atmospheric particles that settled and were further processed on the surface (Bonnefoy et al., 2016).

2.1.5. Fluvial Features and Processes:

Following the Cassini-Huygens mission, one significant discovery is Titan's intricate network of channels (Lorenz et al., 2008)(Burr et al., 2013), which are similar to Earth's in their complexity. This complexity arises from interactions between climate, topography, and geology, involving both surface and subterranean water flows. Near the poles, numerous river networks connect to lakes, which can be either dry or filled (Langhans et al., 2012). The presence of canyons suggests rock layers of varying durability, while straight channels indicate pathways shaped by fractured bedrock. Meandering and braided rivers are influenced by the stream's gradient and the sediment load. These channels show that Titan's surface can be altered by physical erosion or dissolution, with substantial flows from rainfall or underground sources shaping the landscape.

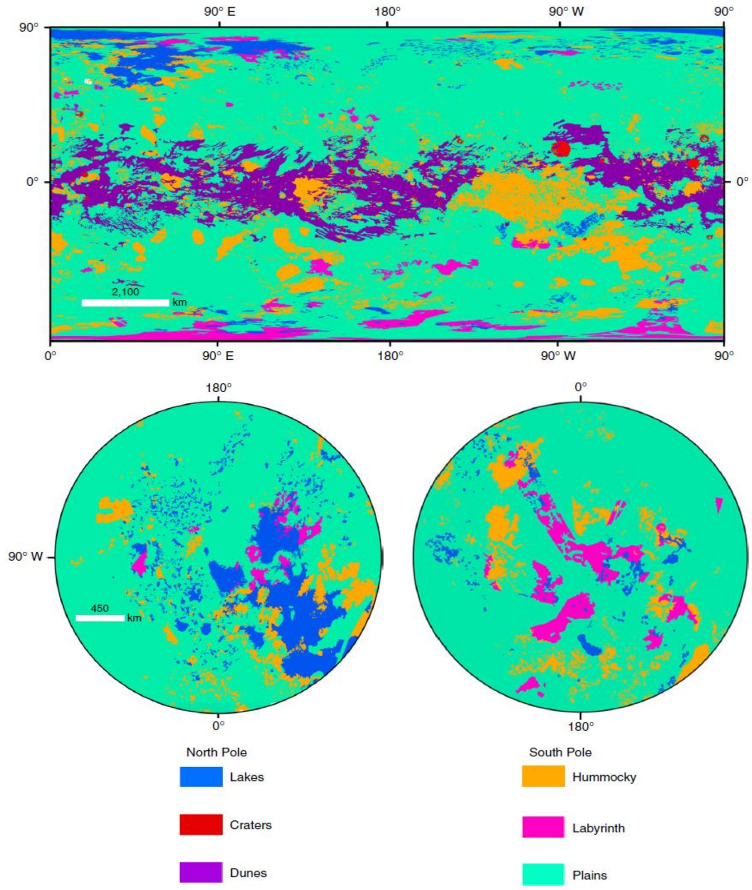

Figure 7: Titan's global map of major geomorphological units (Lopes et al., 2020).

2.1.6. Seas and Lacustrine Features and Processes:

The distinction between seas and lakes on Titan is based on their shapes and sizes. Titan's major seas, such as Kraken Mare, Ligeia Mare, and Punga Mare, are vast, stretching hundreds of kilometers across and featuring complex coastlines shaped by river activity and submerged valleys near highlands. Initial radar analyses estimated the total volume of liquids in Titan's largest lakes and seas to be around 70,000 cubic kilometres (Hayes et al., 2018b), suggesting these bodies of methane are a minor source of methane compared to atmospheric moisture, with the composition varying by location and elevation. A study found that liquid-filled basins at the regional level have similar elevations and are consistently lower than dry basins (Hayes et al., 2017), all located above sea level, indicating a possible underground connection between the lakes through a subsurface layer that replenishes lower-lying areas (Cornet et al., 2012).

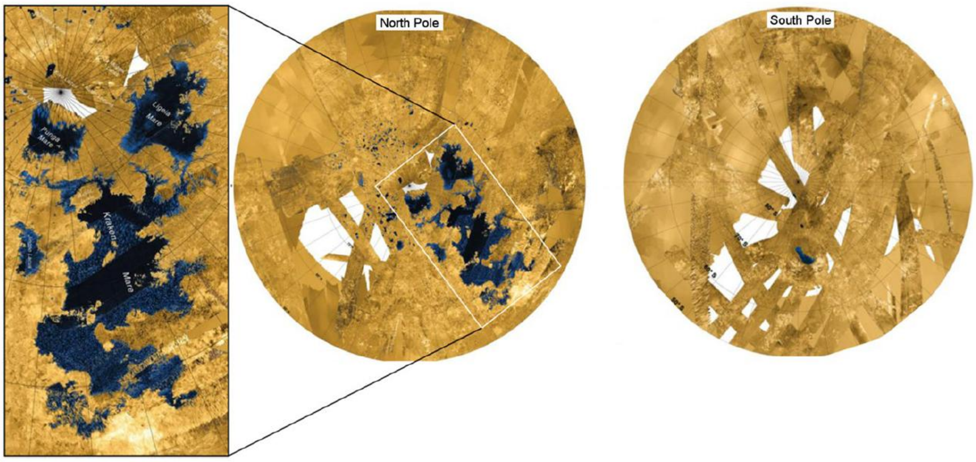

Figure 8: Lakes and Seas (North, South Pole) on Titan. Credits: NASA JPL - Caltech.

2.1.7. Impact Craters, Mountains:

The Cassini spacecraft played a crucial role in uncovering the sparse number of impact craters on Titan, a stark contrast to the previously unknown and hypothesized cratering history of the moon. Approximately 60 potential craters have been identified, with only 23 confirmed (Neish & Lorenz, 2012). This finding suggests Titan's surface is relatively young, estimated to be between 500 million and one billion years old. Analysis of Cassini's data also revealed that Titan's craters have been significantly altered by erosion, including the effects of flowing rivers and sand infill (Neish et al., 2015). Additionally, Titan features mountainous regions with ridges, blocks, and chains, indicating past or present internal stresses (Mitri et al., 2010). These eroded mountains suggest they have undergone similar erosional processes as the crater rims. Moreover, the chemical composition of these craters is essential in understanding Titan’s interior and the influence of the atmosphere on its surface (Solomonidou et al., 2020).

2.1.8. Interior-Surface-Atmosphere Interactions:

During the descent of the Huygens probe into Titan's atmosphere, the HASI-PWA instrument detected unexpected electrical disturbances, suggesting the existence of a subsurface ocean (Béghin et al., 2010). These signals implied a Schumann-type resonance, indicative of two conductive layers. Cryovolcanism has been proposed as a possible source for this replenishment (Sotin et al., 2005), with certain landforms on Titan identified as likely cryovolcanic due to their shapes or observable changes. Data from the Cassini-Huygens mission reveal that Titan's current atmospheric composition results from a series of complex processes, including internal outgassing, photochemistry, atmospheric escape, and surface interactions. The isotopic compositions of gases such as H, C, N, and O in different atmospheric compounds (N_2, CO, CH_4, HCN, and C_2 hydrocarbons) at various altitudes provide critical insights into their origins and evolution over time (Nixon et al., 2012). Also, Titan’s surface chemistry is largely governed by its atmosphere-surface interactions, which remain partially resolved (Solomonidou et al., 2024).

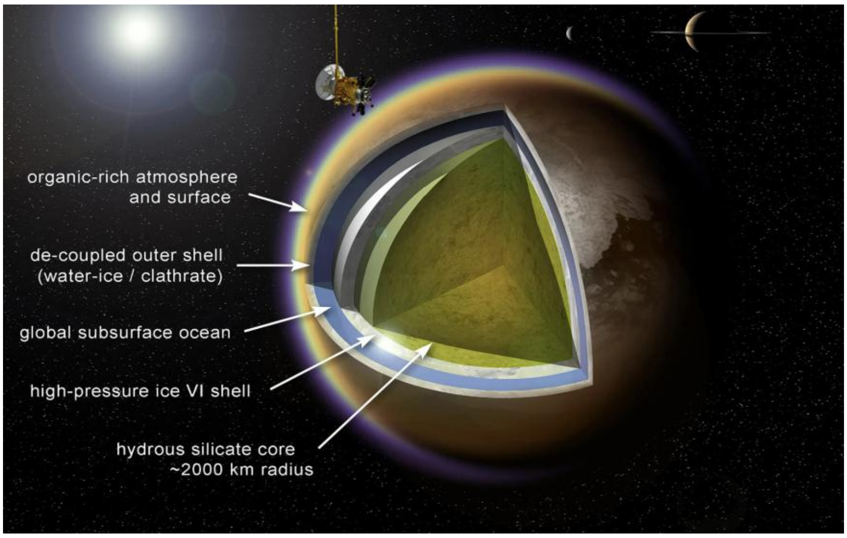

Figure 9: Internal Structure of Titan. Credits: A.D. Fortes / UCL / STFC.

2.1.9. Pre-Biotic Chemistry and Habitability:

Habitable zones are regions that can support the emergence and evolution of life (Lammer et al., 2009), requiring stable conditions, available energy, organic compounds, and a liquid medium. Titan is a notable candidate in the Solar System for potentially hosting life due to its complex organic chemistry, featuring a diverse array of molecules and organic particles, and various energy sources such as sunlight, gravitational tides from Saturn (Sohl et al., 2014), internal heat from its core (Fortes, 2012), and potentially heat-releasing chemical reactions (Schulze-Makuch & Grinspoon, 2005). Titan uniquely contains two types of liquids: a potentially salty underground ocean, possibly containing ammonia (Iess et al., 2012), and hydrocarbon lakes and seas on its surface, particularly in the polar regions (Stofan et al., 2007). This dual solvent system could allow for the development of two distinct biospheres, connected by material exchange driven by geological processes like cryovolcanism. This process is suggested by the presence of argon-40 in Titan's atmosphere, a decay product of potassium-40 from core rocks (Niemann et al., 2010b).

Hence, any future Titan mission that aims to explore any of the aforementioned science about Titan will certainly open new gateways to understanding the process of planetary formation and evolution, besides having high science returns.

2.2. Gaps and Open Questions about Titan

Every interplanetary space mission is a function of the science objectives it aims to fulfil, as well as the mission requirements for the highest science returns possible. The science objectives for a future Titan mission would be based on the gaps and open questions about the current knowledge of Titan. The major gaps and open questions about Titan are listed as follows:

1) **Upper Atmosphere:** Heterogeneous ion-neutral chemistry, upper atmospheric dynamics, physical ionospheric and thermospheric processes.

2) **Middle Atmosphere:** Circulation mechanisms, spatial distribution and characteristics of aerosols (main haze layer), atmospheric coupling between different layers.

3) **Lower Atmosphere:** Methane cycle characteristics, formation and evolution of Titan's clouds, near-surface wind patterns, and chemical exchanges (surface – atmosphere).

4) **Aeolian Features and Processes:** Distribution of aeolian landforms, characteristics of dune materials, morphometry of the dunes.

5) **Fluvial Features and Processes:** Geographic distribution of river networks, erosion and the nature of eroded material, formation and activity of fluvial channels.

6) **Seas and Lacustrine Features and Processes:** Shapes and distribution of seas and lakes, characteristics of lacustrine features, surficial processes.

7) **Impact Craters and Mountains:** Age and composition of geological features, impact of tectonism, evolution of craters and mountains.

8) **Interior-Surface-Atmosphere Interactions:** Characteristics of the subsurface liquid ocean, cryovolcanism dynamics, atmospheric evolution.

9) **Surface Chemistry and Geomorphology:** Origin and evolution of landform and ocean-floor features, physical and chemical processes governing surface chemistry.

10) **Pre-Biotic Chemistry and Habitability:** Synthesis of organic material from atmosphere, material exchange between surface and atmosphere, chirality of hydrocarbons, nature of organic reservoirs.

2.3. Past, proposed and future missions to Titan

There have been a plethora of missions to explore Titan incorporating different mission configurations and frameworks. An overview of the major missions to Titan exploration is provided below. Voyagers 1 and 2, as well as the Cassini-Huygens mission, have exclusively provided substantial data about Titan and are the only missions to date to explore Titan. The upcoming Dragonfly mission is the only future approved mission for Titan exploration, with the rest being innovative mission proposals.

Table-1: Overview of Missions targeted to explore Titan and Saturnian System

Mission	Date and Organization	Type and Status of the Mission
Pioneer 11	Launched 1973, Saturn Flyby 1979, NASA Mission.	Space probe to understand solar system via planetary flybys. End of Operations in 1995.
Voyager 1 and 2	Launched 1977, V1 Saturn Flyby 1980, V2 Saturn Flyby 1981, NASA Mission.	2 identical spacecrafts (interstellar probes) to explore deep solar system via multiple flybys (planetary alignment). Both still in operation.

Cassini-Huygens	Launched 1997, Saturn Orbit 2004-2017, NASA Mission.	Orbiter-lander mission to study Saturn system (Cassini) and Titan (Huygens probe). Disposal 2017.
TandEM	2007, Proposal Mission, ESA	2 spacecrafts (orbiter & in-situ) mission to study Titan and Enceladus. Became TSSM.
Titan Explorer	2007, Proposal Mission, NASA	Orbiter mission to study Titan in greater detail. Became TSSM.
TSSM	2009, Proposal Mission, NASA / ESA	Joint flagship mission (Orbiter-Balloon-Lander) to study Titan and Enceladus, particularly Titan. Not selected for being a mission.
TAE	2010, Proposal Mission, ESA	Balloon in-situ mission to study Titan's atmosphere. Not selected for being a mission.
TiME	2011, Proposal Mission, NASA	Lake lander mission to investigate Titan's lakes and seas. Not selected for being a mission.
TALISE	2012, Proposal Mission, SENER	Propelled lake sampling lander mission to investigate Titan's lakes and seas. Not selected, uncertain project future.
AVIATR	2012, Proposal Mission, University of Idaho	High-powered airplane mission for Titan's surface imaging. Not selected for being a mission, uncertain project future.
JET	2011, Proposal Mission, NASA JPL	Orbiter mission targeted towards astrobiology, potential for habitability on Enceladus & Titan. Not selected for being a mission.
E^2T	2017, Proposal Mission, NASA / ESA	Orbiter's mission aimed at assessing habitability on Enceladus & Titan. Uncertain project future.
Dragonfly	2017, Proposal Mission, NASA / APL	Rotorcraft in-situ mission to study pre-biotic chemistry and habitability markers on Titan. Selected as a mission, expected to launch in 2028.

