



A relocatable lander to explore Titan's
prebiotic chemistry and habitability

The Dragonfly Mission to Titan Planetary Protection Considerations

Committee on Planetary Protection
22 March 2024

Elizabeth (Zibi) Turtle, Dragonfly Principal Investigator
Johns Hopkins Applied Physics Laboratory

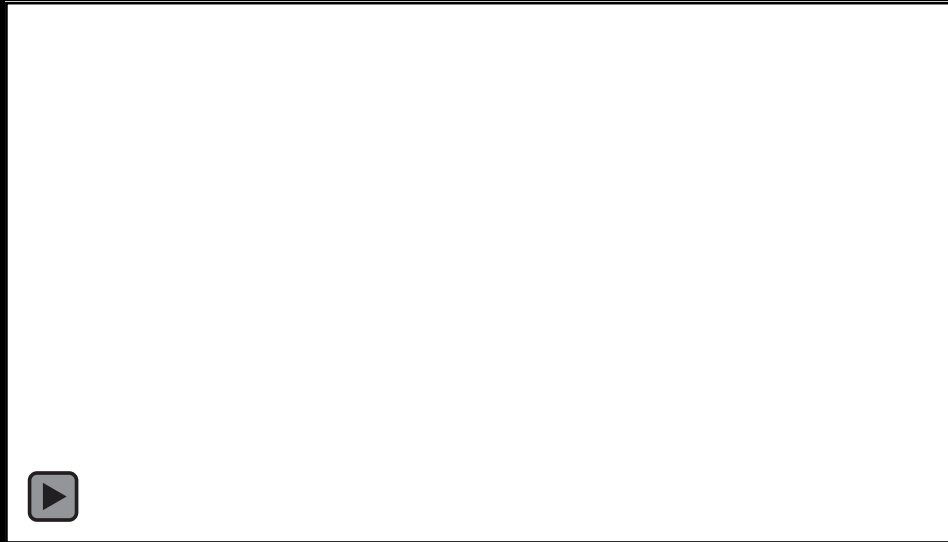
Dragonfly



Outline



- Dragonfly Mission overview
- Nature of Titan's environment
- Planetary Protection considerations and implementation go hand-in-hand with our Mission development



Dragonfly Mission Overview



- 4th mission in NASA's New Frontiers Program, selected in June 2019
- Project Phase B: Preliminary Design and Technology Completion
 - Technology maturation completed
 - *Planetary Protection Category II assigned, October 2022, following science review by NASA's Office of Planetary Protection*
 - Successful Mission Preliminary Design Review (MPDR), February-March 2023
 - NASA Directorate and Agency Program Management Council meetings, Fall 2023
- Detailed design activities underway
- Phase C: Final Design and Fabrication start April 2024



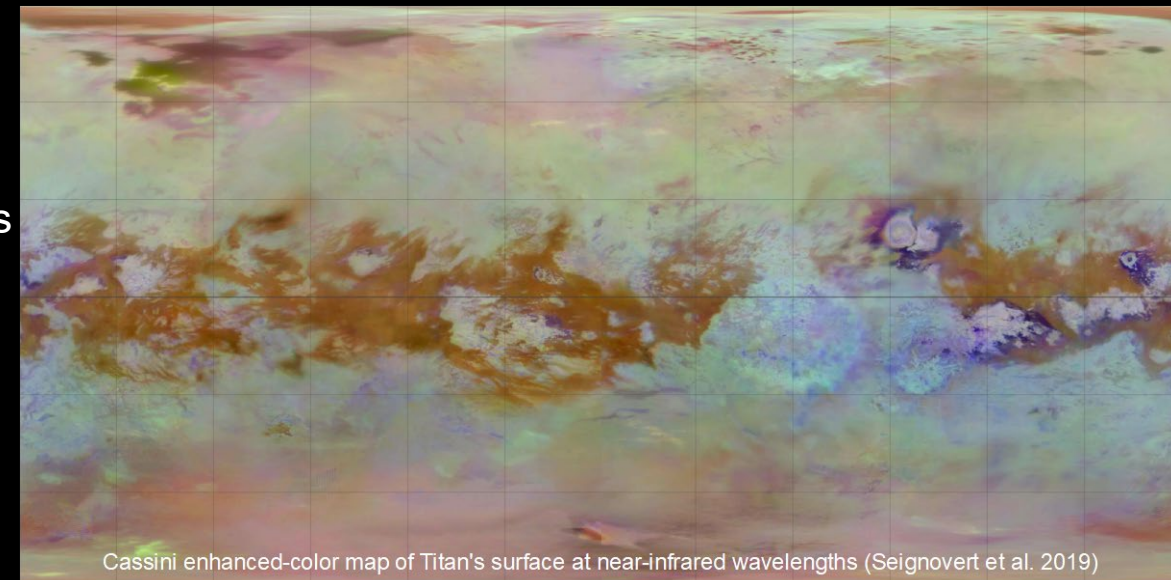
Titan's environment has been well characterized



- Diameter: 5,150 km (3,193 miles)
- Surface gravity: 1.35 m/s^2 (0.14 g)
 - 14% of gravity at Earth's surface, 83% of gravity of Moon
- Surface temperature: 94 K (-179°C , -290°F)
 - Bedrock composition: water ice
 - Atmospheric composition: nitrogen, few % methane
- Surface pressure: 1.5 bar
 - $1.5\times$ pressure & $4\times$ atmospheric density at Earth's surface
 - Dense atmosphere, long days, long seasons $\rightarrow$ calm conditions
 - Diurnal, seasonal, and spatial $\Delta T \sim 1 \text{ K}$; winds $\sim 1\text{-}2 \text{ m/s}$
 - Vertically extended atmosphere
- 8-11 AU from Earth: 1-way light-time $\sim 70\text{-}90 \text{ min}$
 - Autonomous flights and science operations



Voyager 2, 23 August 1981

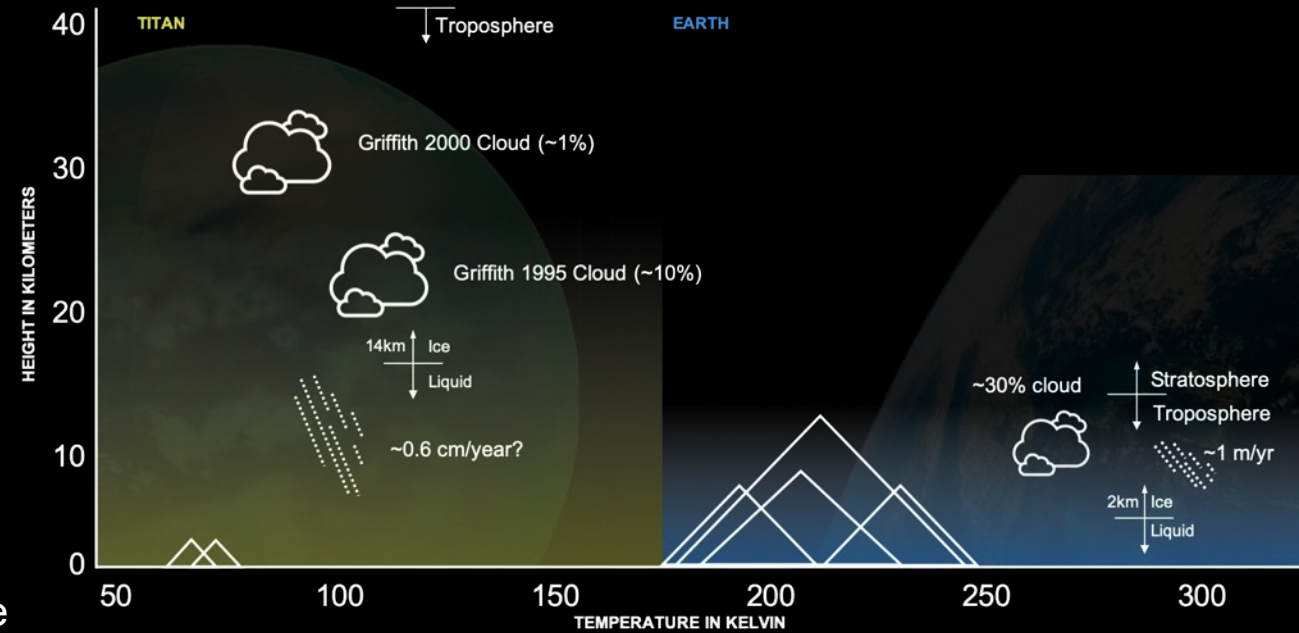


Cassini enhanced-color map of Titan's surface at near-infrared wavelengths (Seignovert et al. 2019)

