# SEAFARER

## Surveying Environments Across the Saturnian System For hAbitability ResEaRch

Summer School Alpbach 2024

Green Team – Mission SEAFARER

# Team Green

## Science Team

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- Johanna Bürger - Germany
- Fabian Weichbold - Austria
- Brent Quanten - Belgium
- Diogo Quirino - Portugal
- Christos Ntinos - Greece
- Julia Wiltenburg - The Netherlands

## Mission Analysis Team

- Vincent Affatato - Italy
- Samuele Vaghi - Italy
- Anike Ohm - Germany


Tutors: Willem Jellema and Martin Volwerk

## Engineering Team

- Agathe Bouis - Scotland
- Elena Sango González - Spain
- Andras Baranyai - Hungary
- Boris Baudel - France
- David Placke - Austria
- Colm Daly - Ireland

Science Case → Mission Analysis → Engineering → Programmatics

**Julia Wiltenburg** | **Vincent Affatato** | **David Placke** | **Colm Daly**

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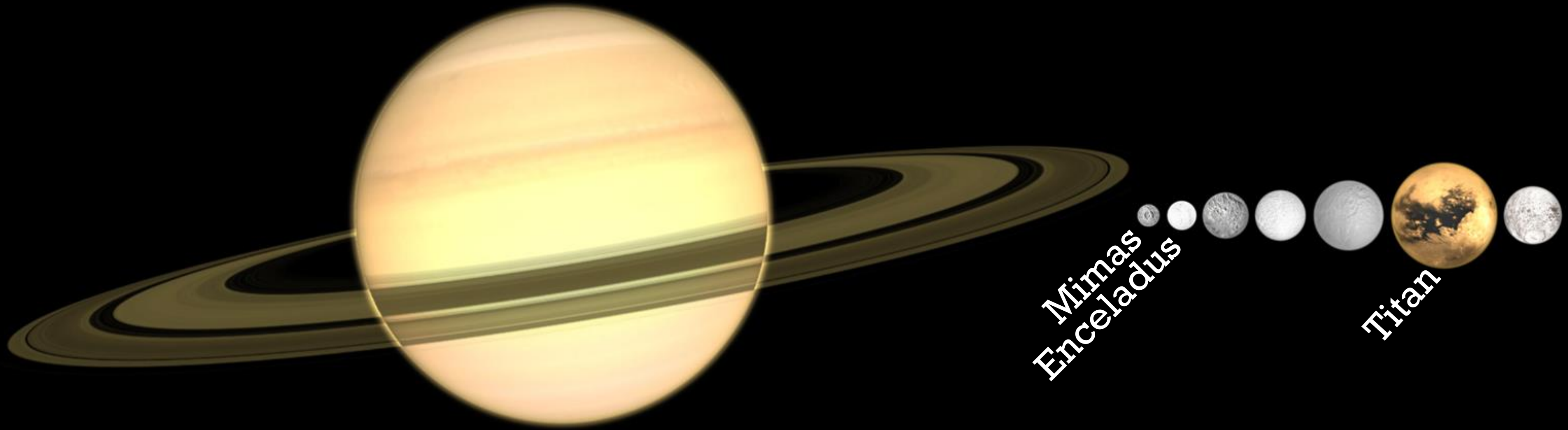
# Our Destination

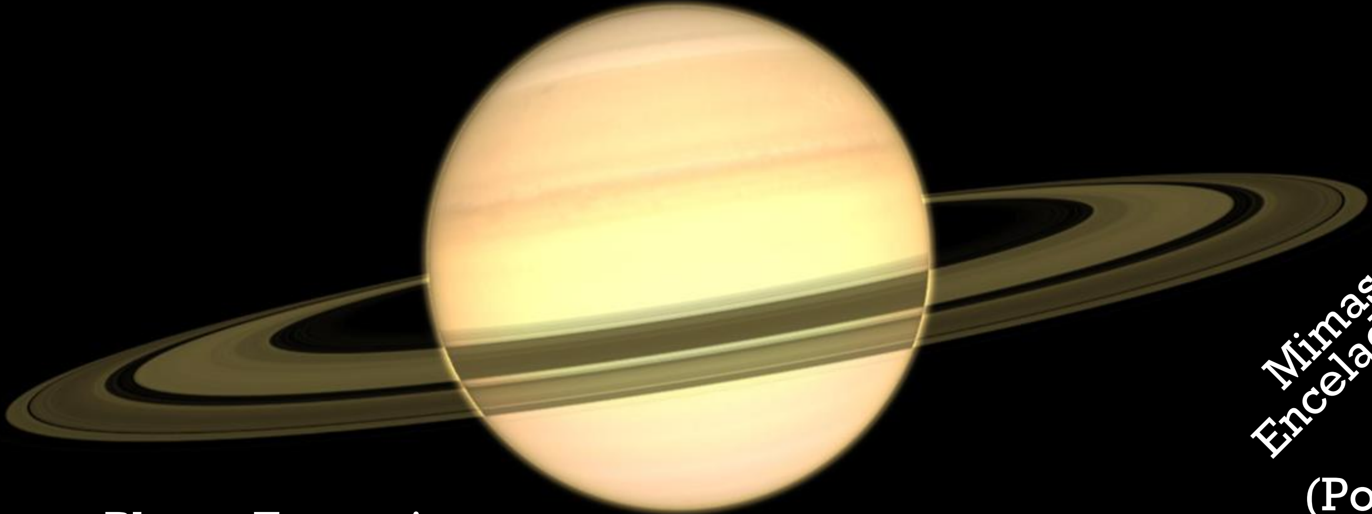
## Saturn and its Moons




But why?

# Our Destination

# Saturn and its Moons



Habitability


(Potential) Ocean Worlds

Early Earth Archetype

Planet Formation

History of Solar System

# Motivation



1997-2017

2028-

## Heritage

- Characterized Saturn's atmosphere
- Discovered Enceladus' plume
  - CHNOPS & organics
- Enceladus mapped
- Huygens landed on Titan
  - Atmosphere
  - Lakes
- Dragonfly to land on Titan
  - Dry equatorial land
  - Habitability

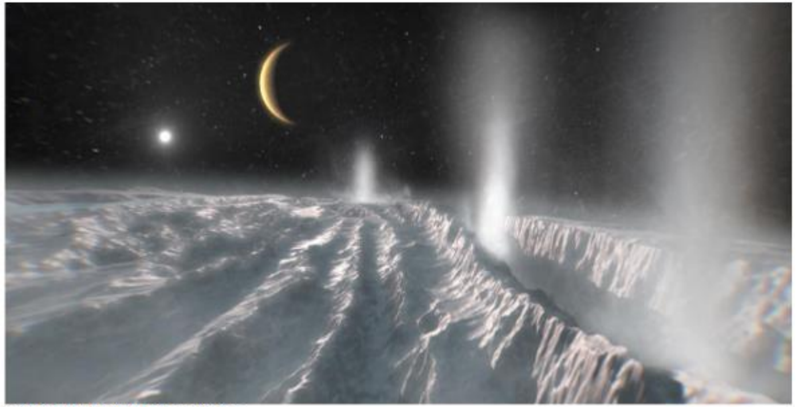
## Open Questions

- Elemental composition poorly known
- Cassini scratched the surface → SEAFARER designed for habitability
- Low resolution → higher resolution for future landers
- Large scale circulations to be addressed
- Complement Dragonfly
  - Lakes (properties remain unknown after Cassini)
  - Habitability

# Motivation



**Report of the Expert Committee for the Large-class mission in ESA's Voyage 2050 plan covering the science theme "Moons of the Giant Planets"**





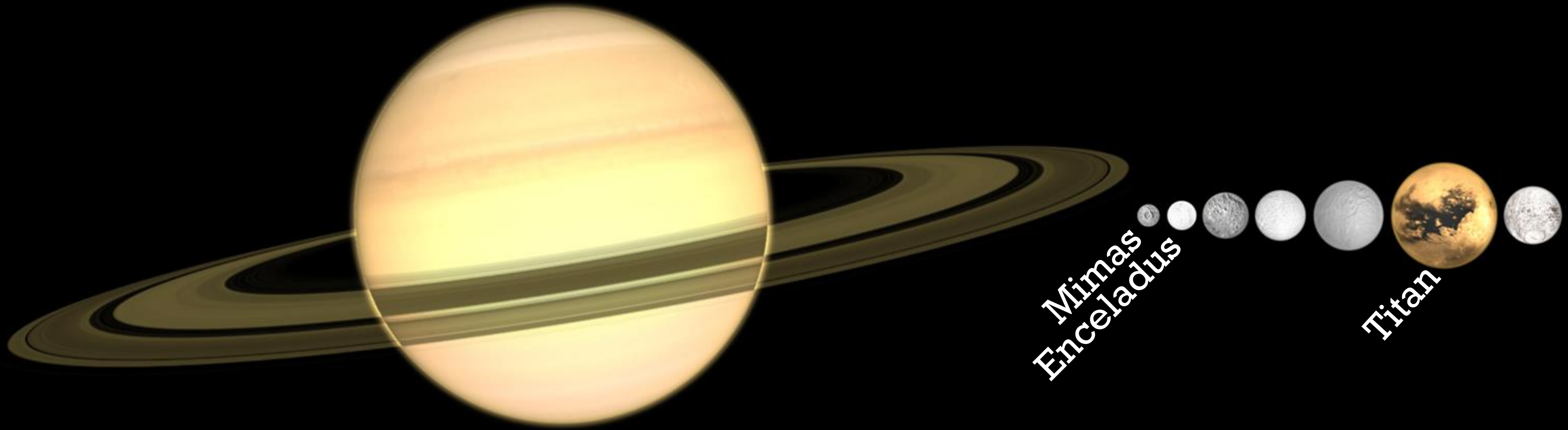
*Expert Committee Report for the Large-class Mission "Moons of the Giant planets":*

1) The issue of **habitability** of ocean worlds and the interaction between the surface and the interior
2) The issue of habitability of **oceans worlds** and the interaction with the external environments
3) The identification of **prebiotic chemistry** and the search for **biosignatures** on ocean worlds.

Most interesting target: Enceladus
2$^{nd}$ place: Titan
Lander and Orbiter

# Our Destination

# Saturn and its Moons




*"SEAFARER shall study and characterise the diversity of habitats in the Saturnian systems"*

# Science Objectives



**Objective 1:** How and where did **Saturn** form?

**Objective 2:** What is the nature and diversity of the **potential habitats**?

**Objective 3:** What is the peculiar nature of the **Titan climate** variability?

# Science Traceability Matrix



SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
|---|---|---|---|---|---|
| 1. Understand Saturn's formation and orbital evolution | 1.1. What is Saturn's formation history, composition and implications for the present-day Solar System architecture? | 1.1.1. *In-situ* isotopic ratios of noble gas and elements (H, He, Ne, Ar, Kr, Xe, C, N, O, and S) in Saturn's atmosphere. 1.1.2. *In-situ* mixing ratios of the species CO, $C_2H_6$, $PH_3$, $NH_3$ in Saturn's atmosphere. | Abundances at a resolution of from 1 to > 150 amu, mass resolution > 1000 M/ΔM. The Tunable laser spectrometer shall have a resolving power of $\sim 10^5$ $\lambda/\Delta\lambda$ at least. | Data retrieval from 1 nbar to 10 bar. | **VESPUCCI** *Atmospheric Probe* Quadrupole Mass spectrometer, Tunable Laser Spectrometer |
| | 1.2. What is the geomorphology and composition of Enceladus' surface, especially in the moon's south polar region? | 1.2.1. Visual and thermal mapping in the IR. 1.2.2. Topography mapping. | Pressure and temperature sampling every 2 s. Altitude resolution: 0.2 to 0.06 km at speeds 100 to 30 m/s. Pressure sensors of three ranges 0.5, 4, and 28 bar full scale, will be read to 10 bit resolution, giving at least count values of 0.5,4, and 28 mb, respectively. The accelerometer shall have 4 ranges in the probe's axial direction with a dynamic range from 3 mg – 400 g. The measurement resolution of the axial accelerometers in the four ranges is nominally 3 mg, 0.1 mg, 3 mg and 0.1 g. The net flux radiometer shall have 6 bandpasses ranging from 0.3–500 $\mu m$ and one blind bandpass. The nephelometer shall probe every km. The lightning radio emissions detector shall have a resolution of 16 s, a time domain of 1 – 100 kHz and a frequency domain of 3, 15, and 100 kHz | Data retrieval from 1 nbar to 10 bar. | **VESPUCCI** *Atmospheric Probe* Atmospheric package with pressure and temperature sensors, Accelerometer, net flux Radiometer, Nephelometer, lightning and radio emissions detector |

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| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
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| 2. Understand the nature and diversity of potential habitats in the Saturnian system. | 2.1. What is the origin and evolution of Saturn's medium-sized moons (Mimas, Enceladus, Rhea, Dione, Tethys)? | 2.1.1. Remote sensing of infrared absorption of $H_2O$ between 1 – 5 $\mu m$ on icy surfaces to find the D/H ratio of Enceladus, Mimas, Rhea, Dione and Tethys from the surface (absorption feature at 4.13 $\mu m$ is representative for deuterium in the ice and 2 $\mu m$ absorption band of $H_2O$). 2.1.2. Remote sensing of the Enceladus plumes | The wavelength coverage shall be 1–5 $\mu m$, with a higher resolution than VIMS, and a minimum resolution of 0.01 $\mu m$. | Perform > 5 flybys of the Saturnian moons (Mimas, Rhea, Dione, Tethys) at an altitude of < 75 km. This needs to be updated! | **SEAFARER** *Orbiter* Visible-Infrared Hyperspectral Imaging Spectrometer |
| | 2.2. What is the geomorphology and composition of Enceladus' surface, namely in the moon's south polar region (Tiger Stripes)? | 2.2.1. Visual and infrared (thermal) mapping of the South Polar Region of Enceladus. 2.2.2. Topography and altimetry mapping. | Image and analyse spectrally the ice surface, with a resolution of 100m/pixel. This needs to be expanded! | How many flybys would you need? | **SEAFARER** *Orbiter* Visible-Infrared Hyperspectral Imaging Spectrometer. Imaging System. Radar Altimetry. |
| | 2.3. What is Enceladus' plumes' activity variability (location, composition, time, interaction with magnetosphere)? | 2.3.1. Thermal mapping (location and intensity) in the South Polar Region. 2.3.2. Magnetic field of Enceladus during the flyby of the moon. | Image and spectral analysis at least 10 m/pixel for the imager and spectrometer 500 m/pixel. We need magnetic measurement requirements. | Flybys | **SEAFARER** *Orbiter* Visible-Infrared Hyperspectral Imaging Spectrometer. Magnetometer. Sub-millimetre wave instrument. Imaging System. |
| | 2.4. What is the current state of water-rock interactions on Enceladus and subsurface ocean longevity and composition? | 2.4.1. Sample the salts, organics and volatiles from the plumes of Enceladus. 2.4.2. Add more. | Molecular weight distribution of organic matter from 16 Da ($CH_4$) to ≥ 1000 Da in plume vapour and icy particles. We need specifications here! | >9 Enceladus flybys at an altitude < 75 km to get to the plumes densest part. S/C velocity shall be 3–5 km/s and 5–9 km/s. | **SEAFARER** *Orbiter* High Resolution Mass Spectrometer. |
| | 2.5. What is the nature of the potential subsurface ocean on Mimas? | 2.5.1. Surface image of tectonism features 2.5.2. Spectral image for detection of endogenous signatures 2.5.3. Thermophysical properties (grain-size) | The spectrometer shall have a wavelength coverage of 0.5 – 5.5 $\mu m$, and 3 – 6 nm spectral resolution. | Shall perform > 9 Mimas flybys at an altitude < TBD | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Sub-mm wave instrument.? |

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| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
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| 2. Understand the nature and diversity of potential habitats in the Saturnian system. | 2.6. What is the nature and habitability potential of the medium-sized moons Dione, Tethys, Rhea? | 2.6.1. Image and spectral analysis of the icy surface 2.6.2. thermophysical properties 2.6.3. Induced magnetic field. | Imager shall measure at a resolution of < 10m/pixel. The spectrometer shall measure at a < 500m/pixel resolution, with a wavelength coverage of 0.5 – 5.5 $\mu m$, and 3–6 nm spectral resolution. | Flyby requirements for each moon | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Magnetometer. |
| | 2.7. What is the current state of interior-surface processes on Titan (cryovolcanism, tectonism, impact-driven liquid water melt pools), their global distribution, geological history and implications for organic material transport across the icy crust? | 2.7.1. Surface mapping of cryovolcanic edifices (domes, calderas, pits) and dynamical features (flows) and their parameters (range, slope, resurfacing rate). 2.7.2. Surface mapping of tectonic features: faults and folds (compression), horst and graben (extension) and lateral displacements (strike-slip) in the icy crust of Titan. 2.7.3. Surface mapping of impact craters and eject to estimate impact melt volume and quantification of morphologies, the spatial distribution of impact melt lakes and outflow valleys (thickness, discharge). 2.7.4. Spatial and temporal (short-term to long-term) thermal anomalies on the surface and near-surface of Titan using IR imaging (5 $\mu m$) and microwave emissivity. | Imager thermal emission: spatial resolution of < 100 m/pixel, the vertical resolution of < 10 m, the signal-to-noise ratio of 50:1. The IR spectrometer will use the 5-$\mu m$ channel (Titan atmospheric window, the only reliable channel in the IR for cryolava detection according to Lorenz et al. 2016). The spectral resolution shall be 3 – 6 nm. Passive off-nadir microwave radiometry: with H and V polarisations, with precision on short-term variations of < 1 K and an absolute accuracy of 2 K. The radar microwave shall have a 13.78 GHz passive Ku-band with a 7 to 310 km resolution. | The orbiter must be at 2000 km of altitude in a high inclination orbit to cover the polar regions. Lower altitudes can be accomplished in the extended phase of the mission. | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Radar: Off-nadir microwave radiometry. " |

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| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
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| 2. Understand the nature and diversity of potential habitats in the Saturnian system | 2.8. What is the relative surface abundance of complex molecules on Titan and Enceladus? | 2.8.1. Image and spectral analysis of the icy surface | Visual and Infrared Spectrometer (0.5-5.5 micrometers, 3-6 nm spectral resolution) Imager shall measure at a resolution of < 10m/pixel. The spectrometer shall measure at a < 500m/pixel resolution, with a wavelength coverage of 0.5 – 5.5 $\mu m$, and 3–6 nm spectral resolution. | Flyby requirements for each moon | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Magnetometer. |
| | 2.9. Are there biogenic elements present in the organic chemistry in Titan, and, if so, what are their abundances and can be reduced and oxidised organic species be detected? | 2.9.1. Elemental chemistry (e.g., Phosphorus, Sulphur) of organic molecules in Titan's atmosphere, aerosols and in *Kraken Mare* 2.9.2. Inventory of reduced and oxidised organic species present in *Kraken Mare*. 2.9.3. Isotopic ratio determination $^{12}C/^{13}C$ (e.g., on chemically abundant species on Titan: C2H2, C2H4, C2H6, C3H8, ...) and D/H parameters from samples collected in the atmosphere and in *Kraken Mare*. 2.9.4. Abundances of noble gases produced by radiogenically processes (e.g. $^{40}Ar$, $^{21}Ne$) in *Kraken Mare*. | Mass range: Mass abundance vs. molecular weight from 2–500 amu of liquid from *Kraken Mare*. Resolution: Mass resolution shall be $1\times10^{-6}$ at 250 amu; Sensitivity: minimum 0.002 counts molecule-1 $cm^3$ $s^{-1}$ and 10x $10^{-10}$ mixing ratio. | Operation requisites: at 75 K at least under a surface pressure of 1.5 bar. | **COLUMBUS** *Drifter* Gas Chromatography-Mass Spectrometer. |

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| 3. Understand the climate variability of Titan | 3.1. How do the large-scale atmospheric features on Titan (superrotation, polar vortex) and wave activity form and evolve and compare to those of Venus (slow-rotator comparison)? | 3.1.1. Doppler shift of spectral lines to directly measure zonal, meridional and vertical winds at higher latitudes. | Resolution specifications | A high inclination orbit is necessary to accomplish wind measurements in the upper atmosphere. Repeated measurements across different seasons must be made across Titan's orbit phase. | **SEAFARER** *Orbiter* Sub-millimeter spectrometer; Ultraviolet Imaging Spectrograph; visible and near-IR imager. |
| | 3.2. How different are the thermal structure and mixing ratios of minor traceable species of the polar atmosphere of Titan compared to the low latitudes? | 3.2.1. Thermal structure in the mid-atmosphere from CO and HCN lines. 3.2.2. Mixing ratio profiles of many molecules and their isotopes in the same altitude range Complete this!. | Resolution specifications | Measurement specifications | **SEAFARER** *Orbiter* Sub-millimeter spectrometer; Ultraviolet Imaging Spectrograph; visible and near-IR imager. |
| | 3.3. How do hazes and clouds form on Titan, from the lower atmosphere to the stratosphere? | 3.3.1. Profile aerosol extinction coefficient to reveal the structure and composition of stratospheric ice clouds. 3.3.2. UV airglow and reflected UV. 3.3.3. Cloud activity in the visible and near-IR. 3.3.4. Cloud methane ($CH_4$) abundance and $CH_4$ droplet size and cristal size from near-IR spectrometry. 3.3.5. Methane abundance profile during lander descent. 3.3.6. Aerosol extinction coefficients during lander descent. | The lander camera should have a wavelength coverage in two channels: visible at 480–960 nm and IR at 0.87 – 1.64 $\mu m$. A resolution of 0.06–0.20" Talk to Fabian about this. | We need mission requirements for this | **SEAFARER** *Orbiter* UV spectrometer; visible and near-IR imager; sub-millimeter wave instrument; near-IR spectrometer. **COLUMBUS** *Lander* Lander camera. Nephelometer |