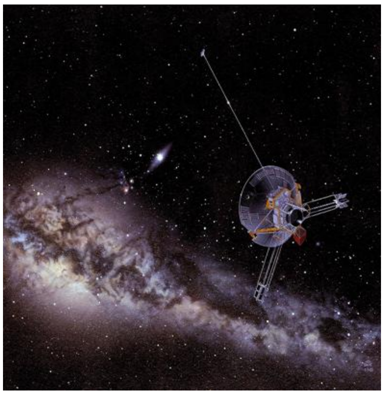

Figure 10: Pioneer 11 Spacecraft. Credits: NASA.

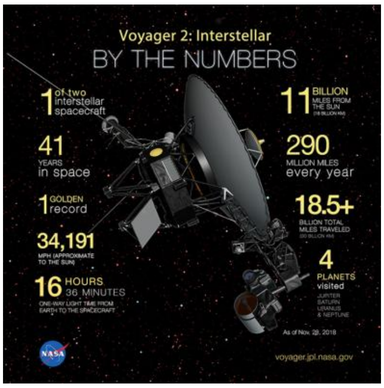

Figure 11: Overview of Voyager 2. Credits: NASA / JPL – Caltech.

Figure 12: Overview of Cassini-Huygens. Credits: NASA / JPL.

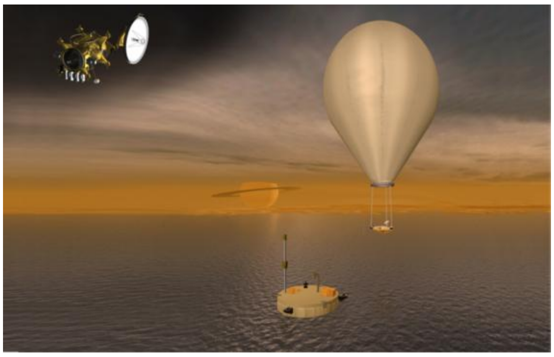

Figure 13: TSSM Architecture. Credits: TSSM Joint Summary Report, NASA / ESA.

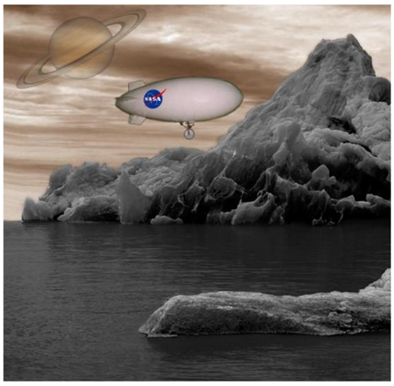

Figure 14: TAE Mission. Credits: NASA / JPL.

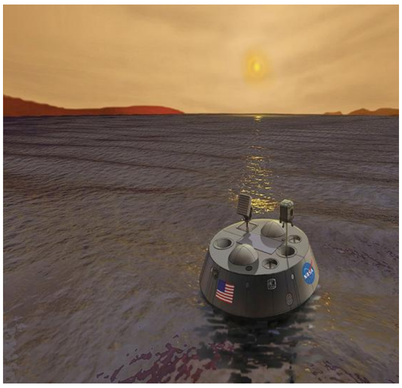

Figure 15: TiME Mission. Credits: NASA / JPL.

Figure 16: AVIATR Mission. Credits: Mike Malaska (Univ. of Idaho).

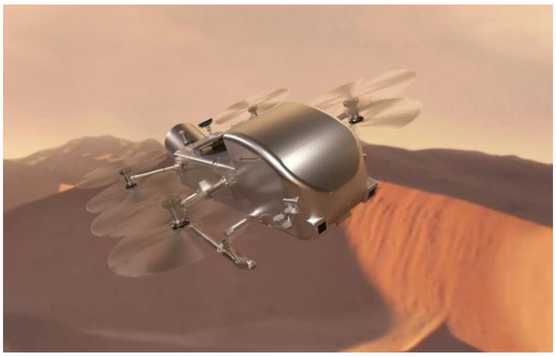

Figure 17: Dragonfly Mission. Credits: Johns Hopkins APL.

3. MISSION CONCEPT FOUNDATION

3.1. Selection of Science Goals and Mission Objectives

The future mission concept has been proposed to focus on Titan’s atmosphere and near-surface environments based on a comprehensive understanding of current scientific knowledge and unresolved questions about Titan. This focus is due to Titan's atmospheric chemical complexity, surface and prebiotic chemistry, atmospheric dynamics and processes, climate modelling, aerosol and haze characteristics, energy balance, and insights into the origin and evolution of Earth’s atmosphere, among other factors. Exploring Titan's atmosphere and pre-biotic evolution in comparison to other spheres and domains offers a unique opportunity to advance our understanding of planetary atmospheres, complex organic chemistry, astrobiological implications, and the potential conditions for life beyond Earth, making it a priority.

An overview of the chosen science goals for the proposed mission concept to answer the open questions of Titan’s atmosphere are as follows:

1) Analysis of heterogeneous ion-neutral chemistry in the upper atmosphere.
2) Radiation and energy distribution among layers of the atmosphere.
3) Dynamic physical and chemical processes in the upper atmosphere.
4) Origin and development of atmospheric super-rotation of the atmosphere.
5) Circulation, atmospheric coupling, and complex chemistry of aerosols in the main haze layer.
6) Meteorological methane cycle and its characteristics in the lower atmosphere.
7) Clouds, weather patterns, and seasonal changes in the lower atmosphere.
8) Chemical exchanges, sedimentation, and deposition by the lower atmosphere.
9) Interactions between atmosphere and near-surface environments, and their global impact.
10) Surface chemistry, geomorphology, and their driving local and global processes.
11) Origin and synthesis of organic biomolecules with astrobiological potential (microbial life).
12) Evolution of rich organics and the pre-biotic environment.

3.2. Titan Mission Configurations and Frameworks

Exploring Titan requires a multifaceted approach due to its unique environment, which includes a dense and thick atmosphere, surface lakes and rivers of liquid methane and ethane, a potential water-ice crust and a subsurface layer of ammonia-rich liquid water. The mission configurations and frameworks for exploring Titan can be diverse, combining various types of spacecrafts with a plethora of scientific objectives and technologies. Here's a comprehensive list of potential mission configurations and frameworks:

1) **Flyby Missions:** Flyby missions are space missions designed to travel close to a celestial body, gathering data without landing on or orbiting it. These missions are pivotal for scientific exploration, offering valuable insights into the characteristics, atmospheres, magnetic fields, and other aspects of planets, moons, comets, and asteroids. They are especially useful for exploring distant or hazardous objects where landing or orbiting might be too challenging or costly.

Possible Frameworks: Single Flyby, Multiple Flybys (Tour), Targeted Flybys, Flyby with Deployables, Orbiter-Flyby Hybrid, etc.

2) **Orbiter Missions:** Orbiter missions involve sending a spacecraft into the orbit of a planet or moon, allowing for long-term study from above. These missions can map the celestial body’s surface, study its atmosphere, and monitor seasonal changes over time. An orbiter could also serve as a communications relay for atmospheric probes, landers, or rovers on the surface.

Possible Frameworks: Stand-alone Orbiter, Orbiter with Subsatellites, Orbiters with Atmospheric Probes, Orbiter with Surface Lander(s), Orbiter with Subsurface Ocean Explorer, Dual-Orbiters etc.

3) **Lander Missions:** Lander missions are space exploration missions that involve sending a spacecraft to land on the surface of a celestial body, such as a planet, moon, asteroid, or comet. Unlike flyby or orbiter missions, which study these bodies from space, lander missions allow direct analysis of the surface and atmosphere, providing invaluable data on composition, geology, meteorology, and potential for life.

Possible Frameworks: Static Lander, Hopper Lander, Lake Landers and Submersibles, Surface Drillers or Penetrators, Cryobots / Hydrobots etc.

4) **Atmospheric Probes:** Atmospheric probes are scientific elements designed to study the atmospheres of other planets, moons, or celestial bodies directly. Unlike orbiters, landers, or rovers, which study from orbit or from the surface, atmospheric probes are specifically designed to enter and often pass through or float in the atmosphere of the target body. They collect data on atmospheric composition, temperature, pressure, cloud structure, dynamics, and other meteorological phenomena. This data helps to understand the climate, weather patterns, and potential habitability of other worlds.

Possible Frameworks: Entry Probes, Balloon Probes, Glider and Airship Probes, Rotorcraft and Powered-flight Probes, Direct-Sampling Rockets etc.

5) **Rovers:** Rover missions are robotic space exploration missions that involve sending a rover, a motorized vehicle designed to travel across the surface of a planet or moon, to gather scientific data. These missions are crucial for understanding the geology, atmosphere, climate, and potential for life on other celestial bodies. Rovers are equipped with various instruments and cameras to conduct experiments, analyze samples, and capture detailed images of the surface.

Possible Frameworks: Wheeled Rovers, Walking Rovers, Hovercraft or Air Cushion Rovers, Swimming or Floating Rovers, Submarine Rovers etc.

6) **Sample Return Missions:** Sample return missions are space missions designed to collect samples of soil, rocks, atmosphere, or other materials from space and return them to Earth for detailed analysis. These missions are critical for deepening our understanding of the solar system, as they enable in-depth experiments with sophisticated equipment that cannot be miniaturized or made rugged enough to send to space. By analyzing these samples, insights into the composition, structure, and history of celestial bodies, including their potential for hosting life can be perceived.

Possible Frameworks: Atmospheric Sample Return, Surface and Subsurface Sample Return, Lake and Sea Sample Return, Cryovolcanism Sample Return etc.

7) **Hybrid Missions:** Hybrid missions to explore celestial bodies like Titan, one of Saturn's moons, combine multiple exploration methods or vehicles to achieve comprehensive scientific objectives. These missions might utilize a blend of orbiters, landers, rovers, and aerial vehicles (such as balloons or drones) to collect data from various perspectives and environments. The integration of different types of vehicles allows for a more versatile exploration strategy, enabling scientists to gather data from the atmosphere, surface, and possibly subsurface of Titan.

Possible Frameworks: Orbiter and Lander / Rover Combination, Orbiter-Lander-Rover Trio, Orbiter, Balloon, and Rover Trio, Orbiter with Submarine, Orbiter with Fleet of Small Landers / Drones, Aerial and Surface Hybrid, Aerobot-Assisted, Submersible-Drone Hybrid, Surface-Subsurface Hybrid, Satellite Constellations etc.

8) **Technology Demonstrators:** Technology demonstrator space missions are specialized missions designed to test and validate new technologies and concepts in space. These missions

play a critical role in advancing space exploration and satellite technology by providing a platform to evaluate new equipment, instruments, systems, or techniques in the harsh environment of space.

Possible Frameworks: New Propulsion Systems, New Communication Systems, Sensors and Instrumentations, Autonomous Systems, Life Detection Platforms etc.

The trade-off analysis about all the possible Titan mission configurations and frameworks can be briefly represented as follows:

Table-2: Trade-off Analysis (Titan Mission Configurations and Frameworks)

Mission Configurations	Merits	Demerits
Flyby Missions	Cost-effective, High Speed and Efficiency, First Reconnaissance, Simpler Mission Design, Extended Mission Lifespan, etc.	Limited Observation Time, Single Opportunity, Low Spatial and Temporal Resolution, Limited Data Volume, No Surface Interaction, etc.
Orbiter Missions	Extended Observation and Data Collection, Detailed Mapping and High-Resolution Imaging, Advanced Scientific Measurements, Communication Relay Support, Cost-effectiveness and Longevity, etc.	Limited Surface Interaction, Data Transmission Delays, Complexity and Risk of Orbital Insertion, High Initial Investment, Environmental, and Space Debris Concerns, etc.
Lander Missions	Direct Surface Analysis, In-situ Experiments, Detailed Imaging and Mapping, Real-time Data Collection, Technology Testing, etc.	High Cost and Complexity, Limited Mobility and Range, Communication Delays and Challenges, Environmental Hazards, Risk of Contamination, etc.
Atmospheric Probes	Direct Data Collection, Validation of Theoretical Models, Exploration of Extreme Environments, Enhancement of Remote Sensing Data, Scientific Discovery and Innovation, etc.	High Cost, Technical Challenges, Limited Lifespan, Communication Delays, Data Transmission Constraints, etc.
Rover Missions	Enhanced Scientific Discovery, Extended Exploration Capabilities, Real-time Data Collection and Experimentation, Technological Advancement, Inspiration and Education, etc.	High Cost, Technical Complexity and Risk, Limited Lifespan, Communication Delays, Restricted Exploration Scope, etc.
Sample Return Missions	Detailed Scientific Analysis, High Precision Measurements, Ability to conduct Long-Term Studies, Cross-Disciplinary Research, Potential for New Discoveries, etc.	High Cost, Technical Challenges, Extended Timelines, Risk of Contamination, Limited Sample Size, etc.

Hybrid Missions	Enhanced Efficiency and Flexibility, Cost Reduction, Maximized Data Collection and Analysis, Enhanced Safety, Technological Advancement, etc.	Complexity in Coordination, High Initial Costs, Dependency on Technology, Limited Human Presence, Ethical and Operational Challenges, etc.
Technology Demonstrators	Innovation and Risk Reduction, Cost-Effective Development, Accelerated Technological Advancement, Education and Skill Development, Enhanced Mission Capabilities, etc.	High Initial Costs, Limited Immediate Returns, Technical Failures and Setbacks, Resource Diversion, Regulatory and Logistical Challenges, etc.