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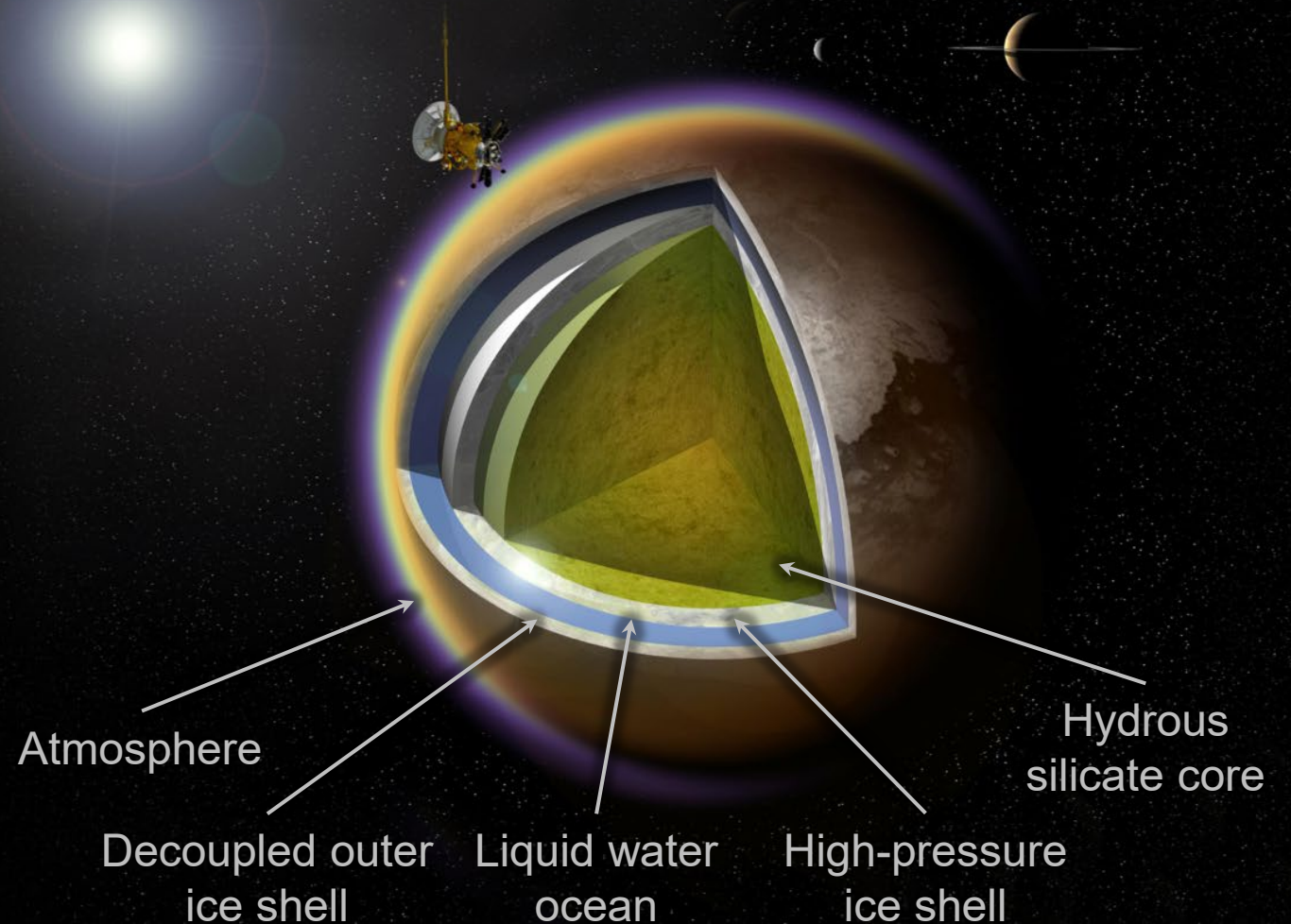


Titan's environment has been well characterized



- Deep interior ocean of liquid water

- Decoupled ice shell ~80–170 km based on recent thermal / gravity modeling (Kronrod et al., 2020)



Titan's molecular complexity and carbon abundance



Most complex (heaviest)
carbon bearing molecule

Complexity (amu)

10^{10}

10,000-10¹⁰
(e.g., DNA)

100,000

1,000-10,000
(e.g., Proteins)

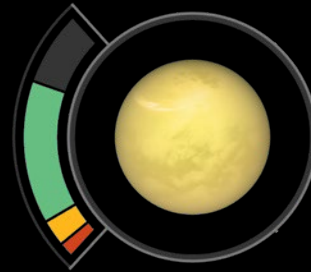
1,000

100-1,000
(e.g., Amino Acids)

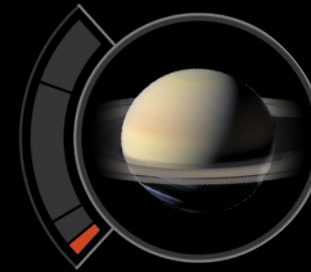
100

0

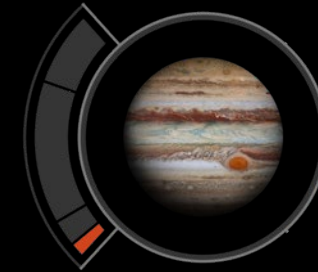
TITAN



SATURN



JUPITER



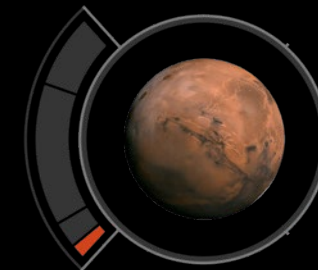
EARTH



VENUS



MARS

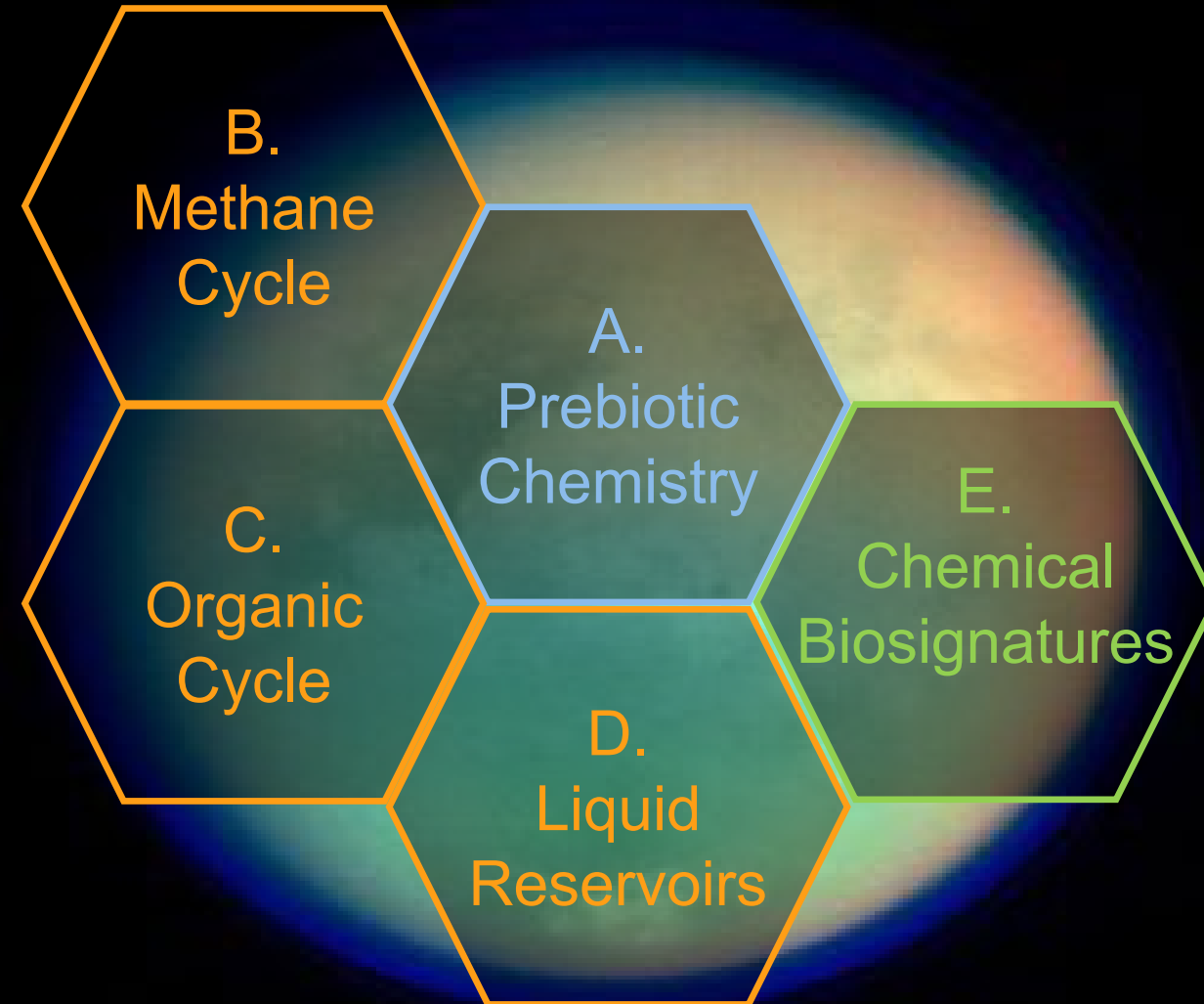


Dragonfly Mission Science

Barnes et al., *PSJ*, 2021
<https://doi.org/10.3847/PSJ/abfdcf>



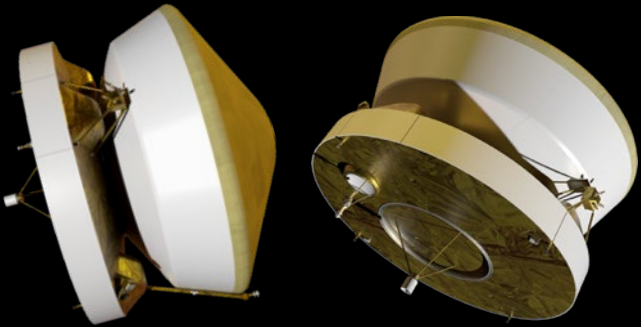
- Prebiotic chemistry
 - Analyze chemical components and processes at work that produce biologically relevant compounds
- Habitable environments
 - Measure atmospheric conditions, identify methane reservoirs, and determine transport rates
 - Constrain processes that mix organics with past surface liquid water reservoirs or subsurface ocean
- Search for biosignatures
 - Search for chemical evidence of water- or hydrocarbon-based life



