Interstellar Probe Study
Webinar Series

Engineering Discussion
Mission Trade Space

Presenters

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- **Wayne Schlei**
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12:05 PM EDT Thursday, 03 September 2020

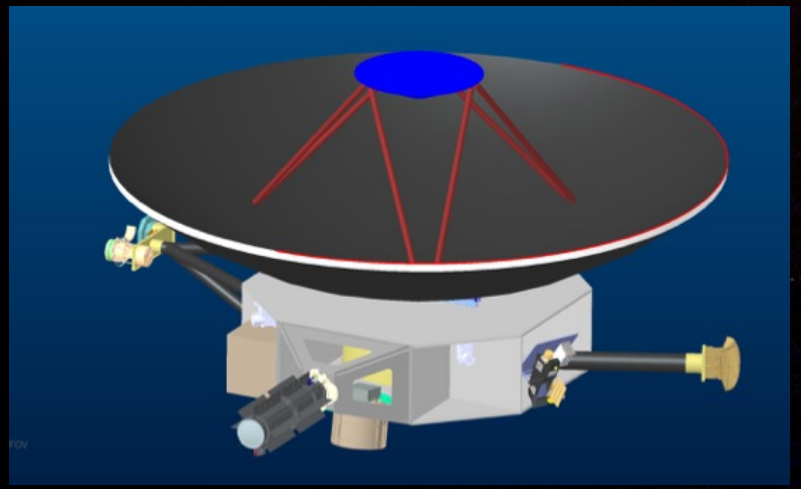
Interstellar Probe Study Website

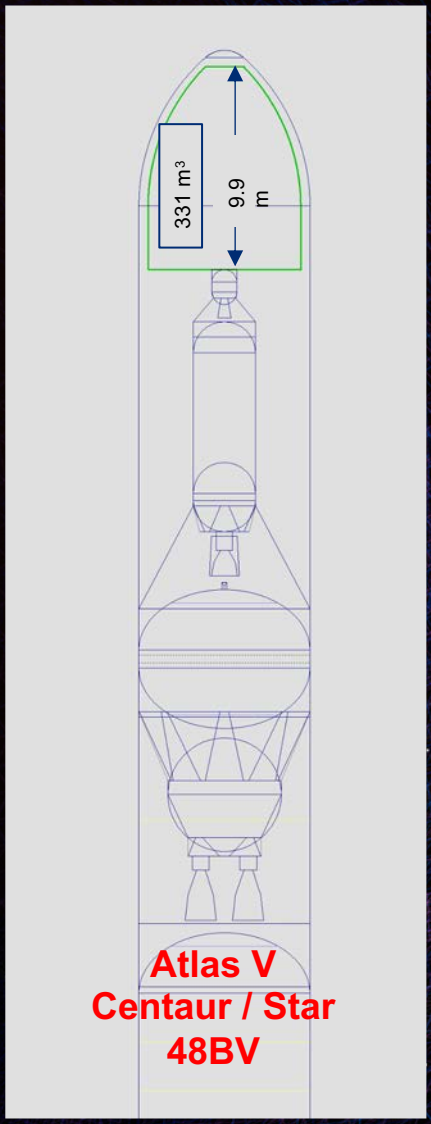
http://interstellarprobe.jhuapl.edu

Trade Space – A Review

- Multiple Trajectory Options
  - Passive Jupiter GA
  - Propulsive Jupiter GA
  - Solar Oberth Maneuver
- Multiple Payload Options
  - Helio instruments with possible Planetary or Astrophysics augmentations
  - Range of payload mass/power by selecting more or fewer instruments
- Path forward
  - Develop a spacecraft concept for intermediate payload of Heliophysics instruments using ballistic and powered JGA
  - Study perturbations of concept across trade space variations

Surrogate Payload	
Fluxgate Magnetometer	Interstellar Dust Analyzer
Plasma Wave Instrument	Neutral Ion Mass Spectrometer
Wire PW Booms	Low Energy ENA
Solar Wind and PUI	High Energy ENA
Suprathermal and Energetic Ions	Ly-alpha Spectrograph
Cosmic Ray Spectrometer	





Notional Operations Scenarios

Identifying Architecture Drivers

Baseline Scenario
(under study now)

- Spin stabilized
- 50m PWS wire antennas

Inner Heliosphere Phase
1-70 AU

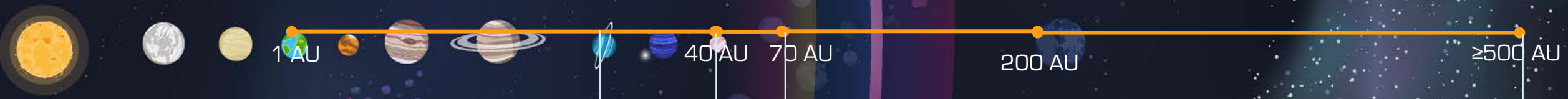
- In-situ measurements of solar wind and PUI
- ENA and Ly-a imaging from a changing vantage point
- PWS observations of 2.5 kHz emission

Outer Heliosphere Phase
70-250 AU

- In-situ measurements through boundary region
- Continued ENA and LYA imaging
- PWS Observations

Interstellar Phase
250+ AU

- In-situ measurements of ISM gas, neutrals and dust
- External ENA imaging



Planetary and Astrophysics Augmentations
(next to study)

- 3-axis stabilized
- Rigid PWS antennas

Planetary Augmentation

- Flyby tracking on thrusters
- Transition to spin mode after flyby

Astrophysics Augmentation

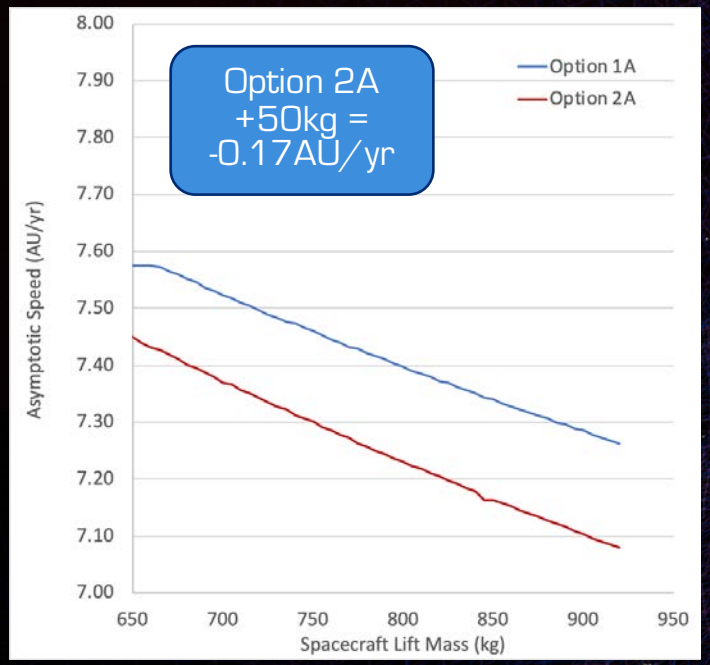
- IR measurements of EBL beyond Zodiacal Cloud

Mass Considerations

- Assumptions
  - Helio only, medium mass payload
  - Spinning spacecraft
  - Mass reserves consistent with NASA & APL requirements
  - Concepts for ballistic and powered JGA
- Mass Drivers
  - Payload
  - High Gain Antenna
  - RTGs and required structure
- Options for Mass Reduction
  - Telecomm trades to reduce HGA size
  - Optimization of spacecraft primary structure
  - Change to payload to reduce/replace assumed wire antennas
- Flyout speed is smooth function of mass for a given target point. Tailoring target point can be used to optimize flyout speed.

Option	Launch Cap. (kg)	Propellant (kg)	Mass Reserve
Ballistic JGA	860	101	28%
Powered JGA	930	170	28%

