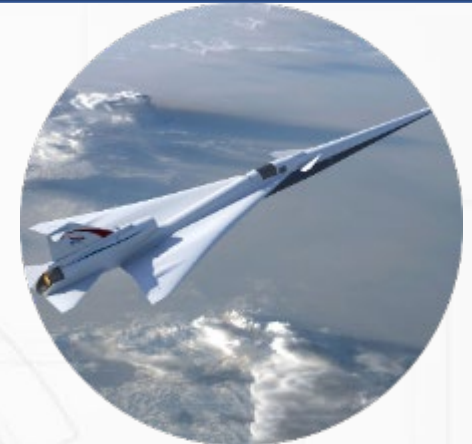
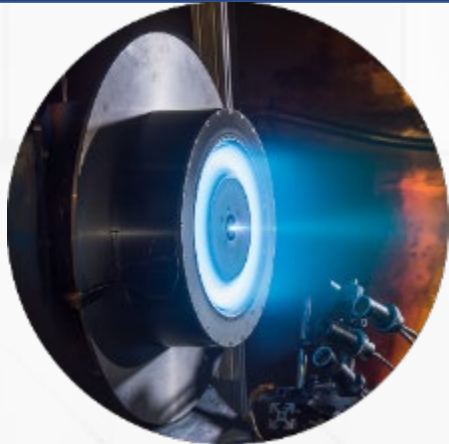


Hampton University Center for Atmospheric Sciences Seminar

National Aeronautics and
Space Administration



Title: Shadow Chaser: A Small Satellite Concept to Probe the Atmospheres of Uranus and Neptune Using Stellar Occultations

PI: Kuno Sayanagi (LaRC E302)

Team: Cindy Young (LaRC E302)

Jonathan Chrone, Joshua Carden (LaRC E402)

William R. Saunders, Paul Withers (Boston University)

Michael J. Person, MIT

Madison Hanrahan (Deep Creek High School, Chesapeake, VA)

Date: February 12, 2024



- Project Title: Shadow-Chaser: A Small Satellite Concept to Probe the Atmospheres of Uranus and Neptune Using Stellar Occultations
- PI: Cindy Young (E302) / Kunio Sayanagi
- Team:
 - Jonathan Chrono, Joshua Carden
- Academic Partners:
 - Paul Withers (Boston University)
 - Michael J. Person (MIT)
- Student Participation:
 - William Saunders (Boston University PhD student)
 - Justin Garland (Hampton University PhD student)
 - Madison Hanrahan (Deep Creek Highschool, Chesapeake, VA)

IDC2 Session Roster



SME List	Organization	Personnel	Contact
Principal Investigator, Customer	E302	Kunio Sayanagi	kunio.m.sayanagi@nasa.gov
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		Katie Bebb	Kaitlyn.m.bebb@nasa.gov
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Mechanical (on Call)	D202	Dave Paddock	-
Mechanical (on Call)	D202	Jared Fell	-
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Power/Avionics	D203	Steve Bowen	stephen.c.bowen@nasa.gov
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Cost	B602C	Stephanie Primeaux	stephanie.j.primeau@nasa.gov
Risk	B602D	Jason Engelhardt	jason.l.engelhardt@nasa.gov
External - Chesapeake Public Schools		Madi Hanrahan	madihanrahan@gmail.com
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	E302	Cindy Young	cindy.young@nasa.gov
	E402	Joshua Carden	joshua.f.carden@nasa.gov

Detector Sensitivity Analysis Follow-up Study



- Kuno Sayanagi (lead)
- Tory Scola (Systems Integration lead)
- John Marketon (LaRC D211), Tamer Refaat (LaRC D211)
- David Franz (GSFC-5530), Murzy Jhabvala (GSFC-5500), Agustyn Waczynski (GSFC-5530)

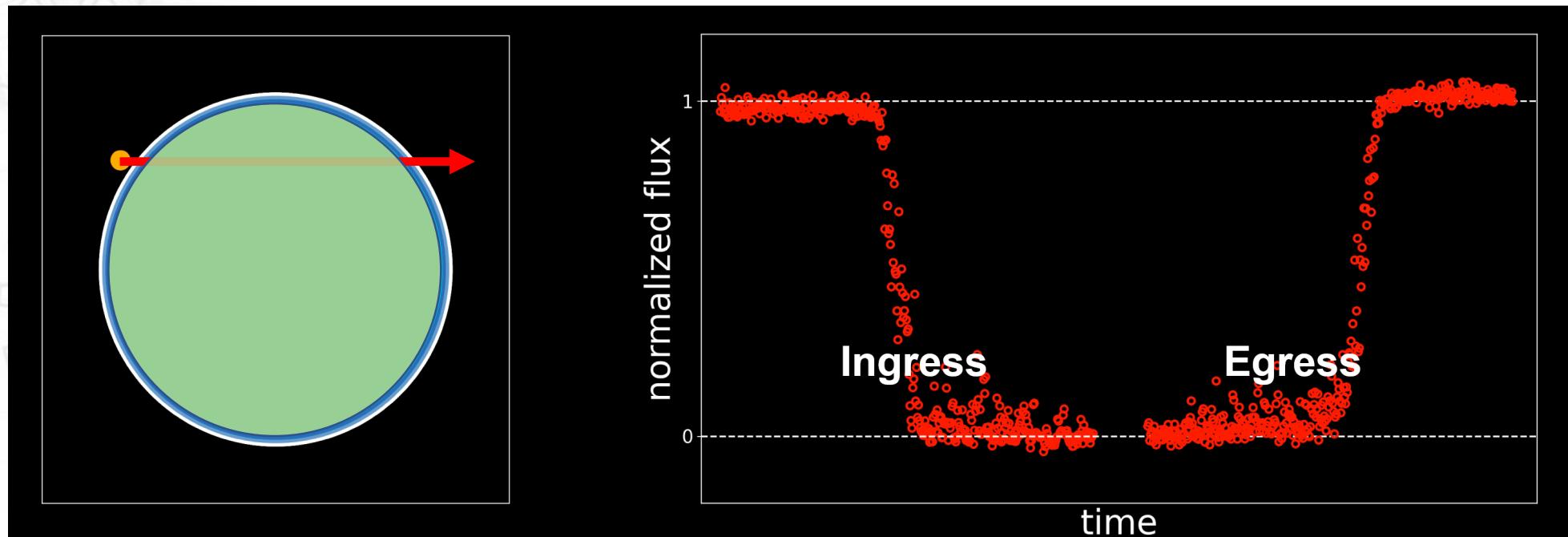
Measurement Sensitivity Analysis Follow-up Study