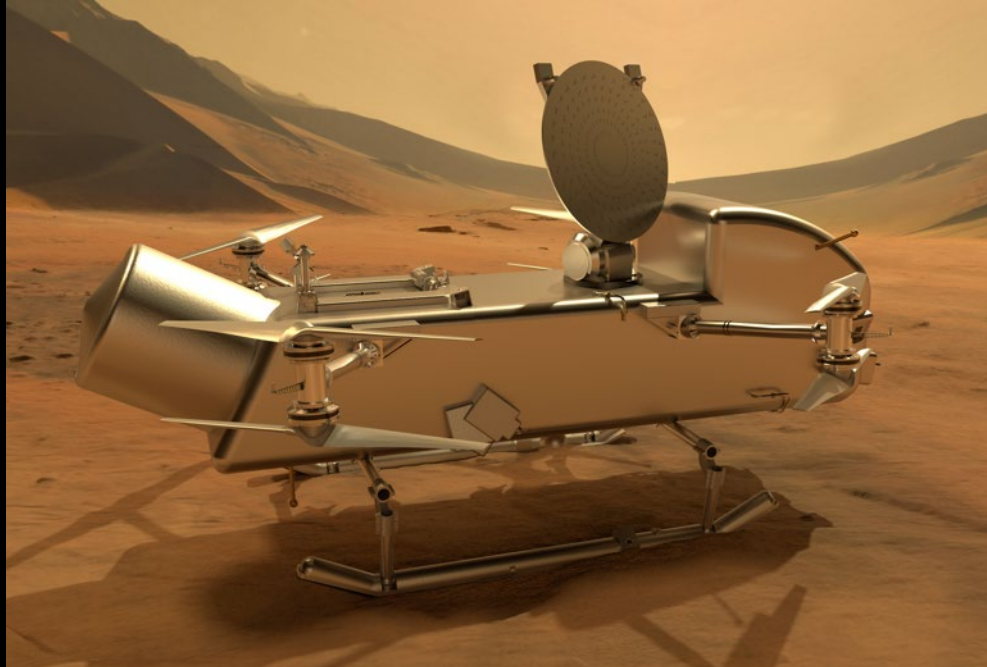
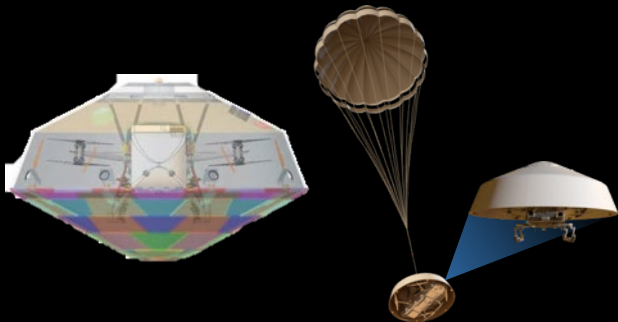
Dragonfly Mission Elements



Spacecraft = Cruise Stage + Entry Vehicle



Entry Vehicle = EDL Assembly (heatshield and backshell) + Lander



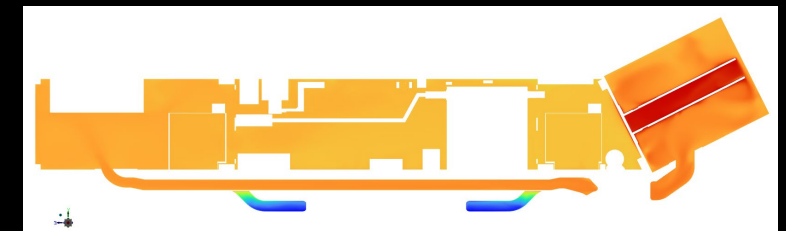
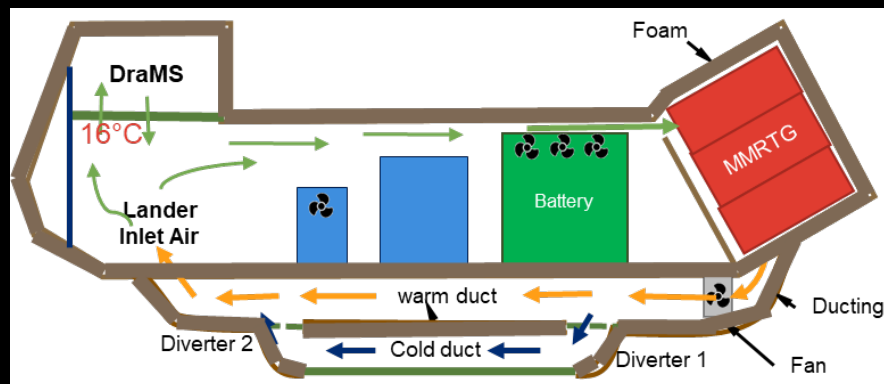
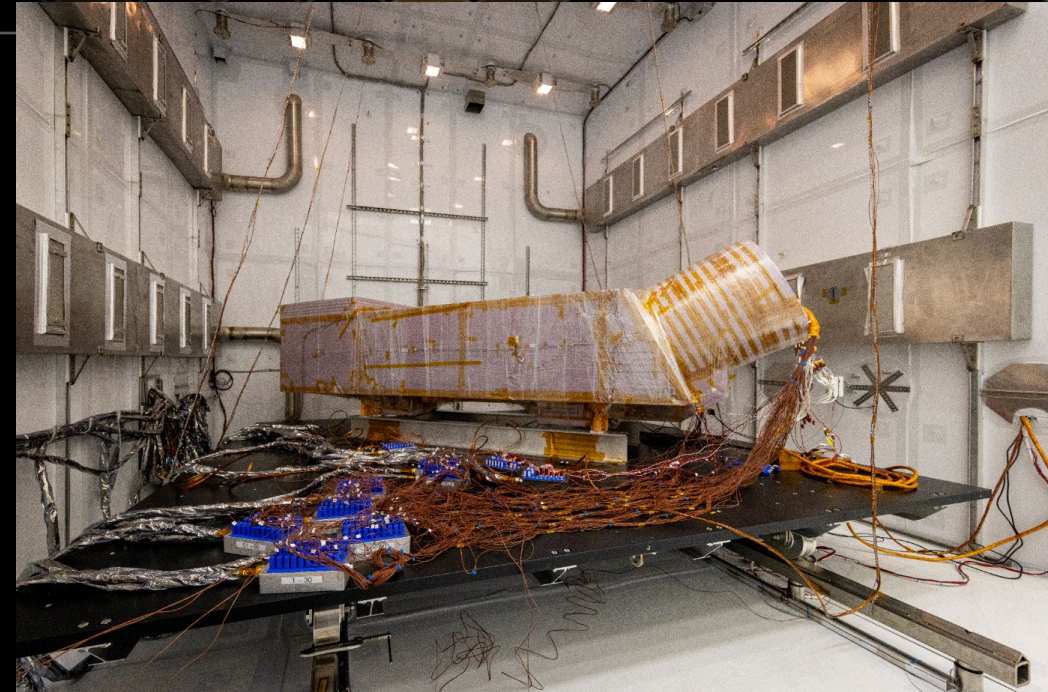
Rotorcraft Lander
*Surface configuration
with HGA deployed*

- **Transport entire payload from place to place – surface and aerial measurements**
- **Direct-to-Earth communication via radial line slot array antenna**
- **MMRTG power source**
 - Charges 11.3 kWh battery to power flight, science activities, and data transmission
 - Heat output is equally important as power – MMRTG maintains nominal thermal environment within the interior of the insulated Lander body

Dragonfly Thermal Development and Testing



- Development Test Module (DTM) – full-scale representation of Lander primary structure
 - Lander utilizes convective heat transfer to control temperature while on Titan
 - Thermal design distributes heat from the MMRTG using fans to maintain T
 - To remove heat, a bypass cold duct with surface area exposed to the cold Titan environment can be opened to cool the air cycled through the lander
 - The thermal DTM was built to test and correlate computational fluid dynamics (CFD) models of the Lander
 - Ambient testing started in August 2023, followed in October 2023 by cold tests in the newly commissioned APL Titan thermal chamber

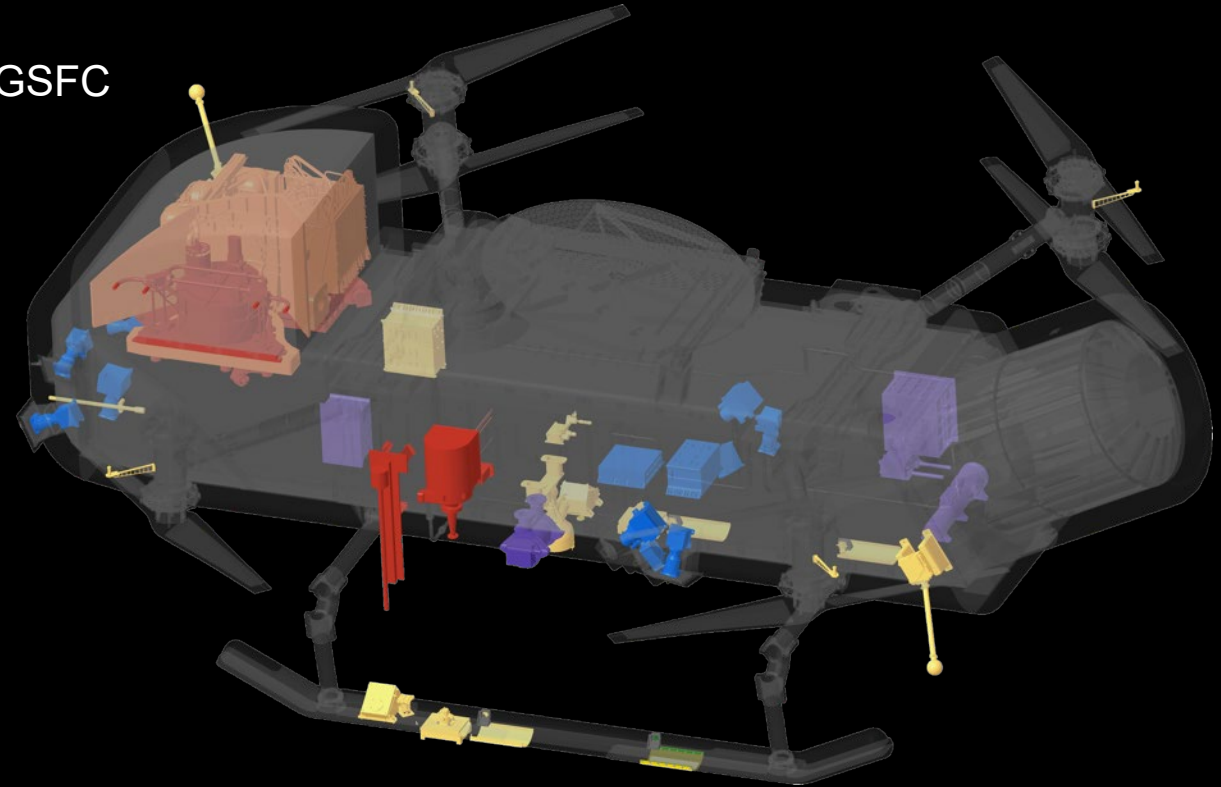


CFD model resulted in fully converged cases behaving similarly to the Titan Chamber experiments