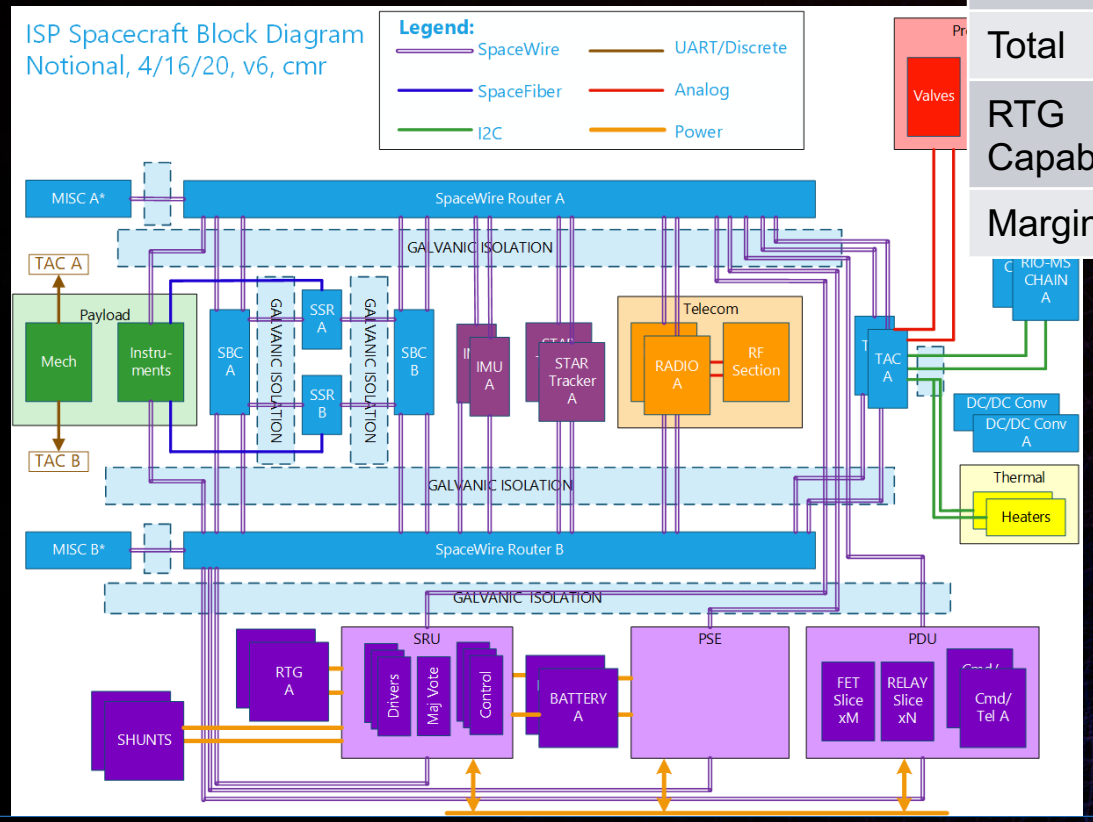
Flyout Speed for Single Target Point



Power Considerations

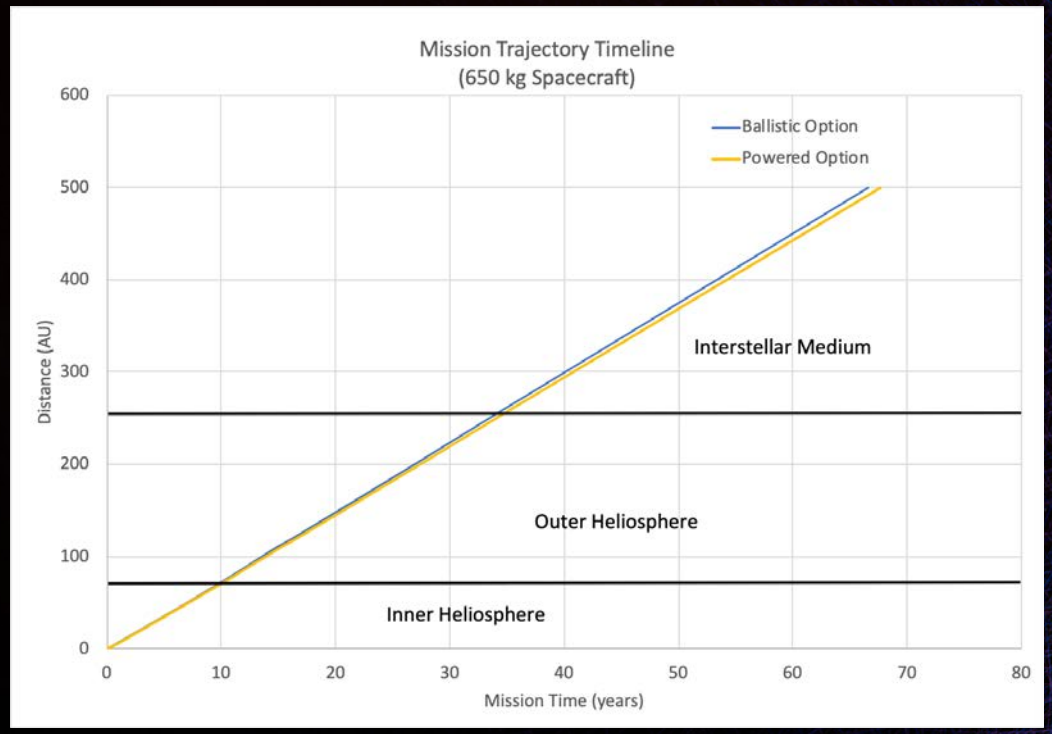
- Two NextGen RTGs
  - Characteristics consistent with Decadal mission concept study inputs
  - Critical power mode is end of life while downlinking and operating instruments
- Power Drivers
  - RF Output
  - Payload configuration
- Power Trades
  - Balance downlink rates with RF design to allow flexible operations
  - How do we treat operations if an RTG should fail?

Subsystem	Power (W)
Payload	94
Telecom	101
Power	25
Avionics	13
Total	233
RTG Capability	300
Margin	22%



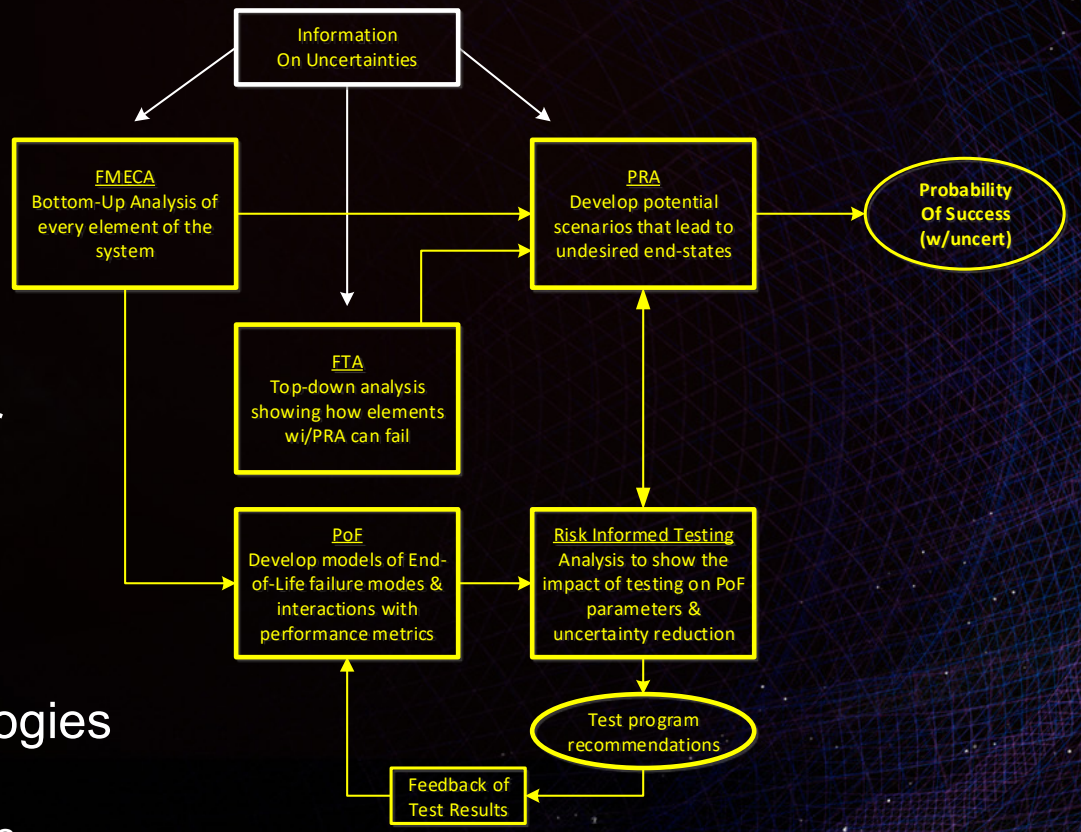
Spacecraft Concept Summary

- Mass: 850-950 kg
- Power: Two Next Generation RTGs with >300 W_e (total) after 50 years
- Payload
  - Mass: ~85 kg, trading lighter and heavier payloads
  - Types: options include heliospheric science, planetary/KBO observation, astrophysics
- Telecom
  - Ka- vs X-band trade to achieve 500 bps downlink at 1000 AU
  - Large fixed dish (5m for X-band) vs more sophisticated antenna systems
  - Need to consider ground station in trade
- Control
  - Spinning or three-axis depending on payload, thruster-only
  - Pointing and control requirements driven by telecom trade