- Kuno Sayanagi (lead)
- Justin Garland (Atmospheric Structure prediction, AMA/LaRC E302, Hampton University)
- Will Saunders (Occultation Lightcurve Modeling, Boston U.)
- John Smith (Sensitivity covariant matrix analysis, LaRC E304)

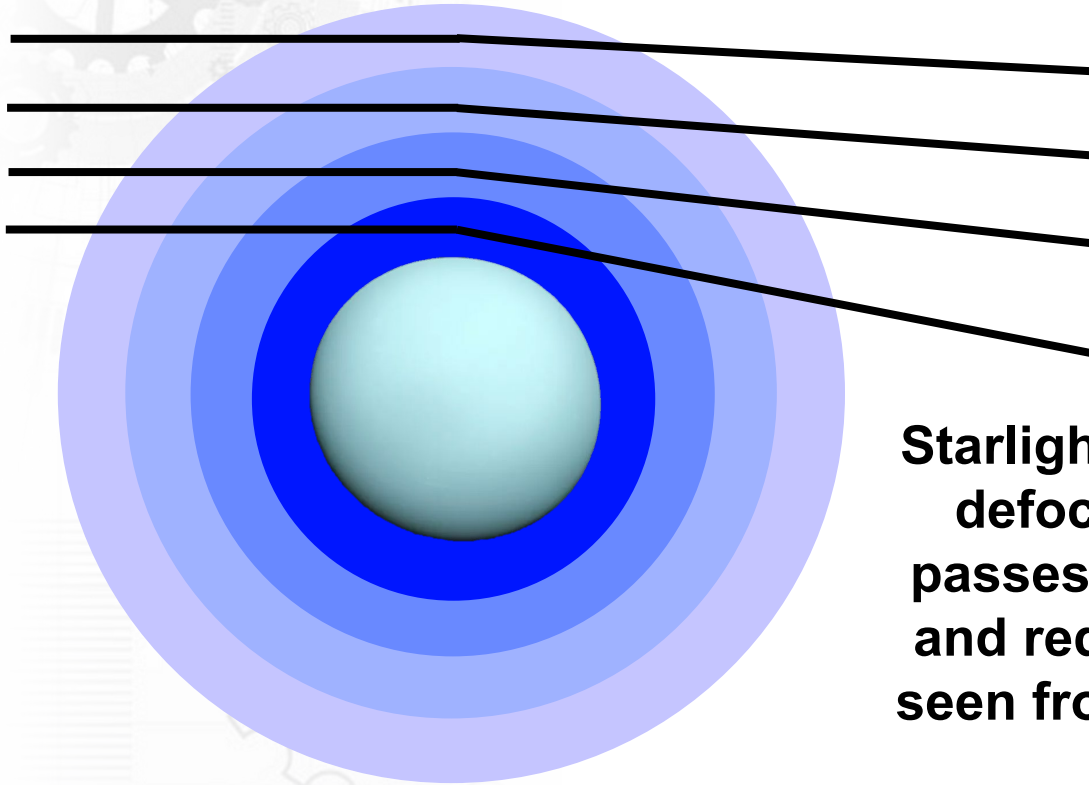
Statement of Problem

- The Shadow Chaser smallsat mission will measure the middle and upper atmospheric temperature and density of Uranus and Neptune through stellar occultation (SO) technique from Earth orbit.
- The mission will address the Planetary Decadal Survey Priority Question “Q7. Giant planet structure and evolution: What processes influence the structure, evolution, and dynamics of giant planet interiors, atmospheres, and magnetospheres?”
- Improved thermospheric characterization will benefit future aerocapture design.



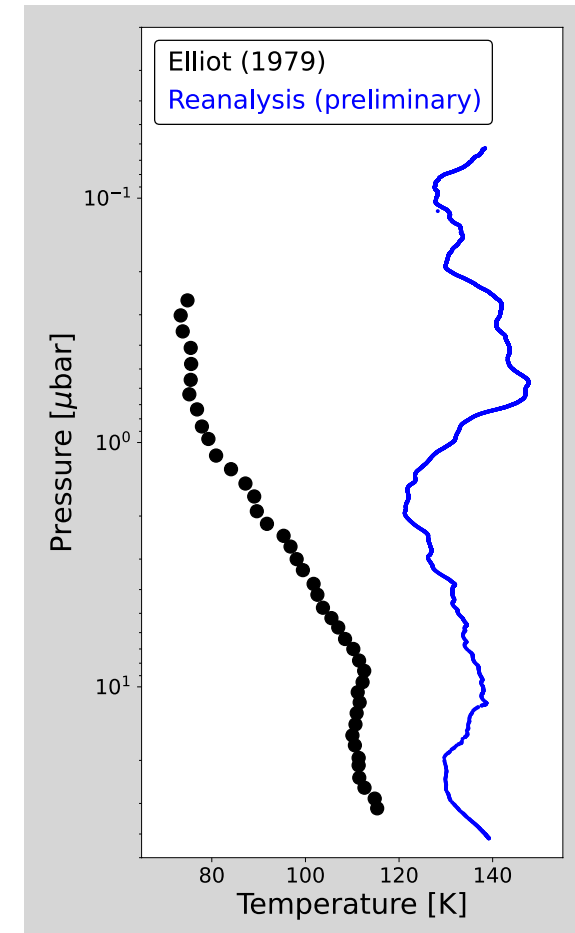
Stellar Occultation Measurement Method

Light path is refracted while the star goes behind the planet (i.e. “ingress”) and when the star re-emerges (“egress”)



Starlight is refractively defocused when it passes deeper layers, and reduces intensity seen from (near) Earth.