Multidisciplinary Science Measurements – Evaluate prebiotic chemistry in the context of Titan's environment



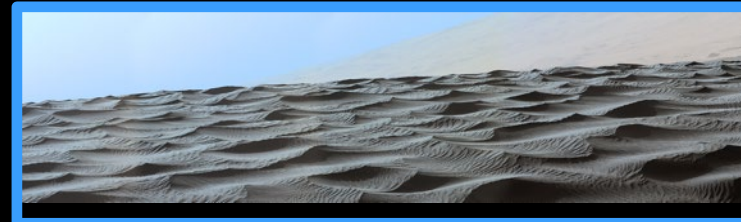
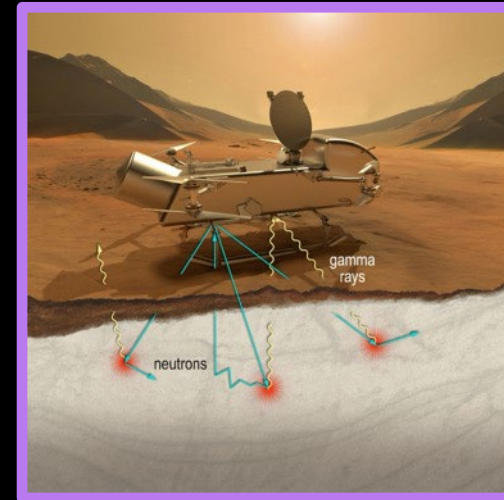
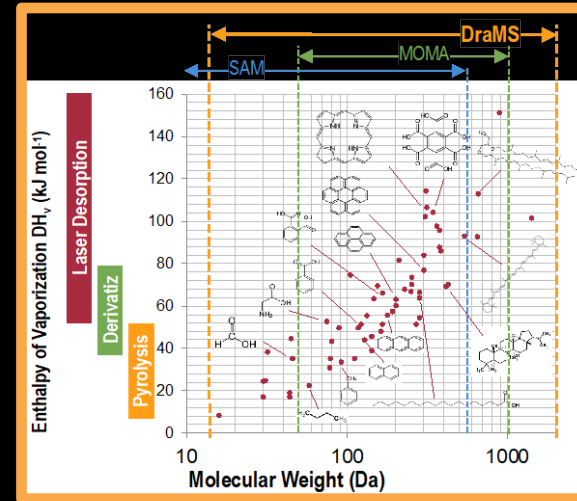
- **DraMS**: Mass Spectrometer – GSFC, CNES
- **DrACO**: Drill for Acquisition of Complex Organics – Honeybee
- **DraGNS**: Gamma-ray and Neutron Spectrometer – APL, LLNL, GSFC
- **DraGMet**: Geophysics & Meteorology – APL, JAXA
- **DragonCam**: Camera Suite – MSSS



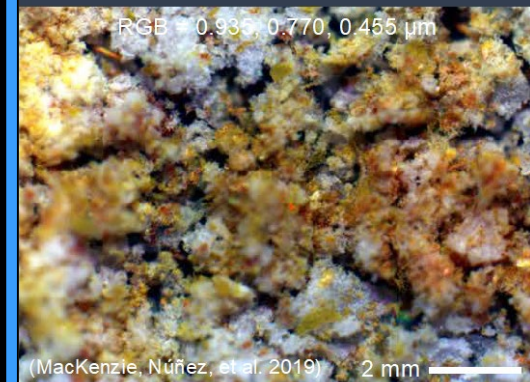
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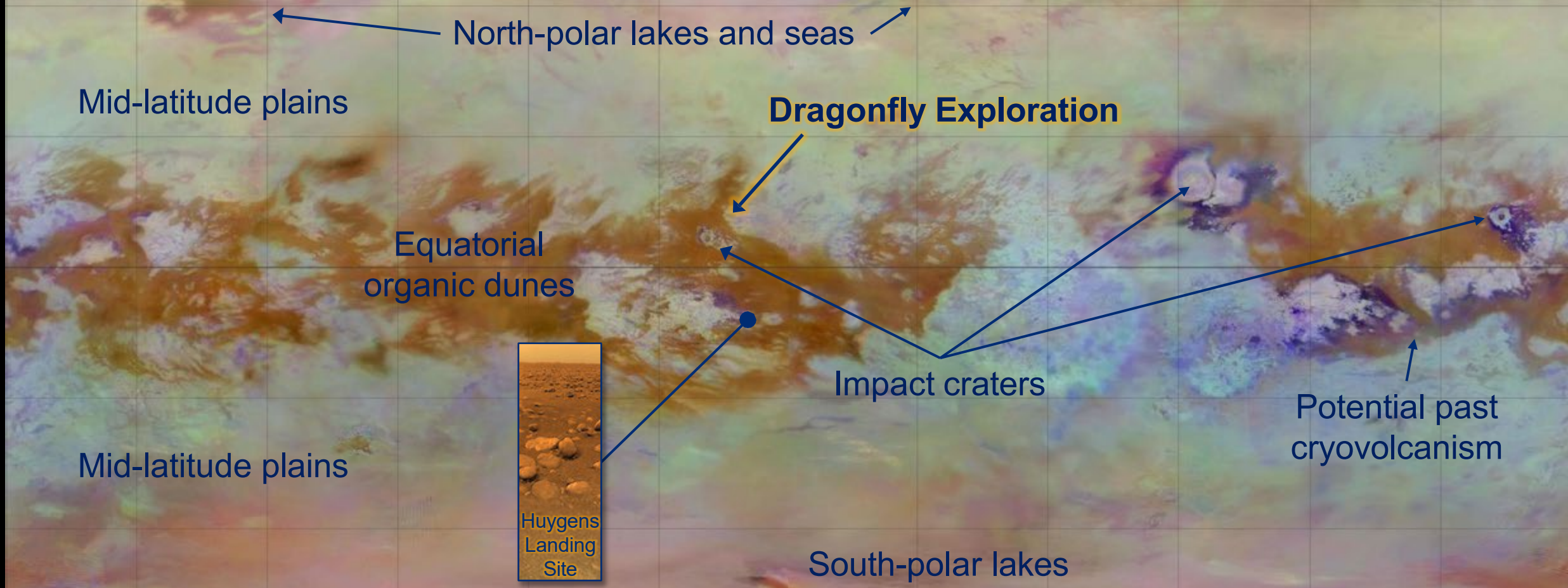
- **DraMS**: Analyze chemical components and processes that produce biologically relevant compounds
 - Laser Desorption: Broad survey and structural analysis
 - Gas Chromatography: Definitive molecular detection, chirality
- **DrACO**: Rotary-percussive drill and blower to sample and pneumatically transfer surface material to DraMS
- **DraGMet**: Monitor atmospheric conditions, constrain regolith properties, detect and characterize level of seismic activity
 - T, P, CH₄, H₂, wind speed & direction
 - Diurnal and spatial variations; aerial meas. & profiles
- **DragonCam**: Characterize landforms and surface processes at multiple scales, surface & aerial imaging
- **DraGNS**: Measure bulk elemental surface composition, including minor inorganics, to classify surface materials



LED illuminated mixture of water ice (white) and two tholin 'flavors' (orange + yellow)



Titan's environment well characterized by Cassini-Huygens

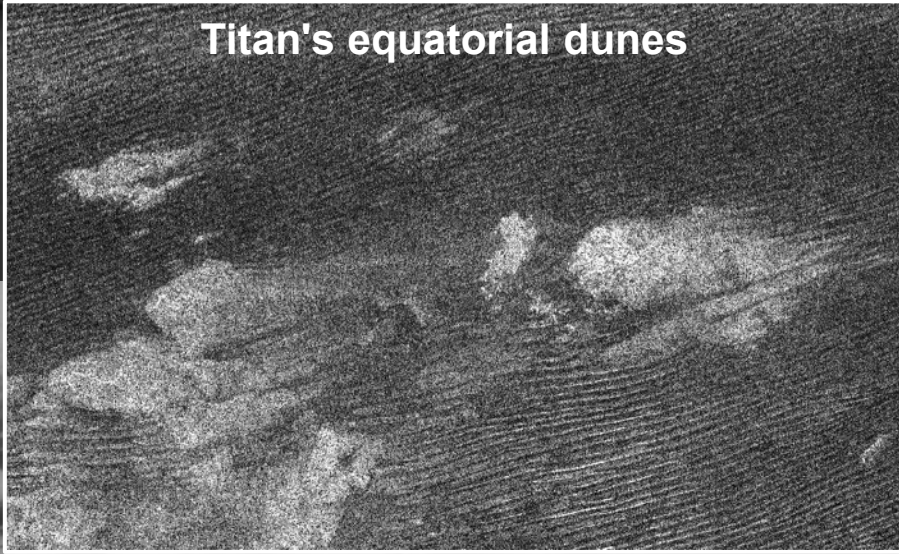


Cassini enhanced-color map of Titan's surface at near-infrared wavelengths (Seignovert et al. 2019)

Dragonfly's region of exploration provides access to a variety of materials of astrobiological interest