Spacecraft Reliability

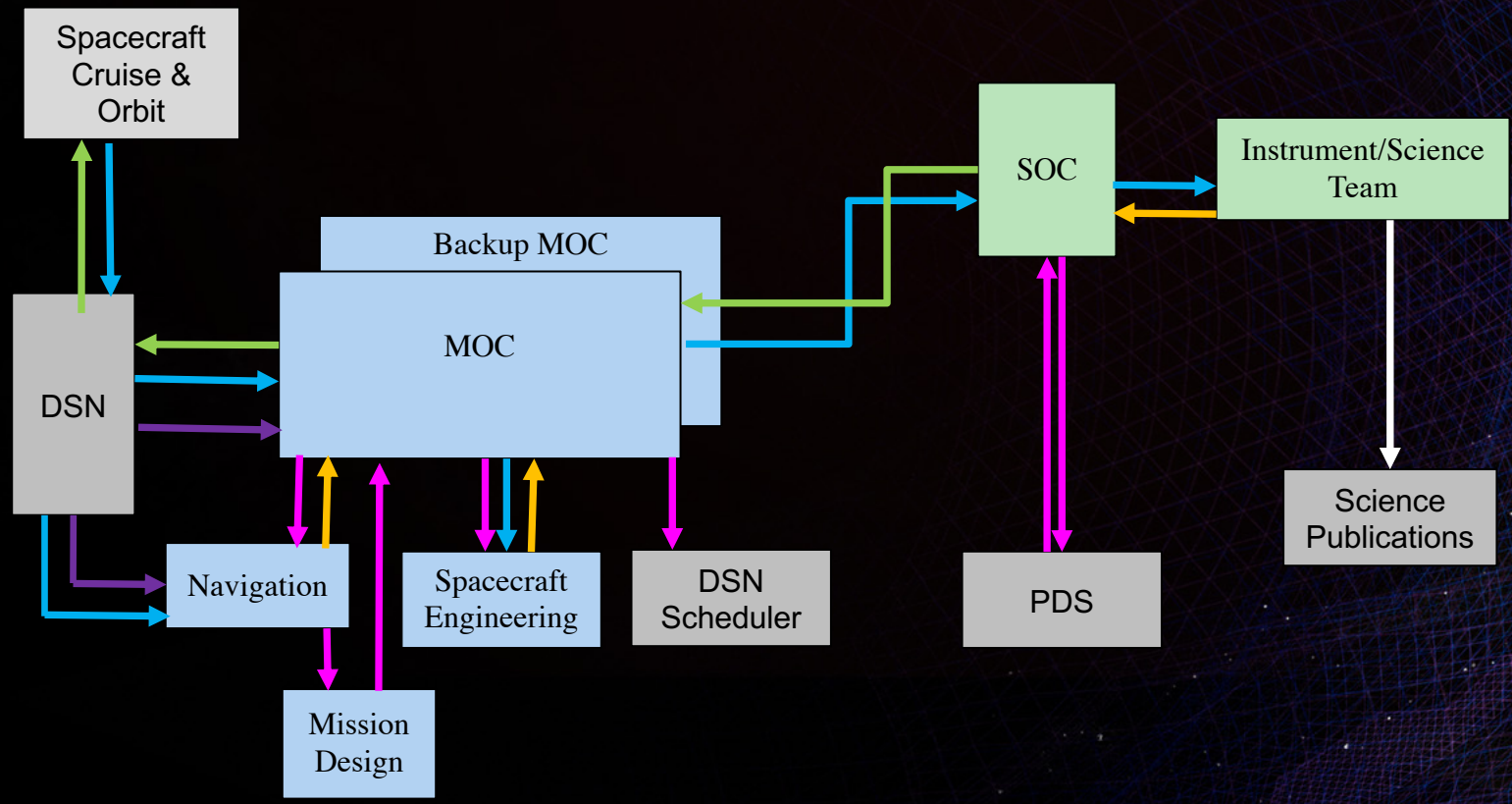
- Defining success with robustness in science requirements
  - Modeling set science requirements as was done for Parker Solar Probe
  - Establishing degraded cases and functional redundancies to maximize science return
- Modeling spacecraft configurations
  - Baseline spacecraft and conops
  - Identified contingencies for inclusion within trade space
- Mining historical record of long-lived missions to better quantify time-dependent failure rates (missions with actual or design life > 15 years)
  - What failed and why
  - More importantly what did not fail
- Examining Physics-of-Failure methods for key technologies
  - Subcontract with Center for Advanced Life Cycle Engineering
    - Electronic components
    - Thruster valves
    - Battery
    - High Voltage Power Supplies
    - Micro-channel Plates
  - RTG technologies (GRC)



Ground Segment Block Diagram

Dimensions of longevity management

- Interfaces
- Ownership
- Upgrade complexity
- Knowledge management



- Commands
- Telemetry
- Schedules
- Data Products
- Requests

Ground Segment Longevity Planning for Interstellar Probe

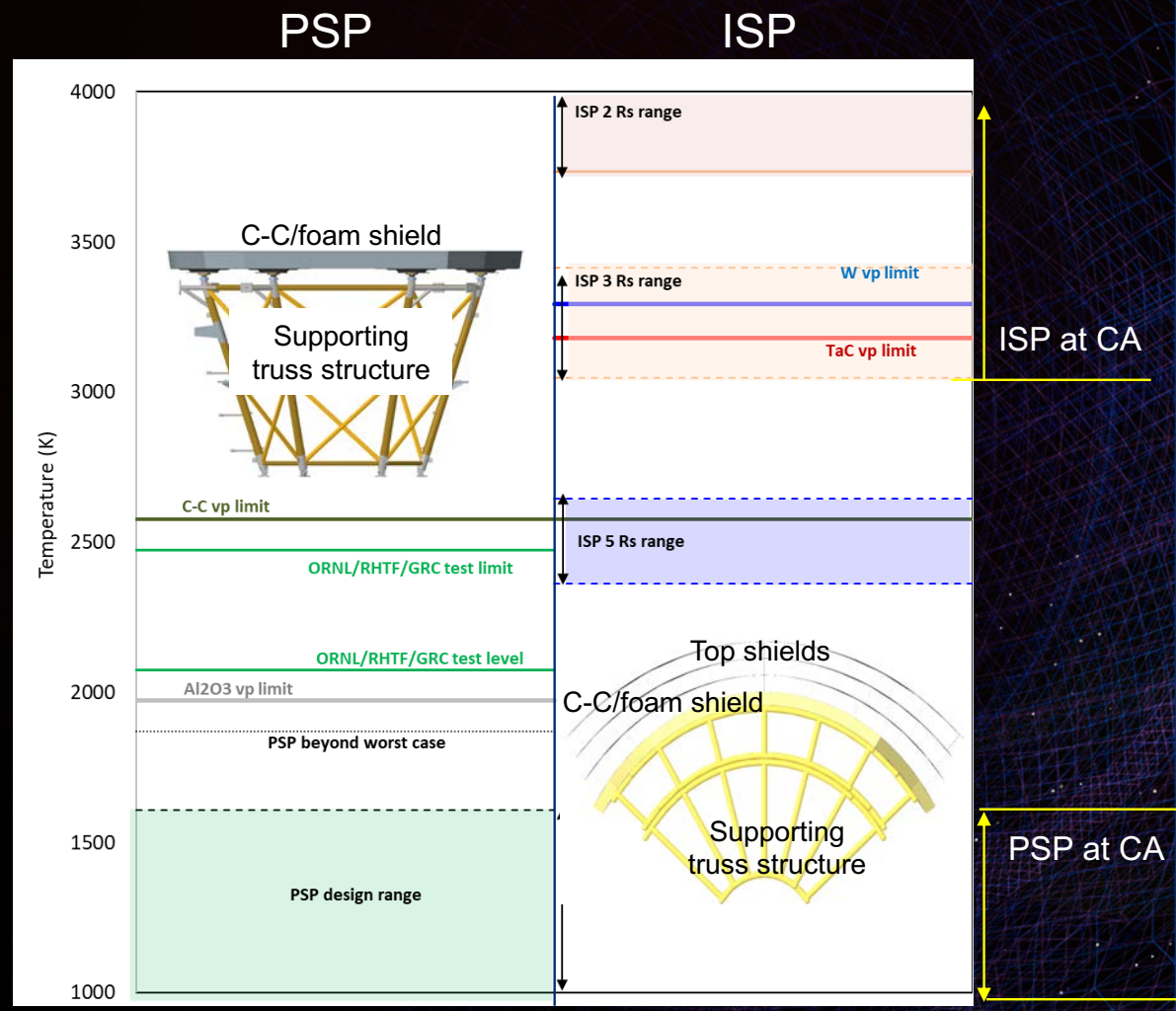
- Challenges and opportunities
  - Interstellar Probe as a pathfinder for long-duration missions
  - Organizational consensus, commitment, and endurance
    - Long-duration missions are, by necessity, decentralized
    - Involved organizations will have to commit to owning certain aspects of the mission
    - Stakeholder organizations have to be long-lived and stable
    - NASA needs contingency plans for the loss of an individual organization's support
  - Long-term infrastructure planning is required – what will DSN look like in 60 years? How will we be recording, storing, and retrieving data in the 2080s?
  - Finally, how do we structure a multi-generational team so that Interstellar Probe can be successful?

Solar Oberth Maneuver

- The concept sounds simple
  - Gravity assist at close solar distance using a solid rocket motor
  - Heat shield to protect the system based on Parker Solar Probe technology
  - Basic spacecraft concept similar to concept for JGA options

- But…
  - Maneuver needs to be done significantly closer to the Sun than even Parker Solar Probe: 1.5– 4 Rs vs 9.8 Rs with significantly higher heat load
  - Using current technology, heat shield is larger than the mass the SLS can lift into the required trajectory
  - Attitude control and trajectory correction become unfeasible

- Ultimately, a low mass heat shield design must be developed. This is a high risk development effort with a very long development, if it is even possible to get the mass low enough.



Engineering Path Forward

- Deeper dive on Operations concept
- Refine concept to include results from ongoing trades and studies
- Document results
  - Yearly Report
  - AIAA Conference info from Glen
  - Annual Interstellar Probe Workshop
  - IEEE Aerospace Conference papers on concept, mission design, guidance and control issues and telecommunications trades
- Develop changes to concept as Planetary and/or Astrophysics augmentations are added
- Develop concept for Solar Oberth Maneuver case
  - Continue exploration of possible heat shield technology

Mission Design

Webinar Brief

Wayne Schlei, PhD
Mission Design Engineer
JHU Applied Physics Laboratory

Architecture Descriptions

Architecture nomenclature for engineering study

- Option 1: Ballistic Jupiter Gravity Assist (JGA)
  - Launch to Jupiter, low altitude flyby yields escape speeds
  - Variant A: Heliophysics focus (only) with medium payload for now
  - Variant B: Heliophysics focus with planetary add-on (KBO flyby)

