MUSEings on Uranus

An Enhanced New Frontiers Class Mission to Uranus

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And NASA Planetary Science Summer School 2013 #1 Members

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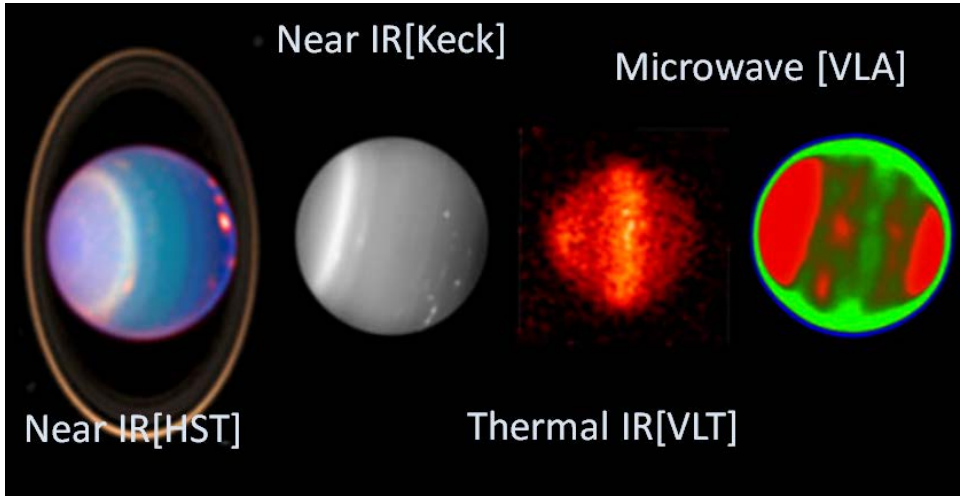
Why Uranus?

"The ice giants are one of the great remaining unknowns of the solar system, the only class of planet that has never been explored in detail."