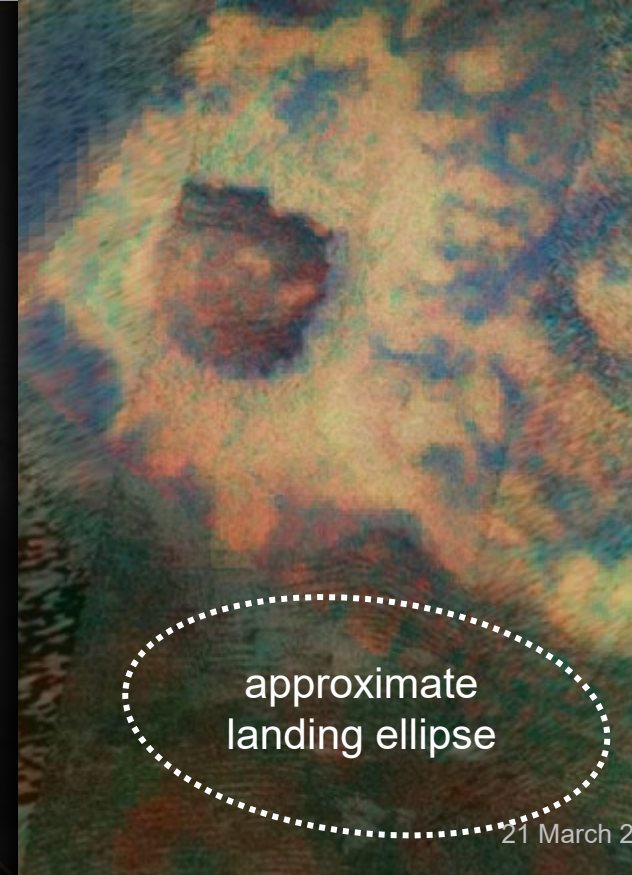
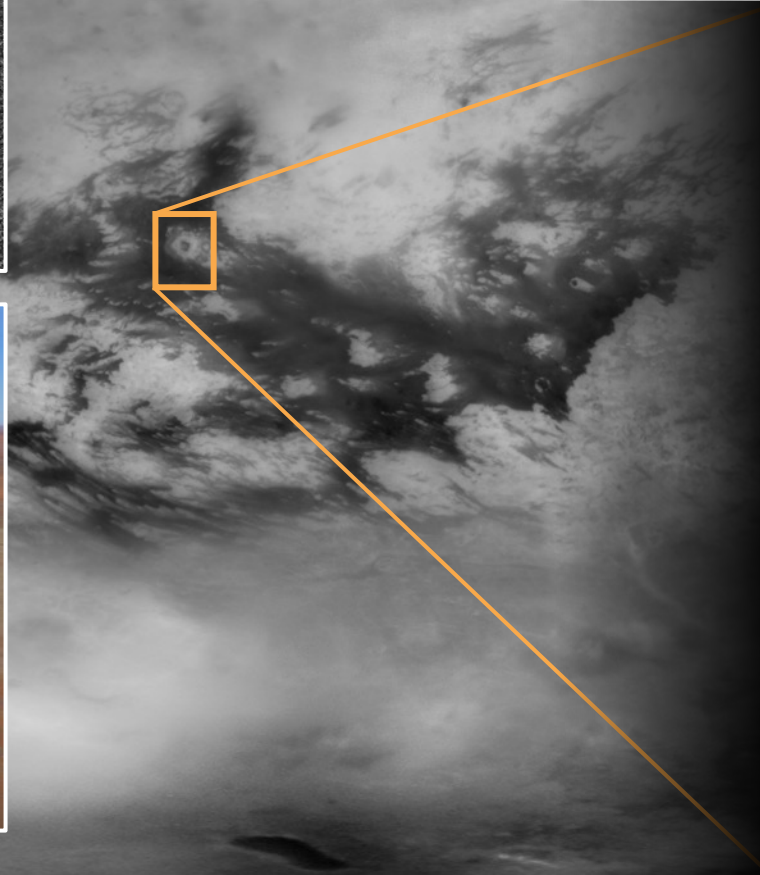
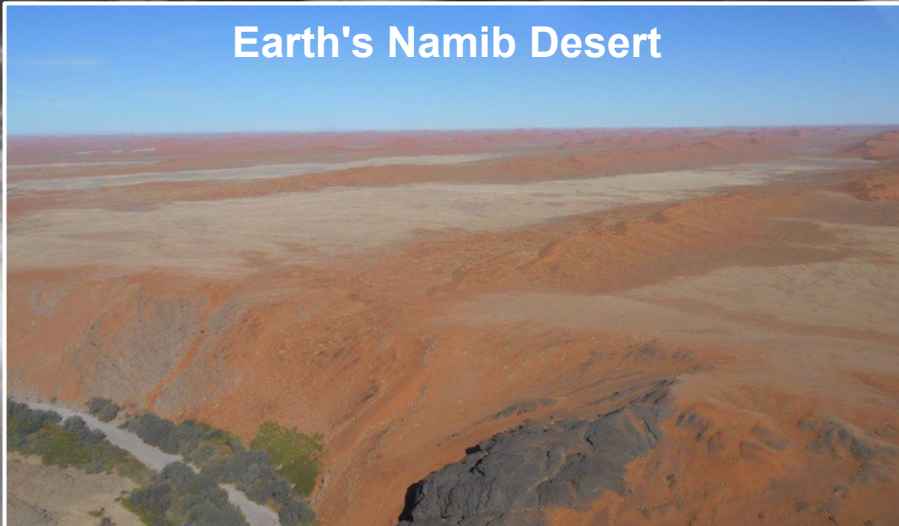


Titan's equatorial dunes



- **Sand dunes:** organic sediments
- **Interdune areas:** materials with a water-ice component
- **Selk impact crater:** materials where organics may have mixed with liquid water impact melt

Earth's Namib Desert

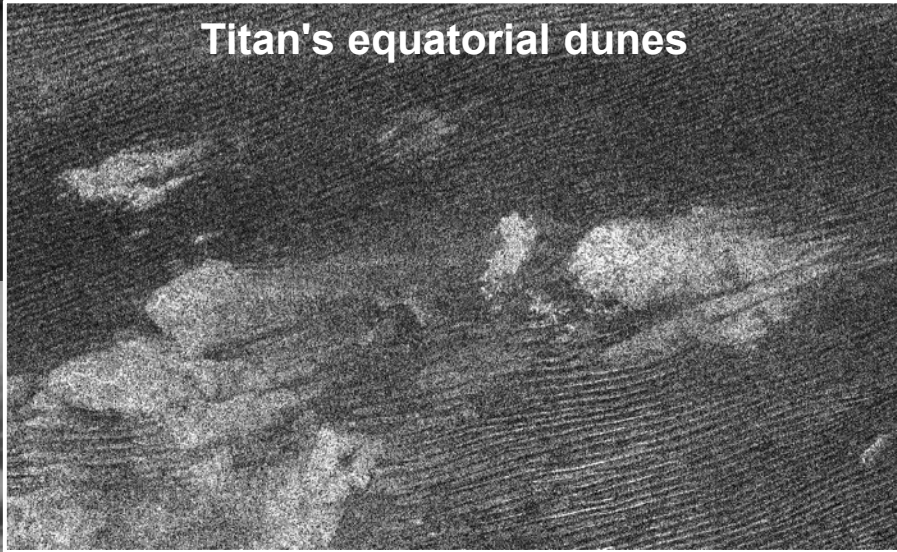


approximate
landing ellipse

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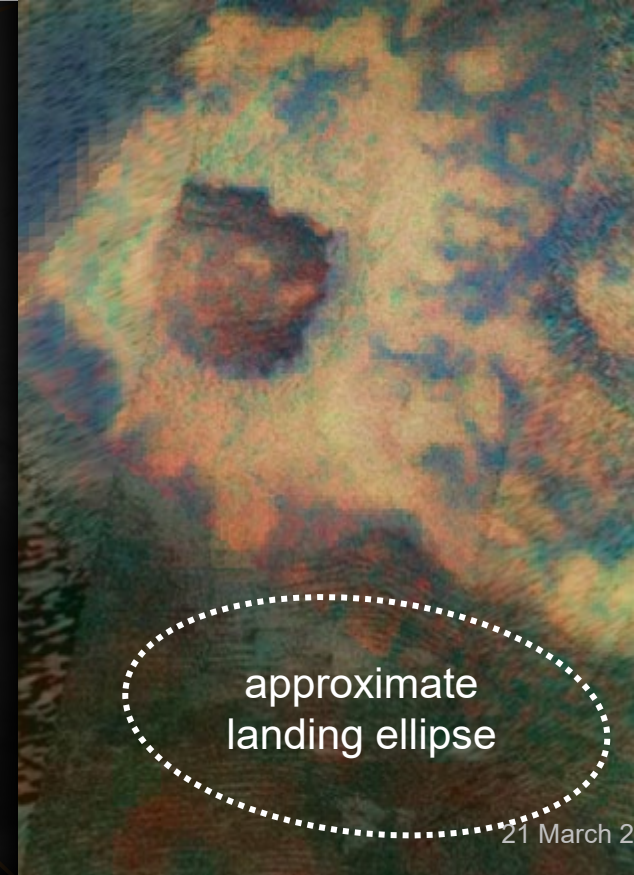
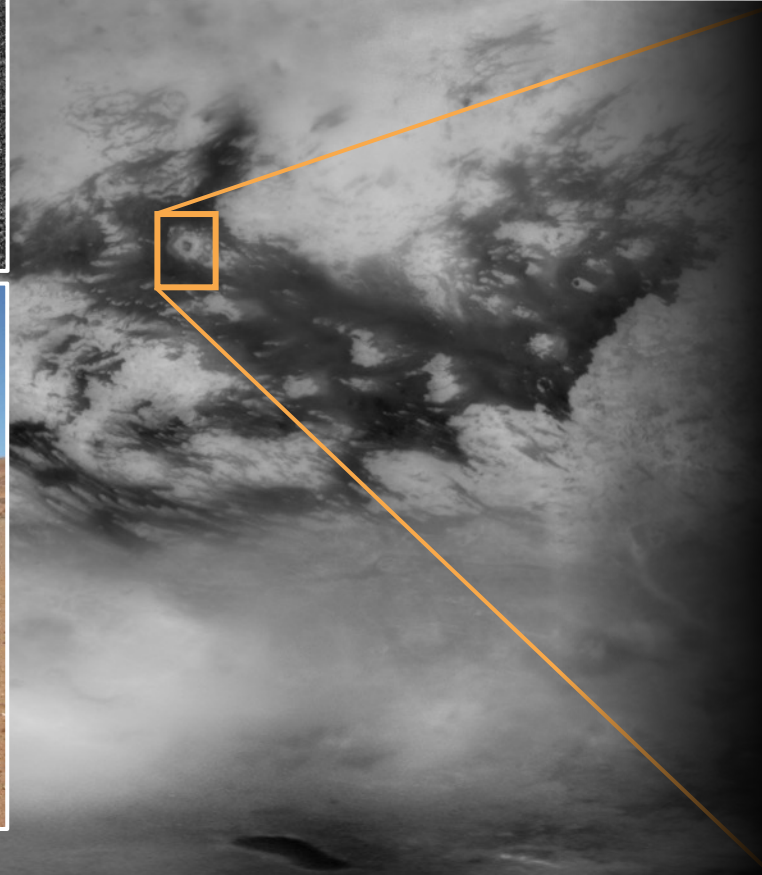
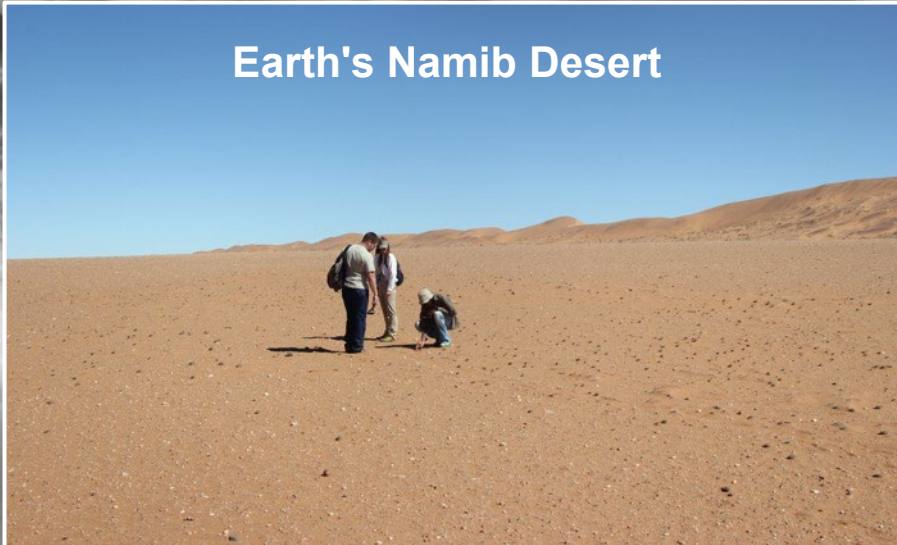