3.3. Final Titan Mission Concept Selection

By the culmination of all the current scientific knowledge about Titan’s atmosphere and its pre-biotic environment, as well as in-depth analysis of various mission configurations and frameworks, a hybrid mission configuration has been chosen, considering the factors of flexibility, data procurement, safety, and technology advancement alongside highest science return possible from Titan.

Within the hybrid mission configuration, an orbiter element has been chosen considering the legacy of a lot of past orbiter missions to the Titan and the Saturnian system. The orbiter mission element is a trial and tested configuration with a high TRL, capable of providing global insights about Titan’s atmosphere and the pre-biotic environment with a high degree of accuracy and precision. Also, the orbiter offers flexibility of operation, as well as greater manoeuvrability in orbits to meet the science objectives.

Moreover, to study Titan’s atmosphere and near-surface environments in detail, as well as to conduct in-situ measurements, heavier-than-air powered flight has been considered with respect to Titan’s high atmospheric density to surface gravity ratio. Flight in Titan’s atmosphere is simple and easy in comparison to Earth, and a heavier-than-air atmospheric probe can utilize the dynamic super-rotating atmosphere of Titan to its advantage. The gravity on Titan is $1/7^{th}$ the gravity on Earth, and the atmospheric column density is 10 times the density of Earth (Flasar et al., 2005), so the power required to hover on Titan is about $1/40^{th}$ the power required on Earth (Ata, 2021). Therefore, a powered atmospheric probe is an ideal choice for making localized and detailed in-situ observations and measurements of Titan’s atmosphere and near-surface environments, while the orbiter provides a global coverage, thereby complementing each other in terms of science procurement and technological coordination.

4. TARA MISSION CONCEPT

4.1. Overview of the Mission:

The mission concept TARA (Titan Atmospheric Research Ascendant) is formulated and developed through comprehensive brainstorming of various mission configurations and frameworks (refer to Table-2) to align with the defined science objectives. This mission concept envisions a dual-element approach, integrating a Titan orbiter and a Titan ornithopter, to perform both remote and in-situ measurements of Titan's atmosphere and near-surface environments.

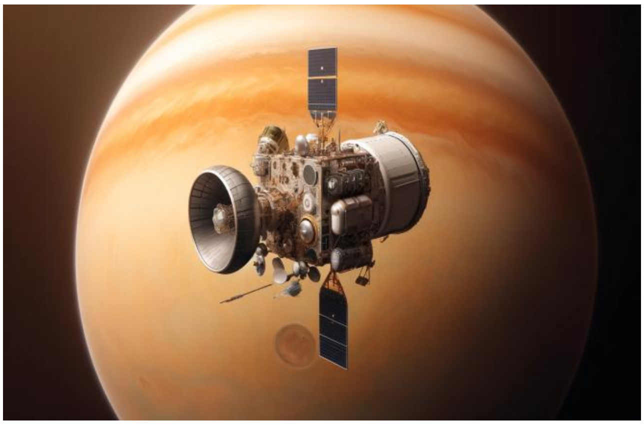

Figure 18: Artistic Renderation of Possible TARA Mission Orbiter.

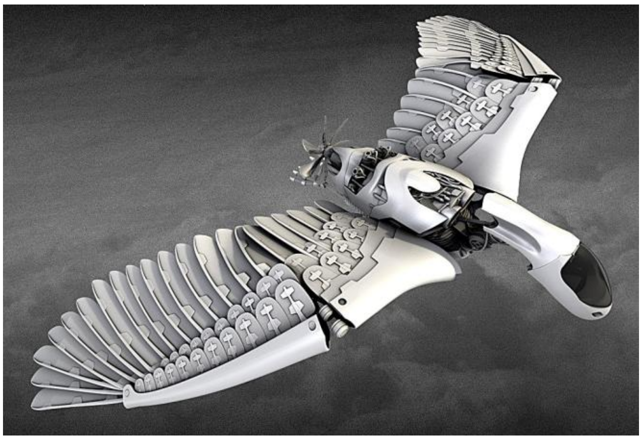

Figure 19: Artistic Renderation of Possible TARA Mission Ornithopter.

The Titan orbiter is defined to follow a near-polar, low eccentricity circular orbit around Titan, ensuring extensive temporal and global coverage. Meanwhile, the Titan ornithopter will conduct highly detailed observations and in-situ measurements of Titan's atmosphere across all altitudes and latitudes during its descent through Titan's atmosphere.

This mission aims to complement NASA's upcoming Dragonfly mission by focusing on the study of pre-biotic chemistry and environmental conditions. The mission will achieve this by mapping higher and mid-level altitudes and conducting in-situ atmospheric observations and measurements in regions that are beyond the reach of the Dragonfly mission. This combined approach will provide a more comprehensive understanding of Titan's atmospheric dynamics and near-surface interactions.

The synergy between Dragonfly and TARA, in terms of complementary timing, geographic focus, and measurement scales, could aid in a level of scientific return that far surpasses what either mission could achieve alone. Dragonfly's mid-2030s exploration of Titan's equatorial regions, complete with in-situ analyses of surface organics and local near-surface conditions, sets the stage for TARA's subsequent arrival near Titan's northern spring of 2039, when its orbiter and ornithopter would focus on the broad characterization of atmospheric processes and pre-biotic organic synthesis, linking atmospheric precursors to surface chemistry. Together, they will span distinct spatial domains, with Dragonfly providing detailed in-situ analyses of dune fields and organics at the equator and TARA monitoring dynamic northern seas, lakes, and polar processes, thus building a global picture of Titan's geological and climate systems. Their differing observational scales and platforms – Dragonfly's high-resolution surface measurements calibrated against

TARA's orbital and ornithopter-based global and intermediate-scale data, will produce a comprehensive understanding of Titan's atmospheric chemistry, the formation and distribution of complex organic molecules, and the coupling of local surface conditions with large-scale environmental drivers. This integrated approach not only enhances the interpretation of each mission's data, but also extends the legacy of Cassini-Huygens by providing a temporal baseline that links pre-2030s observations to the mid-2030s and beyond, ultimately offering unprecedented insights into Titan's evolving atmosphere, climate, geology and potential prebiotic chemistry over an extended timescale.

An overview of the TARA mission with key elements can be represented as follows:

Table-3: TARA Mission at a Glance

Titan Atmospheric Research Ascendant (TARA)	
Key Mission Goals	**Titan's Atmospheric Dynamics and Pre-Biotic Environment** • Origin and Evolution of Atmosphere and Governing Parameters. • Role of Atmosphere in Organic Synthesis of Biomolecules. • Complex interactions between Atmosphere and Surface. • Pre-Biotic Implications and Clues of Terrestrial Habitability.
Architecture	Titan Orbiter with In-situ Atmospheric Probe (Titan Ornithopter)
Model Payload	**Orbiter: 14 instruments with a total mass of 104.28 kg** • Visible and Near-Infrared Imager • Near-Infrared Spectrometer • Mid to Far-Infrared Thermal Spectrometer • Ion and Neutral Mass Spectrometer • Pressure Gauge • Electron and Negative Ion Mass Spectrometer • Langmuir Probe • Mutual Impedance Probe • Magnetometer • Energetic Particle Spectrometer • Plasma Spectrometer • Radio Science Experiment • Sub-Millimeter Heterodyne • UV Spectrometer **Ornithopter: 8 instruments with a total mass of 20.40 kg** • Visual Imaging System (2-Wide Angle and 1-Narrow Angle Cameras) • Imaging Spectrometer • Atmospheric Structure Instrument and Meteorological Package • Electric Environment Package • Icy Grain, Organic Dust and Aerosol Analyser • Mass Spectrometer • Radio Science Experiment • Magnetometer

Overall Mission Profile	01/2030 – Launch by Ariane 62 + Interplanetary Transfer / Cruise 01/2030 – Earth Departure (Interplanetary Departure) + 2.06-yr transfer 02/2032 – Jupiter Flyby + 6.88-yr transfer 12/2038 – Saturn Orbit Insertion 01/2039 – Titan Orbit Insertion (Start of Titan Science Phase) • Elliptical Aerosampling phase (2 months) • Near-polar, low eccentricity circular orbit (96 months) 03/2043 – End of Titan Science Phase 09/2043 – End of Nominal Mission
Orbiter	3-axis stabilized Power: 4 Next-Gen RTGs (3 operational, 1 spare) HGA: 3.5m, body-fixed X and Ka Bands Downlink ≥ 2 Gb / Earth Day Radiation Design Point < 15 krads Dry mass at launch: ~ 1294 kg
Ornithopter	3-axis stabilized Power: 2 Next-Gen RTGs HGA: 0.4m, body-fixed Downlink ≥ 1 Gb / Earth Day Radiation Design Point < 15 krads Dry mass at launch: ~ 350 kg
Average Data Volume Return from Titan Orbit	3 Gb / Earth Day (compressed)
Cumulative Data Volume (Total Mission)	Orbiter > 6 Tb Ornithopter > 500 Gb – 2 Tb
Ground TM Stations	ESTRACK Network
Key Mission Drivers and Technology Challenges	Mass Budget Power Budget
Responsibilities	ESA: manufacturing, launch, spacecraft operations, and data archiving. PI Teams: science payload provision, operations, and data analysis.

The technical details and parameters, such as the selection of telecommunication bands, radiation design point as well as data volume return, have been cross-referenced with historical data from study reports of previous space missions and mission concepts such as TSSM (Spencer & Niebur, 2010), Juno (Bolton et al., 2017) and JUICE (M. Dougherty et al., 2012) for comprehensive analysis. More information about respective trade-offs and reasoning behind the selection of details and parameters are provided in the later sections of the paper.

An ornithopter, designed as an atmospheric probe, offers a futuristic and novel approach to exploring the dense, nitrogen-rich atmosphere of Titan. This bird-like UAV, with its flapping wings, mimics the flight of terrestrial birds, making it exceptionally suitable for maneuvering through Titan’s low-gravity and thick atmospheric conditions. By integrating advanced instruments, sensors, and communication systems, the ornithopter can collect high-resolution data on atmospheric composition, energy redistribution, weather patterns, and near-surface properties. This technology demonstration aims to provide unprecedented insights into Titan’s meteorology and potential habitability, bridging gaps left by traditional rotorcrafts or fixed-wing atmospheric probes (Giacomini et al., 2022). Furthermore, its ability to glide and hover can allow for prolonged observations of intriguing near-surface features and atmospheric phenomena, potentially revolutionizing our understanding of similar celestial bodies in the solar system.

There are several merits and advantages that an ornithopter offers for studying extraterrestrial atmospheres like Titan. The major merits are listed as follows:

1) **Bio-Inspired Efficiency**: An ornithopter mimics the flapping motion of natural flyers such as birds or insects, potentially leading to high efficiency in generating lift and thrust in the dense atmosphere of Titan. The flapping wing motion of an ornithopter can exploit Titan’s dense atmosphere more efficiently, potentially offering superior lift-to-drag ratios compared to fixed-wing or rotary-wing designs.

2) **Minimum Mechanical Constraints:** An ornithopter tackles and avoids conventional problems associated with an unloaded rotor, higher stall performance, no torque-related constraints (comparative to rotorcrafts), and offers combined benefits of plane and helicopter.

3) **Enhanced Maneuverability:** An ornithopter is capable of precise and agile manoeuvres, allowing detailed study of various atmospheric layers and features. It can perform sharp turns, climb and dive steeply, and hover during slow flight, which is beneficial for close-up observations and detailed atmospheric sampling. High efficiency in forward flight enables fast and high temporal coverage.

4) **Energy Efficiency:** The flapping wing motion of the ornithopter can be more energy-efficient in Titan’s thick atmosphere compared to traditional propulsion methods. It exhibits high efficiency in forward flight because of its streamlined shape. Moreover, it can fully utilize the headwind and tailwind conditions of Titan’s atmosphere.

5) **Low-Speed Operation:** An ornithopter can operate effectively at low speeds, which is advantageous in Titan’s dense atmosphere where conventional aircraft might struggle. Effective low-speed flight capability aligns well with the slow wind speeds and dense atmosphere on Titan, providing stable platforms for scientific instruments.

6) **Minimal Noise and Disturbance:** An ornithopter generates less noise, reducing disturbance to the environment and potentially minimizing interference with scientific instruments, onboard sensors and the surrounding atmosphere.

7) **Adaptability to Harsh Conditions:** The flexible wings of an ornithopter can adapt to changing atmospheric conditions, such as gusts of wind and turbulence, more effectively than rigid-wing aircraft, offering superior flexibility in operations.

8) **Extended Mission Duration and Range:** An ornithopter offers potential for longer operational periods due to efficient energy use and the ability to harvest energy from the environment, such as wind currents. Efficient energy use could extend the mission duration, enabling prolonged scientific operations and data collection. The ability to glide or soar using Titan’s atmospheric currents can further extend the range and operational time without expending additional energy.

9) **Reduced Launch and Deployment Costs:** The ornithopter’s lightweight and compact design could reduce the costs and complexity associated with launch and deployment compared to larger, heavier aircraft or rovers.

But there are several demerits and limitations of using an ornithopter as well. The major demerits are listed as follows:

1) **Complexity in Design and Engineering:** The intricate mechanics required for the flapping wing motion of an ornithopter increase the complexity of the design and engineering process, leading to higher costs and potential for mechanical failure.

2) **Control and Stability Challenges:** Maintaining control and stability of an ornithopter in Titan's variable atmospheric conditions can be challenging, requiring advanced algorithms and real-time autonomy for possible adjustments, that are still largely experimental.

3) **Limited Payload Capacity:** The structural and energy constraints of an ornithopter may limit the size and weight of scientific instruments it can carry.

4) **Power Supply Constraints:** The need for a continuous energy supply to maintain flapping motion might pose challenges, especially in Titan's distant and cold environment where solar power is limited.

