National Aeronautics and
Space Administration

EXPLORE

Navigating SmallSat Development: Where to Begin and What to Expect

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Clearance: NF-1676 20205006873

Aug. 4, 1971 Apollo-15 Particles and Fields Subsatellite

Courtesy: NASA Space Science Data Center Catalog

Apollo Subsatellites

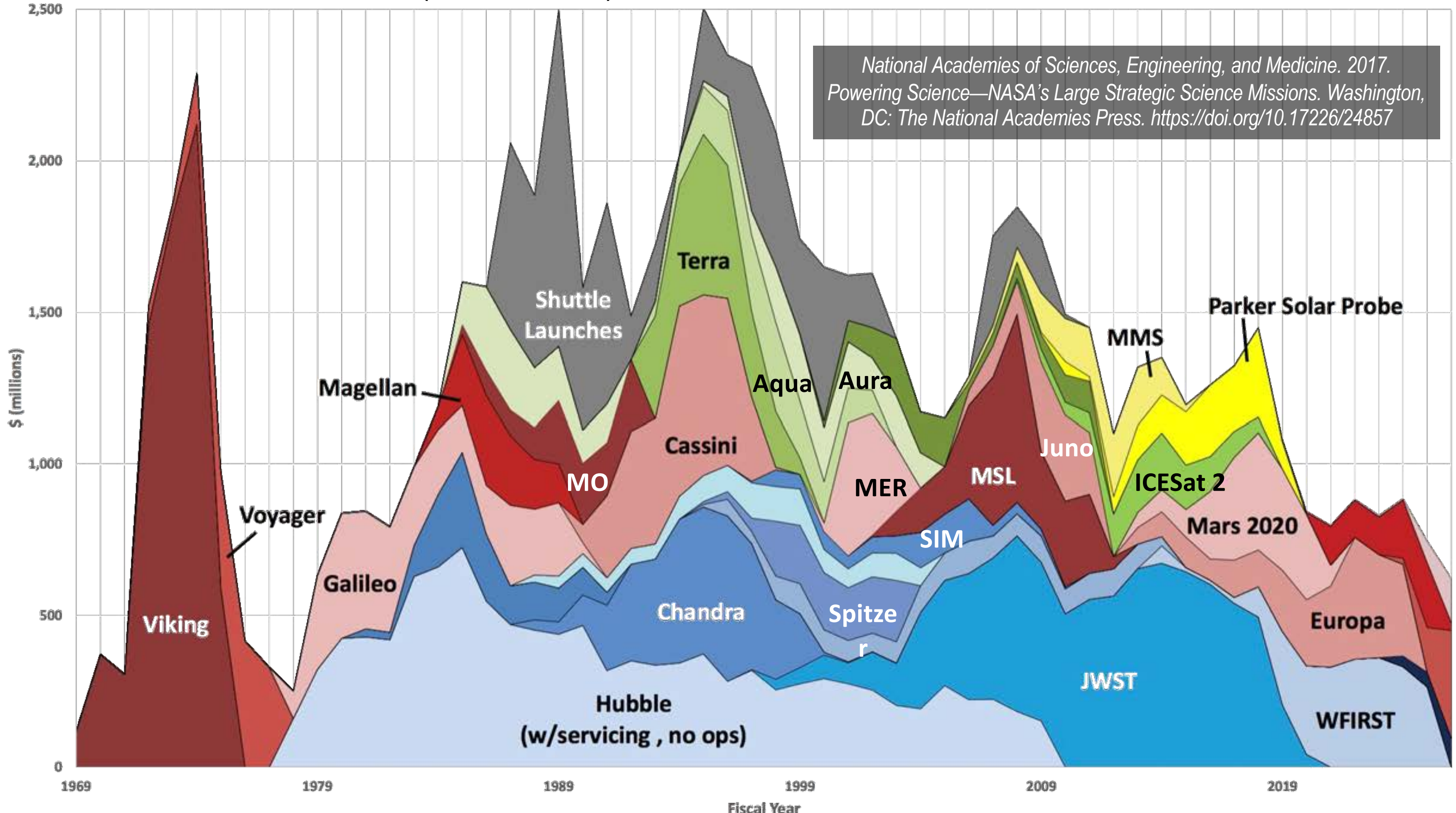
Met objectives to study the plasma, particle, and magnetic field environment of the Moon and to map the lunar gravity field

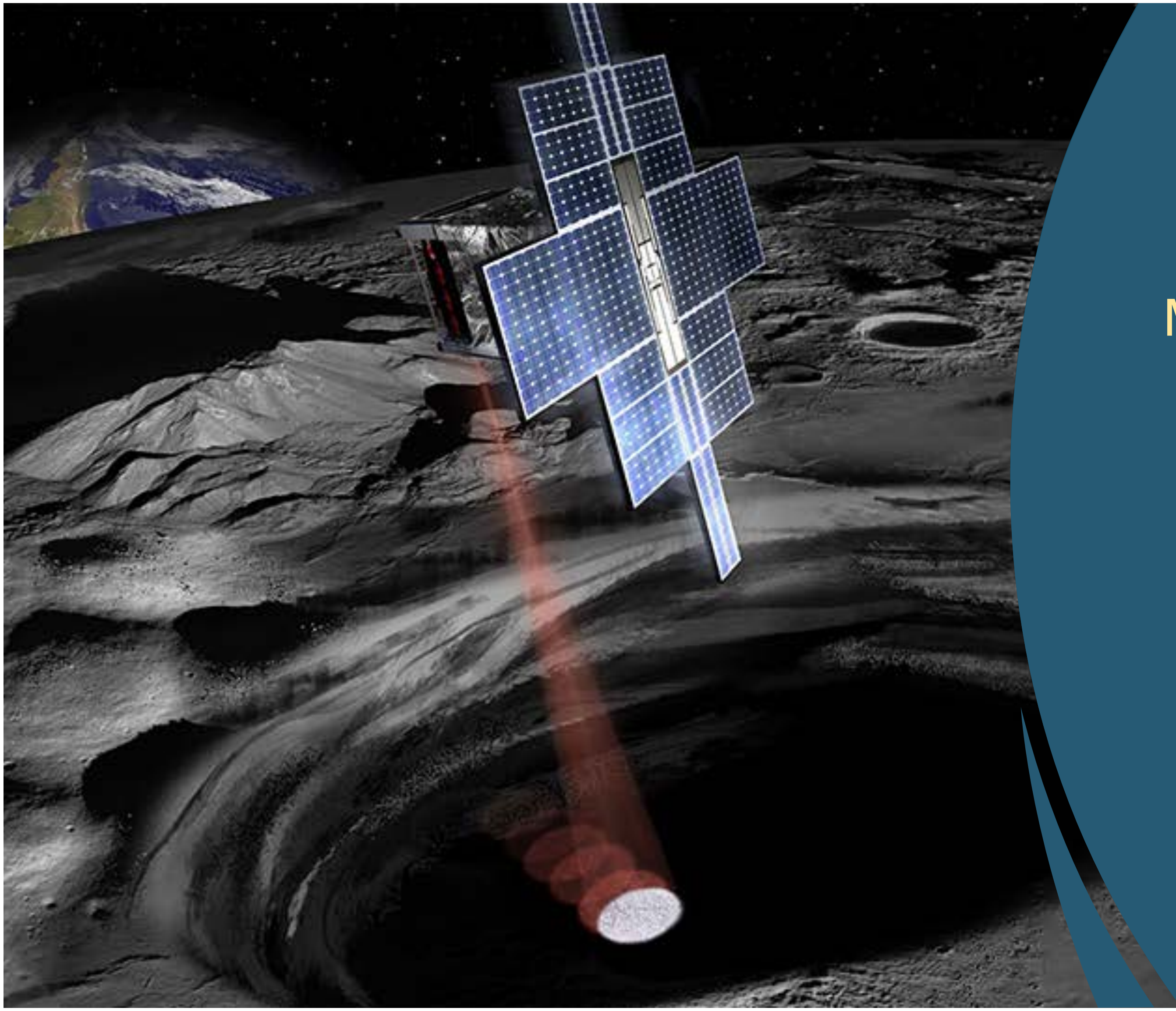
Mass of 35.6 kg carrying 3 instruments: magnetometer, S-band transponder, and charged particle detector

David Scott, Alfred Worden, and James Irwin

NASA Annual Expenditures for Science Missions

In FY15 Millions of Dollars for 57 Years (1969 – 2026)

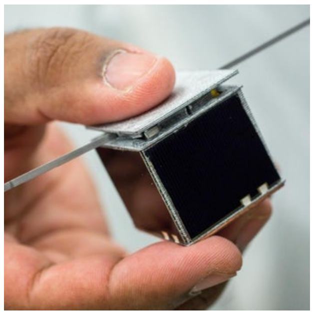




Topics for Discussion

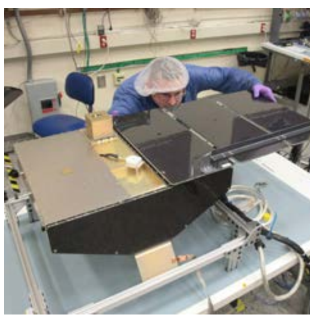
Fundamentals of Small Spacecraft

Spectrum of Satellite Development



Picosatellite
PocketSat (0.1 – 1 kg)

CubeSat/Nanosatellite
MCubed (1 – 10 kg)



Microsatellite
CYGNSS (10 – 100 kg)

Small Satellite
SORCE (100 – 500 kg)

ESPA-Ring
Payload Port Limit (450 kg)

New SMD Working Definition

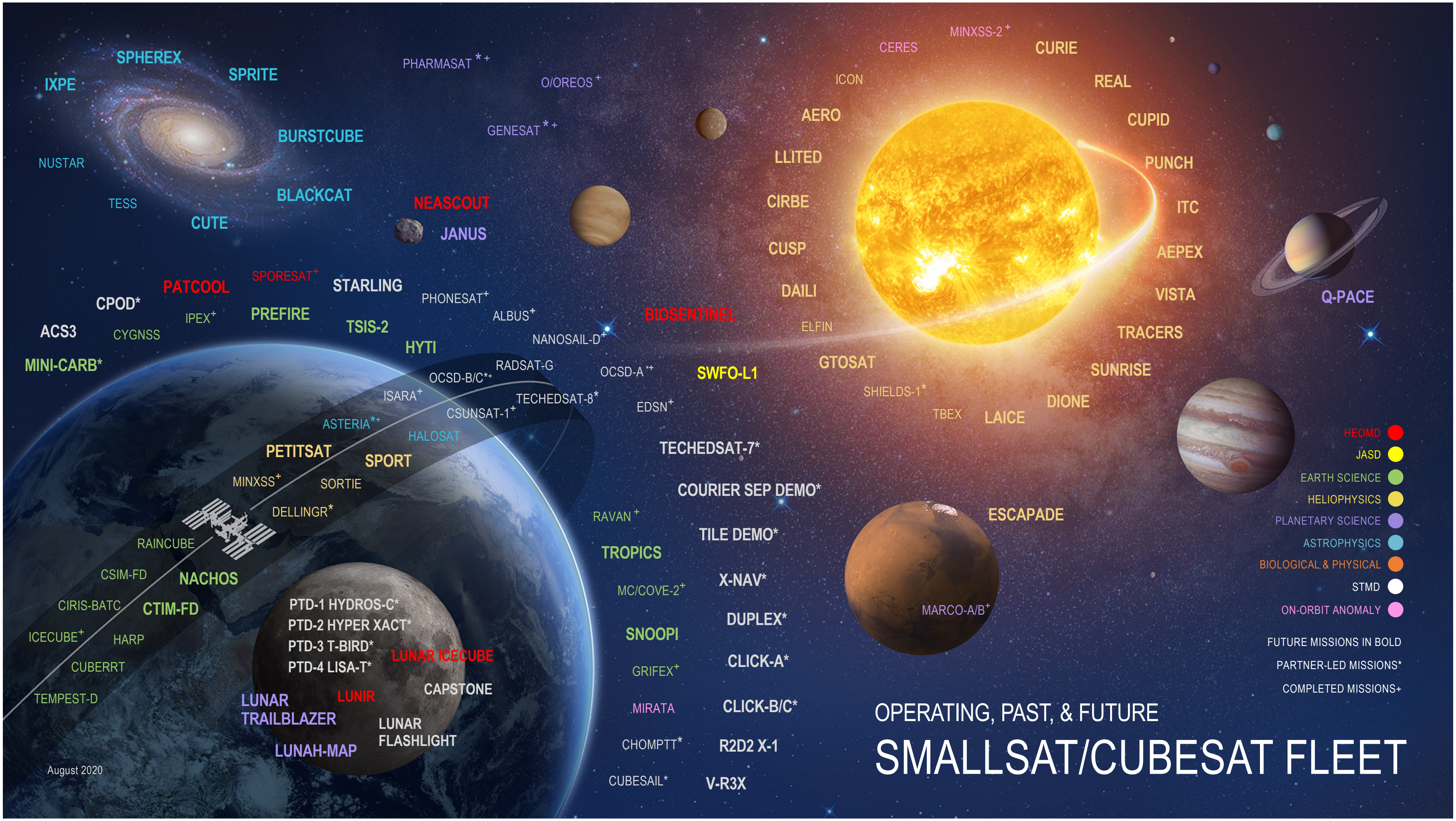
A spacecraft that is interface compatible with an ESPA Ring, a dedicated small or medium-lift launch vehicle, or a containerized dispenser, and with an upper mass limit of approximately 500 kg

The Basics

ISS

Rideshare

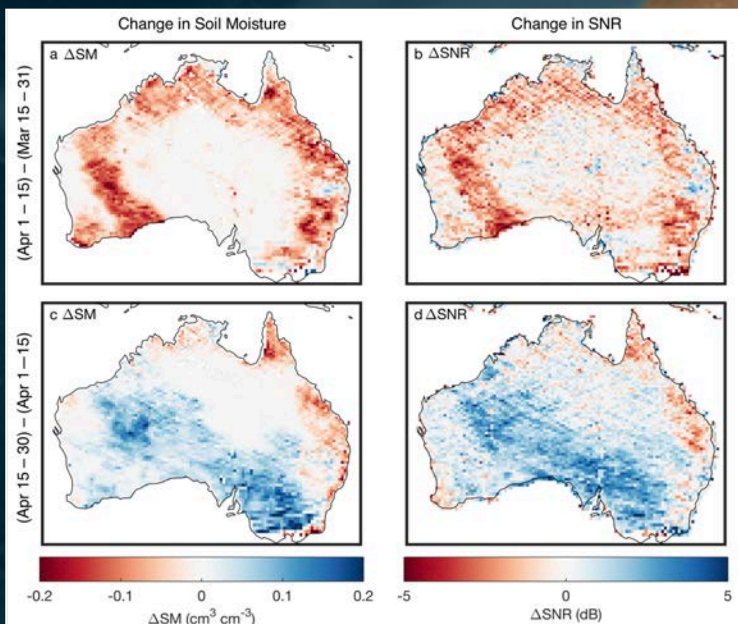
Dedicated



SPHEREX
SPRITE
IXPE
BURSTCUBE
NUSTAR
TESS
BLACKCAT
CUTE
PHARMASAT *+
O/OREOS +
GENESAT *+
NEASCOUT
JANUS
CERES
MINXSS-2+
CURIE
ICON
REAL
AERO
CUPID
LLITED
PUNCH
CIRBE
ITC
CUSP
AEPEX
DAILI
VISTA
Q-PACE
ELFIN
TRACERS
BIOSENTINEL
GTOSAT
SUNRISE
SHIELDS-1*
DIONE
TBEX
LAICE
CPOD*
PATCOOL
SPORESAT+
STARLING
PHONESAT+
IPEX+
PREFIRE
ALBUS+
ACS3
CYGNSS
TSIS-2
NANOSAIL-D+
HYTI
MINI-CARB*
RADSAT-G
OCSD-A*+
SWFO-L1
OCSD-B/C*+
ISARA+
TECHEDSAT-8*
EDSN+
CSUNSAT-1+
ASTERIA*+
HALOSAT
TECHEDSAT-7*
PETITSAT
SPORT
MINXSS+
SORTIE
COURIER SEP DEMO*
DELLINGR*
RAVAN+
TILE DEMO*
ESCAPADE
RAINCUBE
TROPICS
CSIM-FD
NACHOS
MC/COVE-2+
X-NAV*
CIRIS-BATC
CTIM-FD
PTD-1 HYDROS-C*
DUPLEX*
MARCO-A/B+
PTD-2 HYPER XACT*
ICECUBE+
HARP
SNOOPI
PTD-3 T-BIRD*
LUNAR ICECUBE
PTD-4 LISA-T*
CUBERRT
GRIFEX+
CLICK-A*
CAPSTONE
TEMPEST-D
LUNAR TRAILBLAZER
LUNIR
MIRATA
CLICK-B/C*
LUNAR FLASHLIGHT
LUNAH-MAP
CHOMPTT*
R2D2 X-1
August 2020
CUBESAIL*
V-R3X
HEOMD
JASD
EARTH SCIENCE
HELIOPHYSICS
PLANETARY SCIENCE
ASTROPHYSICS
BIOLOGICAL & PHYSICAL
STMD
ON-ORBIT ANOMALY
FUTURE MISSIONS IN BOLD
PARTNER-LED MISSIONS*
COMPLETED MISSIONS+
OPERATING, PAST, & FUTURE
SMALLSAT/CUBESAT FLEET