- NRC's 2013 Planetary Sciences Decadal Survey

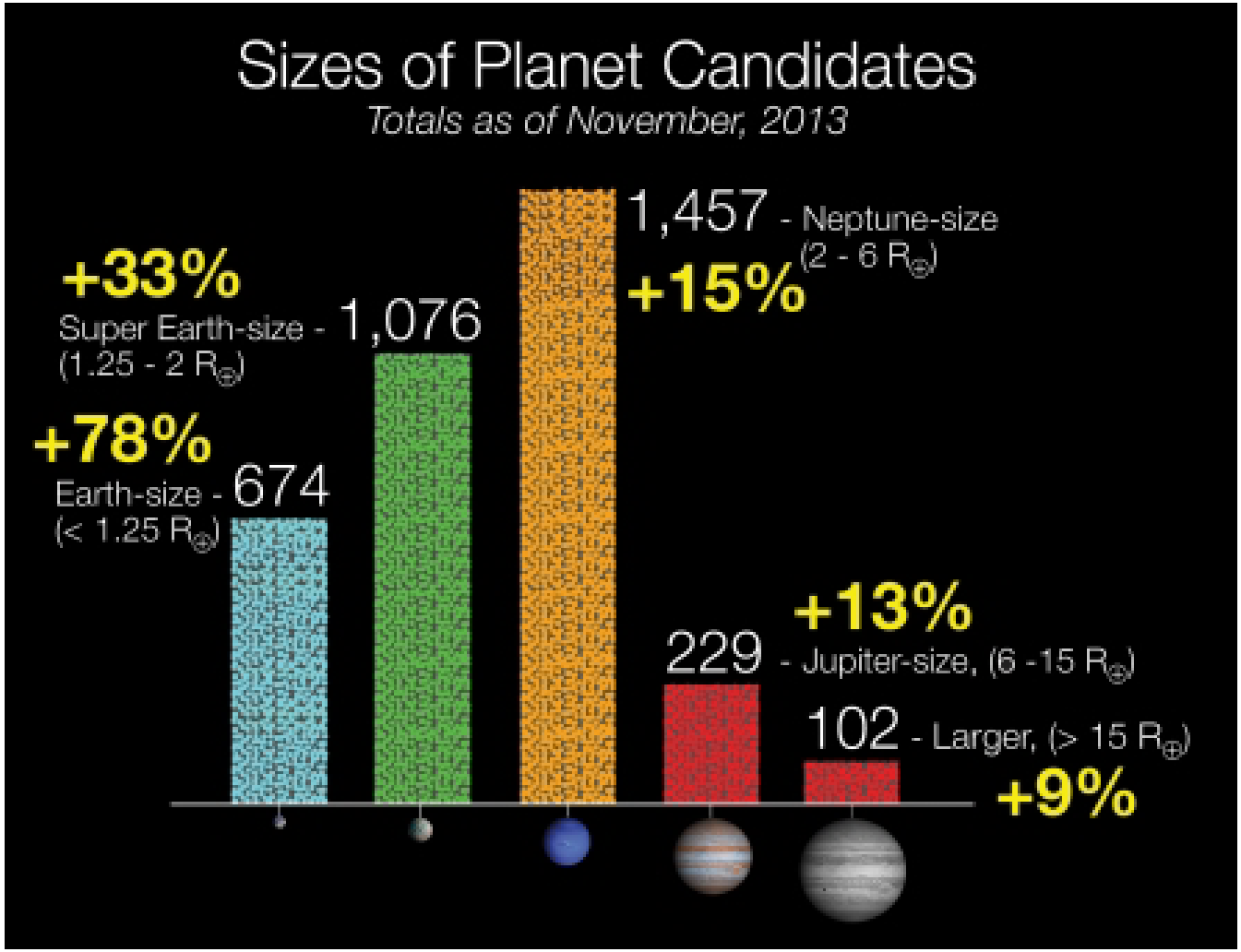
Voyager 2, 1986



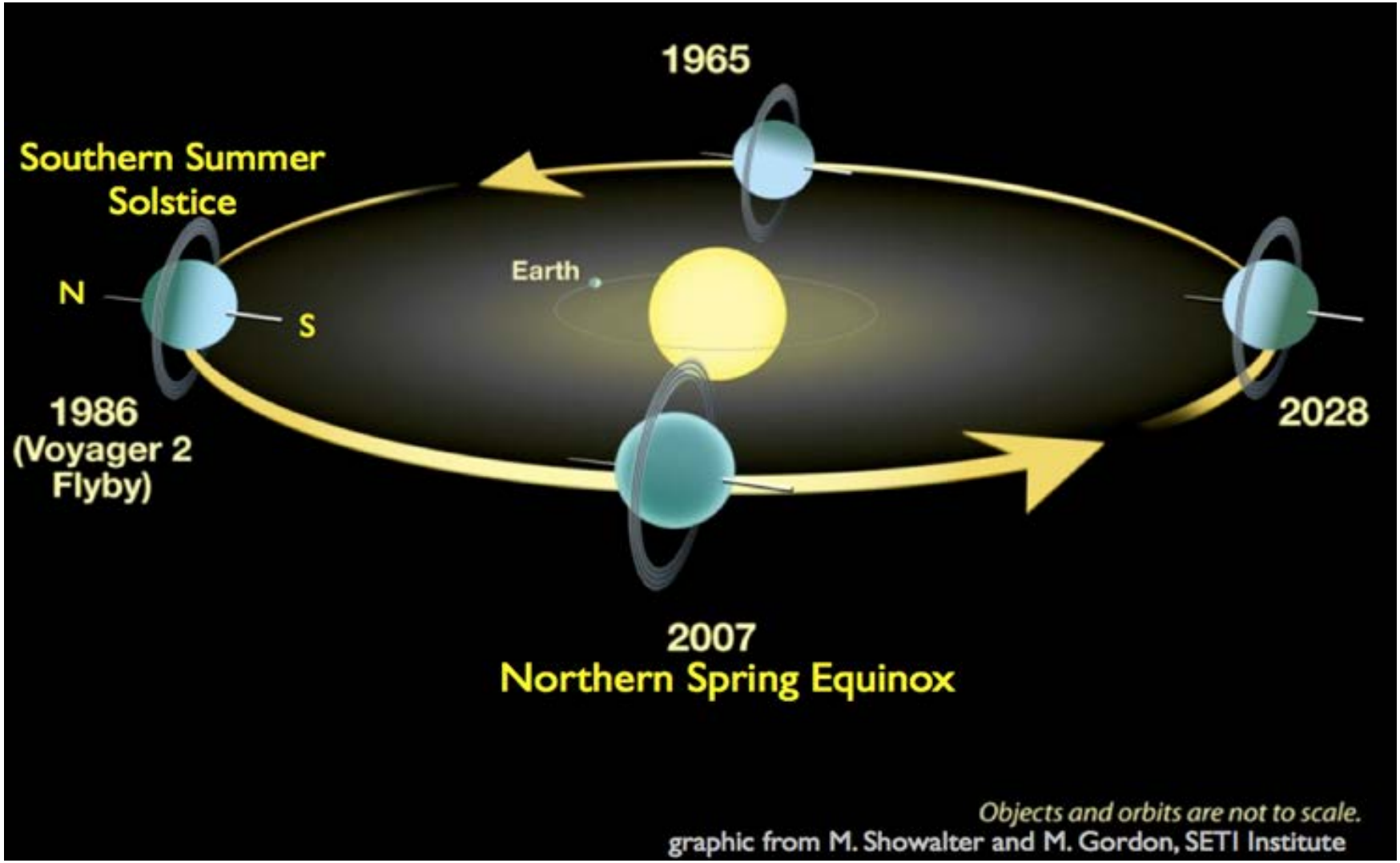
1997 **2004**

MUSE is Mission for Uranus Science and Exploration: MUSEings of Uranus

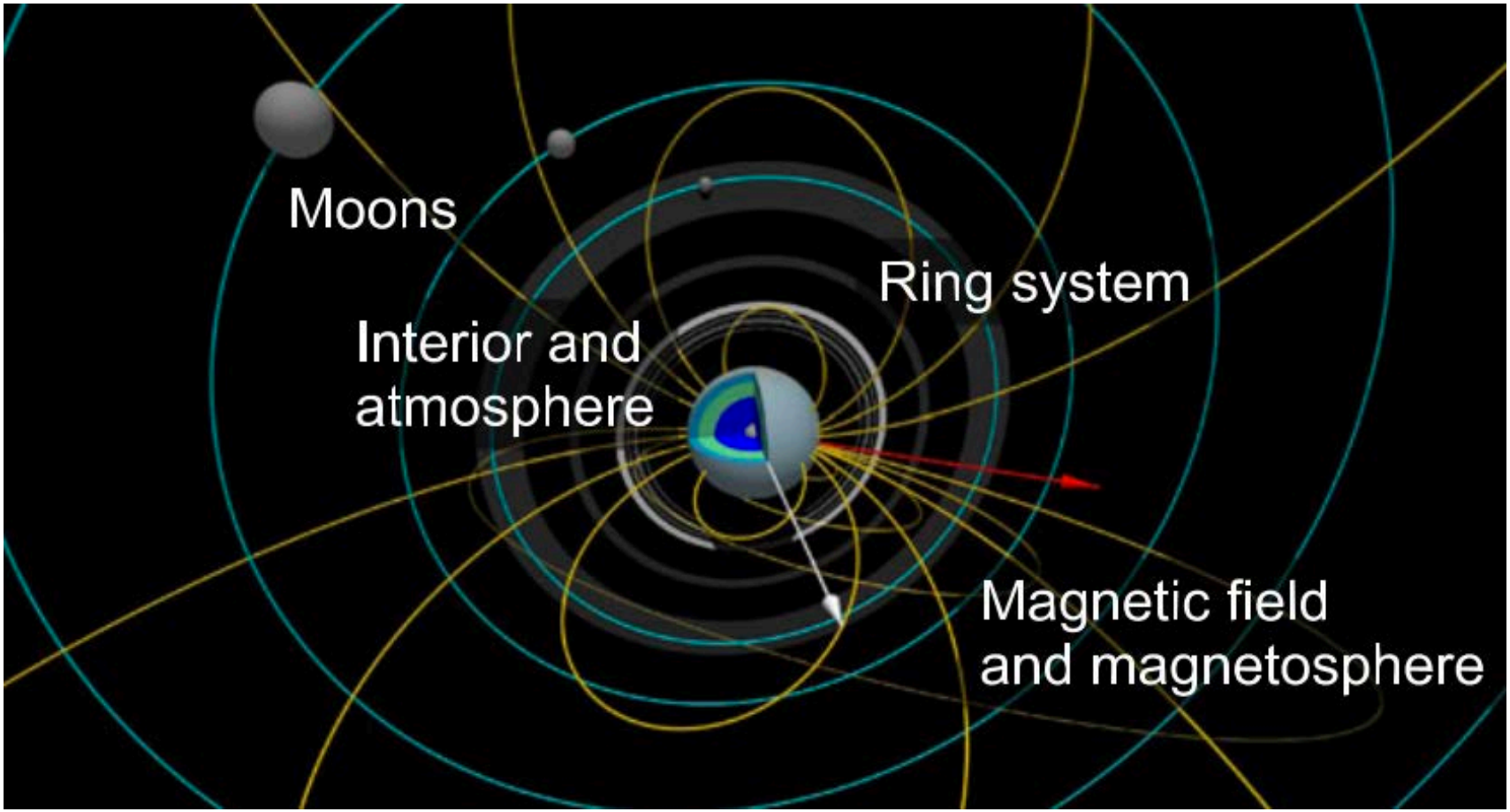
Uranus-Types in Extrasolar Systems



Uranus is Unique



Science Objectives at Uranus



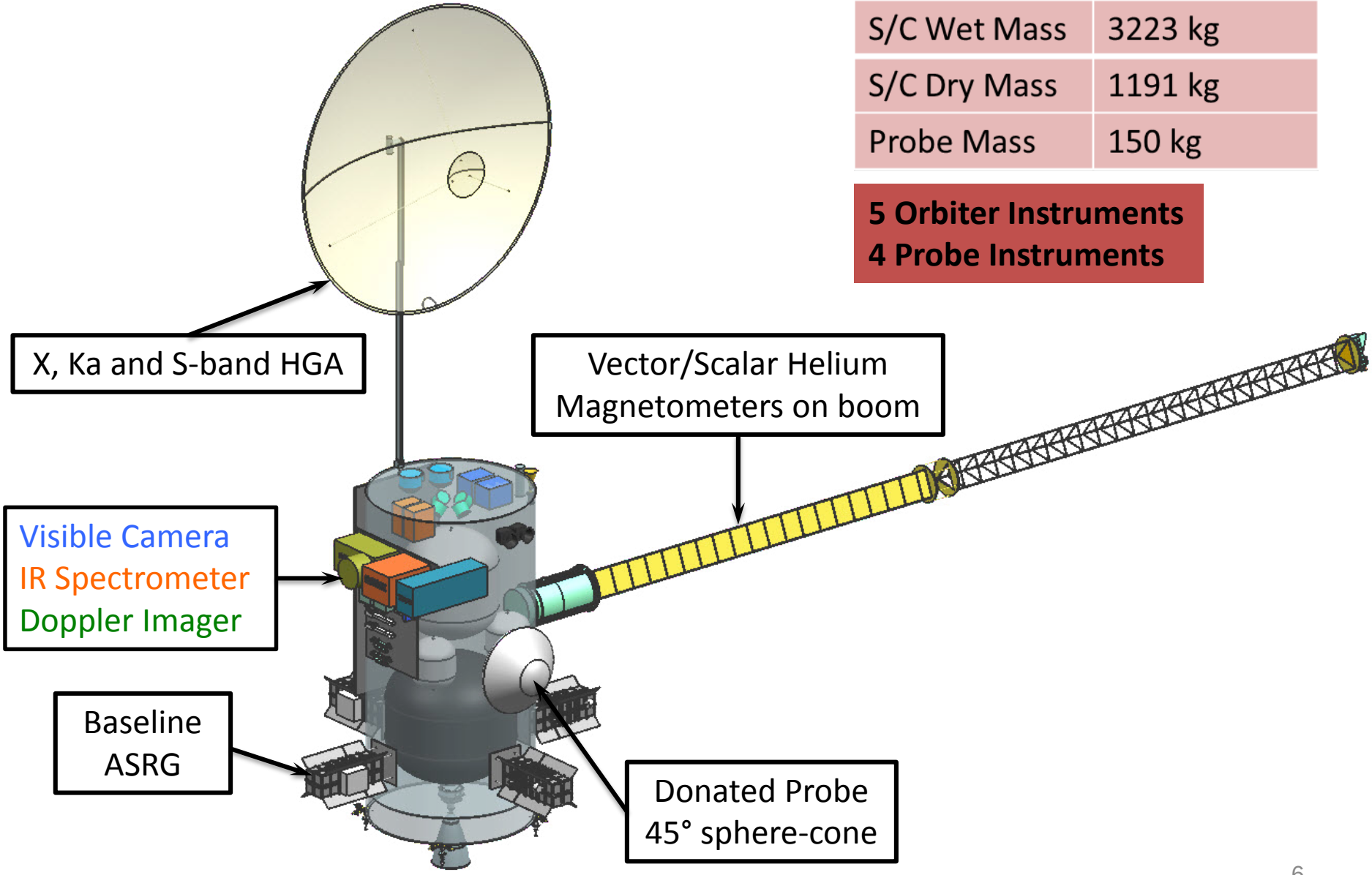
Science Traceability and Instruments

Objective	Investigation	Probe	Far/Mid IR Spec	Visible Camera	Magneto-meters	Doppler Imager	Radio Science
Global Atmosphere Characterization	Composition		■				
	Structure			■		■	