5) **Durability and Maintenance:** The moving parts of an ornithopter are subject to wear and tear, necessitating robust materials and possibly frequent maintenance, which is impractical for remote planetary missions such as Titan.

6) **Communication and Data Transmission:** Ensuring reliable communication and data transmission between the ornithopter and orbiter could be challenging due to the complex flight dynamics and orientation changes of both mission elements.

4.2. Risks and Limitations

Exploring Titan with a combination of an orbiter and an ornithopter presents a unique and innovative approach to planetary exploration. However, such a mission comes with various risks and limitations which are presented as follows:

Engineering and Technical Challenges:

- **Harsh Environmental Conditions:** Titan's average temperature is around -179°C (290°F), which presents challenges for the design of the ornithopter's wings and propulsion system to ensure it can fly efficiently. The electronics and mechanical systems of the ornithopter must be designed to operate in extreme cold, else could lead to material brittleness and failure of electronic components.

- **Energy Generation and Storage:** The extreme distance from the Sun makes solar power much less effective than it is for missions closer to Earth. Alternative energy sources, such as Radioisotope Thermoelectric Generators (RTGs), must be used, but these come with their own limitations and risks, including power density, longevity, heat dissipation, power decay over time and the need for thermal management. These systems must be robust enough to endure Titan's cold while providing sufficient power for flight, scientific instruments, and communication.

- **Atmospheric Entry and Descent:** For the ornithopter, the descent system must be capable of handling high speeds, atmospheric friction, and potential wind shear, all of which could jeopardize the mission during these critical phases.

- **Aerodynamic Modeling Uncertainties:** The unique atmospheric conditions of Titan make it challenging to accurately model and predict the ornithopter's aerodynamics and flight dynamics, potentially impacting mission planning and the craft's ability to achieve its scientific objectives.

- **Flight Dynamics:** The ornithopter's design must be optimized for flight in Titan's atmosphere, which is significantly denser than Earth's. This involves careful consideration of wing design, power requirements, and control mechanisms.

- **Propulsion and Navigation:** The unique propulsion requirements for an ornithopter to efficiently navigate Titan's dense atmosphere and low gravity environment demand novel engineering solutions, potentially untested in space missions. Titan's lack of GPS and the potential for magnetic field anomalies could complicate navigation for the ornithopter, increasing the risk of loss or failure during extended exploration flights.

- **Material Durability and Degradation:** Materials used for both the orbiter and ornithopter must withstand prolonged exposure to cold temperatures and chemical abrasion (potential hydrocarbon rain, and corrosion) from Titan's atmosphere, requiring advancements in material science. This could lead to unforeseen chemical reactions, material degradation, or embrittlement due to prolonged exposure, which might not be fully predictable through terrestrial testing.

- **Sensor Calibration:** Instruments onboard the ornithopter must be calibrated to function accurately in Titan's environmental conditions, including low light levels, dense atmosphere, and potentially interfering chemical compositions.

- **Communication Delay:** The vast distance from Earth results in significant communication delays (about 1.3 to 1.5 hours one way). This requires the orbiter and ornithopter to have a high level of autonomy to perform tasks and handle issues in real-time, which increases complexity and failure, and makes real-time control near-impossible.

Scientific Limitations:

- **Selective Sampling:** The ability to collect and analyze samples, whether atmospheric or surface, could be limited by the ornithopter's design and payload capacity, potentially affecting the mission's scientific return.

- **Instrument Limitations:** The scientific instruments must be miniaturized to fit within the payload constraints while maintaining their efficacy, a balance that is difficult to achieve.

- **Limited Coverage:** While an ornithopter can provide detailed observations of specific locations, its range may be limited compared to orbiters or rovers, potentially leaving large areas of Titan unexplored.

- **Temporal Constraints:** Understanding the seasonal and temporal variations on Titan requires long-term observations that may be beyond the lifespan of the mission's operational capabilities.

- **Spectral and Imaging Constraints:** Titan's thick atmosphere could obscure certain wavelengths of light, limiting the effectiveness of some observational instruments and complicating the analysis of surface features and atmospheric composition. Instruments must be carefully selected and might still face limitations in penetrating the atmospheric veil.

- **Data Acquisition, Transmission, Return, and Bandwidth:** The amount of data that can be collected and transmitted back to Earth is constrained by the orbiter's communication system and the available power. Also, the capacity to transmit data back to Earth is limited by the distance from Saturn to Earth and the available communications technology. This could result in significant delays in receiving data or limits on the amount of data that can be sent, potentially affecting the mission's scientific yield.

Operational Risks:

- **Ornithopter Deployment:** Successfully deploying the ornithopter from the orbiter poses significant risks, including entry, descent, and landing challenges in Titan's thick atmosphere.

- **Limited Payload Capacity:** The need to minimize weight to enable flight in Titan's atmosphere might limit the scientific instruments' capabilities aboard the ornithopter, potentially restricting the range of scientific data collected.

- **Surface Operations:** Operating near Titan's surface involves risks from unknown terrain hazards, such as methane lakes, cryovolcanoes, and complex weather patterns.

- **Orbiter-Ornithopter Coordination:** Ensuring effective communication and coordination between the orbiter and ornithopter for navigation, data relay, and scientific observations could be challenging and adds operational demands, impacting mission effectiveness.

- **Complex Autonomous Operations:** Given the communication delay to Earth, the ornithopter must have highly autonomous capabilities for flight control, navigation, scientific operations, and unexpected events. Developing software and algorithms that can adapt to the unpredictable conditions of Titan while making critical decisions independently adds a significant layer of complexity and risk.

- **Complex Mission Planning:** The dual nature of the mission adds layers of complexity in mission planning and trajectory design, requiring precision and foresight in the deployment and operation of both the orbiter and ornithopter.

- **Failure Modes, Rescue or Recovery Operations:** The mission can face various potential points of failure, including the deployment mechanism for the ornithopter, its launch from the orbiter, and continued operation on Titan's surface or atmosphere. Also, in the event of malfunction or failure, the ability to conduct rescue or recovery operations is virtually non-existent due to the distances involved.

- **Mission Flexibility and Reliability:** The long mission duration required to reach and operate around Titan demands extremely high reliability of all spacecraft systems, increasing the mission's complexity and cost. The mission's success will heavily depend on meticulous planning and the ability to adapt to unforeseen circumstances.

Logistical and Budgetary Constraints:

- **Cost and Resource Allocation:** The development, launch, and operation of such a sophisticated mission is highly expensive. Budget constraints could limit the scope of the mission or its scientific payload. Long-duration missions face the risk of funding cuts or redirection of priorities, especially in shifting political landscapes.

- **International Collaboration:** While collaboration can bring benefits, including shared costs and expertise, it also introduces complexity in coordination, potentially leading to delays or compromises on mission objectives. Collaborations may introduce dependencies on international partners, which could impact mission timelines and objectives due to differing priorities or resource limitations.

Regulatory, Environmental and Ethical Concerns:

- **Planetary Protection:** There are strict protocols to avoid contaminating celestial bodies with Earth-based life. Ensuring the ornithopter and orbiter meet these requirements is essential but challenging. The potential for unintentional harm to Titan's environment, including its atmospheric and surface composition, raises ethical considerations.

- **Space Debris:** The orbiter and ornithopter, once the mission is completed, must be disposed of in a way that does not contribute to space debris or pose a contamination risk to Titan, beyond planetary protection protocols.

Risk Management and Mitigation Strategies:

- Advanced materials and engineering designs to cope with low temperatures and atmospheric conditions, better durability.
- Development of more efficient and sustainable power systems for extended operations.
- Deployment of redundant systems and autonomous capabilities to ensure mission success despite communication delays, and enabling complex decision-making.
- Inclusion of versatile, lightweight scientific instruments to maximize the scientific return within payload constraints.
- Detailed pre-mission simulations and testing on Earth to validate the ornithopter's design and flight capabilities in Titan-like conditions, along with in-depth detailed testing.

4.3. Science Traceability Matrix (STM)

Any comprehensive space mission concept proposal must be able to clearly articulate the significance of achieving the mission's goals and outline the implementation strategy. This is effectively achieved through the use of a Science Traceability Matrix (STM), which has become a mandatory component of all science mission proposals of major space agencies such as NASA, ESA, etc. The STM offers an overview of what the mission aims to accomplish in relation to high-level objectives identified by surveys, roadmaps, or program objectives (Weiss et al., 2005).

The STM ensures a logical progression from the high-level objectives to the science objectives, mission objectives, measurement objectives, measurement requirements, instrument requirements, and spacecraft and system requirements, ultimately leading to data products and publications. It serves as the crucial document that illustrates the relationships among all these key elements. Furthermore, it provides the comprehensive scope necessary to conduct and document high-level trade-offs impacting the science outcomes and overall mission design (Weiss et al., 2005).

The science traceability matrix of TARA Mission elements (orbiter and ornithopter) Is presented below. The technical details and parameters, such as the resolutions, energy ranges, data rates, accuracy and precision values etc., have been cross-referenced with historical data from study reports of previous space missions and mission concepts such as TSSM (Spencer & Niebur, 2010), Juno (Bolton et al., 2017) and JUICE (M. Dougherty et al., 2012) for comprehensive analysis.

Table-4: Science Traceability Matrix: Orbiter (Remote)

Science Objectives	Measurement Objectives	Measurement Requirements	Instruments	Instrument Requirements	Mission Requirements	Data Products
Comprehend the heterogeneous ion-neutral chemistry, oxygen incorporation in photochemical species in the upper atmosphere.	Composition of heavy ions and neutral particles.	High mass resolution (m/Dm) of 100,000.	CosmOrbitrap, Energetic Particle Spectrometer (EPS), Plasma Spectrometer (PS).	CosmOrbitrap composition sampling limit: 1000u, sensitivity: 10^{-3} molecule.cm^{-3}. EPS energy range: 10 keV – 1 MeV. PS energy range: 1eV – 30 keV.	Orbit for sampling above 900 km, high data volume data rate: 48 kbits/s.	Global ion and neutral particle measurements.
	Total densities of positive ions and neutral particles.	High upper-limit density sampling.	Pressure Gauge (Mini-INMS).	High ion and neutral particle sampling rate.	Orbit for sampling above 900 km, high data volume data rate: 48 kbits/s.	Total density values for positive ions and neutral particles at different locations.
Comprehend the electron and negative ion chemistry, formation of negative ions.	Composition of heavy negative ions.	High mass resolution of 10,000 u/q. Electron energy range: 0-1 MeV.	Electron and negative ion mass spectrometer, Energetic Particle Spectrometer (EPS), Plasma Spectrometer.	Composition sampling limit: 10000 u/q. EPS and PS: 20° angular resolution, 30% energy resolution.	Orbit for sampling above 900 km, high data volume data rate: 48 kbits/s.	Global negative ion measurements.

	Total densities and temperatures of electrons and negative ions.	High-upper limit density sampling.	Multi-Needle Langmuir Probe (m-NLP), Mutual Impedance Probe.	High electron and negative ion sampling rate. Time resolution > 60 s.	Orbit for sampling above 900 km, high data volume data rate: 48 kbits/s.	Total density and temperature values of electrons and negative ions at different locations.
	Magnetic field measurements.	High accuracy of magnetic field line intensities.	Magnetometer.	High-accuracy magnetic field sampling. Resolution of order 0.04 nT.	Orbit for sampling above 900 km.	3D Magnetospheric model.
Determine the dynamics of the upper atmosphere, atmospheric waves, thermospheric circulations, and effect on ion densities.	Windspeed measurements (Doppler shifts).	Mapping from surface to 1200 km, vertical resolution of 10 km.	Sub-Millimeter Heterodyne.	High altitude-based spectral resolution, precision > 10%.	In-track and off-track orientation, accurate pointing.	3D wind measurement map.
	Thermal profile from CO and HCN lines.	High spatial and spectral resolution.	Sub-Millimeter Heterodyne, UV Spectrometer	Precision > 10%.	In-track and off-track orientation, accurate pointing.	Thermal energy map.
	Mixing ratio profiles and densities of molecules and respective isotopes.	High spatial and spectral resolution.	Sub-Millimeter Heterodyne, UV Spectrometer.	Precision > 10%.	In-track and off-track orientation, accurate pointing.	Mixing ratio profiles and densities in the upper atmosphere.

Determine atmospheric super-rotation, global dynamics, composition, structure, distribution of stratospheric clouds and aerosols in the middle atmosphere.	Atmospheric wave activity and haze monitoring.	High spatial resolution (1 km).	Visible and Near-IR imager.	Imaging window: 0.4-0.7 µm (2, 2.7, 5-6 µm)	Line-of-sight observations and orbit determination.	Imaging map of wave activity and haze.
	Wind profile measurements, radio occultation.	Mapping from 80 km onwards.	Sub-Millimeter Heterodyne, Radio Science Experiment.	Precision of 3 m/s in 1 min integration. RS: 10^{-13} measurements at 10s integration.	Pole to pole probing, polar orbit.	Wind profile map of middle atmosphere.
	Mixing ratios, composition and distribution of aerosols and atmospheric chemical constituents.	High spatial (< 5 mrad IFOV) and spectral resolution (R > 1000). VNIR imaging spatial resolution (1 km).	Sub-millimeter heterodyne, UV spectrometer, visible and near-IR imager, near-IR spectrometer, mid to far infrared spectrometer.	Imaging and spectral ranges: 0.4-0.7 µm (2, 2.7, 5-6 µm), 0.85-6 µm (NIR), 5-1000 µm (M to FIR). Precision > 10%.	Seasonal dependence, orbit and instrument pointing.	Mixing profiles, aerosol structure, vertical profile, optical constants, spatial variations in the middle atmosphere.
Characterize methane cycle on Titan, cloud formation and evolution.	Methane abundance, temperature monitoring of troposphere and near-surface.	High spatial (< 5 mrad IFOV) and spectral resolution.	Mid to far infrared spectrometer, Sub-Millimeter Heterodyne.	Spectral range: 5-1000 µm.	Seasonal dependence, orbit and instrument pointing.	Methane cycle parameters, temperature profile of lower atmosphere.
	Cloud tracking, precipitation, cloud composition.	High spatial and spectral resolution.	Radio science experiment, visible and near-IR imager, near-IR spectrometer.	Imaging and spectral ranges: 0.4-0.7 µm (2, 2.7, 5-6 µm), 0.85-6 µm (NIR).	Seasonal dependence, orbit and instrument pointing.	Cloud activity, interaction parameters, composition model.