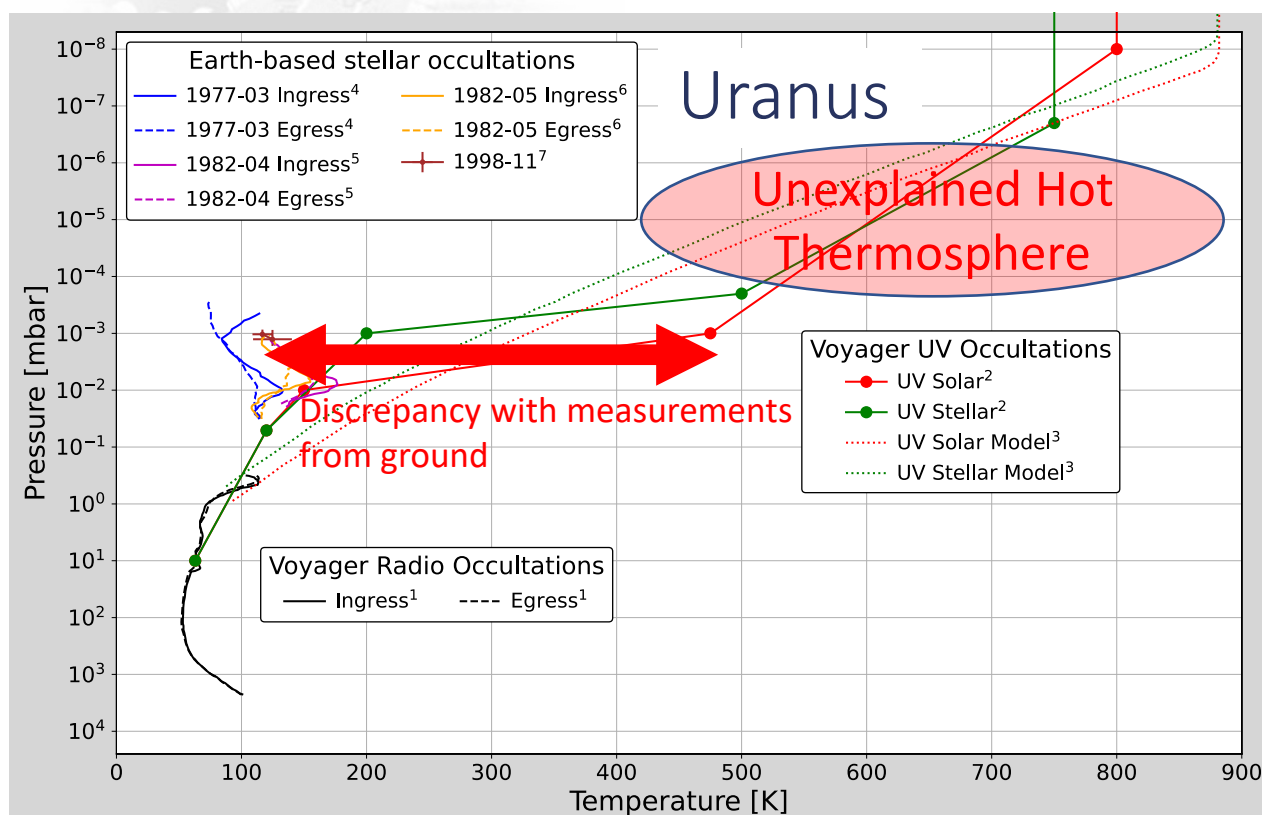
Solve an inverse problem: temperature, pressure, number density



Mission Need



- New improved measurements are needed because highly uncertain hot thermospheres measurements by Voyager 2 are inconsistent with theoretical expectations.
- Space-based measurements are required; Ground-based measurements are hampered by atmospheric scintillations or bad weather.



¹Lindal et al. (1987)

²Herbert et al. (1987)

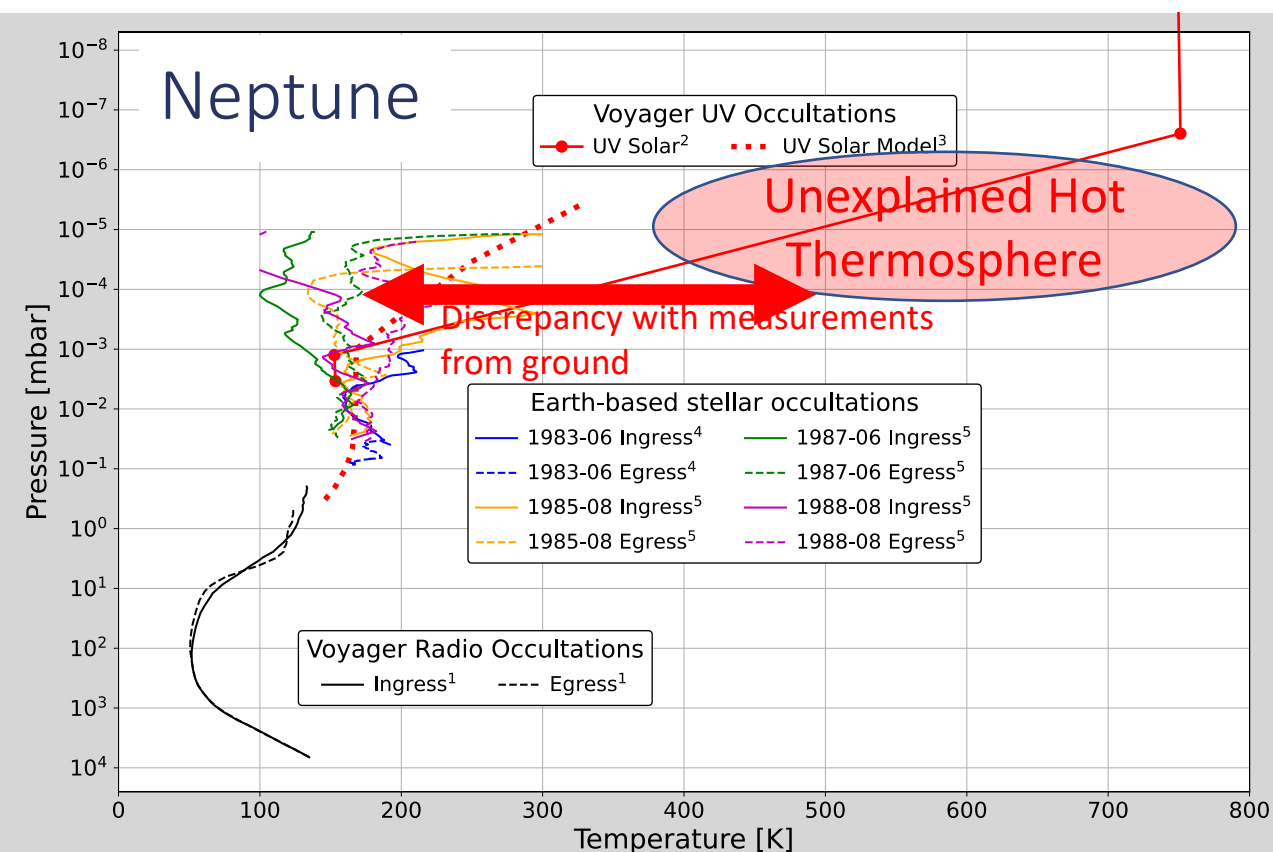
³Stevens et al. (1993)

