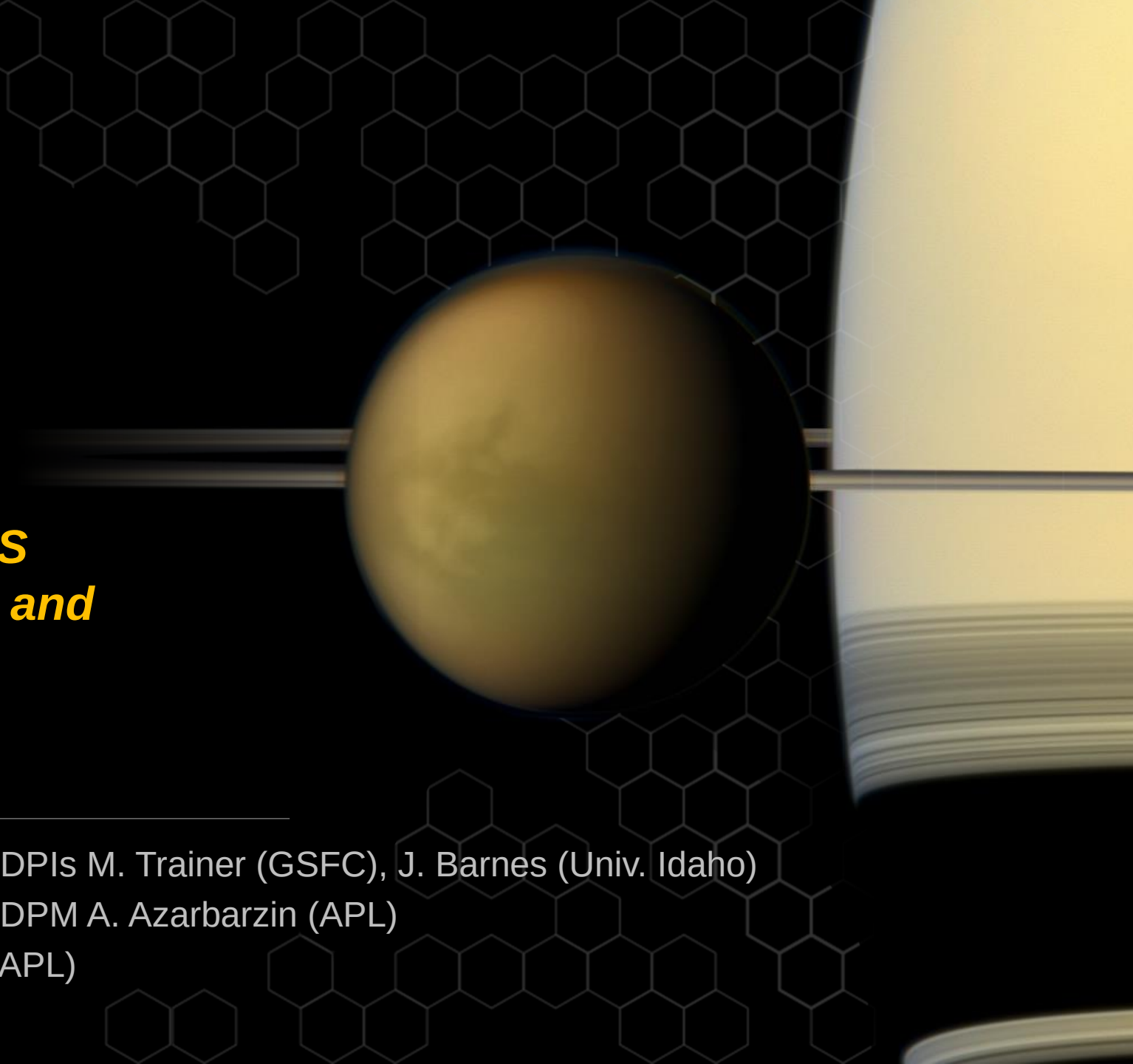
DRAGONFLY

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



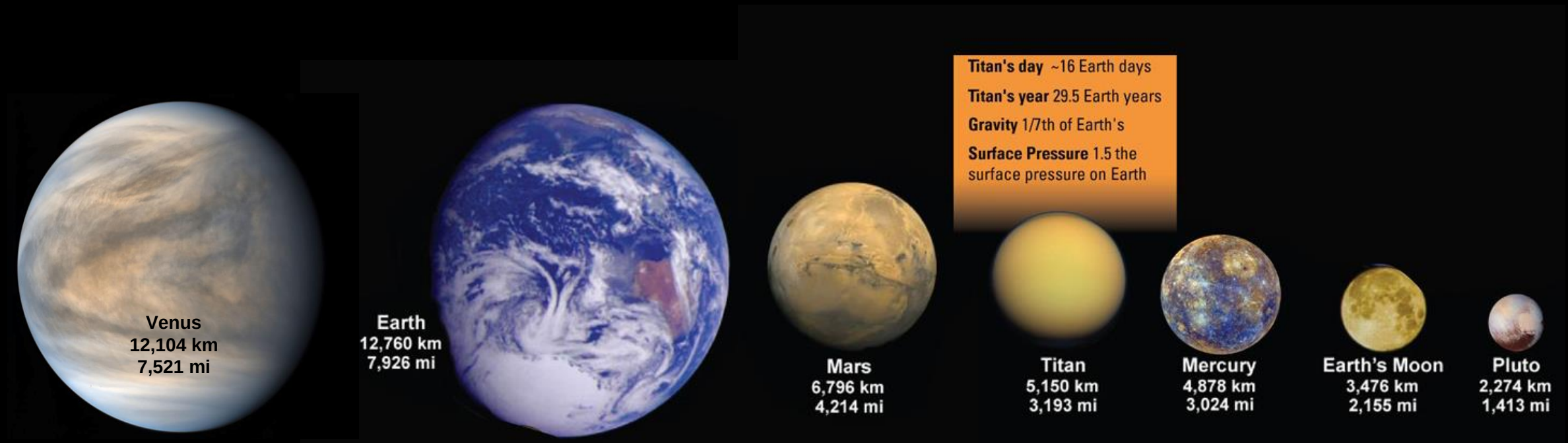
Dragonfly Update to the NAS Committee on Astrobiology and Planetary Sciences

22 October 2024

Principal Investigator: E. Turtle (APL); DPIs M. Trainer (GSFC), J. Barnes (Univ. Idaho)
Project Manager: R. Fitzgerald (APL); DPM A. Azarbarzin (APL)
Mission System Engineer: K. Hibbard (APL)

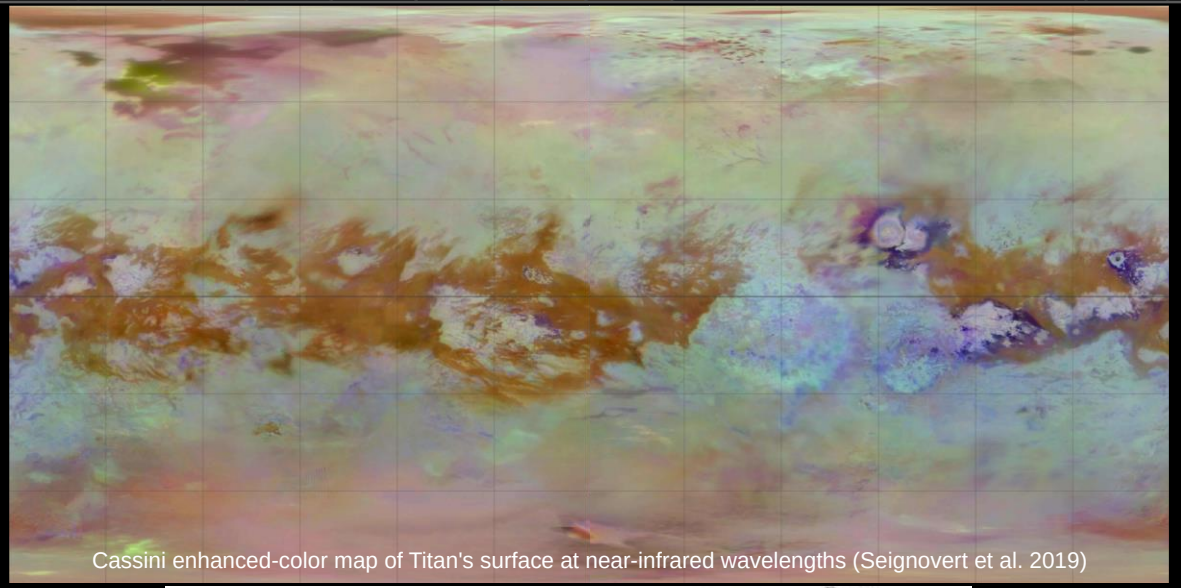

Dragonfly Annual Fall Meeting

Titan's unique environment

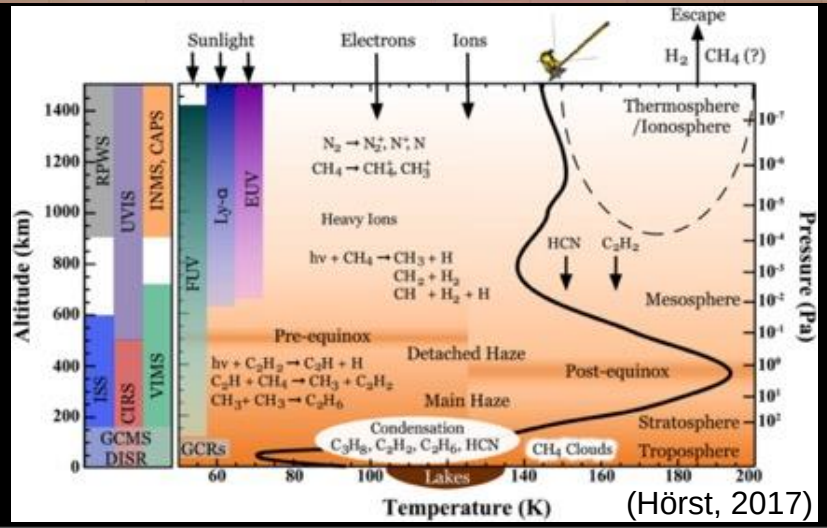


Titan's unique environment has been well characterized

- 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× pressure & 4x atmospheric density at Earth's surface
  - Dense atmosphere, long days, long seasons ➔ calm conditions
  - Diurnal, seasonal, and spatial ΔT ~1 K; winds ~1-2 m/s
  - Vertically extended atmosphere
- 8-11 AU from Earth: 1-way light-time ~70-90 min
  - Autonomous flights and science operations



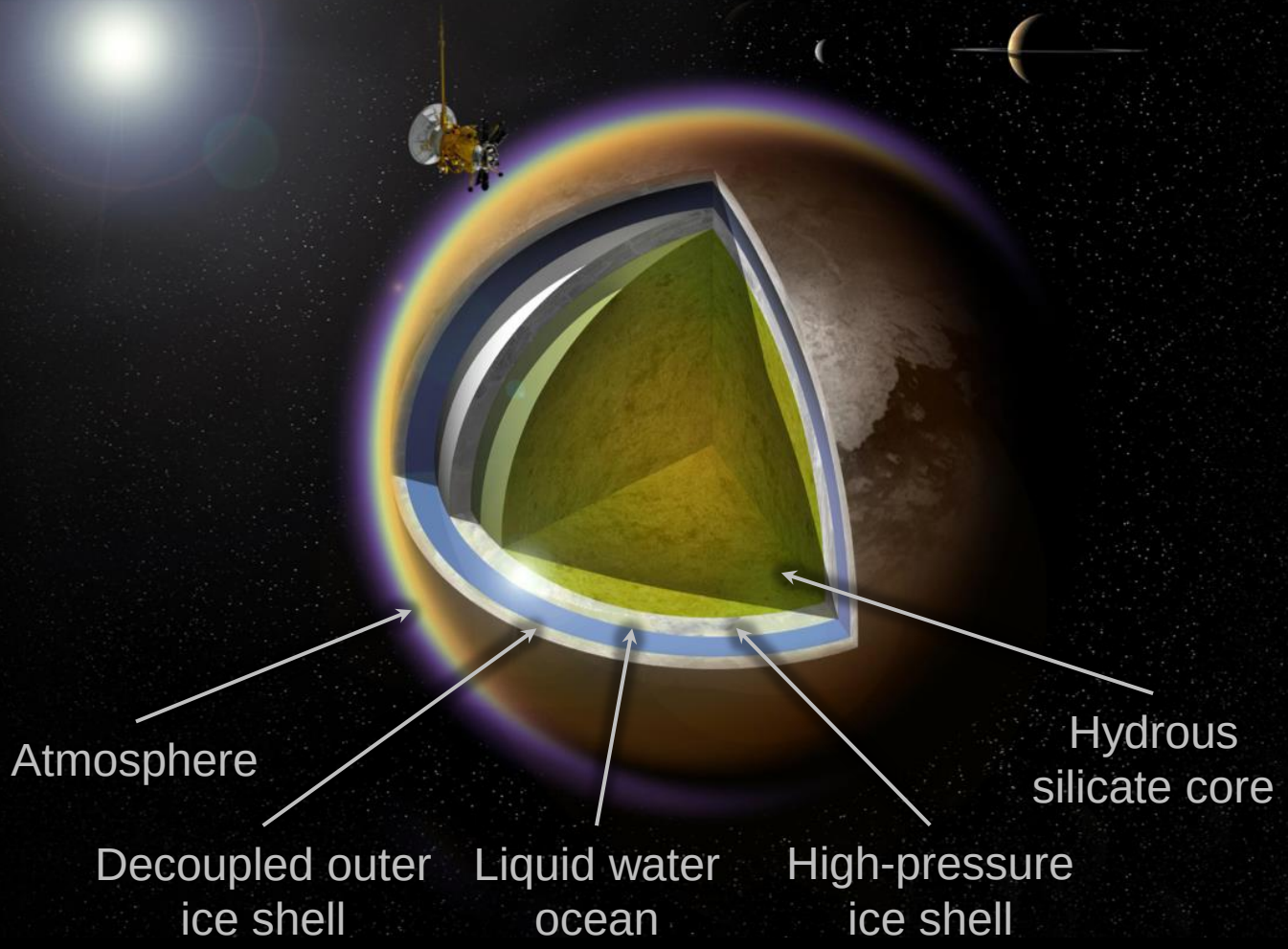
Cassini enhanced-color map of Titan's surface at near-infrared wavelengths (Seignovert et al. 2019)



(Hörst, 2017)

Titan's unique environment has been well characterized

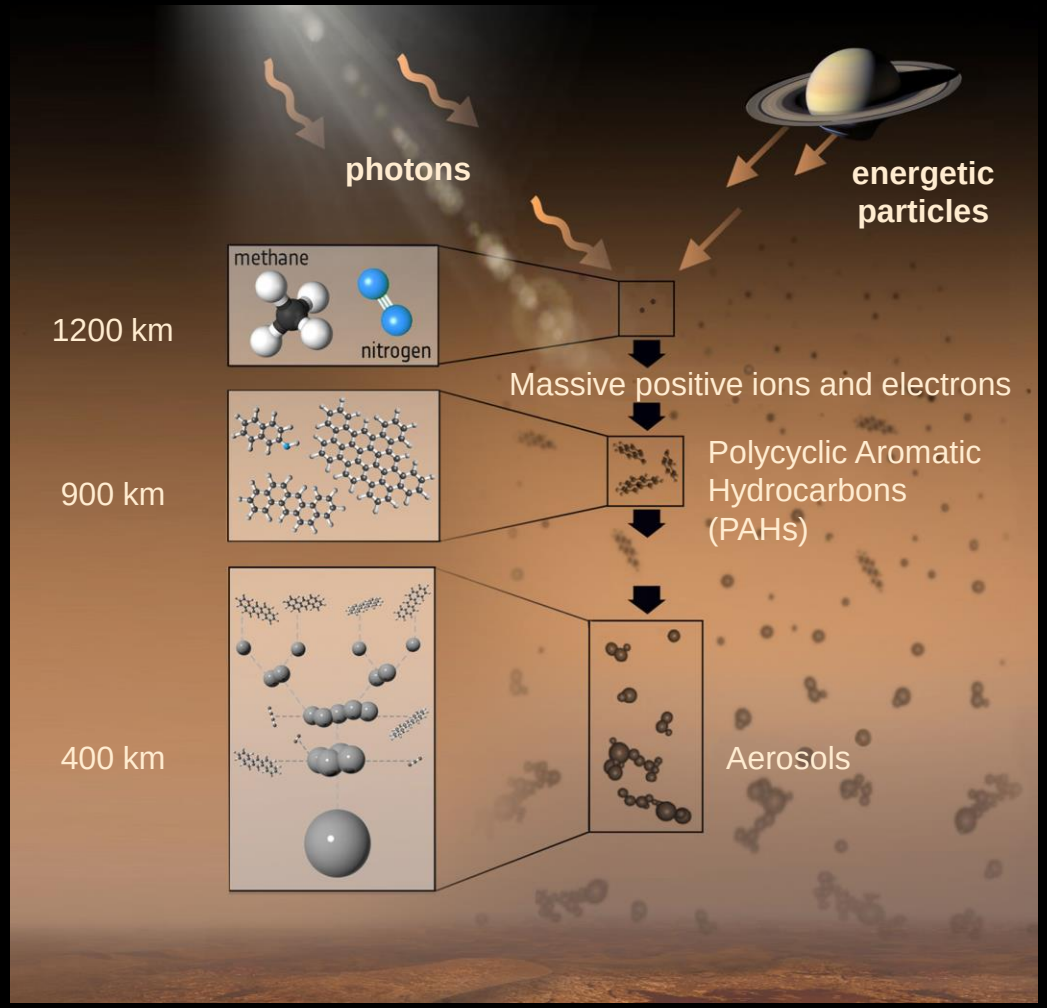
- Deep interior ocean of liquid water
  - Decoupled ice shell ~80–170 km based on recent thermal / gravity modeling (Kronrod et al., 2020)



Complex organic chemistry

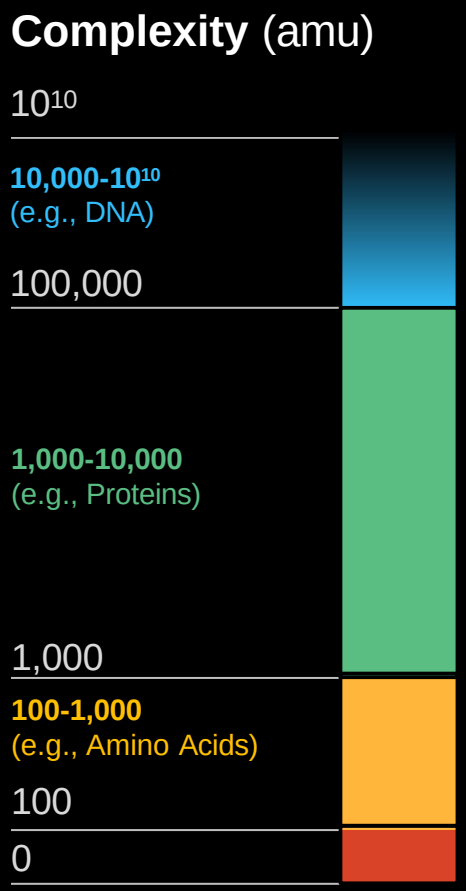
- Photochemistry in upper atmosphere produces complex carbon molecules
- Rich organic material covers the surface
- Potential for organic compounds to have mixed with liquid water for extended periods of time at the surface