Understand aerosol evolution and sedimentation, atmospheric formation and evolution, and organic material synthesis between atmosphere and surface.	Composition and distribution of aerosols.	High mass resolution (m/Dm) of 100,000. Spectral resolution: 0.1-3 wavenumbers.	CosmOrbitrap, UV spectrometer, mid to far-infrared spectrometer.	Composition sampling limit: 1000u, sensitivity: 10^{-3} molecule.cm^{-3}, spectral range: 5-1000 µm.	Seasonal dependence, orbit and instrument pointing.	Aerosol properties.
	Isotopic ratios, noble gases abundance, methane replenishment.	Spatial resolution = 250 m, NIR spectral resolution > 400.	Radio science experiment, magnetometer, visible and near-IR imager, near-IR spectrometer.	High spectral resolution R > 1000. Spectral range: 0.85-6 µm.	Orbit and instrument pointing.	Isotropic ratio distribution, noble gas measurements, methane quantity.
	Organic material deposition, atmosphere-surface chemistry, geomorphology.	High mass resolution (m/Dm) of 100,000. NIR spectral resolution > 400 and spatial resolution = 250 m.	CosmOrbitrap, visible and near-IR imager, near-IR spectrometer.	Composition sampling limit: 1000u, sensitivity: 10^{-3} molecule.cm^{-3}.	Orbit and instrument pointing, high data volume data rate: 48 kbits/s.	Atmosphere-surface constraints, composition of new molecules, geomorphological parameters.

Table-5: Science Traceability Matrix: Ornithopter (In-Situ)

Science Objectives	Measurement Objectives	Measurement Requirements	Instruments	Instrument Requirements	Mission Requirements	Data Products
Determine atmospheric super-rotation, global dynamics, composition, structure, distribution of stratospheric clouds and aerosols in the middle atmosphere.	In-situ windspeed measurements, vertical wind profile, global circulation along with pressure and temperature measurements.	Mapping wind magnitude and direction during descent through the atmosphere (high-resolution). Measuring accurate pressure and temperature values for atmospheric structure. Accuracy: 0.1 K, 1 mPa, resolution: 0.02 K, 0.1%.	Anemometer, temperature and pressure sensors (ASI/MET), radio science experiment.	High wind magnitude, pressure, temperature sampling rate.	Position, orientation and altitude of the in-situ probe. 1 km, 5° attitude.	3D Wind distribution, global circulation as well as high-resolution pressure and temperature map of the entire atmosphere.
	Composition and distribution of air, clouds, aerosols, complex organics.	High mass resolution (m/Dm) of 100,000.	CosmOrbitrap (mass spectrometer), icy grain organic dust and aerosol analyser.	Composition sampling range: 1-600 u, sensitivity: 10^{-3} molecule.cm^{-3}. Precision > 10%.	Position, orientation and altitude of the in-situ probe. Aerosol collection from higher altitudes, 1 km, 5° attitude.	High-resolution air, clouds and aerosol structure, vertical profile, optical constants, and spatial variations over all altitudes and latitudes.

	Air column opacity, average size of aerosol and cloud particles, spectrum analysis.	High spatial and spectral resolution.	Visual imaging system, imaging spectrometer, nephelometer (ASI/MET).	Spectral range: 1-5.6 µm. Precision > 10%.	Position, orientation and altitude of the in-situ probe. 1 km, 5˚ attitude.	High-resolution particle size and densities of aerosols, clouds, and spectral properties.
Characterize methane cycle on Titan, cloud formation and evolution.	Air column opacity, average size of aerosol and cloud particle phases, scattering and light transmission.	High spatial and spectral resolution.	Nephelometer (ASI/MET), visible imaging system, imaging spectrometer, CosmOrbitrap, icy grain, organic dust and aerosol analyser.	Composition sampling range: 1-600 u, sensitivity: 10^{-3} molecule.cm^{-3}. Spectral range: 1-5.6 µm. Precision > 10%.	Position, orientation and altitude of the in-situ probe. 1 km, 5˚ attitude.	High-resolution particle size and densities of aerosols, clouds, and spectral properties.
	Cloud tracking, methane precipitation, cloud composition.	High spatial (10 m) and spectral resolution.	Radio science experiment, ASI/MET, icy grain, organic dust and aerosol analyser.	High-accuracy sampling. Precision > 10%.	Position, orientation and altitude of the in-situ probe. 1 km, 5˚ attitude.	High-resolution cloud activity, interaction parameters, composition model.

Understand aerosol evolution and sedimentation, atmospheric formation and evolution, and organic material synthesis between atmosphere and surface.	Isotopic ratios, noble gases abundance, methane replenishment and precipitation.	High spatial and spectral resolution. High-accuracy mapping.	Radio science experiment, electric environment package, magnetometer, imaging spectrometer.	Spectral range: 1-5.6 µm.	Position, orientation and altitude of the in-situ probe. 1 km, 5° attitude.	High-resolution isotropic ratio distribution, noble gas measurements, methane quantity and precipitation.
	Organic material deposition, atmosphere-surface chemistry, geomorphology.	High mass resolution (m/Dm) of 100,000. High spatial resolution (2.5 km at 10 km), wavelength > 4.8μm.	CosmOrbitrap, visual imaging system, imaging spectrometer.	Composition sampling range: 1-600u, sensitivity: 10^{-3} molecule.cm^{-3}. Spectral range: 5-5.6 μm.	Position, orientation and altitude of the in-situ probe. 1 km, 5° attitude.	Atmosphere-surface constraints, composition of new molecules, geomorphological parameters.
	Electric and magnetic perturbations, EM energy distribution of entire atmosphere.	High accuracy of electric field measurements and magnetic field line intensities.	Electric environment package, magnetometer.	High-accuracy sampling of magnitude, direction and presence. Frequency range: DC to VLF (~ 10 kHz).	Position, orientation and altitude of the in-situ probe. 1 km, 5° attitude.	Energy and radiation budget, thermal, electric and magnetic distribution of the total atmosphere.

4.4. Baseline Payload Mass and Power

The baseline payload mass and power of the orbiter are represented as follows:

Table-6: Payload Mass and Power Budget (Orbiter)

Instrument	Mass			Average Power			Heritage
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)	
High spatial resolution visible and near-infrared imager; High spatial and spectral resolution near-infrared spectrometer	28.40	30	36.92	32.00	30	41.60	HiRIS / TSSM
Mid to far-infrared thermal spectrometer	16.50	30	21.45	17.00	30	22.10	TIRS / TSSM
CosmOrbitrap (high-resolution ion and neutral mass spectrometer	8.00	30	10.40	50.00	30	65.00	Under Development (CNES, FNSA)
Pressure Gauge (Mini INMS)	0.20	30	0.26	1.00	30	1.30	QB50 INMS / MSSL
High-resolution electron and negative ion mass spectrometer	1.50	30	1.95	4.00	30	5.20	EAS / Solar Orbiter, ELS / Cassini
Multi-Needle Langmuir Probe (m-NLP)	0.97	30	1.26	4.22	30	5.48	Under Development (ESA)
Mutual Impedance Probe (MIP)	0.33	30	0.42	1.82	30	2.36	MIP / Rosetta
Magnetometer	1.63	30	2.11	1.82	30	2.36	Cassini, Double Star, Venus Express
Energetic Particle Spectrometer (EPS)	1.50	30	1.95	2.50	30	3.25	EPS / TSSM
Plasma Spectrometer	5.00	30	6.50	9.00	30	11.70	PS / TSSM

Radio Science Experiment	0	30	0	0	30	0	RSA / TSSM
Sub-Millimeter Heterodyne	9.70	30	12.61	39.00	30	50.70	SWI / JUICE
UV Spectrometer	6.50	30	8.45	20.00	30	26.00	UVIS / JUICE
Total Payload Mass and Power	**80.23**	**-**	**104.28**	**182.36**	**-**	**237.05**	**-**

The baseline payload mass and power of ornithopter are represented as follows:

Table-7: Payload Mass and Power Budget (Ornithopter)

Instrument	Mass			Average Power			Heritage
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)	
Visual imaging system (2 wide-angle and 1 narrow-angle cameras)	2.00	20	2.40	5.00	20	6.00	Vista-B / TSSM
Imaging Spectrometer	3.00	20	3.60	10.00	20	12.00	BIS / TSSM
Atmospheric Structure Instrument and Meteorological Package (Nephelometer / Particle Counter, Anemometer, Temperature and Pressure Sensors)	1.00	20	1.20	5.00	20	6.00	ASI, Met / TSSM
Electric Environment Package	1.00	20	1.20	1.00	20	1.20	TEPP-B / TSSM
Icy grain, organic dust, and aerosol analyser	1.50	20	1.80	4.00	20	4.80	Adapted from ELS, CAPS / Cassini
CosmOrbitrap (Mass Spectrometer)	8.00	20	9.60	50.00	20	60	Under Development (CNES, FNSA)
Radio Science Experiment	0	20	0	0	20	0	MRST / TSSM
Magnetometer	0.50	20	0.60	1.50	20	1.80	MAG / TSSM
Total Payload Mass and Power	**17.00**	**-**	**20.40**	**76.50**	**-**	**91.80**	**-**

5. MISSION ARCHITECTURE

5.1. Space Environment of Saturnian System

The space environment of the Saturnian system encompasses a dynamic interplay between the planet's magnetic field, its ring system, the numerous moons, and their interactions with the solar wind and other cosmic forces. This environment is a complex and evolving theatre of natural phenomena that offers rich insights into the dynamics of planetary systems. Here's a focused overview emphasizing these aspects:

1) **Magnetosphere:**

Composition and Structure: Saturn's magnetosphere is predominantly shaped by its strong magnetic field, which is generated deep within its metallic hydrogen core by virtue of the dynamo effect. This field extends far into space, enveloping the planet and its rings, creating a magnetic bubble that shields the system from the solar wind and other external factors.

Interactions with Moons and Rings: The magnetosphere is not static; it interacts vigorously with Saturn's moons, particularly with Titan, Enceladus, and the smaller moonlets embedded within the rings. These interactions can strip away atmospheric particles from the moons, contribute to the formation of Saturn's rings, and induce electrical currents that sculpt the space environment.

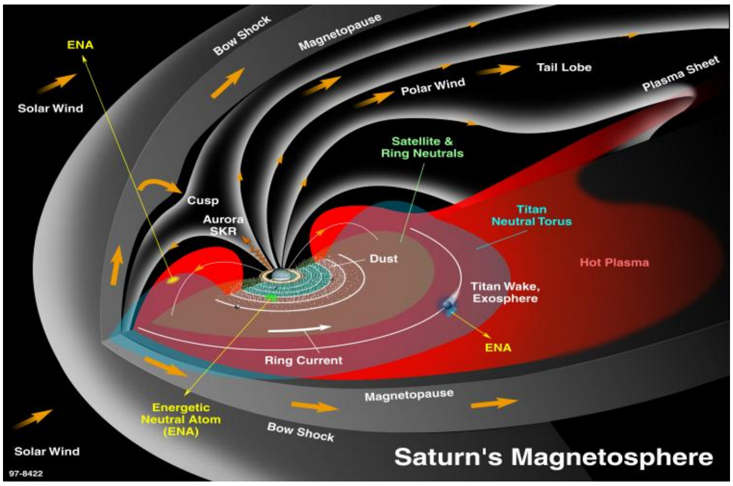

Figure 20: Overview of Saturn's Magnetosphere (Guillot et al., 2009).

2) **Rings and Dust Particles:**

Dynamics and Composition: Saturn's rings are composed of countless ice and rock particles that range in size from microscopic dust to boulders as large as houses. These particles are influenced by Saturn's magnetosphere and gravitational field, leading to complex patterns and gaps within the rings.

Electrostatic Charging: The particles in Saturn's rings can become electrostatically charged due to interactions with solar ultraviolet light and plasma from the magnetosphere. This charging can affect particle dynamics, leading to vertical structures and spokes within the rings, and influence the system's interaction with the solar wind.

3) **Solar Wind Interaction:**

Magnetospheric Dynamics: The solar wind is a stream of charged particles from the Sun that interacts with Saturn's magnetosphere, causing it to fluctuate and compress. These interactions can lead to the generation of auroras at Saturn's poles, similar to the northern and southern lights on Earth.

Energy Transfer and Particles: The interaction between the solar wind and Saturn's magnetosphere accelerates particles within, contributing to the radiation environment around Saturn. This process can energize ions and electrons, which then interact with the rings and moons, affecting their surfaces and atmospheres.

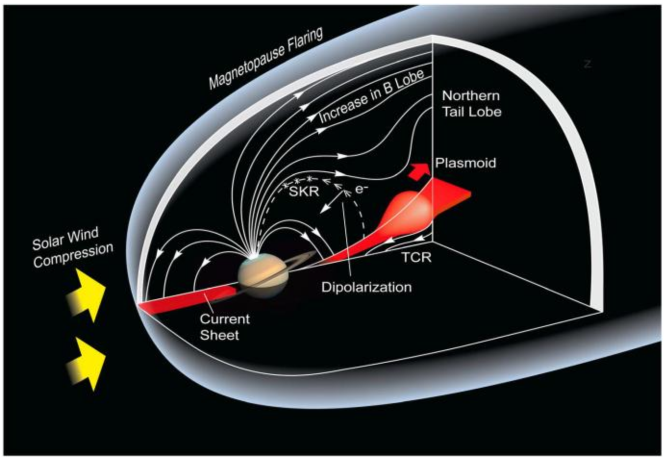

Figure 21: Response of Saturn's Magnetosphere to Solar Wind Compression (Jackman et al., 2010).