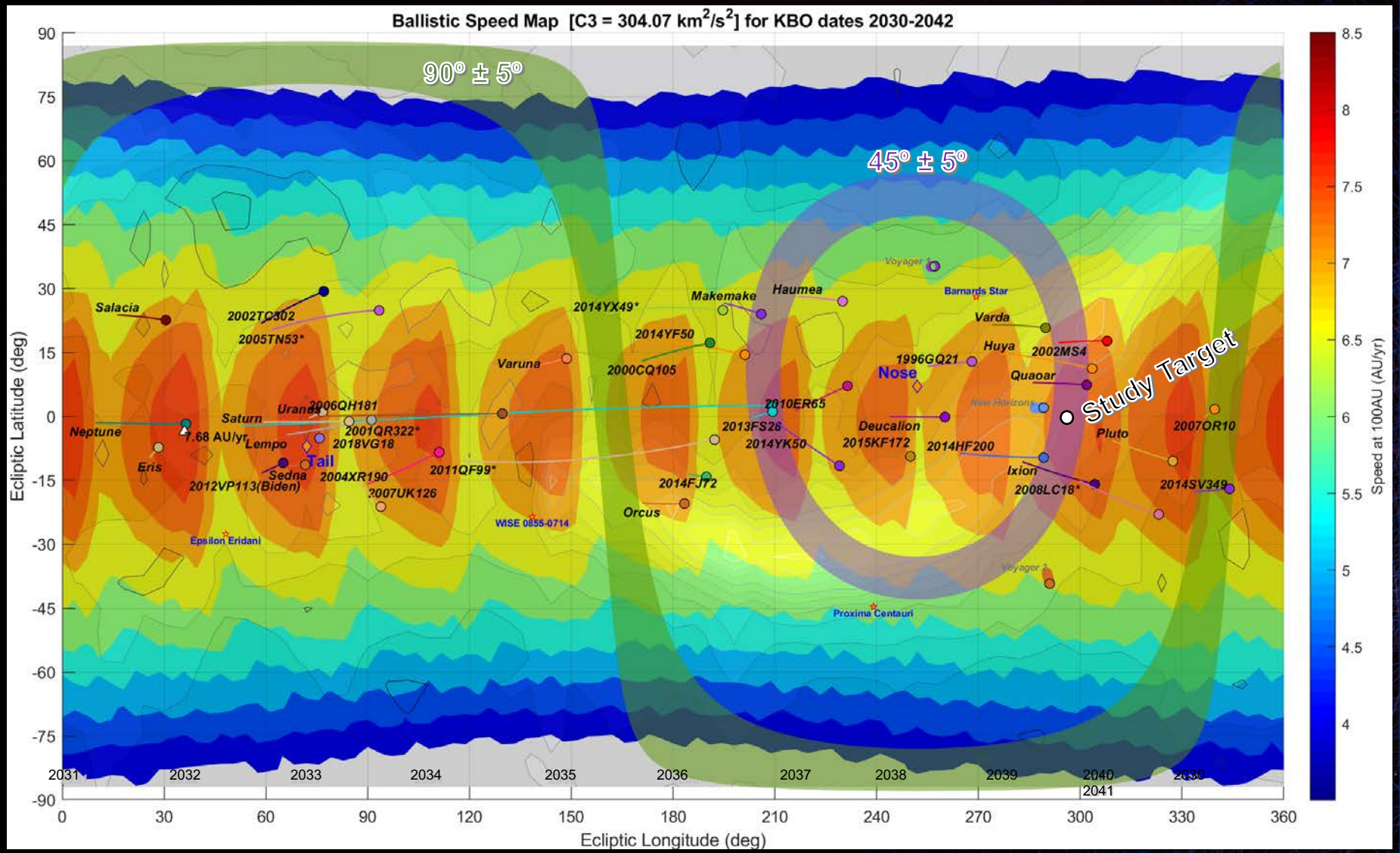
- Option 2: Powered Jupiter Gravity Assist (JGA)
  - Slower path to Jupiter, low altitude flyby with perijove SRM burn
  - Variant A: Heliophysics focus (only) with medium payload for now
  - Variant B: Heliophysics focus with planetary add-on (KBO flyby)

- Option 3: Solar Oberth Maneuver
  - Slower path to Jupiter, JGA lowers solar perihelion, Oberth burn
  - Variant A: Heliophysics focus (only) with medium payload for now
  - Variant B: Heliophysics focus with planetary add-on (KBO flyby)

Study destination, escape speeds, mass trade space, mission CONOPs

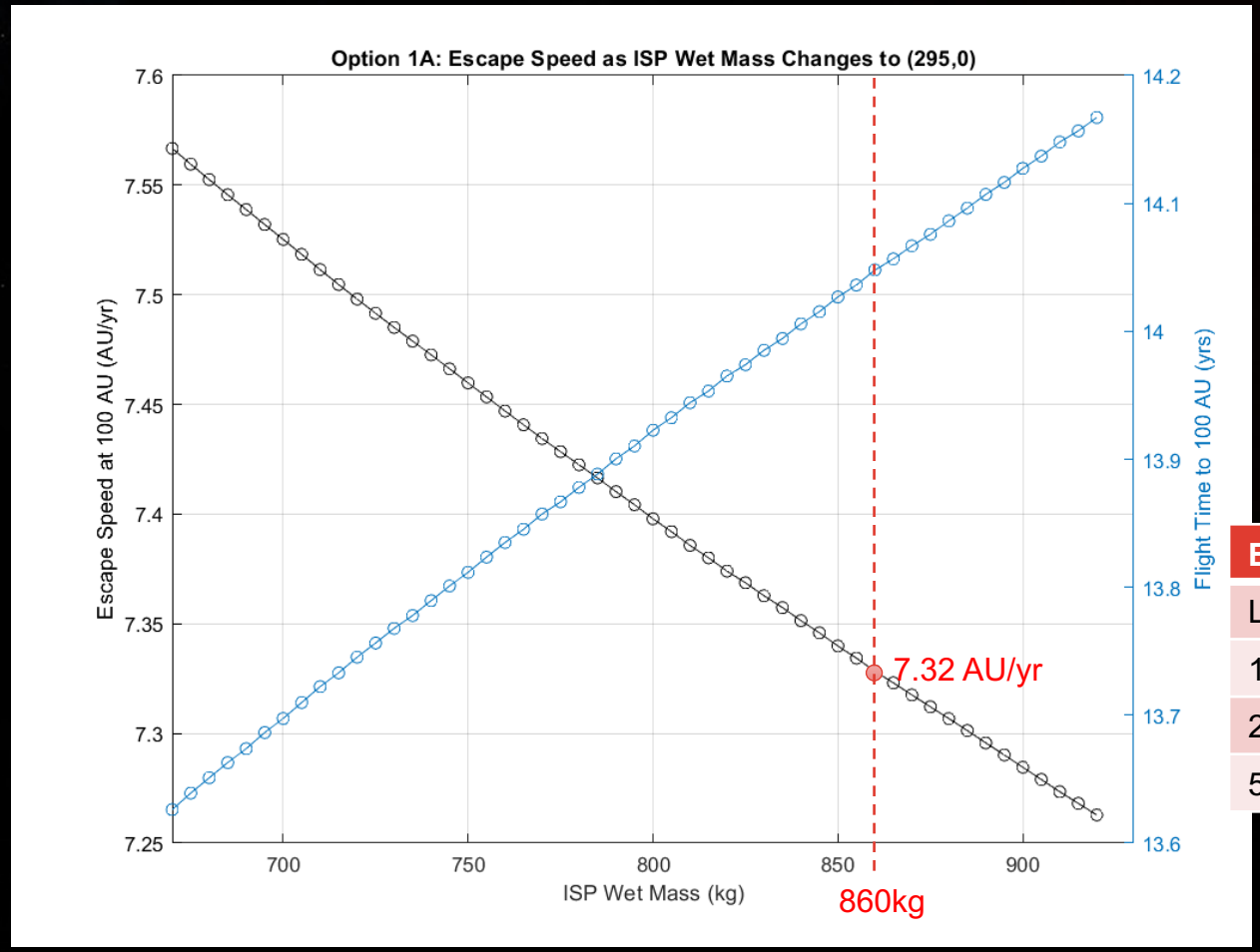
Heliophysics-Only (A) Notional Study Destination

- Skymap of 1A options
  - First iterations increased mass requirements
  - M = 860 kg (wet)
  - C3 = 304.07 km2/s2
    - SLSB2 + AV Centaur + STAR48BV
  - General Trend:
    More spacecraft mass reduces zones spread and shifts zones to East
- Plausible Helio Target
  - High Speed (near-eclip.)
  - Roughly 45º from nose
  - IBEX Ribbon
  - **Target: (295º, 0º)**
    - **Launch 2040/2041**



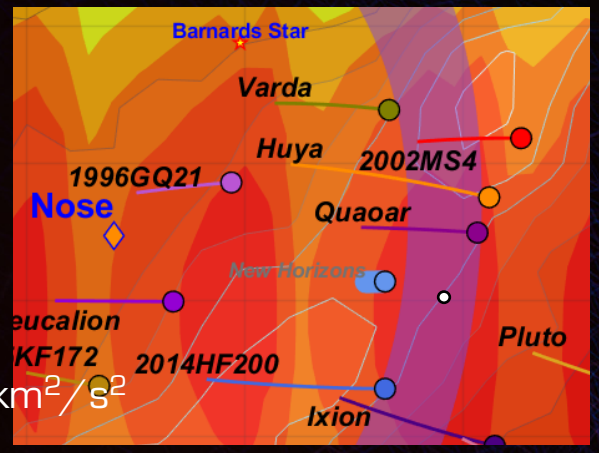
Mass Trades: Option 1A

- Comparing SAME destination **(295º, 0º)**
  - Mostly at 2040/41 hot zone with wider plateau than Opt 2
  - Assumes SLSB2+Centaur+STAR48BV w/ 2.5% parasitic mass