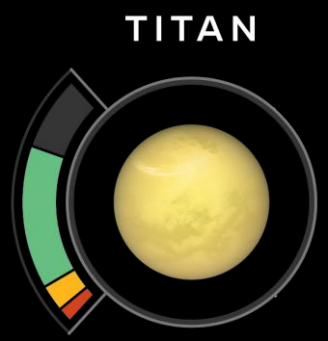
Titan is a singular destination for understanding the chemical processes on our own planet that supported the development of life



Molecular complexity and carbon abundance

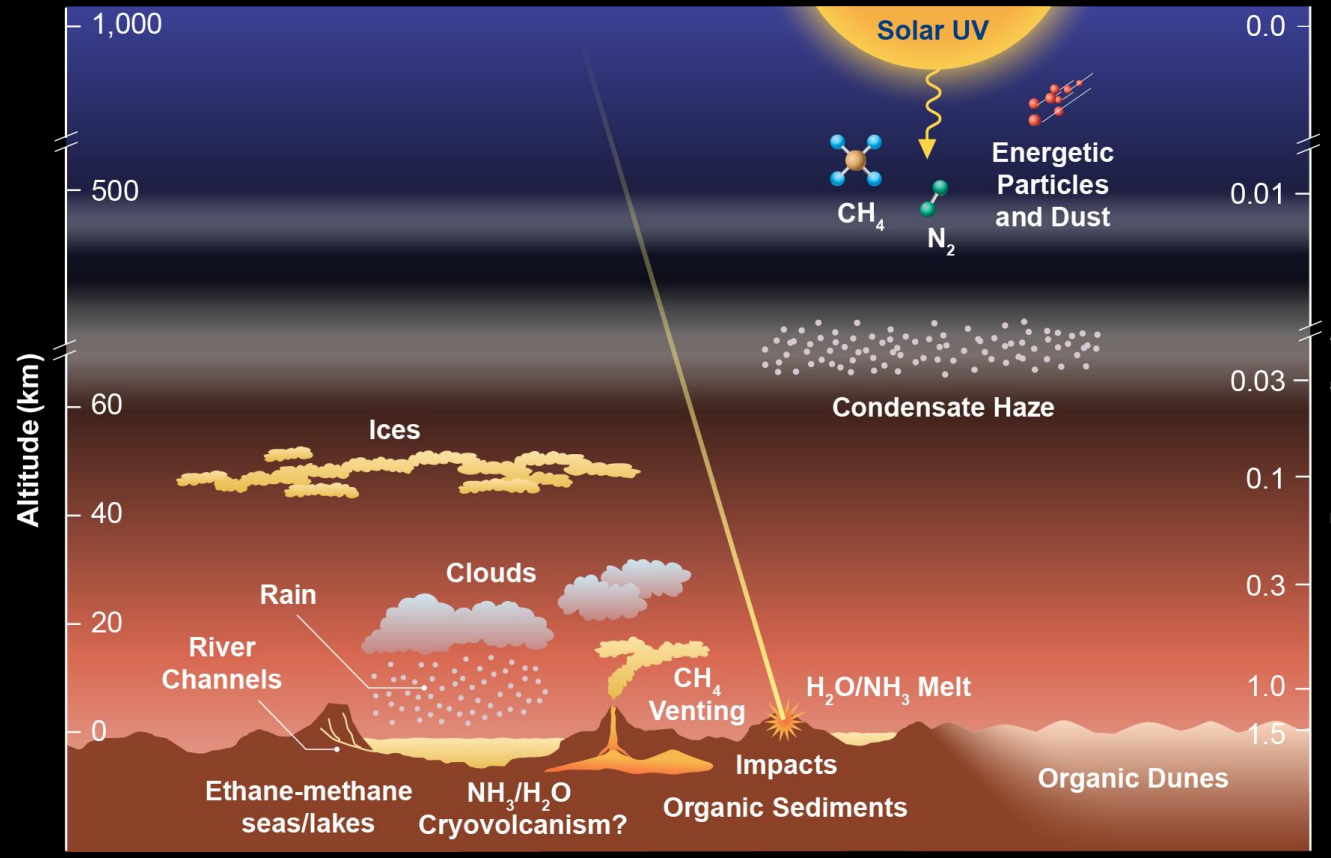
Most complex (heaviest) carbon bearing molecule





Key ingredients necessary for life

- Energy
  - Sunlight, photochemistry
- Organic material
  - Abundant complex organics
- **Two** liquids
  - Water
    - available at the surface in Titan's past
    - interior ocean
  - Methane
    - active methane cycle like Earth’s water cycle
    - liquid methane could support development of alternate biological systems



On Titan, we can study prebiotic chemistry in the full context of a planetary environment with Earth-like surface processes

On Titan, the molecules that have been raining down like manna from heaven for the last 4 billion years might still be there largely unaltered, deep-frozen, awaiting the chemists from Earth.

— Carl Sagan, *Pale Blue Dot*

What makes a world habitable?

Dragonfly will investigate Titan's methane hydrological cycle, geologic processing, and opportunities for organics and liquid water to mix

What chemical processes led to the development of life?

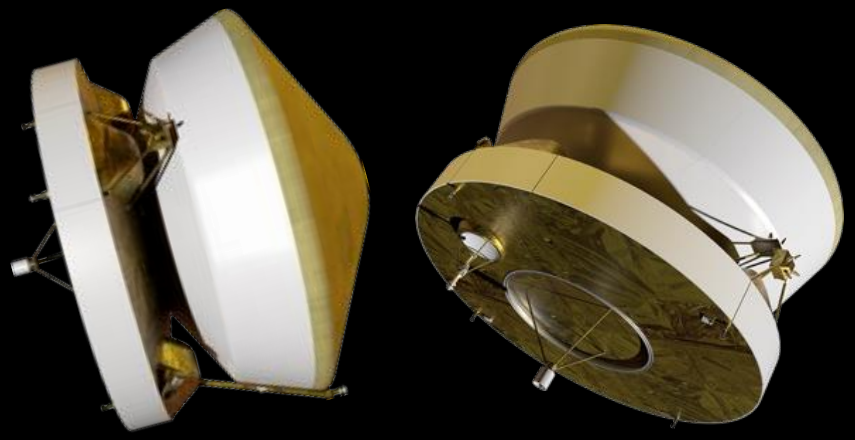
Dragonfly will inventory the diversity of complex carbon-rich materials and the chemistry at work on Titan's surface, revolutionizing our understanding of prebiotic chemistry in the Solar System

Has life developed elsewhere in our Solar System?

Dragonfly will make measurements that allow for a broad, contextualized search for potential chemical biosignatures

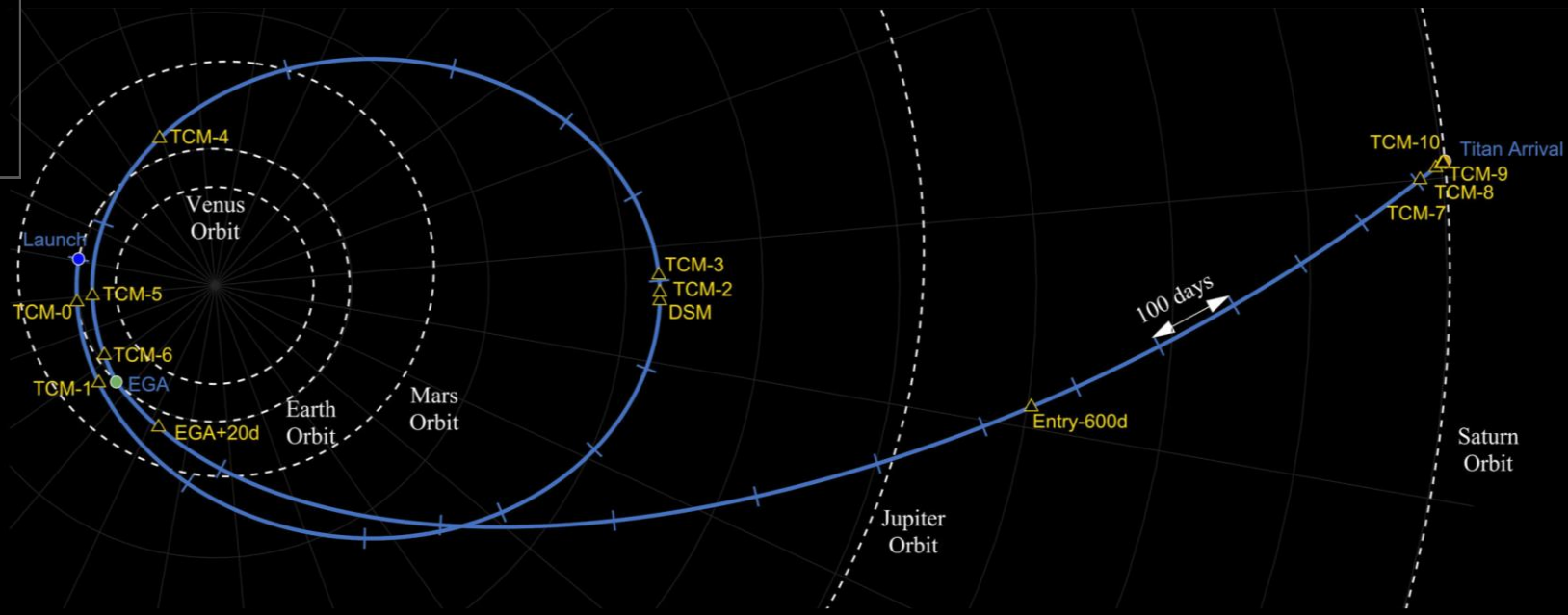
Dragonfly mission elements – Cruise Stage

Spacecraft = Cruise Stage + Entry Vehicle



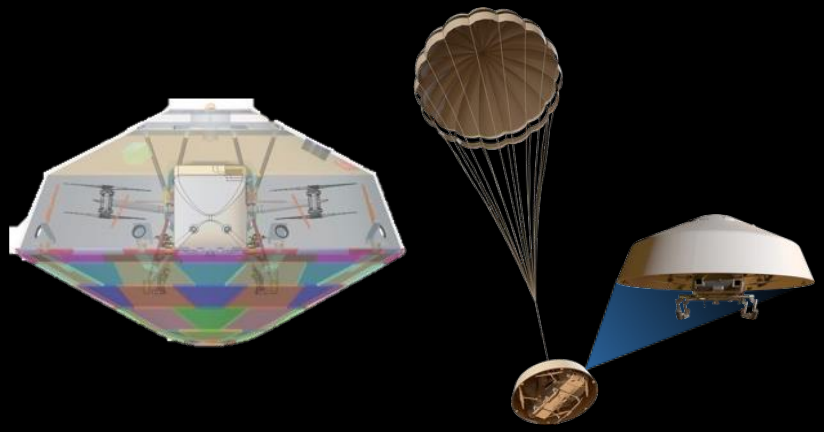
- ~6.5-year cruise
- Cruise stage provides functions needed for travel between Earth and Titan:
  - Propulsion, guidance & control, and telecommunications
- Powered and controlled by the Lander

- Rotorcraft/Lander: APL, Moog, Collins, Penn State, Sikorsky
- Aeroshell & Cruise Stage: Lockheed Martin
- EDL Analysis, Parachutes: NASA Ames & NASA Langley
- MMRTG: DOE & RPS Office
- Mission Ops / Navigation: APL & JPL



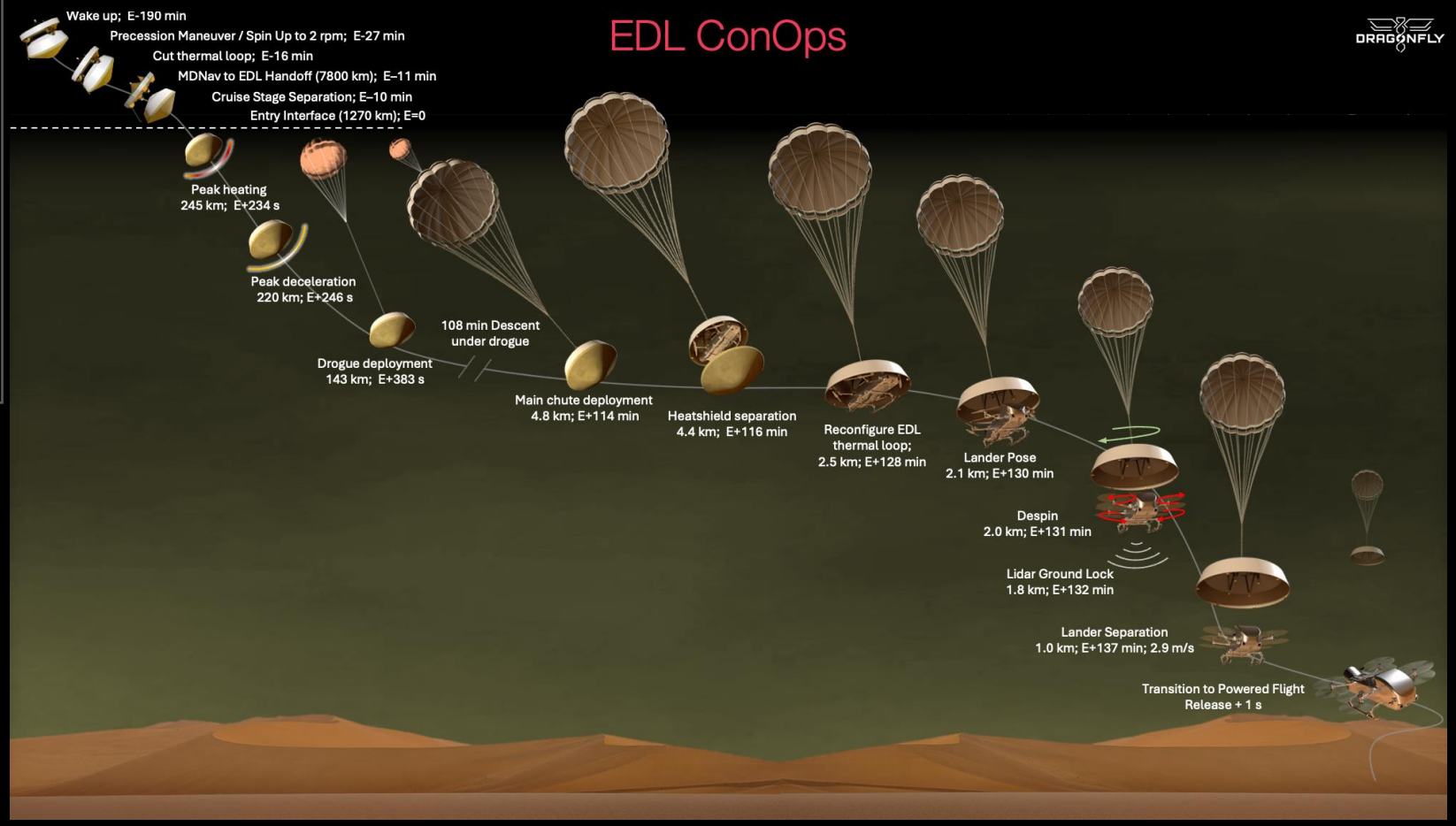
Dragonfly mission elements – Entry Vehicle

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

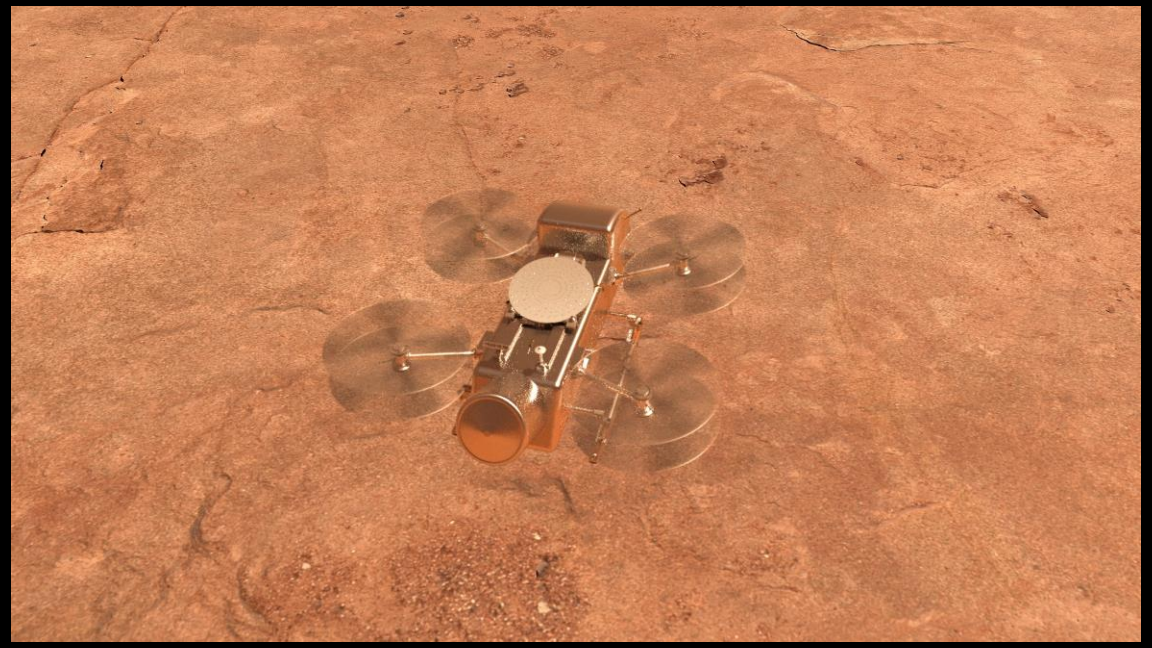


- Rotorcraft/Lander: APL, Moog, Collins, Penn State, Sikorsky
- Aeroshell & Cruise Stage: Lockheed Martin
- EDL Analysis, Parachutes: NASA Ames & NASA Langley
- MMRTG: DOE & RPS Office
- Mission Ops / Navigation: APL & JPL

- EDL Assembly provides functions for safe descent through Titan's atmosphere:
  - Heatshield, backshell, parachute system, separation systems, and low-gain antenna