4) **Moons' Influence:**

Gravitational Interactions: The moons, especially Titan and Enceladus, play a significant role in shaping the space environment. Their gravitational forces can create gaps in the rings, influence the distribution of charged particles, and even induce waves and oscillations within Saturn's magnetosphere.

Geological Activity: Enceladus, with its geysers ejecting water vapour and ice, contributes material to Saturn's E ring and interacts with the magnetosphere, providing a fresh source of ions and influencing the magnetic field's dynamics.

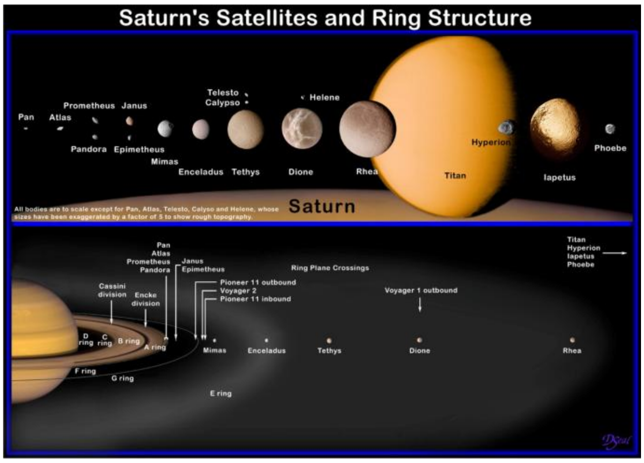

Figure 22: Satellites and Ring Structure of Saturn (Sulaiman et al., 2022).

5) **Cosmic Influences and Anomalies:**

Magnetic Field Anomalies: Saturn's magnetic field is almost perfectly aligned with its rotation axis, which is unusual compared to other planets. This unique feature influences how the magnetosphere interacts with the solar wind and the distribution of charged particles within the system.

Radiation Belts: The radiation belts around Saturn are shaped by the magnetic field and the particle influx from the solar wind and the moons, posing challenges for spacecraft navigation and offering insights into cosmic radiation dynamics.

5.2. Mission Trajectory and Timeline

The mission design and profile of the TARA mission are driven by the timing of Titan's next equinox. Titan's equinox is the optimal time to study tropical storms and their effects on fluvial and aeolian features. It is also the prime period to observe significant changes in global atmospheric dynamics and their impact on the distribution of photochemical compounds and the thermal field (Rodriguez et al., 2022). During the ESA Voyage 2050 period, Titan's equinoxes will occur on January 22, 2039 (northern spring equinox), and October 10, 2054 (northern autumn equinox) (Rodriguez et al., 2022). Planning a mission with an orbiter to monitor the seasonal transition over the 2039 northern spring equinox offers a unique opportunity to potentially coincide with the NASA Dragonfly mission, complementing its scientific goals and possibly serving as a communication relay (Rodriguez et al., 2022).

The TARA mission, comprising an orbiter and ornithopter, is scheduled for launch in January 2030 aboard an Ariane 62 medium-heavy launch vehicle. Initially, the spacecraft will be positioned in a temporary Low-Earth Orbit (200 km) before beginning its journey to Saturn. On January 19, 2030, the spacecraft will leave Earth for a 2.06-year interplanetary cruise. On February 10, 2032, it will perform a Jupiter flyby, allowing for additional scientific observations. Following this, the spacecraft will continue its interplanetary cruise for another 6.88 years, arriving at Saturn on December 27, 2038.

Upon arrival, the spacecraft will enter a 1-month configuration phase for orbital maneuvers, trajectory corrections, and preparations for Titan Orbit Insertion (TOI) and ornithopter deployment. By January 2039, it will enter Titan's orbit and begin a 2-month aerobraking phase, initiating the mission's science phase. After aerobraking, the spacecraft will achieve a near-polar, low eccentricity circular orbit (1000 km), and the ornithopter, equipped with a DLS, will be deployed at an altitude of 900-1000 km within Titan's atmosphere.

The orbiter and ornithopter will operate until the end of the nominal science phase in March 2043. At the mission's conclusion, a small de-orbit burn will place the spacecraft into a decaying orbit, eventually impacting Titan within a six-month decommissioning and disposal phase. This controlled decay will ensure the spacecraft avoids any regions of planetary protection concern, particularly areas where potential biosignatures might have been identified during the mission.

The following mission phases of the TARA Mission can be identified (at a glance):

1. 01/2030 – Launch by Ariane 62
2. 01/2030 – Earth Departure + Interplanetary Cruise (2.06 years)
3. 02/2032 – Jupiter Flyby + Interplanetary Cruise (6.88 years)
4. 12/2038 – Saturn Orbit Insertion
5. 01/2039 – Titan Orbit Insertion (Beginning of Titan Science Phase)
    - Elliptical Aerosampling phase (2 months)
    - Near-polar, low eccentricity circular orbit (96 months)
6. 03/2043 – End of Titan Science Phase
7. 09/2043 – End of Nominal Mission

The total mission duration amounts to close to 13.5 years, out of which 4.8 years would be spent in the Saturnian system. The mission would end in September 2043. The required propellant mass would be 2400 kg, providing a mission ΔV of 2088 m/s.

The mission trajectory can be represented using the NASA AMES Trajectory Web Browser for preliminary considerations as follows:

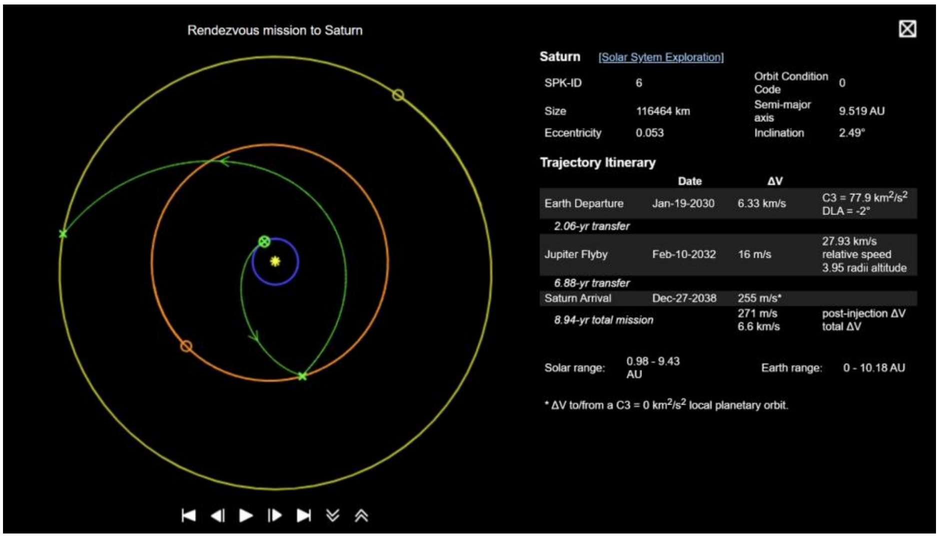

Figure 23: TARA Mission Trajectory. Credits: NASA Trajectory Web Browser.

The total ΔV budget for the mission, with key phases is represented as follows: (Strange et al., 2010)(Strange et al., 2010)

Table-8: Total ΔV Budget (TARA Mission)

	Propellant ΔV [m/s]	**Description**
Low Earth Orbit (LEO) Insertion (200 km)	9500	Spacecraft placed at a temporary Low Earth Orbit (LEO) before interplanetary departure. Comprises ΔV components for 200 km orbit insertion, as well as due to atmospheric and

		gravity effects.
Earth Departure	6330	Earth Departure modelled as finite impulsive burn. The size can be minimized by incorporating flybys and gravity assists from Earth and neighbouring planets.
Jupiter Flyby	16	Jupiter Flyby modelled as an impulsive ΔV at periapsis (flyby).
Interplanetary Trajectory Correction Maneuvers (TCMs)	4	Several small maneuvers needed for final Saturn targeting.
Saturn Orbit Insertion (SOI)	746	Saturn Orbit Insertion modelled as finite impulsive burn with gravity losses. The size of the SOI can be reduced by longer flight time to Saturn, and by longer flight time from SOI to first Titan encounter.
Ornithopter Targeting Maneuver (OTM)	261	Ornithopter Targeting Maneuver modelled to deliver ornithopter to Titan entry target. The size of OTM can be reduced by increasing the period of initial Saturn orbit.
Periapsis Raise Maneuver (PRM)	309	Periapsis Raise Maneuver to set up first Titan flyby. The size of PRM can be reduced by increasing the period of initial Saturn orbit.
Leveraging Pump-Down	197	ΔV to decrease Titan V-infinity prior to TOI.
Beta Adjustment	25	DV needed to achieve proper orientation of Titan orbit with respect to Sun. The size can be reduced with refinements to trajectory design.
Titan Orbit Insertion (TOI)	388	Titan Orbit Insertion modelled as finite impulsive burn with gravity losses. The size of the TOI can be reduced by further refinement of leveraging pump-down and aerobraking phase.
Aerobraking Maintenance	79	ΔV from 2-month simulated aerobraking design with drag and Saturn gravity.
Circularization	45	ΔV required to raise the periapsis and to circularize the orbit at the end of aerobraking (near-polar circular orbit with low eccentricity – 1000 km).
De-orbit and Disposal	18	15 m/s for de-orbit plus additional DV margin to control the 6-month orbit decay.
Total ΔV	**17918**	

5.3. Mission Operations and Lifetime

The Titan orbiter is proposed to be revolving around Titan in a near-polar low eccentricity circular orbit, orbiting at around 1000 km from the Titan’s surface. The choice of a polar orbit around Titan is essential to making sophisticated measurements and monitoring the polar regions, which are of particular interest in terms of the science objectives of the TARA mission. Various phenomena and the associated open questions about Titan’s atmosphere, as well as Titan’s habitability, are based on unexplored polar regions such as the reversal of global atmospheric dynamics, seasonal migration of clouds from southern to northern polar regions, polar vortices and stratospheric clouds, evolution of pre-biotic environment around surface lakes and seas, etc. Also, the 1000 km low-eccentricity polar orbit would allow for rapid revisit times around Titan, orbiting once in about 3.94 hours, enabling the Titan orbiter to provide a continuous and comprehensive high temporal global coverage of Titan.

The Titan ornithopter (with DLS) is proposed to be deployed at an altitude of 900-1000 km in the Titan’s atmosphere. The orientation of deployment is optimized in a way to maximize the reduction of speed in the least time possible, utilizing the extended dense atmosphere of Titan. The DLS comprises of a full aeroshell with front and back shields alongside a drogue parachute, to protect the ornithopter from the intense heat caused by the substantial atmospheric drag of Titan’s atmosphere, as well as aid in significant speed reduction for the ornithopter. The ornithopter is proposed to be deployed from the DLS at an altitude of 500-600 km, in Titan’s agnotosphere (the region of 500-950 km which connects the photochemical source regions of Titan’s ionosphere to the bulk neutral atmosphere housing seasonal weather and circulation dynamics) over the equatorial regions for traversing the greater atmospheric length and covering as much atmosphere as possible in the direction of super-rotation to utilize tailwind conditions. The ornithopter is expected to perform scientific measurements during the entire atmospheric descent, utilizing the hovering capabilities in key atmospheric regions of interest.

The ornithopter is proposed to explore the near-surface environments of Titan, in the vicinity of the Selk crater, in order to complement the Dragonfly mission, as well as for the highest pre-biotic science return due to the importance and significance of the Selk crater (Lorenz et al., 2021). From the near-surface environments, the ornithopter can fly up to an altitude of 16-17 km (see Appendix A) with a minimal speed of 15 m/s. At higher altitudes, the ornithopter can dive and rise as per the requirements based on its speed and angle of attack with respect to the atmosphere, thereby generating adequate lift as necessary. Also, the ornithopter can utilize the thermospheric circulation currents to generate uplift similar to a glider.

Operating at an altitude of 16-17 km from the surface, in Titan's atmosphere, an in-situ ornithopter can effectively study the stratified atmospheric layers and complex organic molecules. This altitude range allows the ornithopter to gather data on haze and cloud formation processes, providing insights into Titan's weather patterns and potential prebiotic chemistry, crucial for understanding Titan's potential for life.

The Titan orbiter is proposed to have a nominal science lifetime of about 96 months after the Titan Orbit Insertion (TOI), which is at par with other recent missions targeted towards solar system exploration. The Titan ornithopter is proposed to operate for a nominal science lifetime of 72 months after arrival after entering into the Titan's atmosphere, which sounds like a reasonable estimate for a new-age advanced, powered, heavier-than-air atmospheric probe operating constantly within the Titan's atmosphere.

5.4. Spacecraft Bus and Payload Overview

The Titan orbiter, as well as the ornithopter, are designed to incorporate all the necessary sub-systems such as structures, shielding, mechanisms, thermal control, propulsion, attitude control, command and data handling, telecommunications, power, and instruments.

The technical details and parameters of the subsystems for the orbiter and ornithopter, such as specific impulse, sensory information, command and data handling parameters, etc., have been cross-referenced with historical data from study reports of previous space missions and mission concepts such as TSSM (Spencer & Niebur, 2010), Juno (Bolton et al., 2017) and JUICE (M. Dougherty et al., 2012) for comprehensive analysis.