CYGNSS

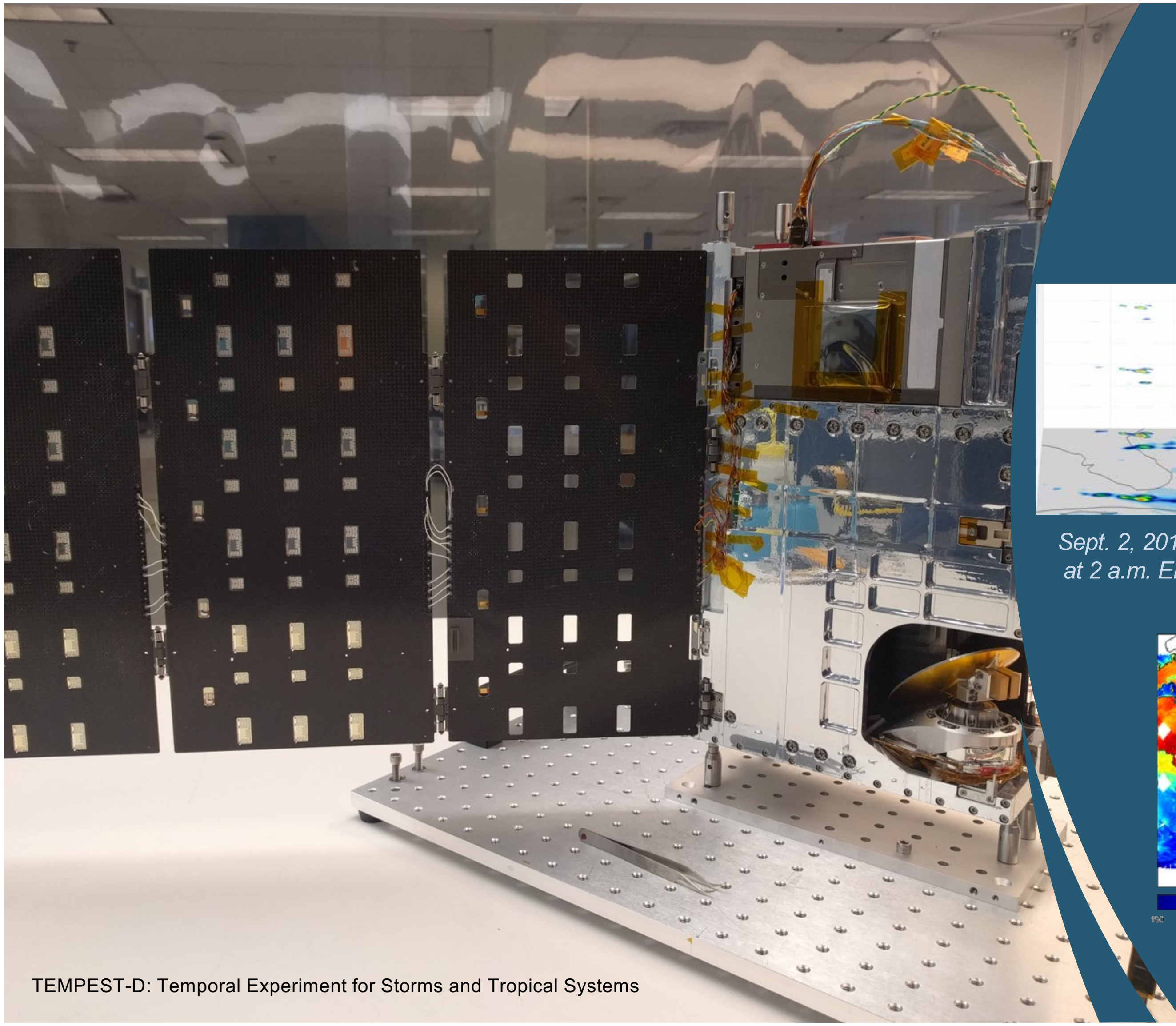
Land Hydrology Opportunistic Measurement
Near-Surface Soil Moisture

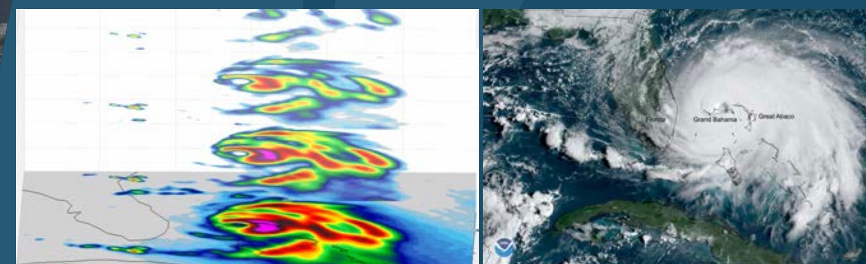


Nature Scientific Reports: Change in mean SMAP soil moisture compared to change in CYGNSS SNR

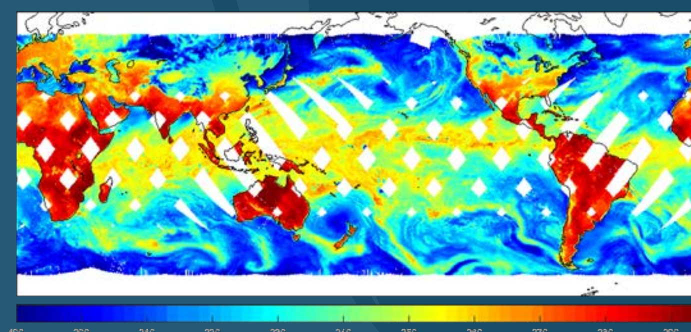
TEMPEST-D

Weather Observations



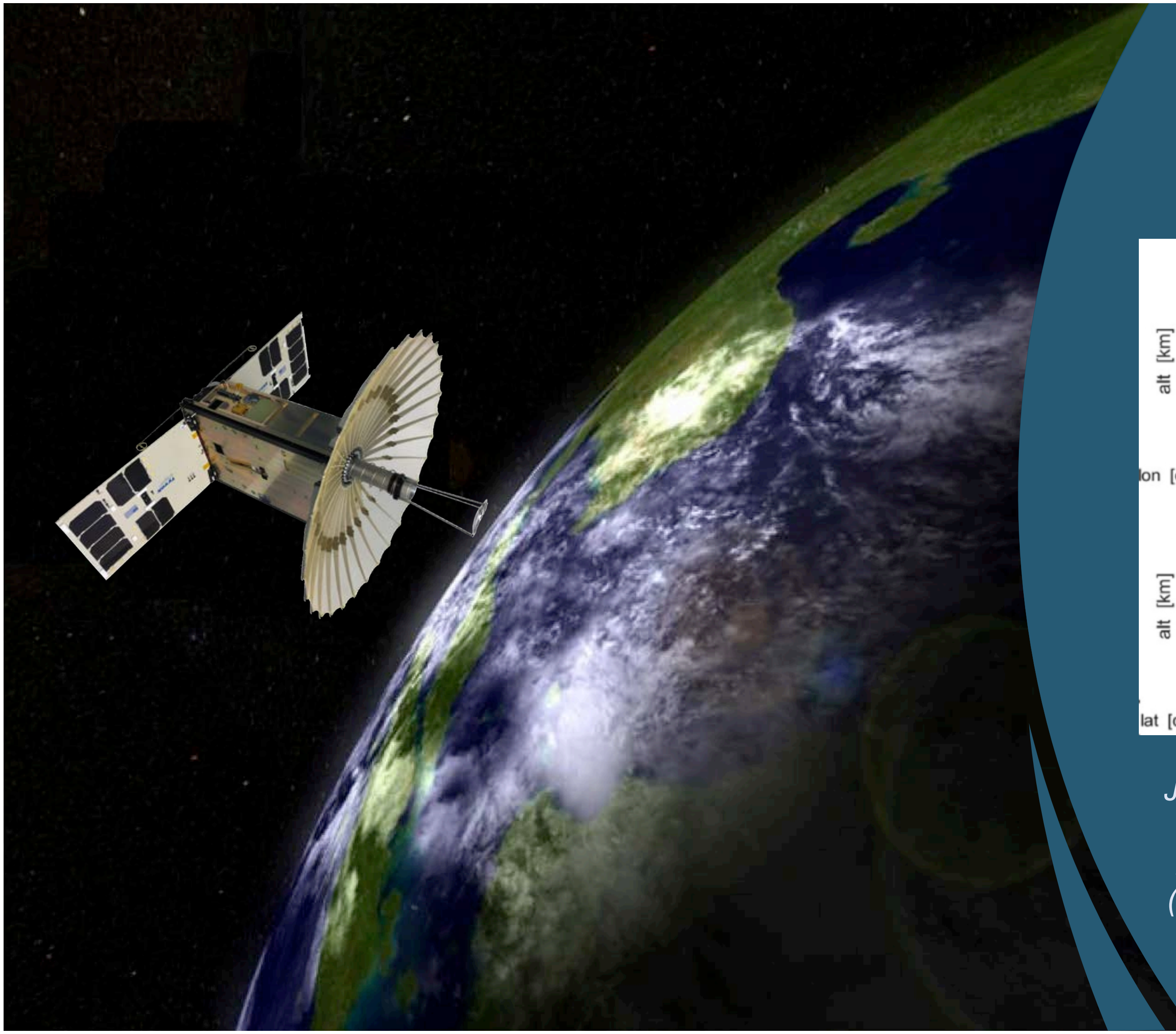


Sept. 2, 2019 – Layers inside of Hurricane Dorian as seen by Tempest-D at 2 a.m. EDT with yellow, red and pink indicating areas of most intense rainfall and moisture inside the storm

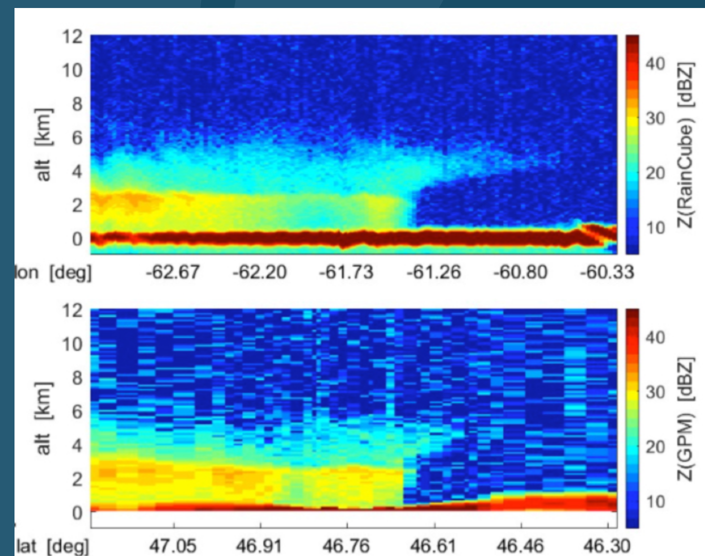


Dec. 8-12, 2018 – TEMPEST-D 87 GHz near-global brightness temperatures in ISS orbit

TEMPEST-D: Temporal Experiment for Storms and Tropical Systems



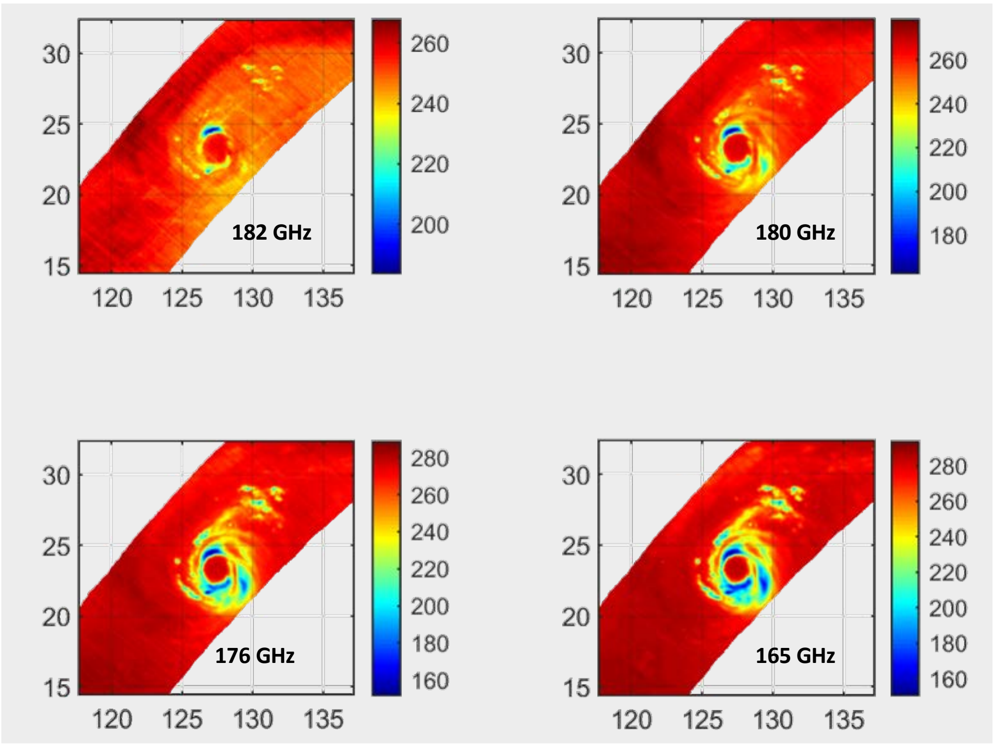
RainCube / GPM
Precipitation Radar



Jan. 2019 – Near-collocated measurements of vertical rain reflectivity profiles from RainCube (top) and GPM's Ka-band radar (bottom) RainCube points Nadir while GPM scans along-track

RainCube/TEMPEST-D Observing Typhoon Trami

Spacecraft constellation separated by 5 minutes revealing 3D storm structure



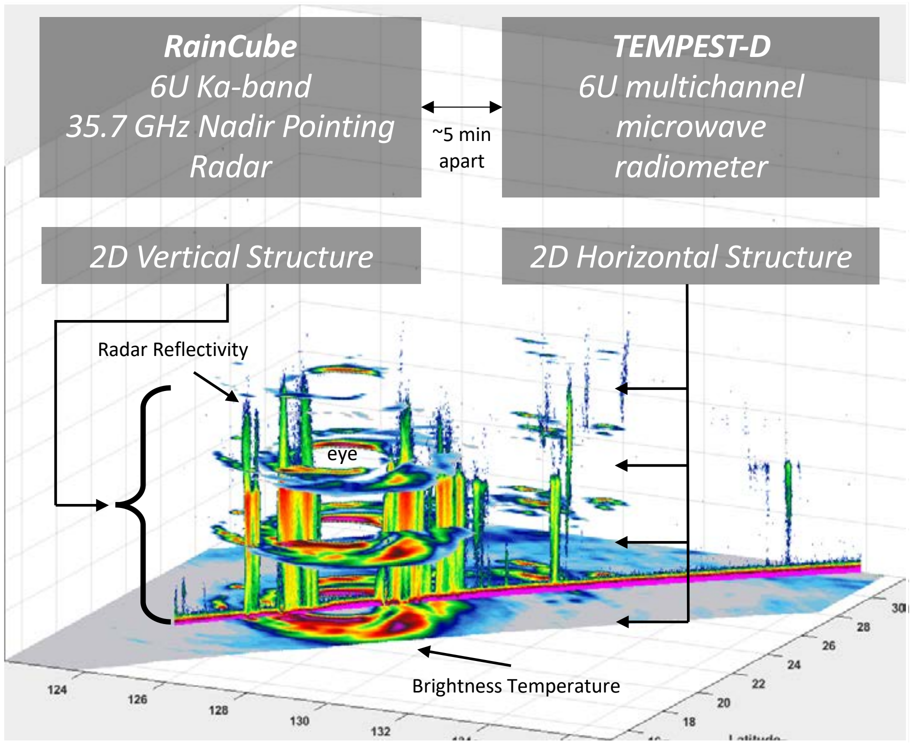
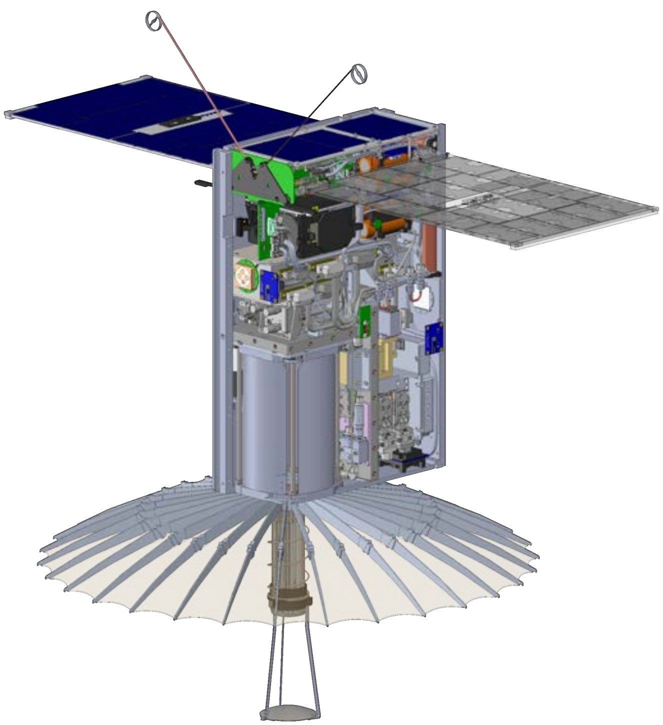


Illustration of complementary nature of these sensors flown in constellation for observing precipitation