Dragonfly mission elements – Rotorcraft Lander

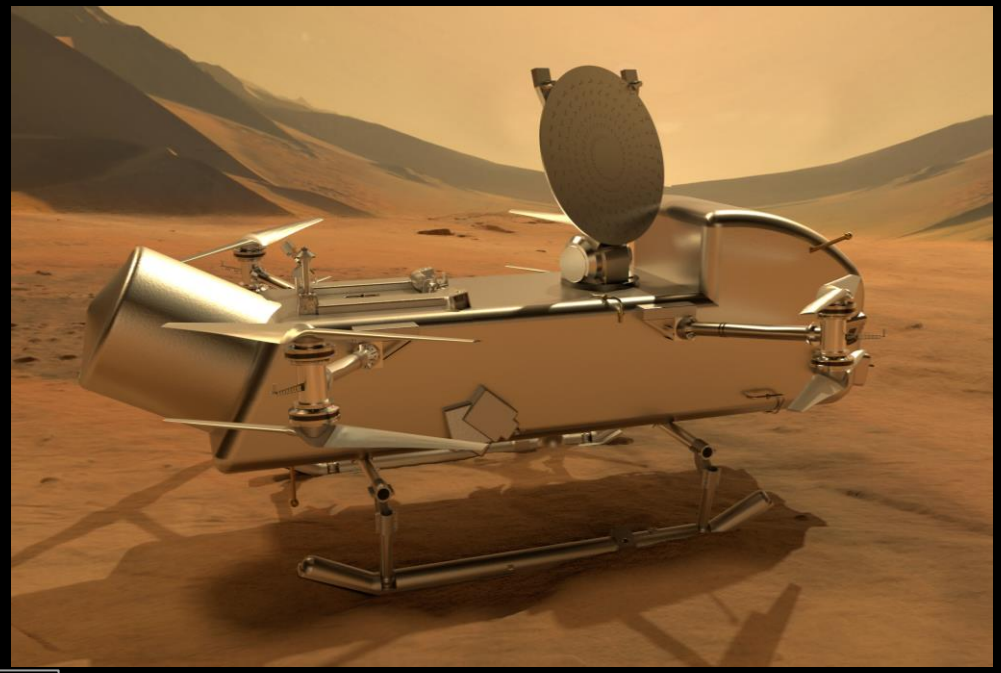


Flight configuration with HGA stowed

- Rotorcraft/Lander: APL, Moog, Collins, Penn State, Sikorsky
- Aeroshell & Cruise Stage: Lockheed Martin
- EDL Analysis, Parachutes: NASA Ames & NASA Langley
- MMRTG: DOE & RPS Office
- Mission Ops / Navigation: APL & JPL

- **Transport entire payload – 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 mission elements – Rotorcraft Lander

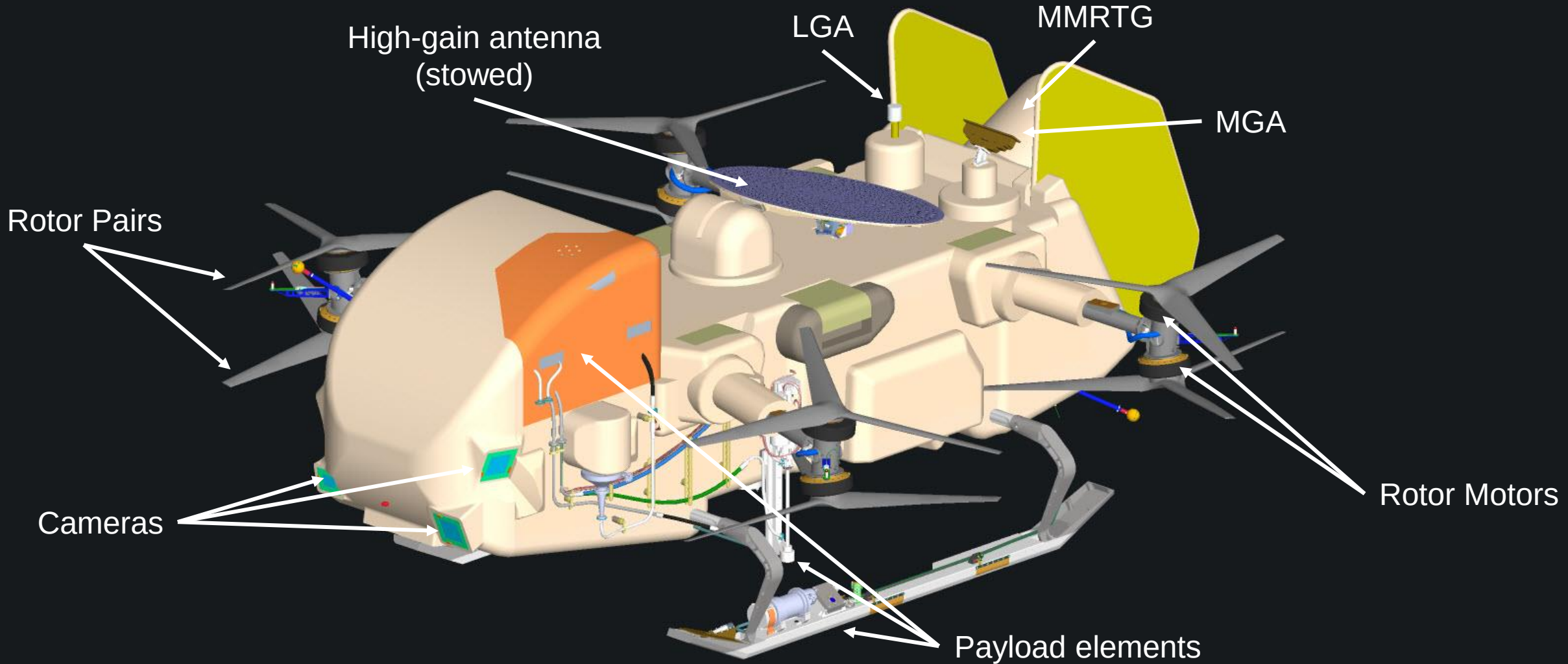


Surface configuration with HGA deployed

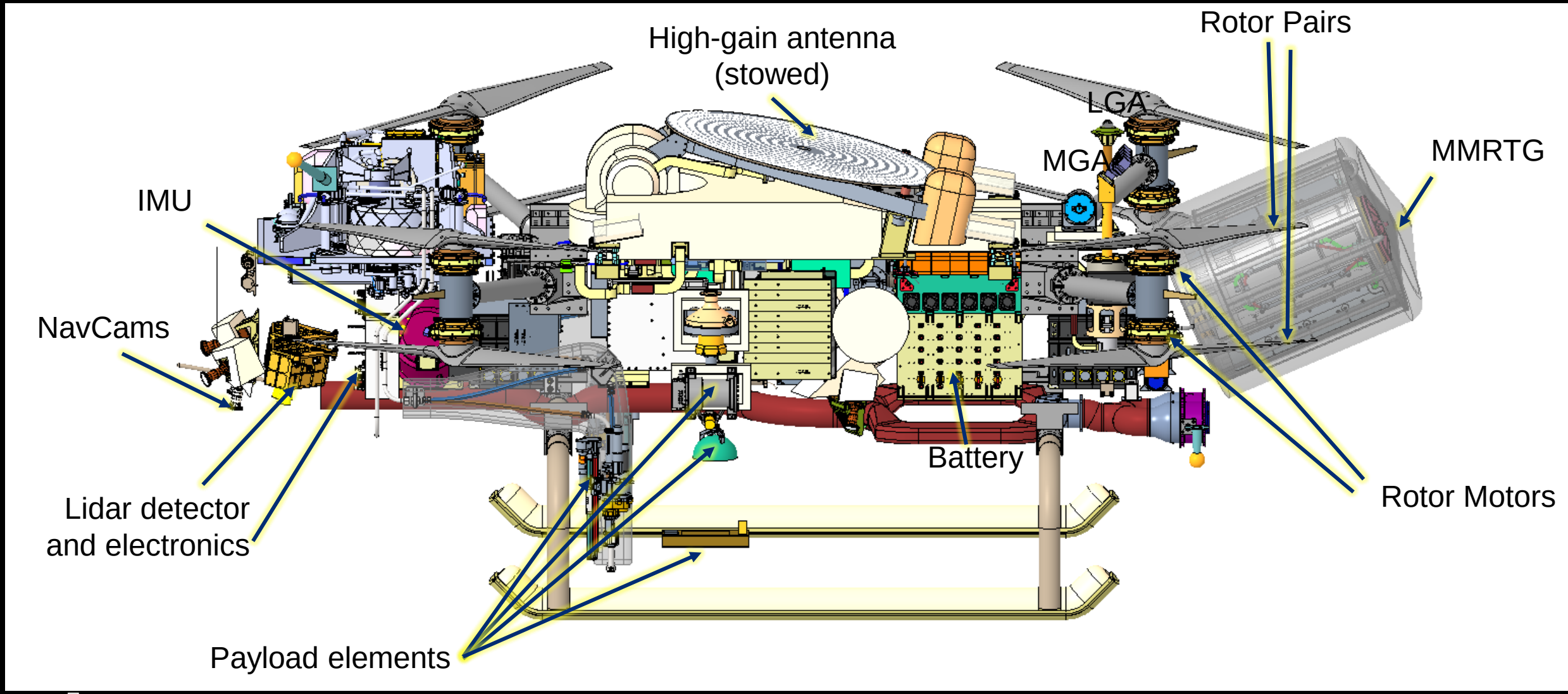
- Rotorcraft/Lander: APL, Moog, Collins, Penn State, Sikorsky
- Aeroshell & Cruise Stage: Lockheed Martin
- EDL Analysis, Parachutes: NASA Ames & NASA Langley
- MMRTG: DOE & RPS Office
- Mission Ops / Navigation: APL & JPL

- **Transport entire payload – 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

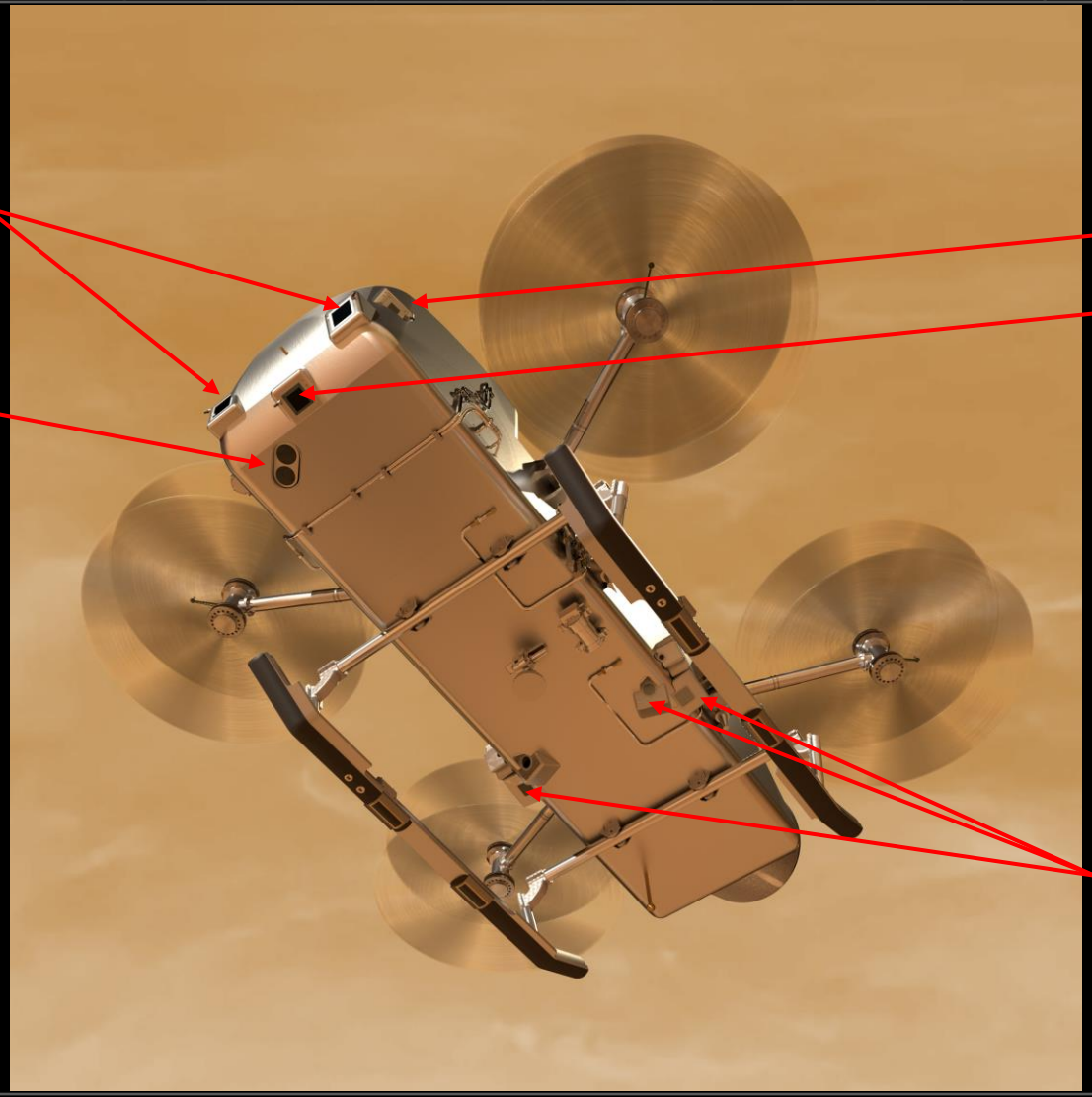
Dragonfly mission elements – Rotorcraft Lander



Dragonfly mission elements – Rotorcraft Lander



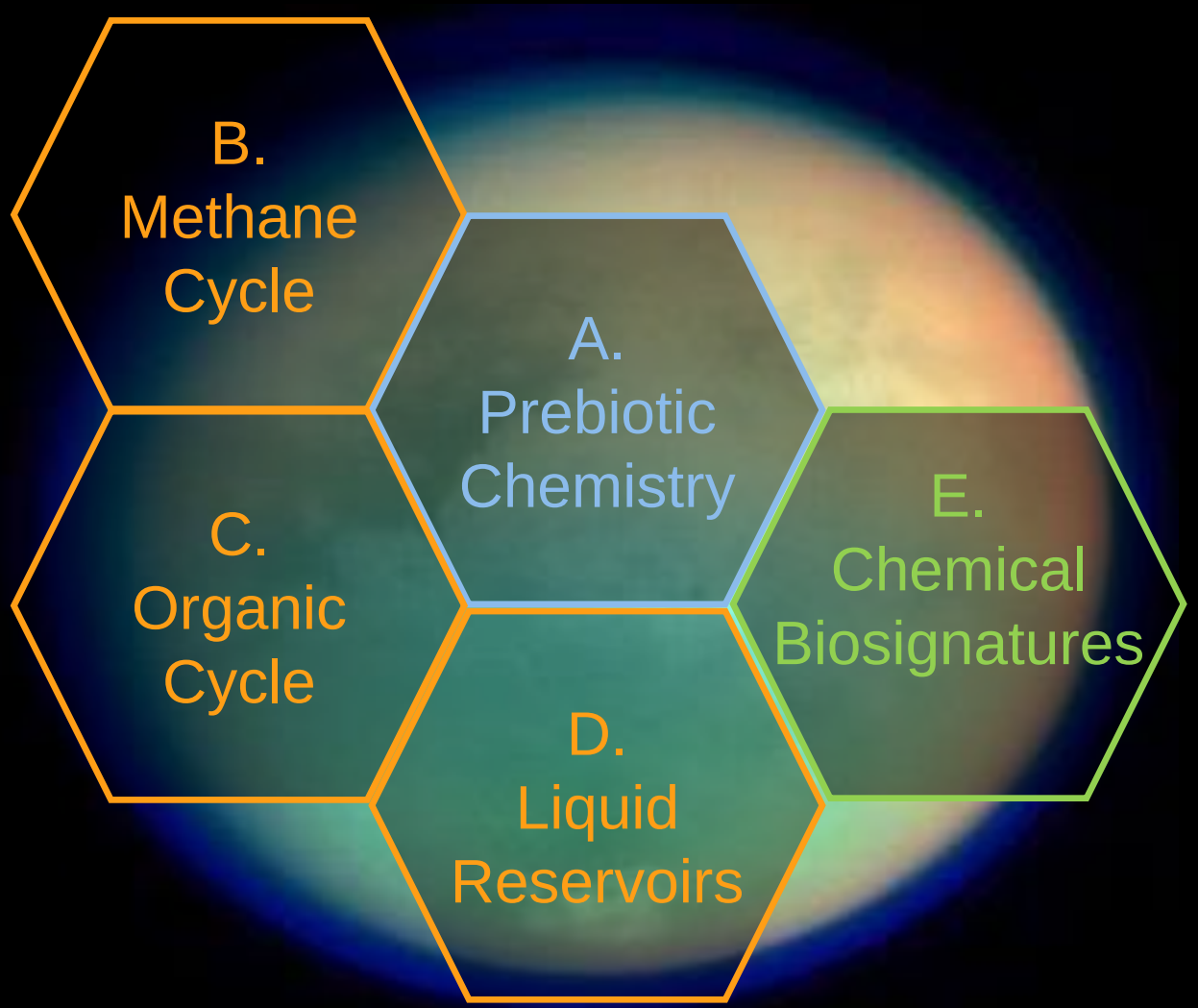
Dragonfly autonomous aerial flight



Dragonfly mission science

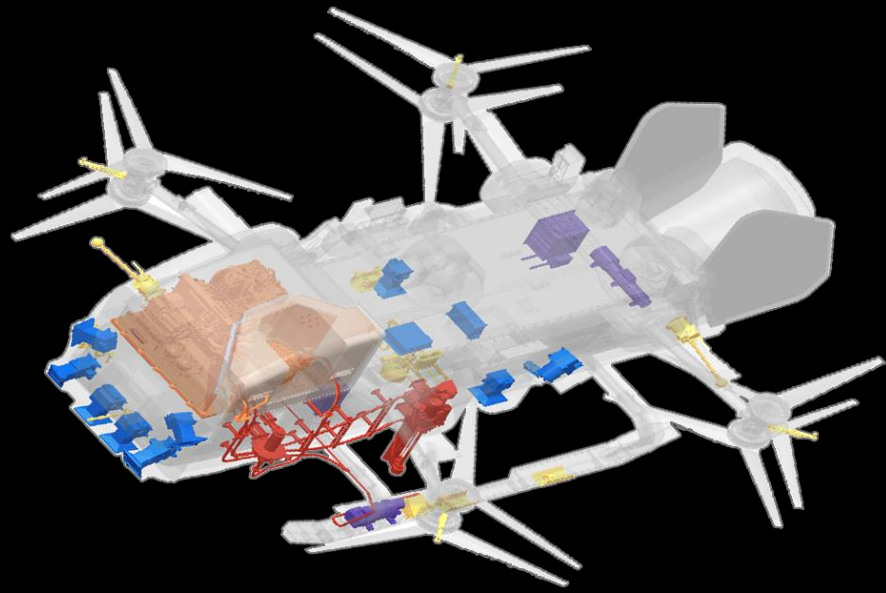
Barnes et al., *PSJ,* 2021
https://doi.org/10.3847/PSJ/abfdcf

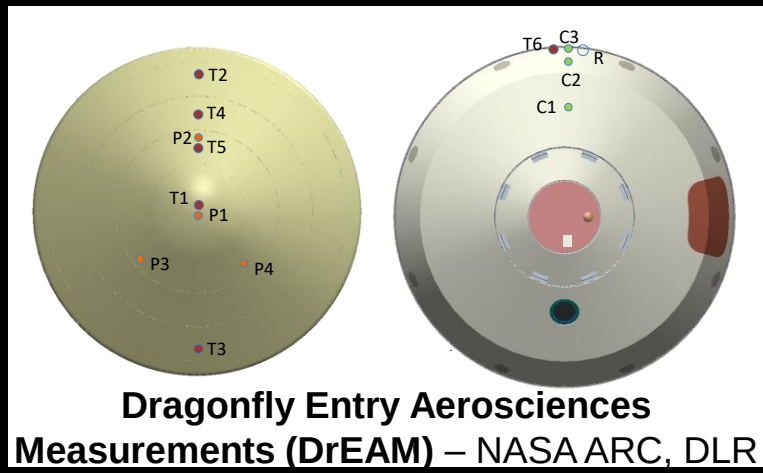
- Prebiotic chemistry
  - Analyze chemical components and processes at work that produce biologically relevant compounds
- Habitable environments
  - Measure atmospheric conditions, identify methane reservoirs, and determine transport rates
  - Constrain processes that mix organics with past surface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