⁴Elliot (1979)

⁵Sicardy et al. (1985)

⁶French et al. (1987)

⁷Young et al. (2001)



¹Lindal (1992)

²Broadfoot et al. (1989)

³Bishop et al. (1998)

⁴French et al. (1985)

⁵Roques et al. (1994)

Shadow Chaser: Science Goals and Objectives



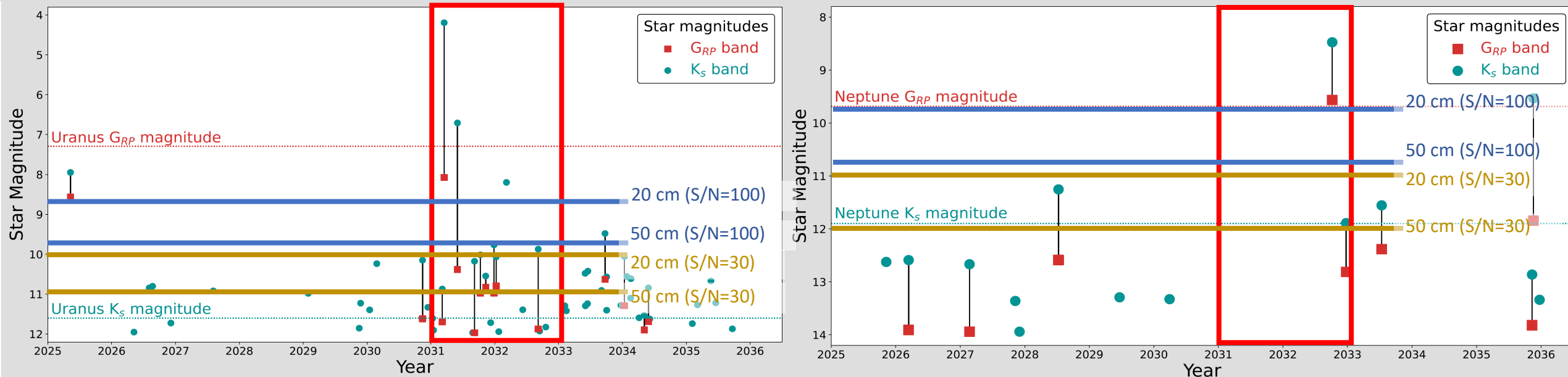
- Goal:
 - Science: Understand Energy Balance in the Upper Atmospheres of Uranus and Neptune
 - Technical: Reduce needed margin for future aerocapture maneuver for Uranus Orbiter and Probe mission expected to arrive Uranus in the 2040s
- Science Objectives:
 1. Definitively measure the upper atmospheric temperature and pressure as a function of altitude
 2. Characterize longitudinal variability in the thermospheric structure potentially caused by perturbation from deep atmospheric structure
 3. Characterize seasonal variabilities in the upper atmospheres of Uranus and Neptune

Stellar Occultation Predictions and Inst Req. (FY22 Result)



- Predicted 56 Uranus and 14 Neptune Occultations between 2025-2035
- 20 Uranus and 6 Neptune occultations are observable from the ground
 - Demonstrated the value of future orbital mission
- Instrument Requirement: Threshold aperture size of 20 cm to measure vertical structure
- 2031-2033 period has multiple viable SO events
- Published as Saunders et al (2022, Planetary and Space Science)

Magnitudes of occulted stars for Predicted SO events in 2025-2035



(Saunders et al. 2022, Planetary and Space Science)

Gaps / Opportunities / Goals

Gaps at the beginning of FY23:

- Need to determine Orbit/Trajectories to make measurements
 - FY22 IRAD efforts identified Occultation Event Opportunities, and minimum instrument requirement
 - Analyze measurement feasibility from GTO and SSO (e.g. visibility, radiation risk)
 - Determine trajectories that allow accessing those measurement opportunities
 - Determine propulsion delta-V requirements to reach those orbits
- Need to design instrument that satisfy measurement requirements
- Need to determine spacecraft bus that accommodate payload + delta-V requirements

Goals:

- Determine orbits that enable targeting multiple predicted events
 - Determine radiation dose expected for the mission orbit
 - Determine the propulsion delta-V requirements to:
 - Enter required orbit
 - Re-phase orbit to place spacecraft to optimize target visibility
 - Disposal at the end of mission
- Determine the instrument telescope aperture size and detector
- Design spacecraft bus that satisfy delta-V and payload requirements

Approach/Innovation

Goal 1: Determine orbits that enable targeting multiple predicted events

- Leverage the occultation simulation STK tool developed during FY22 IRAD
- Consider Geostationary Transfer Orbit (GTO) and Sun Synchronous Orbits (SSO)
- Ensure that radiation dose is tolerable for low-cost mission
- Determine propulsion delta-V requirements

Goal 2: Determine the instrument telescope size and detector

- Analyze total flux
- Select suitable detector
- Design telescope

Goal 3: Design spacecraft bus that satisfy delta-V and payload requirements

- Craft a spacecraft bus and end-to-end mission design
- Demonstrate that that mission concept can achieve science closure

Determine optimal launch opportunity to observe the February 2031 Occultation Event

- GTO:
 - Pro: Ingress+Egress visible from single satellite with little orbital constraints
 - Con: High delta-V requirement
 - Con: Radiation Concern
 - Con: Dearth of NASA Launch Opportunities
- LEO / Sun Sync
 - Pro: Launches and ride-share opportunities are relatively common
 - Pro: Certain Sun Sync configurations go in/out of occultation shadow multiple times, increasing the value of each event
 - Con: Occultation visibility can be obstructed by Earth
 - May require multiple satellites
 - Observations may be compatible with a narrow range of orbital inclinations