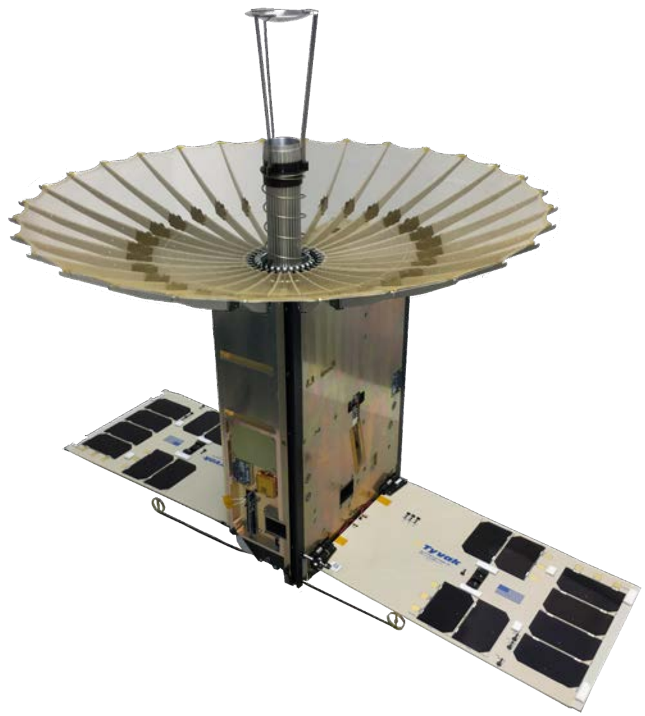
RainCube Flight System Design

Anatomy of the Spacecraft System Design

RainCube



CAD System Model

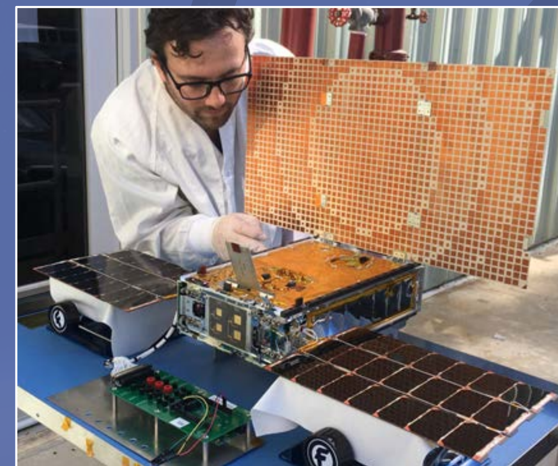


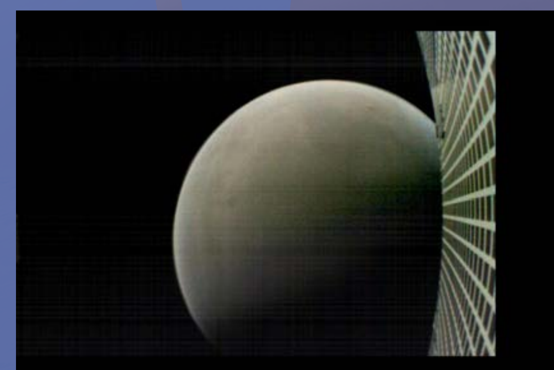
Flight Model Design

Subsystems
C&DH Processors
ADCS Processors
Battery Modules
Solar Panels
UHF Radio
S-Band Radio
ADCS Control
Thermal Control
Antennas
GPS

The Basics

The Basics

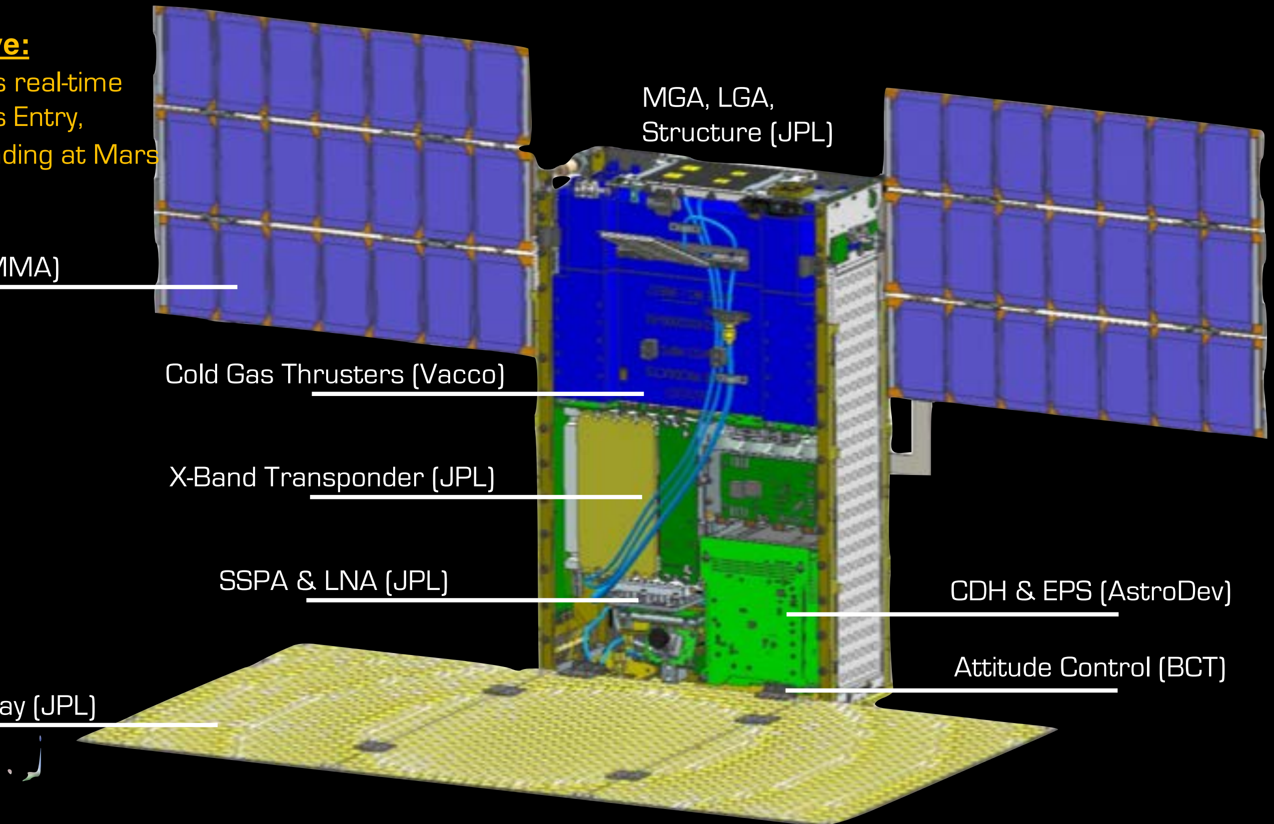




Nov. 26, 2018 - MarCO-B image of Mars from approximately 4,700 miles away during its flyby

The Basics

Mission Objective:
- Provide an 8kbps real-time relay for InSight's Entry, Descent and Landing at Mars



MarCO Overview:
Volume: 2 x 6U (12x24x36cm)
Mass: 14.0 kg
Power Generation:
Earth: 35 W
Data Rates: 62-8,000 bps
Delta-V: >40 m/s

Software:
FSW: *protos (JPL)*
GSW: AMPCS (NASA/JPL)

I&T:
In-house S/C I&T, testing,
Tyvak NLAS/Launch Integration

Operations:
Primary: DSN 34m
EDL: Madrid 70m

Evolution of SmallSats
(Past 5 Years)

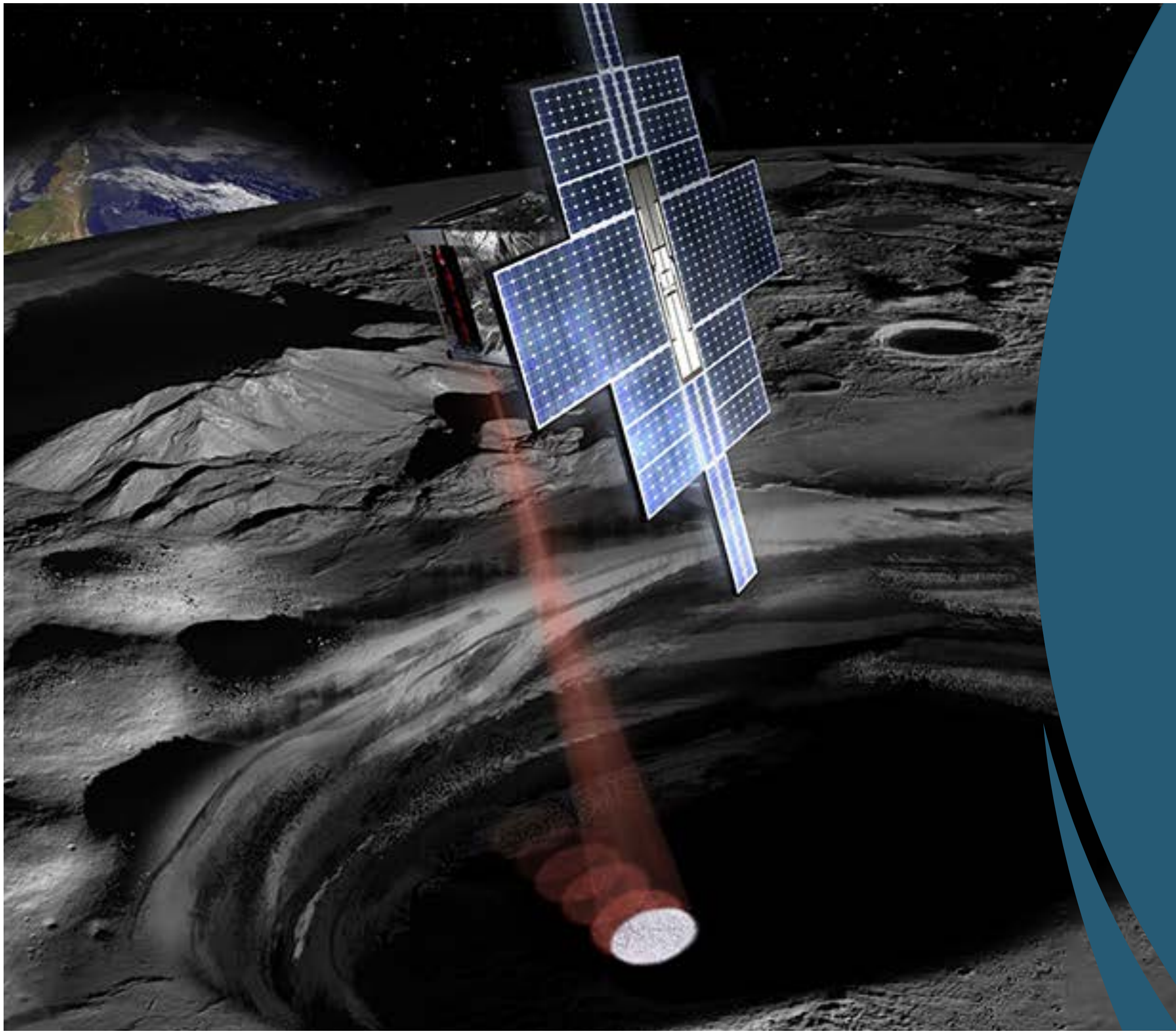
Growth and establishment of commercial flight systems

Expansion of measurement capability from innovative miniaturized instruments

Increased design space of measurement opportunities

Diversity of options for access to space (ISS, dedicated launch, and containerized/ESPA rideshare)

TEMPEST-D and CubeRRT ISS Deployment



Topics for Discussion

The Basics

Mission Formulation

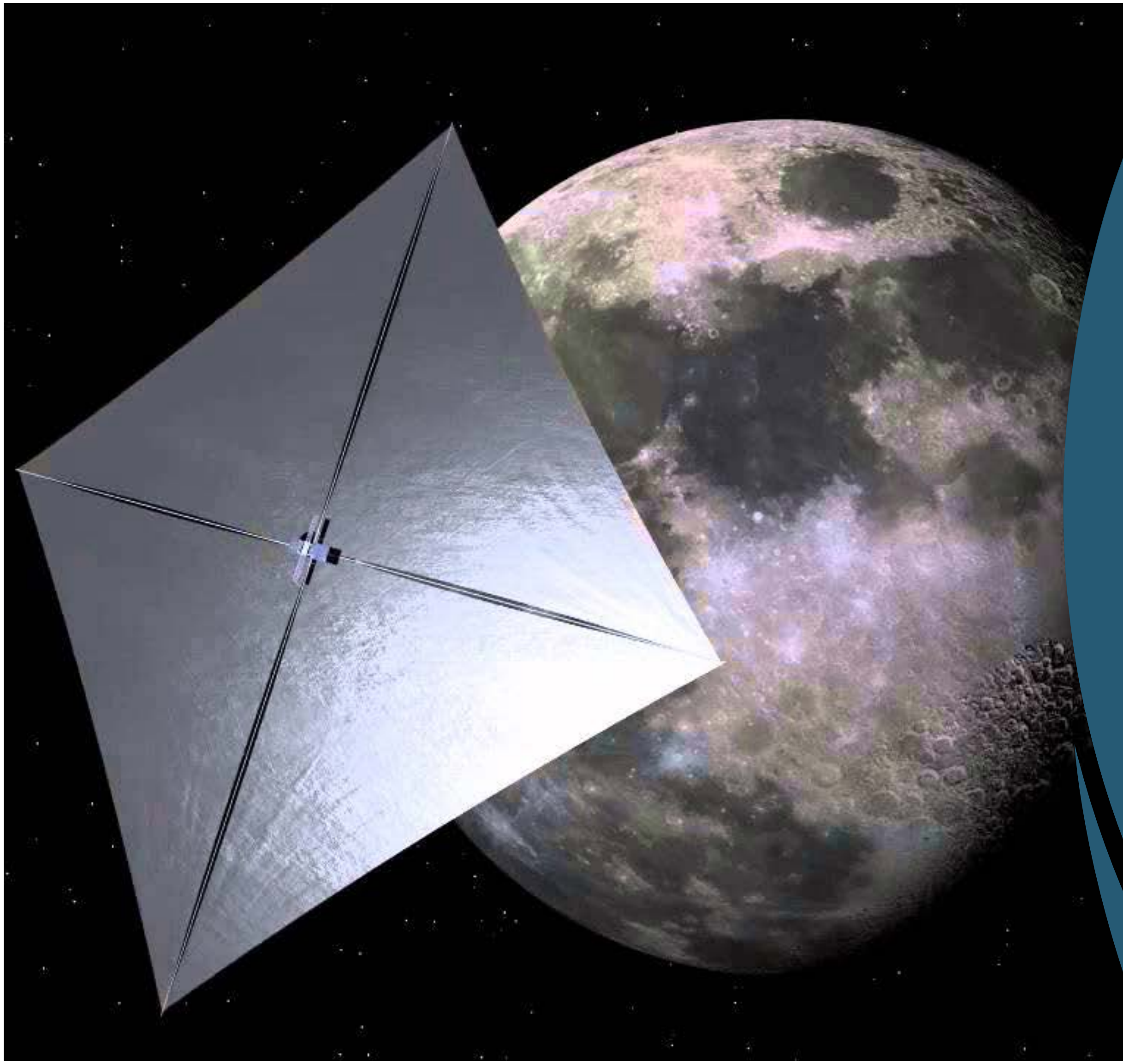
Realities of Flight Development

Access to Space

Mission Operations

Closing Remarks

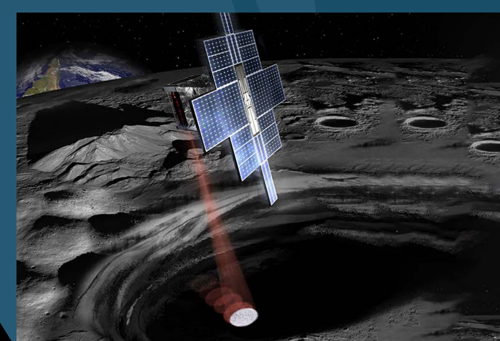
Mission Formulation

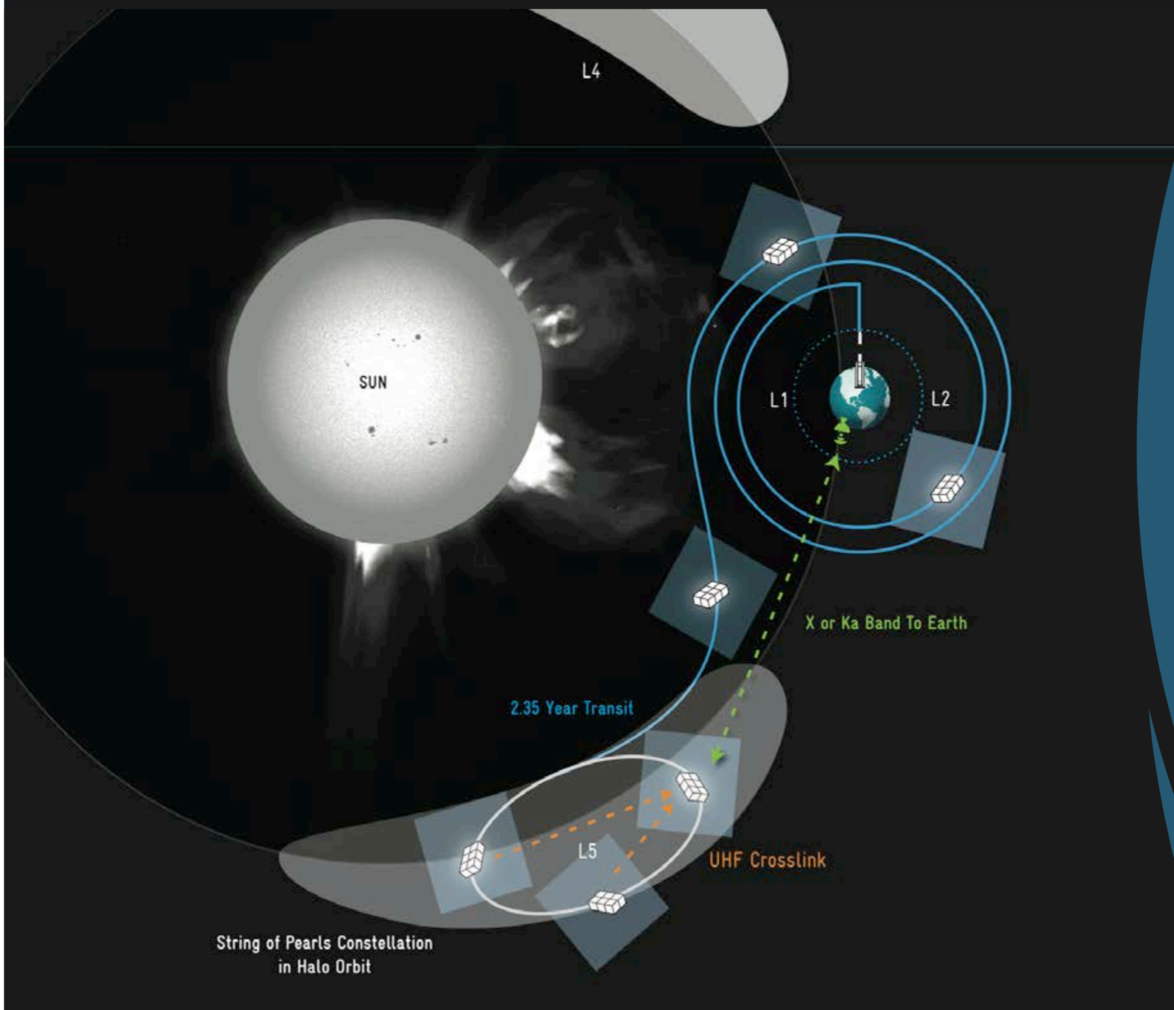


The "Original" Lunar Flashlight Mission Concept

Courtesy: EON Productions, Die Another Day (2002)