Multidisciplinary science measurements –
Evaluate prebiotic chemistry in the context of Titan's environment

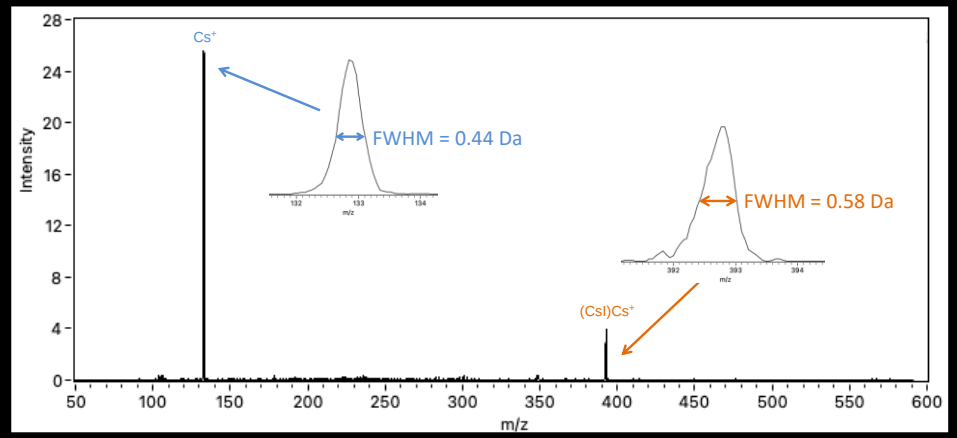
- **DraMS**: Mass Spectrometer – GSFC, CNES
  - Analyze chemical components and processes that produce biologically relevant compounds
- **DrACO**: Drill for Acquisition of Complex Organics – Honeybee
  - Rotary-percussive drill to sample and pneumatically transfer surface material to DraMS
- **DraGNS**: Gamma-ray and Neutron Spectrometer – APL, LLNL
  - Measure bulk elemental surface composition, including minor inorganics, to classify surface materials
- **DraGMet**: Geophysics & Meteorology – APL, JAXA
  - Monitor atmospheric conditions, constrain regolith properties, detect and characterize level of seismic activity
- **DragonCam**: Camera Suite – MSSS
  - Characterize landforms and surface processes at multiple scales, surface & aerial imaging



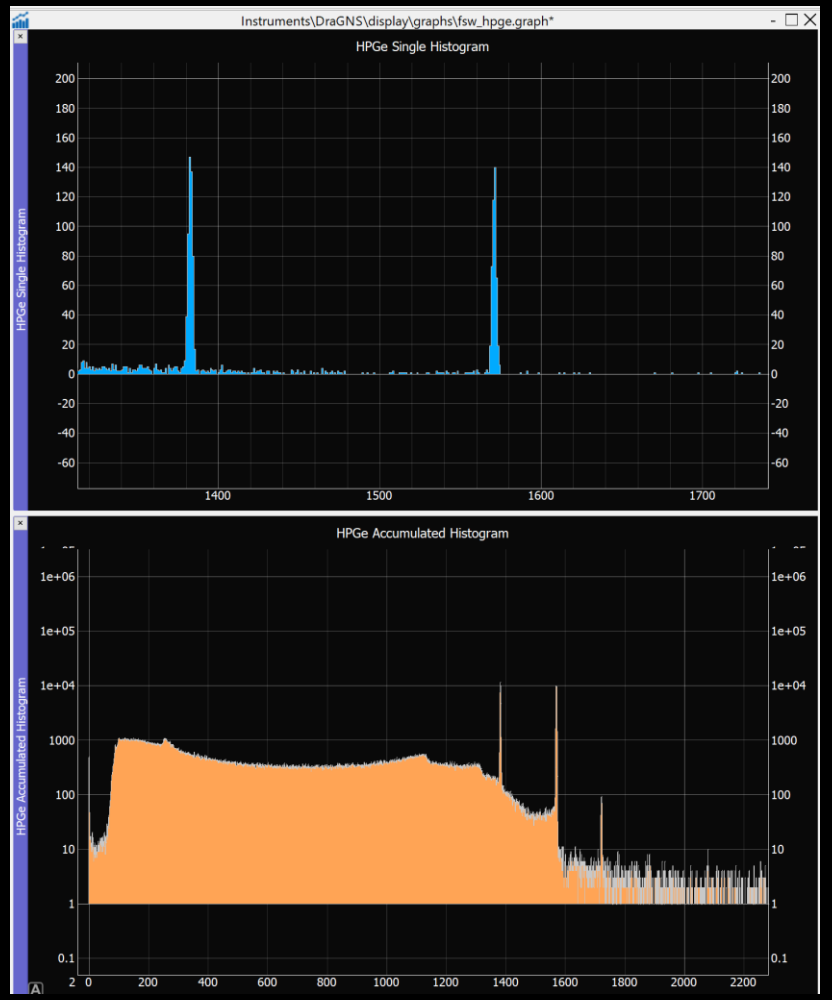


Dragonfly Entry Aerosciences Measurements (DrEAM) – NASA ARC, DLR

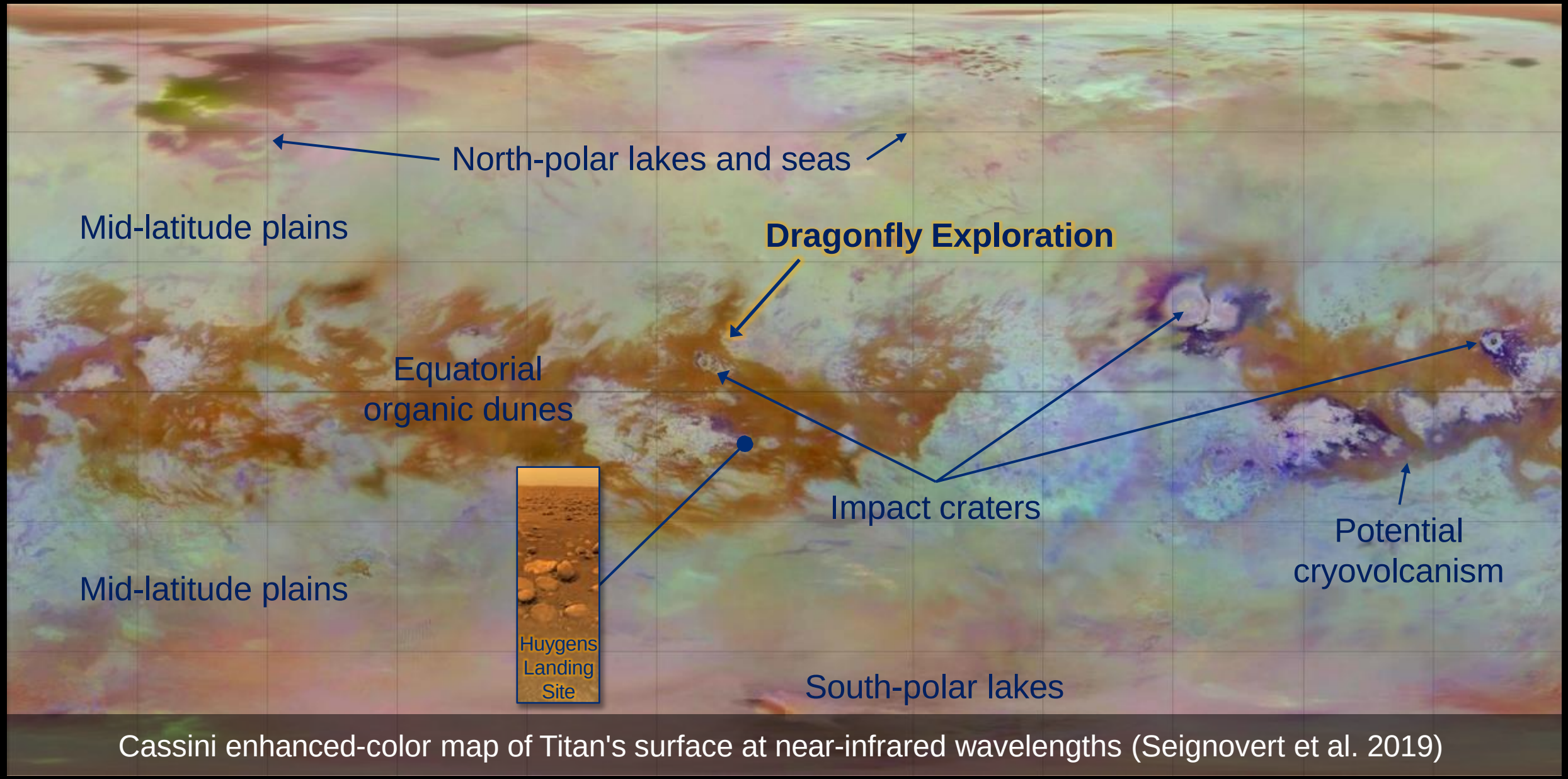
Recent Payload Milestones



First data from DraMS Laser Desorption Mass Spectrometer (LDMS) Engineering Model (EM), Cesium Iodide (CsI) target

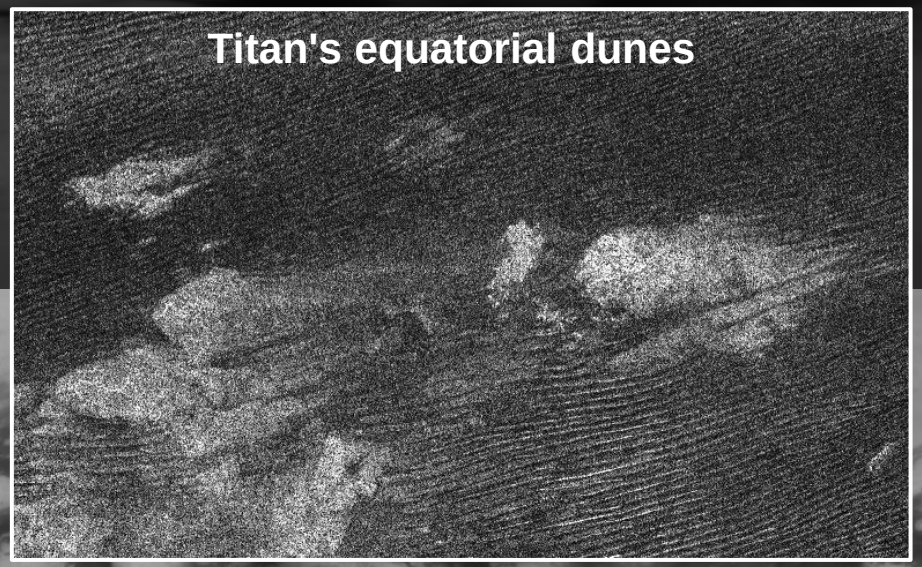


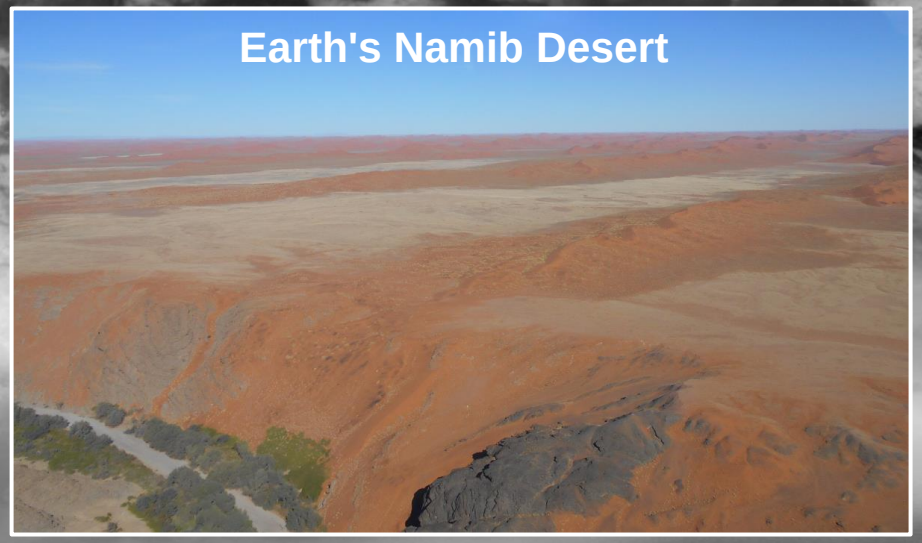
First data from the DraGNS Gamma Ray Spectrometer (GRS) Engineering Model (EM) of the Cobalt-60 calibration target Top: High-Purity Germanium (HPGe) Detector linear-scale short-duration histogram. Bottom: HPGe Detector log-scale accumulated histogram.



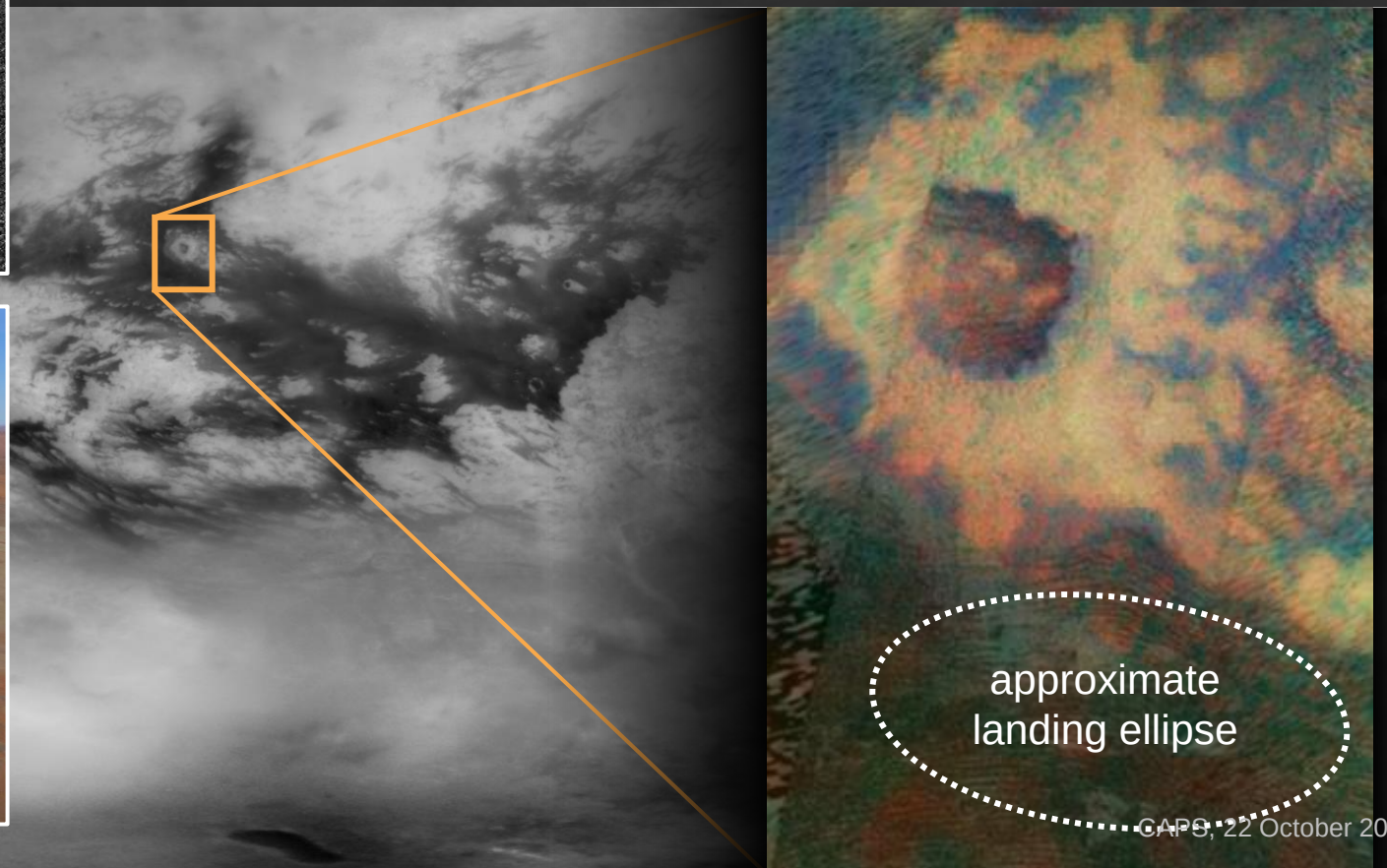
Cassini enhanced-color map of Titan's surface at near-infrared wavelengths (Seignovert et al. 2019)

Access to variety of materials of astrobiological interest

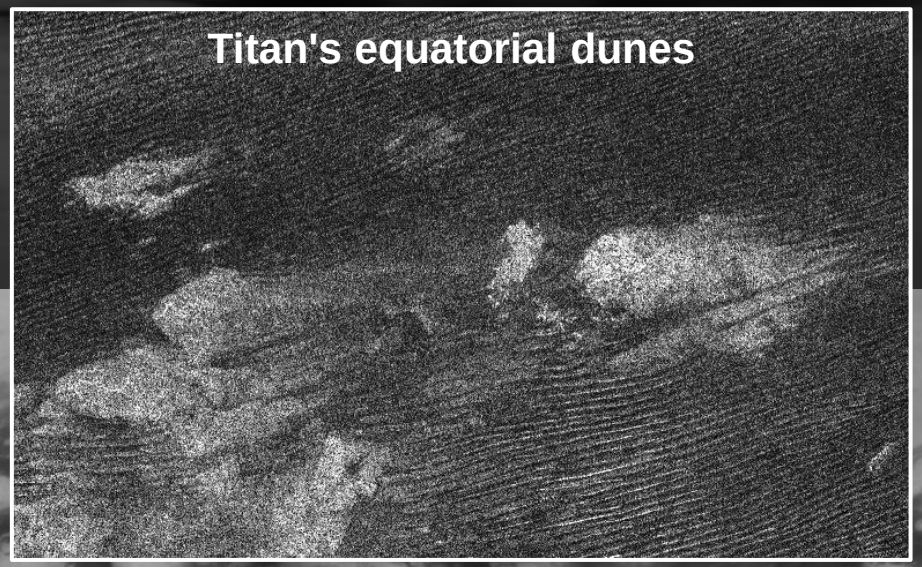


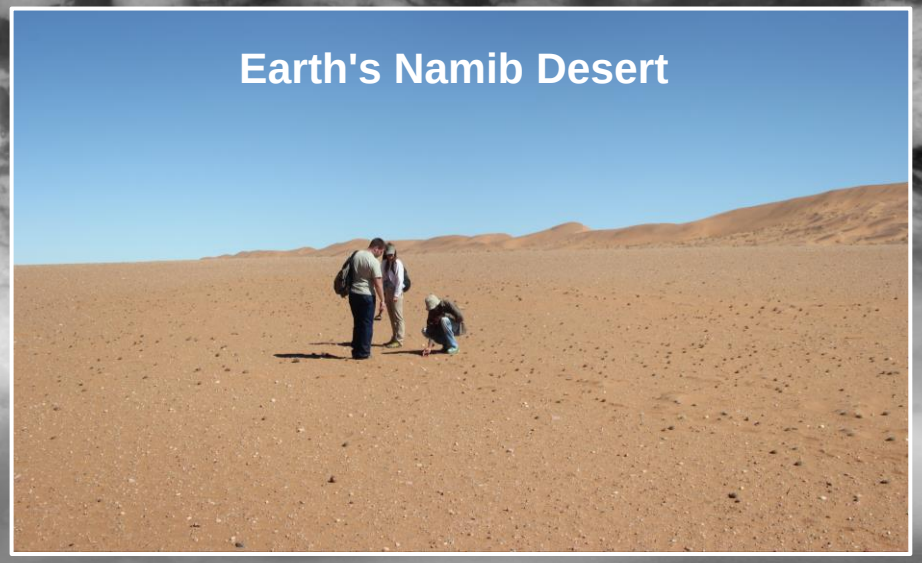


- **Sand dunes:** organic sediments
- **Interdune areas:** materials with a water-ice component
- **Selk impact crater:** materials where organics may have mixed with liquid water impact melt