	Zonal Winds		■	■		■	
Single Location Atmosphere Characterization	Composition	■					
	Atmospheric Structure	■					
	Cloud Structure; Particles	■					
Magnetosphere	Structure				■		
	Internal Dynamics				■	■	
Interior	Structure					■	
	Gravity Field						■
Large Satellites	Interior				■		
	Surface Composition/Temp		■	■			
	Geology			■			
Thermal Emission	Horizontal Variation		■				
	Depth Variation		■				
	Temporal Variation		■				

Spacecraft and Entry Probe

S/C Wet Mass	3223 kg
S/C Dry Mass	1191 kg
Probe Mass	150 kg

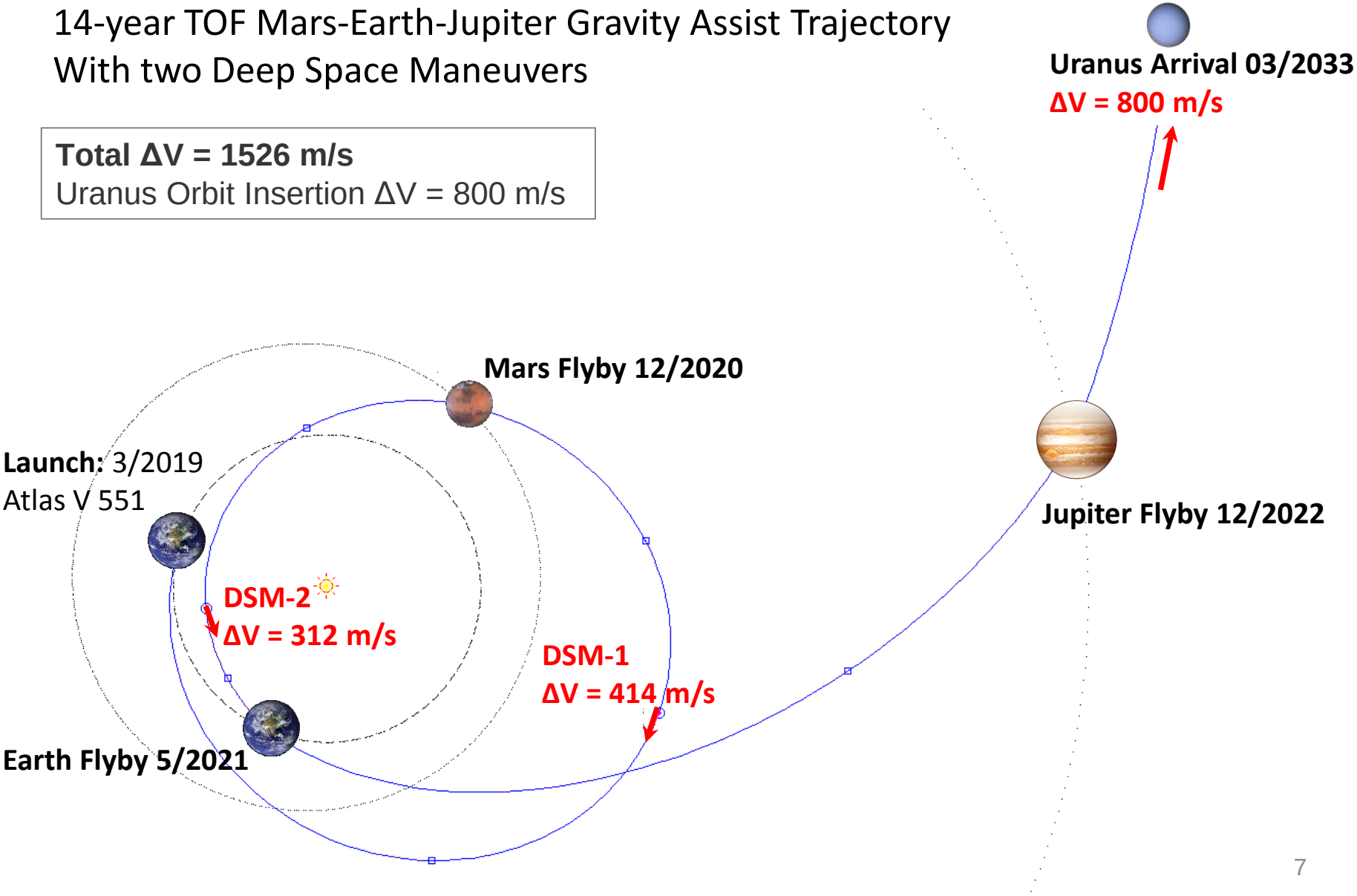
5 Orbiter Instruments
4 Probe Instruments