The Revised Mission Design

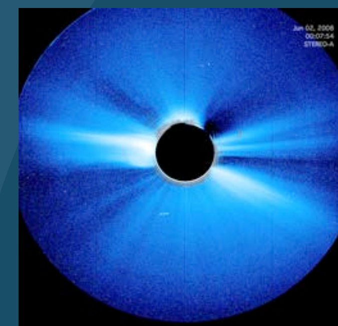


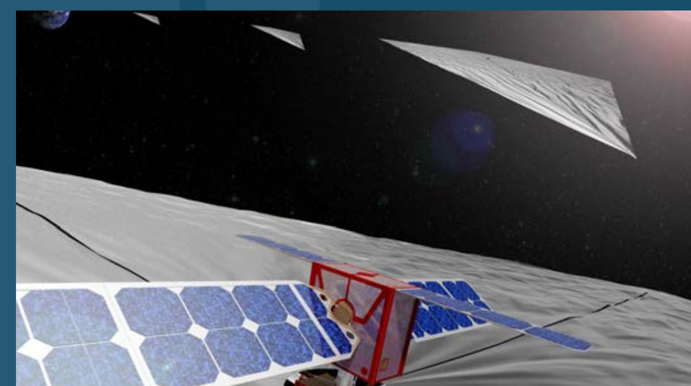


Heliospheric Science

Heliospheric Imager

Coronagraph



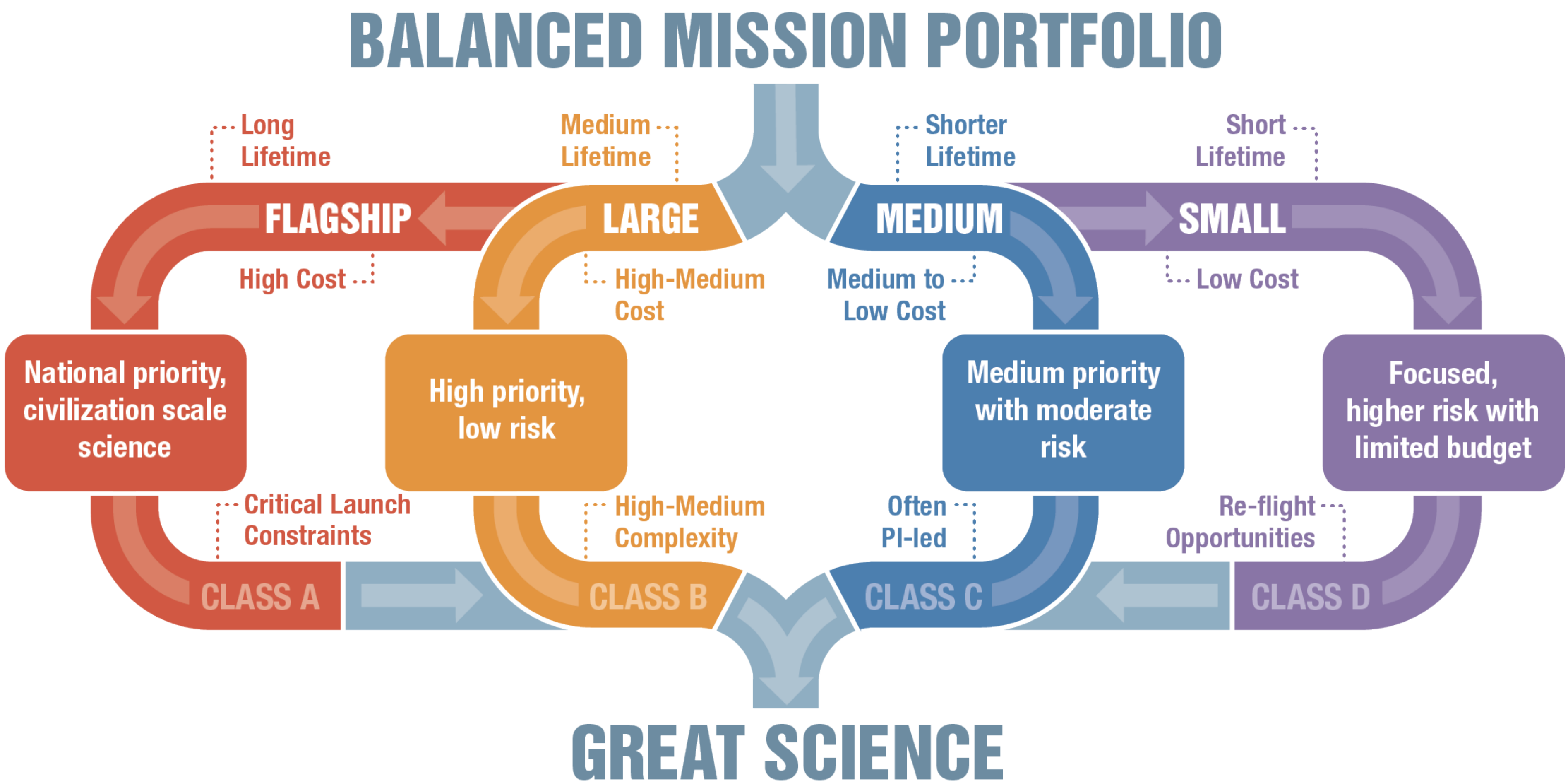


L5SWS

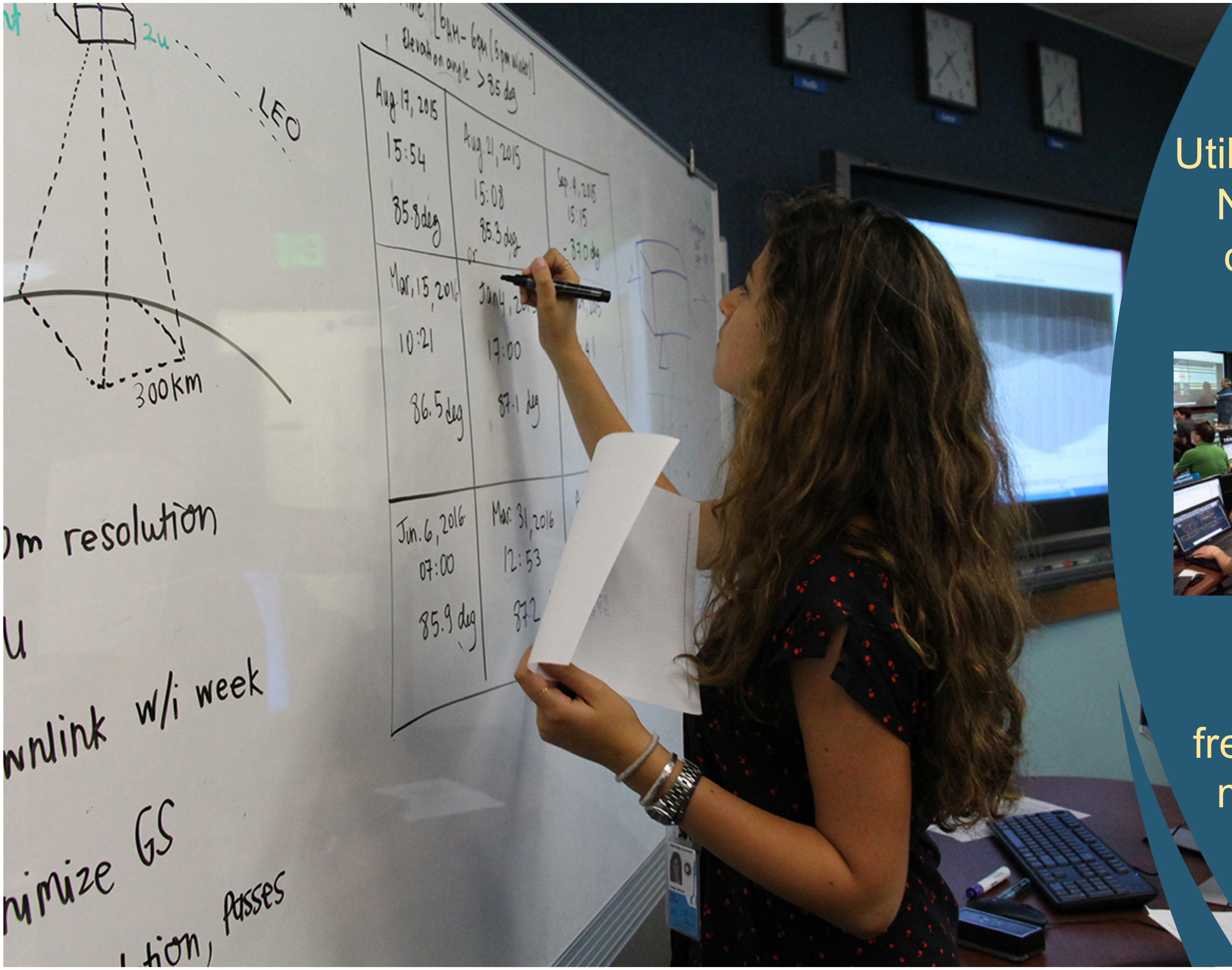
L5 Space Weather Sentinel Constellation Concept

For Prediction and Understanding of Solar Variability

Mission Formulation

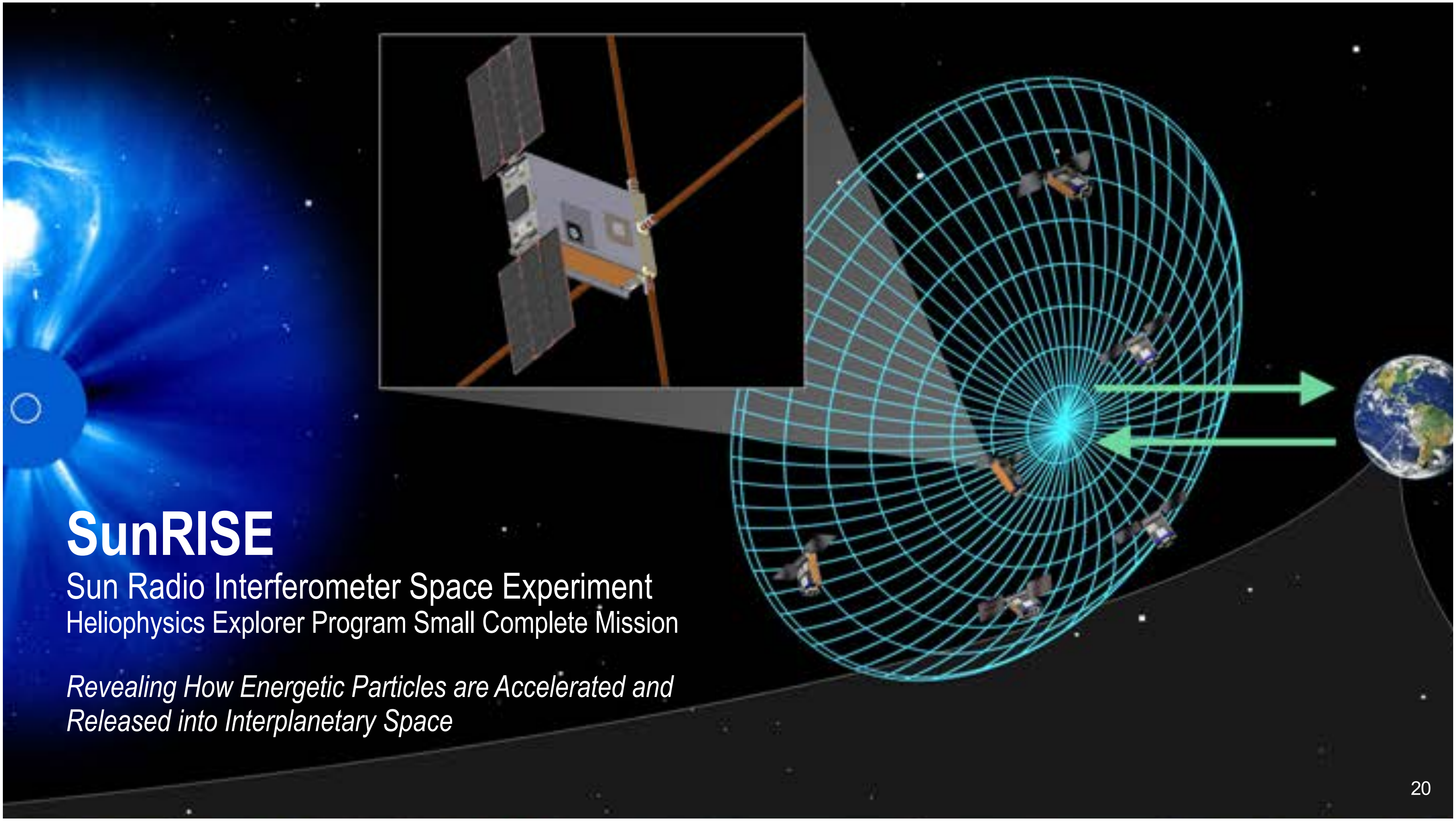


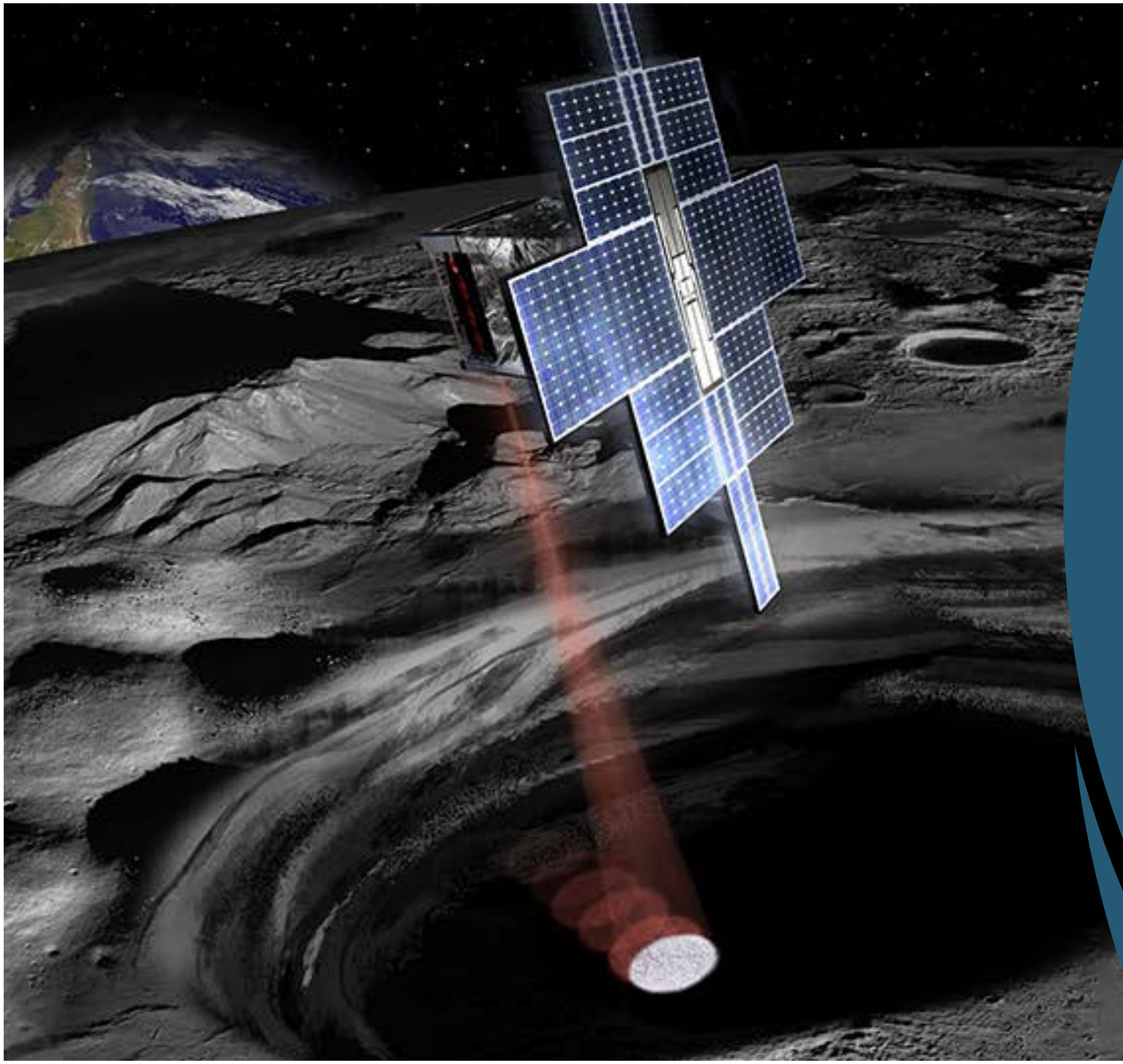
Mission Formulation



Utilize expertise from NASA's concurrent design formulation teams

Such services are appearing more frequently within the mission solicitation process


SunRISE
Sun Radio Interferometer Space Experiment
Heliophysics Explorer Program Small Complete Mission
Revealing How Energetic Particles are Accelerated and Released into Interplanetary Space
20