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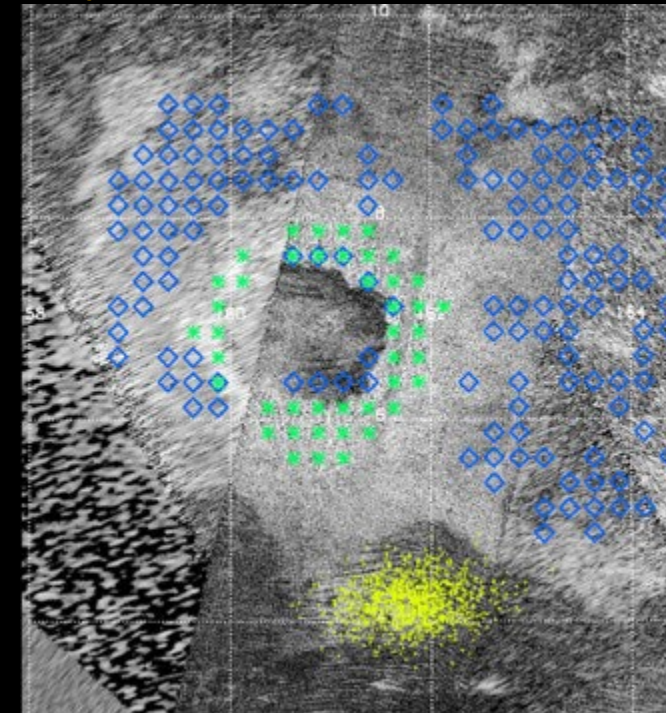


Dragonfly Exploration Strategy

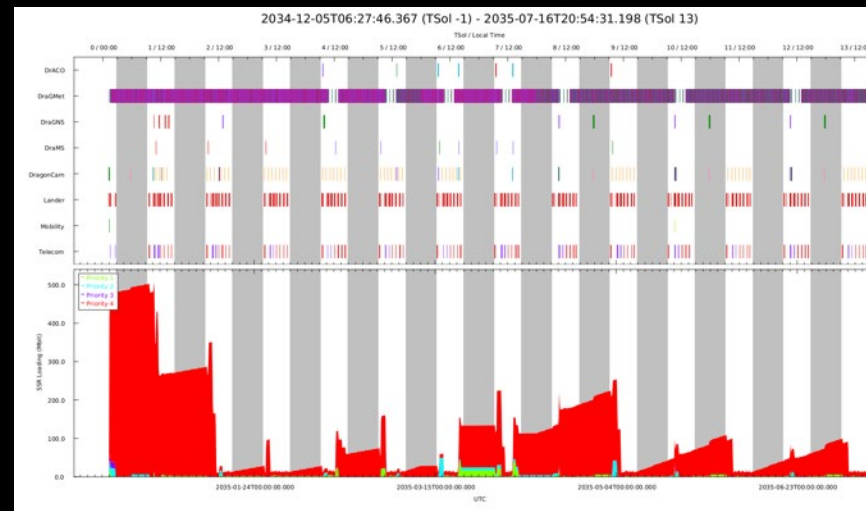
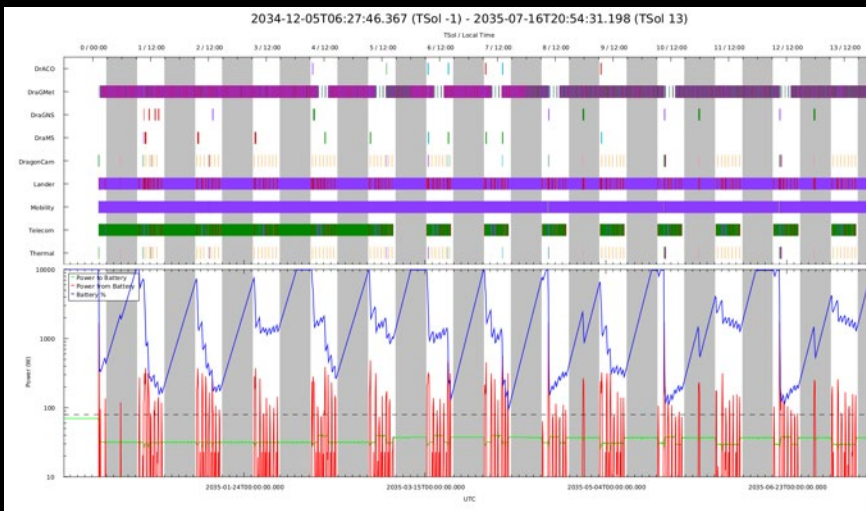


- **~3 years, ~74 Tsols (Titan days) of science operations**
 - Individual flights of several kilometers; total traverse distance several tens of km
 - Exploration of >30 unique sites
 - Aerial scouting of future landing sites
- **Design Reference Mission shows requirements are met with margin**
 - Nominal flight schedule is once per 2 Tsols (~1 flight / Earth month)
 - Most of time (99.9%) is spent on the surface
 - Flexible surface operations facilitates reacting to discoveries

Cassini mapping shows impact melt may be encountered in the ejecta and near the crater rim



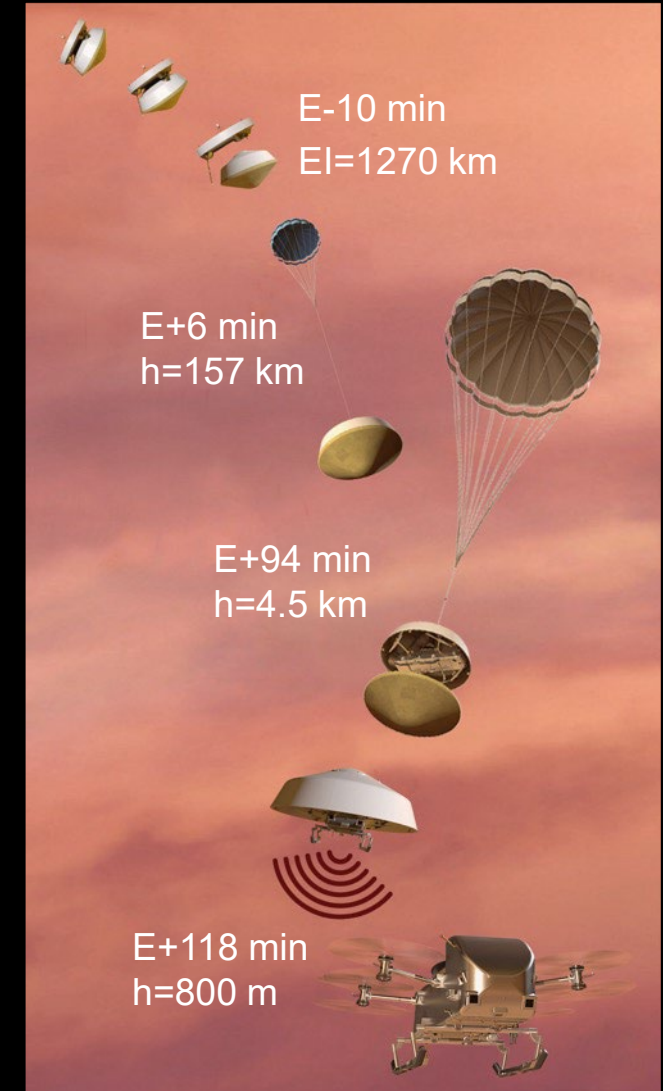
Monte Carlo landing sites
Crater rim
Water-ice component
(Cassini VIMS "blue unit")