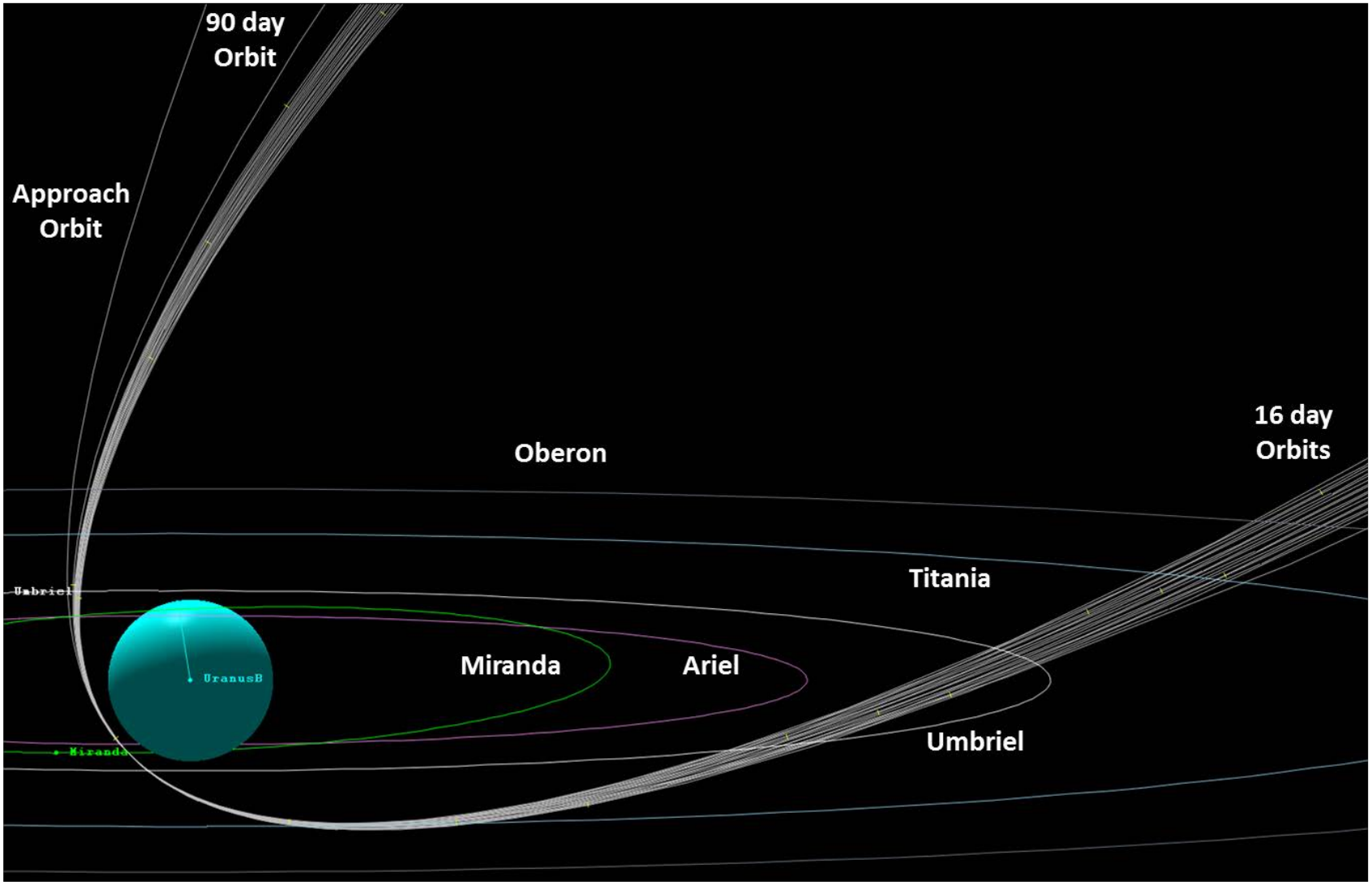
Interplanetary Trajectory

14-year TOF Mars-Earth-Jupiter Gravity Assist Trajectory
With two Deep Space Maneuvers

Total ΔV = 1526 m/s
Uranus Orbit Insertion ΔV = 800 m/s



Approach, Ring Crossings, Flyby Opportunities



Mission Cost

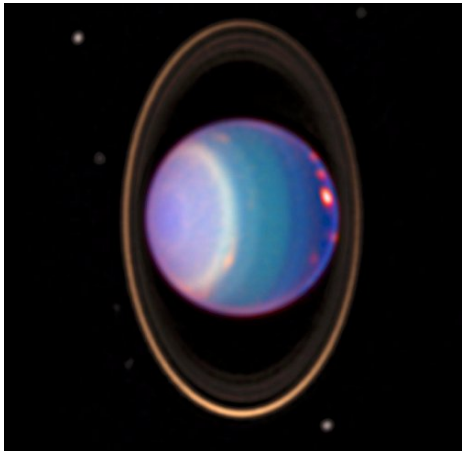
- Reserves: 50% Phases A—D, 25% for Phases E and F
- Cost cap (FY2013 $): $1425 M

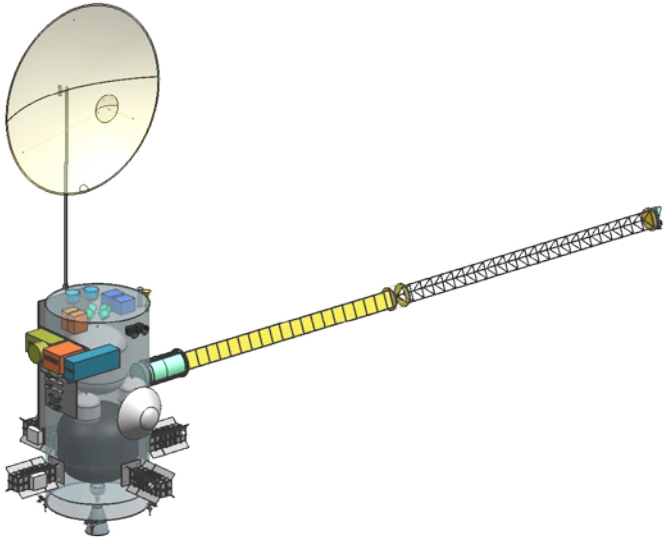
	Current Best Estimate		Project Baseline Estimate
COST SUMMARY (FY2013 $M)	CBE	Res.	PBE
Launch Vehicle Payload Support	$18.0 M	0%	$18.0 M
Project Cost (w/o LV)	$912.1 M	44%	$1310.6 M
Development Cost	$708.5 M	50%	$1061.8 M
Operations Cost	$203.6 M	22%	$248.8 M
Project Cost	$930.1 M	43%	$1328.6 M

Summary

Enhanced New Frontiers class mission to Uranus

- 2-year nominal science mission
- Cost $1.3 billion
- Five orbiter instruments
- Four probe instruments
- Fulfills 2013 Decadal Survey objectives





MUSEings on Uranus

Unusual tilt of 98 degrees, what should I do?
But, this is what makes me so interesting;
I know you like it too!

Titania, Oberon, Miranda, Ariel, Umbriel, and many others
make me so cool;
The amazing discoveries to make in these,
should make the scientists and engineers drool.

Bring in spectrometer, magnetometer, visible, and near infrared,
and may be a Doppler imager too;
and make scientific discoveries about our own and extra solar systems,
which are absolutely new!

Acknowledgments

IPPW11 SOC

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MUSE Team Members - 2013 PSSS Session 1

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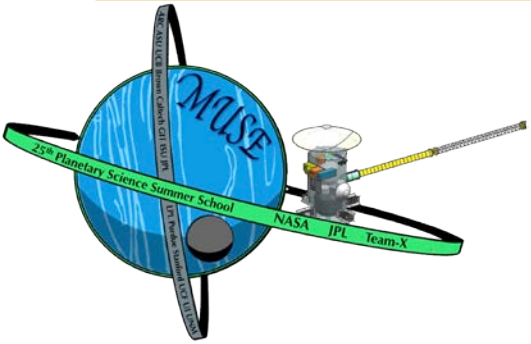

Questions?

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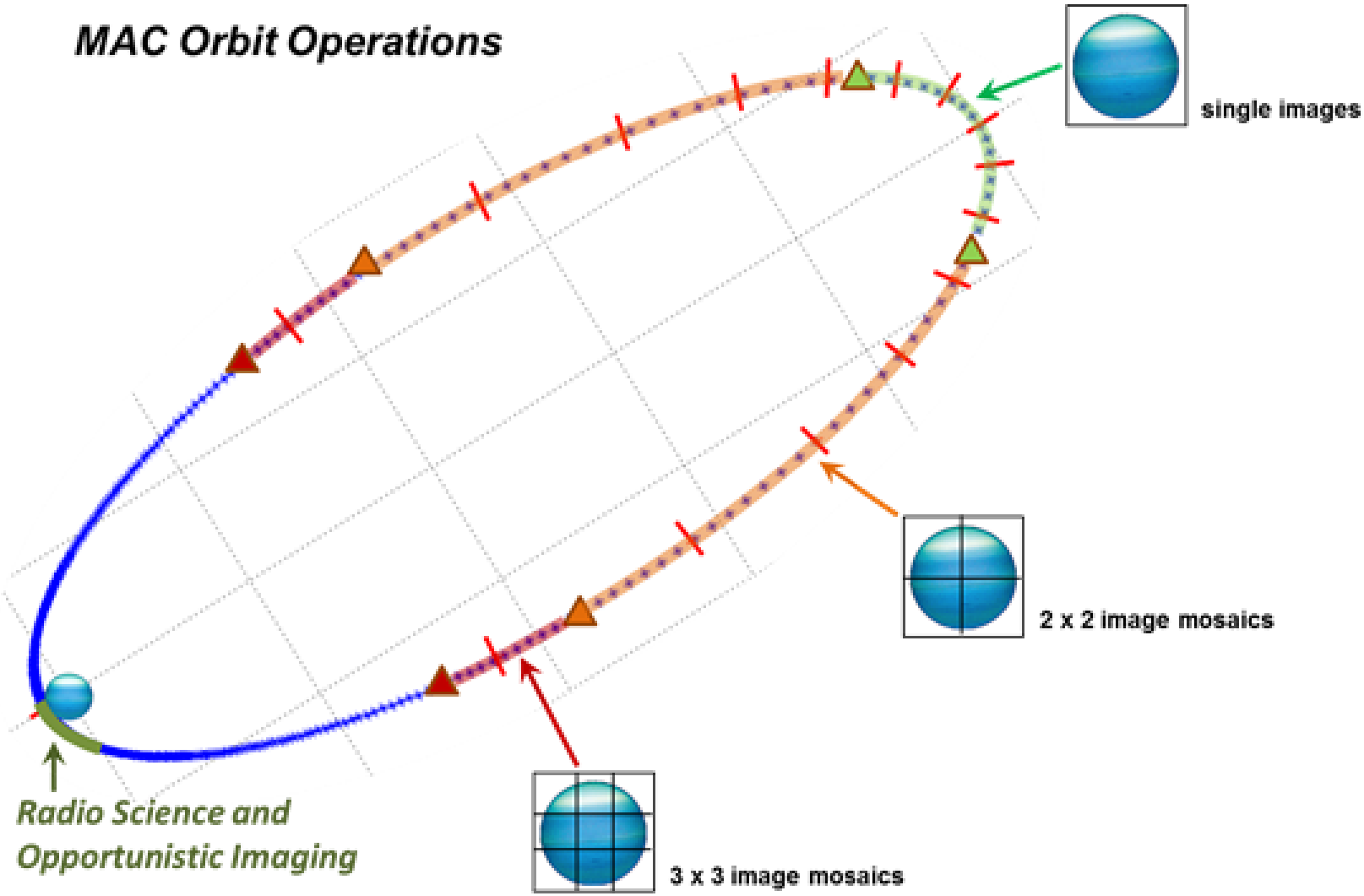
BACK UP