Topics for Discussion

Flight Development Reality

Mission Assurance Requirements

Lifecycle Reviews

Mission Success Criteria

Formal and Informal Review Boards

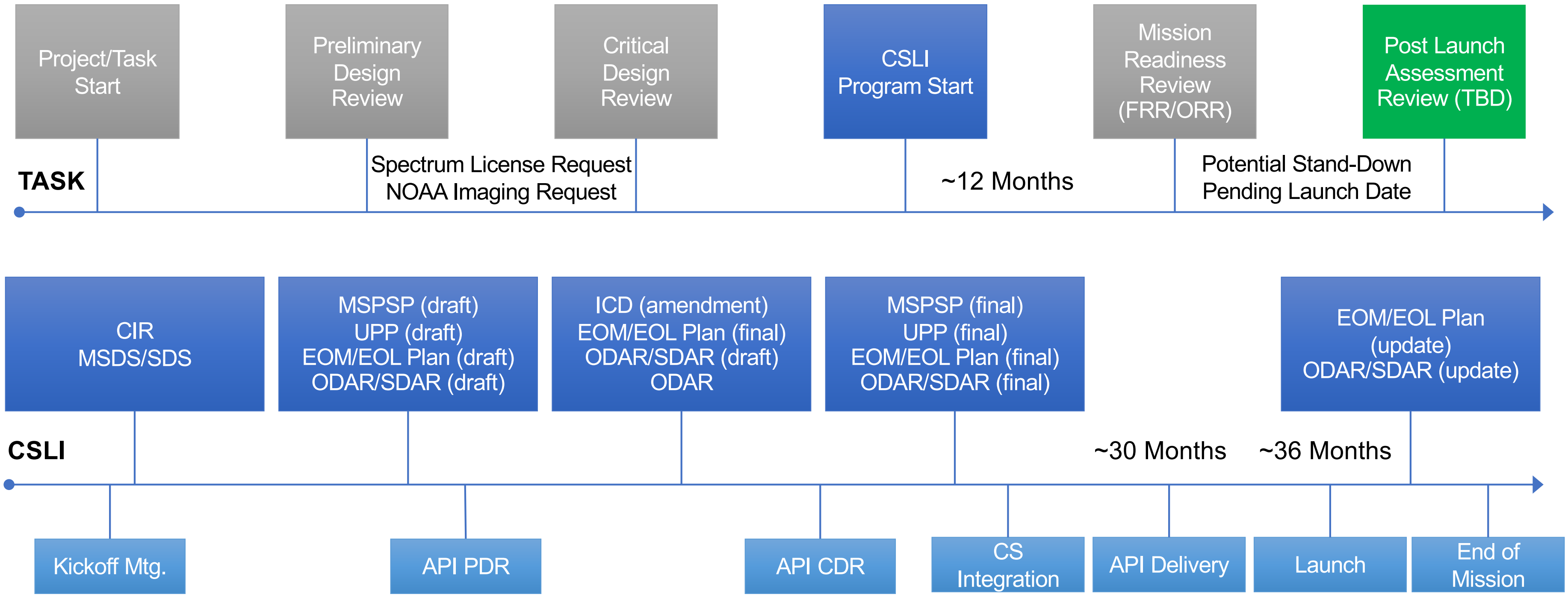
Independent Cost and Schedule Estimates

Managing The Unexpected

Overview of Key Documentation Required (Not Comprehensive)

Acronym	Document	Comments
CIR	CubeSat Interface Review	General information from flight projects
MSDS	Mission Safety Data Sheet	Documentation of materials hazards
MSPSP	Missile System Pre-Launch Safety Package	Documents range safety hazards and containment
ODAR/SDAR	Orbital/Space Debris Assessment Report	Documents orbital debris hazards and containment
EOM/EOL Plan	End-of-Mission / End-of-Life Plan	End-of-Life passivation and de-orbit plan
UPP	Uplink Protection Plan	Documents plan to maintain spacecraft control
ICD	Interface Control Document	Integration Status, Risk Assessment, Open Items
ODR	Orbital Data Request	JFCC Space / JSpOC Collision/Conjunction Request
CDS	CubeSat Design Specification	Standards document for fit-check requirements
CAC	CubeSat Acceptance Checklist	Verifies form factor adherence to CDS guidelines

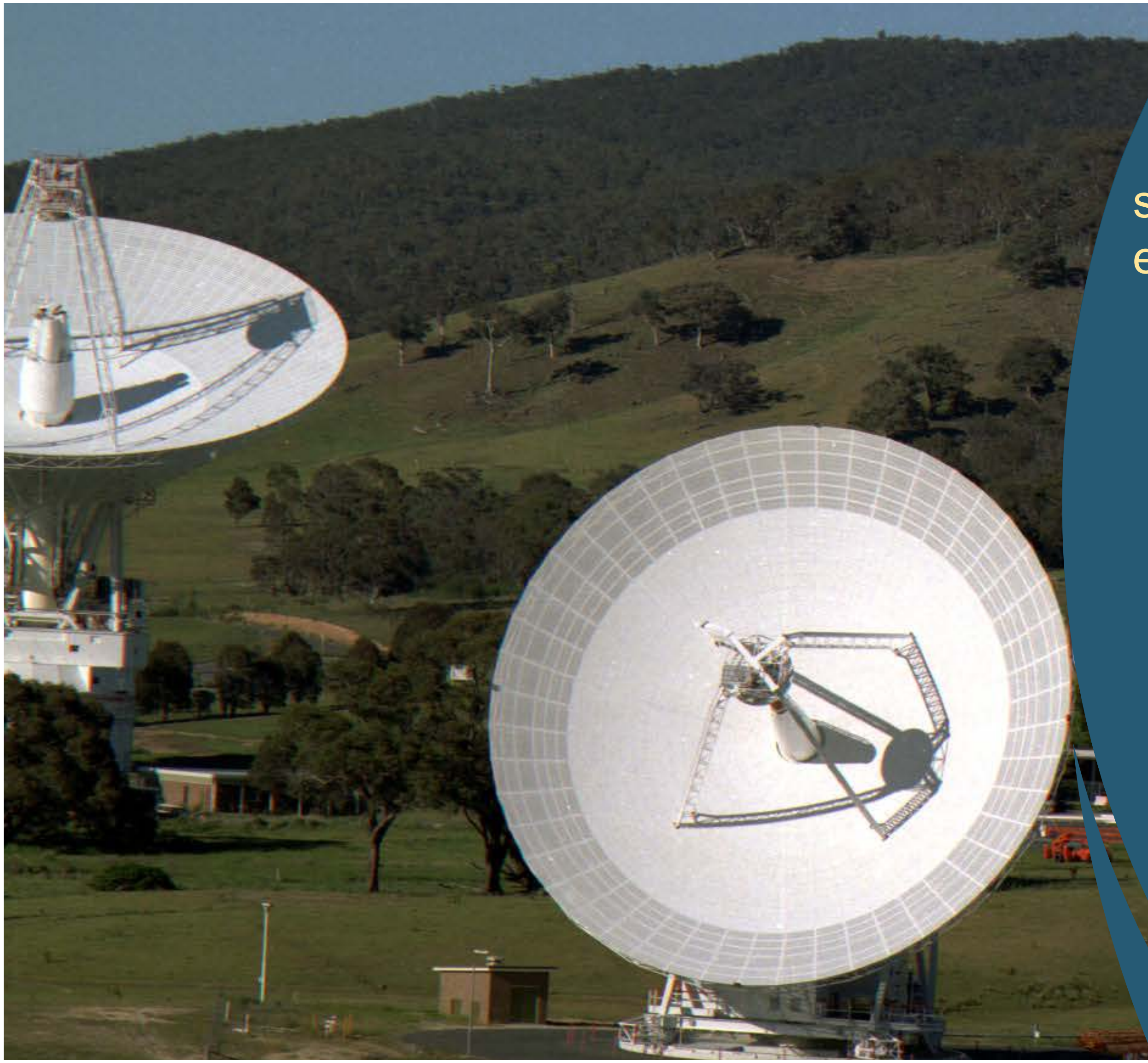
Notional Mission/Launch Manifest Integrated Program Schedule



CS: CubeSat
AP: Auxiliary Payload Integrator

Flight Development Reality

Flight Development Reality



Please submit your spectrum allocation request early as an approved Radio Frequency Authorization (RFA) is required for mission integration

RFA should include all Earth stations planned for mission operations

Should exceptional issues arise a Special Temporary Authority (STA) request may be requested

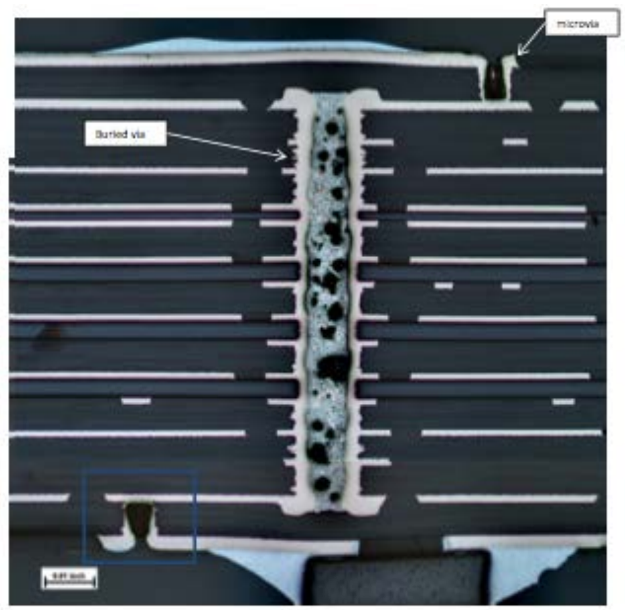
Read your RFA for special directions

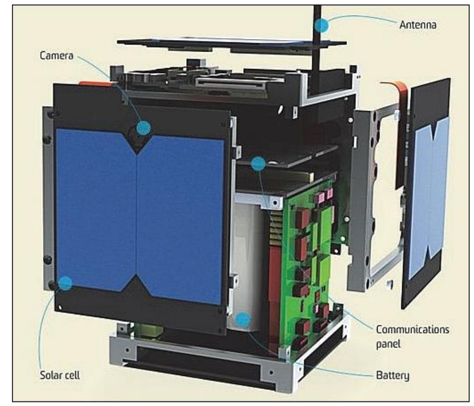
Microvia Separation in SpaceCube-Mini Subsystem

PCB manufacture passed vendor QA, but NASA detected open circuits

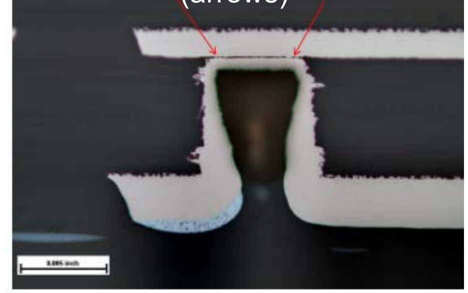
Computer Tomography (CT) scans were inconclusive thus destructive testing and microsection analysis were required

Subsystem descoped and replaced with contingency gumstix processor as SpaceCube-Mini was not a Level-1 requirement





NASA Destructive testing confirms microvia separation (arrows)



More on Testing

General Guidelines:

- Project team is responsible for all testing up to delivery where acceptance testing is performed under the CubeSat Acceptance Checklist (CAC)
- If you build an EM for qualification testing build it as a flight spare
- Paths are qualification to acceptance test on an EM (promoted to an FM) or protoflight to acceptance on an FM
- Photo document all build/test activities, processes and procedures
- If you will have Test-As-You-Fly (TAYF) Exceptions seek waivers early (where allowed)

Table 1 – Dispenser and CubeSat Environments Test Table

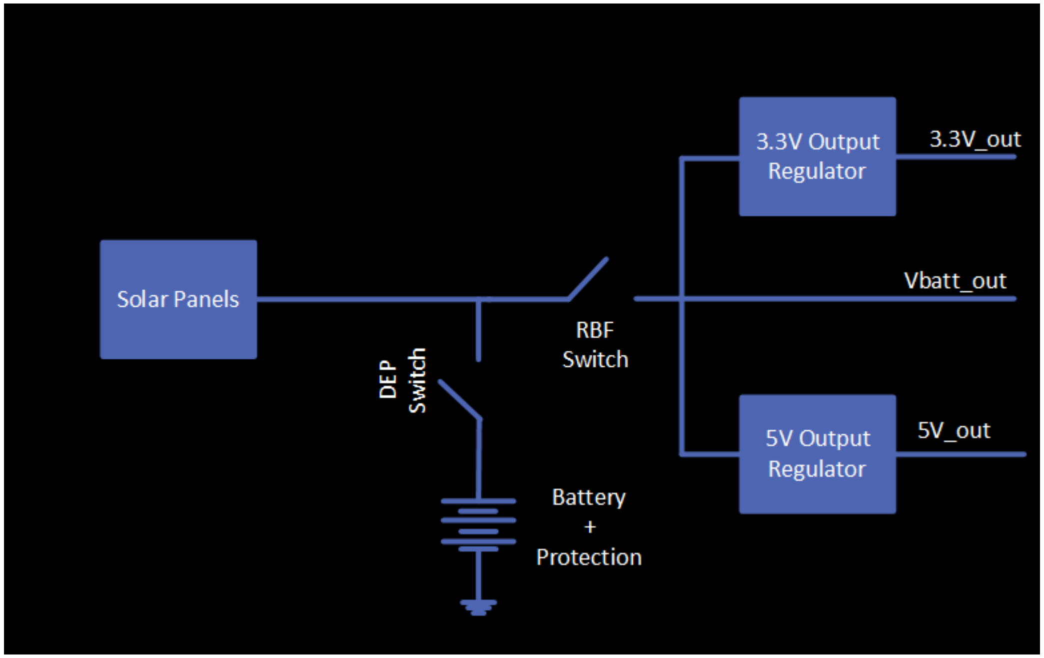
Tests	Qualification by Test	Protoflight Test	Acceptance Test
Random vibration[6] (CubeSat and Dispenser) Ref Mil-Std 1540C	MPE + 6 dB for (3) minutes, each of (3) axes [1]	MPE+3 dB for (2) minutes, each of (3) axes [1]	MPE for (1) minute, each of (3) axes [1]
Sinusoidal Vibration[6] (CubeSat and Dispenser) Ref Mil-Std 1540C	MPE + 6 dB. Testing shall be performed for content that is not covered by random vibration testing	1.25 x MPE. Testing shall be performed for content that is not covered by random vibration testing	MPE. Testing shall be performed for content that is not covered by random vibration testing [1]
Shock[6] (CubeSat and Dispenser) Ref Mil-Std 1540C	MPE + 6 dB, 3 times in both directions of 3 axes [1,3]	MPE + 3 dB, 1 times in both directions of 3 axes [1,3]	N/A
Thermal Vacuum Cycle (Dispenser Only) Ref.: MIL-STD 1540 B, GSFC-STD-7000	MPE[2] +/- 10° C Minimum Range = -14 -3/+0°C to +71 -0/+3°C Cycles = 8 Dwell Time = 1 hour min. @ extreme Temp. after thermal stabilization Transition = < 5° C/minute Vacuum = $1x10^{-4}$ Torr	MPE[2] +/- 10° C Minimum Range = -14 -3/+0°C to +71 -0/+3°C Cycles = 4 Dwell Time = 1 hour min. @ extreme Temp. after thermal stabilization Transition = < 5° C/minute Vacuum = $1x10^{-4}$ Torr	MPE[2] +/- 5° C Minimum Range = -9 -3/+0°C to +66-0/+3°C Cycles = 2 Dwell Time = 1 hour min. @ extreme Temp. after thermal stabilization Transition = < 5° C/minute Vacuum = $1x10^{-4}$ Torr
Thermal Vacuum Bake out (Dispenser Only) Ref.: MIL-STD 1540 B, GSFC-STD-7000	N/A	Min. Temp 70°C [4,7] Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = N/A Vacuum = $1x10^{-4}$ Torr	Min. Temp 70°C [4,7] Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = N/A Vacuum = $1x10^{-4}$ Torr
Thermal Vac Bake out (CubeSat Only) Ref.: MIL-STD 1540 B, GSFC-STD-7000	N/A	Min. Temp 70°C [5,8] Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = < 5° C/minute Vacuum = $1x10^{-4}$ Torr	Min. Temp 70°C [5,8] Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transiton = < 5° C/minute Vacuum = $1x10^{-4}$ Torr
Hardware Configuration	Dispenser – Flight identical unit (includes NEA, cable and connector) **CubeSat** – Flight Identical unit	Dispenser – Flight unit (includes flight NEA, cable and connector) **CubeSat** – Flight unit	Dispenser – Flight unit (includes flight NEA, cable and connector) **CubeSat** – Flight unit

Remove Before Flight (RBF) Pin Functionality, Power, and Inhibits

With the RBF pin in place the batteries and the solar panels are isolated from the spacecraft bus