Titan's Environmental Parameters



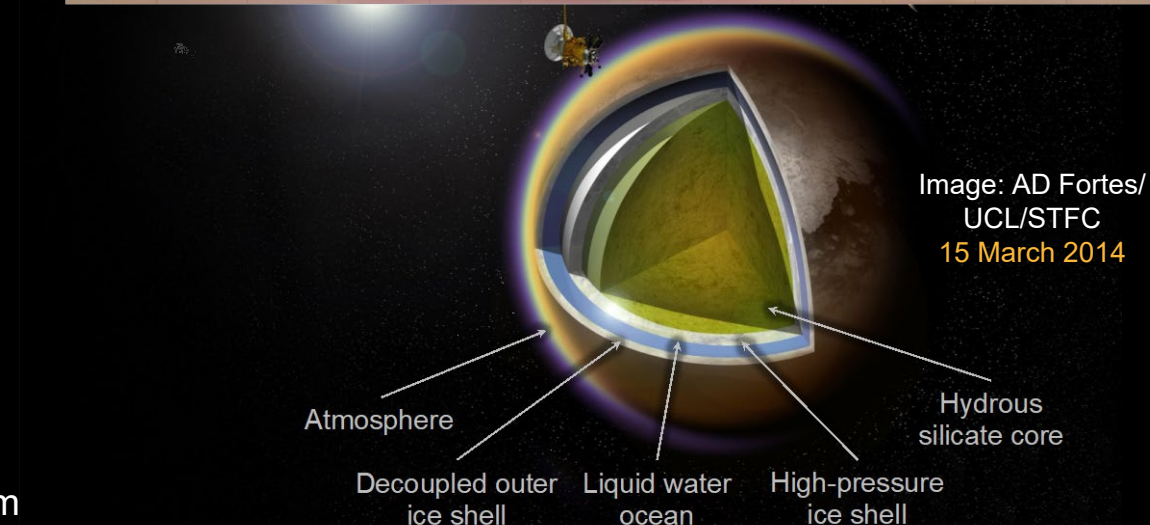
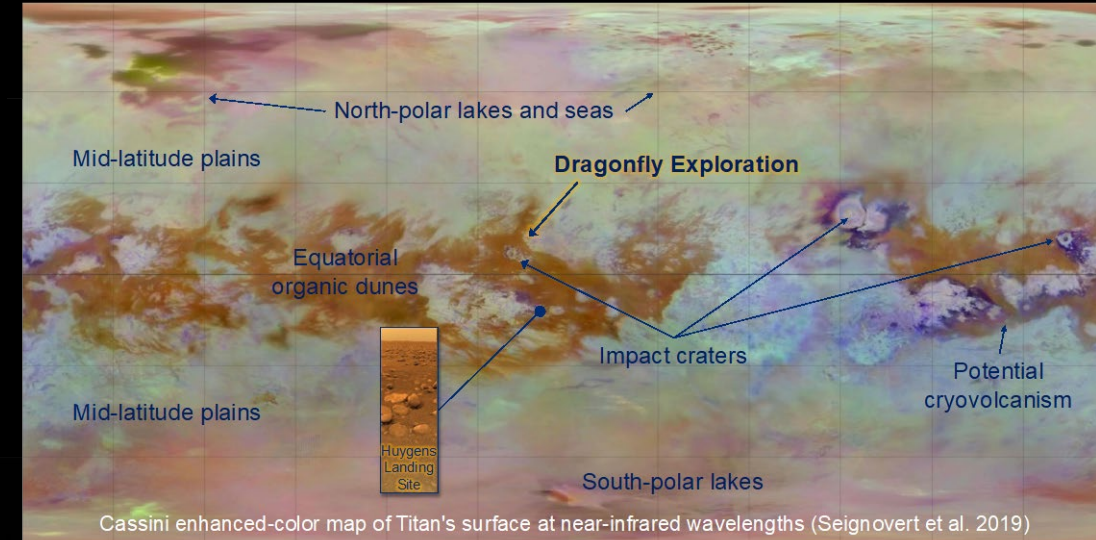
- Surface gravity: 14% of Earth's
- Atmosphere: pressure $\sim 1.5 \times$ Earth's; density $\sim 4 \times$ Earth's
 - Dense atmosphere, long days & seasons $\rightarrow$ calm conditions
 - Diurnal, seasonal, and spatial $\Delta T \sim 1$ K; winds ~ 1 -2 m/s
 - Vertically extended atmosphere
 - Removal of arrival energy; terminal velocity ~ 7 m/s ($\sim 20\%$ Earth's)
 - Efficient chilling of external surfaces
 - Atmospheric composition: nitrogen, few % methane
- Surface temperature: 94 K, -179°C
 - Far below viability limit for biota
 - Low tidal heating – heat flow only ~ 6 mW/m² so near-surface temperature gradient < 1 K/km
 - Bedrock composition: water ice
- Depth to interior water ocean: ~ 100 km
 - Pre-Cassini models (Sohl et al., 2003): 65-110 km
 - Recent thermal / gravity modeling (Kronrod et al., 2020) suggests 80-170 km



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Planetary protection considerations and implementation

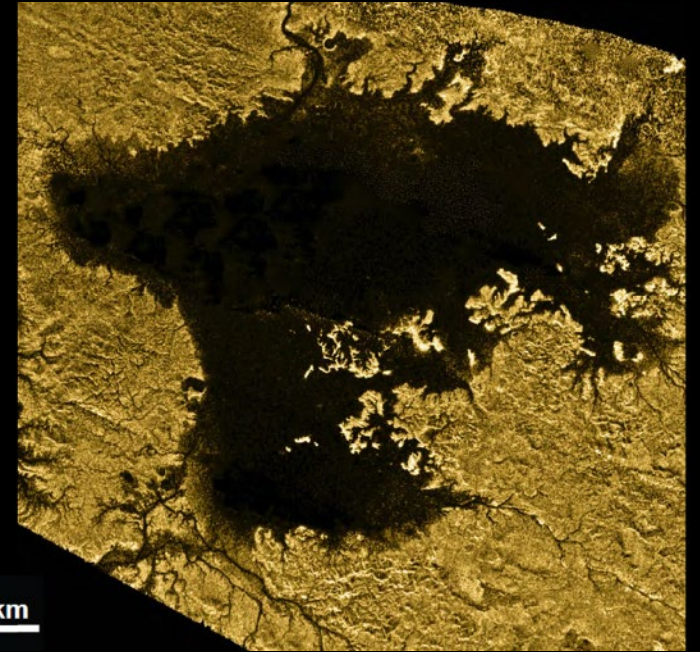


- NASA mission requirements require the demonstration that the current implementation of the Dragonfly mission to Titan would have a probability of less than 1×10^{-4} of a biological inoculation event into a potentially habitable extraterrestrial environment
 - NPR 8715.24 Planetary Protection Provisions for Robotic Extraterrestrial Missions, 24 September 2021
 - NASA-STD-8719.27 Implementing Planetary Protection Requirements for Space Flight, 30 August 2022
- Dragonfly has worked with NASA's Office of Planetary Protection, who coordinated science review of our categorization proposal, and Dragonfly was assigned Category II, which the Project Team is implementing
 - Category II “Of significant interest relative to the process of chemical evolution but only a remote chance that contamination by spacecraft could compromise future investigations.”
 - The Cassini orbiter and the Huygens probe were also classified as Category II
 - The Science Review also recommended several avenues of additional research that would be highly valuable regarding the nature and efficiency of different transport mechanisms on Titan and within its crust
- The Dragonfly Planetary Protection Requirements Document (PPRD) and Planetary Protection Implementation Plan (PPIP) have been reviewed by NASA's Planetary Protection Officer

Titan's Surface: Methane Hydrology



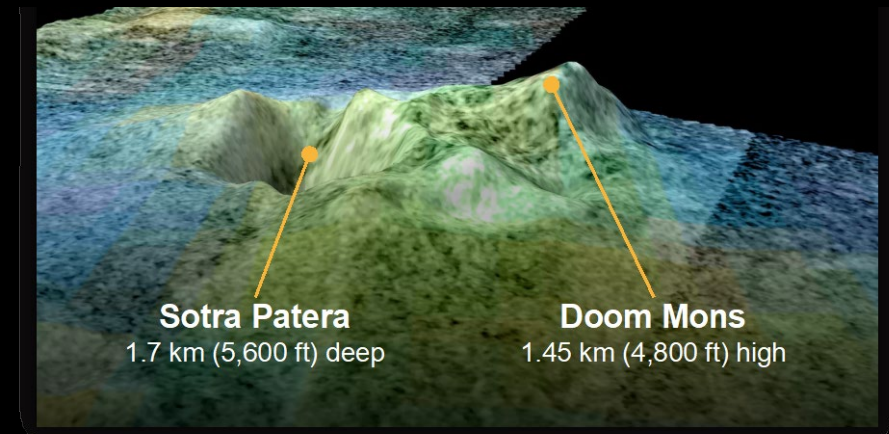
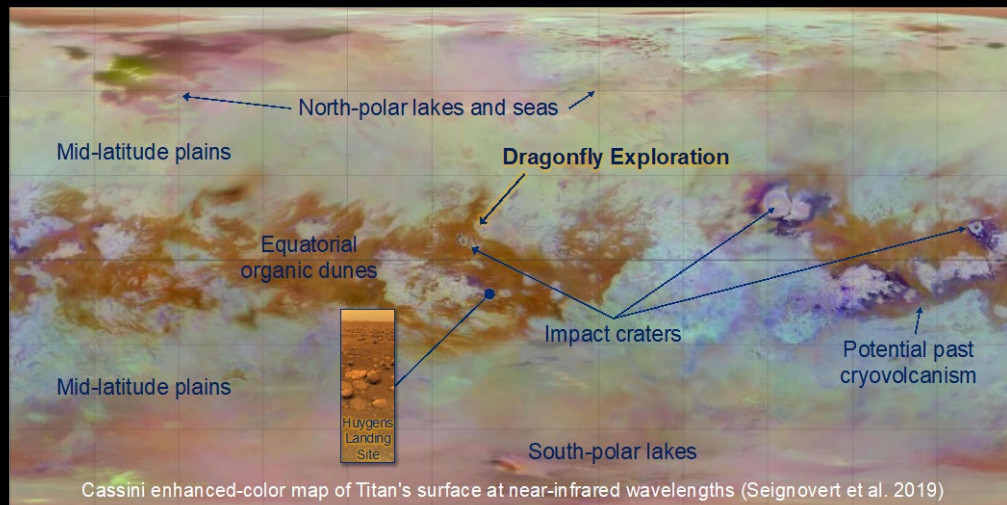
- Liquid methane and ethane at 94K are highly effective refrigerants
- Methane rainfall may wash some fraction of material from the Lander and flow into the shallow porous subsurface (or seas in an off-nominal scenario) where it will remain inert
- Methane/ethane seas occupy ~1% of Titan's surface, far from Dragonfly's targeted landing ellipse and exploration region
- Immersion of Dragonfly Lander in sea as a result of an off-nominal entry would simply result in chilled exterior
- Deposition of a separated MMRTG in a methane sea would result in efficient chilling of surfaces ($h > 20 \text{ W/m}^2\text{K}$, $T \sim 140\text{K}$).
- Any interaction of liquid methane/ethane with cryolava (water) results in instant solidification of cryolava surface, inhibiting further interaction. (Analog is pillow lava on Earth, or rainfall on lava flow.)