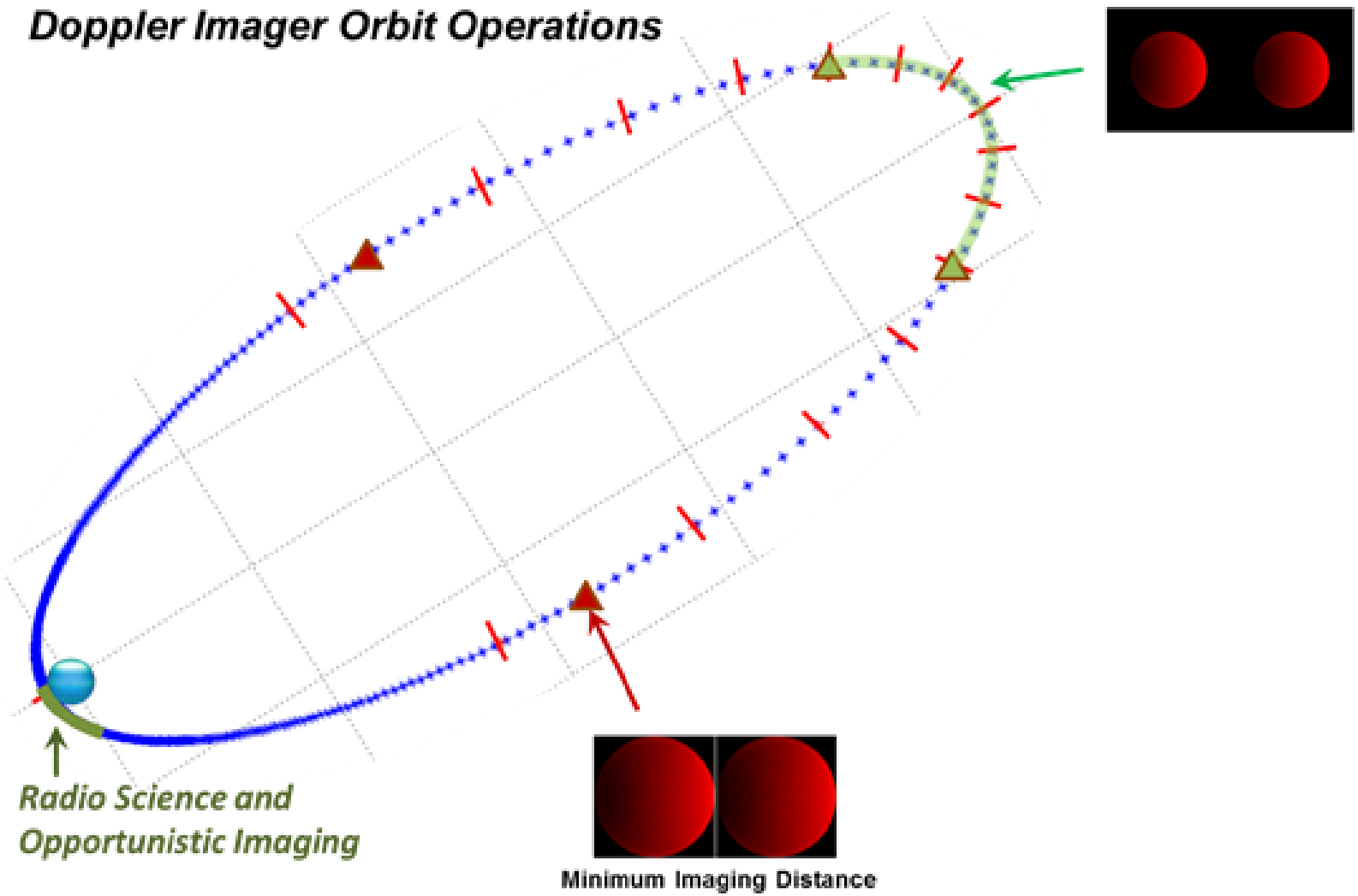
Key Trades

Single vs. Repeated Ring-plane Passage	Delta-V requirement to push periapsis beyond rings is mass prohibitive
Gimbaled vs. Static Antenna	Gimballing antenna required to return probe science and monitor orbit insertion
Solar Power vs. ASRG	Solar power would require prohibitively massive solar array