m = 478 kg

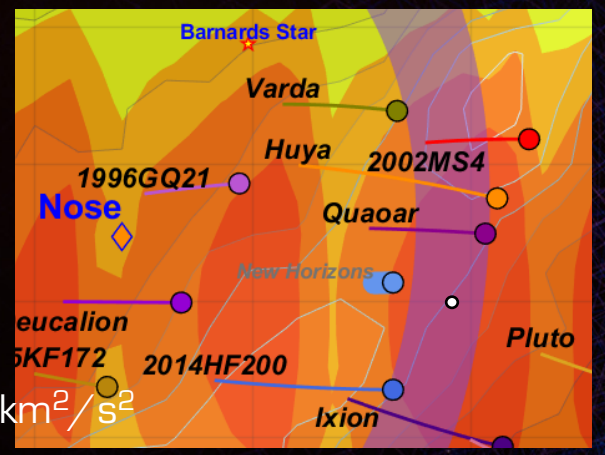
C3 = 349.65km^2/s^2



Option 1A +50kg = -0.17AU/yr

m = 650 kg

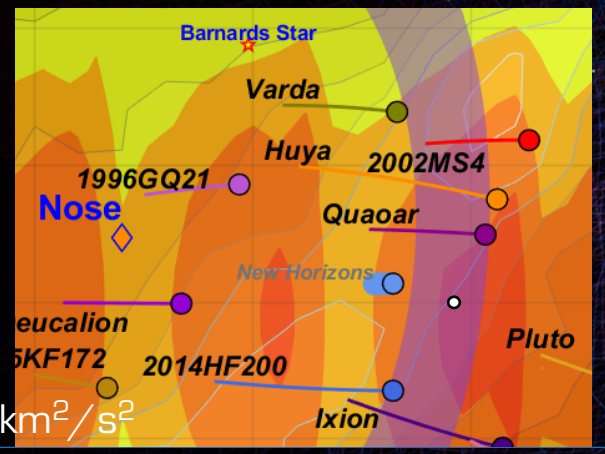
C3 = 325.82km^2/s^2



Event	MET
Launch	16 Jan 2041
100 AU	14.1 yrs
200 AU	28.3 yrs
500 AU	70.5 yrs

m = 755 kg

C3 = 312.15km^2/s^2



Mass Trades: Option 2A

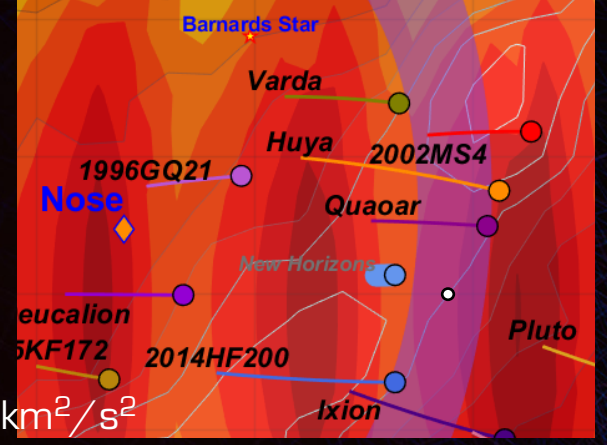
- Comparing SAME destination **(295º, 0º)**
  - Skinnier plateau versus 1A, near middle of 2039 and 2040/41 areas
  - Assumes SLSB2+Centaur+STAR48BV w/ 2.5% parasitic mass

Option 2A +50kg = -0.17AU/yr (similar)

Event	MET
Launch	02 Jan 2041
100 AU	14.7 yrs
200 AU	29.0 yrs
500 AU	71.9 yrs

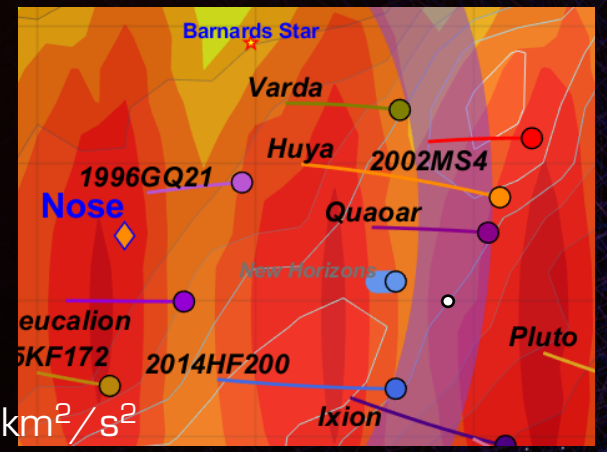
m = 478 kg

C3 = 214.62km^2/s^2



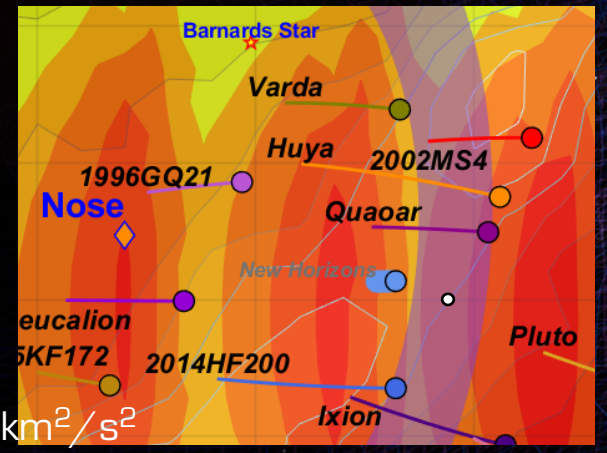
m = 650 kg

C3 = 210.44km^2/s^2



m = 855 kg

C3 = 205.62km^2/s^2



Mission Architecture Delta-V Budgets

- Delta-V Budgets to **(295º, 0º)** [assuming wet mass m_{Opt1}= 860kg and m_{Opt2} = 930kg]
  - Rigid booms estimates w/10kg ACS prop for A & B | B: Extra 30 kg ACS prop for 3-axis at KBO
  - Wire booms require *extra* 50 kg of ACS prop for precession control

Option 1A: ΔV Budget

Ballistic Helio-Only Concept	Determ. ΔV (m/s)	Stat. ΔV (m/s)	Total ISP ΔV (m/s)
Launch Cleanup + Jupiter Target		90	90
Jupiter Gravity Assist	0		0
Post Jupiter to Target TCM		0	0
Spin/attitude (equivalent ΔV)		10.9	10.9
Subtotal	0	100.94	100.94
Unallocated Margin			25.2
Unallocated Margin Percentage			25%
Total			**126.2**

m_d = 802.8 kg (747.0)

m_p= 57.2 kg (113.0)

I_{sp} = 210 s

C3 = 304.07 km^2/s^2

V_{100} = 7.32 AU/yr

Option 1B: ΔV Budget

Ballistic Helio+KBO Mission	Determ. ΔV (m/s)	Stat. ΔV (m/s)	Total ISP ΔV (m/s)
Launch Cleanup + Jupiter Target		90	90
Jupiter Gravity Assist	0		0
Post Jupiter to Target TCM		20	20
Spin/attitude (equivalent ΔV)		44.6	44.6
Subtotal	0	154.6	154.6
Unallocated Margin			38.6
Unallocated Margin Percentage			25%
Total			**193.2**

m_d= 759.3 kg (703.3)

m_p= 100.7 kg (156.7)

I_{sp} = 210 s

C3 = 304.07 km^2/s^2

Option 2A: ΔV Budget

Powered JGA Helio-Only Concept	Determ. ΔV (m/s)	Stat. ΔV (m/s)	Total ISP ΔV (m/s)
Launch Cleanup + Jupiter Target		78	78
Jupiter Gravity Assist	2790		0
Post Jupiter to Target TCM		0	0
Spin/attitude (equivalent ΔV)		11.1	11.1
Subtotal	2790	89.1	89.1
Unallocated Margin			22.3
Unallocated Margin Percentage			25%
Total			**111.4**

m_d = 790.4 kg (734.0)

m_p= 139.6 kg (196.0)

I_{sp} = 210 s

C3 = 203.91km^2/s^2

V_{100} = 7.07 AU/yr

Option 2B: ΔV Budget

Powered JGA Helio+KBO Mission	Determ. ΔV (m/s)	Stat. ΔV (m/s)	Total ISP ΔV (m/s)
Launch Cleanup + Jupiter Target		78	78
Jupiter Gravity Assist	2790		0
Post Jupiter to Target TCM		30	30
Spin/attitude (equivalent ΔV)		45.3	45.3
Subtotal	2790	153.3	153.3
Unallocated Margin			38.3
Unallocated Margin Percentage			25%
Total			**191.6**

m_d = 741.5 kg (684.9)

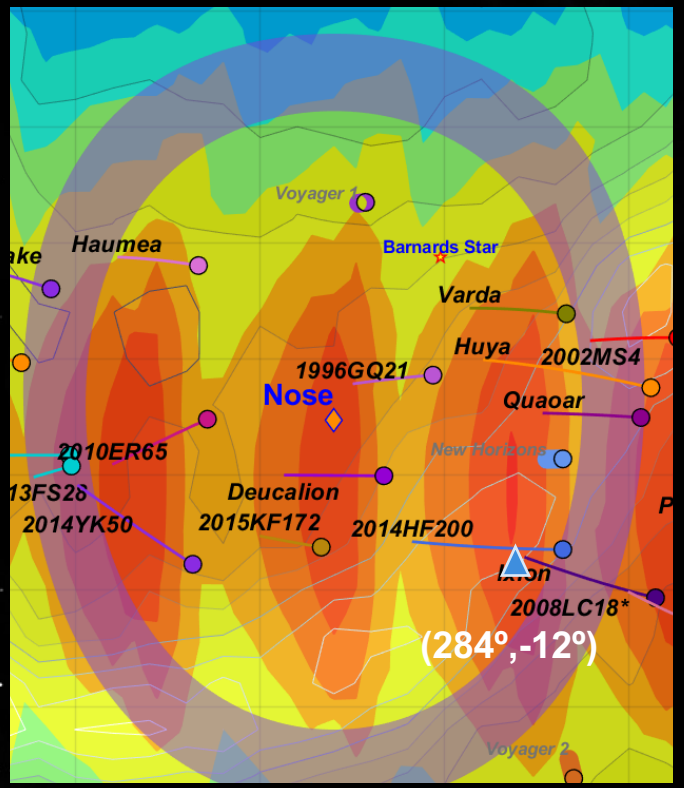
m_p= 188.5 kg (245.1)