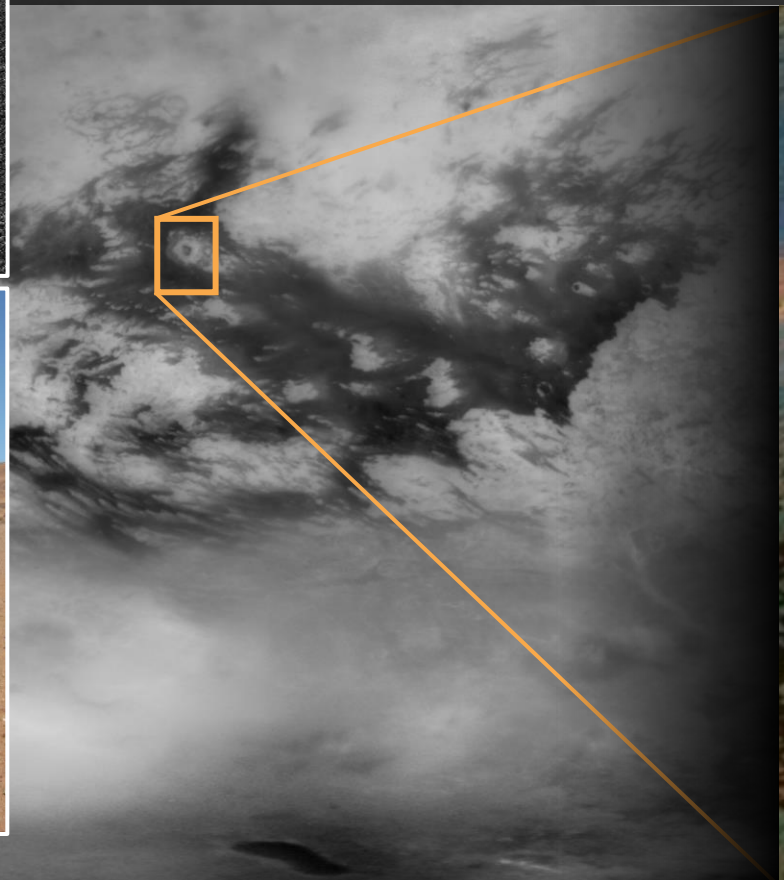


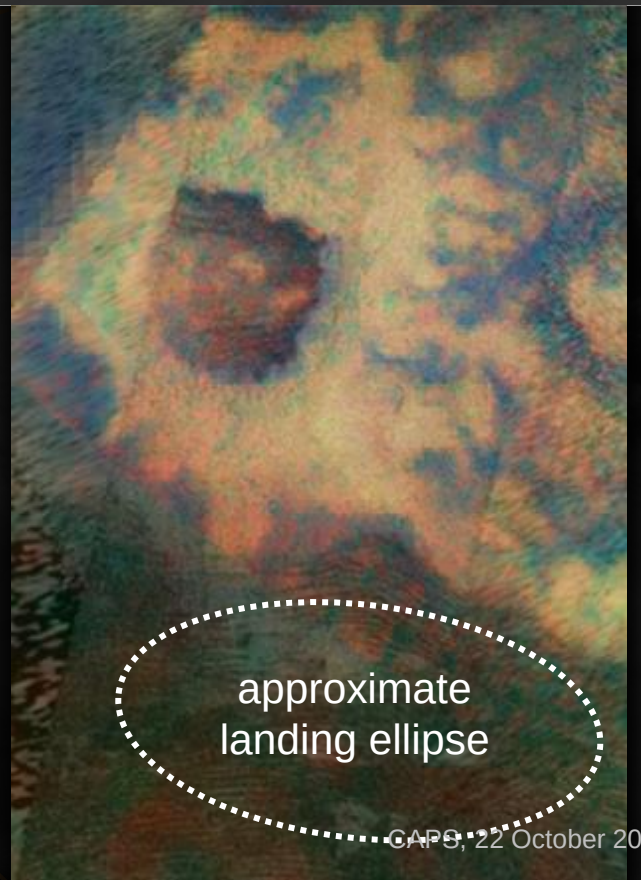
Access to variety of materials of astrobiological interest





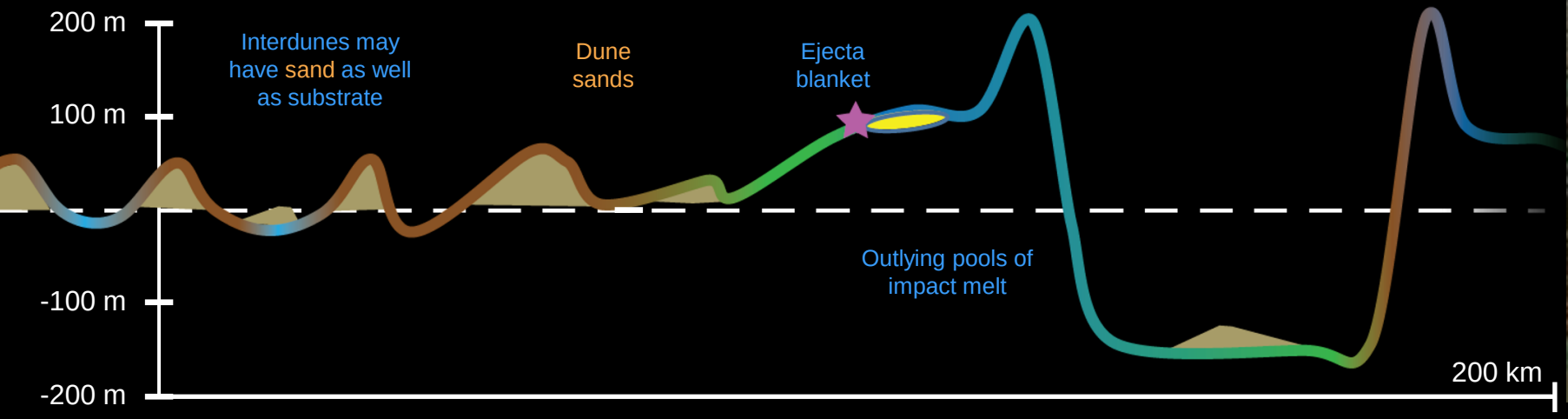
- **Sand dunes:** organic sediments
- **Interdune areas:** materials with a water-ice component
- **Selk impact crater:** materials where organics may have mixed with liquid water impact melt

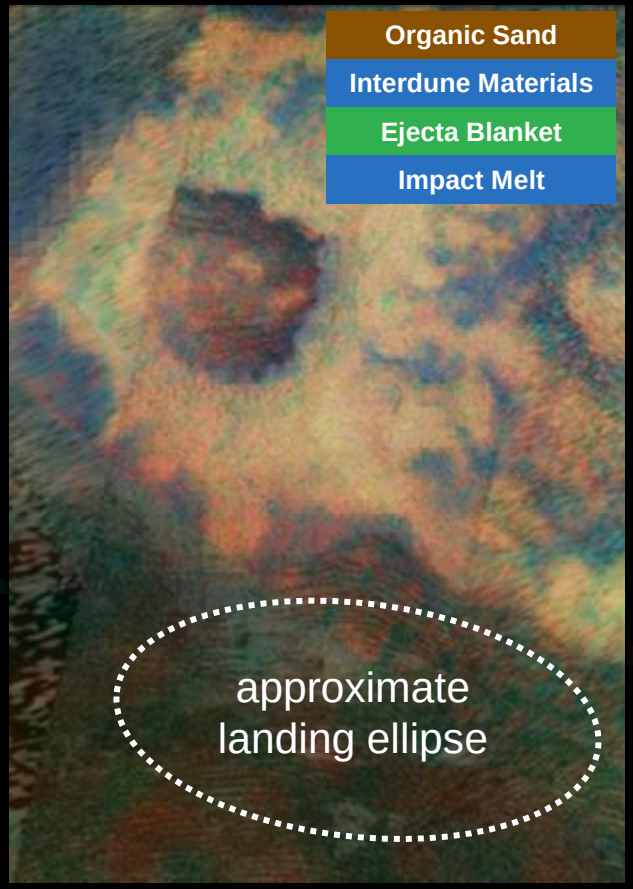




Dragonfly exploration strategy

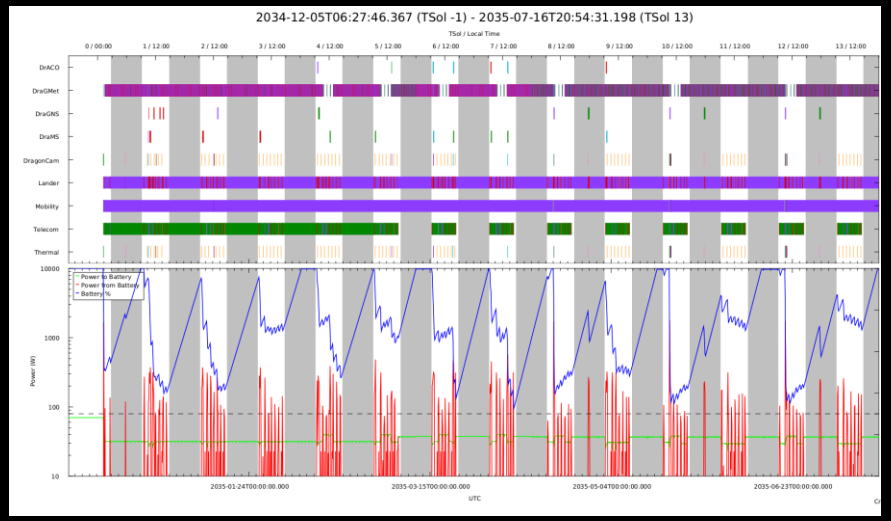
- **~3 years, ~74 Tsols (Titan days) of science operations**
  - Individual flights of several kilometers; total traverse distance several tens of km
  - Exploration of >30 unique sites
  - Aerial scouting of future landing sites
- **Design Reference Mission shows requirements are met with margin**
  - 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

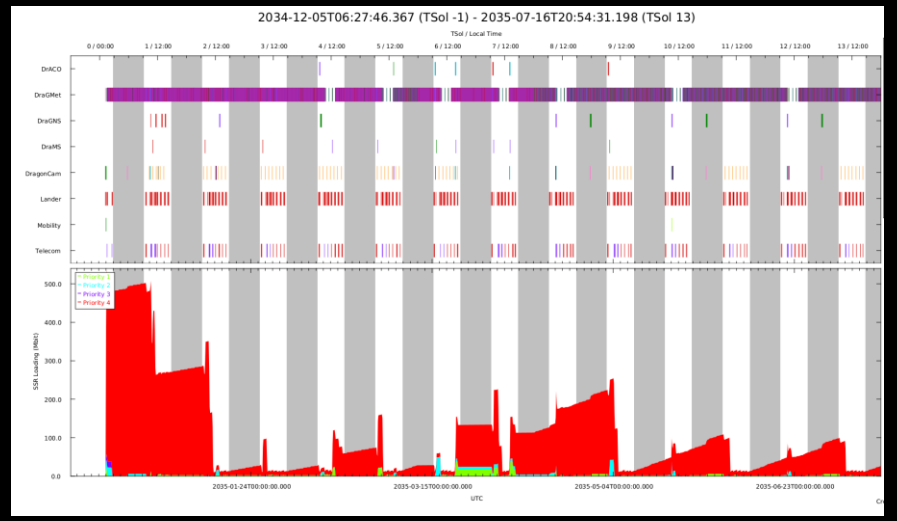




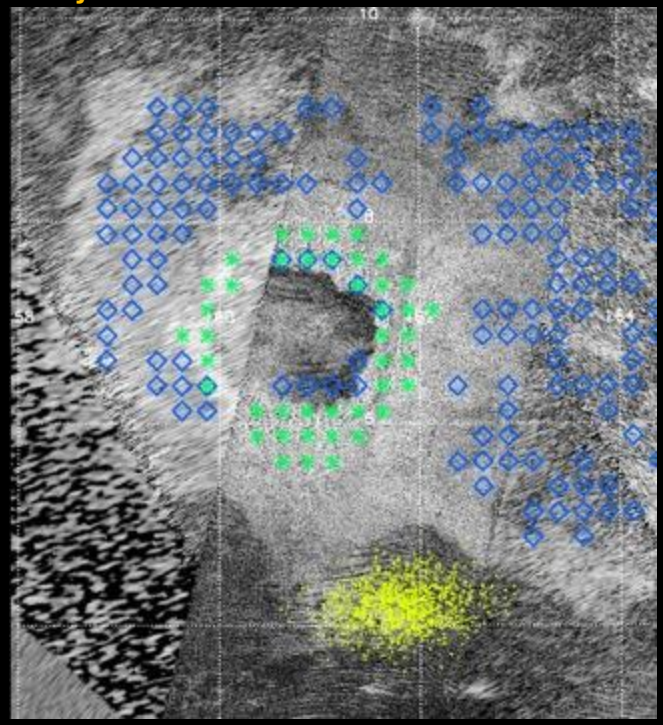
Dragonfly exploration strategy

- **~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





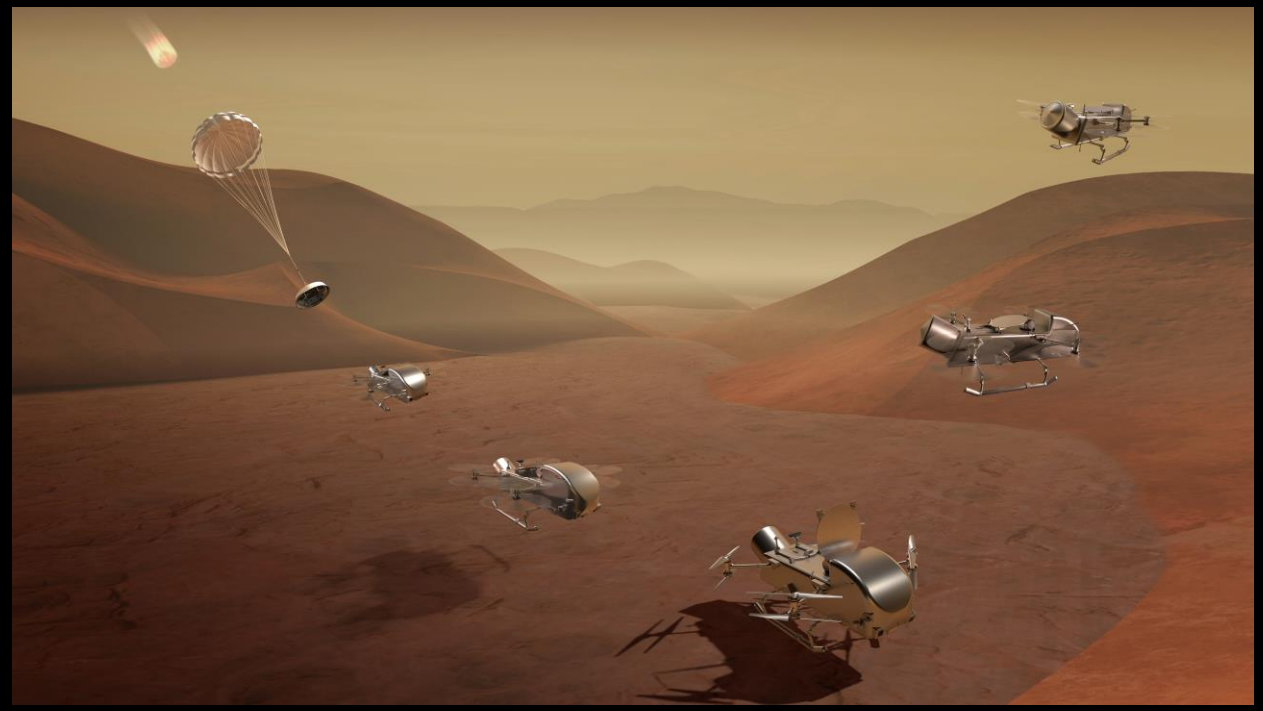
Cassini mapping shows impact melt may be encountered in the ejecta and near the crater rim



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

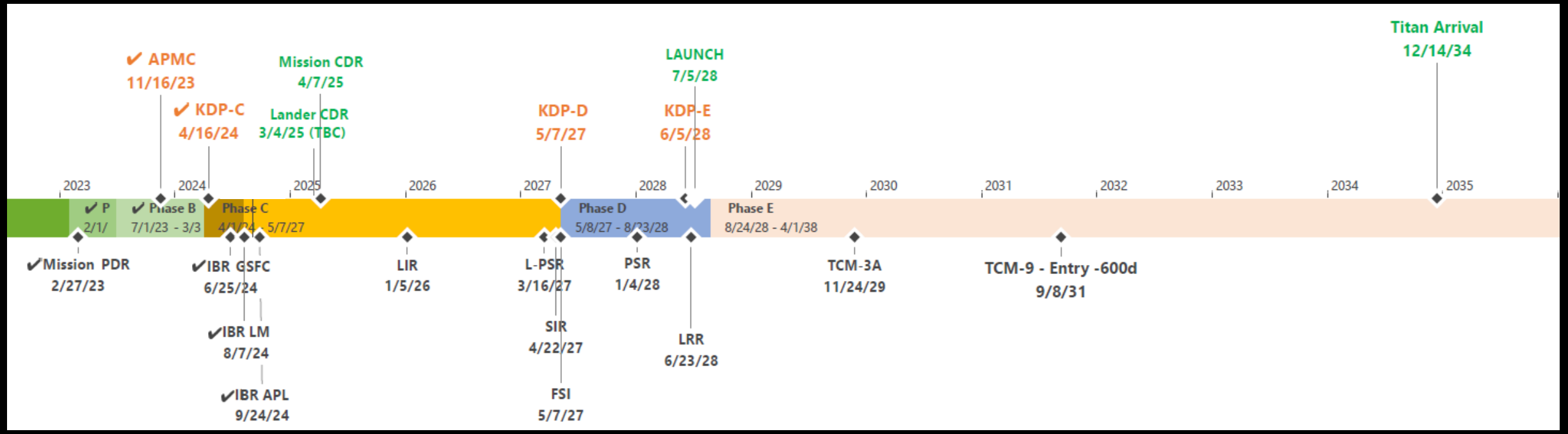
Dragonfly Mission Timeline and Status

- 4th mission in NASA's New Frontiers Program, selected in June 2019
- Project Phase B: Preliminary Design and Technology Completion
  - Technology maturation completed
  - Successful Mission Preliminary Design Review (MPDR), February-March 2023
- NASA Mission Confirmation, April 2024
  - Baseline schedule with Launch Readiness Date in July 2028 and Titan Arrival in December 2034
- Project Phase C: Final Design and Fabrication underway
  - Team is continuing technical progress toward Mission Critical Design Review (MCDR), April 2025



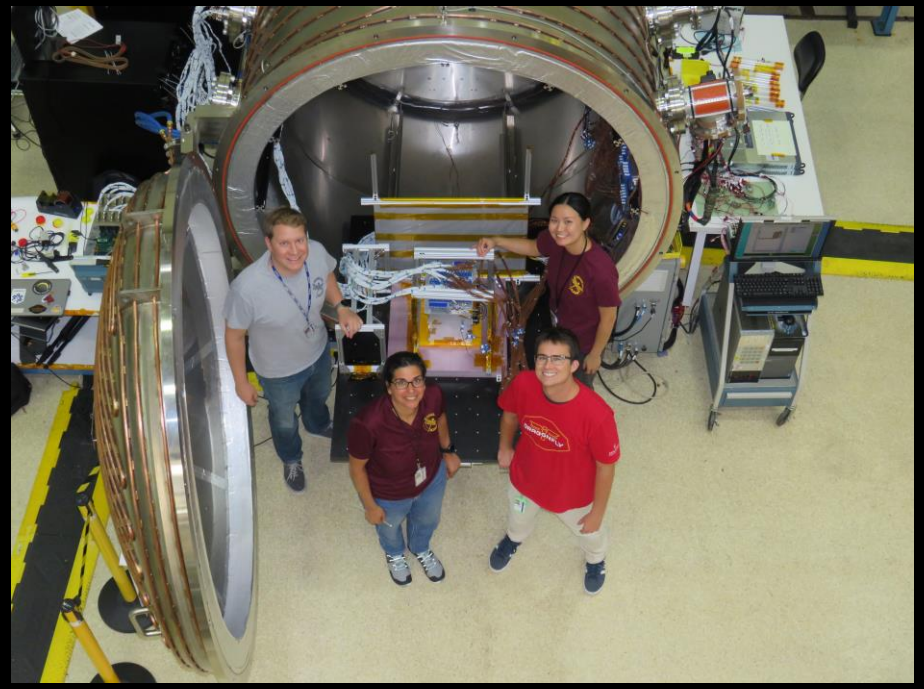
The Team has been working tremendously hard and we greatly appreciate NASA's confidence in the team and the broad support from NASA, the Decadal Survey, the scientific community, and the public for this mission to explore the surface of another ocean world!