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| 3. Understand the climate variability of Titan | 3.8. What are the local physical and dynamical properties of *Kraken Mare* as a proxy for Titan's lakes and seas? | 3.6.1. Sea depth and sound speed from SONAR, located in the upper buoy of the lander Columbus. 3.8.2. Temperature, pressure and dielectric constant for permittivity assessment of the lake, to be gathered from lower buoy (for surface). 3.8.3. Temperature, pressure and dielectric constant profiles for the dropping compartment in the lower buoy. 3.8.4. Wave activity, surface currents, floating films (including recognition of floating islands) and debris from sea surface images of lander camera and information from lander attitude. 3.6.5.Turbidity from LED below the waterline, located in the upper buoy of the lander Columbus. | "Sensitivity: (1) sound speed shall be recorded with a 1% sensitivity in the range of 1000 to 2000 m/s. The sea depth shall be measured with an accuracy of ¡ 5 m and over nominal distances of 10 to 500 m from the SONAR instrument and with a nominal requirement for instrument work at < 50 dB/Pa2/Hz.; (2) The sea surface temperature and temperature profiles shall be determined with a sensitivity of 0.1 K. The dielectric constant shall be measured in the range 1-3 with an accuracy of +/- 0.01; (3) same as in (2); (4) Wave activity: camera and lander attitude information. (5) The power of the LED must be taken into consideration and what it is the light extinction under the waterline. | | **SEAFARER** *Orbiter* Radar, IR Spectrometer, IR camera **COLUMBUS** *Lander*: upper buoy, lower buoy + falling compartment). |

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| 2. Understand the nature and diversity of potential habitats in the Saturnian system | 2.8. What is the relative surface abundance of complex molecules on Titan and Enceladus? | 2.8.1. Image and spectral analysis of the icy surface | Visual and Infrared Spectrometer (0.5-5.5 micrometers, 3-6 nm spectral resolution) Imager shall measure at a resolution of < 10m/pixel. The spectrometer shall measure at a < 500m/pixel resolution, with a wavelength coverage of 0.5 – 5.5 μm, and 3 6 nm spectral resolution. | Flyby requirements for each moon | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Magnetometer. |
| | 2.9. Are there biogenic elements present in the organic chemistry in Titan, and, if so, what are their abundances and can be reduced and oxidised organic species be detected? | 2.9.1. Elemental chemistry (e.g., Phosphorus, Sulphur) of organic molecules in Titan's atmosphere, aerosols and in *Kraken Mare* 2.9.2. Inventory of reduced and oxidised organic species present in *Kraken Mare*. 2.9.3. Isotopic ratio determination $^{12}C/^{13}C$ (e.g., on chemically abundant species on Titan: C2H2, C2H4, C2H6, C3H8, ...) and D/H parameters from samples collected in the atmosphere and in *Kraken Mare*. 2.9.4. Abundances of noble gases produced by radiogenically processes (e.g. $^{40}Ar$, $^{21}Ne$) in *Kraken Mare*. | Mass range: Mass abundance vs. molecular weight from 2-500 amu of liquid from *Kraken Mare*. Resolution: Mass resolution shall be $1\times10^{-6}$ at 250 amu; Sensitivity: minimum 0.002 counts molecule-1 $cm^3$ $s^{-1}$ and 10x $10^{-10}$ mixing ratio. | Operation requisites: at 75 K at least under a surface pressure of 1.5 bar. | **COLUMBUS** *Drifter* Gas Chromatography-Mass Spectrometer. |

SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
|---|---|---|---|---|---|
| 3. Understand the climate variability of Titan | 3.1. How do the large-scale atmospheric features on Titan (superrotation, polar vortex) and wave activity form and evolve and compare to those of Venus (slow-rotator comparison)? | 3.1.1. Doppler shift of spectral lines to directly measure zonal, meridional and vertical winds at higher latitudes. | Resolution specifications | A high inclination orbit is necessary to accomplish wind measurements in the upper atmosphere. Repeated measurements across different seasons must be made across Titan's orbit phase. | **SEAFARER** *Orbiter* Sub-millimeter spectrometer; Ultraviolet Imaging Spectrograph; visible and near-IR imager. |
| | 3.2. How different are the thermal structure and mixing ratios of minor traceable species of the polar atmosphere of Titan compared to the low latitudes? | 3.2.1. Thermal structure in the mid-atmosphere from CO and HCN lines. 3.2.2. Mixing ratio profiles of many molecules and their isotopes in the same altitude range Complete this!. | Resolution specifications | Measurement specifications | **SEAFARER** *Orbiter* Sub-millimeter spectrometer; Ultraviolet Imaging Spectrograph; visible and near-IR imager. |
| | 3.3. How do hazes and clouds form on Titan, from the lower atmosphere to the stratosphere? | 3.3.1. Profile aerosol extinction coefficient to reveal the structure and composition of stratospheric ice clouds. 3.3.2. UV airglow and reflected UV. 3.3.3. Cloud activity in the visible and near-IR. 3.3.4. Cloud methane ($CH_4$) abundance and $CH_4$ droplet size and cristal size from near-IR spectrometry. 3.3.5. Methane abundance profile during lander descent. 3.3.6. Aerosol extinction coefficients during lander descent. | The lander camera should have a wavelength coverage in two channels: visible at 480-960 nm and IR at 0.87 – 1.64 μm. A resolution of 0.06-0.20" Talk to Fabian about this. | We need mission requirements for this | **SEAFARER** *Orbiter* UV spectrometer; visible and near-IR imager; sub-millimeter wave instrument; near-IR spectrometer. **COLUMBUS** *Lander* Lander camera. Nephelometer |

SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
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| 3. Understand the climate variability of Titan | 3.8. What are the local physical and dynamical properties of *Kraken Mare* as a proxy for Titan's lakes and seas? | 3.6.1. Sea depth and sound speed from SONAR, located in the upper buoy of the lander Columbus. 3.8.2. Temperature, pressure and dielectric constant for permittivity assessment of the lake, to be gathered from lower buoy (for surface). 3.8.3. Temperature, pressure and dielectric constant profiles for the dropping compartment in the lower buoy. 3.8.4. Wave activity, surface currents, floating films (including recognition of floating islands) and debris from sea surface images of lander camera and information from lander attitude. 3.6.5.Turbidity from LED below the waterline, located in the upper buoy of the lander Columbus. | "Sensitivity: (1) sound speed shall be recorded with a 1% sensitivity in the range of 1000 to 2000 m/s. The sea depth shall be measured with an accuracy of ¡ 5 m and over nominal distances of 10 to 500 m from the SONAR instrument and with a nominal requirement for instrument work at < 50 dB/Pa2/Hz.; (2) The sea surface temperature and temperature profiles shall be determined with a sensitivity of 0.1 K. The dielectric constant shall be measured in the range 1-3 with an accuracy of +/-0.01; (3) same as in (2); (4) Wave activity: camera and lander attitude information. (5) The power of the LED must be taken into consideration and what it is the light extinction under the waterline. | | **SEAFARER** *Orbiter* Radar, IR Spectrometer, IR camera **COLUMBUS** *Lander*: upper buoy, lower buoy + falling compartment). |


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# Science Traceability Matrix



SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
|---|---|---|---|---|---|
| 1. Understand Saturn's formation and orbital evolution | 1.1. What is Saturn's formation history, composition and implications for the present-day Solar System architecture? | 1.1.1. *In-situ* isotopic ratios of noble gas and elements (H, He, Ne, Ar, Kr, Xe, C, N, O, and S) in Saturn's atmosphere. 1.1.2. *In-situ* mixing ratios of the species CO, $C_2H_6$, $PH_3$, $NH_3$ in Saturn's atmosphere. | Abundances at a resolution of from 1 to > 150 amu, mass resolution > 1000 M/ΔM. The Tunable laser spectrometer shall have a resolving power of $\sim 10^5$ $\lambda/\Delta\lambda$ at least. | Data retrieval from 1 nbar to 10 bar. | **VESPUCCI** *Atmospheric Probe* Quadrupole Mass spectrometer, Tunable Laser Spectrometer |
| | 1.2. What is the geomorphology and composition of Enceladus' surface, especially in the moon's south polar region? | 1.2.1. Visual and thermal mapping in the IR. 1.2.2. Topography mapping. | Pressure and temperature sampling every 2 s. Altitude resolution: 0.2 to 0.06 km at speeds 100 to 30 m/s. Pressure sensors of three ranges 0.5, 4, and 28 bar full scale, will be read to 10 bit resolution, giving at least count values of 0.5,4, and 28 mb, respectively. The accelerometer shall have 4 ranges in the probe's axial direction with a dynamic range from 3 mg – 400 g. The measurement resolution of the axial accelerometers in the four ranges is nominally 3 mg, 0.1 mg, 3 mg and 0.1 g. The net flux radiometer shall have 6 bandpasses ranging from 0.3–500 μm and one blind bandpass. The nephelometer shall probe every km. The lightning radio emissions detector shall have a resolution of 16 s, a time domain of 1 – 100 kHz and a frequency domain of 3, 15, and 100 kHz | Data retrieval from 1 nbar to 10 bar. | **VESPUCCI** *Atmospheric Probe* Atmospheric package with pressure and temperature sensors, Accelerometer, net flux Radiometer, Nephelometer, lightning and radio emissions detector |

SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
|---|---|---|---|---|---|
| 2. Understand the nature and diversity of potential habitats in the Saturnian system. | 2.6. What is the nature and habitability potential of the medium-sized moons Dione, Tethys, Rhea? | 2.6.1. Image and spectral analysis of the icy surface 2.6.2. thermophysical properties 2.6.3. Induced magnetic field. | Imager shall measure at a resolution of < 10m/pixel. The spectrometer shall measure at a < 500m/pixel resolution, with a wavelength coverage of 0.5 – 5.5 μm, and 3–6 nm spectral resolution. | Flyby requirements for each moon | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Magnetometer. |
| | 2.7. What is the current state of interior-surface processes on Titan (cryovolcanism, tectonism, impact-driven liquid water melt pools), their global distribution, geological history and implications for organic material transport across the icy crust? | 2.7.1. Surface mapping of cryovolcanic edifices (domes, calderas, pits) and dynamical features (flows) and their parameters (range, slope, resurfacing rate). 2.7.2. Surface mapping of tectonic features: faults and folds (compression), horst and graben (extension) and lateral displacements (strike-slip) in the icy crust of Titan. 2.7.3. Surface mapping of impact craters and eject to estimate impact melt volume and quantification of morphologies, the spatial distribution of impact melt lakes and outflow valleys (thickness, discharge). 2.7.4. Spatial and temporal (short-term to long-term) thermal anomalies on the surface and near-surface of Titan using IR imaging (5 μm) and microwave emissivity. | Imager thermal emission: spatial resolution of < 100 m/pixel, the vertical resolution of < 10 m, the signal-to-noise ratio of 50:1. The IR spectrometer will use the 5-μm channel (Titan atmospheric window, the only reliable channel in the IR for cryolava detection according to Lorenz et al. 2016). The spectral resolution shall be 3 – 6 nm. Passive off-nadir microwave radiometry: with H and V polarisations, with precision on short-term variations of < 1 K and an absolute accuracy of 2 K. The radar microwave shall have a 13.78 GHz passive Ku-band with a 7 to 310 km resolution. | The orbiter must be at 2000 km of altitude in a high inclination orbit to cover the polar regions. Lower altitudes can be accomplished in the extended phase of the mission. | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Radar: Off-nadir microwave radiometry. " |

SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

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| 3. Understand the climate variability of Titan | 3.1. How do the large-scale atmospheric features on Titan (superrotation, polar vortex) and wave activity form and evolve and compare to those of Venus (slow-rotator comparison)? | 3.1.1. Doppler shift of spectral lines to directly measure zonal, meridional and vertical winds at higher latitudes. | Resolution specifications | A high inclination orbit is necessary to accomplish wind measurements in the upper atmosphere. Repeated measurements across different seasons must be made across Titan's orbit phase. | **SEAFARER** *Orbiter* Sub-millimeter spectrometer; Ultraviolet Imaging Spectrograph; visible and near-IR imager. |
| | 3.2. How different are the thermal structure and mixing ratios of minor traceable species of the polar atmosphere of Titan compared to the low latitudes? | 3.2.1. Thermal structure in the mid-atmosphere from CO and HCN lines. 3.2.2. Mixing ratio profiles of many molecules and their isotopes in the same altitude range Complete this!. | Resolution specifications | Measurement specifications | **SEAFARER** *Orbiter* Sub-millimeter spectrometer; Ultraviolet Imaging Spectrograph; visible and near-IR imager. |
| | 3.3. How do hazes and clouds form on Titan, from the lower atmosphere to the stratosphere? | 3.3.1. Profile aerosol extinction coefficient to reveal the structure and composition of stratospheric ice clouds. 3.3.2. UV airglow and reflected UV. 3.3.3. Cloud activity in the visible and near-IR. 3.3.4. Cloud methane ($CH_4$) abundance and $CH_4$ droplet size and cristal size from near-IR spectrometry. 3.3.5. Methane abundance profile during lander descent. | The lander camera should have a wavelength coverage in two channels: visible at 480–960 nm and IR at 0.87 – 1.64 μm. A resolution of 0.06–0.30° Talk to Fabian about this. | We need mission requirements for this | **SEAFARER** *Orbiter* UV spectrometer; visible and near-IR imager; sub-millimeter wave instrument; near-IR spectrometer. **COLUMBUS** *Lander* Lander camera. Nephelometer |

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| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
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SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
|---|---|---|---|---|---|
| 2. Understand the nature and diversity of potential habitats in the Saturnian system. | 2.1. What is the origin and evolution of Saturn's medium-sized moons (Mimas, Enceladus, Rhea, Dione, Tethys)? | 2.1.1. Remote sensing of infrared absorption of $H_2O$ between 1 – 5 μm on icy surfaces to find the D/H ratio of Enceladus, Mimas, Rhea, Dione and Tethys from the surface (absorption feature at 4.13 μm is representative for deuterium in the ice and 2 μm absorption band of $H_2O$). 2.1.2. Remote sensing of the Enceladus plumes | The wavelength coverage shall be 1–5μm, with a higher resolution than VIMS, and a minimum resolution of 0.01 μm. | Perform > 5 flybys of the Saturnian moons (Mimas, Rhea, Dione, Tethys) at an altitude of < 75 km. This needs to be updated! | **SEAFARER** *Orbiter* Visible-Infrared Hyperspectral Imaging Spectrometer |
| | 2.2. What is the geomorphology and composition of Enceladus' surface, namely in the moon's south polar region (Tiger Stripes)? | 2.2.1. Visual and infrared (thermal) mapping of the South Polar Region of Enceladus. 2.2.2. Topography and altimetry mapping. | Image and analyse spectrally the ice surface, with a resolution of 100m/pixel. This needs to be expanded! | How many flybys would you need? | **SEAFARER** *Orbiter* Visible-Infrared Hyperspectral Imaging Spectrometer. Imaging System. Radar Altimetry. |
| | 2.3. What is Enceladus' plumes' activity variability (location, composition, time, interaction with magnetosphere)? | 2.3.1. Thermal mapping (location and intensity) in the South Polar Region. 2.3.2. Magnetic field of Enceladus during the flyby of the moon. | Image and spectral analysis at least 10 m/pixel for the imager and spectrometer 500 m/pixel. We need magnetic measurement requirements. | Flybys | **SEAFARER** *Orbiter* Visible-Infrared Hyperspectral Imaging Spectrometer. Magnetometer. Sub-millimeter wave instrument. Imaging System. |
| | 2.4. What is the current state of water-rock interactions on Enceladus and subsurface ocean longevity and composition? | 2.4.1. Sample the salts, organics and volatiles from the plumes of Enceladus. 2.4.2. Add more. | Molecular weight distribution of organic matter from 16 Da ($CH_4$) to ≥ 1000 Da in plume vapour and icy particles. We need specifications here! | >9 Enceladus flybys at an altitude < 75 km to get to the plumes densest part. S/C velocity shall be 3–5 km/s and 5–9 km/s. | **SEAFARER** *Orbiter* High Resolution Mass Spectrometer. |
| | 2.5. What is the nature of the potential subsurface ocean on Mimas? | 2.5.1. Surface image of tectonism features 2.5.2. Spectral image for detection of endogenous signatures 2.5.3. Thermophysical properties (grain-size) | The spectrometer shall have a wavelength coverage of 0.5 – 5.5 μm, and 3 – 6 nm spectral resolution. | Shall perform > 9 Mimas flybys at an altitude < TBD | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Sub-mm wave instrument.? |

SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

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| | 2.9. Are there biogenic elements present in the organic chemistry in Titan, and, if so, what are their abundances and can be reduced and oxidised organic species be detected? | 2.9.1. Elemental chemistry (e.g., Phosphorus, Sulphur) of organic molecules in Titan's atmosphere, aerosols and in *Kraken Mare* 2.9.2. Inventory of reduced and oxidised organic species present in *Kraken Mare*. 2.9.3. Isotopic ratio determination $^{12}C/^{13}C$ (e.g., on chemically abundant species on Titan: C2H2, C2H4, C2H6, C3H8, ...) and D/H parameters from samples collected in the atmosphere and in *Kraken Mare*. 2.9.4. Abundances of noble gases produced by radiogenically processes (e.g. $^{40}Ar$, $^{21}Ne$) in *Kraken Mare*. | Mass range: Mass abundance vs. molecular weight from 2-500 amu of liquid from *Kraken Mare*. Resolution: Mass resolution shall be $1\times10^{-6}$ at 250 amu; Sensitivity: minimum 0.002 counts molecule-1 $cm^3$ $s^{-1}$ and 10x $10^{-10}$ mixing ratio. | Operation requisites: at 75 K at least under a surface pressure of 1.5 bar. | **COLUMBUS** *Drifter* Gas Chromatography-Mass Spectrometer. |

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# Science Traceability Matrix

SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

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| | **1.2.** What is the geomorphology and composition of Enceladus' surface, especially in the moon's south polar region? | **1.2.1.** Visual and thermal mapping in the IR. **1.2.2.** Topography mapping. | Pressure and temperature sampling every 2 s. Altitude resolution: 0.2 to 0.06 km at speeds 100 to 30 m/s. Pressure sensors of three ranges 0.5, 4, and 28 bar full scale, will be read to 10 bit resolution, giving at least count values of 0.5,4, and 28 mb, respectively. The accelerometer shall have 4 ranges in the probe's axial direction with a dynamic range from 3 mg – 400 g. The measurement resolution of the axial accelerometers in the four ranges is nominally 3 mg, 0.1 mg, 3 mg and 0.1 g. The net flux radiometer shall have 6 bandpasses ranging from 0.3–500 μm and one blind bandpass. The nephelometer shall probe every km. The lightning radio emissions detector shall have a resolution of 16 s, a time domain of 1 – 100 kHz and a frequency domain of 3, 15, and 100 kHz | Data retrieval from 1 nbar to 10 bar. | **VESPUCCI** *Atmospheric Probe* Atmospheric package with pressure and temperature sensors, Accelerometer, net flux Radiometer, Nephelometer, lightning and radio emissions detector |

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| | **2.7.** What is the current state of interior-surface processes on Titan (cryovolcanism, tectonism, impact-driven liquid water melt pools), their global distribution, geological history and implications for organic material transport across the icy crust? | **2.7.1.** Surface mapping of cryovolcanic edifices (domes, calderas, pits) and dynamical features (flows) and their parameters (range, slope, resurfacing rate). **2.7.2.** Surface mapping of tectonic features: faults and folds (compression), horst and graben (extension) and lateral displacements (strike-slip) in the icy crust of Titan. **2.7.3.** Surface mapping of impact craters and eject to estimate impact melt volume and quantification of morphologies, the spatial distribution of impact melt lakes and outflow valleys (thickness, discharge). **2.7.4.** Spatial and temporal (short-term to long-term) thermal anomalies on the surface and near-surface of Titan using IR imaging (5 μm) and microwave emissivity. | Imager thermal emission: spatial resolution of < 100 m/pixel, the vertical resolution of < 10 m, the signal-to-noise ratio of 50:1. The IR spectrometer will use the 5-μm channel (Titan atmospheric window, the only reliable channel in the IR for cryolava detection according to Lorenz et al. 2016). The spectral resolution shall be 3 – 6 nm. Passive off-nadir microwave radiometry: with H and V polarisations, with precision on short-term variations of < 1 K and an absolute accuracy of 2 K. The radar microwave shall have a 13.78 GHz passive Ku-band with a 7 to 310 km resolution. | The orbiter must be at 2000 km of altitude in a high inclination orbit to cover the polar regions. Lower altitudes can be accomplished in the extended phase of the mission. | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Radar: Off-nadir microwave radiometry. " |

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| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
|---|---|---|---|---|---|
| **2.** Understand the nature and diversity of potential habitats in the Saturnian system. | **2.1.** What is the origin and evolution of Saturn's medium-sized moons (Mimas, Enceladus, Rhea, Dione, Tethys)? | **2.1.1.** Remote sensing of infrared absorption of $H_2O$ between 1 – 5 μm on icy surfaces to find the D/H ratio of Enceladus, Mimas, Rhea, Dione and Tethys from the surface (absorption feature at 4.13 μm is representative for deuterium in the ice and 2 μm absorption band of $H_2O$). **2.1.2.** Remote sensing of the Enceladus plumes | The wavelength coverage shall be 1–5μm, with a higher resolution than VIMS, and a minimum resolution of 0.01 μm. | Perform > 5 flybys of the Saturnian moons (Mimas, Rhea, Dione, Tethys) at an altitude of < 75 km. This needs to be updated! | **SEAFARER** *Orbiter* Visible-Infrared Hyperspectral Imaging Spectrometer |
| | **2.2.** What is the geomorphology and composition of Enceladus' surface, namely in the moon's south polar region (Tiger Stripes)? | **2.2.1.** Visual and infrared (thermal) mapping of the South Polar Region of Enceladus. **2.2.2.** Topography and altimetry mapping. | Image and analyse spectrally the ice surface, with a resolution of 100m/pixel. This needs to be expanded! | How many flybys would you need? | **SEAFARER** *Orbiter* Visible-Infrared Hyperspectral Imaging Spectrometer. Imaging System. Radar Altimetry. |
| | **2.3.** What is Enceladus' plumes' activity variability (location, composition, time, interaction with magnetosphere)? | **2.3.1.** Thermal mapping (location and intensity) in the South Polar Region. **2.3.2.** Magnetic field of Enceladus during the flyby of the moon. | Image and spectral analysis at least 10 m/pixel for the imager and spectrometer 500 m/pixel. We need magnetic measurement requirements. | Flybys | **SEAFARER** *Orbiter* Visible-Infrared Hyperspectral Imaging Spectrometer. Magnetometer. Sub-millimetre wave instrument. Imaging System. |
| | **2.4.** What is the current state of water-rock interactions on Enceladus and subsurface ocean longevity and composition? | **2.4.1.** Sample the salts, organics and volatiles from the plumes of Enceladus. **2.4.2.** Add more. | Molecular weight distribution of organic matter from 16 Da ($CH_4$) to ≥ 1000 Da in plume vapour and icy particles. We need specifications here! | >9 Enceladus flybys at an altitude < 75 km to get to the plumes densest part. S/C velocity shall be 3–5 km/s and 5–9 km/s. | **SEAFARER** *Orbiter* High Resolution Mass Spectrometer. |
| | **2.5.** What is the nature of the potential subsurface ocean on Mimas? | **2.5.1.** Surface image of tectonism features **2.5.2.** Spectral image for detection of endogenous signatures **2.5.3.** Thermophysical properties (grain-size) | The spectrometer shall have a wavelength coverage of 0.5 – 5.5 μm, and 3 – 6 nm spectral resolution. | Shall perform > 9 Mimas flybys at an altitude < TBD | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Sub-mm wave instrument.? |

SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
|---|---|---|---|---|---|
| **2.** Understand the nature and diversity of potential habitats in the Saturnian system | **2.8.** What is the relative surface abundance of complex molecules on Titan and Enceladus? | **2.8.1.** Image and spectral analysis of the icy surface | Visual and Infrared Spectrometer (0.5-5.5 micrometers, 3-6 nm spectral resolution) Imager shall measure at a resolution of < 10m/pixel. The spectrometer shall measure at a < 500m/pixel resolution, with a wavelength coverage of 0.5 – 5.5 μm, and 3 6 nm spectral resolution. | Flyby requirements for each moon | **SEAFARER** *Orbiter* Imaging System. Visual and Infrared Spectrometer. Magnetometer. |
| | **2.9.** Are there biogenic elements present in the organic chemistry in Titan, and, if so, what are their abundances and can be reduced and oxidised organic species be detected? | **2.9.1.** Elemental chemistry (e.g., Phosphorus, Sulphur) of organic molecules in Titan's atmosphere, aerosols and in *Kraken Mare* **2.9.2.** Inventory of reduced and oxidised organic species present in *Kraken Mare*. **2.9.3.** Isotopic ratio determination $^{12}C/^{13}C$ (e.g., on chemically abundant species on Titan: C2H2, C2H4, C2H6, C3H8, ...) and D/H parameters from samples collected in the atmosphere and in *Kraken Mare*. **2.9.4.** Abundances of noble gases produced by radiogenically processes (e.g. $^{40}Ar$, $^{21}Ne$) in *Kraken Mare*. | Mass range: Mass abundance vs. molecular weight from 2–500 amu of liquid from *Kraken Mare*. Resolution: Mass resolution shall be $1\times10^{-6}$ at 250 amu; Sensitivity: minimum 0.002 counts molecule-1 $cm^3$ $s^{-1}$ and $10\times\ 10^{-10}$ mixing ratio. | Operation requisites: at 75 K at least under a surface pressure of 1.5 bar. | **COLUMBUS** *Drifter* Gas Chromatography-Mass Spectrometer. |

SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
|---|---|---|---|---|---|
| **3.** Understand the climate variability of Titan | **3.8.** What are the local physical and dynamical properties of *Kraken Mare* as a proxy for Titan's lakes and seas? | **3.6.1.** Sea depth and sound speed from SONAR, located in the upper buoy of the lander Columbus. **3.8.2.** Temperature, pressure and dielectric constant for permittivity assessment of the lake, to be gathered from lower buoy (for surface). **3.8.3.** Temperature, pressure and dielectric constant profiles for the dropping compartment in the lower buoy. **3.8.4.** Wave activity, surface currents, floating films (including recognition of floating islands) and debris from sea surface images of lander camera and information from lander attitude. **3.6.5.**Turbidity from LED below the waterline, located in the upper buoy of the lander Columbus. | "Sensitivity: (1) sound speed shall be recorded with a 1% sensitivity in the range of 1000 to 2000 m/s. The sea depth shall be measured with an accuracy of ¡ 5 m and over nominal distances of 10 to 500 m from the SONAR instrument and with a nominal requirement for instrument work at < 50 dB/Pa2/Hz.; (2) The sea surface temperature and temperature profiles shall be determined with a sensitivity of 0.1 K. The dielectric constant shall be measured in the range 1-3 with an accuracy of +/- 0.01; (3) same as in (2); (4) Wave activity: camera and lander attitude information. (5) The power of the LED must be taken into consideration and what it is the light extinction under the waterline. | | **SEAFARER** *Orbiter* Radar, IR Spectrometer, IR camera **COLUMBUS** *Lander*: upper buoy, lower buoy + falling compartment). |

SEAFARER: A mission to study Habitability in the Saturnian System — Green Team

| Scientific Goals | Scientific Question | Scientific Measurements | Measurement Requirements | Mission Requirements | Instrument |
|---|---|---|---|---|---|
| **3.** Understand the climate variability of Titan | **3.8.** What are the local physical and dynamical properties of *Kraken Mare* as a proxy for Titan's lakes and seas? | **3.6.1.** Sea depth and sound speed from SONAR, located in the upper buoy of the lander Columbus. **3.8.2.** Temperature, pressure and dielectric constant for permittivity assessment of the lake, to be gathered from lower buoy (for surface). **3.8.3.** Temperature, pressure and dielectric constant profiles for the dropping compartment in the lower buoy. **3.8.4.** Wave activity, surface currents, floating films (including recognition of floating islands) and debris from sea surface images of lander camera and information from lander attitude. **3.6.5.**Turbidity from LED below the waterline, located in the upper buoy of the lander Columbus. | "Sensitivity: (1) sound speed shall be recorded with a 1% sensitivity in the range of 1000 to 2000 m/s. The sea depth shall be measured with an accuracy of ¡ 5 m and over nominal distances of 10 to 500 m from the SONAR instrument and with a nominal requirement for instrument work at < 50 dB/Pa2/Hz.; (2) The sea surface temperature and temperature profiles shall be determined with a sensitivity of 0.1 K. The dielectric constant shall be measured in the range 1-3 with an accuracy of +/- 0.01; (3) same as in (2); (4) Wave activity: camera and lander attitude information. (5) The power of the LED must be taken into consideration and what it is the light extinction under the waterline. | | **SEAFARER** *Orbiter* Radar, IR Spectrometer, IR camera **COLUMBUS** *Lander*: upper buoy, lower buoy + falling compartment). |


Green Team – Mission SEAFARER

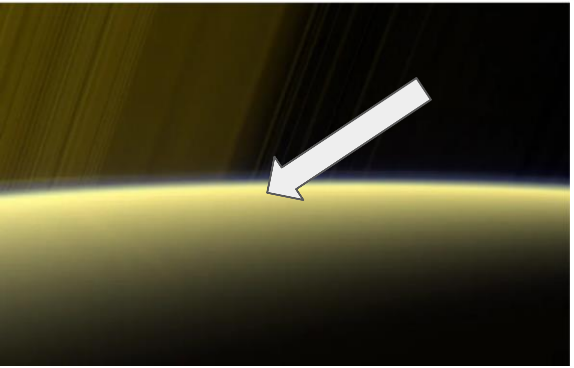
# Science Questions

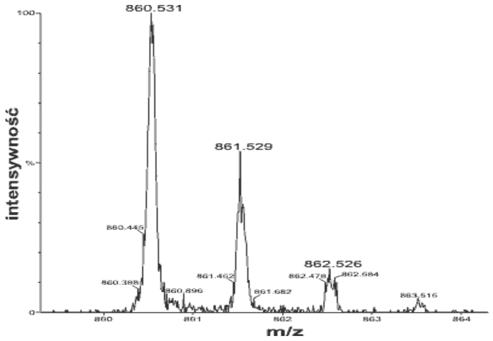


| Science objectives | Science questions |
| --- | --- |
| SO1: How and where did **Saturn** form? | • Q1.1: What is Saturn's formation history, composition and implications for the present-day Solar System architecture?<br><br>• Q1.2: What are the physical, dynamical and radiative conditions of the upper atmosphere of Saturn in the pressure range between <1 bar and 10 bar? |

# Q1.1: What is Saturn's formation history, composition and implications for the present-day Solar System architecture?








- Measure in situ isotopic ratios of noble gases and elements (H, He, Ne, Ar, Kr, Xe, C, N, O, and S)
- Quadrupole mass spectrometer
  - Mass range [1,150] amu
  - Resolution >1000 M/ΔM
- Measure in situ mixing ratios of CO, $C_2H_6$, $PH_3$,, $NH_3$
- Tunable Laser Spectrometer
  - Resolution $10^5$ λ/Δλ
- Measurements <1-10 bar

→ Atmospheric probe VESPUCCI

# Science Questions



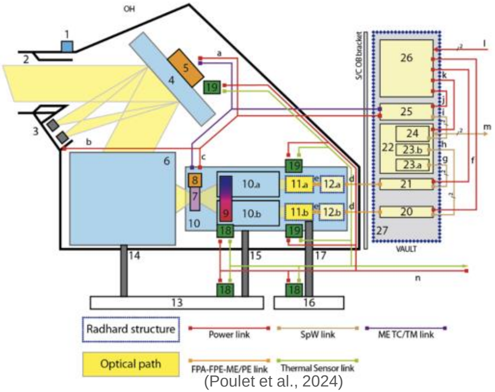
| Science objectives | Science questions |
| --- | --- |
| SO2: What is the nature and diversity of **potential habitats** in the **Saturnian system**? | • Q2.2: What is the geomorphology and composition of Enceladus' surface, namely in the moon's south polar region (Tiger Stripes)?<br>• Q2.3: What is Enceladus' plume activity variability (location, composition, time, interaction with magnetosphere)?<br>• Q2.5: What is the nature of the potential subsurface ocean on Mimas?<br>• Q2.7: What is the current state of interior-surface processes on Titan, their global distribution, geological history and implications for organic material transport across the icy crust?<br>• Q2.9: Are there biogenic elements present in the organic chemistry in Titan, and, if so, what are their abundances? |

# Q2.1: What is the geomorphology and composition of Enceladus' surface namely in the moon's south polar region?

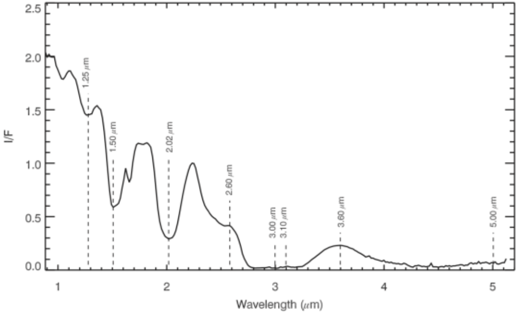


- Measure spectra of the south polar terrain to extract composition and physical properties of water ice
    - resolve smallest feature → spatial resolution of 100 m/pixel
- Visual and Infrared Spectrometer
    - range 0.5-5μm (two multi-band spectrometers: VIS & IR)
    - spectral resolution ~10nm
- Minimum of 10 flybys to cover the whole south polar area at an altitude of 100km

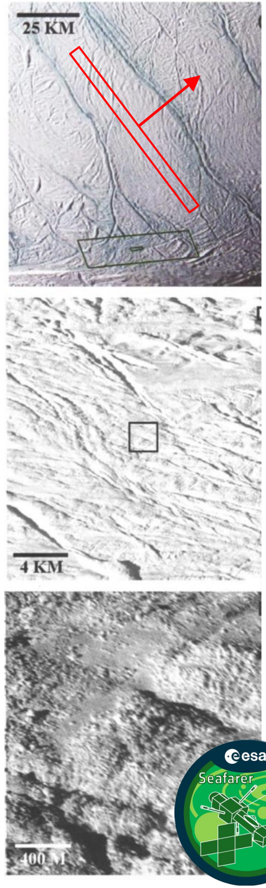
→ Orbiter



(Poulet et al., 2024)



(Sciopini et al., 2007)



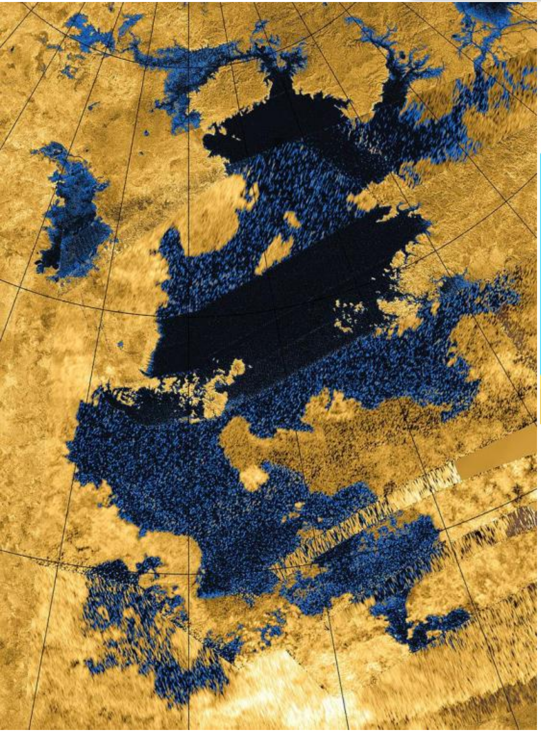
(Porco et al., 2006)

# Science Questions



| Science objectives | Science questions |
|---|---|
| SO3: What is the peculiar nature of the **Titan climate** variability? | • Q3.1: How do the large scale atmospheric features on Titan(superrotation, polar vortex) evolve?<br>• Q3.2: What is the meteorology (temperature, surface winds, pressure, methane humidity precipitation, heat flux) in the northern polar region of Titan?<br>• Q3.6: What is the complete distribution, physical and dynamic properties of lakes and river networks on Titan and their temporal variability across different latitudes?<br>• Q3.8: What are the local physical and dynamical properties of Kraken Mare as a proxy for Titan's lakes and seas? |

# Q3.8: What are the local physical and dynamical properties of Kraken Mare as a proxy for Titan's lakes and seas?



Credit: NASA / JPL-Caltech / Agenzia Spaziale Italiana / USGS

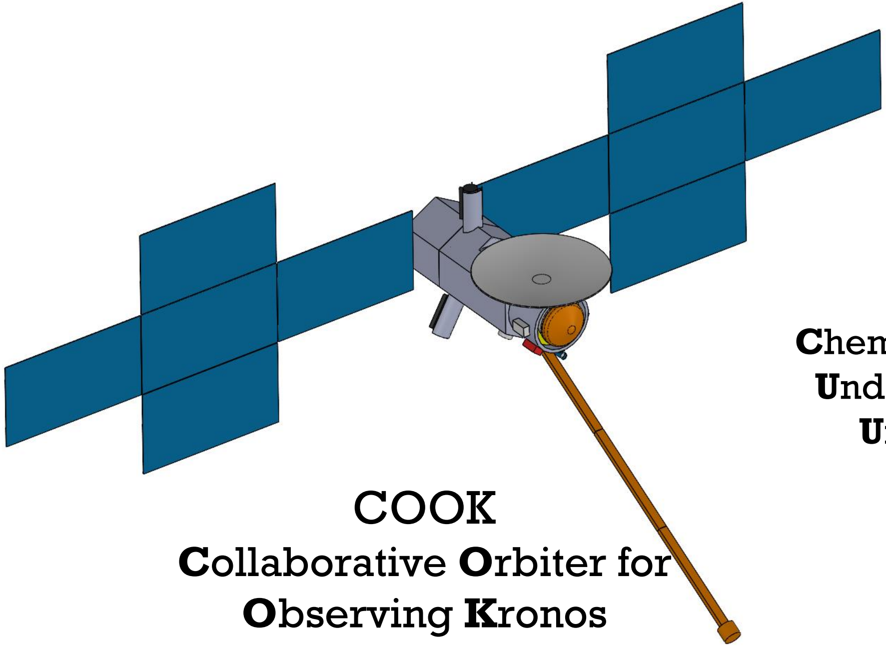

Credit: Americanoceans.org

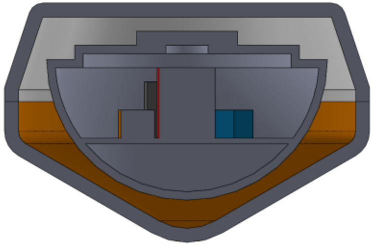
- Measure the sea depth and sound speed

- 1% sensitivity with 1000 to 2000 m/s range
- Depth accuracy of <5m at nominal distances of 10 to 500m from instrument
- Operate at <50 dB/Pa²/Hz

- SONAR
  → Lander COLUMBUS

# SEAFARER

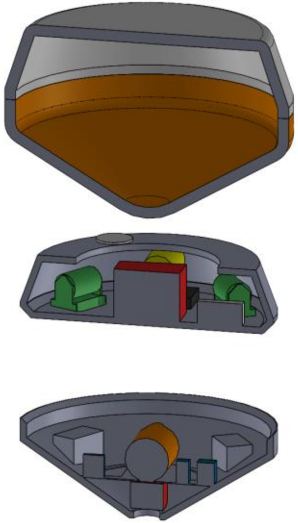




## COLUMBUS

**C**hemical and **O**rganic **L**ander for
**U**nderstanding **M**ethane-**B**ased
**U**nderwater Environment**S**

*Lander*



## COOK

**C**ollaborative **O**rbiter for
**O**bserving **K**ronos

*Orbiter*

## VESPUCCI

**V**ertical **E**ntry probe for **S**aturn's
**U**pper **C**loud **C**hemistry and
habitability **I**nvestigation

*Probe*

# COOK Orbiter Instruments

| Science Objective | Science Question | UV-Spectro-meter | Infrared Spectro-meter | Mass Spectro-meter | Camera | Magneto-meter | Radar | Sub-mm Wave Instrument | Dust Analyzer | Gravity Science Experiment |
|---|---|---|---|---|---|---|---|---|---|---|
| Formation and Composition of Saturn | Q1.1 Atmospheric Composition | | X | | | | | X | | |
| | Q1.2 Atmospheric Dynamics and Properties | X | X | | X | | | X | | |
| Nature and Diversity of Potential Habitats | Q2.2 Enceladus Surface | | X | | X | | X | X | | |
| | Q2.3 Enceladus Plumes | | X | X | X | X | | X | X | |
| | Q2.5 Mimas Subsurface Ocean | | X | | X | | X | | | |
| | Q2.7 Titan Interior-Surface Processes | | X | | | | X | | | X |
| | Q2.9 Titan Organic Chemistry | | X | X | | | X | | | |
| Titan's Climate | Q3.1 Large-scale Atmospheric Features | X | X | | X | X | | X | | |
| | Q3.5 Meteorology Polar Regions | | X | | X | | | X | | |
| | Q3.6 Lake and River Networks | | X | | | | X | | | |

# VESPUCCI Probe Instruments



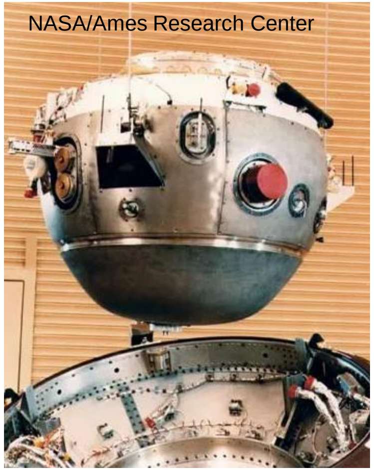
| Science Objective | Science Question | Temperature Sensor | Pressure Sensor | Mass Spectro-meter | Nephelo-meter | Accelero-meters | Net Flux Radio-meter | Lightning and Radio Emissions Detector | Laser Spectro-meter |
|---|---|---|---|---|---|---|---|---|---|
| Formation and Composition of Saturn | Q1.1 Atmospheric Composition | | | X | | X | | | X |
| | Q1.2 Atmospheric Dynamics and Properties | X | X | | X | X | X | X | |

# COLUMBUS Lander Instruments

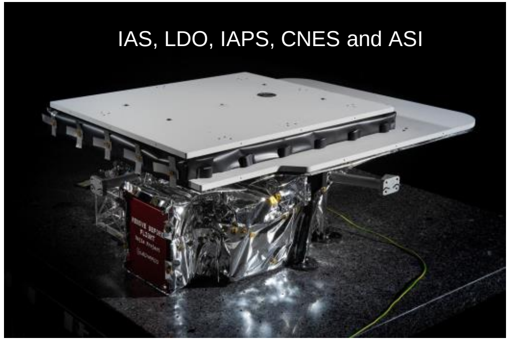


| | | Upper Buoy | | | | | Lower Buoy | | |
|---|---|---|---|---|---|---|---|---|---|
| **Science Objective** | **Science Question** | **Sonar** | **Nephelo meter** | **Camera** | **GC-Mass Spectro-meter** | **Atmopsheric Structure Instrument** | **Thermo-meter** | **Dielectric Sensor** | **Pressure Sensor** |
| **Nature and Diversity of Potential Habitats** | **Q2.9 Titan Organic Chemistry** | | X | X | X | | | | |
| **Titan's Climate** | **Q3.5 Meteorology Polar Regions** | | X | X | X | X | | | |
| | **Q3.8 Properties of Kraken Mare** | X | | X | X | | X | X | X |

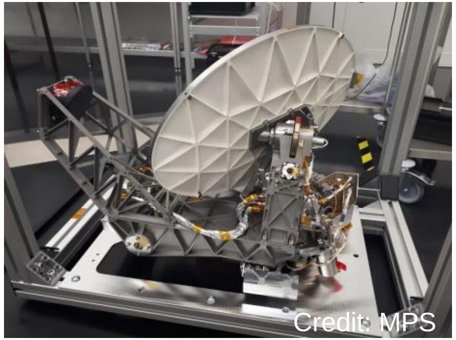
# Instrument Heritage




Galileo Atmospheric Probe

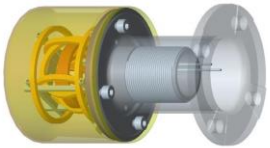



MAJIS (JUICE)




SWI (JUICE)