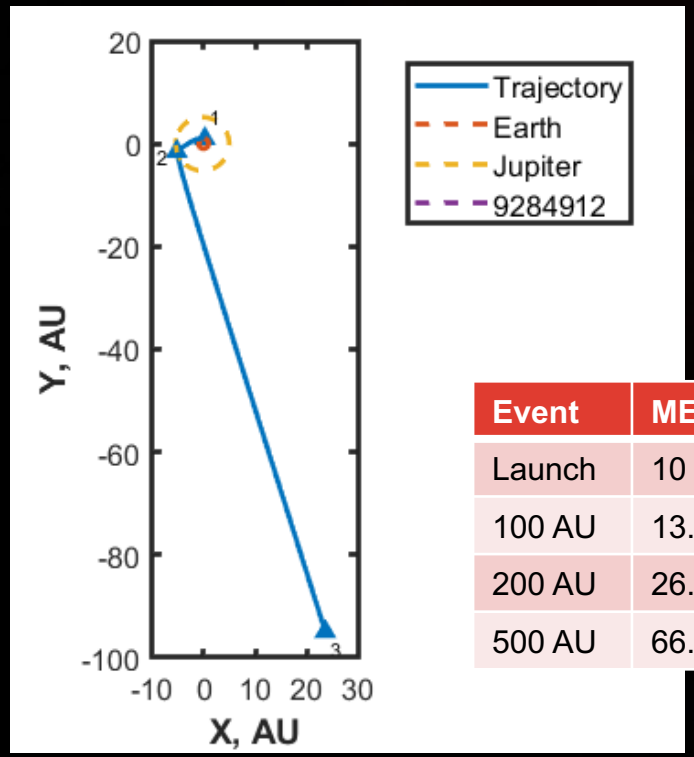
I_{sp} = 210 s

C3 = 203.91km^2/s^2

Alternative Target Direction (2A)

- Examining a different (but similar) target for powered JGA
  - Original target is trending out of high-speed zone
  - Similar location at (284º,-12º) for 2039 : IBEX, 37º off nose
    - Opt 2A at 930kg in 2039 (284º,-12º) is *faster* than 1A with 650kg
    - **Launch 10 Dec 2039 => Speed 7.68 AU/yr, 13.8 yrs to 100 AU**

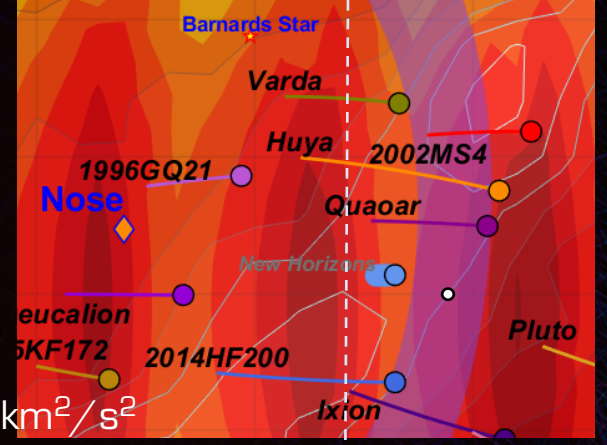




Event	MET
Launch	10 Dec 2039
100 AU	13.8 yrs
200 AU	26.8 yrs
500 AU	66.1 yrs

m = 478 kg

C3 = 214.62km^2/s^2



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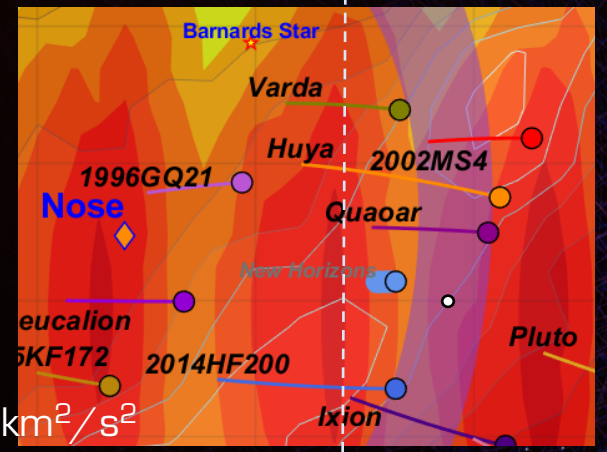
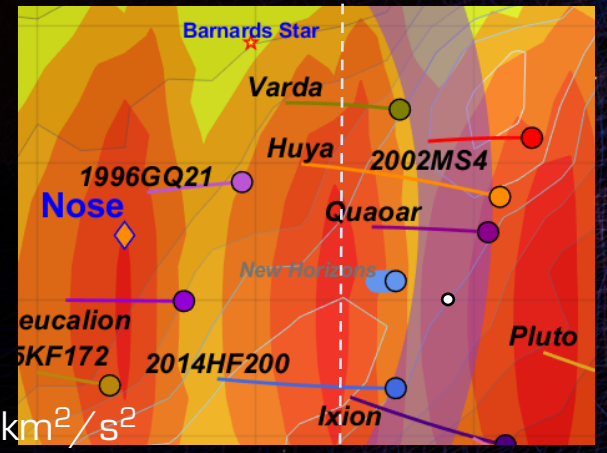


m = 855 kg

C3 = 205.62km^2/s^2



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APPLIED PHYSICS LABORATORY

Interstellar Probe Telecommunications

Dave Copeland and Reza Ashtari

The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

Acknowledgement: Almost 200 professional scientists and engineers world-wide actively working in support for Interstellar Exploration

What Determines the Data Rate?

Data Rate ∝ Received Signal/Noise Ratio

$$P_{Rx}/_{N0} = \frac{P_{Tx} A_{Tx} A_{Rx} f^2}{R^2 c^2 k_B T_{Rx}}$$

P_{Tx} = *Transmitted Power*
R = *Range (distance)*
A_{Tx} = *Transmitting Antenna Effective Area*
A_{Rx} = *Receiving Antenna Effective Area*
f = *Frequency*
TRx = *Receiving noise temperature*
c = *speed of light*
k_B = *Boltzmann constant*

Data Rate ∝

- 1 / Distance^2
- Transmitter Output Power
- Receiving Antenna Area
- 1/Receiving Noise Temperature

- Operating Frequency^2
- Transmitting Antenna Area
  - Gain limited by pointing error!
  - Pointing degradation offsets the frequency gain

Telecommunications Trade Space

Beam Pointing Control	Frequency Band	Aperture Size/ Technology	Ground Station Capability	Transmit Power Scaling
Body-Fixed: dependent on S/C	X-band	Solid	Current DSN Capability	Total RTG power limited
Active Pointing: independent of S/C	Ka-band	Mesh / Membrane	ngVLA Capability	Failed RTG power limited/Extended Mission
	Optical		Telescope (e.g. Hale)	

Trades Achievable Pointing Control vs Complexity
- Body-fixed limit: 0.2 deg

Maps Directivity to Physical Aperture
- Higher F -> higher aperture gain
- Secondary effects limit benefit

Determines Mass for Required Gain

Trade Ground Performance vs Ground Complexity

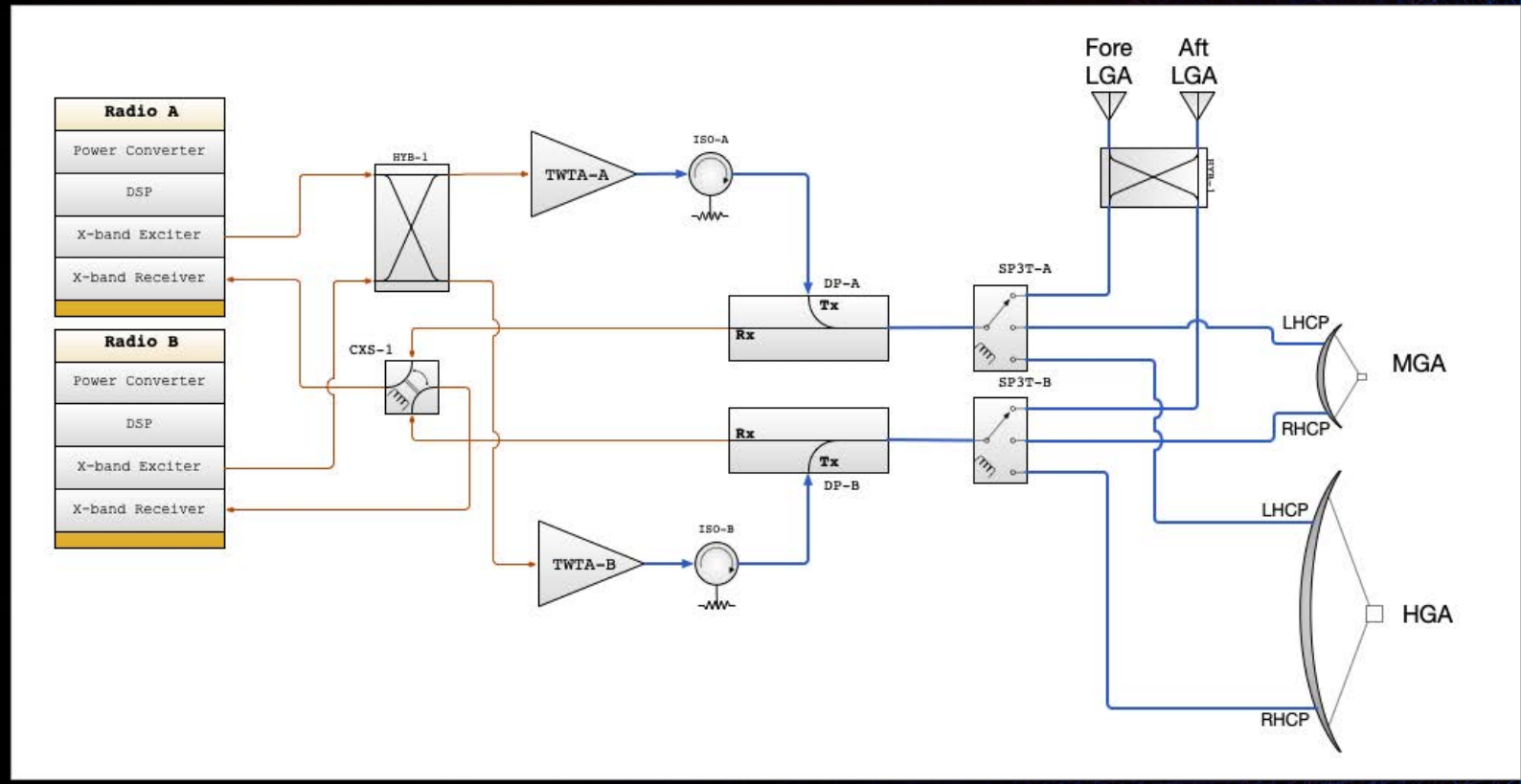
Note: Assume DSN stations for all uplink