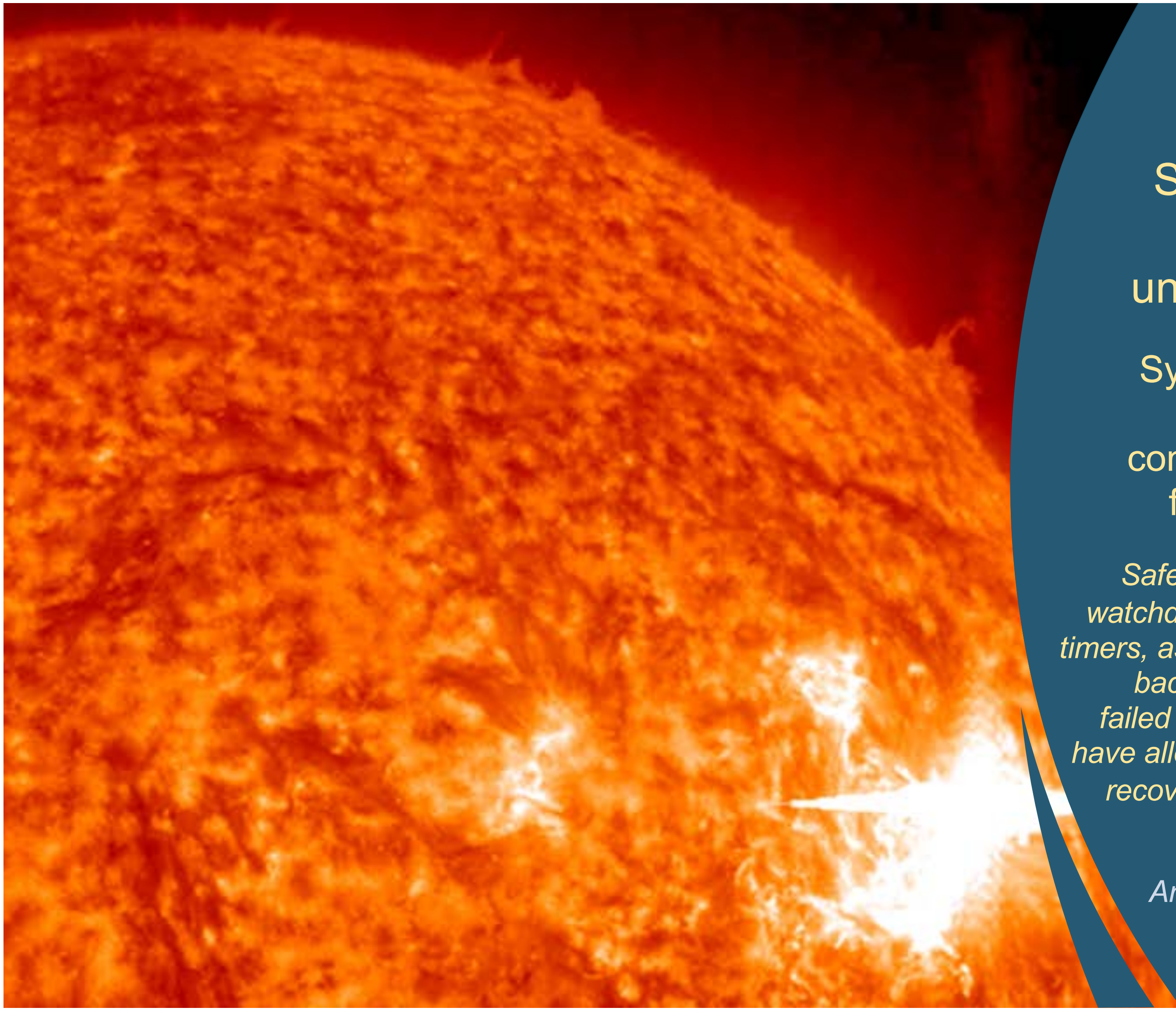
However, once the RBF is removed (in the dispenser) an electron flow path does exist from the solar panels to the spacecraft bus

Analysis proved insufficient current to drive the flight hardware during P-POD integration, but careful inhibit design must be followed



Power system design used successfully in multiple flight projects

Flight Development Reality



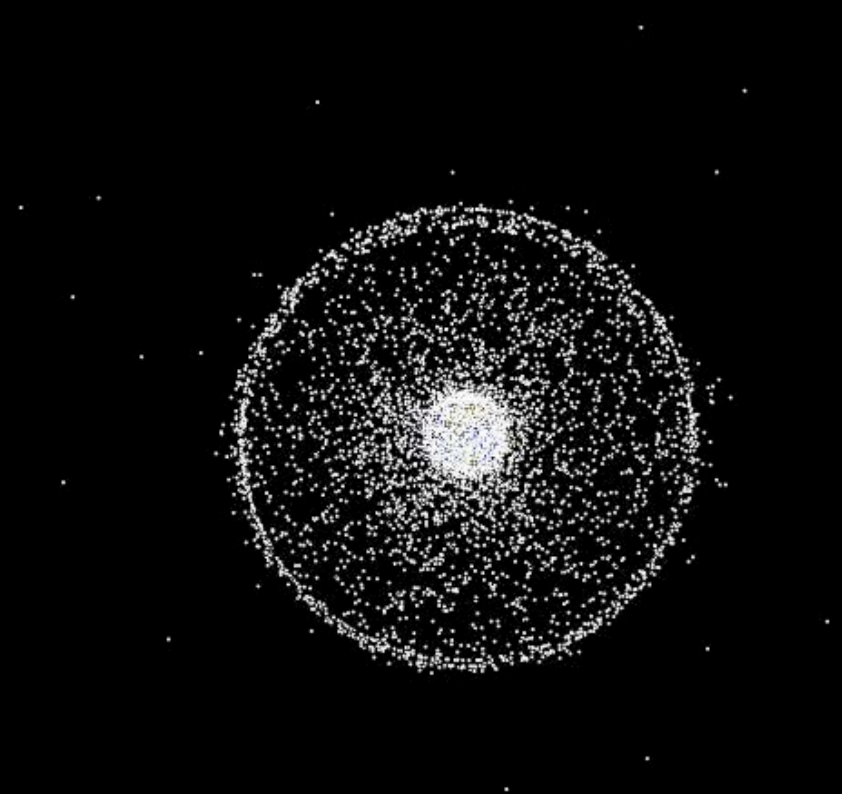
Radiation effects from SEPs, and the SAA, do impact missions with unprotected COTS parts

Symptoms include increased current draw, random command execution, SD card failures, data corruption, …

Safe modes, watchdog reset timers, as well as backups for failed devices, have allowed for recovery from SEUs

An aside…watch out for the impact of helium on MEMs devices

Flight Development Reality



Accounting for orbital debris ensures good stewardship of the space environment

It's also required and directly impacts your spacecraft and mission design

Avoid high melting point materials to satisfy re-entry energy and risk of human casualty requirements

Flight Development Reality

Additional Practical Advice

All export control rules apply even if you develop and launch your spacecraft within the US

Be mindful of the import of components from foreign countries and their potential export when repairs are needed

Have appropriate protections in place to firewall FNs from ITAR/EAR data and always secure and/or encrypt sensitive information

Always consult with an authorized export control authority at your institution

Reality of Mission Cost Estimation

ROM example work breakdown structure (WBS) for typical SmallSat mission

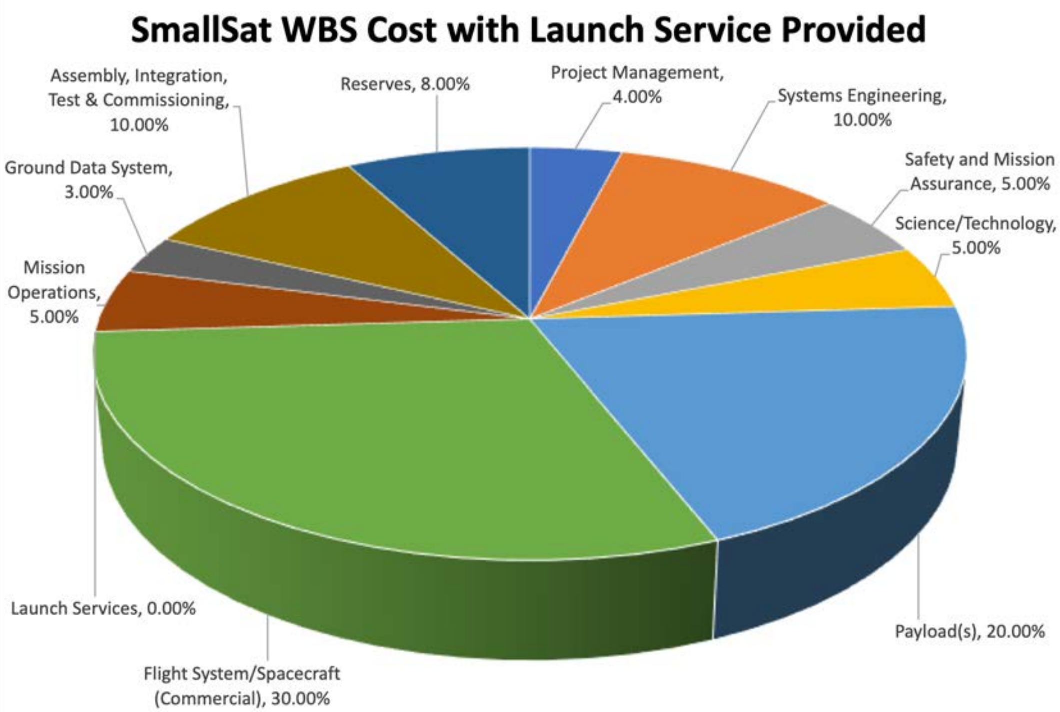
Notional view of WBS by budget percentage for typical SmallSat

Personal opinion and not a basis for future proposed cost breakdown

SmallSat ROM Estimate (no launch cost)

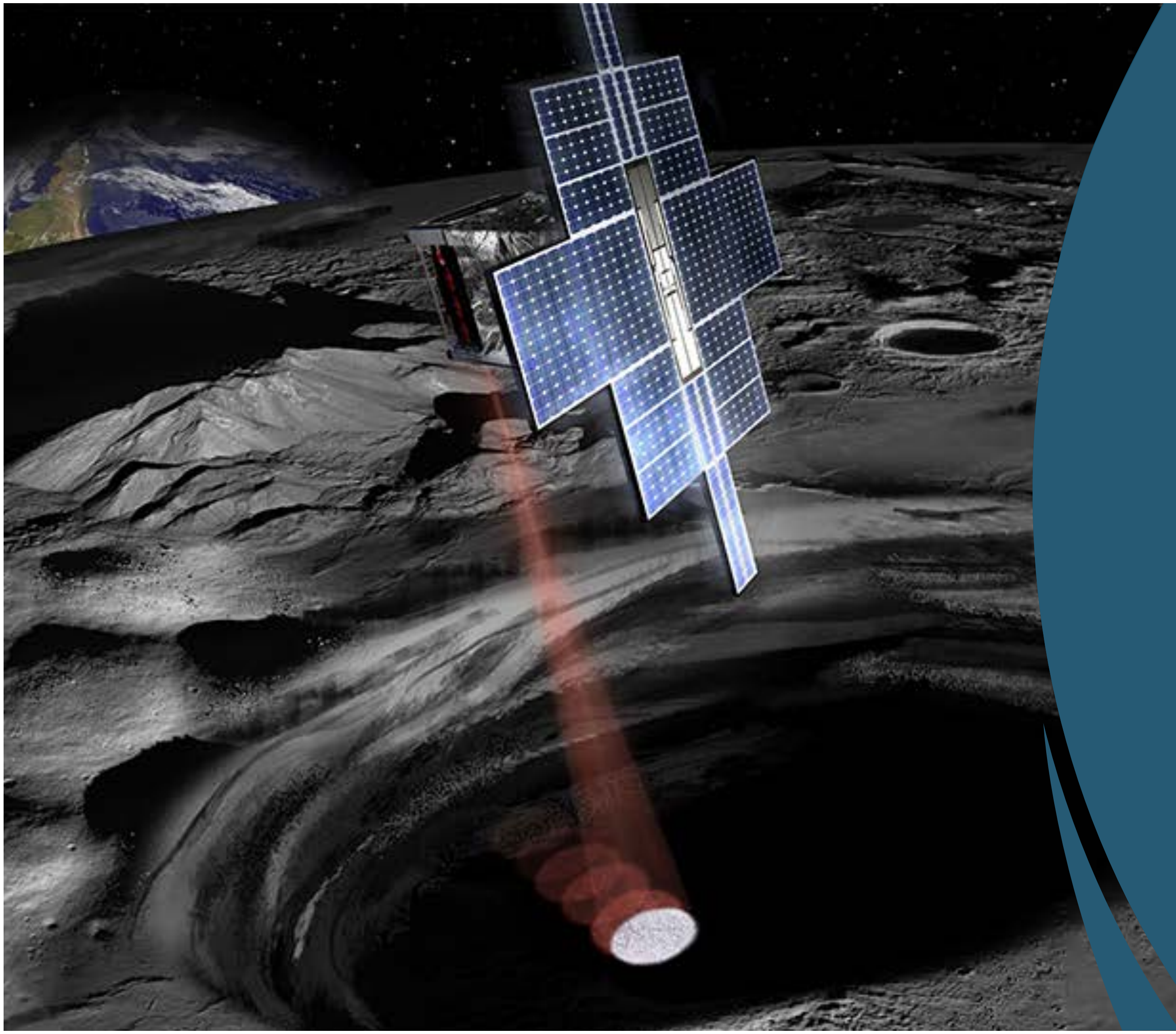
Note: Under CSLI the first $300K of services is covered

	WBS Element	Percent
1	Project Management	4 %
2	Systems Engineering	10 %
3	Safety and Mission Assurance	5 %
4	Science/Technology	5 %
5	Payload(s)	20 %
6	Flight System/Spacecraft (Commercial)	30 %
7	Launch Services	0 %
8	Mission Operations	5 %
9	Ground Data System	3 %
10	Assembly, Integration, Test, & Commissioning	10 %
11	Reserves	8 %



Flight Development Reality

Solicitation caps, cost estimation, tracking, analysis, and database tools (i.e. COMPACT) need attention



Topics for Discussion

- The Basics
- Mission Formulation
- Realities of Flight Development
- <u>Access to Space</u>
- Mission Operations
- Closing Remarks

Access to Space

Commercial and Government Rideshare is a hot topic, but there is complexity

Some industry forecasts show SmallSat lunar activity will triple in the next 5 years

Respondents may need to reimburse NASA for integration and launch activities if contract obligations are not met

ISS Deployment

HaloSat/RainCube deploy from the ISS

Access to Space

Courtesy: Spaceflight Industries

Access to Space

Image Credit: Northrop Grumman ESPA-Star

Future mission architectures will leverage propulsive ESPA as the complete spacecraft bus

Could provide a mission unique capability for managing complex deployments for a single mission application

Emerging Launch Capabilities Beyond LEO

Rideshare and Direct Inject Vehicle Development

Industry transition to higher capability launch vehicles will provide greater opportunities

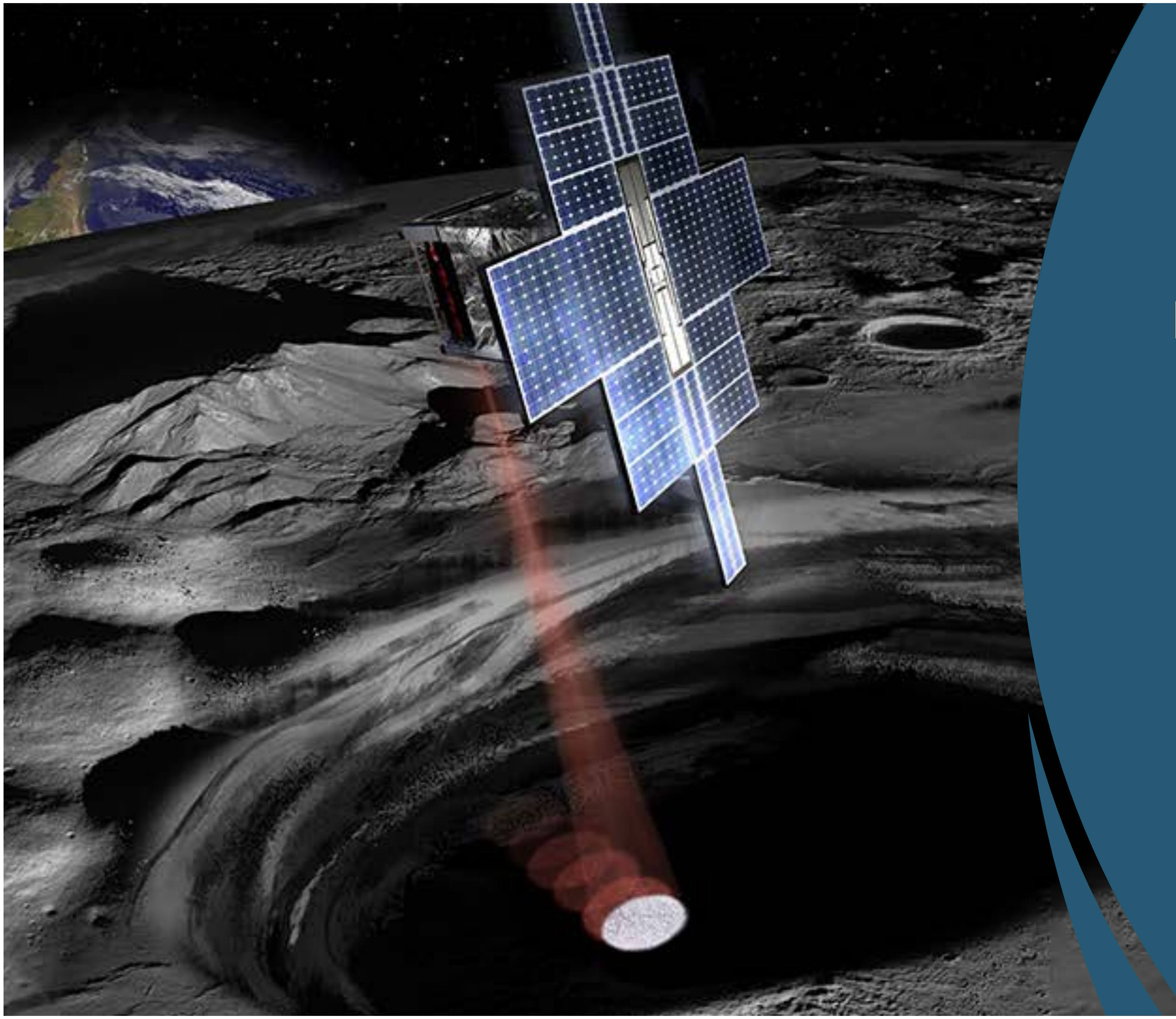
Partnerships, via multi-mission or secondary payload manifests, will be essential to the future of beyond LEO science and exploration