JANUS (JUICE)




J-MAG (JUICE)

Science case → **Mission Analysis** → Engineering → Programmatics

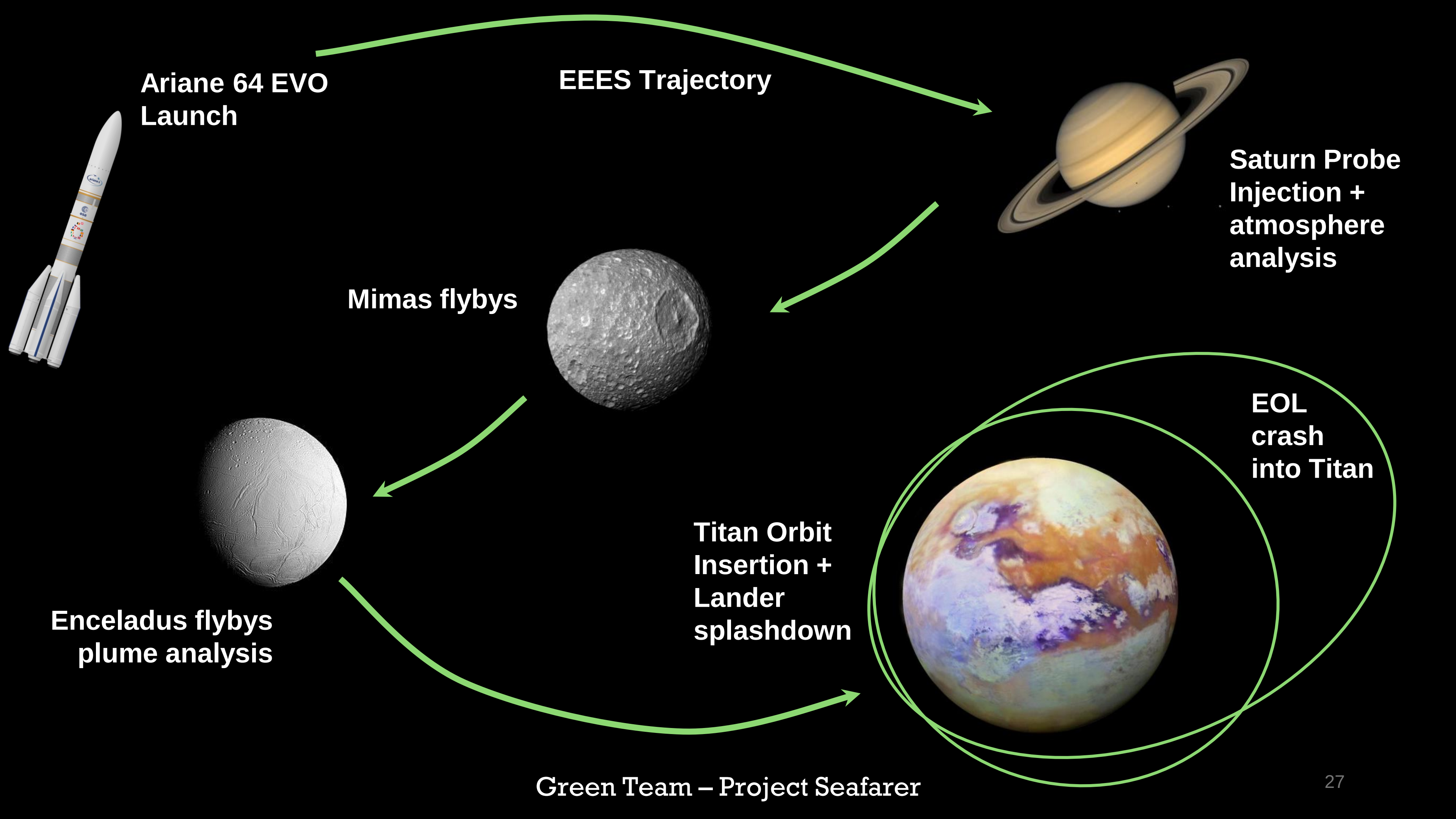
Julia Wiltenburg

Vincent Affatato

David Placke

Colm Daly

Green Team – Mission SEAFARER

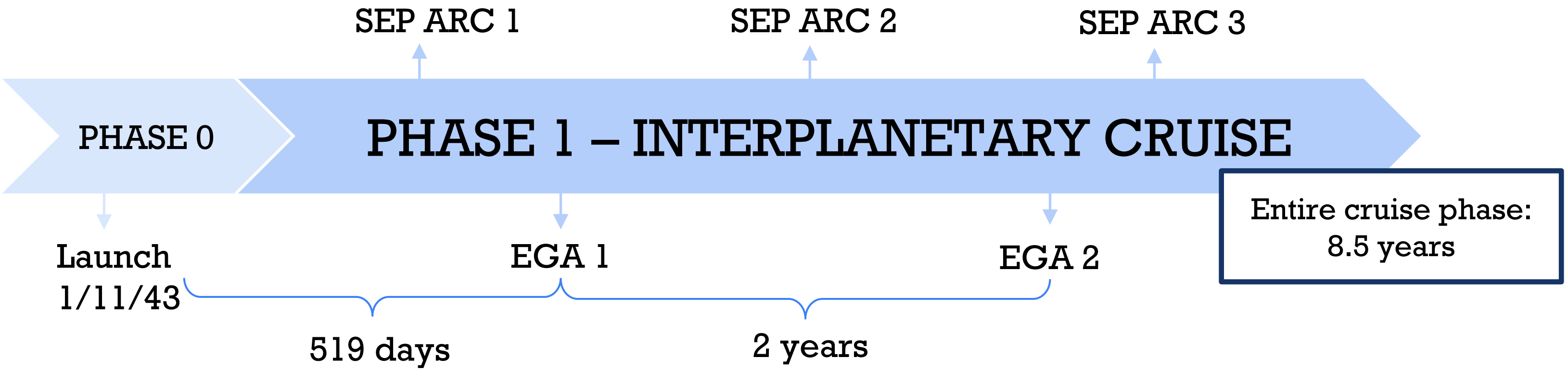

Ariane 64 EVO
Launch
EEES Trajectory
Saturn Probe
Injection +
atmosphere
analysis
Mimas flybys
Enceladus flybys
plume analysis
Titan Orbit
Insertion +
Lander
splashdown
EOL
crash
into Titan
Green Team – Project Seafarer
27

# Phase 1 – Interplanetary Cruise

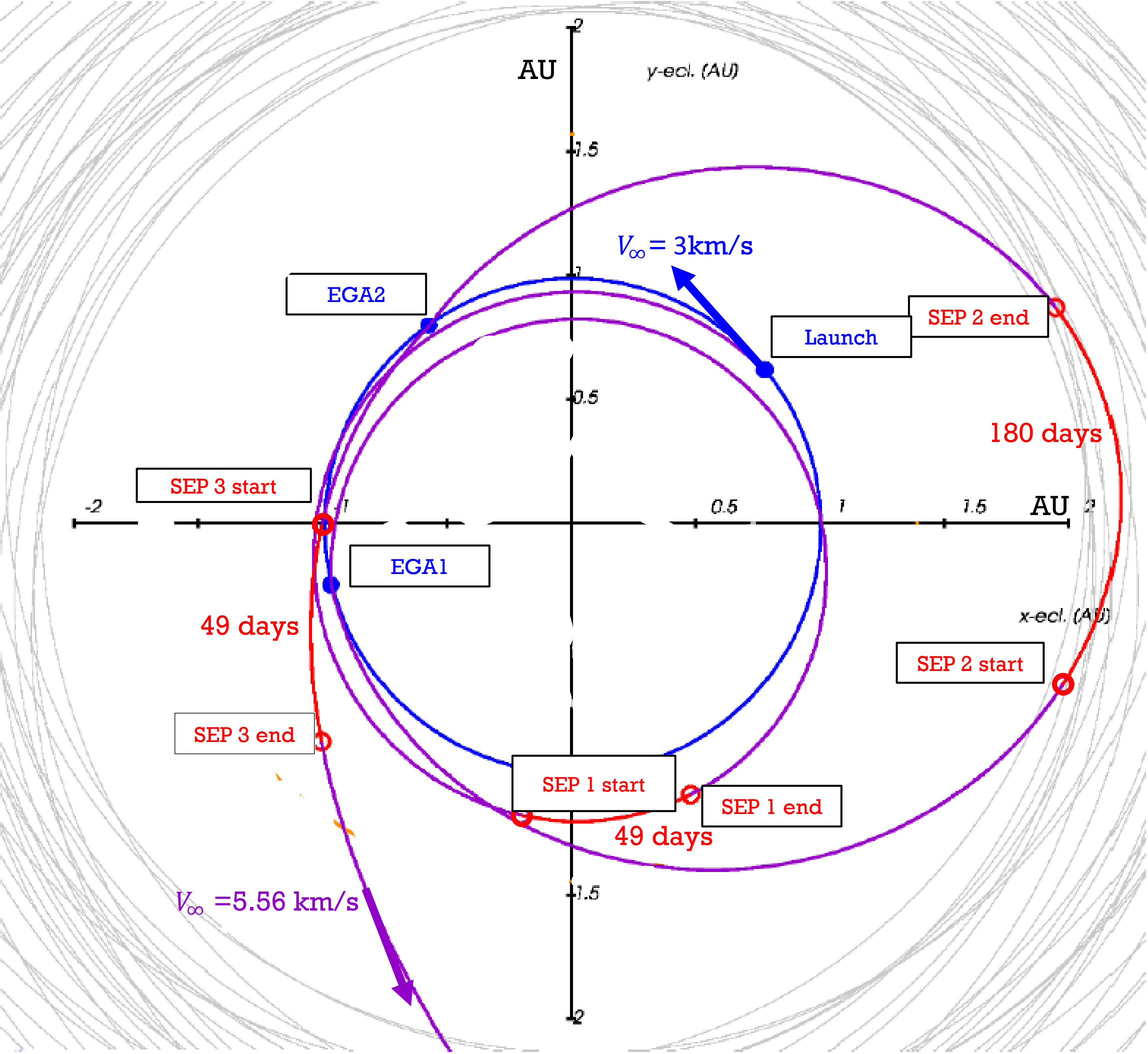
**Interplanetary Cruise**

- Proved by CDF studies
- Launch with an ARIANE 64 EVO

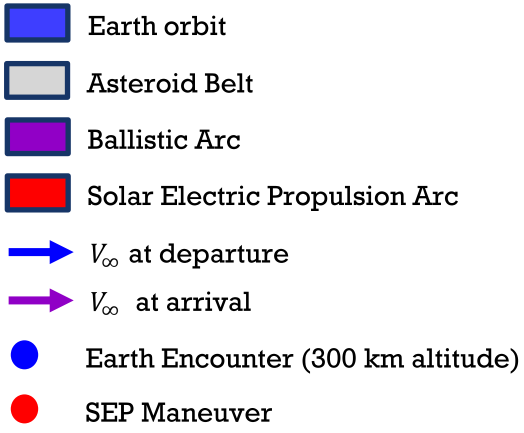
- Solar electronic propulsion (SEP)
- Launch window of ~21 days, with limited to no variations of $V_\infty$, and launch opportunities every 12.5 months




SEP: Solar Electric Propulsion
EGA: Earth Gravity Assist
CDF: Concurrent Design Facility




# Trajectory



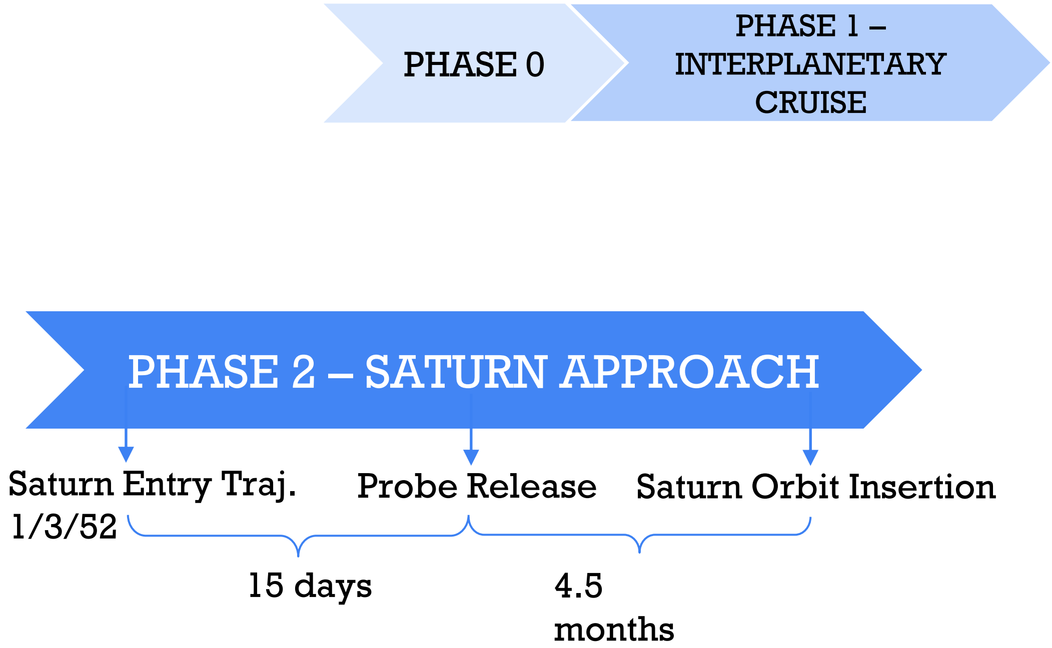

| Manoeuver | Duration | Max. Sun distance |
|---|---|---|
| SEP ARC 1 | 49 days | <1.2 AU |
| SEP ARC 2 | 180 days | <2.2 AU |
| SEP ARC 3 | 49 days | <1.2 AU |

Adapted by Rocchi and Khan, SOLAR ELECTRIC PROPULSION BOOSTED TRANSFERS TO THE OUTER SOLAR SYSTEM, 2023

# Phase 2 – Saturn Approach

**Action Sequence**

- Jettison of the SEP → Switch to RTGs
- Entry Trajectory to Saturn with a 55° inclination
- Probe Release 5 months before perikrone
- SOI in a safe orbit with perikrone at 2000 km altitude from 1-bar level




SEP: Solar Electric Propulsion
SOI: Saturn Orbit Insertion

# Phase 2 – Saturn Approach

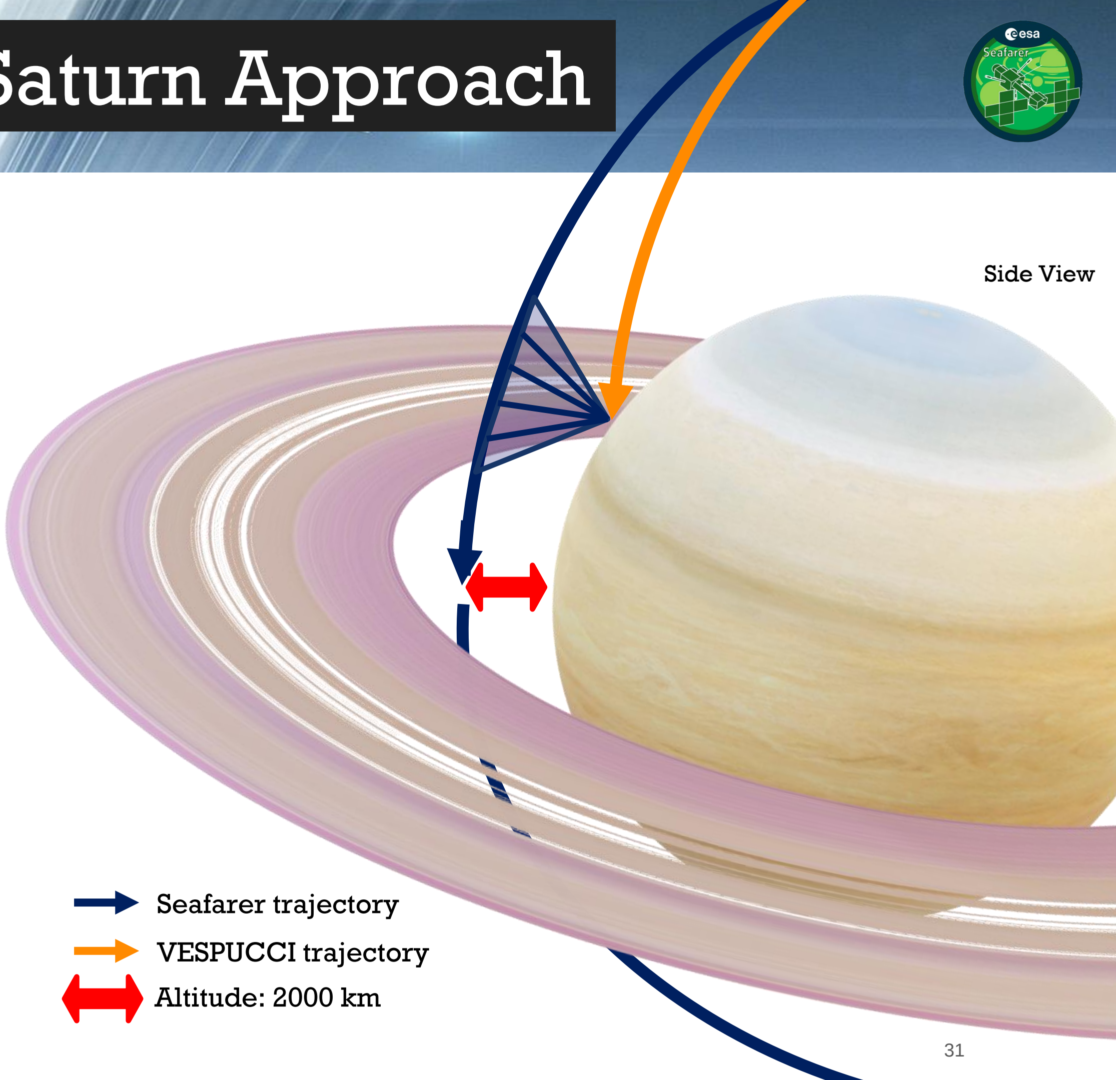
**Key Aspects**

- The SOI shall also:

1) reduce the velocity of the spacecraft
2) increase the altitude

→ wait for the entry of the probe into the atmosphere and maximise the communication window

- The early close approach has been proved safe by Cassini but still needs particular attention for communication overload

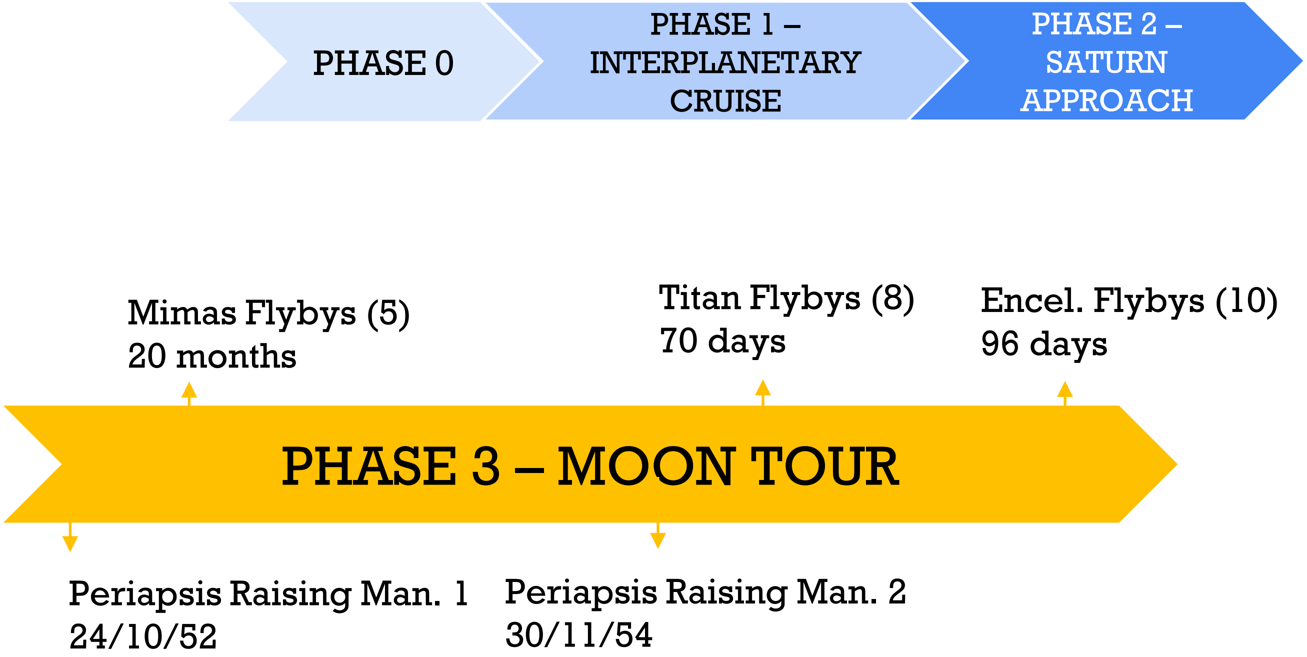



SOI: Saturn Orbit Insertion

# Phase 3 – Moon Tour

**Action Sequence**

- PRM at the apoapsis of the first Saturn orbit to enlarge the periapsis at Mimas
- Flybys to Mimas at different altitudes
- Inject in 7:1 resonance flyby sequence of Enceladus using Titan swingbys for the second PRM