Fits Telecom DC Power to RTG degradation and failure scenarios

Baseline Design

Beam Pointing Control	Frequency Band	Aperture Size/ Technology	Ground Station Capability	Transmit Power Scaling
Body-Fixed: dependent on S/C	**X-band**	**Solid**	Current DSN Capability	**Total RTG power limited**
Active Pointing: independent of S/C	Ka-band	**Membrane**	**ngVLA Capability**	Failed RTG power limited

HGA Diameter (m)	5
TWTA Power (W)	52
Reflector Material	Solid Composite
Subsystem Mass (kg, CBE)	72.9 kg HGA – 53.7 kg
Ground Station	ngVLA (244x18m)
Downlink Data Rate[1]	2591 bps (375 AU) 364 bps (1000 AU)
Uplink Data Rate[2]	2000 bps (375 AU) 250 bps (1000 AU)



1 – Turbo R1/6 encoding
2 – DSN 70m station w/ 80 kW Tx, LDPC encoding

RF-based Paths Under Investigation

Low Mass X-band

- 5m membrane antenna
- Subsystem Mass: 37 kg
- DL 2500 bps @ 375 AU
  350 bps @ 1000 AU

Beam Pointing Control	Frequency Band	Aperture Size/ Technology	Ground Station Capability	Transmit Power Scaling
Body-Fixed: dependent on S/C	**X-band**	**Solid**	Current DSN Capability	**Total RTG power limited**
Secondary Pointing	Ka-band	**Membrane-5m**	**ngVLA Capability**	Failed RTG power limited

Ka-band Option

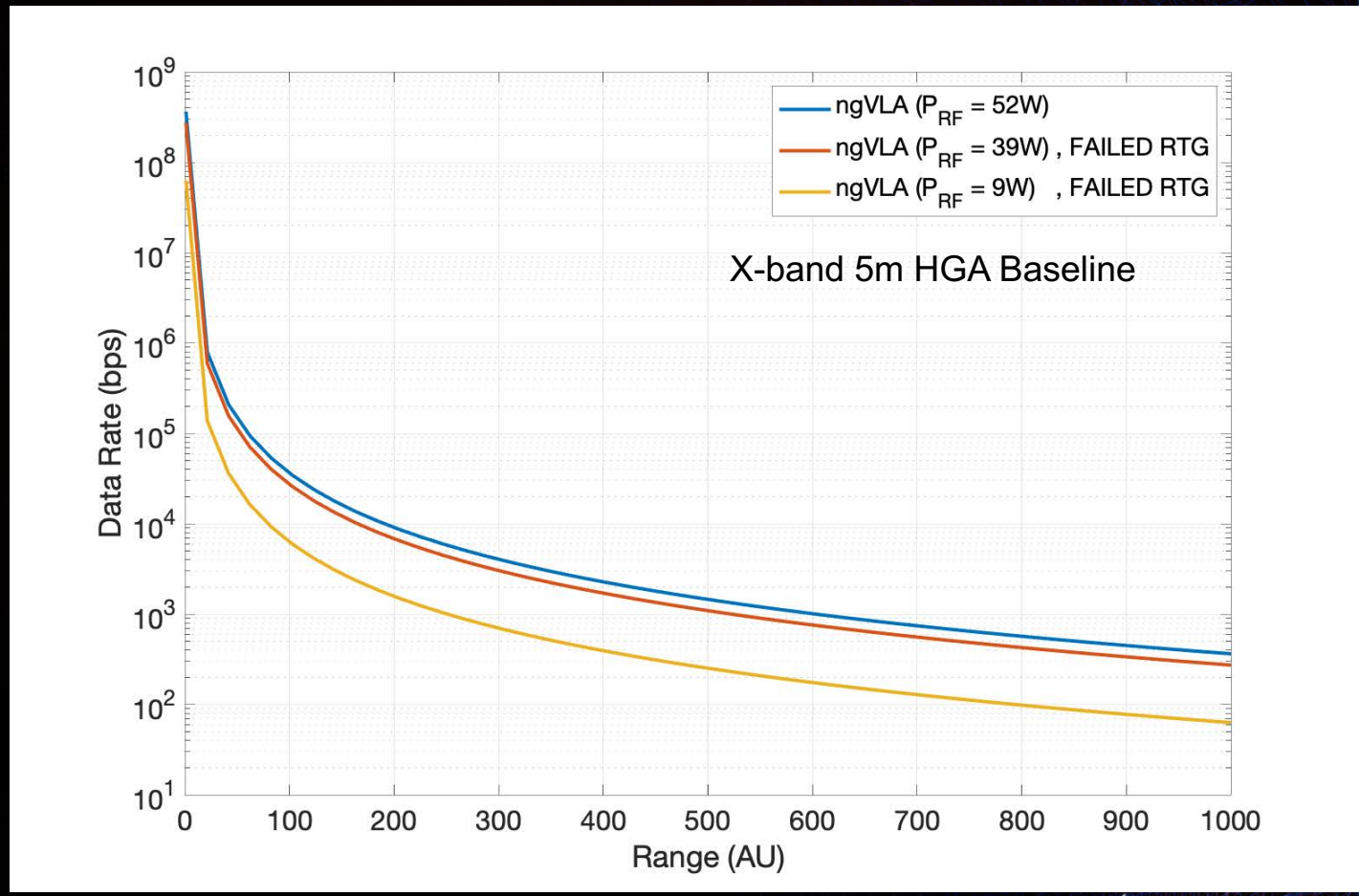
- 2.28m Antenna
- Actively steered subreflector: 0.03 deg
- Subsystem Mass: 31 kg
- DL 3671 bps @ 375 AU
  516 bps @ 1000 AU
- UL ~ 250 bps @ 375 AU

Beam Pointing Control	Frequency Band	Aperture Size/ Technology	Ground Station Capability	Transmit Power Scaling
Body-Fixed: dependent on S/C	X-band	**Solid – 2.28m**	Current DSN Capability	**Total RTG power limited**
Secondary Pointing	**Ka-band**	Membrane	**ngVLA Capability**	Failed RTG power limited

Power Amp Scaling

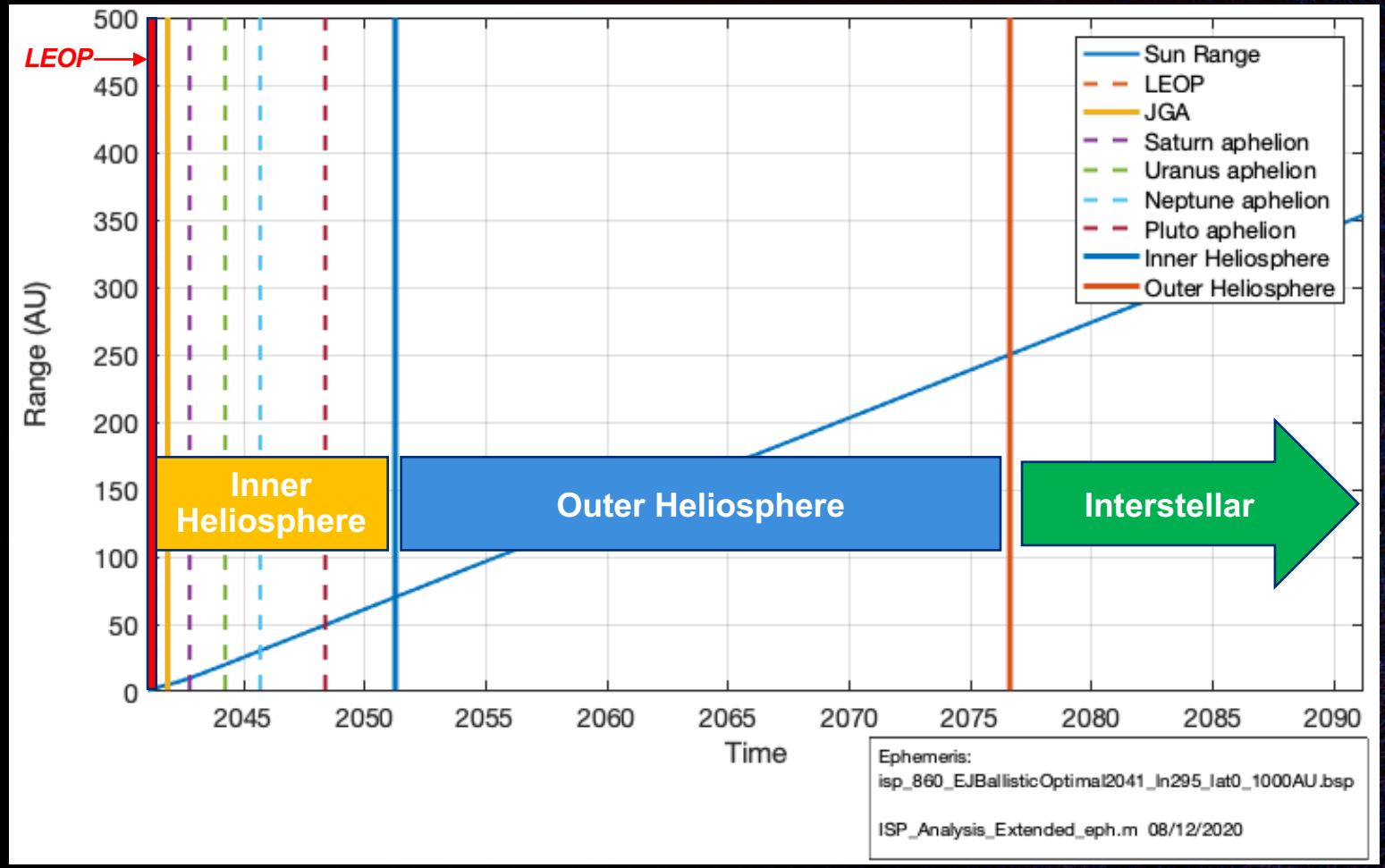
Scale TWTAs to accommodate different scenarios