The flight system characteristics of the Titan orbiter, as well as the Titan ornithopter, can be summarized as follows:

Table-9: Flight System Element Characteristics – Orbiter

Flight System Parameters (as appropriate)	Value / Summary, Units
General	
Design Life (months)	107.35-month Interplanetary Cruise (Chemical) 1-month Configuration 2-month Aerobraking 96-month Titan Orbit 6-month De-orbit / Disposal
Structure	
Structures material	Graphite Composite, Carbon-Fiber Reinforced Plastics (CRFPs), Aluminum Honeycomb
Number of Articulated Structures	1
Number of Deployable Structures	0
Aeroshell Diameter, m	N/A
Thermal Control	
Type of Thermal Control Used	MLI, radiators, pumped fluid loops, RHUs, both fixed and variable
Propulsion	
Estimated delta-V budget, m/s	2088
Propulsion type(s)	Dual-mode
No. of Thrusters and Tanks	1 biprop main plus 16 monoprop
Specific impulse for each propulsion mode, seconds	400 biprop, 250 monoprop
Attitude Control	
Control Method	3-axis

Control Reference	Sun sensors, star trackers, IMU
Articulation Axes	2 axes for both HGA and main engine
Sensor and Actuator Information	4 RWAs with 30 Nms of angular storage, 16 5-N RCS thrusters
Command and Data Handling	
Flight element housekeeping data rate, kbps	15
Data Storage Capacity, Mbits	40,000
Maximum Storage Record Rate, kbps	50,000
Power	
Type of Array Structure	4 Next-Gen RTGs (3 operational, 1 spare)
Expected Power Generation, Watts	Electrical: 735 (BOL), 531 (EOL – 17 years) Thermal: 2000
On-orbit Average Power Consumption, Watts	400
Battery Type	Li-ion
Battery Storage Capacity, Amp-hours	Two 30 Amp-hours

Table-10: Flight System Element Characteristics – Ornithopter

Flight System Parameters (as appropriate)	Value / Summary, Units
General	
Design Life (months)	72 months after arrival
Structure	
Structures material	Carbon-Fiber Reinforced Plastics (CRFPs), Titanium Honeycomb Shells, Multiple Composites
Number of Articulated Structures	1
Number of Deployable Structures	4
Aeroshell Diameter, m	4 m
Thermal Control	
Type of Thermal Control Used	Waste Heat
Propulsion	
Estimated delta-V budget, m/s	N/A
Propulsion type(s)	Wings, Parachute
No. of Thrusters and Tanks	N/A
Specific impulse for each propulsion mode, seconds	N/A
Attitude Control	
Control Method	3-axis
Control Reference	N/A
Sensor and Actuator Information	3 accelerometers, 3 fine gyros, 3 Sun / Saturn sensors, IMU, pressure sensors
Command and Data Handling	
Flight element housekeeping data rate, kbps	TBD
Data Storage Capacity, Mbits	30,000

Power	
Type of Array Structure	2 Next-Gen RTGs
Expected Power Generation, Watts	Electrical: 490 (BOL), 354 (EOL – 17 years) Thermal: 1000
On-orbit Average Power Consumption, Watts	200
Battery Type	N/A

A brief overview of the model payload for the TARA mission is presented as follows:

Table-11: Main Characteristics of TARA Mission Payload

Model Instrument	Science Contribution
Titan Orbiter	
Visible and Near-Infrared Imager	Monitoring atmospheric wave activity and haze distribution, distribution of aerosols and atmospheric constituents, cloud tracking, organic material deposition, surface chemistry, and geomorphology.
Near-Infrared Spectrometer	Mixing ratios, composition and distribution of aerosol, atmospheric and chemical constituents, precipitation and cloud composition, measurements of isotopic ratios, noble gases, atmosphere-surface chemistry and geomorphology.
Mid-to-Far Infrared Thermal Spectrometer	Atmospheric composition, temperature monitoring, thermal redistribution and radiation balance, overall temperature profile of atmospheric layers and energy budget.
CosmOrbitrap (Ion and Neutral Mass Spectrometer)	Monitoring ion-neutral chemistry in the ionosphere, aerosol composition and distribution, composition of organic material and sedimentation, composition of clouds, neutral complex organics, surface chemistry.
Pressure Gauge	Density measurements of ions and neutral particles.
Electron and Negative Ion Mass Spectrometer	Analysis of electron and negative ion chemistry in the upper atmosphere, growth of negative ions and anions, temperature and density profiles of electrons and negative ions.
Multi-Needle Langmuir Probe	Density measurements of electrons and negative ions.
Mutual Impedance Probe	Measurements of in-situ space plasma bulk properties of protons, electrons and energetic particles.
Magnetometer	Magnetic field measurements, magnetic perturbations and response, EM energy distribution.

Energetic Particle Spectrometer	Nature and composition of high-energy particles.
Plasma Spectrometer	Characterization of space plasma and its interaction with the upper atmosphere.
Radio Science Experiment	Tracking (occultation), bulk measurements.
Sub-Millimeter Heterodyne	Windspeed measurements (Doppler shifts), thermal profiling of CO and HCN lines, atmospheric dynamics, temperature, and energy measurements.
UV Spectrometer	High-energy spectrometry, upper atmospheric interactions with higher energy particles.
Titan Ornithopter	
Visual Imaging System	Air column opacity, size measurements of aerosol and cloud particles, near-surface imaging and mapping, surface chemistry.
Imaging Spectrometer	Density and temperature profiles of clouds, aerosols and atmospheric constituents, methane cycle monitoring, surface chemistry, and geomorphology.
Atmospheric Structure Instrument and Meteorological Package	Vertical profile and global dynamics of atmosphere, global circulation, pressure, density and windspeed measurements, scattering and opacity.
Electric Environment Package	Electric field measurements, response to EM radiation.
Icy Grain, Organic Dust and Aerosol Analyser	Characterization and composition measurements of icy particles, organic compounds and aerosols, and their respective abundance within different layers of the atmosphere.
CosmOrbitrap (Mass Spectrometer)	In-situ measurements of aerosol and organics in the atmosphere and near-surface environments.
Radio Science Experiment	Tracking (occultation), bulk measurements.
Magnetometer	Magnetic field measurements, magnetic perturbations and response, EM energy distribution.

The baseline mass and power budget for the orbiter can be represented as follows:

Table-12: Baseline Mass and Power Budget (Orbiter)

Baseline Item	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures	220	30	286	05	49	7.45
Shielding	120	30	156	-	49	-

Mechanisms	30	30	39	05	49	7.45
Thermal Control	70	30	91	25	49	37.25
Propulsion (Dry Mass)	160	27	203.20	60	49	89.40
Attitude Control	50	21	60.50	70	49	104.30
Command and Data Handling	30	17	35.10	40	49	59.60
Telecommunications	60	27	76.20	80	49	119.20
Power (Radioisotope Power Systems)	110	49	163.90	10	49	14.90
Cabling	60	30	78	15	49	22.35
Instruments	104.28	-	104.28	237.05	-	237.05
Total Orbiter Dry Mass and Power	**1014.28**	**-**	**1293.18**	**547.05**	**-**	**698.95**
System Margin	200	-	200	-	49	-
Propellant	2000	20	2400	-	49	-
Total Orbiter Wet Mass and Power	**3214.28**	**-**	**3893.18**	**547.05**	**-**	**698.95**

The baseline mass and power budget for the ornithopter can be represented as follows:

Table-13: Baseline Mass and Power Budget (Ornithopter)

Baseline Item	**Mass**			**Average Power**		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures	70	20	84	0	0	0
Mechanisms	20	12	22.40	150	0	150
Thermal Control	80	06	84.80	0	0	0
Attitude Control	06	14	6.84	05	0	05
Command and Data Handling	06	10	6.84	07	0	07
Telecommunications	12	17	14.04	50	0	50
Power (Radioisotope Power Systems)	65	17	76.05	-	0	-

DLS (front & back shields, drogue parachute)	20	10	22	0	0	0
Cabling	10	20	12	06	0	06
Instruments	20.40	-	20.40	91.80	-	91.80
Total Ornithopter Mass and Power	**309.40**	**-**	**349.37**	**309.80**	**-**	**309.80**

5.5. Power Generation

The power system design for the spacecraft must accommodate the energy needs of various science instruments and subsystems while considering the distance from the Sun. A mission power architecture utilizing solar arrays is impractical due to the low solar irradiance at a distance of 9.5 astronomical units (AU) from the Sun. Additionally, such an architecture would likely exceed the spacecraft's mass constraints. Next-Generation RTGs (Next-Gen RTGs) emerged as an ideal choice owing to their high-power output capability at the end of life (EOL) and low annual power degradation.

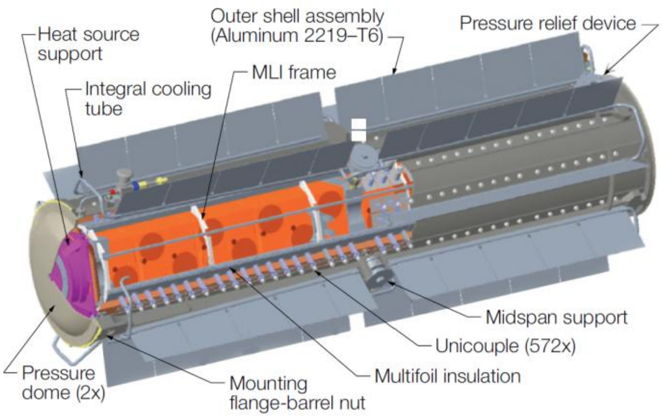

Figure 24: Next Generation RTG Mod 1 Concept. Credits: Aerojet Rocketdyne.

For the TARA mission, the selected Next-Gen RTG variant is the Segmented-Modular RTG comprising 8 General Purpose Heat Source (GPHS) units. The orbiter element requires 3 units, which collectively produce 735 W of total electrical power output by the end of the mission. To manage peak power demands and ensure a positive power balance throughout the mission, two 30-Ah Li-ion batteries are incorporated. Similarly, the ornithopter requires 2 units, producing 490 W of electrical power.

In the TARA mission concept, MMRTGs using ^{238}Pu are considered and were to be supplied by NASA. Meanwhile, in Europe, the radioisotope ^{241}Am is seen as a viable alternative to ^{238}Pu and can be used to generate heat for small-scale RTGs and RHUs, although it has a higher mass (Sarsfield et al., 2012). Stored civil plutonium at reprocessing sites contains about 1000 kg of isotopically pure ^{241}Am in the UK and France's civil PuO_2 stockpile. A study is currently underway to develop a process for the chemical separation of ^{241}Am (Sarsfield et al., 2012). The ESA is considering developing ^{241}Am-based RTGs, aiming to have them at a high technology readiness level before the proposed Voyage 2050 launch windows.

5.6. Thermal Design

The thermal design of the TARA mission spacecraft had to be engineered to ensure all components remained within operational or survivable temperature ranges in the extreme conditions of the outer solar system. To achieve this, a suitable MLI would wrap the spacecraft to minimize heat transfer with the external environment, enhancing thermal stability and control. When within 1 AU of the Sun, the High Gain Antenna (HGA) would be oriented towards the Sun to shield the spacecraft from direct solar radiation. Radiators, along with a pumped fluid loop, would be employed in the hot environment to dissipate excess heat. In the colder regions of the outer solar system, waste heat from the Radioisotope Thermoelectric Generators (RTGs) would warm the spacecraft. The RTGs would be partially inside the MLI for passive heating, and the pumped fluid loop would transfer this waste heat to the propellant tanks and electronic components. Additionally, RHUs would be strategically placed to maintain component warmth. Although a pumped fluid loop is more costly and less frequently used in space missions compared to electric heaters, it requires significantly less power by utilizing waste heat from the RTGs.

5.7. Propulsion and Launchers

The propulsion system for TARA spacecraft would utilize commercially available, flight-proven hardware and incorporate built-in redundancies to ensure reliability. The primary engine will utilize a bipropellant of monomethylhydrazine (MMH) as fuel and nitrogen tetroxide (NTO) as oxidizer. Hydrazine would be used as a monopropellant for sub-engines. For trajectory and attitude control, the TARA spacecraft would use 16 5-N RCS thrusters alongside 4 RWAs. The propellant would be supplied through a blow-down feed system pressurized by helium.

For launch, Ariane 62 medium-heavy launch vehicle has been chosen based on the launch capacity, spacecraft volume and DV constraints. Ariane 62 can place a maximum payload of approx. 10,000 kg in LEO and 4,500 kg in GTO around Earth using LH_2 / LO_x propellant with solid rocket boosters (SRBs) and 2-stage liquid propulsion modules.

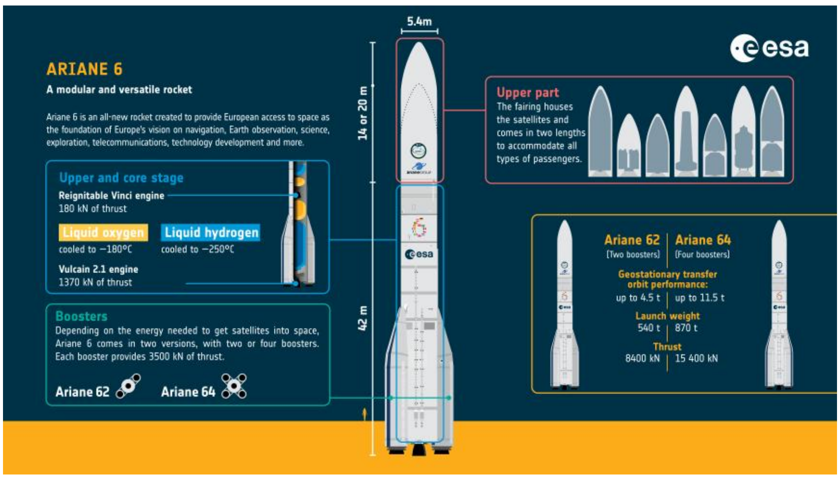

Figure 25: Ariane 6 at a glance. Credits: ESA.

5.8. Telecommunications and Data Handling

The TARA mission would employ the European Space Tracking (ESTRACK) Network of ESA for its data downlink, telemetry, and communications, leveraging its proven capability in interplanetary communications. The design would feature a fully redundant X-band and Ka-band subsystem, which has the capability to downlink data at 10 kilobits per second (kbps) using a fixed 3.5m HGA, and uplink data at 5 kbps, even at the maximum anticipated solar distance of 9.5 astronomical units (au). The science data could require a Ka-band during maximum distances in Titan's orbit from Earth. The telecommunication subsystem is designed with a 3 dB link margin.