PRM: Periapsis Raising Maneuver

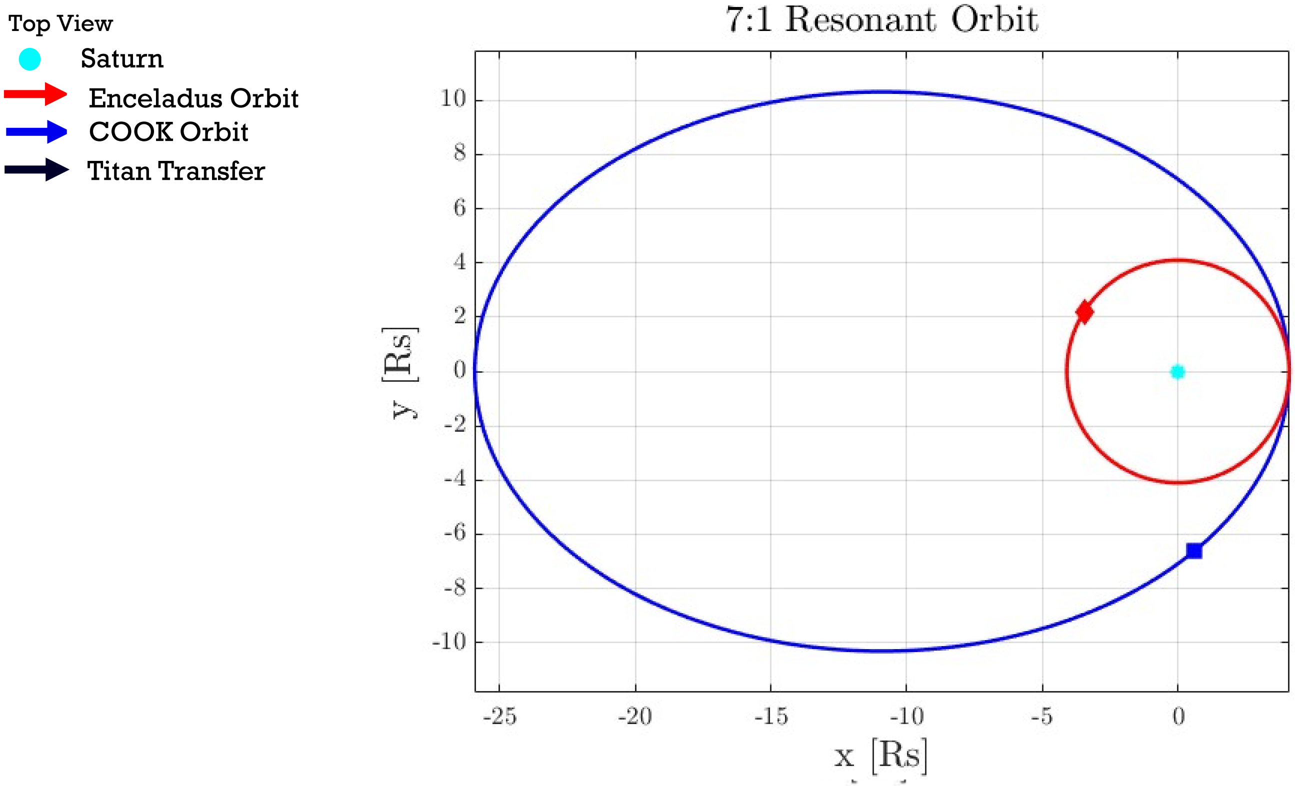
# Phase 3 – Moon Tour

**Key Aspects**

- Mimas flybys require 4 months each due to the high initial $V_\infty$ from the cruise

- Possible visit to other medium-size moons is based on opportunity windows

- Reduction of the inclination wrt equatorial plane to <20°

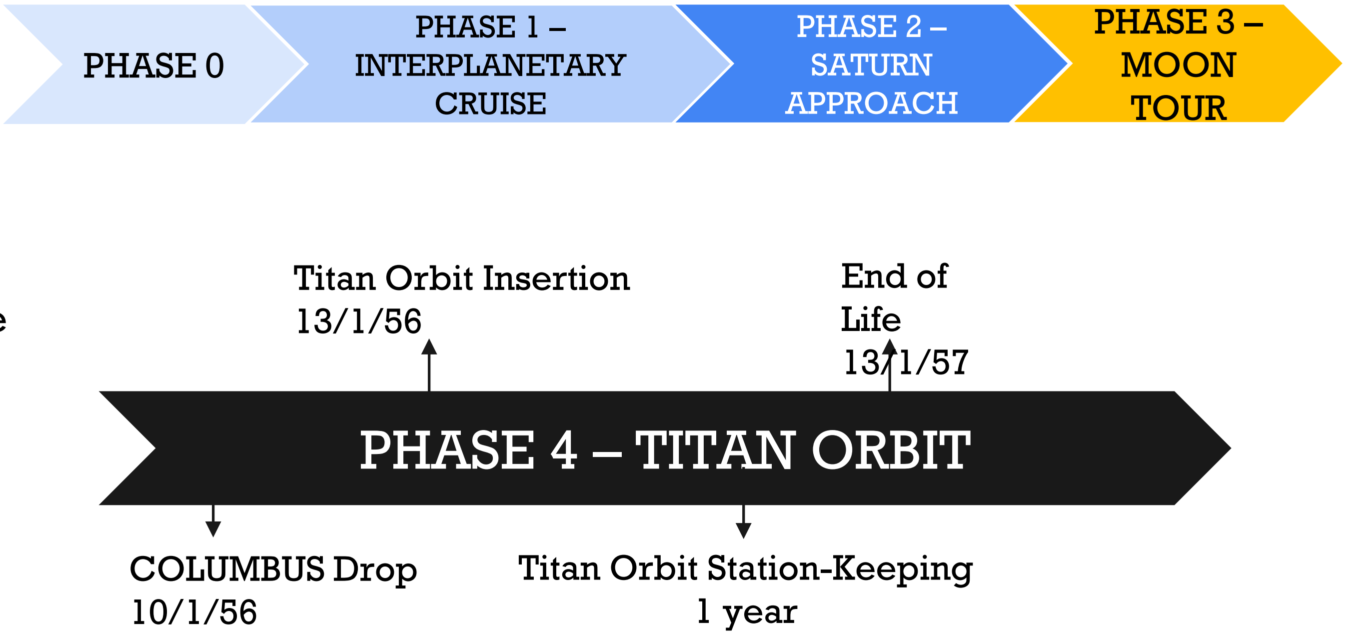



PRM: Periapsis Raising Maneuver

# Phase 4 – Orbiting Titan

**Action Sequence**

- Entry trajectory to Titan to release the lander
- TOI into a safe, circular orbit at 2500 km altitude
- One-year-long station-keeping with the possibility of mission extension
- Disposal on Titan caused by Saturn perturbations




TOI: Titan Orbit Insertion

# Phase 4 – Orbiting Titan

**Lander Key Aspects**

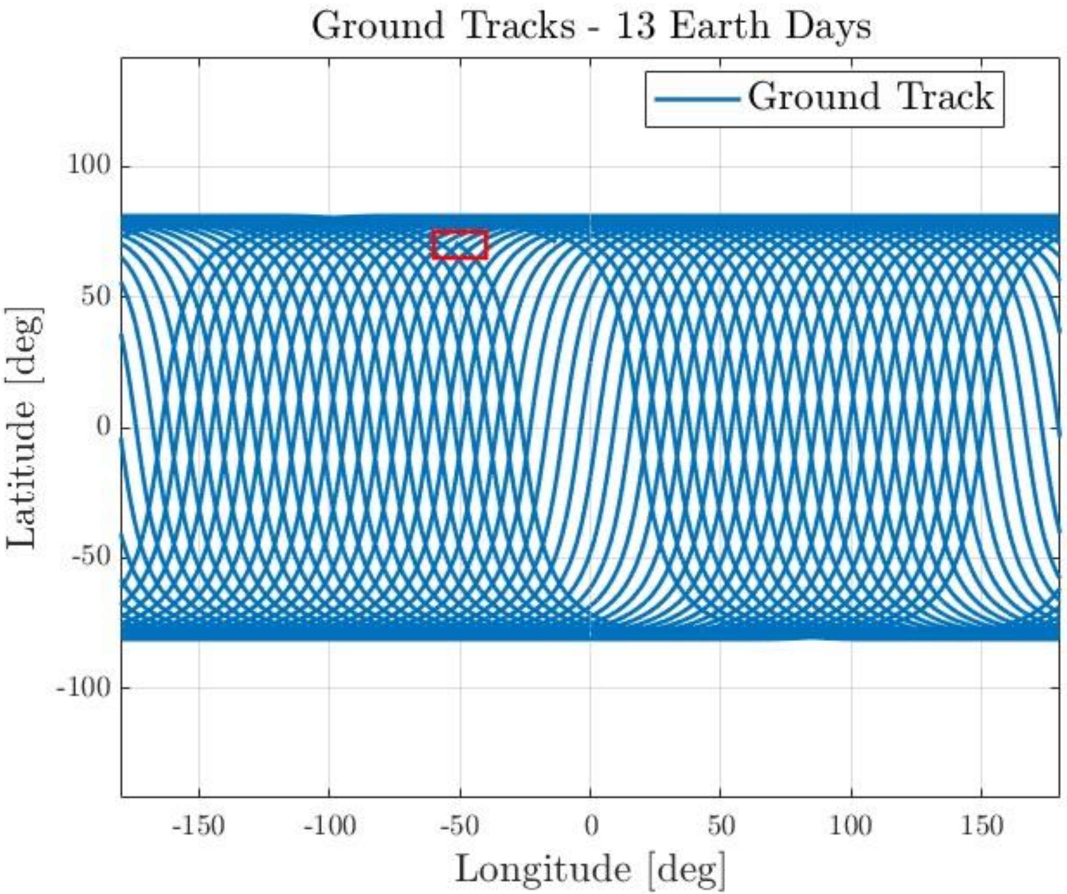
- Lander drop ~3 days before orbit insertion

- Landing site constraints:

1) Cassini mapped three large lakes within 70° and 78° N latitude
2) DeltaV budget and mitigation of perturbations

- Final Choice: Kraken Mare (70° N, 50°E)

- The orbit provides coverage to the lander for operative life



# ΔV budget and dimensioning

| PHASE | ΔV [km/s] (5% margin) | Propellant Mass [kg] | Propellant Mass [kg] 10% margin |
|---|---|---|---|
| 1 – Interpl. Cruise | 3,11 | 520 | 572 |
| 2 – Saturn Approach | 0,72 | 1107 | 1218 |
| 3 – Moons Tour | 0,45 | 676 | 744 |
| 4 – Titan Orbit | 0,81 | 986 | 1084 |
| AOCS allocation | 0,1 | 198 | 218 |
| TOTAL | 5,1 | 3489 | 3838 |

**Dimensioning constraints**

- **ΔV for SEP cruise** → Solar panel size 110m$^2$
- **ΔV for Saturn Tour** → Total bipropellant mass
  → Iteration on maximum initial spacecraft mass: 7.5t

| Propellant System | Isp [s] |
|---|---|
| Xenon propellant | 4400 |
| MMH+$N_2O_4$ | 321 |

Science Case → Mission Analysis → **Engineering** → Programmatics

Julia Wiltenburg | Vincent Affatato | David Placke | Colm Daly

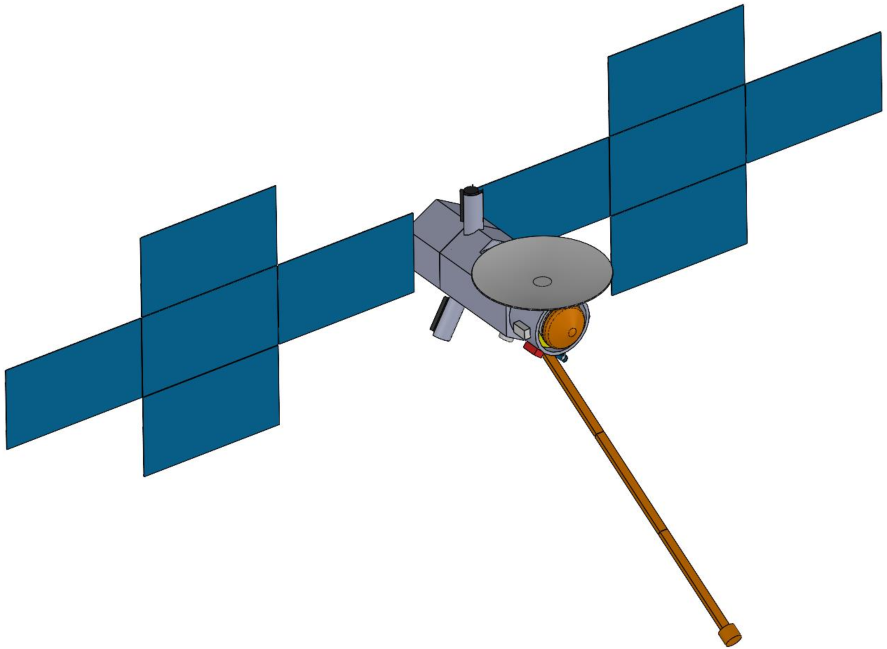
Green Team – Mission SEAFARER

# Systems

# Mission Design

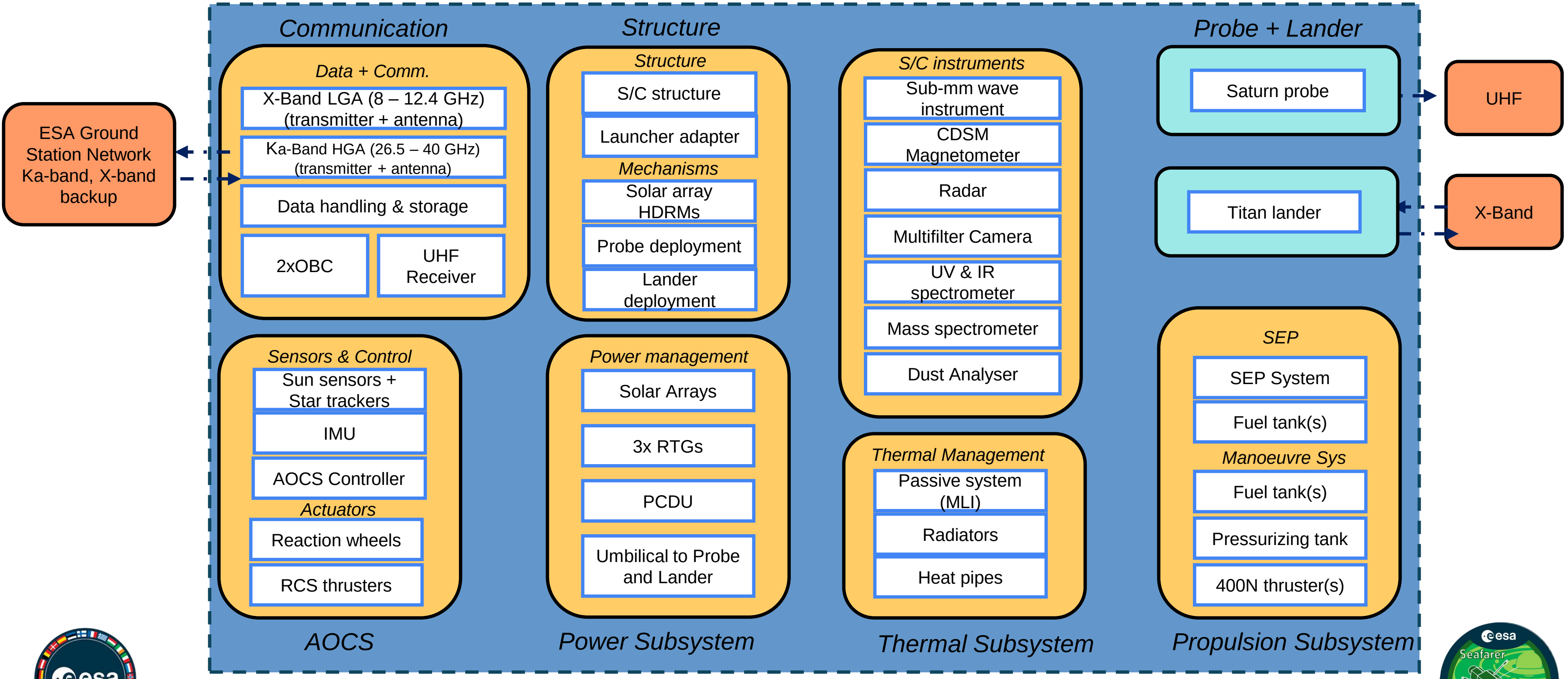
## Key features:

- 6,9 m height
- 10 m long magnetometer boom
- 3 GPHS-RTGs
- 110 m² SEP Solar Arrays
- 4 m stiff gimbaled High Gain Antenna (HGA)
- Gimballed low gain antenna (LGA)



# Orbiter System Architecture






S/C system

# Orbiter Mass Budget



| Subsystem total | Mass (kg) | Mass fraction to M_dry |
|---|---|---|
| Communication | 216 | 7,9% |
| SC Instruments | 297 | 10,8% |
| Titan lander | 298 | 10,9% |
| Saturn probe | 269 | 9,8% |
| AOCS | 97 | 3,5% |
| Power | 216 | 7,9% |
| Thermal | 63 | 2,3% |
| Solarelectric prop. | 394 | 14,4% |
| Chemical prop. | 210 | 7,7% |
| Structure | 679 | 24,8% |

| Subsystem | Mass (kg) |
|---|---|
| Dry mass total | 2739 |
| Dry mass with 30% margin | 3698 |
| SEP propellant | 573 |
| Chemical propellant | 3265 |
| **Total wet mass at launch** | **7538** |
| Dry mass after array jettison | 2849 |
| Dry Mass after Probe Ejection | 2519 |
| Dry Mass after Titan Splasher Ejection | 2220 |

All components tagged with margins depending on maturity (5%, 10%, 20%)

# Orbiter Mission Modes



| Phase/Mode | Mode description |
|---|---|
| **LEOP** | Commissioning of the spacecraft, communication with Earth using X-band. |
| **Safe mode** | Spacecraft kept in safe state, pointing to Earth for comms. |
| **Recovery/Reboot mode** | Recovery from safe mode. |
| **SEP cruise** | SEP cruising using Solar arrays and SEP fuel |
| **Cruise** | Cruising following SEP |
| **Probe Internal Checkhout** | Biannual check of probe and lander instruments during cruise |
| **Standby** | Instruments powered ON at low power. |
| **Science mode** | Instruments powered ON at full power, data recorded to onboard storage |
| **Manoeuvre** | Trajectory changes using chemical propulsion |
| **Earth Comms** | Communication with Earth using Ka-band (or backup X-band) |
| **Science Comms** | Communication with probe/lander using UHF and X-band respectively |

# Orbiter Power Budget

| Power Budget | LEOP | Safe mode | Reboot | SEP cruise | Chem. cruise | PIC mode | Standby | Science | Man. | Earth comm. | Science comm. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Communication | | | | | | | | | | 289 | 268 |
| SC Instruments | | | | | | | | 372 | | | |
| AOCS | | | | | | | | 82 | | 64 | 64 |
| Thermal | | | | | | | | | | | |
| Solar Electric Propulsion | | | | | | | | | | | |
| Chemical Propulsion | | | | | | | | | | | |
| Structure | | | | | | | | | | | |

Driving modes:

Science ~ 454W

Earth comms w/ Ka-band HGA ~353W

Science comms w/ probe and lander. Most power when using X-band MGA ~332W

Margins taken into account, according to ESA ECSS margin standards

| Low | Med. | High |
|---|---|---|

# Link Budget

| Orbiter-Earth Budget | | Orbiter-Payloads Budget | |
|---|---|---|---|
| Frequency (Ka-Band) [GHz] | 32 | Frequency (X-Band) [GHz] | 8.5 |
| Maximum range [AU] | 10.5 | Maximum range [km] | ~ 3000 |
| Orbiter Transmitter Power [W] | 40 | Lander Transmitter Power [W] | 15 |
| Data rate [kbps] | 0 | Data rate [kbps] | 40 |
| **Final $E_B/E_N$ [dB]** | **3.6** | **Final $E_B/E_N$ [dB]** | **5.7** |

- **ESA DSN Network**: 35m dishes at Cebreros, New Norcia, and Malargue
- Saturn moon tour: single 4-hour DSN pass per day
- Titan orbit: expect 5h to 8h DSN pass per day → data downlink every 4 orbits.
- Min. datarate: 40 kbps (total between: 720 Mb/day and 1.15 Gb/day)

# Orbiter Design

# Orbiter Design

**STR-1** : Launch with Ariane 64 EVO.
**COM-1** : Shall sustain Telemetry, Science downlink, and relay links.

| **Structure** | |
|---|---|
| Structure material | Composite, Aluminium |
| # articulated structures | 1 HGA, 2 Solar Arrays |
| # deployed structures | 2 solar arrays, 3 RTGs, 1 magnetometer boom, 1 radar antenna, Lander deployment mechanism, Probe deployment mechanism |
| **Communications** | |
| Antennas and gain | 4m stiff gimballed HGA for Ka-band, 61dBi<br>16cm Horn MGA X-band , 22.6 dBi<br>25cm UHF Antenna |
| Data rates | 50/40 kbps to Earth (40 W transmitter power)<br>40 kbps relay link (lander)<br>1000 bps relay link (probe) |

**Challenges:**

Stow orbiter + SAs + SEP system + probe + lander + adapters in Ariane 64 EVO fairing.

Keeping sufficient data rate between Earth and Orbiter (to manage on-board science and relay links)

- When close to Earth (8.5AU) - expect rate 50 kbps
- When at maximum distance (10.5AU) - can only sustain rate of 40 kbps.

Inspiration: Mars Reconnaissance Orbiter, PEP probes, SPRITE, TSSM, EPIG

# Orbiter Design

**POW-1 :** Shall sustain the S/C during the SEP and nominal mission lifetime.
**POW-2** : Shall provide power and charge the batteries of the probe and lander prior to release.
**TC-1** : Maintain temperature of instruments between ~250 K and 280 K.
**TC-2** : Maintain temperature of batteries between 278 K and 298 K.

| **SEP Power** | |
|---|---|
| Solar array type and size, m2 | Ga-As, 110 |
| Expected power generation, W/m2 | 375,75 (BOL) and 77,63 (EOL) |
| Expected power consumption, W | 7500 |
| **Science Power** | |
| Power Source | 3 GPHS-RTGs (New Horizon, Cassini) |
| Battery type | LiSO2 to stabilise RTG power |
| Driving power mode, W | Science ~500W & Telecoms ~400W |
| **Thermal Control** | |
| Type of thermal control | MLI, Heat Pipes and RHUs |
| Heat output of RTGs, K | 3 x 3850 |

## Trade-off:

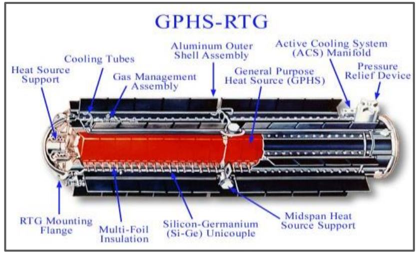
Solar Arrays vs Nuclear power vs RTGs (higher TRL & less moving parts)

## Challenges:

Selection of duty cycles for Power Modes

GPHS-RTG heat dissipation with fins with a fin root temperature of approx. 200°C. Astroquartz insulation.