Titan's Surface: Potential for Cryovolcanism



- ~46% of surface imaged by Cassini RADAR. Only one good example of a possible cryovolcanic feature, Doom Mons (almost antipodal to Selk, ~7000 km away). Statistically there are probably one or two more in unobserved areas.
- No evidence that erupted fluid was water, possibly buried/remobilized hydrocarbons
- If fluid was aqueous, no evidence that it originated from the subsurface ocean
- No evidence that it is presently or even recently (100 Myr) active
- Analogy with terrestrial lava lakes and vents suggests if active, then exposed liquid $\ll 100 \times 100\text{m}$
- Even if it were active ($p \sim 0.001$, typical volcanic active/dormancy ratio) retraction of surface material to deep interior ($p \sim 0.001?$) hindered due to buoyancy of ice:water and thermal environment

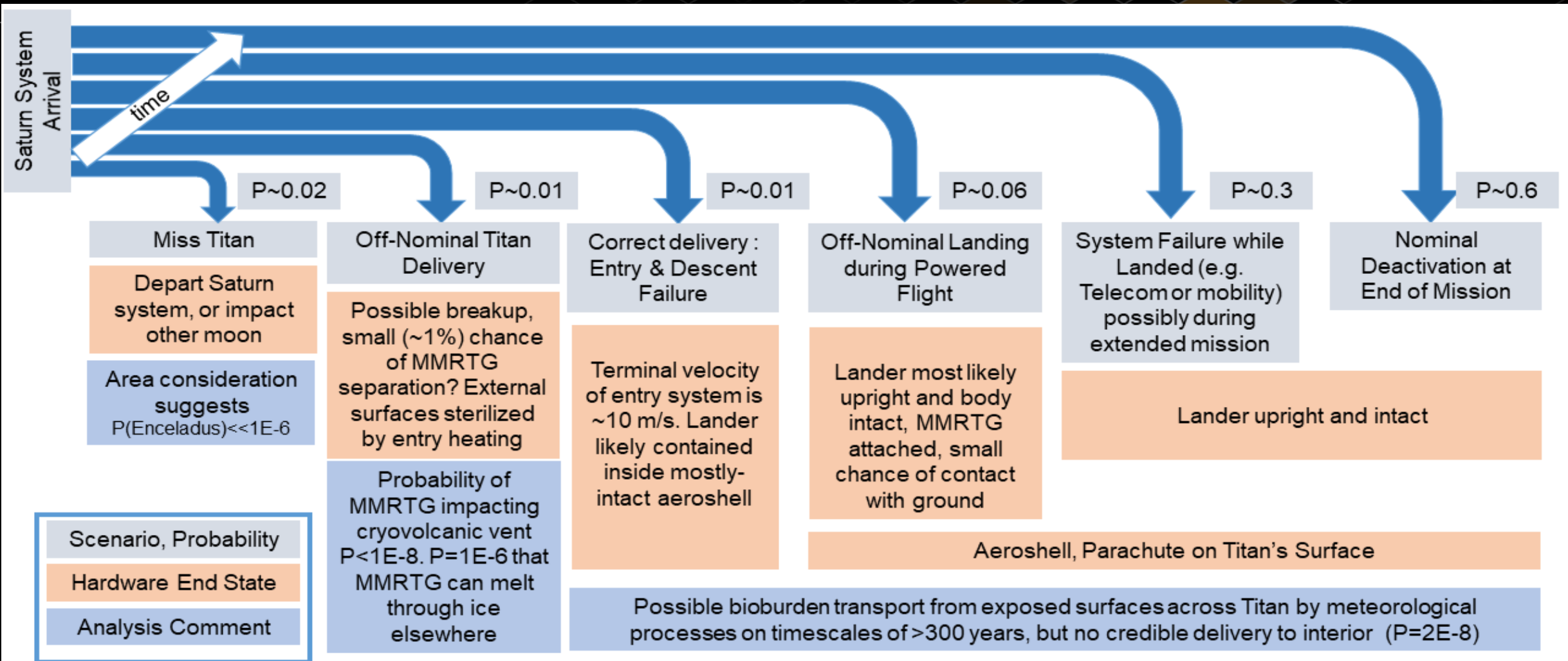


Potential for Access to Liquid Water

- Terminal velocity on Titan ~ 7 m/s (approx. impact speed falling off table on Earth)
 - Terminal velocity on Earth ~ 35 m/s $\rightarrow$ impact energy on Titan is 28x lower than on Earth
- In the event of entry breakup or other off-nominal landing that resulted in separation of the MMRTG from the Lander, minimal damage would be expected (e.g., bent fin)
- Not enough kinetic energy for the MMRTG to embed itself deeply in surface, unless in exceptionally soft material (e.g. penetration ~ 14 cm in organic sand dune). Burial in sediment would (as on Mars, Shotwell et al., 2017) simply result in sublimation of any ice away from the warm zone, sealing in any bioburden
- A simple averaged convective + radiative thermal balance model indicates the surface temperature of exposed MMRTG surfaces on Titan would be ~ 180 - 250 K
- Thermal conductivity of water ice is strongly temperature-dependent. At Titan's low temperatures, surface temperatures of an MMRTG somehow embedded in ice would be below the melting point of water.
- Thermal drilling in cold ice is ineffective, $\gg$ Pu $\frac{1}{2}$ -life to penetrate to ocean



Probabilistic Assessment of Hardware End-States



Per Cromwell's Rule, all $P > 0$. We assign $P = 1\text{E-}6$ for scenarios assessed to be 'physically impossible' to allow for epistemological uncertainty

Dragonfly Planetary Protection Protocols



- The Category II classification drives Dragonfly requirements, documentation, and implementation practices
- The mission shall build, maintain, and integrate instruments, conduct System Integration and Test build, and maintain the Flight System, in ISO-8 cleanroom or better
- All of the Dragonfly prime hardware, subassemblies, components and ground support equipment will be cleaned with certified precision cleaning
- Proper hardware shipment and storage, facility certification, and personnel training are essential for Contamination Control and Planetary Protection

Summary



- Although transport of terrestrial material from the Dragonfly Lander to locations on Titan's surface is technically not impossible, comprehensive evaluation of transport and interaction scenarios shows none that credibly permit transfer of material from the lander to the subsurface ocean
- Heat output of a single MMRTG is too small to permit thermal drilling through the ~100-km-thick ice crust
- Off-nominal deposition in methane sea would result in efficient chilling of exposed MMRTG surfaces (heat transfer coefficient $h > 20 \text{ W/m}^2\text{K}$, $T \sim 140 \text{ K}$)
- Combination of individually improbable circumstances could potentially allow transiently habitable microenvironments on the surface of the MMRTG if buried in porous/insulating ice-bearing material. However, these could persist only for 1-2 Pu half-lives before freezing to unviable temperatures
- Ongoing research into efficiency of various transport mechanisms on Titan (aeolian, fluvial, pluvial, etc.) and within its crust (methane hydrology, cryovolcanism, impact) and their potential to carry or concentrate bioburden will be highly valuable
- The Dragonfly project has worked with NASA's Office of Planetary Protection, who coordinated science review of our categorization proposal, and Dragonfly has been assigned Mission PP Category II, October 2022
- The Planetary Protection Officer has reviewed and concurred with the Dragonfly Planetary Protection Requirements Document (PPRD) and Planetary Protection Implementation Plan (PPIP), February 2023

Dragonfly Student and Early Career Guest Investigator Program: Broadening Mission Participation

<https://dragonfly.jhuapl.edu/Student-Opportunities/>



- Goals of Program

- Extend opportunities for graduate students to work with *Dragonfly* scientists and engineers
- Encourage broader participation by making it easier for students who **don't** already have connections to *Dragonfly* or NASA spacecraft missions and/or who **don't** have a planetary science background
- Provide networking opportunities and expand training of the next generation of mission team members and leaders

Quick et al., 2021:
<https://www.hou.usr.a.edu/meetings/lpsc2021/pdf/2653.pdf>

Cohort	Project	Dragonfly Team Mentors	Grad Student Guest Investigators
1 2021-23	Seismic investigation of Titan's interior using full waveform modeling	Mark Panning, JPL	Andrea Bryant , University of Chicago, Physics
	Spectral/compositional library for interpretation of DragonCam / DraGNS measurements	Shannon MacKenzie & Richard Miller, APL	Karla Negrete , University of Maryland Baltimore County (UMBC), Mechanical Eng.
	Development of the DragonCam microscopic imager multispectral LED arrays	Jorge Núñez, APL	Brianna Wylie , Florida Agricultural & Mechanical University (FAMU), Mechanical Eng.
2 2022-24	Tuning DraGNS' Interpretations to Titan's Surface	Ann Parsons, GSFC & Patrick Peplowski, APL	Anna Engle , Northern Arizona Univ. (NAU), Astronomy and Planetary Sci.
	Development of DraMS Instrument Operational Guidelines	Melissa Trainer, GSFC	Will Suero Amparo , New Jersey Institute of Tech., Biomedical Engineering
3 2022-24	Volatility of Titan-Relevant Compounds and Implications for Dragonfly Analyses	Morgan Cable & Rob Hodyss, JPL	A'Laura Hines , George Mason University, Chemistry
	Building a Library of Diagnostic Fracture Patterns and Erosional Morphologies for Interpretation of DragonCam Images	Ellen Stofan and Dr. Emily Martin, Smithsonian NASM	Shahrose Khan , Univ. of California San Diego, Aerospace Engineering
	Background Research for DrEAM* Aeroscience Experiment	Aaron Brandis, NASA Ames	Alyssa Vellucci , Univ. of Texas Dallas, Mech. Eng.
4 2023-25	Data visualization library for Dragonfly science operations	Jake Strang, APL	M. René Castillo , Ohio State Univ., Geophysics
	Dragonfly science planning tool development	Sarah Hasnain & Hari Nair, APL	Navya Annapareddy , Univ. Virginia, Data Science



DRAGONFLY

<http://dragonfly.jhuapl.edu>