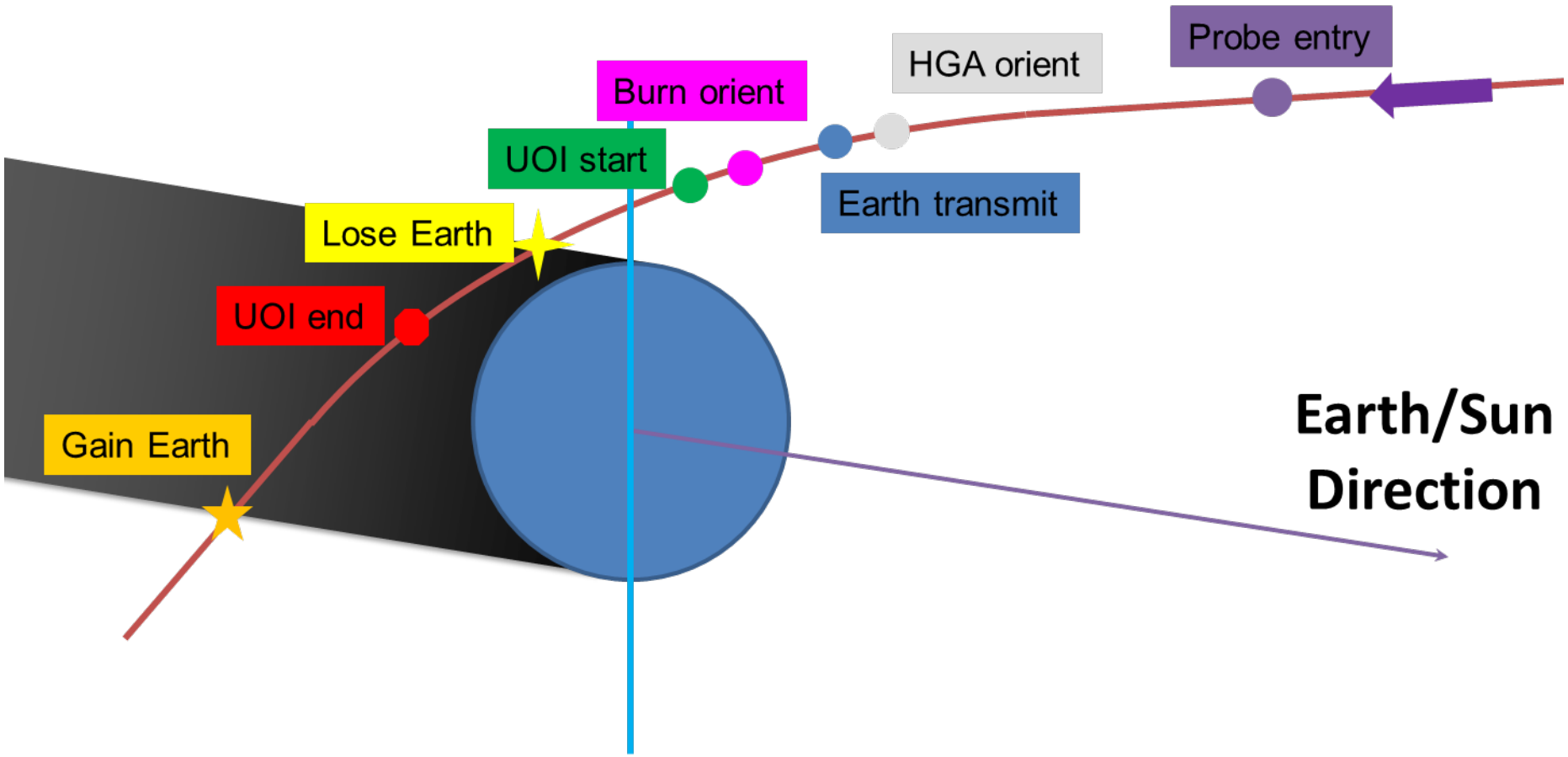
Medium Angle Camera Orbit Operations



Science Orbit Operations



Uranus Approach and Orbit Insertion



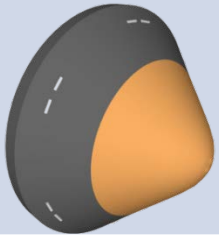
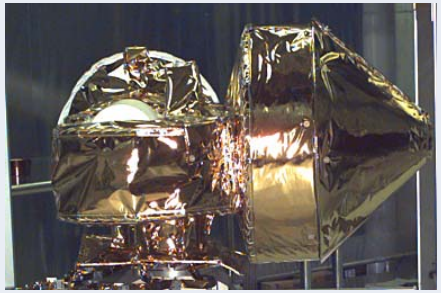
Risks and Mitigations

- Ring plane crossing
- Constrained launch schedule
- ASRG Use: Protection and Power
- Lifetime reliability of parts
- Uranus Orbit Insertion: critical events

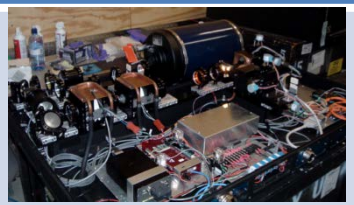
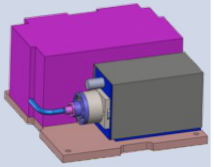
Science Traceability Matrix