How to manage RTG booms and heat? Especially with temperature sensitive Instruments?



# Orbiter Design



**AOC-2 :** Shall orient orbiter to ensure at least 13 min of Orbiter-Lander communication (after handshake).
**AOC-3 :** Shall maintain ponting loss to less than 0.11 deg (same as Mars Reconnaissance Orbiter).
**OBDH-1**: Shall handle, process, and store all Scientific data produced during 2 Orbits.

| **Attitude Control** | |
|---|---|
| Control methods | 3-axis (w/ Inertial, Nadir, Solar references) |
| Attitude knowledge limit | Sun sensors (radial accuracy <±0.5 deg), Star trackers (pitch/yaw accuracy within ±18 arcsec), IMUs (bias stability within ±0.015 arcsec/sec) |
| Articulation #axes | 2 axes for HGA |
| Sensor and actuator information | 4 RWs with 25 Nms angular storage, 16 4,5-N RCs thrusters for desaturation of reaction wheels |
| **Command and Data Handling** | |
| Data storage capacity | 3 Gbits (2 days worth of orbiter titan science & lander data) |

**Trade-off:**
Current 100 m/s in delta-V budget to account for pointing requirements.

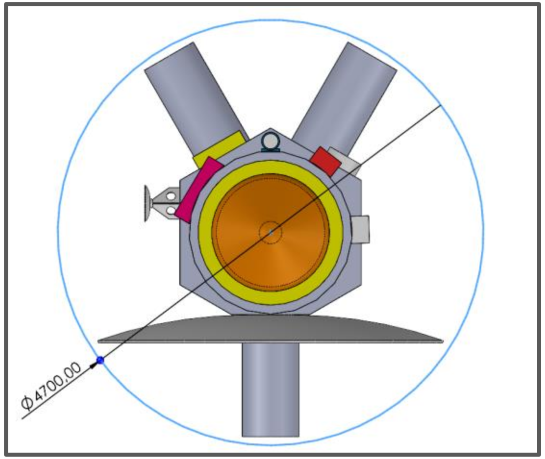
**Issues:**
Challenge in deriving pointing accuracy of instruments.
Pointing requirement for Earth & Science Comms (w/ Lander).
Prior to probe release, CoM expected to be unbalanced - increasing delta-V for manoeuvers and AOCS pointing.

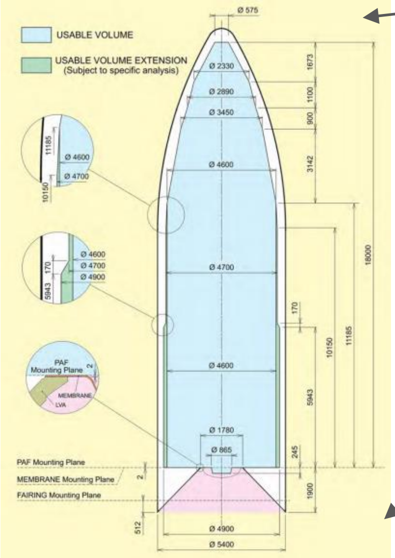
Heritage/Inspiration: MRO, Enceladus Orbiter, TSSM

# Launcher - Ariane 6.4 Evo



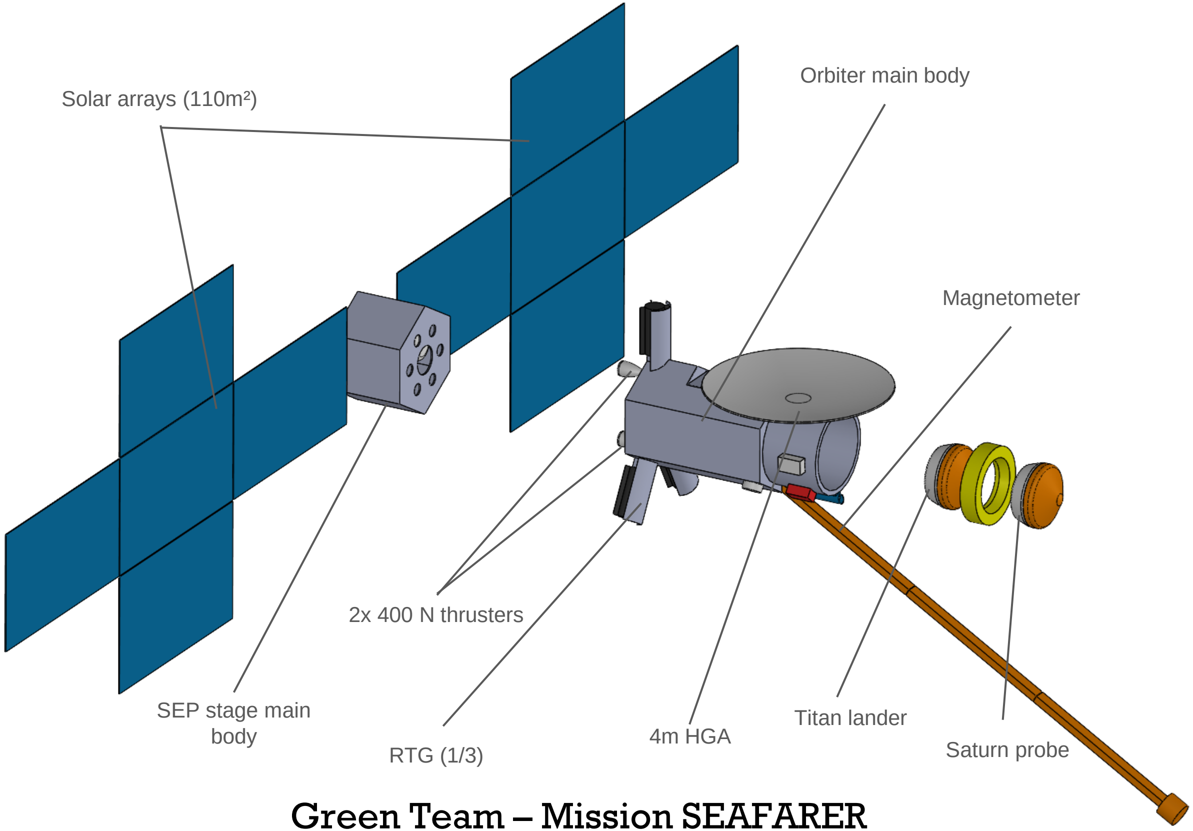
| | |
|---|---|
| Fairing Diameter (Internal) | 4.7 m |
| Fairing Height (Internal) | 18 m |



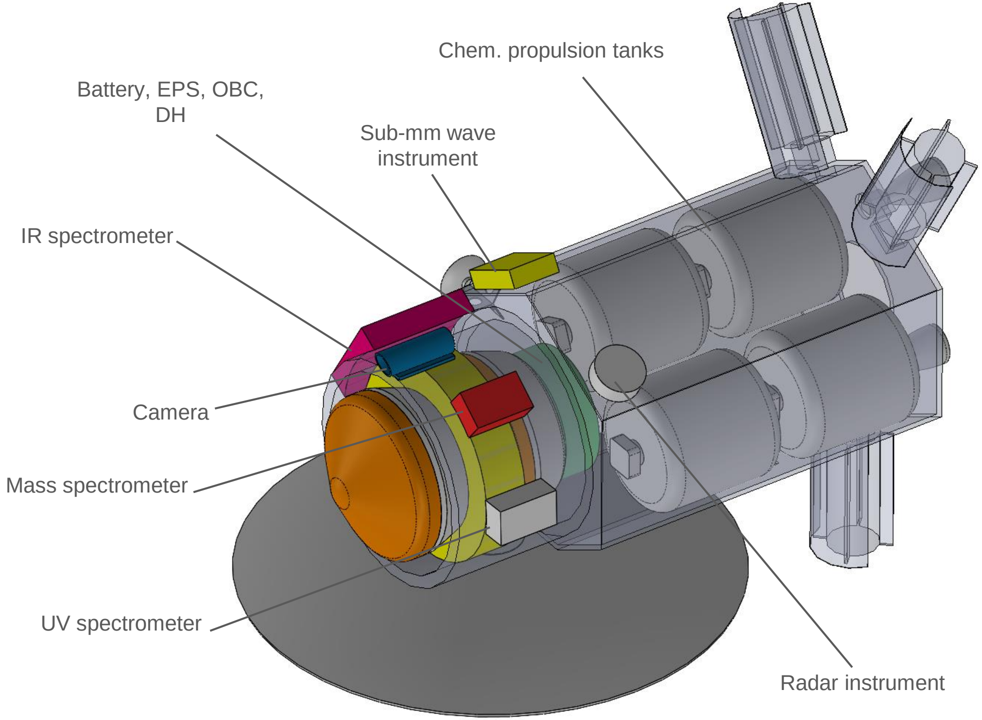

# Orbiter model

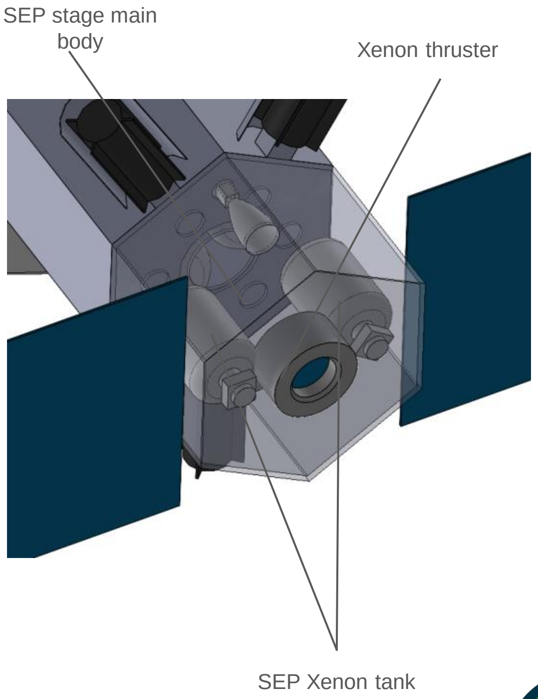




# Orbiter model

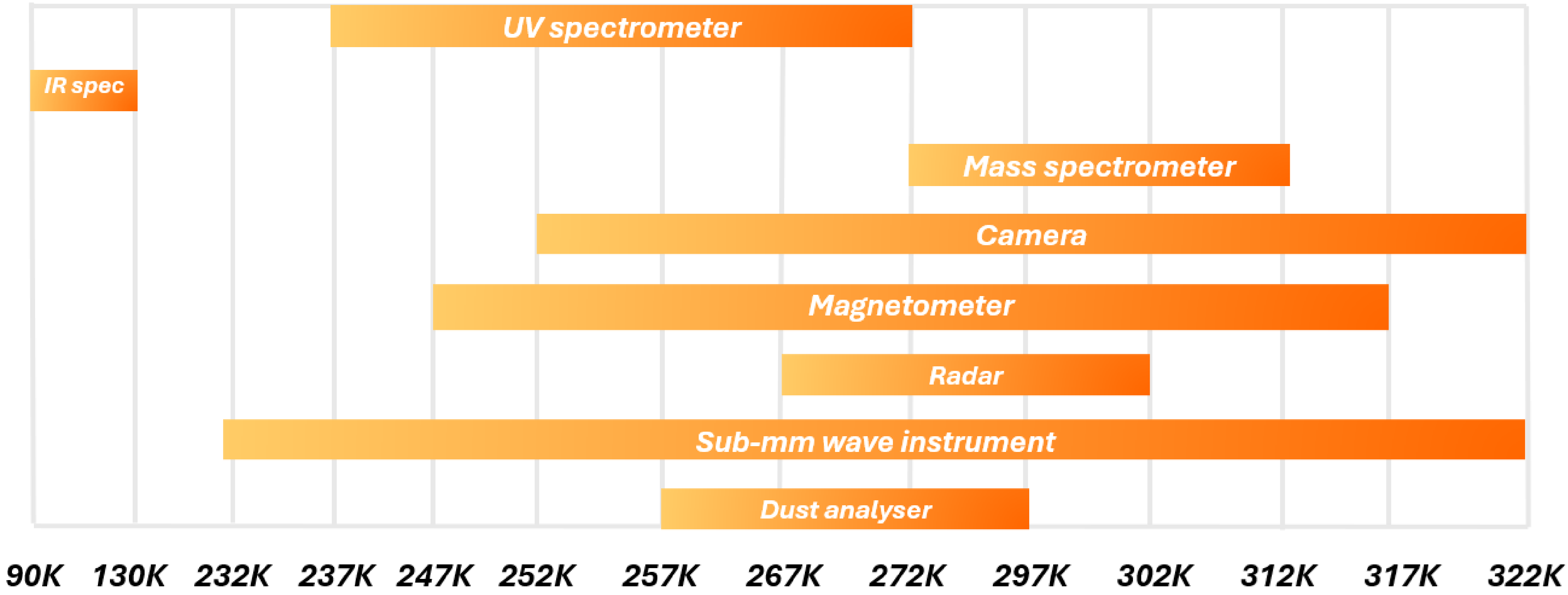




# Orbiter Thermal Envelope





# Instrument Priority

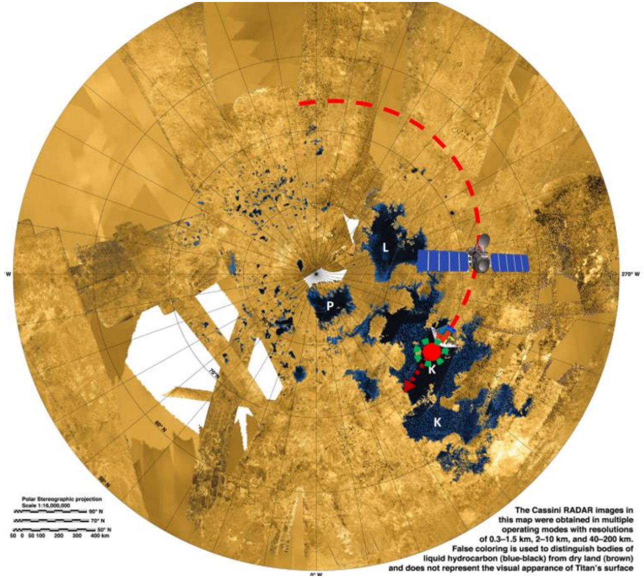
| Instrument | Complexity | Thermal score | Size score | Science score | Total score |
|---|---|---|---|---|---|
| Weight | 2 | 2 | 5 | 10 | 190 |
| UV-spectrometer | 8 | 2 | 7 | 3 | 85 |
| Infrared spectrometer | 7 | 1 | 5 | 10 | 141 |
| Mass spectrometer | 7 | 7 | 5 | 7 | 123 |
| Camera | 8 | 8 | 5 | 9 | 147 |
| Magnetometer | 4 | 8 | 4 | 6 | 104 |
| Radar | 8 | 4 | 3 | 10 | 139 |
| sub-mm wave instrument | 7 | 9 | 7 | 10 | 167 |
| Dust Analyser | 7 | 4 | 7 | 3 | 87 |
| Gravity science experiment | 6 | 8 | 8 | 3 | 98 |
| **Average** | 6 | 5 | 6 | 7 | **128** |

# Lander

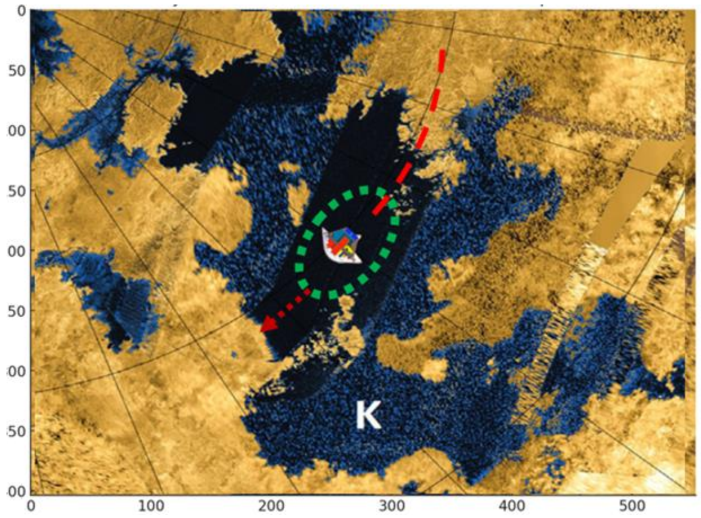
# Lander Mission



**Mission Concept:** Land on Kraken Mare (70 deg inclination) and perform analysis of atmosphere and the liquid methane lake for ~10 days.




Landing location in Kraken Mare confidence: +/- 50 km




Lander has no movement capabilities:
**Maximum possible drift shown above**

# Mission Timeline

## **Aim:** Soft Landing on Liquid Methane Lake Kraken Mare

Lander released from orbiter

Lander enters atmosphere

FS release, Re-entry science, uplink back to orbiter

Commissioning, Stability acquisition, Lander/buoy separation

Drift of lander due to winds & waves


Battery support sized for ~10 days

M~20 M~1.5 v~100m/s

POWER ON and Commissioning

BC release Main parachute deployed

Kraken Mare Landing

Science uplink when orbiter in FOV (~13 min every 6 hrs)

**Key Features:**

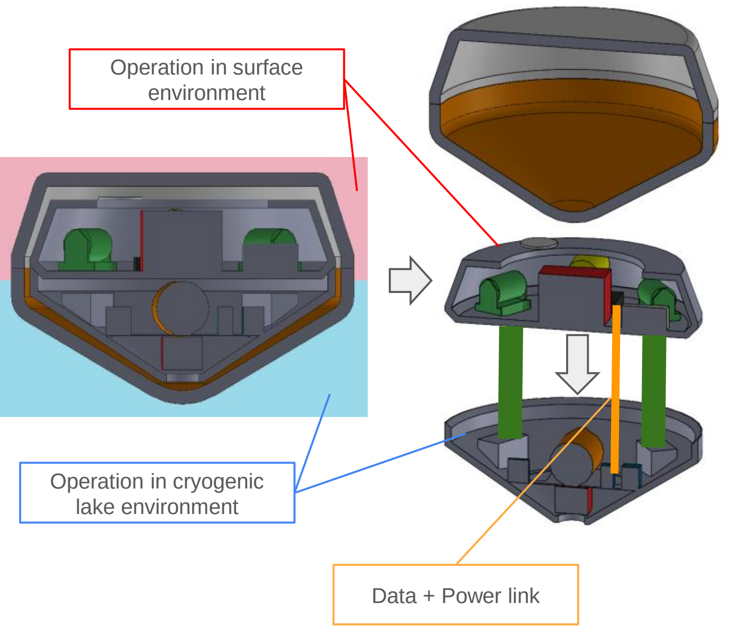
- Huygens-like descent w/ drogues and 8.3 m main parachute
- Data uplink during descent following BC removal
- Once landed on Kraken Mare → Lander separates
    - "Warm" top buoy: batteries, heaters, and atmospheric instruments
    - "Cold" bottom buoy: GCMS and sonar

**Comms:**

- X-band Transceiver
- Helical, omni-directional antenna on lander

# Lander Design

**STR-1:** Shall survive Titan atmospheric re-entry (~18gs, 14,000K) & perform a soft landing on the Kraken Mare.
**STR-2** : shall **stay upright** (waves, wind, drift, landing)
**TH-1**: Shall resist a Titan's atmospheric (91 K) and liquid temperature (91 K), and hydrostatic pressure.
**SCI-1**: Shall drop sample sensor and **collect the data** from it.




| Part | Spec |
|---|---|
| **Mass (kg)** | 297 |
| **Power (W)** | Max 150 |
| **Thermal (K)** | 14000 Heat shield |
| **Data Rate (kbps)** | 40 |
| **Base Diameter (m)** | 1.3 |

**Trade-off:**

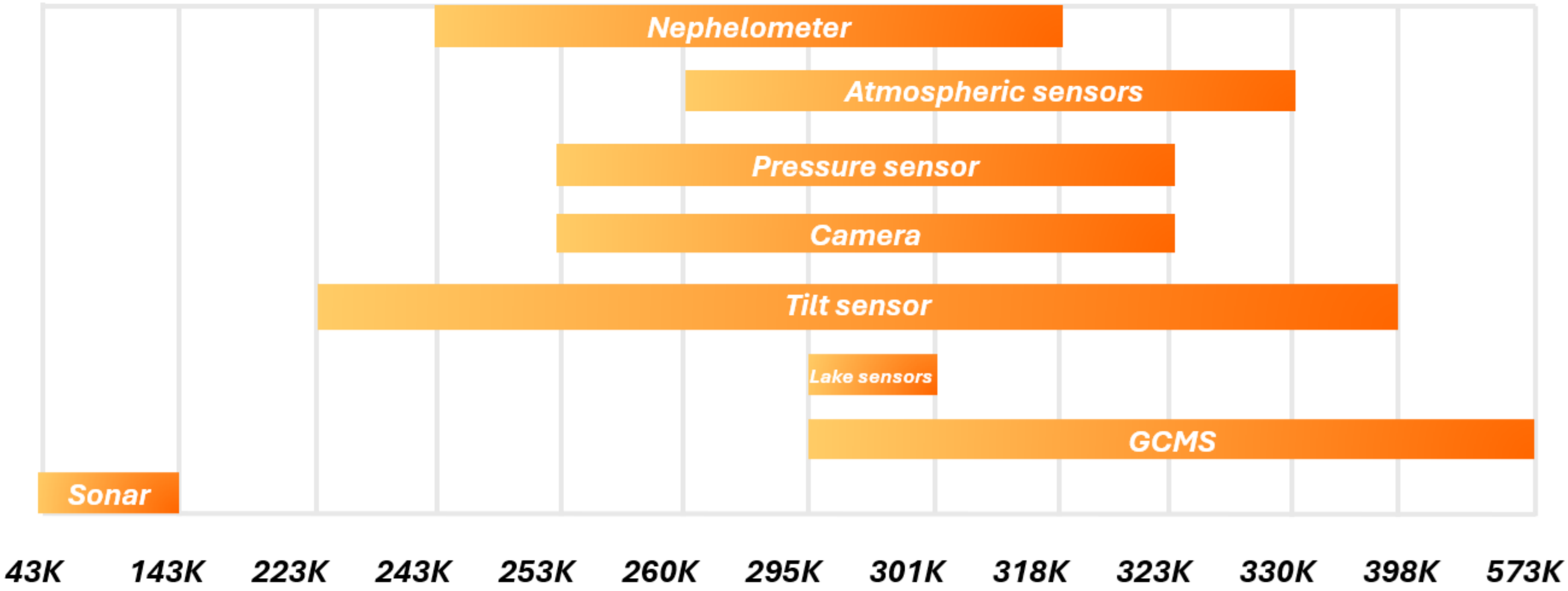
- 5 m maximum deployment depth
- Can not measure the entire temperature profile

**Challenges:**

- **Thermal management**: warm batteries & instruments vs. cold outside.
- Impact of hot lander on environment being measured.
- **Hoist mechanism** for lowering the bottom "cold" buoy.
- Cryogenic temperatures → compliance of material.