Future launch vehicles will drive greater innovation in mission design and science return

Image Courtesy: eBaum's World

Failures Occur

Antares ORB-3 Launch Failure



Topics for Discussion

The Basics

Mission Formulation

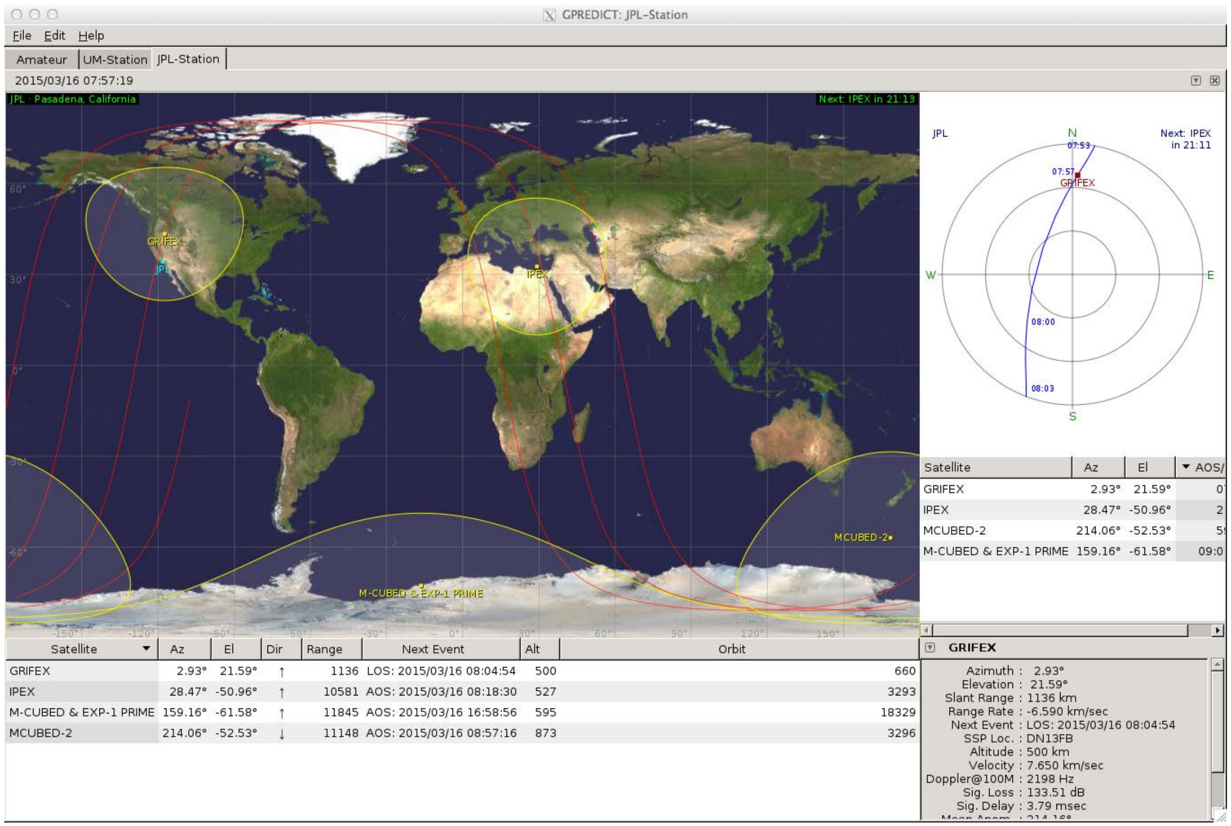
Realities of Flight Development

Access to Space

<u>Mission Operations</u>

Closing Remarks

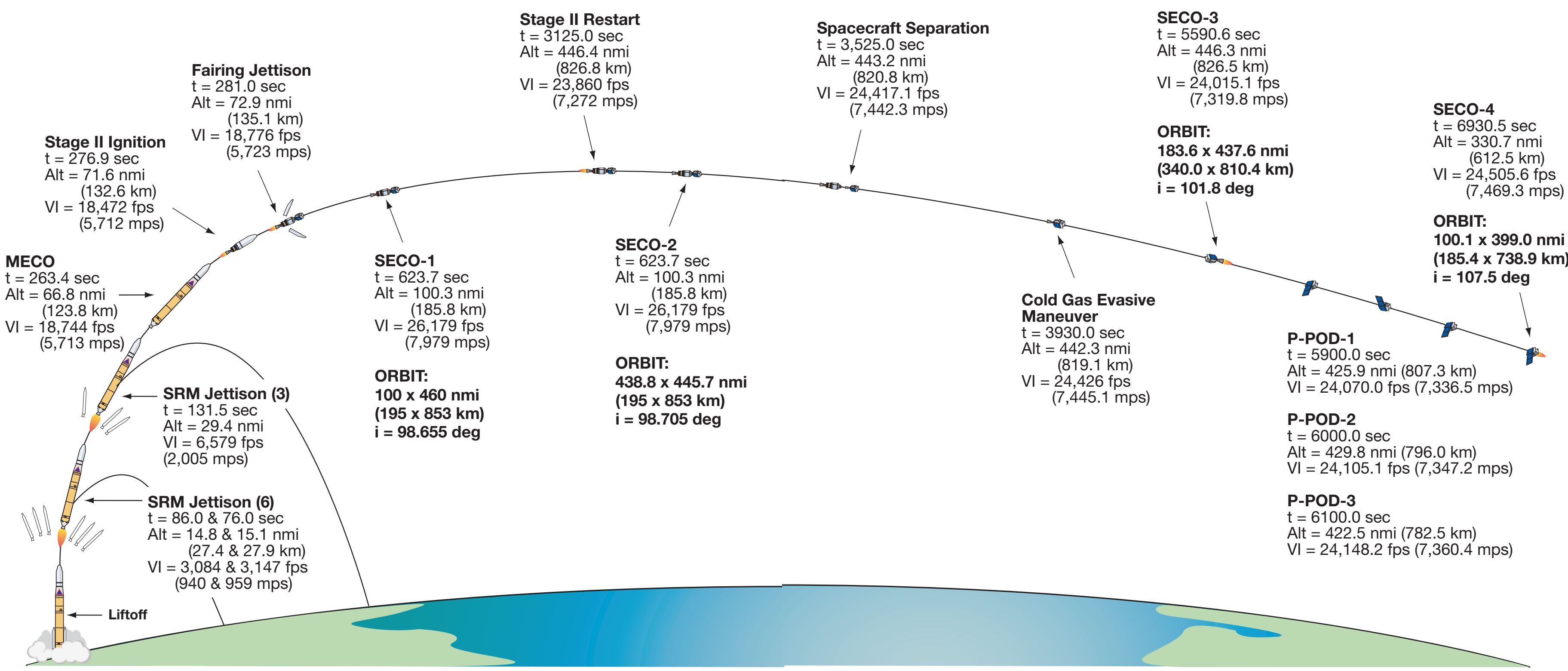
Ground Station Preparation



Mission Operations

Launch Profile and Deployment Sequence

NPP Mission Flight Profile

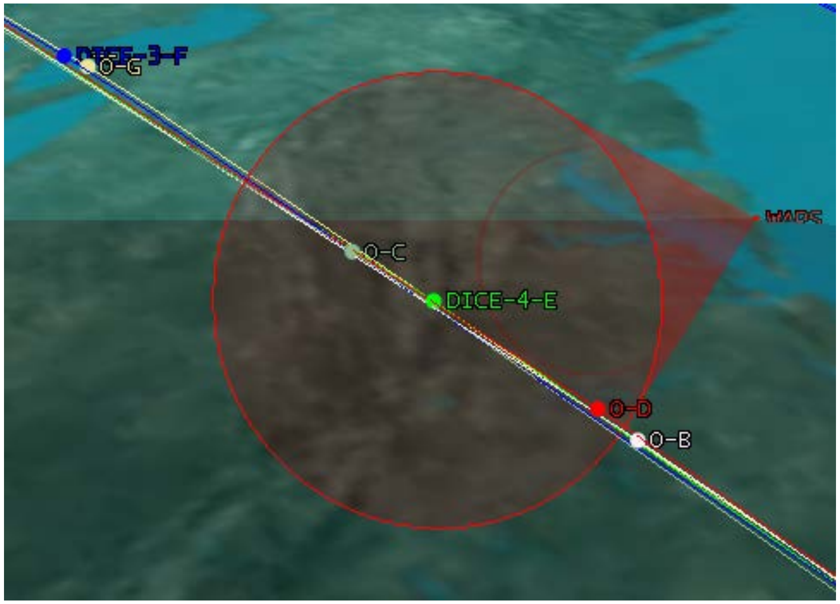


Two-Line Element (TLE) Identification and Analysis

USSTRATCOM (28^{th} Air Force Wing) Provides Position Estimates and Radar Cross Section (RCS)

Mission Operations

M-CUBED & EXP-1 PRIME
1 37855U 11061F   11346.19686108 .00005502 00000-0 44695-3 0   412
2 37855 101.7076 296.1999 0254710 165.5785 195.2864 14.78355333 6590



WFF October 29^{th} Pass

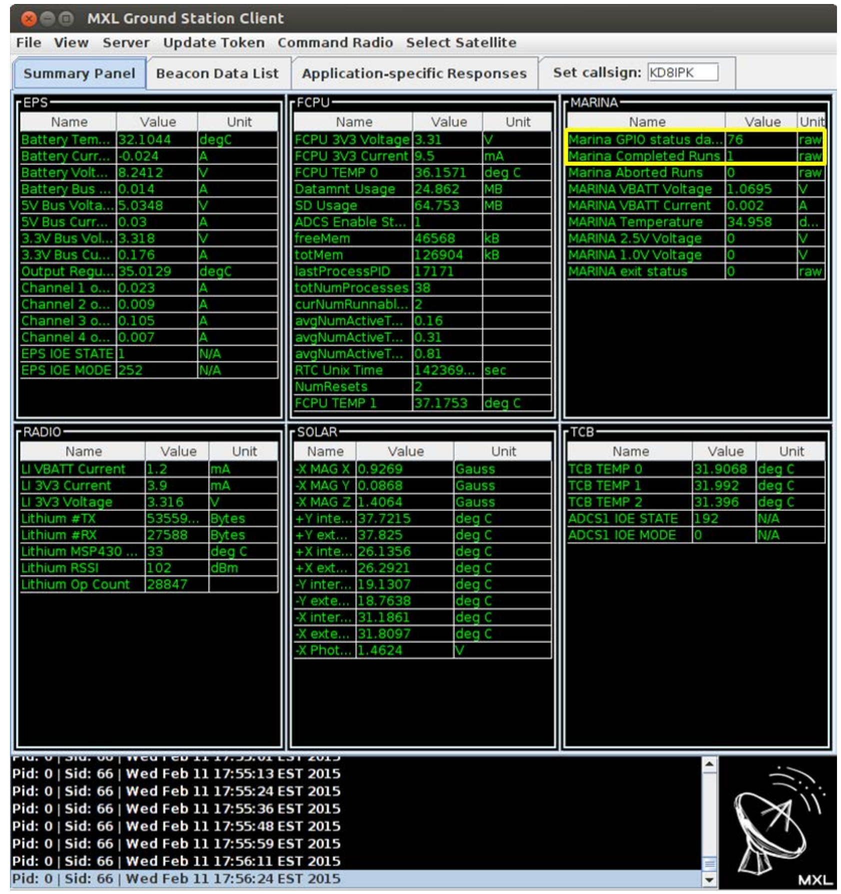
WFF November 2^{nd} Pass

USSTRATCOM tracked NPP and 6 other objects from launch (Objects B, C, D, E, F, G)
Object B was not an NPP launch object

Telemetry Housekeeping Data Beacons from Global HAM Operators

Producing telemetry beacons, with a public client for global tracking of spacecraft health, is a valuable status monitoring tool

Must ensure compliance with all regulatory agencies



Mission Operations

Mission Operations

Cybersecurity

Protecting space and ground-based assets via encryption and monitoring network security

New NASA Directive has defined criteria for uplink protection for cybersecurity and enterprise protection

Directive does not apply to SmallSats without propulsion capability

Propulsion capability and maneuverability are not the same thing

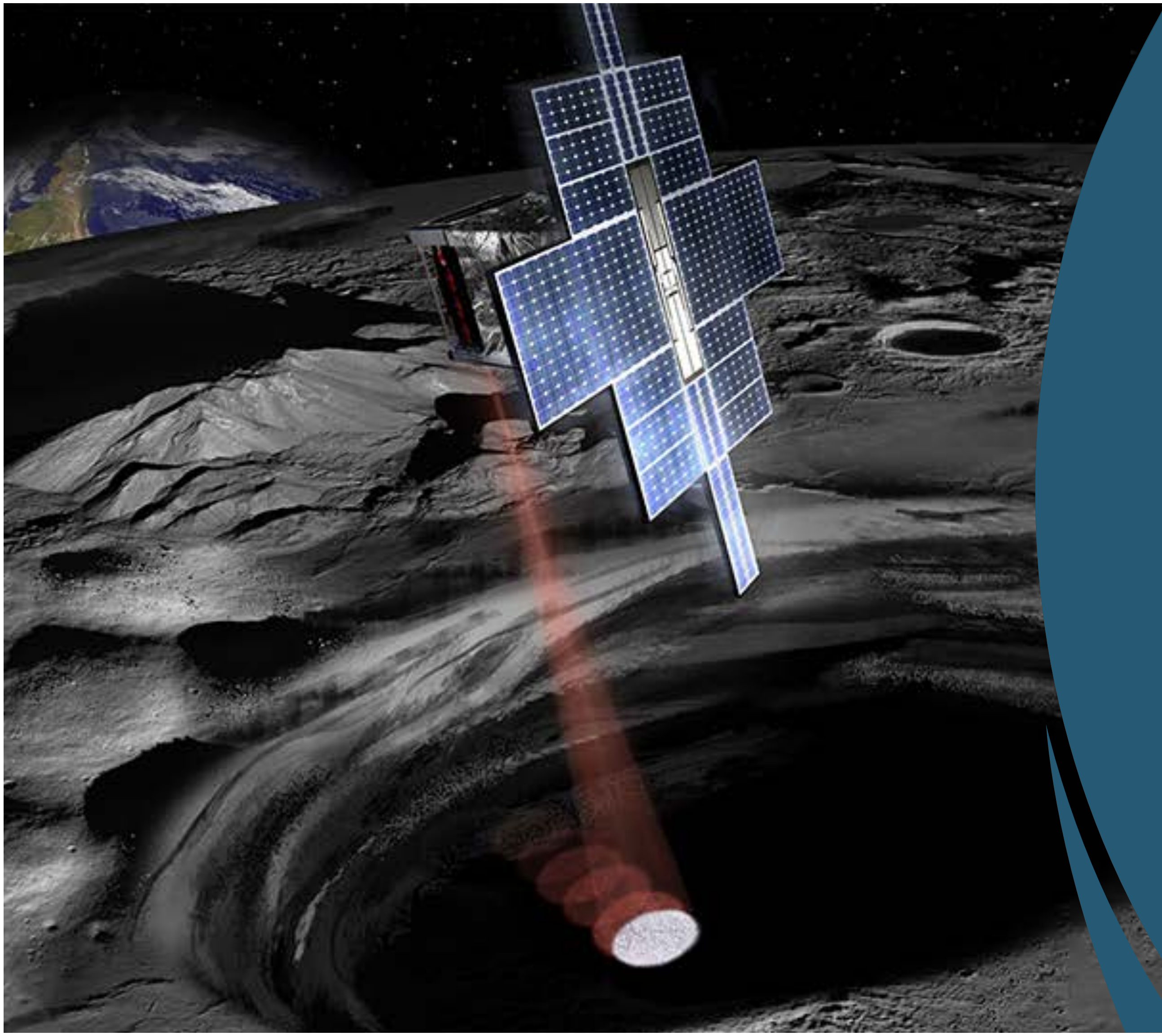
Image: Courtesy of KSAT

Mission Operations

Schedule rehearsals prior to launch, focusing on anomaly procedures

Perform field testing to verify, to the extent possible, link budget and margins

Operation budgets are not flight delivery reserve funds, so plan accordingly



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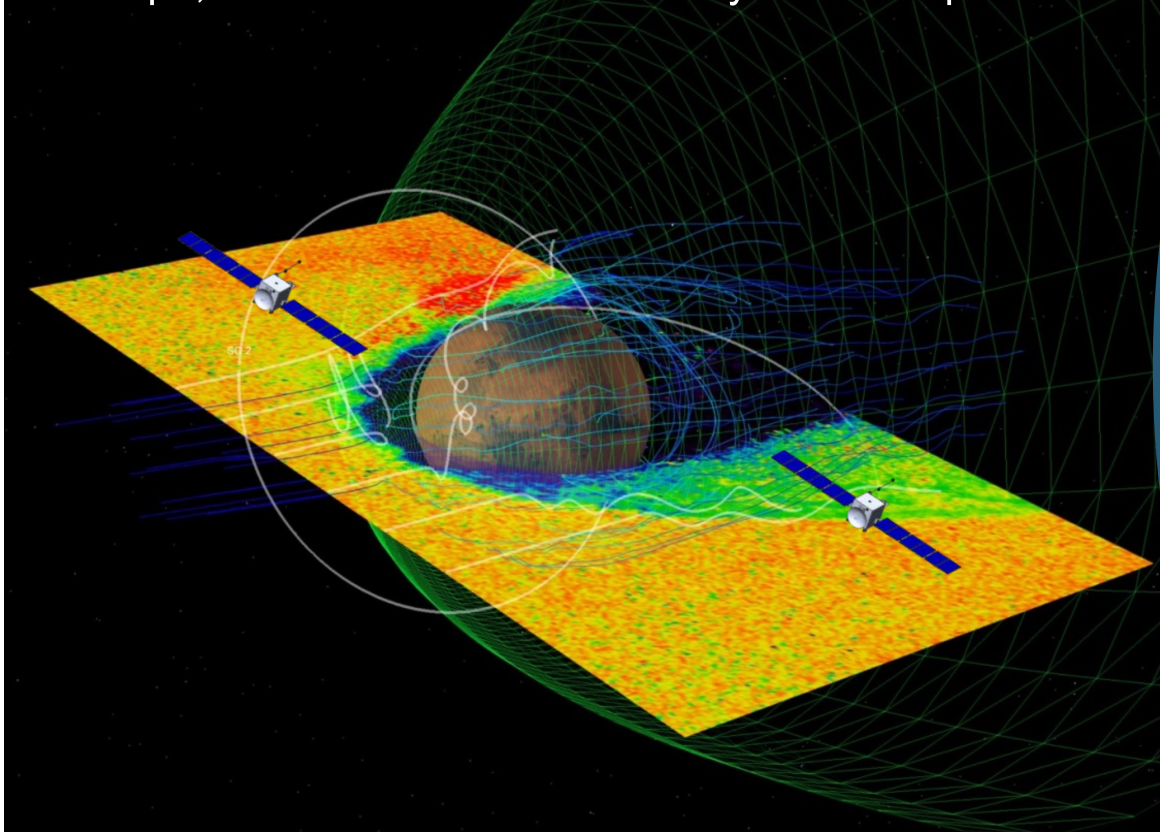
ESCAPADE