Mission Timeline



Titan environment test facilities built by APL

Titan Pressure Environment Chamber (TPEC)



The Rotor Drive Electronics (RDE) thermal module team successfully characterized performance under Titan conditions

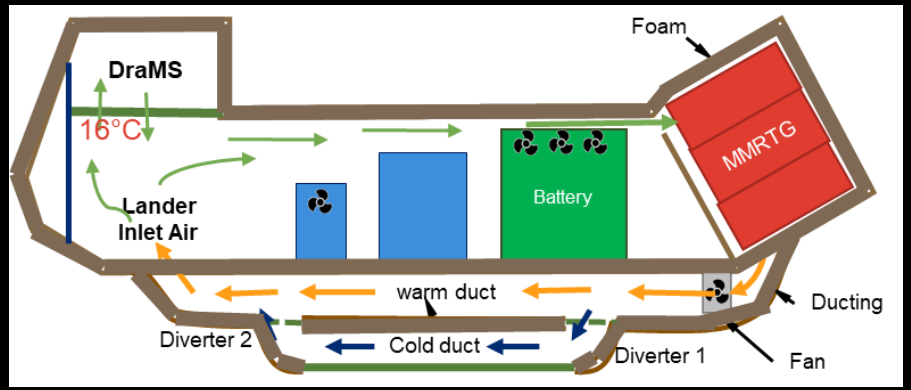
Titan

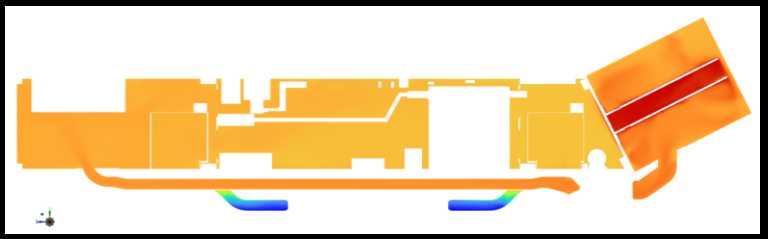
Commissioning and first cold testing, Summer-Fall 2023

Site Acceptance, Spring 2024

Recent activities: 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

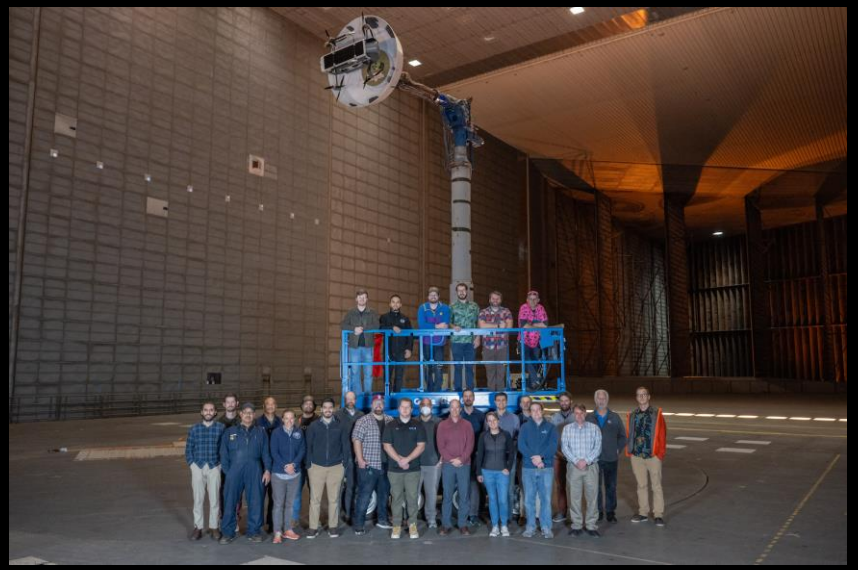




CFD model resulted in fully converged cases behaving similarly to the Titan Chamber experiments

Recent activities: Mobility development and testing

- Mobility subsystem development and model validation
  - Rotor testing in NASA Langley Research Center (LaRC) Transonic Dynamics Tunnel (TDT)
  - Test campaigns in ~1/2-scale Dragonfly lander in LaRC 14' x 22' wind tunnel and with lander and back-shell at the National Full scale Aerodynamics Complex (NFAC)
  - Data to validate computational fluid dynamics (CFD) models and aerodynamics databases



Recent activities: Mobility development and testing

- Mobility capstone test flights with ~half-scale integrated test platform (ITP)
  - Hardware and software similar to what will fly on Dragonfly: 8 independent rotor assemblies, flight computer and digital image processor, navigation camera, inertial measurement unit (IMU) with comparable gyroscopes and accelerometers, and image processing and flight control algorithms
  - Demonstrate guidance & control algorithms; optical navigation; autonomous takeoff, hover, hop, landing, and scouting flights

Outreach and engagement

- Broad range of science and technical disciplines
  - Multi-instrument *Cassini-Huygens* analysis
  - Lab work, e.g., generating tholins for testing
  - Testing sample acquisition and transfer
  - Aeronautics: wind-tunnel and flight testing, rotor design, modeling
  - AR/VR simulations for spacecraft design and planning and executing operations
- Opportunities for engagement
  - Dragonfly Student and Early Career Guest Investigator Program, Phases B-D and Phase E
  - NASA meeting observers and Here to Observe (H2O) Programs
    - H2O partnership with Virginia State Univ. 2021-2022
    - Kingsborough Community College (KBCC), 2023-2025
  - Future NASA Participating Scientist Program
  - Community workshops, town halls at scientific conferences, e.g.,
    - Titan Through Time, Aug 2021 & June 2023
    - AbSciCon, May 2022 & 2024

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

Quick et al., 2021: https://www.hou.usra.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 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

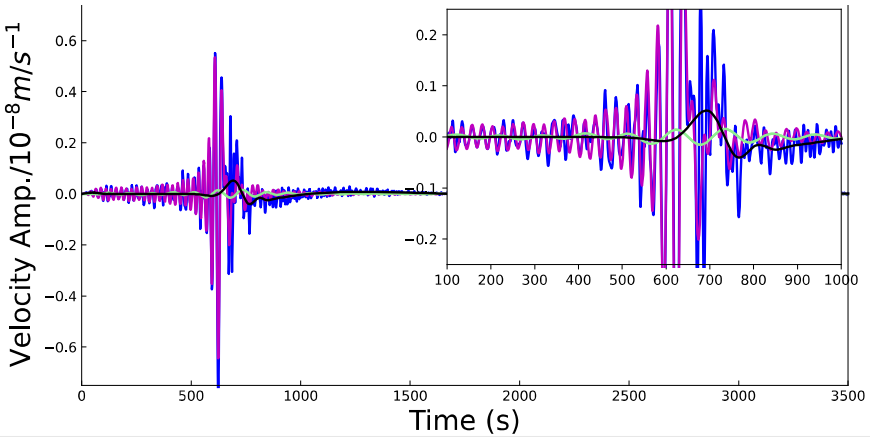
- Goals of Program
  - Extend opportunities for graduate students to work with *Dragonfly* scientists and engineers
  - Encourage broader participation by making it easier for students who ***don't*** already have connections to *Dragonfly* or NASA spacecraft missions and/or who ***don't*** have a planetary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

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

Quick et al., 2021: https://www.hou.usra.edu/meetings/lpsc2021/pdf/2653.pdf

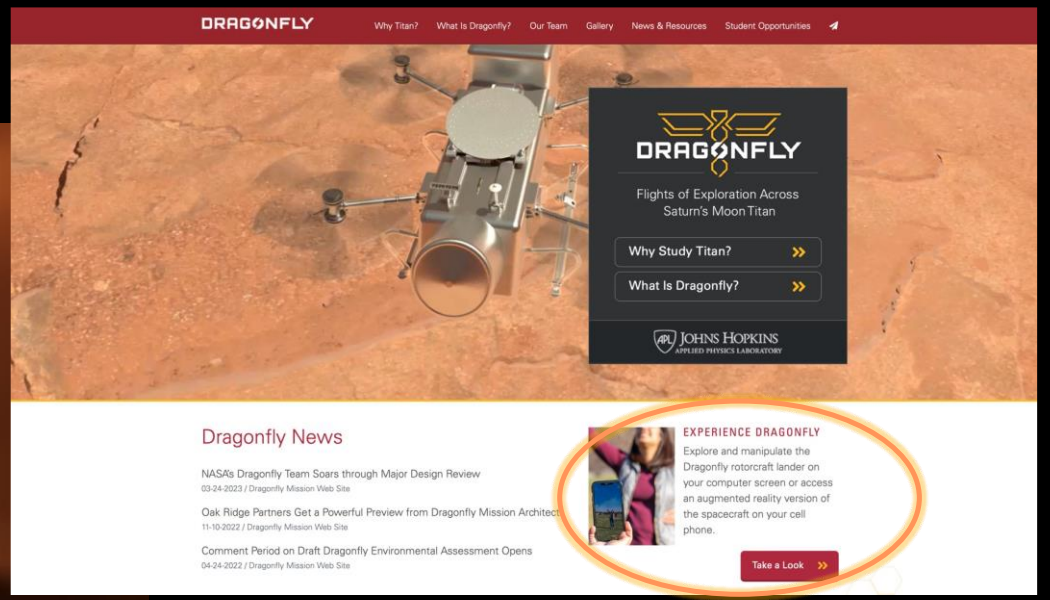
Cohort	Project	Dragonfly Team Mentors	Grad Student Guest Investigators
1 2021-23	Seismic investigation of Titan's interior using full waveform modeling	Mark Panning, JPL	**Andrea Bryant**, University of Chicago, Physics
	Spectral/compositional library for interpretation of D measurements		**Karla Negrete**, University of Maryland Baltimore County (UMBC), Mechanical Eng.
	Development of the DragonCam microscopic imag		**Brianna Wylie**, Florida Agricultural & Mechanical University (FAMU), Mechanical Eng.
2 2022-24	Tuning DraGNS' Interpretations to Titan's Surface		**Anna Engle**, Northern Arizona Univ. (NAU), Astronomy and Planetary Sci.
	Development of DraMS Instrument Operational Gu		**Will Suero Amparo**, New Jersey Institute of Tech., Biomedical Engineering
3 2022-24	Volatility of Titan-Relevant Compounds and Implica		**A'Laura Hines**, George Mason University, Chemistry
	Building a Library of Diagnostic Fracture Patterns a Interpretation of DragonCam Images		**Shahrose Khan**, Univ. of California San Diego, Aerospace Engineering
	Background Research for DrEAM* Aeroscience Ex		**Alyssa Vellucci**, Univ. of Texas Dallas, Mech. Eng.
4 2023-25	Data visualization library for Dragonfly science ope		**M. René Castillo**, Ohio State Univ., Geophysics
	Dragonfly science planning tool development	Sarah Hasnain & Hari Nair, APL	**Navya Annapareddy**, Univ. Virginia, Data Science

Dr Andrea Bryant: Hypothetical Icy Moon Seismic Profiles for Comparison to Future Seismic Data



- 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 to expand training of the next generation of mission team members and leaders

Preliminary augmented reality model posted at https://dragonfly.jhuapl.edu

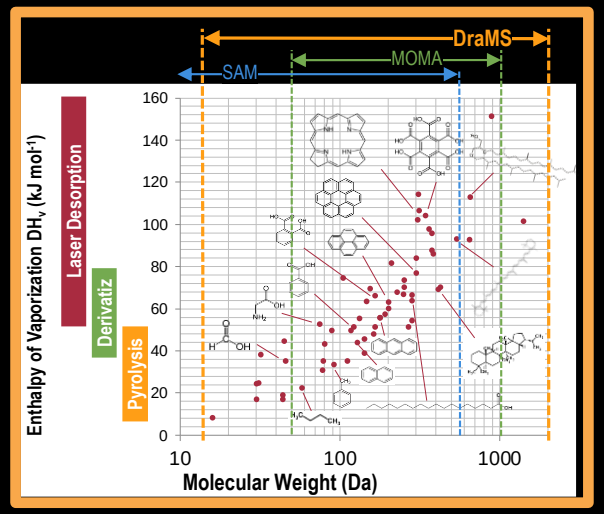


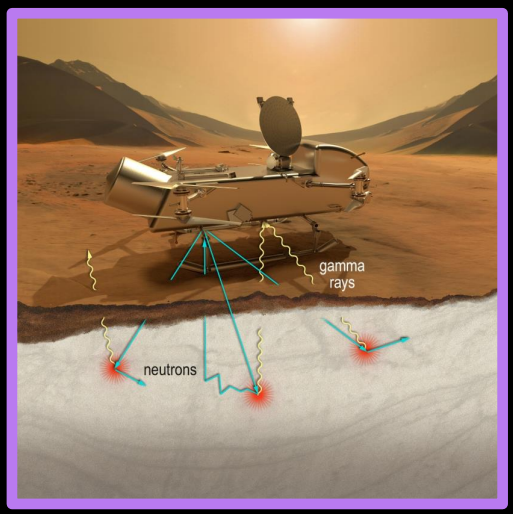
DRAGONFLY

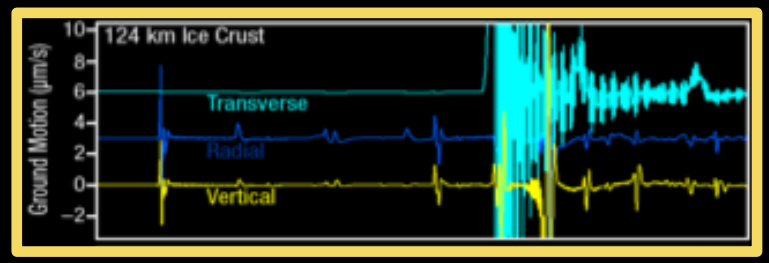
http://dragonfly.jhuapl.edu

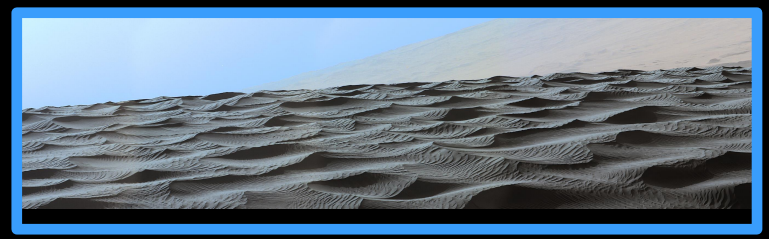
Multidisciplinary science measurements –
Evaluate prebiotic chemistry in the context of Titan's environment

- **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, CH_4, H_2, 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