# Lander Thermal Envelope





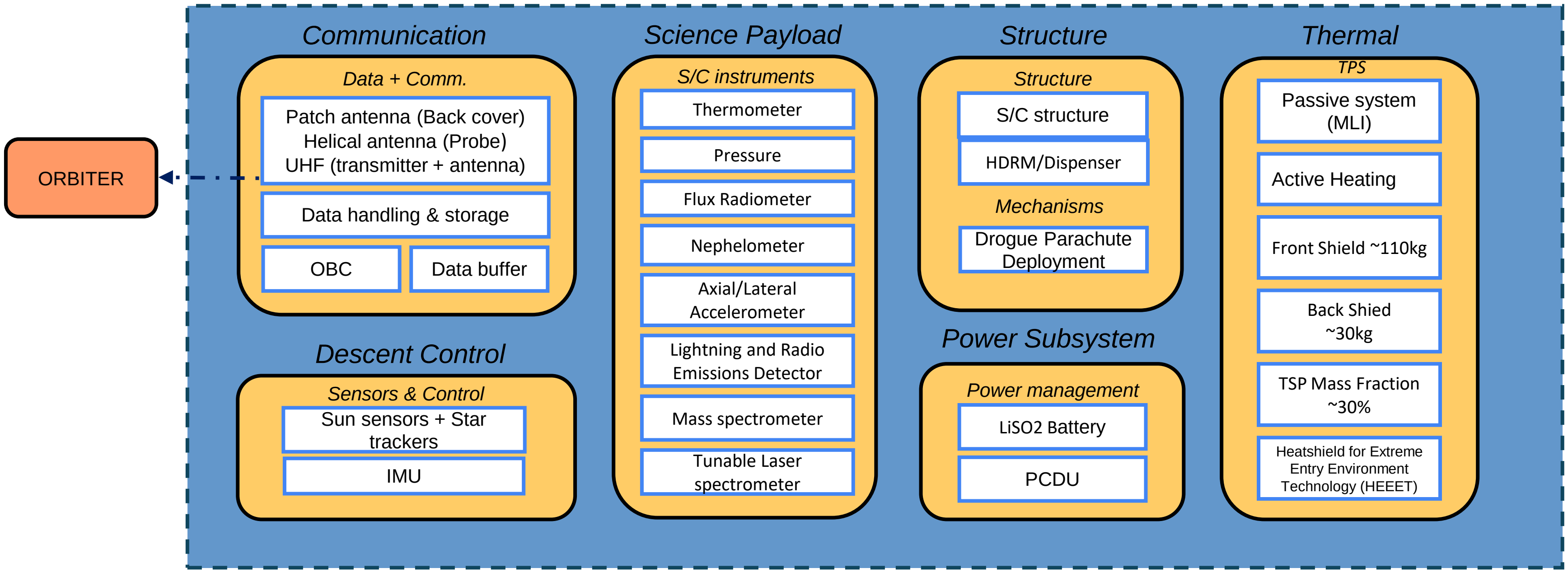
# Lander Science Instrument Priority



| Instrument | **Complexity** | **Thermal score** | **Size score** | **Science score** | **Total score** |
|---|---|---|---|---|---|
| Weight | 2 | 2 | 5 | 10 | 170 |
| **Upper buoy** | | | | | |
| Sonar | 8 | 8 | 9 | 8 | 141 |
| Nephelometer | 6 | 5 | 3 | 9 | 115 |
| Camera | 8 | 2 | 5 | 10 | 129 |
| GCMS | 7 | 6 | 3 | 10 | 127 |
| Atmospheric Structure Instruments | 10 | 4 | 4 | 7 | 98 |
| **Lower buoy** | | | | | |
| Thermometer | 10 | 10 | 10 | 7 | 140 |
| Dielectric constant sensor | 10 | 10 | 10 | 7 | 140 |
| Pressure sensor | 10 | 10 | 10 | 7 | 140 |
| **Average** | 8 | 6 | 7 | 8 | **133** |

# Probe

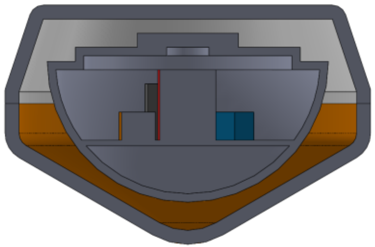
# Probe System Architecture



# Probe Design



**STR-1**: The probe shall reach at a depth where the pressure is of at least **10 bar.**
**POW-1**: Probes power system shall be able to **provide 140 W** throughout the measurement phase.
**OBDH-1**: The probe OBDH shall be able to **handle 32 bps.**
**TH-1** : The probe shall survive a **maximum temperature of 2000 K.**
**TH-2** : The internal temperature shall not exceed the instrumental **temperature range of 253.15 K - 323.15 K.**



| Part | Spec |
|---|---|
| **Mass (kg)** | 270 |
| **Power (W)** | Max 140 |
| **Thermal (k)** | 14,000 |
| **Parachute Diameter (m)** | 2.5 |
| **Base Diameter (m)** | 1.3 |

## Challenge:

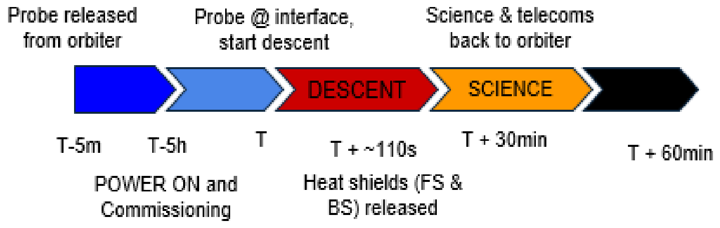
Thermal shielding as probe descends through Saturn's cloud

Communication window with S/C

Heritage/Inspiration: PEP probes & Galileo

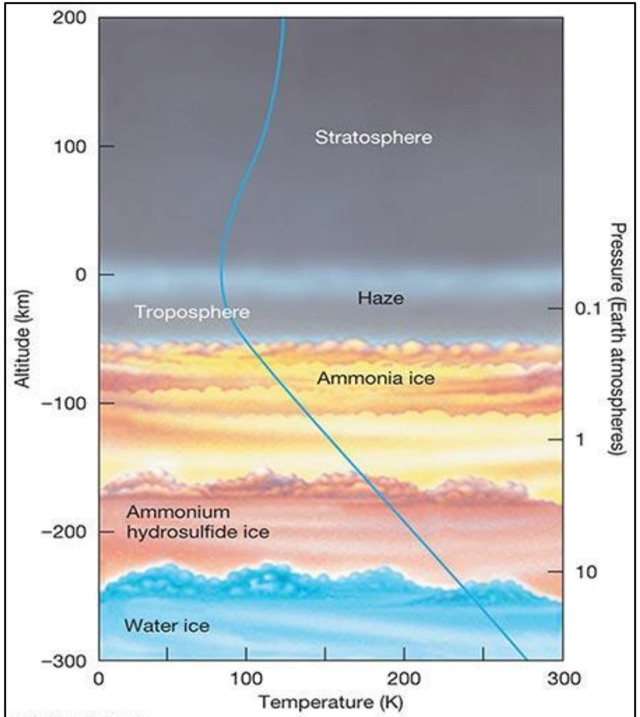
## Components:

**Descent:** 2 parachutes with main parachute D=2.5 m
**Communication:** UHF transceiver to orbiter, 0.5 m patch antenna on back cover and helix antenna during descent.
**Thermal:** expected at entry: 2000 K



# Probe - Instruments



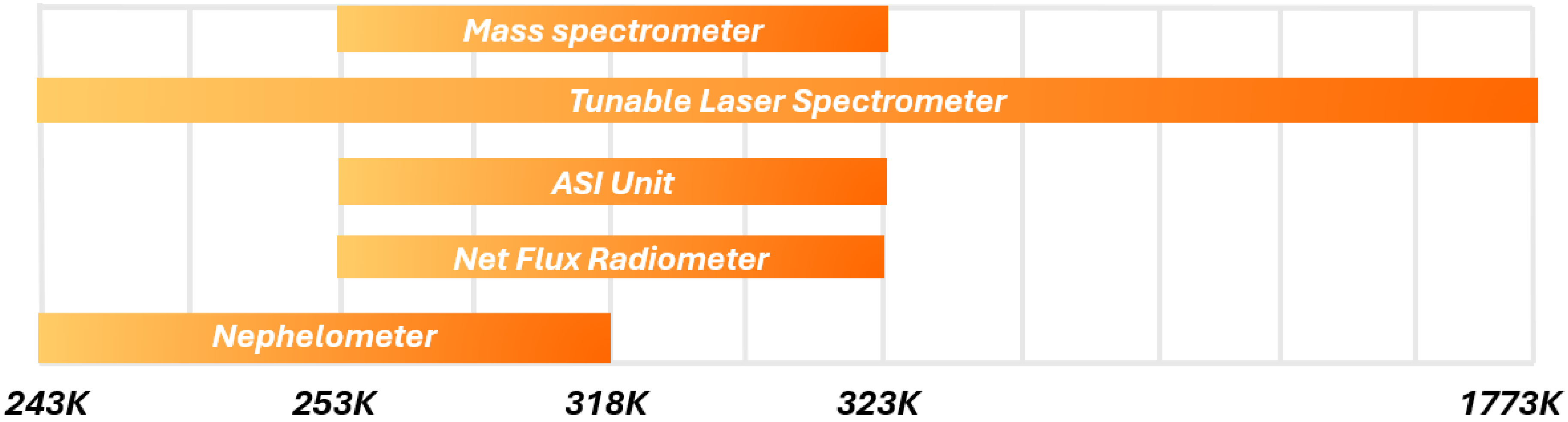




| Payload Instrument | Instrument Requirement |
|---|---|
| Mass spectrometer | Shall have a resolution of >1000 M/ΔM |
| | Shall measure in a mass range between 1-150 amu |
| Tunable Laser Spectrometer (TLS) | Shall have a resolving power of ~$10^5$ λ/Δλ |
| ASI Unit (Temp. / Press. / Accel.) | Shall measure every 4&2, 6 seconds |
| Net Flux Radiometer | Shall measure every 4&2, 6 seconds |
| Nephelometer | Shall measure every 5 mins |
| Lightning and Radio Emissions Detector | Shall measure every 256 s |

# Probe Thermal Envelope





# Probe Instrument Priority



| Instrument | Complexity | Thermal score | Size score | Science score | Total score |
|---|---|---|---|---|---|
| Weight | 2 | 2 | 5 | 10 | 190 |
| Temperature sensor | 10 | 8 | 10 | 4 | 126 |
| Pressure sensor | 10 | 4 | 10 | 5 | 128 |
| Mass spectrometer | 6 | 4 | 3 | 8 | 115 |
| Nephelometer | 6 | 8 | 5 | 6 | 113 |
| Accelerometers | 10 | 7 | 5 | 5 | 109 |
| Net Flux Radiometer | 7 | 4 | 5 | 3 | 77 |
| Lightning and Radio Emissions | 9 | 7 | 10 | 5 | 132 |
| Tunable Laser Spectrometer | 6 | 10 | 8 | 7 | 142 |
| **Average** | 7 | 6 | 7 | 6 | **126** |

Science Case → Mission Analysis → Engineering → Programmatics

| Science Case | Mission Analysis | Engineering | Programmatics |
| --- | --- | --- | --- |
| **Julia Wiltenburg** | **Vincent Affatato** | **David Placke** | **Colm Daly** |

Green Team – Mission SEAFARER

# Technology Readiness Level

**All components TRL >6 except:**

| Payload Component | TRL |
| --- | --- |
| Sonar (Lander) | 4 |
| Tunable Laser Spectrometer (Probe) | 4 |

| System Component | TRL |
| --- | --- |
| Thermal Control System (Lander) | 1 |
| Structure | 2 |

| Level | Technology Readiness |
| --- | --- |
| 4 | Component and/or broadband functional verification in laboratory environment |
| 5 | Component and/or broadband critical functional verification in laboratory environment |
| 6 | Model demonstrating the critical functions of the element in a relevant environment |
| 7 | Model demonstrating the element performance for the operational environment |
| 8 | Actual system completed and accepted for flight ("Flight Qualified") |
| 9 | Actual system "flight proven" through successful mission operations |

# Risk Matrix



## Risk Inventory

| Risk ID | Risk | Likelihood | Severity | Mitigation |
|---|---|---|---|---|
| 1 | Communication system failure on S/C | Possible | Very High | Test all subsystem on Earth |
| 2 | No power (lost of solar array, RTG problems) | Possible | Very High | |
| 3 | Planetary Contamination | Rare | Impact | Follow Deep Space build requirement (ISO3) |
| 4 | Communication issues at ground station | Unlikely | Very Low | Fix or use another Ground Station |
| 5 | Collision with micro meteoroid | Rare | Low | Use proper MLI on S/C |

## Risk Matrix

| | | Consequence | | | | |
|---|---|---|---|---|---|---|
| | | Very Low | Low | Medium | High | Very High |
| Likelihood | Highly Probable | | | | | |
| | Probable | | | | | 1,2 |
| | Possible | | | | | |
| | Unlikely | 4 | | | | |
| | Rare | | 5 | | 3 | |

# Planetary Protection

***Mission SEAFARER = Category II***

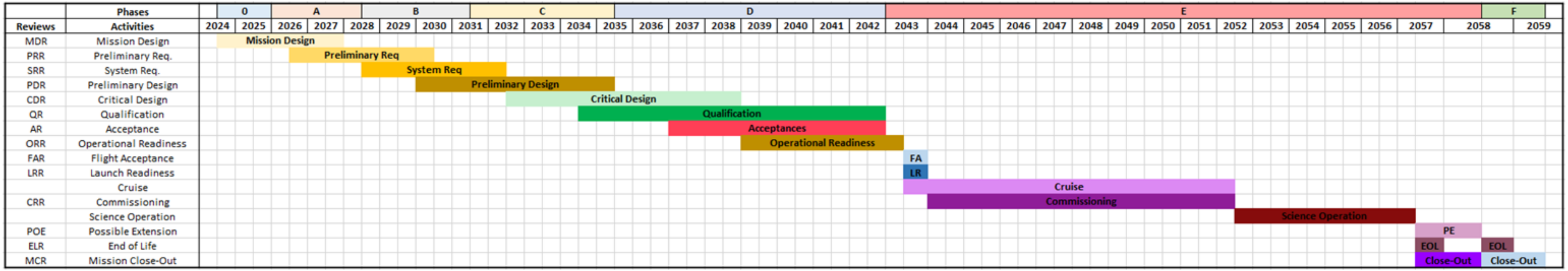
***Spacecraft Protection***

- ISO 3 cleanroom (Fed. Class 1)

**Planetary Protection**

- Titan: Harsh environment kills microorganisms
- Enceladus: Fly By
- Saturn: Disintegrate Upon Entry

# Development Schedule




## Key Dates

Begin: 2024

Requirements: 2032

Design: 2039

Qualified: 2042

Launch: 2043

Science: 2052

End Mission: 2057

**30% Safety Margin**

**Mission Duration**
33 Years

**Ready to Launch**
20 Years

## Durations

Phase A: 2.5 Years

Phase B: 3 Years

Phase C: 4 Years

Phase D: 6.5 Years

Phase E: 15.5 Years

Phase F: 1 Years

# Finances



**Cassini-Huygens:** €3.6 Billion
**L Mission Costs**
Juice = €1.6 Billion
Athena = €1.9 Billion

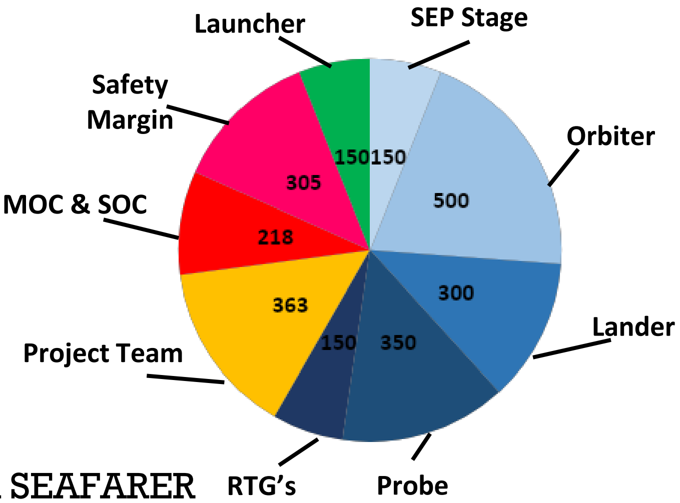
Instrument Cost:
**€200 Million**

Total Cost:
**€2.7 Billion**

## Options

| Cost (€) | ESA | NASA/JAXA |
|---|---|---|
| €2.5 Billion | Orbiter | |
| | Lander | |
| | Probe | |
| €2.0 Billion | Orbiter | Probe |
| | Lander | |
| €1.5 Billion | Orbiter | Probe |
| | | Lander |

## Mission Cost Breakdown



# Descoping Options



1. **De-Scope probe instruments**

**De-Scope Probe**

Save €500 Million

25% Science Lost

| *Probe De-Scoping Options* | | | |
|---|---|---|---|
| **Instrument** | **Measures** | **Probe Science Fraction** | **Saving (kg)** |
| Lightning Detector | Storm Activity | 10% | 2.5 |
| Radiometer | Atmospheric Dynamics | 20% | 3.15 |
| Nephelometer | Wind Speed + Cloud Properties | 20% | 4.4 |
| Laser Spectrometer | Heavy Molecules | 50% | 3.5 |

# Descoping Options

## 2. De-Scope Lander Instruments

### De-Scope Lander

Save €500 Million
25% Science Lost

| *Lander De-Scoping Options* | | | |
|---|---|---|---|
| **Instrument** | **Measures** | **Probe Science Fraction** | **Saving (kg)** |
| Atmospheric Instruments | Atmospheres Structure | 15% | 2.5 |
| Thermometer | Temperature | | |
| Dielectric constant sensor | Permittivity | 30% | 1.5 |
| Pressure sensor | Pressure | | |

# Outreach

- **Scientific Community**
  - Publications & attending scientific conferences
  - Different calls for observation proposals
  - Invite Students to participate in mission meetings

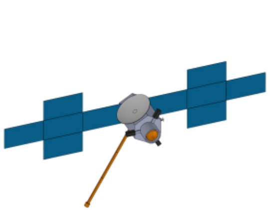
- **General Public**
  - Social Media, website & press releases
  - Provide educational resources

# Mission Overview

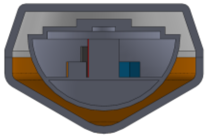


*"To study and characterise the diversity of habitats in the Saturnian systems"*

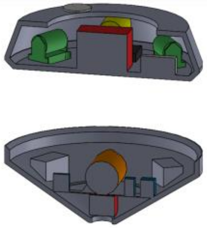
COOK
(Orbiter)

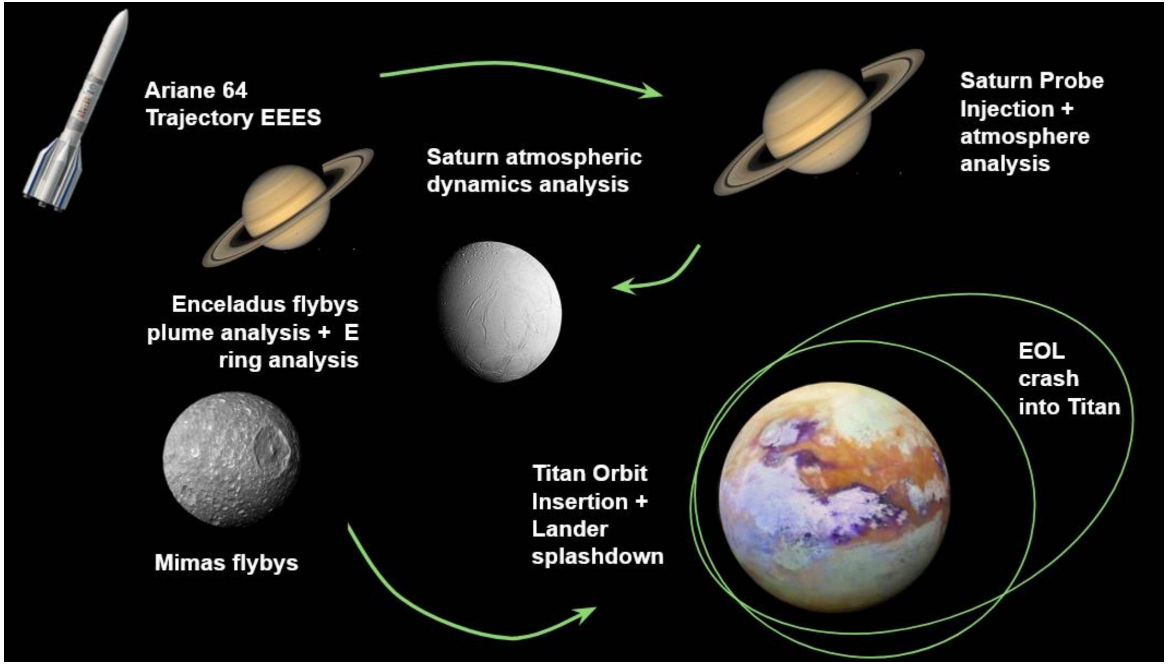


VESPUCCI
(Probe)