- 2 RTGs @ 50 years => 300W DC
- Nominal design
  - RF Power = 52 W
- What if 1 RTG fails?
  - All Instruments at survival power:
    - RF Power = 9 W
  - Reduced instrument suite:
    - RF Power = 39 W
- Extend mission to 1000 AU?
  - RTG Degradation: 1.9% /year
  - 61 W available after 133 years



Communications Concept of Operations Mission Phases

- LEOP: Launch to L+101d
  - Use Spacecraft LGAs
  - Single 34m DSN station
- Inner Heliosphere: 1 AU to 70 AU
  - Use MGA to Jupiter (~L+300d)
  - Start Science collection after JGA
  - Switch to HGA
  - Use DSN stations only (10 years)
- Outer Heliosphere: 70 AU to 250 AU
  - Switch to ngVLA
  - 1 contact every 2 weeks
- Interstellar Phase: beyond 250 AU
  - Spacecraft HGA
  - ngVLA
  - 1 contact per week

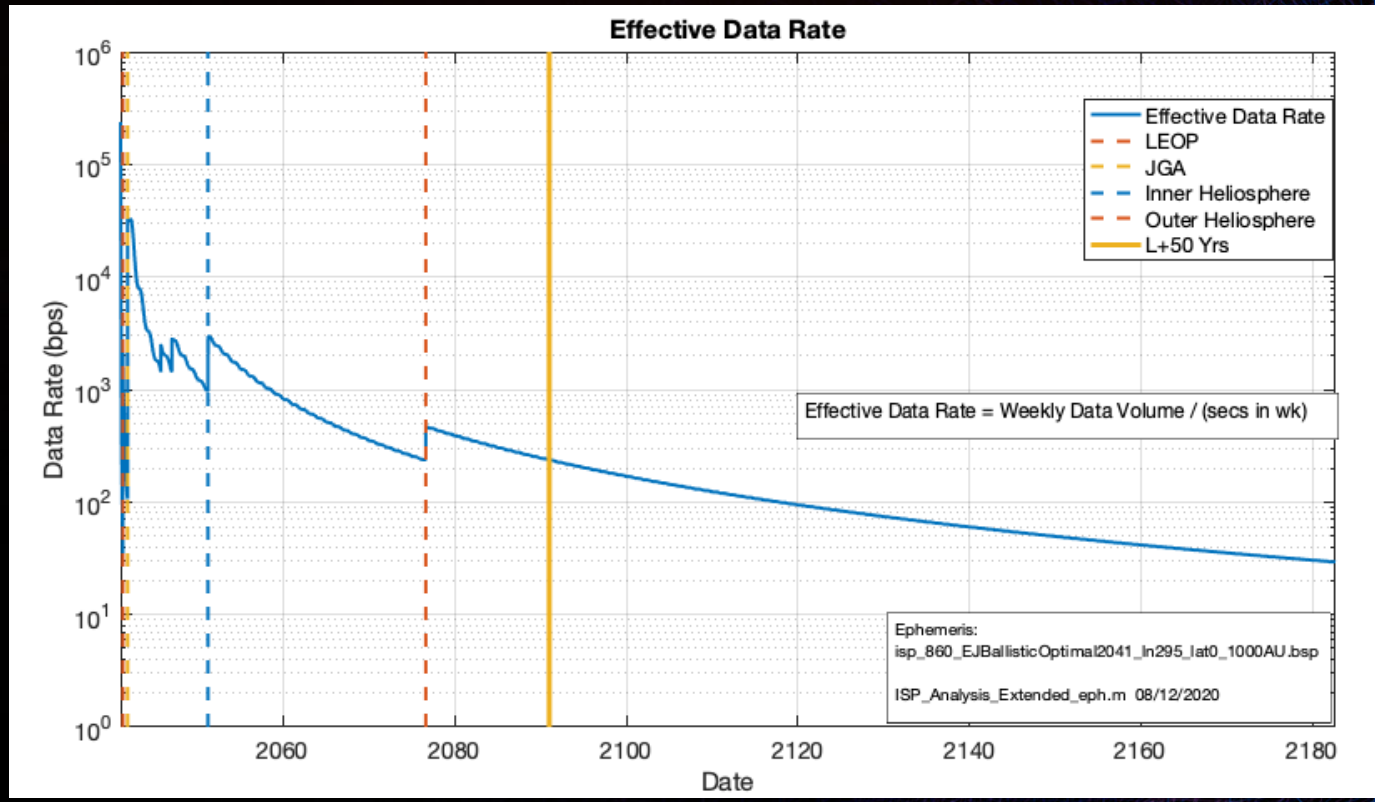


Effective Data Rate

Effective Data Rate:

Weekly Data Volume / seconds in a week

Effective Data Rate to 1000 AU



Question and Answer Session

Interstellar Probe Study
Webinar Series

Engineering Discussion
Long Duration Mission Study

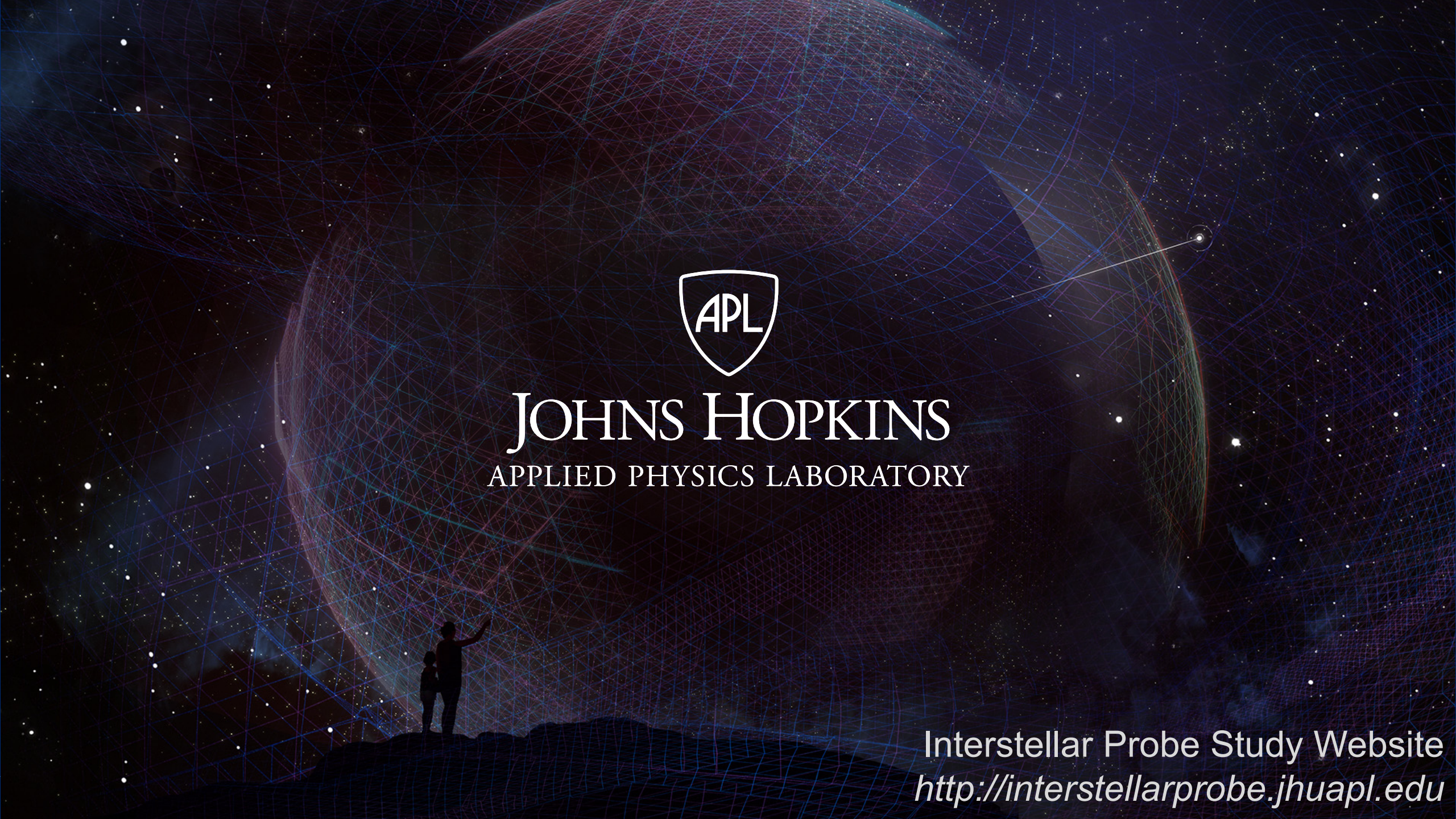
Presented by

- **Interstellar Probe Study Engineering Team**

12:05 PM EDT Thursday, 17 September 2020

Interstellar Probe Study Website

http://interstellarprobe.jhuapl.edu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Interstellar Probe Study Website
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