Science Objectives	Investigations	Scientific Measurement Requirements	Instrument Requirements	Projected Performance	Mission Requirements (Orbit and Trajectory)	Data Products
(1) Determine the vertical atmospheric zonal wind speeds, composition, and structure at high spatial resolution, as well as the temporal evolution of atmospheric dynamics.	(a) Atmospheric composition	Measurements of atmospheric compositions of CH4, NH3, H2S, H2O, CO2, D2O	IR Spec: Spectral resolution capable of discerning bands	7-333 um (1400-30 cm-1 with 0.1 cm-1 resolution) 5 mrad/pix	Highly Inclined Orbit Preferred (>65 deg); Able to image full disk with one sweep near apoapse	Calibrated spectra, Composition maps
	(b) Atmospheric structure	Observations of atmospheric pressure, temperature.	Doppler Imager: Optics have FOV > 80 mrad; 2 narrow bandpass filters at 767 nm and 777 nm	Range: 40 mAngstroms at 767 nm and 777 nm K absorptions. Detectors: 2 2048x2048. IFOV: 80 mRad. Summing of pixels to 200x200 bins. 1 image/2 mins	1) Time Interval for a) Uranus in full FOV, b) Uranus diameter > 200 pixels, and c) Sun-Uranus-Spacecraft angle < 90 deg is larger than time interval of image campaign 2) No impulsive maneuvers or momentum dumps during imaging	Calibrated pressure and temperature data, P and T maps
			Radio occultation: 1) dual frequency X, Ka-band, 2) USO, 3) Dedicated DSN time	Same as instrument requirement	Atmosphere must be between Uranus and spacecraft	
	(c) Atmospheric zonal winds	Measurements of atmospheric zonal wind speeds	Visible Camera: Global coverage of atmosphere with ~2-hour interval at a minimum resolution of 33 km/pix at 60 R_U		Able to image full disk at apoapse in a single image. High inclination orbit with polar coverage. Near-Global coverage for days, months, and a year.	Wind speed by pressure level, Cloud heights
			IR Spec: Spectral resolution capable of discerning bands and rapid imaging at close range (high spatial resolution).	7-333 um (1400-30 cm-1 with 15 cm-1 resolution) 5 mrad/pix; 2 seconds per exposure	Sufficient resolution to resolve clouds at approach	
			Doppler Imager: Optics have FOV > 80 mrad; 2 narrow bandpass filters at 767 nm and 777 nm	Range: 40 mA at 767 nm and 777 nm K absorptions. Detectors: 2 2048x2048. IFOV: 80 mRad.	1) Time Interval for a) Uranus in full FOV, b) Uranus diameter > 200 pixels, and c) Sun-Uranus-Spacecraft angle < 90 deg is larger than time interval of image campaign 2) No impulsive maneuvers or momentum dumps during imaging	
(2) Understand the basic structure of the planet's magnetosphere as well as the high-order structure and temporal evolution of the planet's interior dynamo.	(a) Magnetosphere structure	Make continuous measurements of the vector magnetic field; full latitude and longitude coverage	Magnetometers: 0.1-2000 nT. 360 deg. field of view (~10 m long boom)	Range of ± 2000 nT with 8 pT resolution and continuous measurements at 1-10 Hz.	Precessing polar orbit with high eccentricity (periapsis ~1.1 R_U, apoapsis 40-70 R_U). Orbit through magnetopause on day-side and twisted tail on night side.	Magnetic strength and direction in x,y, and z; Temporal variability
	(b) Internal dynamics	Measurements of strain, eigenfrequencies, thermal structure and radial structure	Magnetometers: 0.1-2000 nT. 360 deg. field of view (~10 m long boom)	Range of ± 2000 nT with 8 pT resolution and continuous measurements at 1-10 Hz.	Precessing polar orbit with high eccentricity (periapsis ~1.1 R_U, apoapsis 40-70 R_U). Orbit through magnetopause on day-side and twisted tail on night side.	Magnetic strength and direction in x,y, and z; Temporal variability
			Doppler Imager: Optics have FOV > 80 mrad; 2 narrow bandpass filters at 767 nm and 777 nm	Range: 40 mA at 767 nm and 777 nm K absorptions. Detectors: 2 2048x2048. IFOV: 80 mRad.	1) Time Interval for a) Uranus in full FOV, b) Uranus diameter > 200 pixels, and c) Sun-Uranus-Spacecraft angle < 90 deg is larger than time interval of image campaign 2) No impulsive maneuvers or momentum dumps during imaging	Maps: Strain, Eigenfrequencies, Thermal structure, Radial structure
(3) Determine abundances of H_2O, He, Ne, Ar, Kr, and Xe and isotopic ratios (H, C, N, and O) in the planet's atmosphere and the atmospheric structure at the probe descent location.	(a) Compositions	H_2O, He, Ne, Ar, Kr, Xe abundances. Isotopic ratios of H, C, N and O. Particulate abundances and size distribution range. Structure. Observations made between 100 mbar and 5 bar	Probe Mass Spectrometer: Detector threshold range: 10 H2O ppmv; 1 Kr, 1 Xe ppbv	As provided	Drop in a location where atmosphere is well-mixed, possibly near mid-latitudes. Entry flight path angle of -40 deg ideal. Probe must be in contact with the orbiter during ~75 minute descent.	Calibrated spectra, Composition profile
	(b) Atmospheric structure		Atmosphere Structure Instrument: Pressure (0.1-5 bars), Temperature (0-500K), Accelerometers (3μg-409g).	As provided		Pressure, temperature, acceleration profiles
	(c) Cloud Structure and Particles		Probe Nephelometer: Particulate abundances and sampling rate	As provided		Particulate distribution, abundances
(4) Determine both the interior mass distribution and the penetration depth of the atmospheric zonal flow.	(a) Structure	Measure the normal oscillation models to determine the interior structure and measure up to L=10.	Doppler Imager: Optics have FOV > 80 mrad; 2 narrow bandpass filters at 767 nm and 777 nm	Range: 40 mA at 767 nm and 777 nm K absorptions. Detectors: 2 2048x2048. IFOV: 80 mRad.	1) Time Interval for a) Uranus in full FOV, b) Uranus diameter > 200 pixels, and c) Sun-Uranus-Spacecraft angle < 90 deg is larger than time interval of image campaign 2) No impulsive maneuvers or momentum dumps during imaging	Normal Oscillation Modes, Interior model
	(b) Gravity Field	Measure the gravity moments to determine the gravity field.	Radio: 1) 2-way X-band, 2) Dedicated DSN time 3) Doppler 0.5 mm/s	Same as instrument requirement	High inclination orbit, low periapse, 1.2 R_U	Gravity moments to J6
(5) Remote sensing observations of large satellites (will be viewing the previously obscured side).	(a) Interior	Magnetometer measurements test for the presence of sub-surface oceans.	Magnetometers: 0.1-2000 nT. 360 deg. field of view (~10 m long boom)	Range of ± 2000 nT with 8 pT resolution and continuous measurements at 1-10 Hz.	Precessing polar orbit with high eccentricity (periapsis ~1.1 R_U, apoapsis 40-70 R_U). Orbit through magnetopause on day-side and twisted tail on night side.	Magnetic field properties
	(b) Surface composition and temperature	Determine composition and thermal emission of the surface	IR Spec: IFOV of 25 m/pix @ 100 km; FOV 64 mrad	7-333 um (1400-30 cm-1 with 0.1 cm-1 resolution) 5 mrad per pix	Ideally fill FOV with a satellite.	Composition/temperature data for selected areas
			Visible Camera: Use the clear, H alpha, Violet, Methane, near UV, RGB filter			Composition maps
	(c) Geology	Observe surface morphology at resolutions of 12 km/pix or better	Visible Camera: Global coverage of satellite at 30+ km/px	6 km/pix at 10 Ru		Images, mosaic
(6) Determine horizontal distribution of atmospheric thermal emission, as well as the upper atmospheric thermal structure and changes with time and location at low resolution	(a) Horizontal variation	At least one full disk image of planet with IR; 15 cm-1 resolution is sufficient.	IR Spec: At least one full disk image of planet with IR; 15 cm-1 resolution is sufficient.	7-333 um (1400-30 cm-1 with 15 cm-1 resolution) 5 mrad/pix	May be obtained by contingency images at low resolution. High inclination orbit desired for better coverage.	Temperature map and difference maps
	(b) Depth variation	Conduct observations at various phase angles	IR Spec: Rapid imaging (less than 2 minutes per exposure)	7-333 um (1400-30 cm-1 with 15 cm-1 resolution) 5 mrad/pix; 2 seconds per exposure	Ability to change pointing direction of instrument (or spacecraft)	Thermal emission profile
	(c) Temporal variation	Repeat observations at least every 8 hours	IR Spec: Measure 2D thermal emission every 2 hours	Achieved by high spectral resolution (0.1 cm-1) IR compositional imaging; targeted opportunistic imagining at 15 cm-1	Orbital period of at least several days	Difference maps
(7) Remote sensing observations of inner small satellites and rings.	(a) Rings Structure	Range of illumination per orbit of rings at less than 10 R_U.	Visible Camera: large pixel sizes to increase contrast			Particle and moon distribution
	(b) Rings Composition	Occultation of rings with IR source. Varied scattering angles.	IR Spec: IFOV of 25 m/pix @ 100 km; FOV 64 mrad	7-333 um (1400-30 cm-1 with 0.1 cm-1 resolution) 5 mrad/pix	Occultation of rings with IR source. Varied scattering angles.	Composition maps
	(c) Rings Particle size distribution	Observe particle sizes	Radio occultation: 1) dual frequency X, Ka-band, 2) USO, 3) Dedicated DSN time	Same as instrument requirement	Atmosphere must be between Uranus and spacecraft	Particle size distribution maps
	(d) Rings Dynamical stability and evolution	Image behind the rings during occultation	Visible Camera: large pixel sizes to increase contrast and observations at regular intervals		Regular passes near rings	Images/movies
	(e) Small satellite composition	Pass close enough to obtain global view of small satellite	IR Spec: IFOV of 25 m/pix @ 100 km; FOV 64 mrad	7-333 um (1400-30 cm-1 with 0.1 cm-1 resolution) 5 mrad/pix	Pass close enough to obtain global view of small satellite	Spectra, composition maps
	(f) Small satellite dynamics	As high of a resolution as possible depending on opportunistic fly-offs	Visible Camera: large pixel sizes to increase contrast and observations at regular intervals			Images, mosaics
(8) Measure the magnetic field strength, plasma, and currents to determine how the tilted/offset/rotating magnetosphere interacts with the solar wind over time.	(a) Measure the magnetic field strength	Observe magnetic field	Magnetometers: 0.1-2000 nT. 360 deg. field of view (~10 m long boom)	0.1-2000 nT. 360 deg. field of view (~10 m long boom)	Precessing polar orbit with high eccentricity (periapsis ~1.1 R_U, apoapsis 40-70 R_U). Orbit through magnetopause on day-side and twisted tail on night side.	Magnetic strength and direction maps
	(b) Aurora	Observe changes in magnetic field and infer interactions with solar wind	Visible Camera: Image when nearest the poles			Images
(9) Remote sensing observations of outer irregular small satellites.	(a) Composition	Full surface observations at 12 km/pix resolution	Visible Camera: Image satellites opportunistically	6 km/pix at 10 Run		Images, mosaics
	(b) Dynamics	Opportunistic observations throughout mission	IR Spec	7-333 um (1400-30 cm-1 with 0.1 cm-1 resolution) 5 mrad/pix	Opportunistic global view of at least one outer small satellite	Spectra, composition maps
			Visible Camera: Use the clear, H alpha, Violet, Methane, near UV, RGB filter			Composition maps

Instruments Characteristics

Instruments	Characteristics	Similar Instruments	Example Image
Probe	• Pressure range: 100 mbar – 5 bar • Provides measurements on noble gas abundances, isotopic ratios, temperature, pressure, gravity, density, cloud presence as a function of depth, radio tracking	• Galileo Probe • Pioneer Venus Probe	
IR Spectrometer	• FIR: 17-333 µm 75 mrad FOV (4.3 deg) single pixel • MIR: 7-17 µm 50 mrad FOV (3 deg) 5 mrad/pixel 1x10 pushbroom • Exposure Time: 2-250 sec	• Thermal Infrared Spectrometer (TIRS) (Modernized Cassini CIRS; Proposed in Decadal Survey Titan Mission)	
Visible Camera	• 8 filters (R, G, B, clear, alpha H, methane, violet, near IR) • 2048 x 2048 CCD • FOV = 2.5 deg • Pixel resolution: 22 µrad • Exposure time: 4 msec – 4 min • Aperture = 0.09 m • EFL = 458 mm	• Deep Impact MRI	

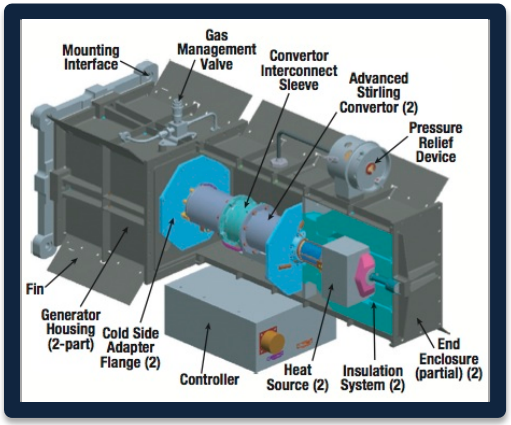
Instrument Characteristics

Instruments	Characteristics	Similar Instruments	Example Image
Doppler Imager	• Two 40 mÅ-width narrow band filters centered at 767 nm and 777 nm potassium (K) absorptions • Two 2048 x 2048 pixel detectors • IFOV: 80 mrad (4.6 deg) • 2 min sampling frequency	• SOHO Michelson Doppler Imager	
Radio Tracking and Occultations	• X- band (3.5 cm); Ka-band (0.94 cm) • 2 way X-band Doppler with 0.5 mm/s resolution • 8 h/day tracking nominal • Ka-band and Ultra Stable Oscillator for Occultations	• Cassini-Huygens • MESSENGER • Venus Express • Mariner 2-10 • Voyager 1,2	
Magnetometers	• Two Vector/Scalar He Magnetometers • Range: ±2000 nT • Resolution: 8 pT • Absolute Accuracy: 20 pT • 1-10 Hz measurements • Low noise, precise offset stability	• Cassini V/SHM Magnetometer • Ulysses	