Escape, Plasma and Acceleration Dynamics Explorer

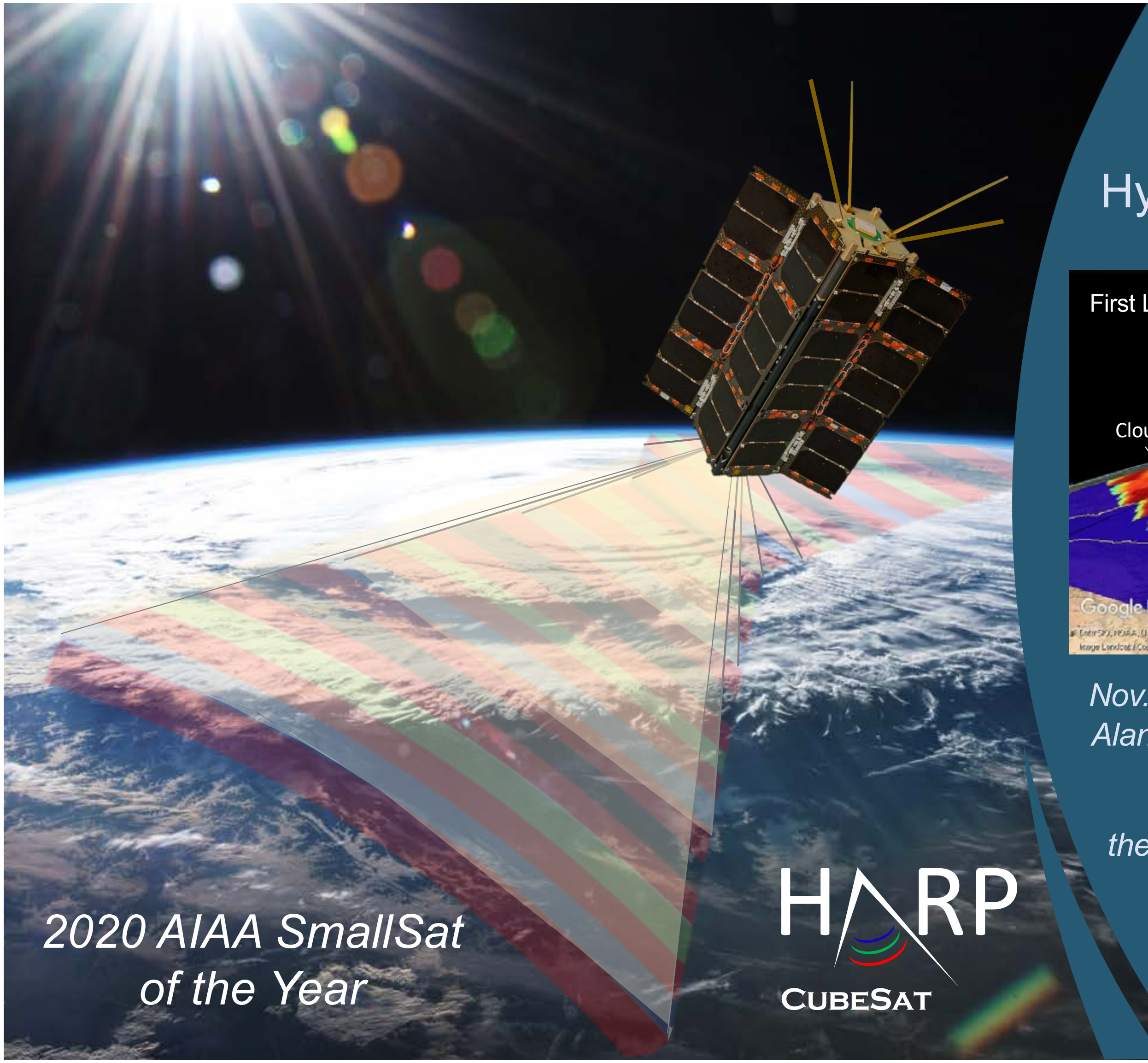


SpaceX Falcon Heavy Rideshare planned with PSYCHE
Image Courtesy: Robert Lillis, Shannon Curry, et. al

Martian SmallSats

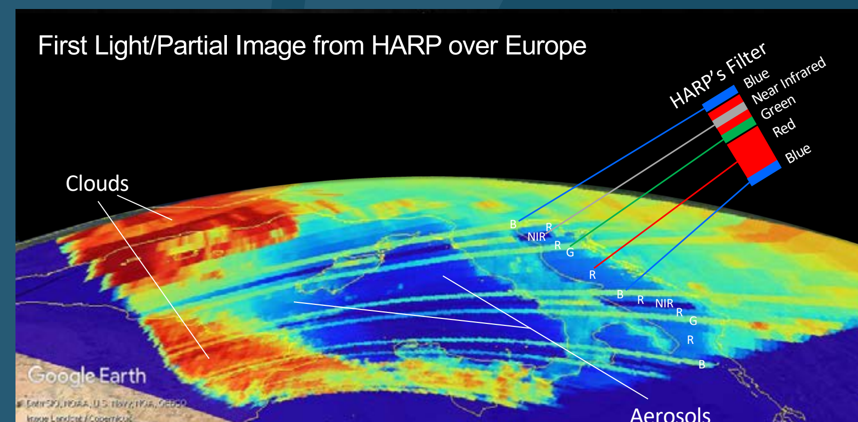
Understanding how solar wind momentum and energy flows throughout Mars' magnetosphere to drive ion and sputtering escape shaping Mars' climate evolution

MarCO's interplanetary transit and radio occultation experiment paves the way for future Mars planetary atmosphere SmallSat science, such as ESCAPADE



HARP

Hyperangular Rainbow Polarimeter



Nov. 2, 2019 – HARP launches to the ISS aboard S.S. Alan Bean (NG-12). HARP will demonstrate the ability to characterize aerosol particles and measure properties of cloud particles including their thermodynamic phase (ice or water) and the size of cloud water droplets

100th CubeSat under CSLI

Feb. 17, 2020 ISS Deployment

Information Systems Needs

Data Science and Analytics

Autonomous constellation operations, observation planning, data fusion, and execution

Distributed science data system management

Technology for flight system design verification and validation

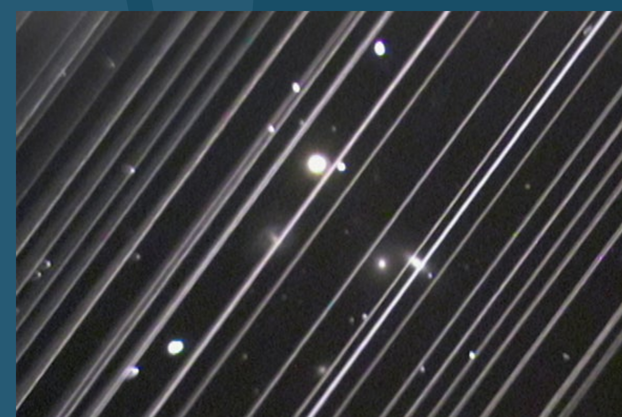
Analysis of mission design-trade options

Jan. 16, 2020 - Potential litigation against the FCC in ignoring federal environmental legislation in licensing Starlink satellites

Mega Constellations

Amazon, One-Web, Planet, and SpaceX may help or harm future science observations

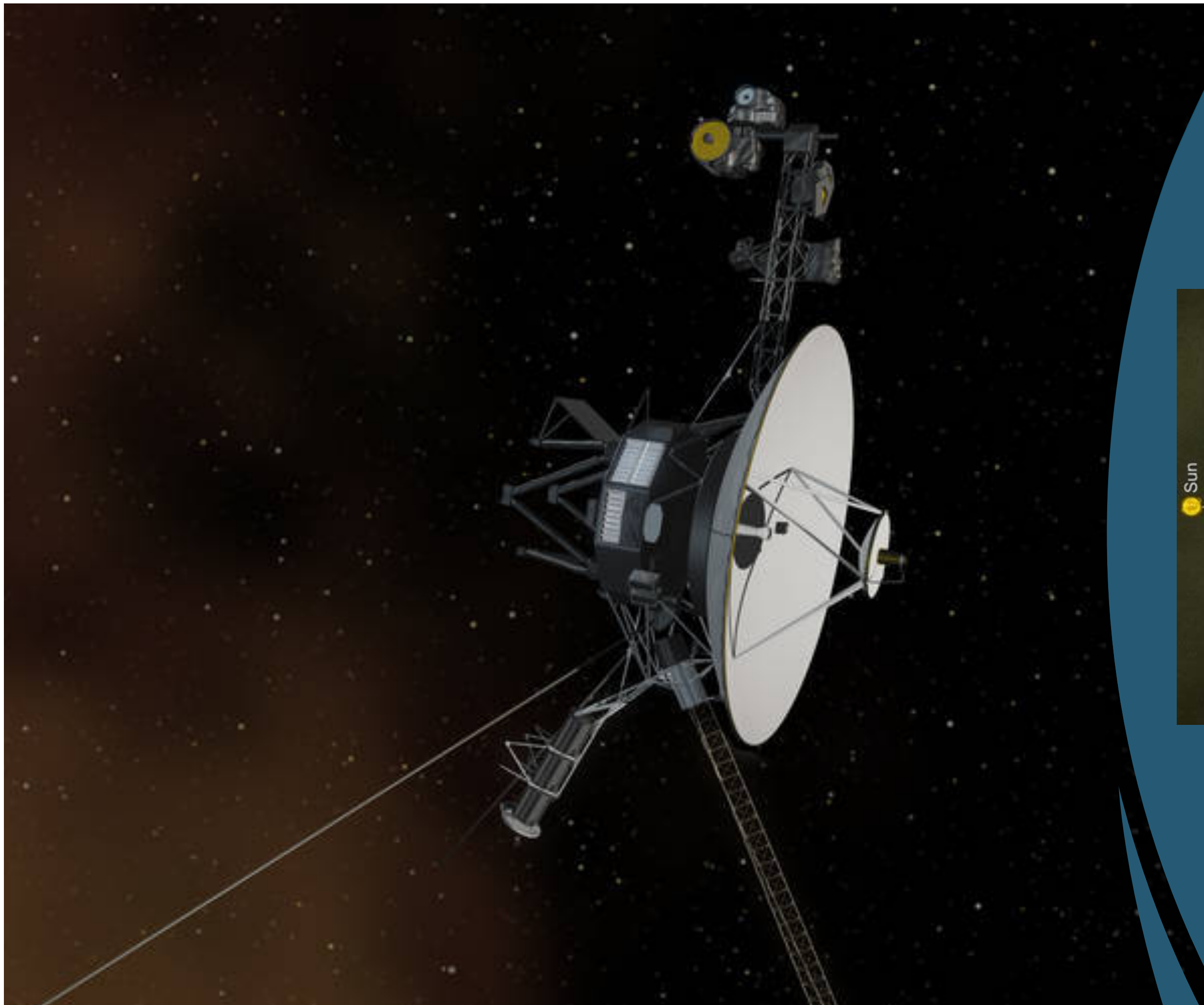
NRAO concerned about Ku-band interference from OneWeb



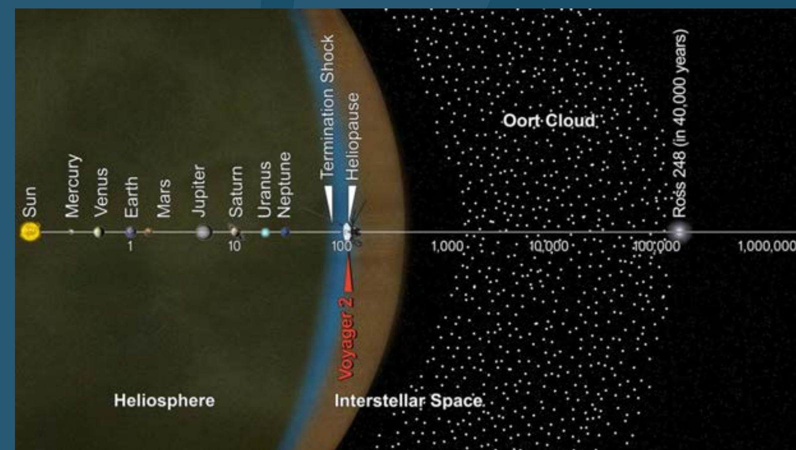
May 25, 2019 – Starlink satellite trails obscure NGC 5353/4 galaxy group (Lowell Observatory)

Interstellar Missions

Beyond Voyager

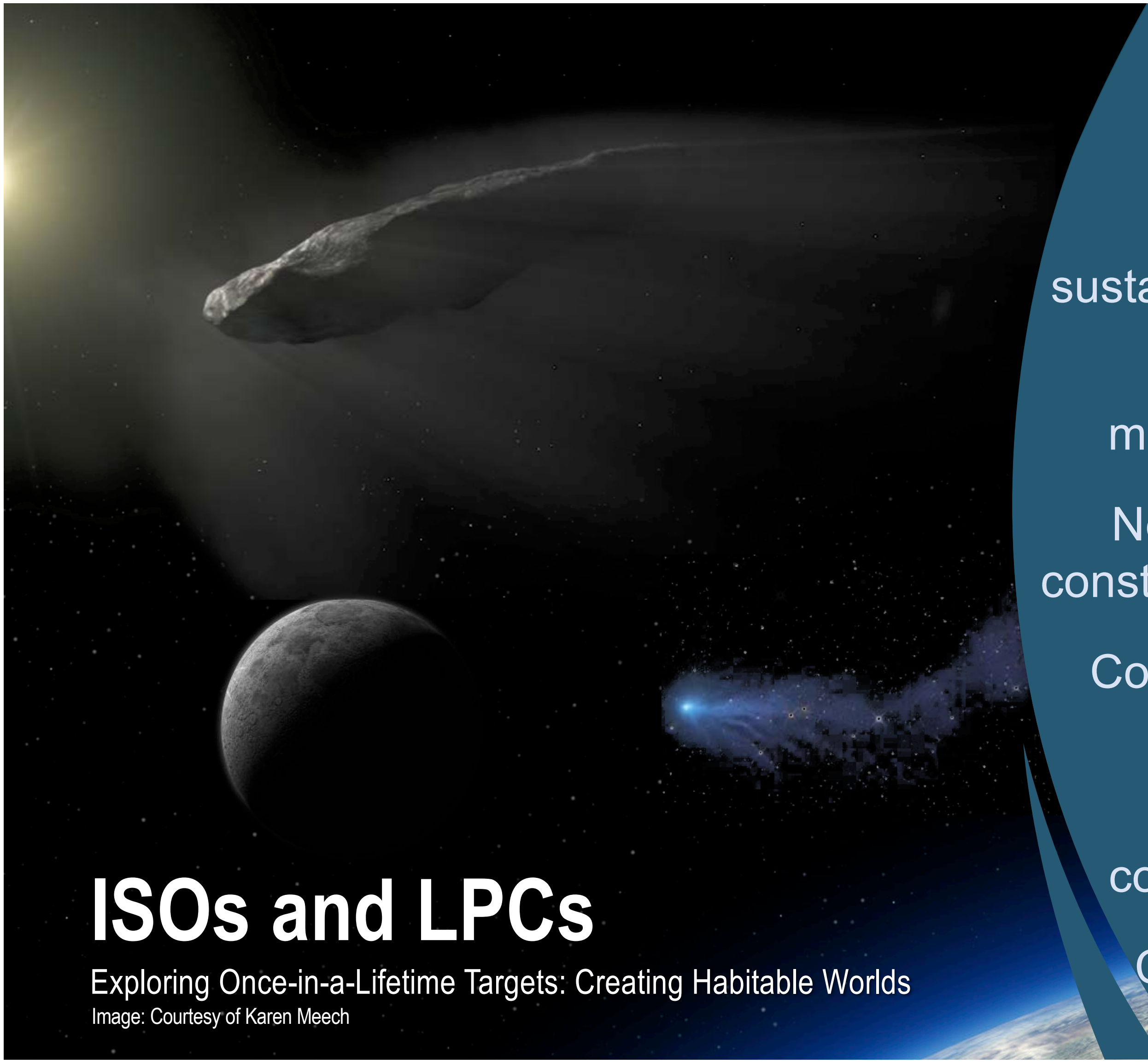


Voyager 1 (2012) and 2 (2018) cross the heliopause entering interstellar space



Opportunity to study material from beyond the heliosphere

New technologies could reduce travel time to <40 years



Future of SmallSats

Minisatellites (30-150 kg) for sustained decadal-class observations

Data products from large/small missions become indistinguishable

New insights from multi-instrument constellation data fusion and analytics

Cooperative synergies among large and small missions

International cooperation on key community science measurements

Costs will keep rising, but plateau

Acknowledgements

Mission Investigators and Teams

Government Agencies

Universities

Industry Partners


NASA
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