COLUMBUS
(Lander)





# Thank You For Listening
# We are happy to answer your questions


## Summer School Alpbach 2024

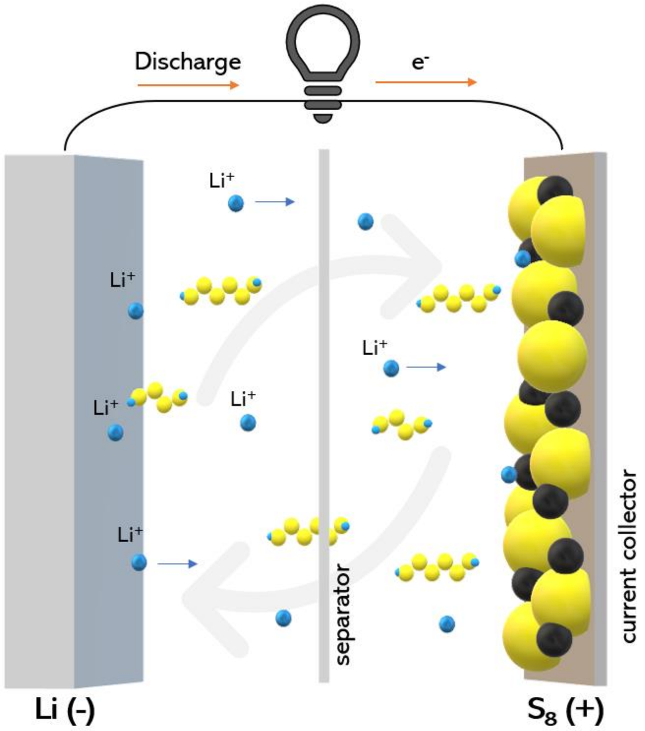
Green Team – Mission SEAFARER

# Extra Slides

# Extra Slides

# Lander

# Lander batteries




| | |
|---|---|
| **Battery type** | LiSO2 |
| **Specific energy** | 450 Wh/kg |
| **Energy density** | 550 Wh/L |
| **Capacity** | 2900 Wh |
| **Mass** | 6.5 kg |
| **Science Mode** | 5% duty cycle |

# Thermal

# Thermal -RTGS



| RTGs | ASRG |
|---|---|
| efficiency of 6 - 7 % | efficiency 22 - 30 % |
| lifetime >= 25 years | lifetime >= 14 years |
| much heritage | ease of assembly |
| no moving parts | less complex interface |
| | slower surface temperature |
| | greater flexibility |
| | lower mission cost |
| | decreased mass |

# Thermal -RTGS - Heritage



| | Cassini | Galileo |
|---|---|---|
| Number of RTGs | 3 | 2 |
| typical housing temperature while rejecting 4000 W | 240 °C | 240 °C |
| thermal radiation to warm components (usually up to 500 W) | 140 W + electrical heaters + 157 RHUs (35 for Huygens) | relied solely on elec. heaters, + 120 RHUs |

→ estimate that most planetary spacecraft would use **at most 500 W of heat for thermal management**

# RTGs - Fin Sizing



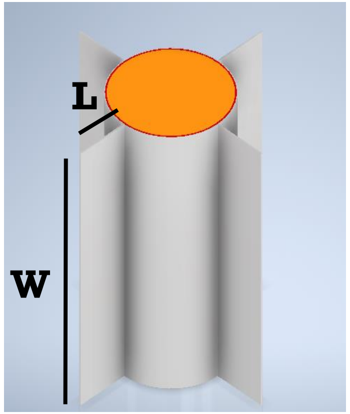
- Fin heat dissipation Q through radiation: $Q_{\text{fin}} = \epsilon\sigma A_{\text{fin}}(T_b^4 - T_\infty^4)$
- Assuming rectangular fin shape with width w and thickness t: $A_{\text{fin}} = 2(Lw + Lt + wt)$
- Given total heat dissipation we can calculate the number N of fins needed: $N = \frac{Q_{\text{total}}}{Q_{\text{fin}}}$
- Calculating the thickness of astroquartz-insulation needed: $R = \frac{\Delta T}{Q}$ $R = \frac{ln(r_1/r_i)}{2\pi\lambda_a \cdot L}$ $\lambda_a = 1.0\frac{W}{mK}$

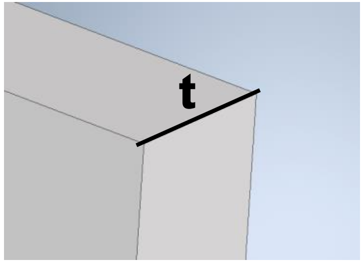
| $Q_{RTG,dissipated}$ | $\epsilon_{aluminium}$ | $\sigma$ | L | w | t | $T_{b,fins}$ | $T_\infty$ | $T_{RTG}$ | $r_1$ |
|---|---|---|---|---|---|---|---|---|---|
| 4285 W | 0.6 | $5.67 \cdot 10^{-8} \frac{W}{m^2K^4}$ | 0.35 m | 1.0 m | 0.01 m | 473 K | 2.7 K | 870 K | 0.2 |

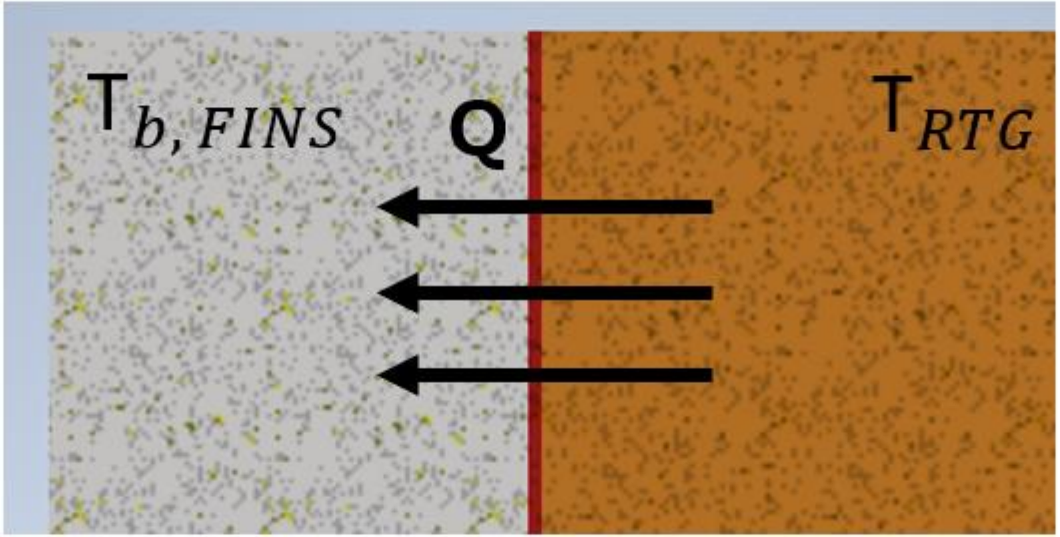
**Four aluminium fins** with a **8 cm astroquartz insulation layer of 2 kg**.

# RTGs - Fin Sizing

L = 35 cm
w = 1 m
t = 10 mm



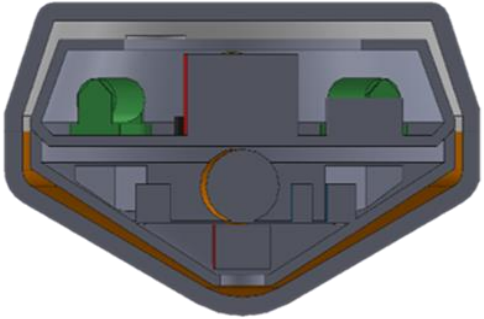



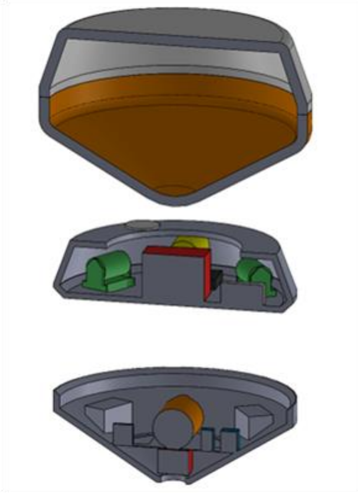

Aluminium fin

Astroquartz III ® insulation layer

PuO2

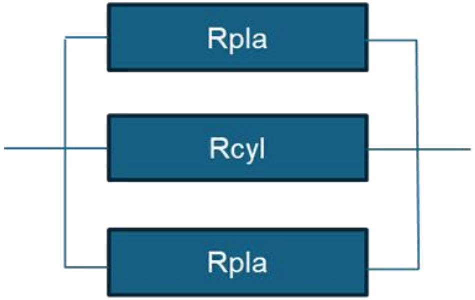
# Thermal protection

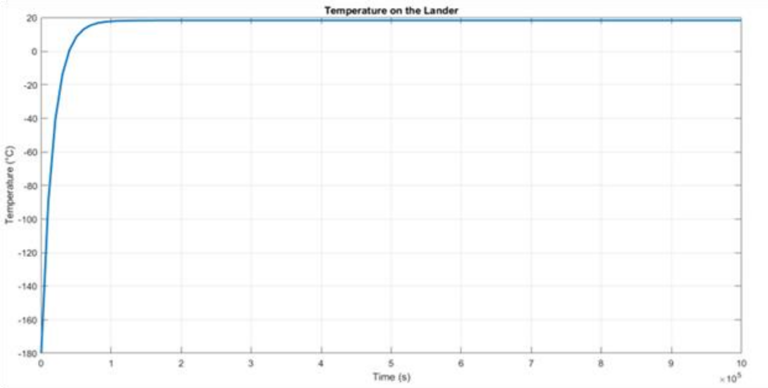




Power estimation : **30 W**
Isolation : 20 cm
MLI : 0.0004W/m2
L =1 m

$$mC_p\frac{dT}{dt} = -\frac{1}{R_H}(T(t) - T_{ext}) + P$$



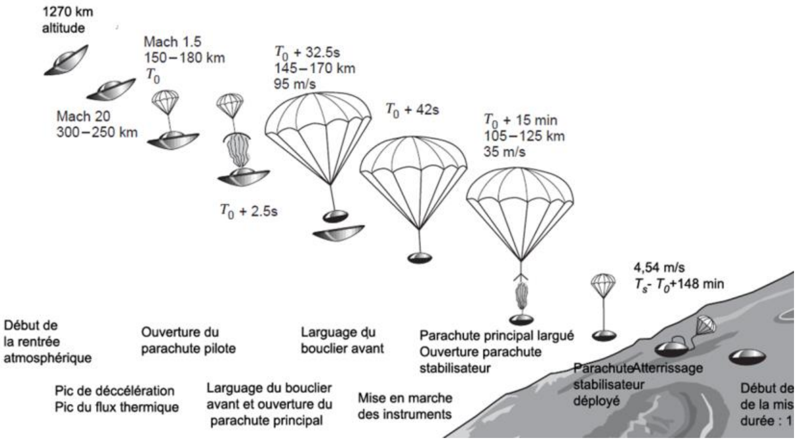



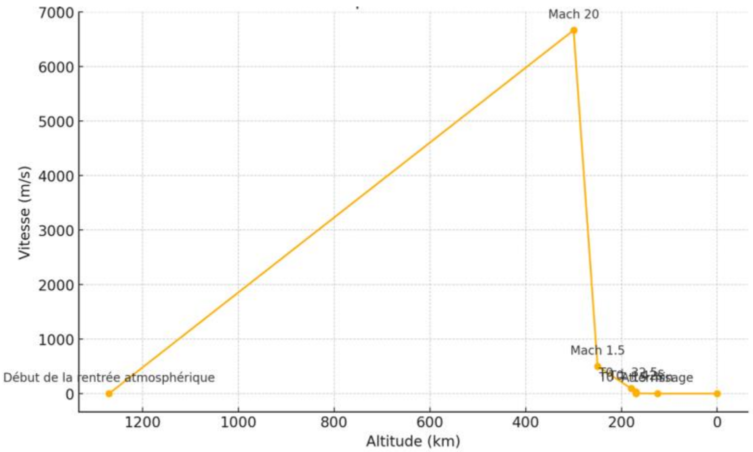

$$R_{\text{pla}} = \frac{e}{\lambda\, S}$$

$$R_{cyl} = \frac{\ln(r_2/r_1)}{2\pi\lambda L}.$$

$$T(t) = (T_i - T_{\text{ext}} - PR_H)\, e^{-\frac{1}{R_H C}t} + T_{\text{ext}} + PR_H$$

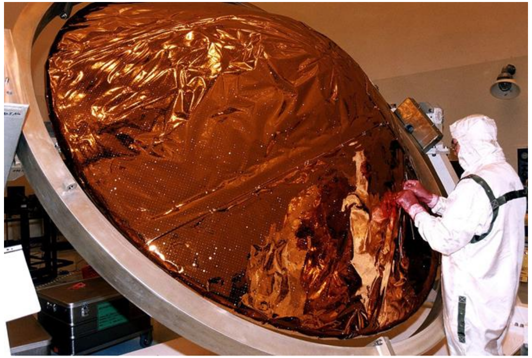
# Track Lander trajectory




$$
\begin{cases}
m\dfrac{d^2x}{dt^2} = mg\cos(\theta) - D\left(\dfrac{dx}{dt}\right)^2, \\
m\dfrac{d^2y}{dt^2} = -mg\sin(\theta) + D\left(\dfrac{dy}{dt}\right)^2.
\end{cases}
$$

# Protection



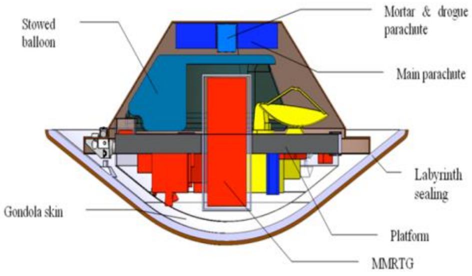
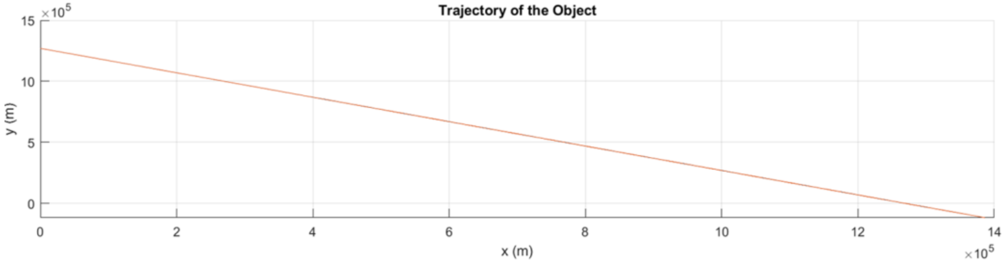



Figure 5 : montgolfière configuration (ESA TSSM assessment report).

$$v_x(t) = \sqrt{g\cos(\theta)/k}\tanh\left(\sqrt{g\cos(\theta)k}t + \tanh^{-1}\left(\frac{kv_x(0)}{g\cos(\theta)}\right)\right)$$

$$v_y(t) = \sqrt{g\sin(\theta)/k}\tanh\left(\sqrt{-g\sin(\theta)k}t + \tanh^{-1}\left(\frac{kv_y(0)}{g\sin(\theta)}\right)\right)$$

$$k = \frac{\rho C_d A}{2m}$$



# Structure

# Mechanisms



| Orbiter | Lander | Probe |
|---|---|---|
| - Solar arrays deployment x2<br>- Boom for the RTG x3<br>- Boom for the magnetometer (10m)<br>- Radar antenna deployment (4m)<br>- Probe separation subsystem<br>- Lander separation subsystem | - Lander separation subsystem<br>- Parachutes deployment<br>- Upper cover deployment<br>- Heat shield deployment<br>- Drop de lower buoy part | - Probe separation subsystem<br>- Parachutes deployment |

**Cameras** are used on the **orbiter** to **confirm the deployment**.

# Outreach

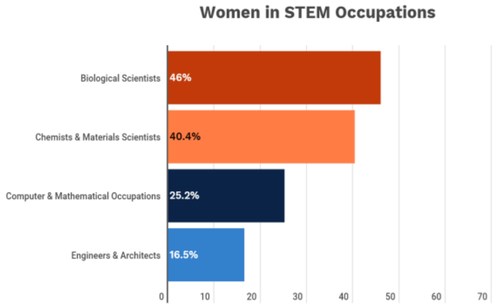


- Scientific Community
  - Publications & attending scientific conferences
  - Different calls for observation proposals
  - Invite Students to participate in mission meetings

- General Public
  - Social Media, website & press releases
  - Podcast
  - VR/App design to follow the orbiters observations
  - Provide educational resources
  - Touring, interactive exhibition

## Call and Inspiration for Minorities in STEM

Ambassadors engage young students



# Planetary Protection

# Planetary protection



**Risk of carrying bacteria from Earth or pollute Titan?**

- Given the fact that Titan is too cold and that there is no liquid water for life as we know it to evolve, the **risk of contamination is practically non-existing**. The harsh environment is expected to kill microorganisms that may have hitchhiked from Earth on board the clean space probe.

**Risk of carrying bacteria from Earth or pollute Enceladus?**

- Care has been taken to ensure that the orbiter does not crash into a body which has a significant chance for hosting life, such as Enceladus.
- Enceladus' plumes will be studied with **fly-bys** (no lander or probe).

**Risk of carrying bacteria from Earth or pollute Saturn?**

- Scientists have decided to impact the probe into the atmosphere of Saturn to ensure biological contamination will not occur. Although the possibility that Saturn might host life is unlikely, the spacecraft will not risk even that unlikely scenario.
- The **probe will disintegrate** and be scattered into the giant gaseous planet's atmosphere, preventing possible contamination from Earth

# Cleanroom Design for Deep Space Satellites

Deep Space satellites demand greater consideration for microbe counts. **The requirement is ISO 3 cleanroom (Fed. Class 1) or better**: partitioned cleanrooms with air lock entry systems, HIPA filters, special protective clothing for people assure that entry and exit does not introduce contamination.

Tools, raw materials and packaging must be wiped down and enter through integrated passthrough chambers. Items are sterilized with IPA wipedowns, autoclaves or by gamma sterilization.

**Reason**
**It's possible that rogue earth microbes (fungus, bacteria, viruses) could colonize or even cannibalize other life on distant planets and spacecraft.**

**CONTAMINANT**: any unwanted molecular or particulate matter (including microbiological matter) on the surface or in the environment of interest, that can affect or degrade the relevant performance or life time.

**CONTAMINATION**: An unwanted material or substance that causes degradation in the desired function of an instrument or flight hardware.

**Table 1 — ISO Classes of air cleanliness by particle concentration**

| ISO Class number (*N*) | Maximum allowable concentrations (particles/m³) for particles equal to and greater than the considered sizes, shown below[a] | | | | | |
|---|---|---|---|---|---|---|
| | 0,1 µm | 0,2 µm | 0,3 µm | 0,5 µm | 1 µm | 5 µm |
| 1 | *10*[b] | d | d | d | d | e |
| 2 | 100 | *24*[b] | *10*[b] | d | d | e |
| 3 | 1 000 | 237 | 102 | *35*[b] | d | e |
| 4 | 10 000 | 2 370 | 1 020 | 352 | *83*[b] | e |
| 5 | 100 000 | 23 700 | 10 200 | 3 520 | 832 | d, e, f |
| 6 | 1 000 000 | 237 000 | 102 000 | 35 200 | 8 320 | 293 |
| 7 | c | c | c | 352 000 | 83 200 | 2 930 |
| 8 | c | c | c | 3 520 000 | 832 000 | 29 300 |
| 9[g] | c | c | c | 35 200 000 | 8 320 000 | 293 000 |

a All concentrations in the table are cumulative, e.g. for ISO Class 5, the 10 200 particles shown at 0,3 µm include all particles equal to and greater than this size.

b These concentrations will lead to large air sample volumes for classification. Sequential sampling procedure may be applied; see Annex D.

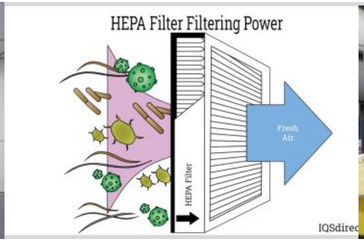
c Concentration limits are not applicable in this region of the table due to very high particle concentration.

d Sampling and statistical limitations for particles in low concentrations make classification inappropriate.

e Sample collection limitations for both particles in low concentrations and sizes greater than 1 µm make classification at this particle size inappropriate, due to potential particle losses in the sampling system.

f In order to specify this particle size in association with ISO Class 5, the macroparticle descriptor M may be adapted and used in conjunction with at least one other particle size. (See C.7.)

g This class is only applicable for the in-operation state.




# Preventing Extra-Terrestrial Contamination

A satellite cleanroom prevents earth-borne contamination from invading extraterrestrial environments, so the project must undergo a review to establish a threshold of allowed microbial counts based on a risk assessment. See: COSPAR Planetary Protection Policy

**Committee on Space Research**

# Lander Mission : Protection

***Category II*** *missions comprise all types of missions to those target bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote 1 chance that contamination carried by a spacecraft could compromise future investigations. The requirements are for simple documentation only.*

*Preparation of a short planetary protection plan is required for these flight projects primarily to outline intended or potential impact targets, brief Pre- and Post-launch analyses detailing impact strategies, and a Post-encounter and End-of-Mission Report which will provide the location of impact if such an event occurs.*

***Category II*** *Flyby, Orbiter, Lander: Venus; Moon; Comets; Carbonaceous Chondrite Asteroids; Jupiter; Saturn; Uranus; Neptune; Ganymede*; Callisto;* ***Titan****; Triton*; Pluto/Charon*; Ceres; Kuiper-belt objects > ½ the size of Pluto*; Kuiper-belt objects < ½ the size of Pluto; others TBD*

https://cosparhq.cnes.fr/assets/uploads/2021/07/PPPolicy_2021_3-June.pdf