Results/Knowledge Gained (1.1) GTO visibility and delta-V



- Event visibility is excellent from GTO
- Total mission delta-V requirement of 156 m/s to observe x5 events

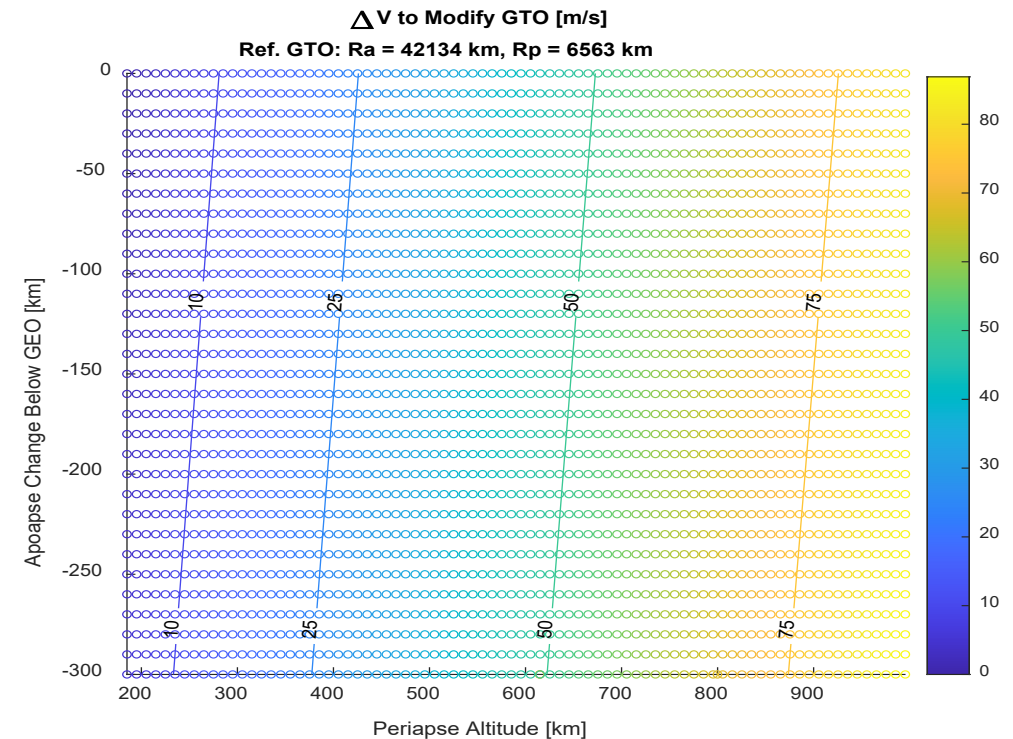
February 15, 2031 Uranus Event

- Duration: 86.3 minutes

Total Mission Delta-V estimate after GTO insertion

- Raise periapsis to 800 km: 63 m/s
- Lower apoapsis to 300 km below GEO: 5 m/s
- Phase adjustment: 5 m/s per event x5 = 25 m/s
- Deorbit: 63 m/s

Total Delta-V Requirement = 156 m/s



Results/Knowledge Gained (1.2) GTO Radiation Dosage



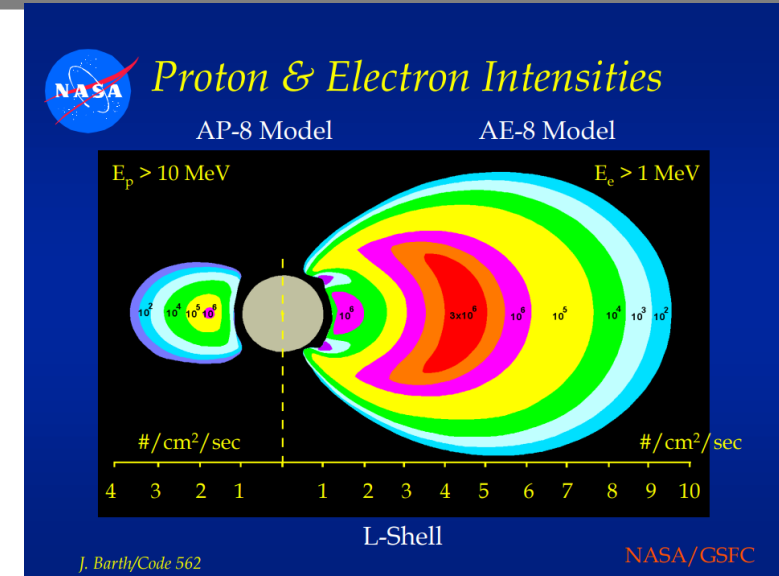
GTO goes through Van Allen radiation belt

- GTO can have:
 - 28.5-deg inclination (KSC launch before plane change maneuver)
 - 0-deg inclination (after plane change maneuver)

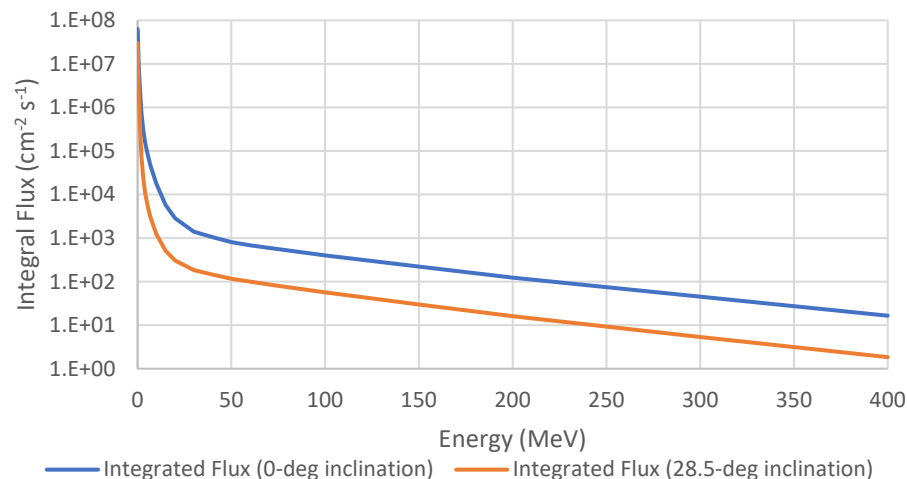
Higher-inclination GTO receives lower radiation exposure

Regardless of inclination, radiation flux too high for a low-cost spacecraft to stay in GTO for 2 years.