Figure 26: ESTRACK Network Map. Credits: ESA.

The command and data handling processor, utilizing the Leon 2 model, will encompass spacecraft management functions, mass memory management, and remote terminal operations. Instruments and sensors will connect through MIL-STD-1553, with SpaceWire used for higher data rate instruments like cameras and spectrometers. Additionally, for higher data rates as well as fault detection and recovery mechanisms, the SpaceFibre protocol (ECSS-E-ST-50-11C) can be utilized, which is currently under development.

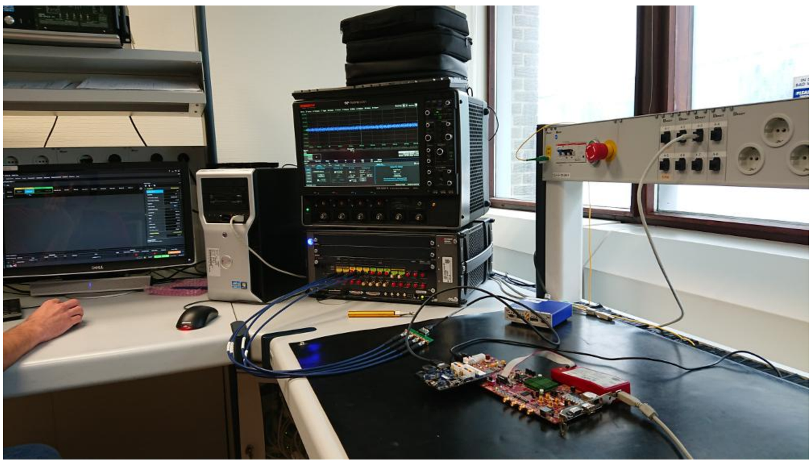

Figure 27: SpaceFibre Layer Testing. Credits: ESA.

6. TRADES AND CHALLENGES

Designing a deep-space planetary science mission requires careful consideration of numerous factors. A key challenge is developing an architecture that meets all necessary constraints to be both viable and selectable, while also addressing the community's priority science questions. Missions aimed at habitability and life detection often encounter problems related to contamination and outgassing. These missions necessitate a comprehensive contamination control assessment in accordance with the planetary protection policies set by the international Committee on Space Research (COSPAR) (Spiers et al., 2021).

6.1. Launch Windows

The launch windows of space missions are meticulously calculated timeframes that optimize the trajectory, energy efficiency, and mission success. These windows consider orbital mechanics, planetary alignments, and spacecraft performance. One primary trade is balancing the ideal launch date with the readiness of the spacecraft and ground systems. Missing a narrow window could delay the mission significantly, requiring adjustments and recalibrations. Weather conditions, technical issues, and unexpected delays present further challenges. For missions to distant planets or specific orbits, the alignment of celestial bodies dictates limited opportunities, necessitating precise timing and coordination to ensure that the spacecraft reaches its intended destination with the required fuel and resources.

The TARA mission is strictly constrained to be launched by 2030 due to the high science value during Titan’s Spring equinox as discussed in the mission trajectory section. A launch window at the beginning of the ESA Voyage 2050 cycle or sooner is thereby proposed. Given the estimated 7–8-year journey from Earth to Saturn, a launch by 2031–2032 at the latest is necessary. Time is of the essence! However, even if the spacecraft arrives outside the pre-decided timeframe complementing both the Titan’s equinox as well as the Dragonfly mission, the mission would still yield significant scientific value using both an orbiter and an in-situ element. It would address fundamental unanswered questions about Titan's system that cannot be resolved from Earth-based or space-based observations.

6.2. Selection of Power System

Designing a suitable power system for this mission concept presented a significant challenge. Next-Gen RTGs were selected for the power system because MMRTGs and potential eMMRTGs lack sufficient performance and required power output. With solar irradiance at Saturn being less than 1/100th of that on Earth, manageable-sized solar arrays would not generate sufficient power. MMRTGs and eMMRTGs were unsuitable due to their low end-of-mission power output and high average annual power degradation. Next-Gen RTGs provide notable benefits, such as significant mass and nuclear fuel savings, while boosting power by 1.5 to 2 times compared to previous RTGs [64]. Given the current TRL of Next-Gen RTGs is between 1 and 3, it is essential to continue investing in the development of high-performance thermoelectric materials and supporting RTG maturation efforts to fulfill the power needs of future planetary science missions.

6.3. Spacecraft Shielding

Spacecraft shielding for a mission to Titan must address a range of key trades and challenges to ensure the spacecraft's integrity and the success of the mission. The primary trade-off involves balancing the mass and thickness of the shielding with the overall weight constraints of the mission. Thicker, more robust shielding can provide better protection against cosmic rays, micrometeoroids, and the intense radiation of Saturn's magnetosphere but adds significant weight and complexity. Another critical challenge is designing shielding that can withstand Titan's dense, nitrogen-rich atmosphere, which poses unique aerodynamic stresses during entry. Material selection is also crucial, requiring a balance between lightweight composites and durable metals to optimize performance and cost. Additionally, thermal protection systems must be integrated to manage the extreme cold and potential heat generated during atmospheric entry. Engineers must also consider the long-term effects of radiation on electronic components, necessitating advanced radiation-hardened designs. Overall, the complexity of shielding for a Titan mission lies in optimizing these factors to ensure the spacecraft can safely reach and explore the moon's surface while adhering to stringent mission constraints.

6.4. Technological Developments

The ESA has not previously considered drones for planetary exploration in a concrete manner. However, with current advancements in drone technology, they appear well-suited for exploring planetary atmospheres and surfaces, particularly in remote areas. Inspired by NASA's initiatives with Dragonfly and the Mars Helicopter Scout (Ingenuity), it is proposed that ESA should undertake technical analyses focused on the feasibility and technological development of planetary flying drones. A comprehensive comparison of various approaches will be necessary to identify the most effective method for exploring Titan's atmosphere and surface.

6.5. Planetary Protection

Planetary protection of Titan is a critical aspect of astrobiological exploration due to its unique and potentially habitable environment. Ensuring the prevention of forward contamination: introduction of Earth-origin microbes to Titan, and backward contamination: bringing extraterrestrial organisms back to Earth, poses significant challenges and trade-offs. Key challenges include the harsh and complex environment of Titan, characterized by its dense, nitrogen-rich atmosphere, cryogenic temperatures, and hydrocarbon lakes, which complicate sterilization and contamination control measures. Additionally, the development of stringent sterilization protocols must balance the need for effective microbial reduction against the risk of damaging delicate scientific instruments and potential biological samples. Furthermore, the trade-off between thorough sterilization and the cost, weight, and energy constraints of spacecraft design adds to the complexity of mission planning. Ensuring robust planetary protection requires international collaboration, adherence to evolving space treaty regulations, and the integration of advanced sterilization technologies, all while striving to preserve Titan’s pristine environment for future scientific discovery.

7. RESULTS AND DISCUSSION

7.1. Results and Discussion

The proposed deep-space TARA mission concept aims to explore Titan with a dual-vehicle configuration, featuring both an orbiter and an ornithopter. The orbiter is designed to conduct comprehensive and global remote sensing operations, mapping Titan's near-surface pre-biotic environments and atmosphere to identify key regions of astrobiological interest and monitor atmospheric dynamics. Meanwhile, the ornithopter, a novel aerial vehicle capable of powered flight in Titan's dense atmosphere, will enable localized and detailed in situ analysis of atmospheric and near-surface conditions. This dual approach aims to synergistically enhance our understanding of Titan's atmospheric processes and the evolution of its pre-biotic environment. Initial results suggest that this configuration will provide unprecedented spatial and temporal resolution in data acquisition, significantly advancing our knowledge of Titan's complex atmospheric chemistry and potential for hosting pre-biotic chemistry. Furthermore, the ornithopter's ability to navigate Titan's diverse terrains offers a unique opportunity to explore and characterize previously inaccessible areas, thus contributing valuable insights into the moon's geophysical and environmental history.

The final conclusions that can be derived from the TARA mission concept are represented below, although there is a lot of potential for further improvements and refinement for building a solid mission concept proposal to the level expected by space organizations like NASA / ESA:

1) **Provisional Feasibility Established:** The TARA mission concept demonstrates the technical and logistical feasibility of exploring Titan’s atmosphere and near-surface environments with current and near-future technology incorporating a dual-mission architecture of an orbiter and ornithopter.

2) **High Scientific Potential Demonstration:** The TARA mission promises to provide unprecedented insights into Titan's unique environment, potentially revealing new aspects of prebiotic chemistry and planetary formation using instruments from legacy missions / mission concepts such as TSSM, JUICE, Dragonfly, etc.

3) **Bridging the Knowledge Gap:** The TARA mission aims to bridge the knowledge gap by answering the open questions about Titan, and its evolution over time. As the name of the mission represents, the mission aims to be a potential successor and ascendant of legacy missions such as Voyager 2, Cassini-Huygens etc., and strives to complement upcoming futuristic missions to Titan such as the Dragonfly mission.

4) **New-Age Technology Demonstration:** The TARA mission will serve as an opportunity and proving ground for advanced technologies, such as autonomous UAV navigation in extraterrestrial atmospheres and cryogenic-resistant materials.

8. CONCLUSION AND FUTURE PERSPECTIVES

The multitude of unanswered questions surrounding Titan as a system underscores the tremendous success of the Cassini-Huygens mission. Titan is likely second only to Earth in terms of its geological and atmospheric dynamism. These unresolved questions not only pertain to Titan itself but also have significant implications for our understanding of habitable conditions both within our Solar System and beyond. Therefore, it is proposed that Titan be prioritized in ESA's Voyage 2050 program, which includes exploring the icy moons of the giant planets. Collaboration in science and technology with international agencies is vital to launch a dedicated and ambitious M-class or L-class mission to Titan. The TARA mission concept is designed to complement NASA's Dragonfly mission in terms of timing, location, and scope. This mission framework will drive considerable technological advancements by necessitating the development of innovative components for exploration. The TARA mission will help pinpoint critical areas for technological development and facilitate the creation of a comprehensive technology plan. Collaborative efforts among international space agencies, particularly ESA, NASA, and other potential partners, are essential to realize this ambitious project due to the multitude of elements and requirements involved, as well as crucial for achieving the mission's scientific goals, which will significantly enhance our understanding of the Titan system, Earth, and the origins of life within the Solar System.

Titan exploration stands at the forefront of future solar system exploration, promising unparalleled scientific discovery and innovation. As the only moon with a dense atmosphere and liquid hydrocarbon lakes, Titan offers a unique opportunity to study prebiotic chemistry and potential extraterrestrial life. The upcoming Dragonfly mission by NASA, set to launch in the mid-2020s, exemplifies the growing interest in Titan. Titan's complex organic chemistry, dynamic weather patterns, and varied surface features make it an enticing target for researchers and space enthusiasts alike, solidifying its status as a hot topic in the realm of planetary exploration. With each mission, we edge closer to unlocking the secrets of this enigmatic moon, paving the way for unprecedented advancements in our understanding of the universe.

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Conflict of Interest: The authors declare that there is no conflict of interest in any terms regarding the manuscript.

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Appendix A

Ornithopter Altitude Estimation (Rough Estimate):

$M = Mass\ of\ Ornithopter = 349.37\ kg.$
$g = Acceleration\ due\ to\ gravity\ (Titan) = 1.35\ m/s^2.$
$W = Weight\ of\ Ornithopter = Mg = 363.64 \times 1.35 = 471.64\ N.$
$\rho_h = Density\ of\ Titan's\ Atmosphere\ at\ altitude\ (h).$
$\rho_0 = Surface\ level\ density\ of\ Titan's\ Atmosphere = 5.4\ kg/m^3.$
$v = Velocity\ of\ Ornithopter = 15\ m/s\ \ (say).$
$S = Wingspan\ of\ Ornithopter = 2\ m^2\ (say).$
$C_l = Coefficient\ of\ Lift = 1\ (say).$
$H = Scale\ height\ of\ Titan's\ Atmosphere = 20\ km = 20{,}000\ m.$

For steady, unaccelerated flight, the lift acting on the ornithopter should be equal to the weight of the ornithopter. This relation can be expressed using the lift equation as follows:

$$L = W = \frac{1}{2}\rho_h v^2 S C_l \ - - - \rightarrow Mg = \frac{1}{2}\rho_h v^2 S C_l - - - \rightarrow (1)$$

We know that, considering hydrostatic equilibrium and isothermal atmosphere, the variation of density with altitude is represented with respect to scale height as follows:

$$\rho_h = \rho_0 e^{-\frac{h}{H}} - - - \rightarrow (2)$$

Substituting Eq. (2) in Eq. (1), we get:

$$Mg = \frac{1}{2} \times \rho_0 e^{-\frac{h}{H}} \times v^2 SC_l - - - \rightarrow e^{-\frac{h}{H}} = \frac{Mg}{\frac{1}{2}\rho_0 v^2 SC_l} - - - \rightarrow \frac{-h}{H} = \ln\left(\frac{Mg}{\frac{1}{2}\rho_0 v^2 SC_l}\right)$$

$$h = -H \times \ln\left(\frac{Mg}{\frac{1}{2}\rho_0 v^2 SC_l}\right) - - - \rightarrow Equation\ for\ Altitude\ (h)$$

Substituting the values, we get:

$$h = -20000 \times \ln\left(\frac{471.64}{\frac{1}{2} \times 5.4 \times 15^2 \times 2 \times 1}\right) \approx 18925.66\ m \approx 18.925\ km\ (Ans).$$

This is a rough estimate of how high an ornithopter with a certain wingspan and velocity can fly in the Titan's atmosphere. Taking into account various types of atmospheric drag, efficiency, as well as turbulence effects, a reasonable altitude of 16-17 km, is achievable by an ornithopter with a mass of 350 kg, wing span of 2m^2 and velocity of 15 m/s.