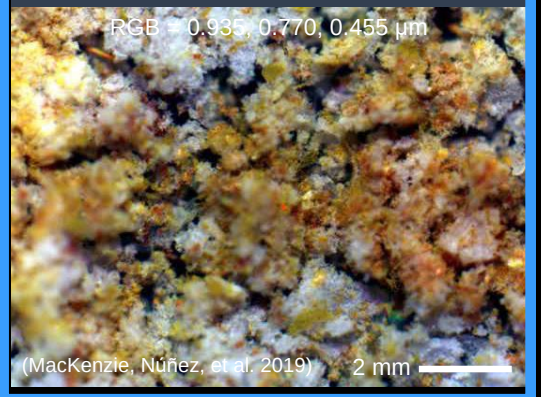






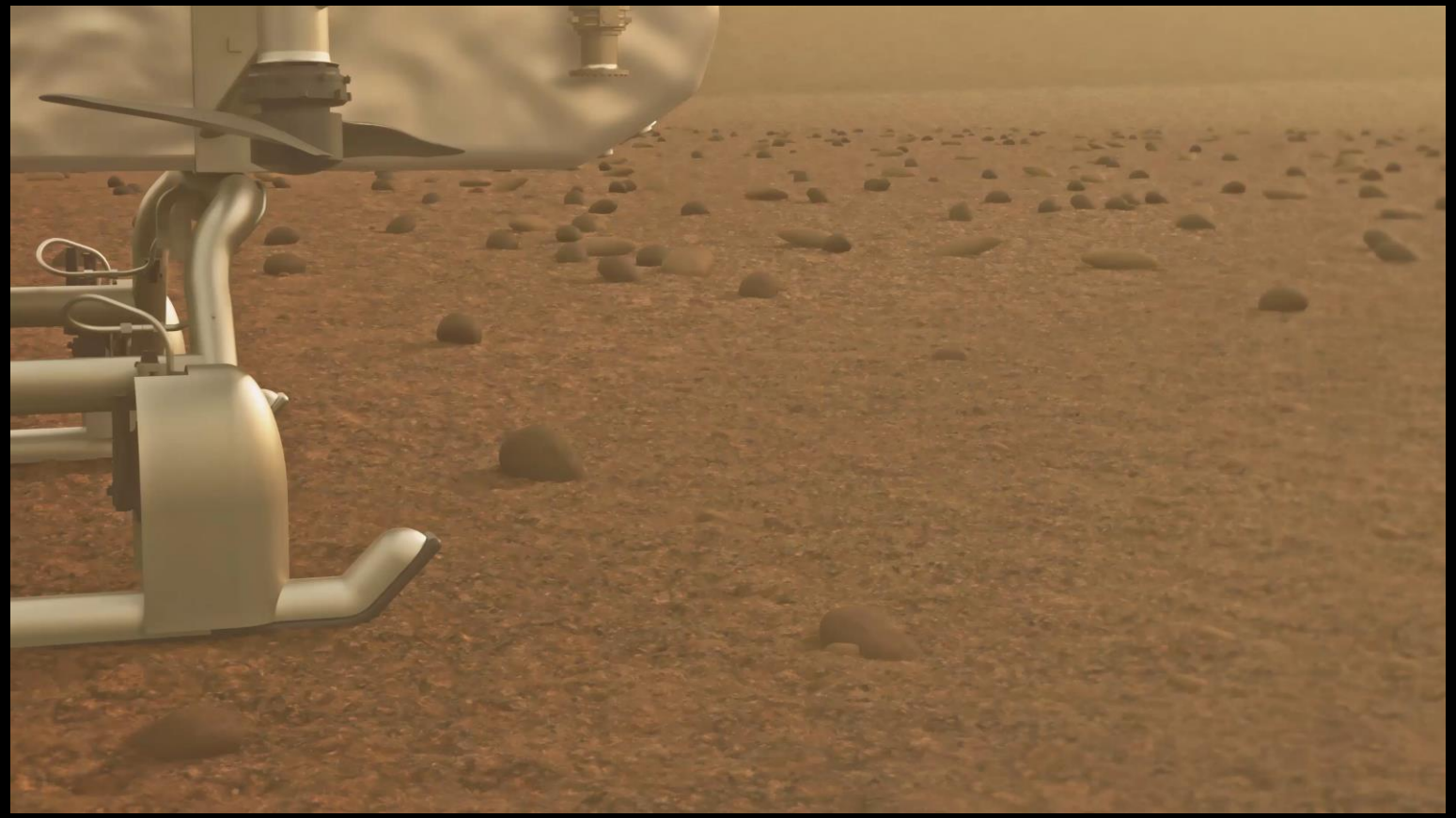


LED illuminated mixture of water ice (white) and two tholin 'flavors' (orange + yellow)



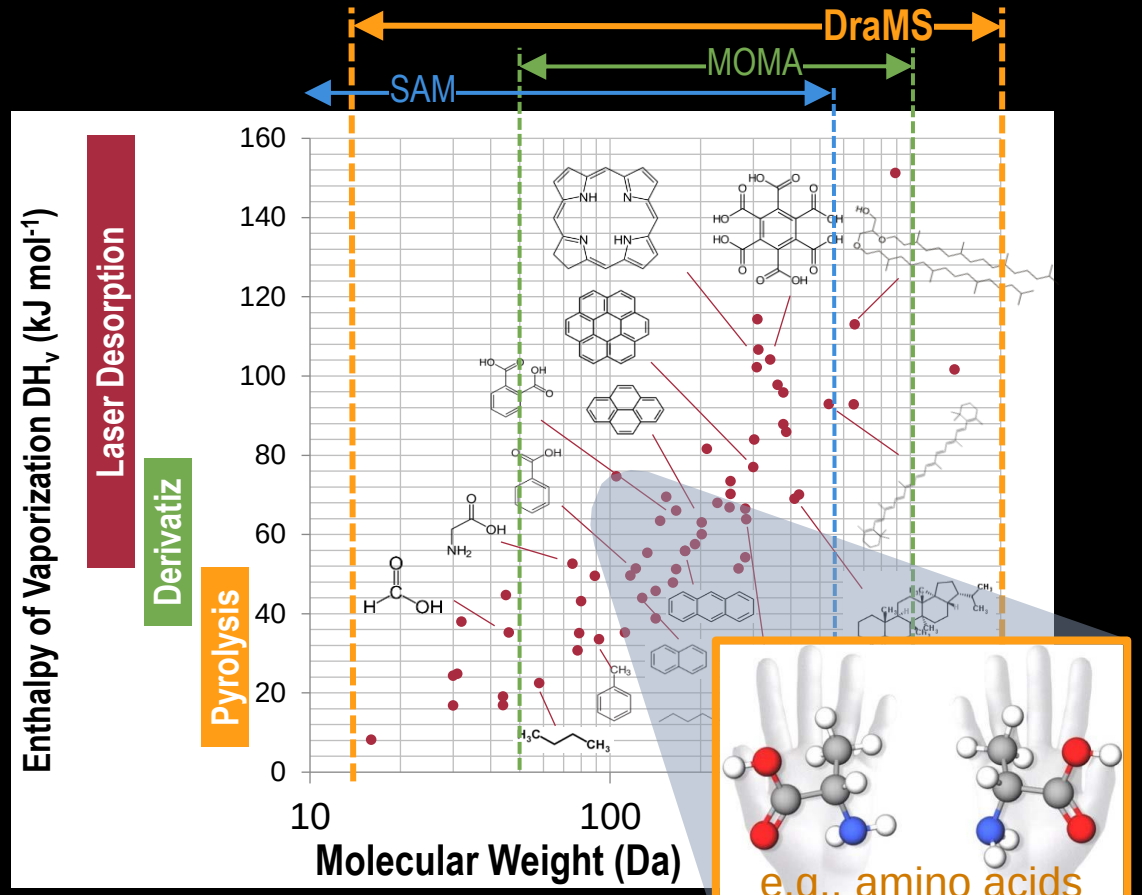
Comprehensive study of the chemical complexity and diversity of Titan's solid surface

DrACO uses rotary-percussive drills and blowers to pneumatically transfer surface material to DraMS for detailed chemical analyses



Comprehensive study of the chemical complexity and diversity of Titan's solid surface

- Analyze chemical components and processes that produce biologically relevant compounds
- Complementary sample analysis modes:
  - Laser Desorption MS: Broad survey and structural analysis
  - Gas Chromatography MS: Definitive molecular detection, chirality

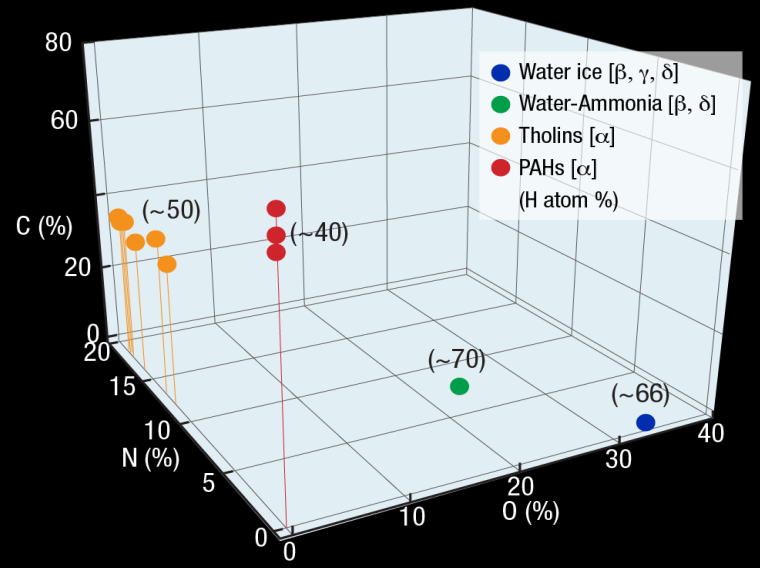


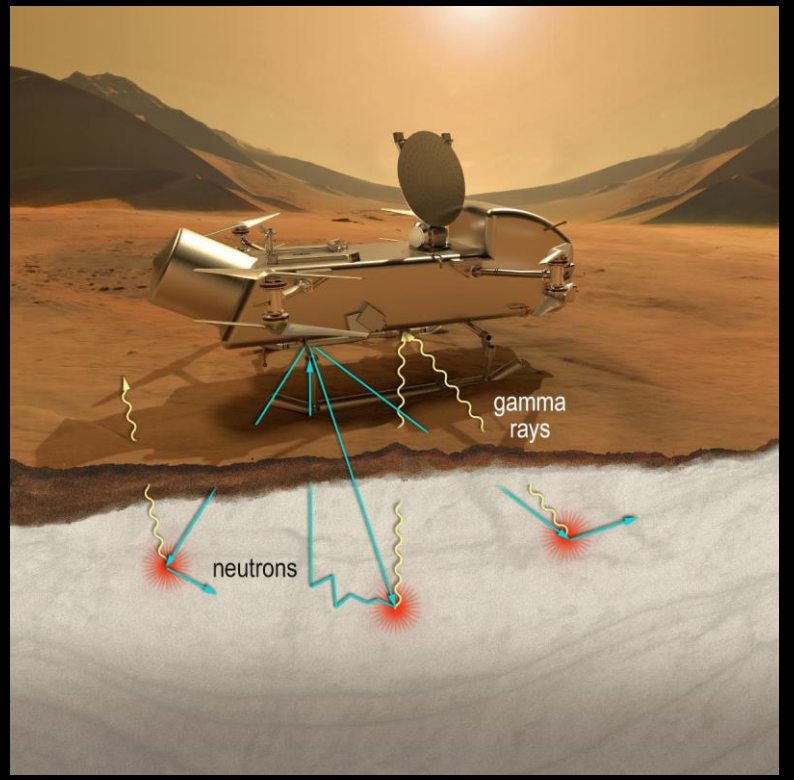
(Trainer et al., 2017)

(Hand et al., 2017, Europa Lander SDT Report)

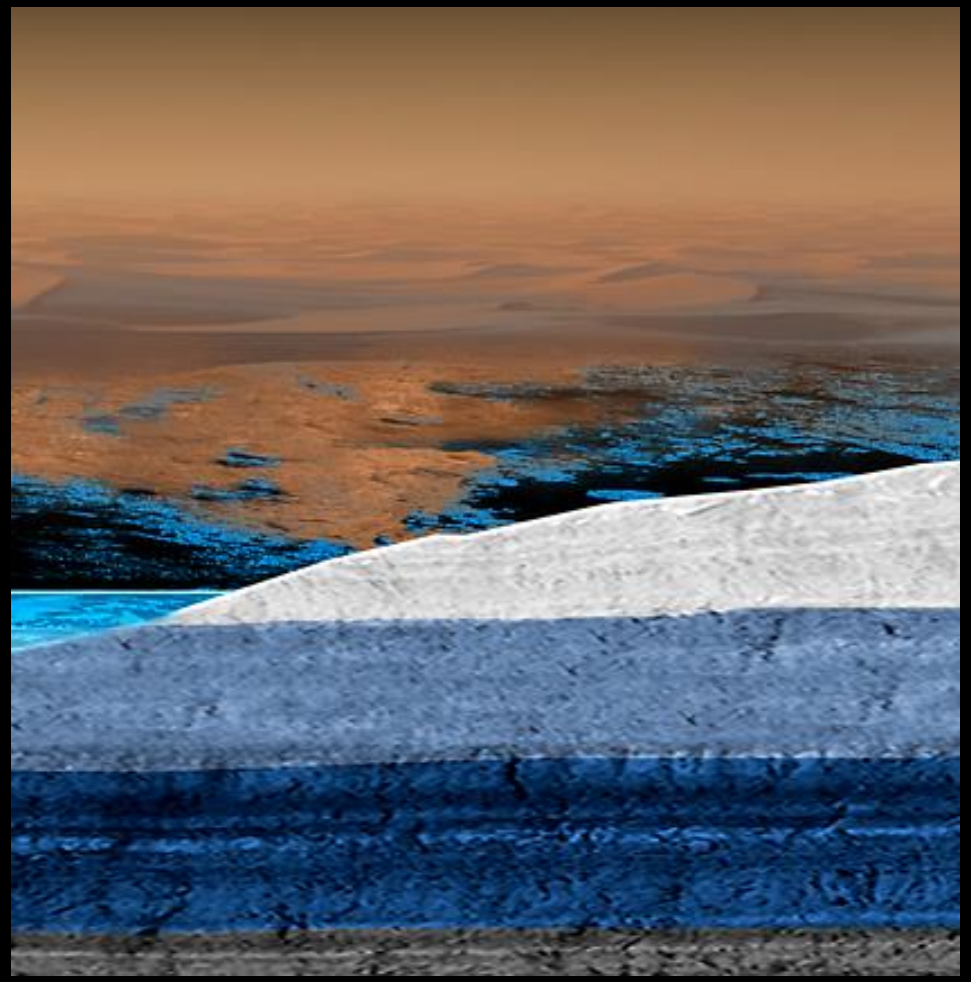
Classification of surface materials

- Measure bulk elemental surface composition
  - Classify surface material
  - Detect minor inorganic elements
  - Reveal near-surface stratigraphy





Meteorological and geophysical monitoring of Titan as an interconnected system



Monitor atmospheric conditions, identify CH_4 reservoirs, and determine transport rates

- Temperature, pressure, CH_4, H_2, wind speed & direction
- Diurnal and spatial variations; atmospheric profiles

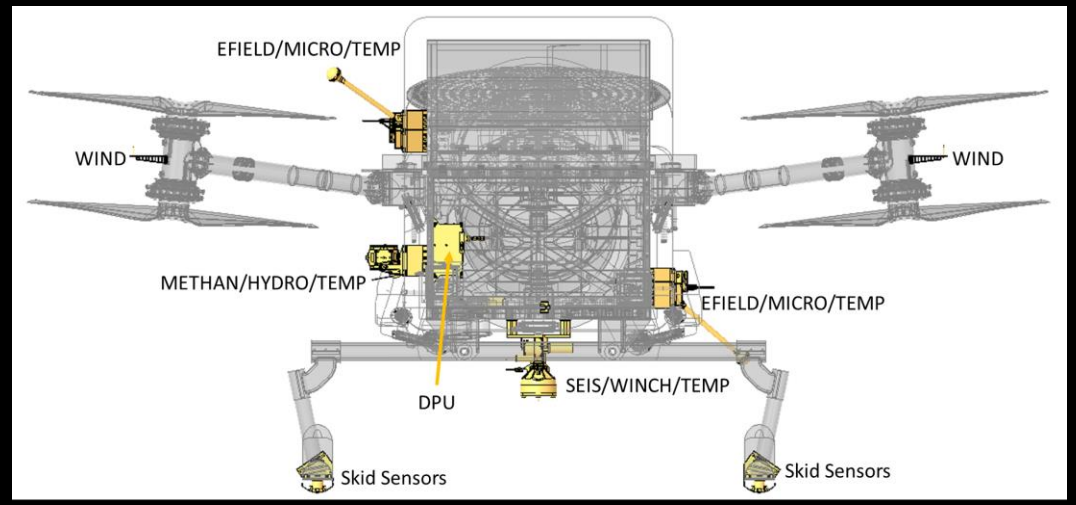
Constrain regolith properties (e.g., porosity)

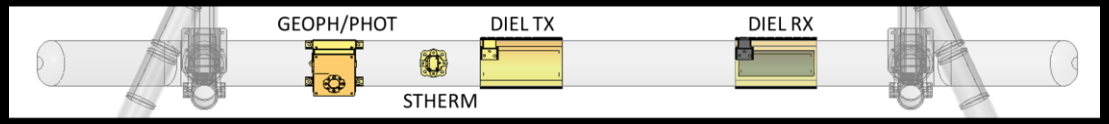
- Thermal response (dampness), dielectric constant

Constrain processes that mix organics with past surface liquid water or subsurface ocean

- E-Field (Schumann resonance), seismic activity

Meteorological and geophysical monitoring of Titan as an interconnected system





Monitor atmospheric conditions, identify CH_4 reservoirs, and determine transport rates

- Temperature, pressure, CH_4, H_2, wind speed & direction
- Diurnal and spatial variations; atmospheric profiles

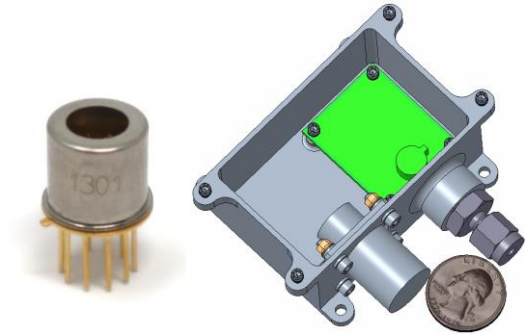
Constrain regolith properties (e.g., porosity)

- Thermal response (dampness), dielectric constant

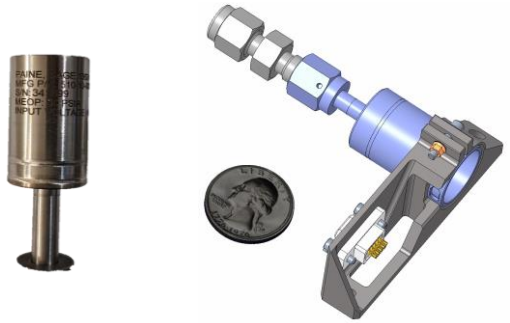
Constrain processes that mix organics with past surface liquid water or subsurface ocean

- E-Field (Schumann resonance), seismic activity

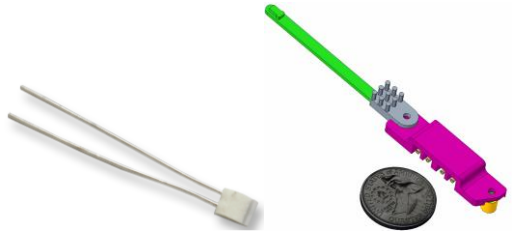
DraGMet sensor suite



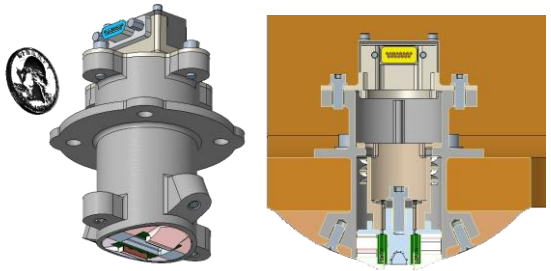
Hydrogen Sensor (HYDRO) (Qnty 2)



Pressure Sensor (PRES) (Qnty 2)



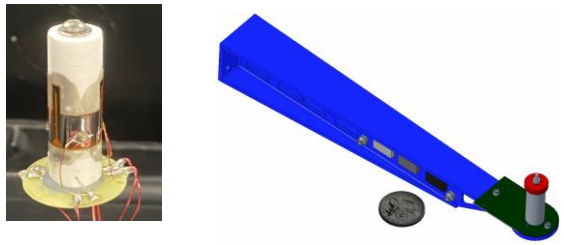
Temperature Sensor (TEMP) (Qnty 4)



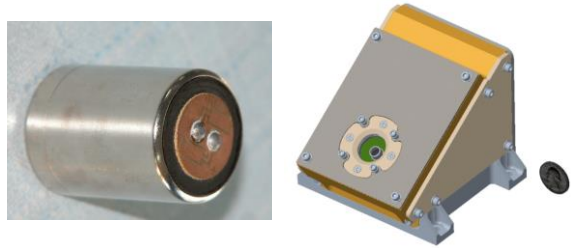
Surface Thermal (STHERM) (Qnty 2)