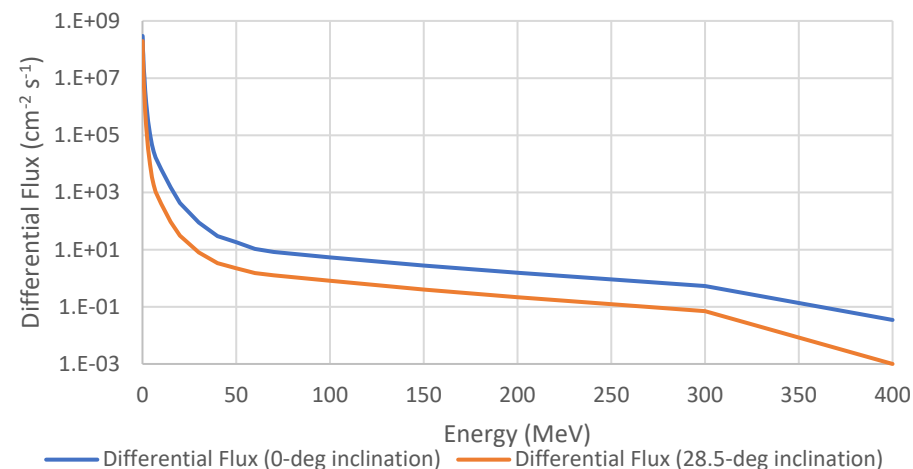
The radiation issue rules out GTO for Shadow Chaser



Trapped Proton Integral Flux (2-year Mission Average)



Trapped Proton Differential Flux (2-year Mission Average)