Power

Baseline: 4 ASRG's: each contain <1 kg Pu-238

- Provided as 2 GPHS modules per unit
- 140 W/each beginning of mission
- 121 W/each end of mission



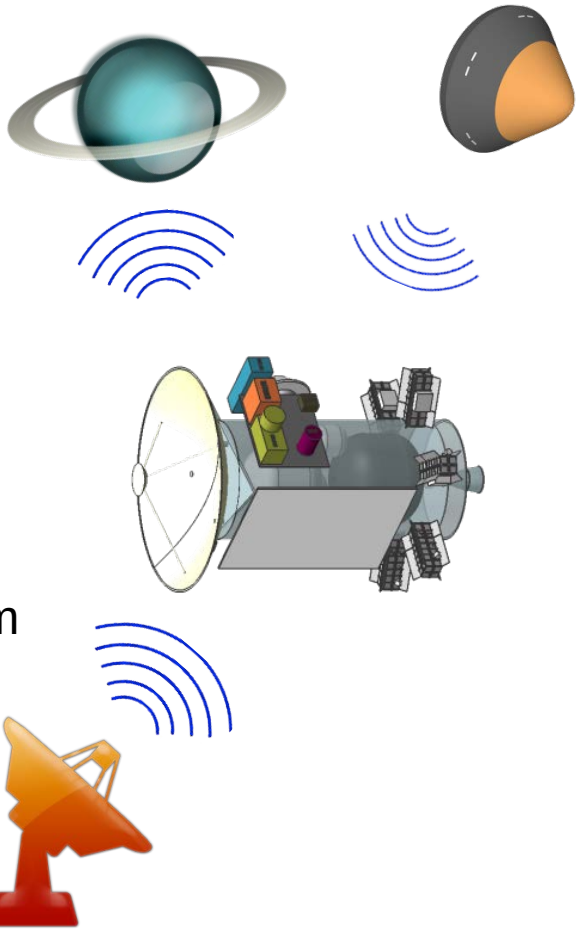
2 Li-Ion batteries

- 100 A-h/each beginning of life
- 50 A-h end of mission (50% degradation over time)
- Deepest discharge down to 62 Ah once during mission (orbit insertion fault case)

- Electronics are MSL/SMAP design
- Batteries are DoD design
- Propulsion system is MSL/SMAP design with development for our configuration

Telecommunications

HGA	Gimballed, 2-way X (downlink 4.5 kb/s), Ka (carrier only) downlink, S band for probe, 46 dB gain		
MGA, 2 LGA	2-way X-band (downlink 10 b/s to 20 kb/s depending on range), support to launch, early cruise and safe mode		
Navigation support	5 m ranging, 0.5 mm/s Doppler		
	Cruise mode	Science mode	Radio Science
Data rate	Down 10 b/s to 20 kb/s	4.5 kb/s (30 kb/s with 70 m antenna)	Dual band X and Ka, Doppler and Occultation



- Support 2-way communication for critical events
- All equipment has flight heritage and redundant system

Threshold Science Mission

- **Loss of one ASRG**
  - Reduce power consumption by re-scoping operations plan
  - Downlink data reduced
  - Loss of 20% of science data
  - Can selectively prioritize data
- **Loss of Doppler Imager**
  - Loss of Tier 2 scientific objective: internal structure boundaries
  - Get J6 from radio science
  - Gain simultaneous operations of remaining instruments
- **Shorten Magnetometer boom**
  - Negatively impacts objective but does not preclude it

Tier	Objective	Investigation	Baseline	Threshold
1	Global Atmosphere Characterization	Composition		
		Structure		
		Zonal Winds		
	Single Location Atmosphere Characterization	Compositions		
		Atmospheric Structure		
		Cloud Structure; Particles		
	Magnetosphere	Structure		
		Internal Dynamics		
	Interior	Structure		
		Gravity Field		
2	Large Satellites	Interior		
		Surface Composition/Temp		
		Geology		
	Thermal Emissions	Horizontal Variation		
		Depth Variation		
		Temporal Variation		

Descoping

Risk Identification	Suggested Descope	Savings	Impact
Mass	**Remove 1 ASRG from operational plan**	45 kg $25 M	This results in a loss of power redundancy and ~20% of science
Schedule	**Remove the Doppler Imager instrument**	26 kg $24 M Secures launch window	▪ Degrades Tier 2 science. ▪ Baseline science is achieved by shifting science dependence to other instruments. ▪ Power availability is sufficient to run other instruments simultaneously
Mass	**Shorten magnetometer boom to 5m**	3 kg	Offset noise from spacecraft will be increased but calibration can be adjusted

Flight System Cost Breakdown

WBS Elements	NRE	RE	1st Unit
06.0 Flight System	$169.9 M	$259.5 M	$429.4 M
6.01 Flight System Management	$3.9 M		$3.9 M
6.02 Flight System Systems Engineering	$29.2 M		$29.2 M
Flight System Elements	$131.5 M	$257.7 M	$389.2 M
6.04 Power	$12.8 M	$155.4 M	$168.3 M
6.05 CDS	$15.8 M	$18.4 M	$34.2 M
6.06 Telecom	$23.3 M	$19.9 M	$43.2 M
6.07 Structures (includes Mech. I&T)	$37.9 M	$13.4 M	$51.3 M
6.08 Thermal	$4.1 M	$19.6 M	$23.7 M
6.09 Propulsion	$12.7 M	$14.3 M	$27.0 M
6.10 ACS	$8.3 M	$8.3 M	$16.6 M
6.11 Harness	$2.6 M	$1.7 M	$4.3 M
6.12 S/C Software	$13.3 M	$6.7 M	$20.0 M
6.13 Materials and Processes	$0.6 M	$0.1 M	$0.7 M
6.14 Spacecraft Testbeds	$5.3 M	$1.8 M	$7.1 M

Payload System Cost Breakdown

WBS Elements	NRE	RE	1st Unit
05.0 Payload System	$54.6 M	$36.8 M	$91.4 M
5.01 Payload Management	$4.3 M		$4.3 M
5.02 Payload Engineering	$3.6 M		$3.6 M
Science Instruments	$46.7 M	$36.8 M	$83.4 M
IR Spectrometer	$15.7 M	$11.4 M	$27.1 M
Visible Camera	$8.7 M	$6.3 M	$15.0 M
Magnetometers	$4.1 M	$5.9 M	$10.0 M
Doppler Imager	$18.2 M	$13.2 M	$31.3 M

Operations Cost Breakdown

WBS Elements	NRE	RE	1st Unit
Operations Cost (Phases E - F)	$243.3 M	$5.5 M	$248.8 M
01.0 Project Management	$15.7 M		$15.7 M
02.0 Project Systems Engineering	$0.0 M	$0.3 M	$0.4 M
03.0 Mission Assurance	$1.6 M	$0.5 M	$2.1 M
04.0 Science	$50.3 M		$50.3 M
07.0 Mission Operations	$102.0 M		$102.0 M
09.0 Ground Data Systems	$23.4 M		$23.4 M
11.0 Education and Public Outreach	$6.2 M	$3.5 M	$9.7 M
12.0 Mission and Navigation Design	$0.0 M		$0.0 M
Operations Reserves	$44.1 M	$1.1 M	$45.2 M
8.0 Launch Vehicle	$18.0 M		$18.0 M
Launch Vehicle Payload Support	$18.0 M		$18.0 M