Microphone Sensor (MICRO) (Qnty 3)

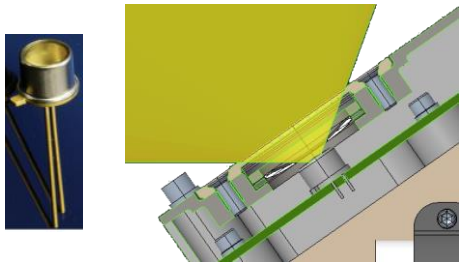
Electric Field Sensor (EFIELD) (Qnty 2)



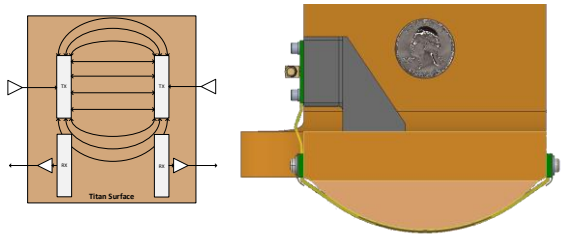
Wind Sensor (WIND) (Qnty 4)



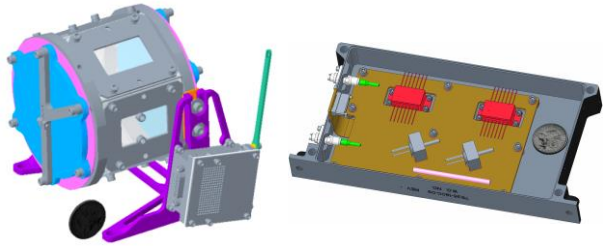
Geophone Sensor (GEOPH) (Qnty 6)



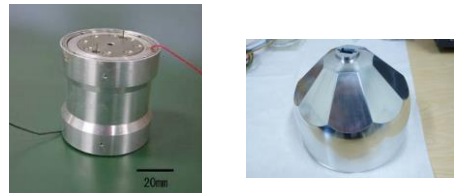
Photodiode Sensor (PHOT) (Qnty 2)



Dielectric Sensor (DIEL) (Qnty 1)



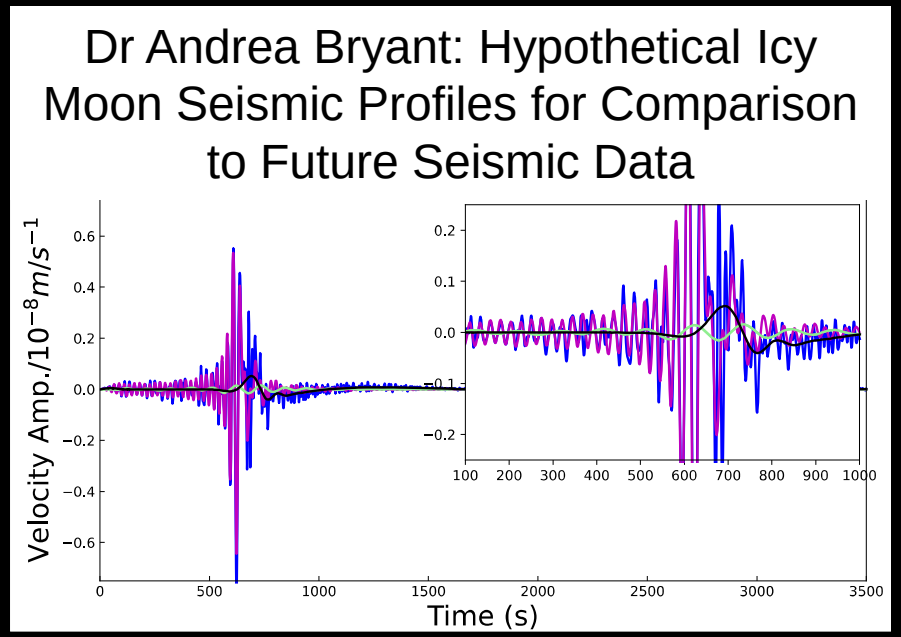
Methane Sensor (METHAN) (Qnty 1)

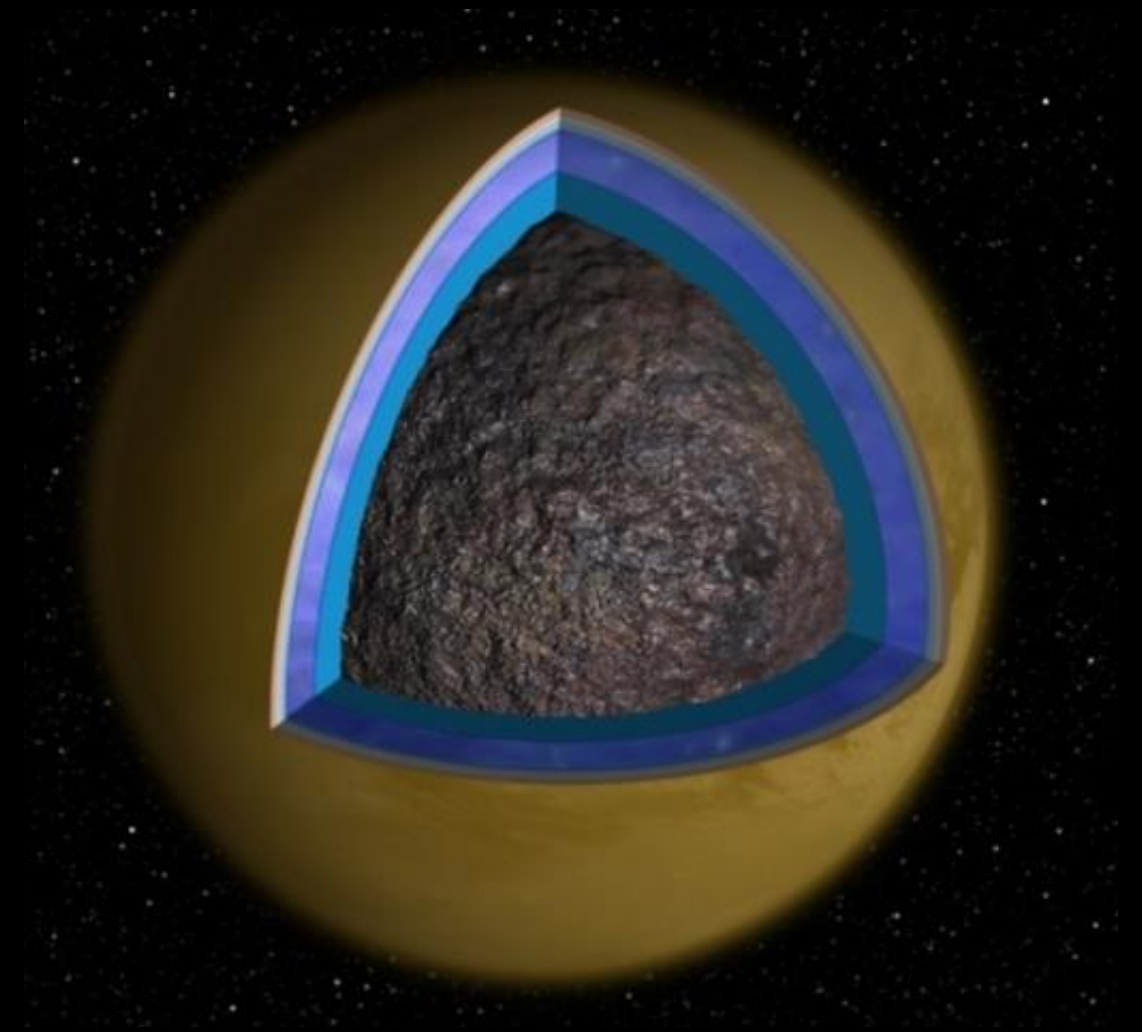


Seismometer (SEIS) (Qnty 1) [JAXA]

Seismological monitoring of an ocean world

- Detection and characterization of level of seismic activity
- Variation with orbital phase

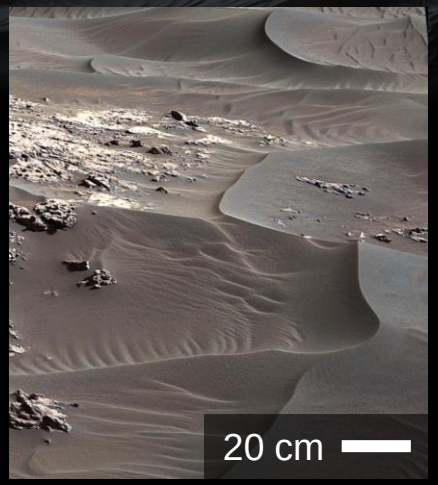




Characterization of landforms and surface processes in multiple geologic settings

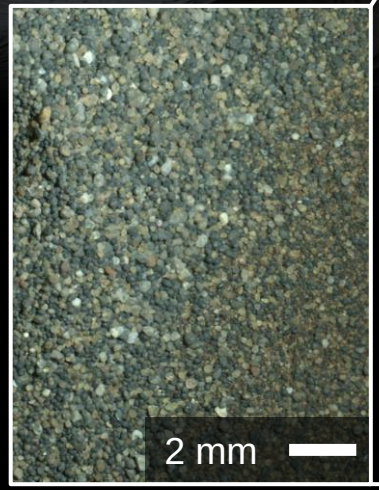
Panorama

Forward



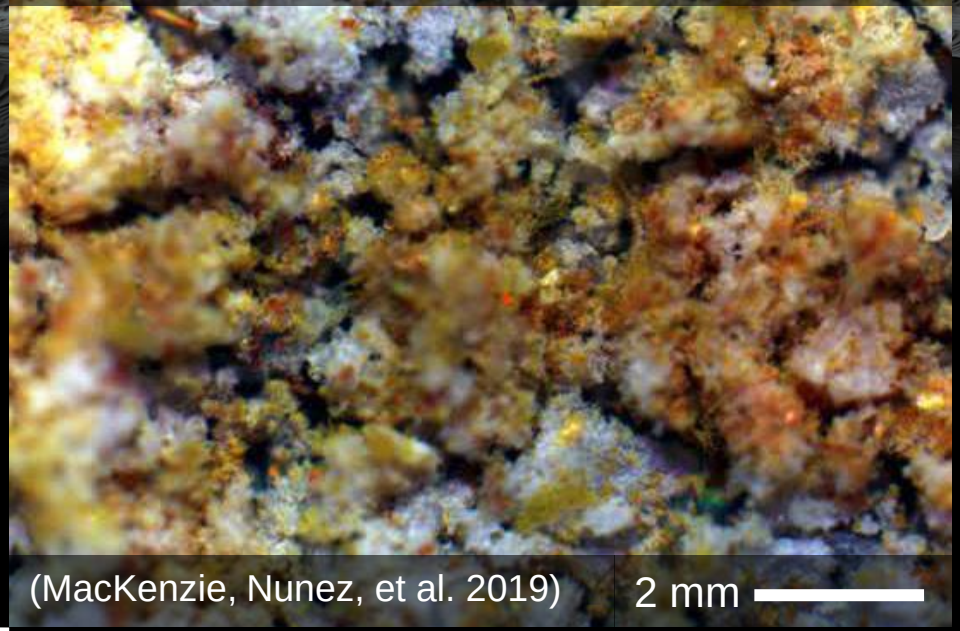
Downward

Microscopic



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

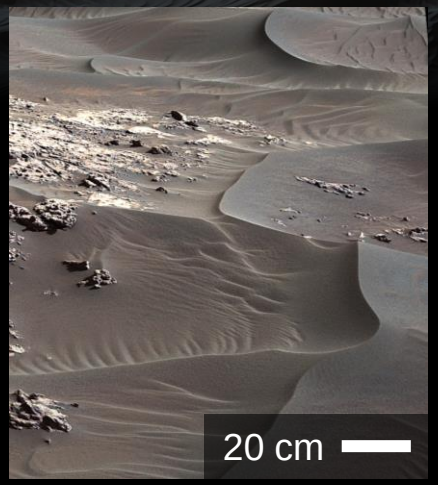
RGB = 0.935, 0.770, 0.455 μm



Characterization of landforms and surface processes in multiple geologic settings

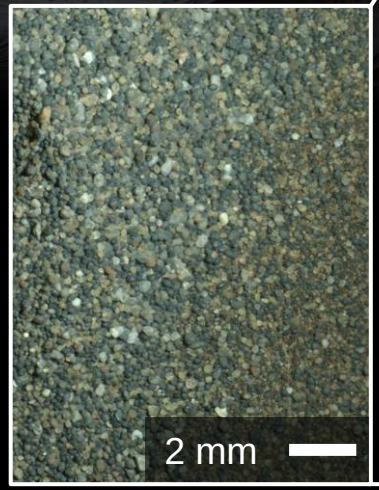
Panorama

Forward

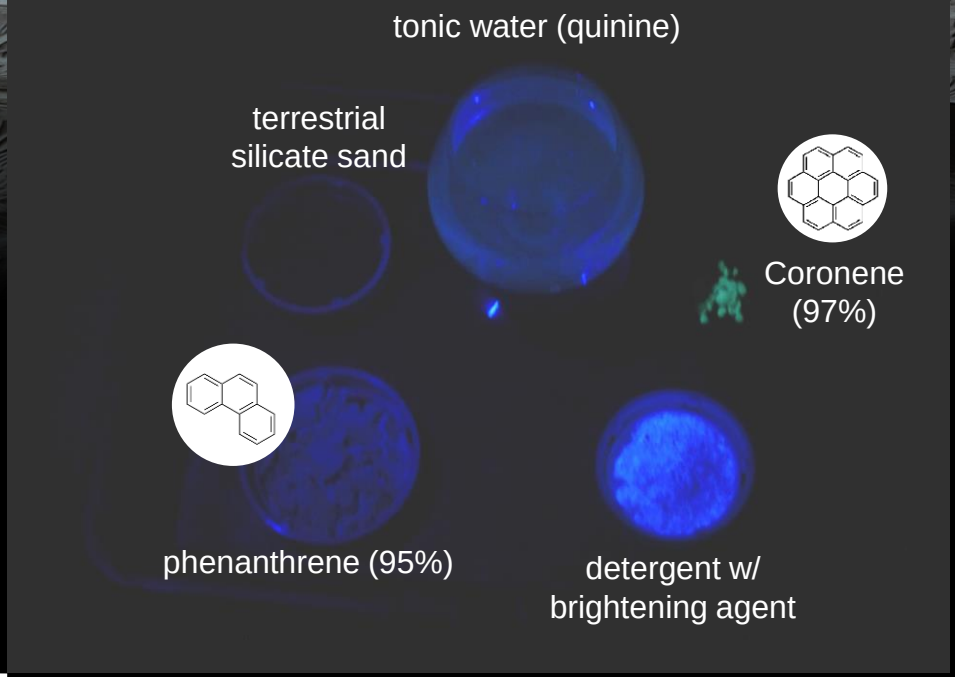


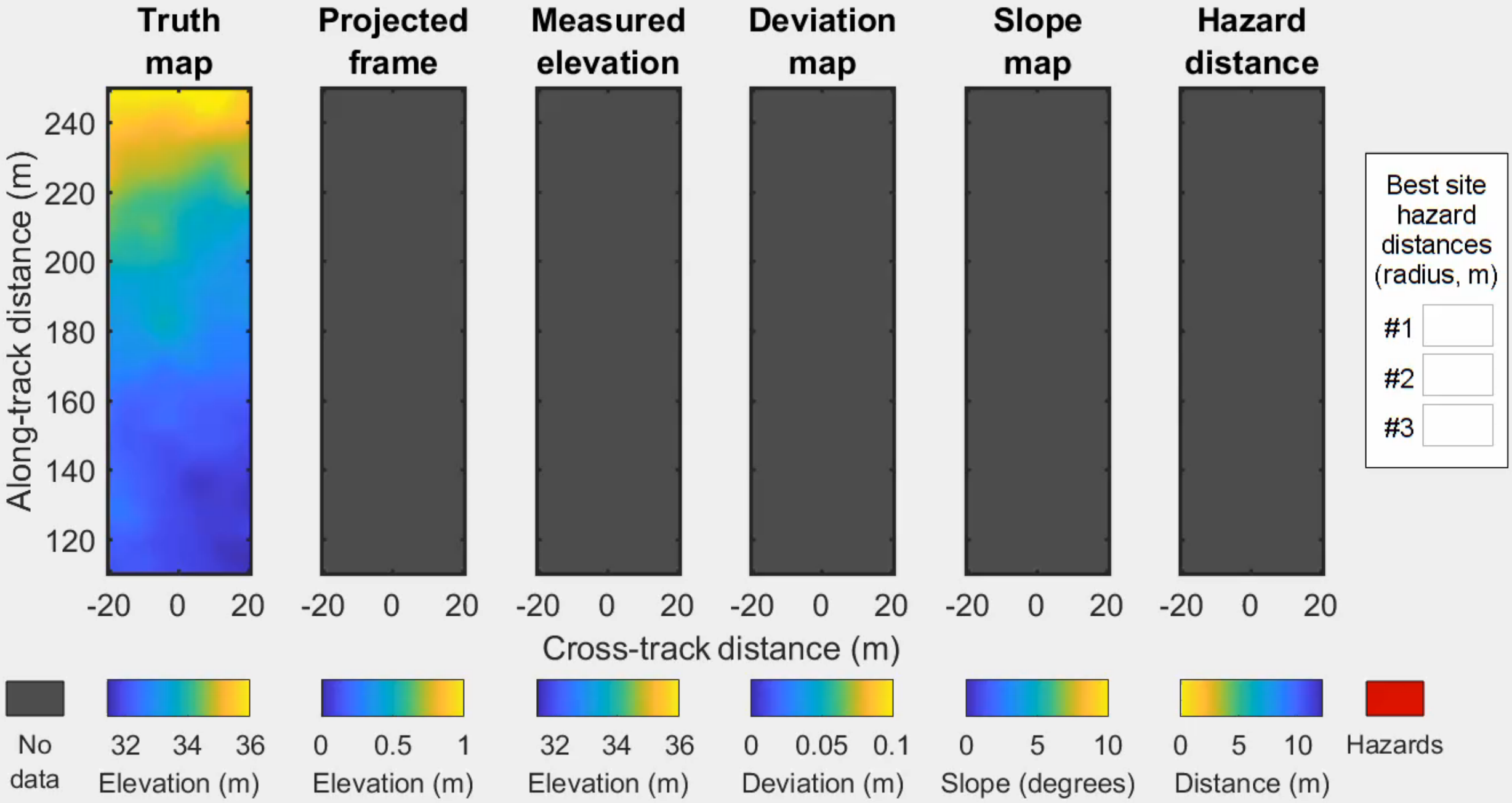
Downward

Microscopic



Aromatic organics, especially PAHs, exhibit fluorescence when stimulated by near-UV light




Truth map
Projected frame
Measured elevation
Deviation map
Slope map
Hazard distance
Along-track distance (m)
240
220
200
180
160
140
120
-20 0 20
Cross-track distance (m)
Best site hazard distances (radius, m)
#1
#2
#3
No data
32 34 36
Elevation (m)
0 0.5 1
Elevation (m)
32 34 36
Elevation (m)
0 0.05 0.1
Deviation (m)
0 5 10
Slope (degrees)
0 5 10
Distance (m)
Hazards