Calculated using the
SPENVIS tool

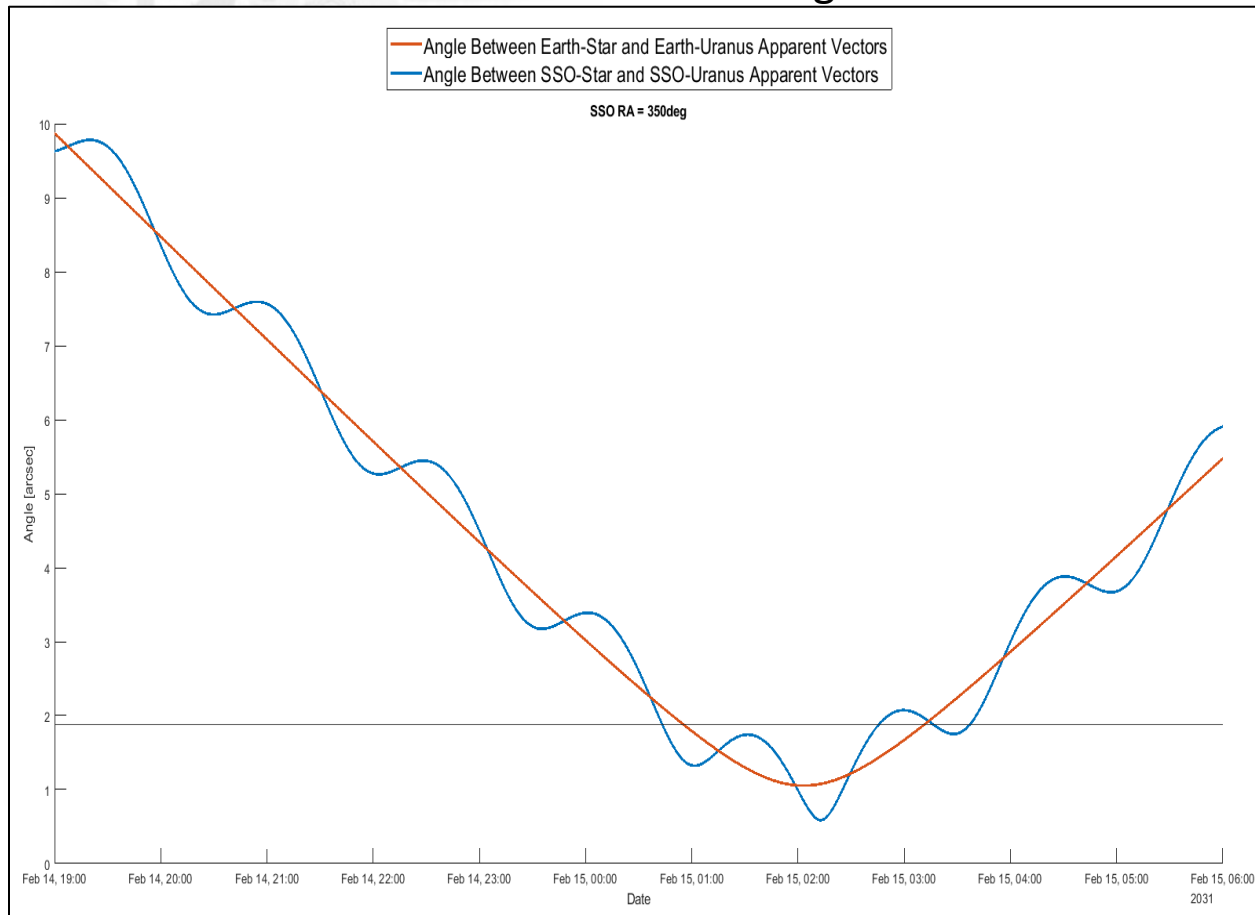
<https://www.spenvis.oma.be/>



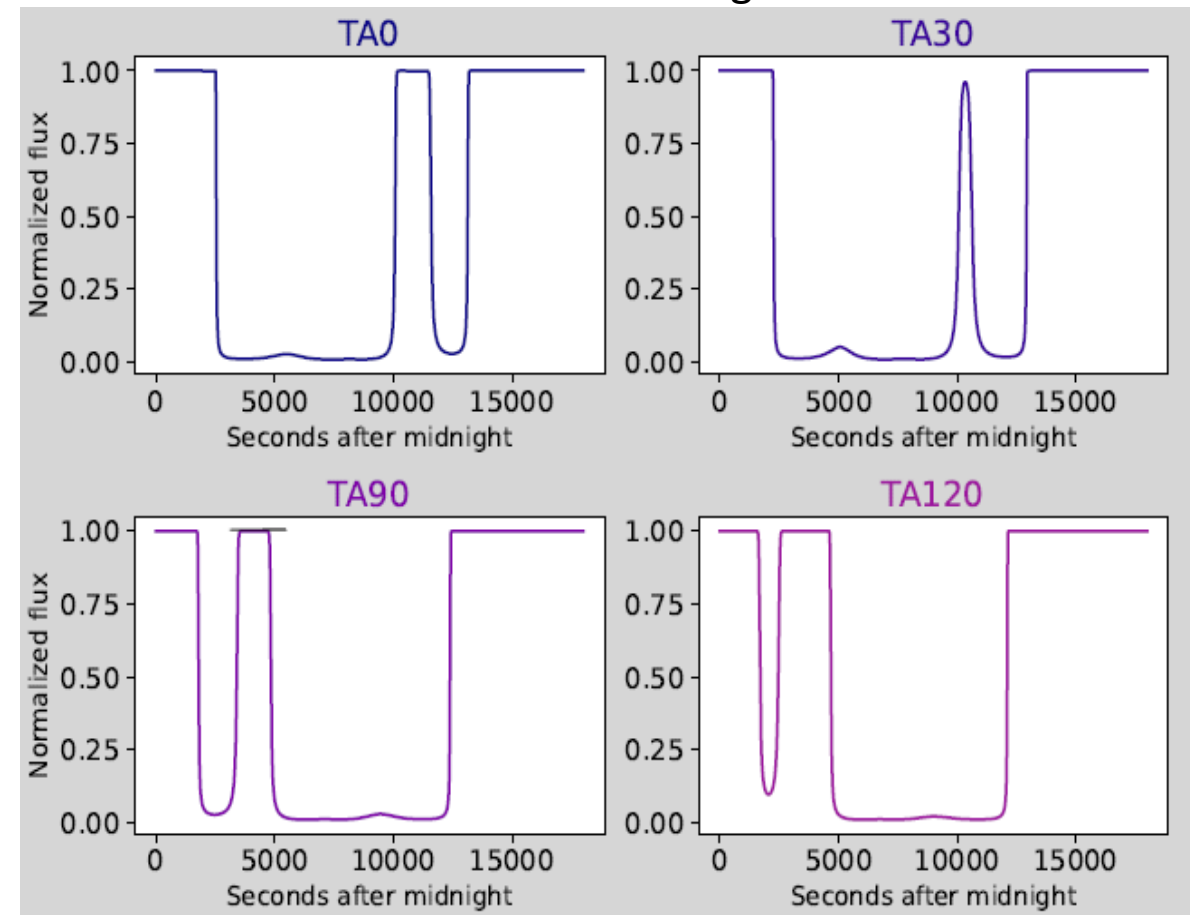
Results/Knowledge Gained (1.3) SSO Multi. Shadow Crossing

- SSO's short orbital period allows SC to enter/leave occ shadow multiple times during a single event and increase value of measurement
- A-train SSO orbit offer excellent visibility of the February 2031 event

Uranus-Observer-star angle vs. time



Simulated Occultation Light Curve



Results/Knowledge Gained (1.4) SSO Event Visibility



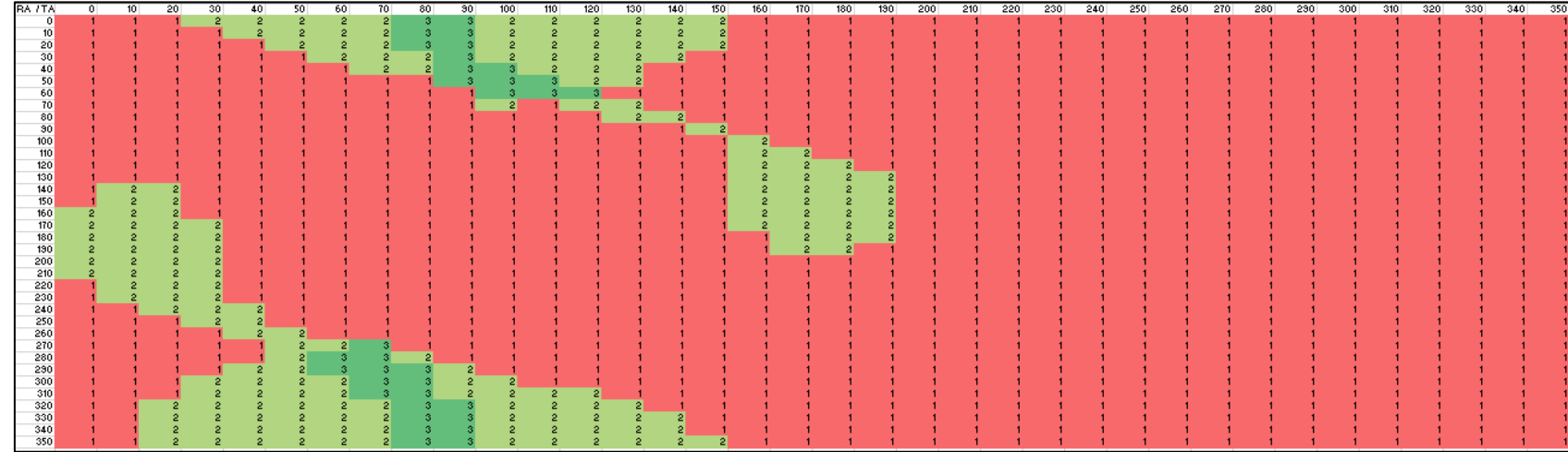
Red = Single Crossing
Light Green = x2 crossings
Dark Green = x3 crossings

Analysis for 600 km SSO

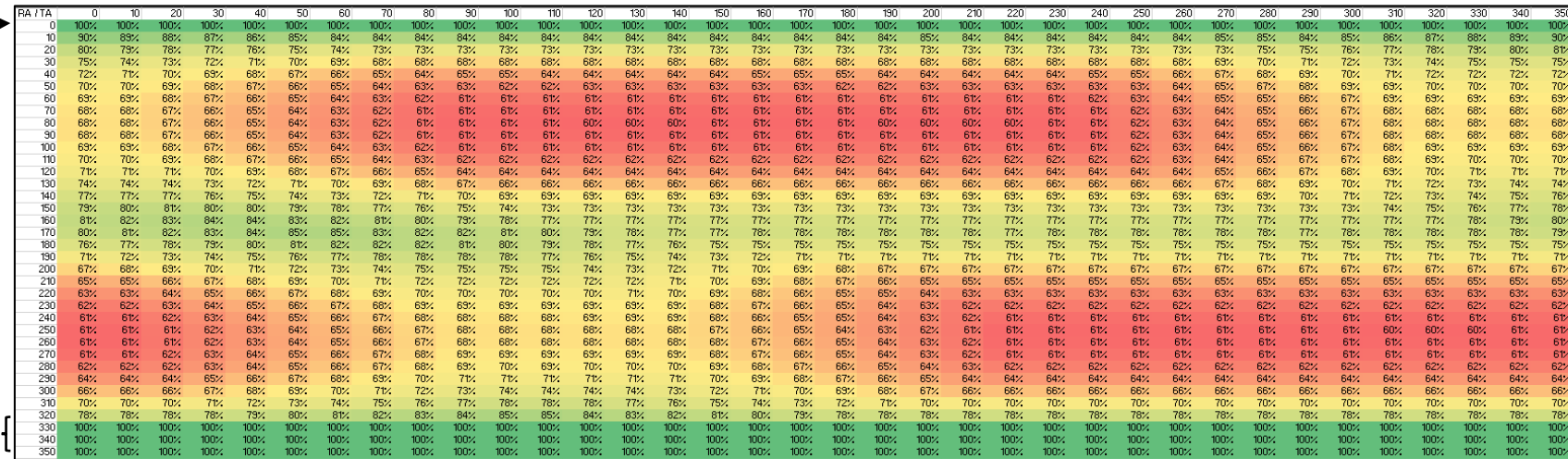
- X axis – true anomaly
- Y axis – right ascension

- Right ascensions with increased visibility also have increased multi-occultation viewing opportunities as expected
- Even with perfect visibility, the orbit must be phased properly to view multiple occultations

Multiple Shadow Crossing



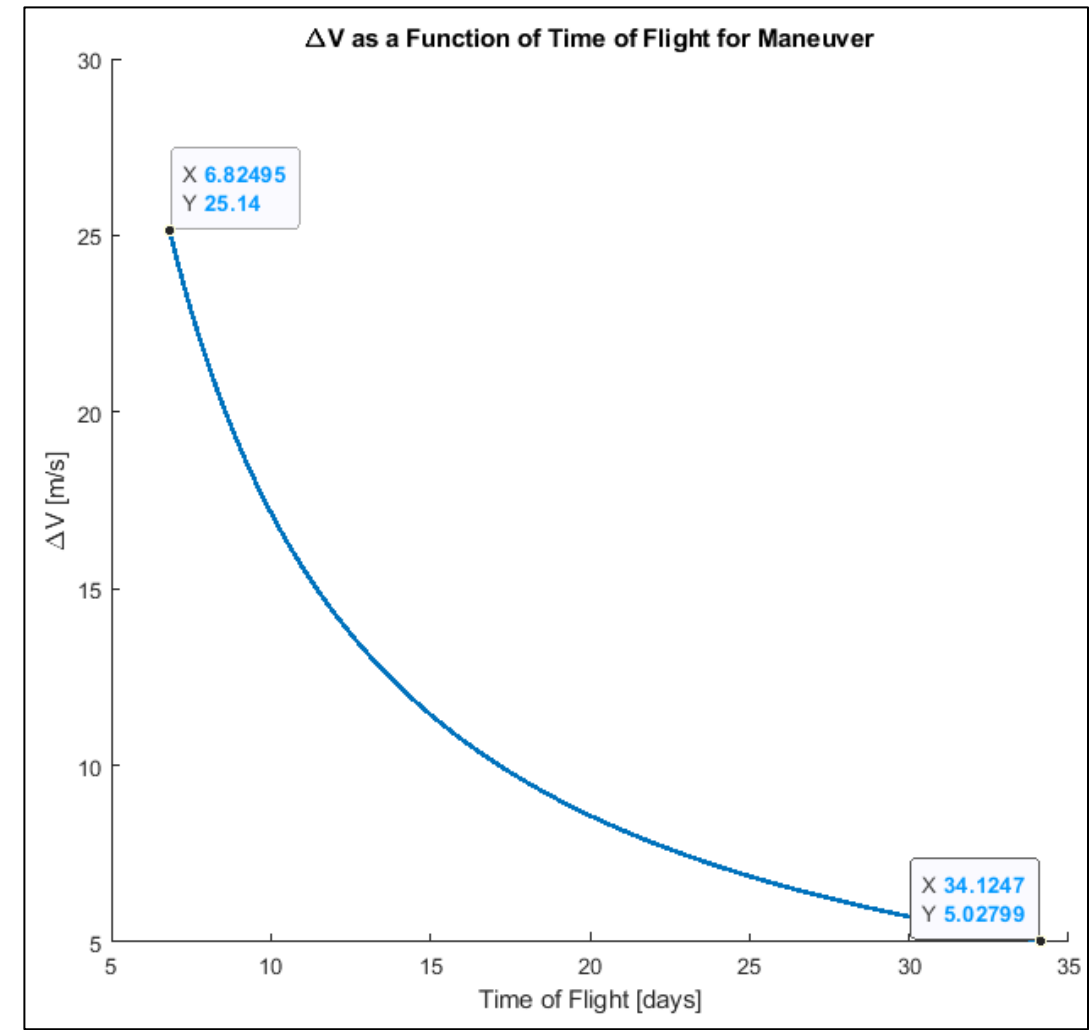
Occultation Visibility during orbit



Results/Knowledge Gained (1.4) SSO delta-V Requirement



- Assuming that >35 days are available for each orbit re-phasing, delta-V for each maneuver is <5 m/s.
- Observing x5 events = 25 m/s
- Assume that natural orbit decay is sufficient to satisfy the de-orbiting requirement.



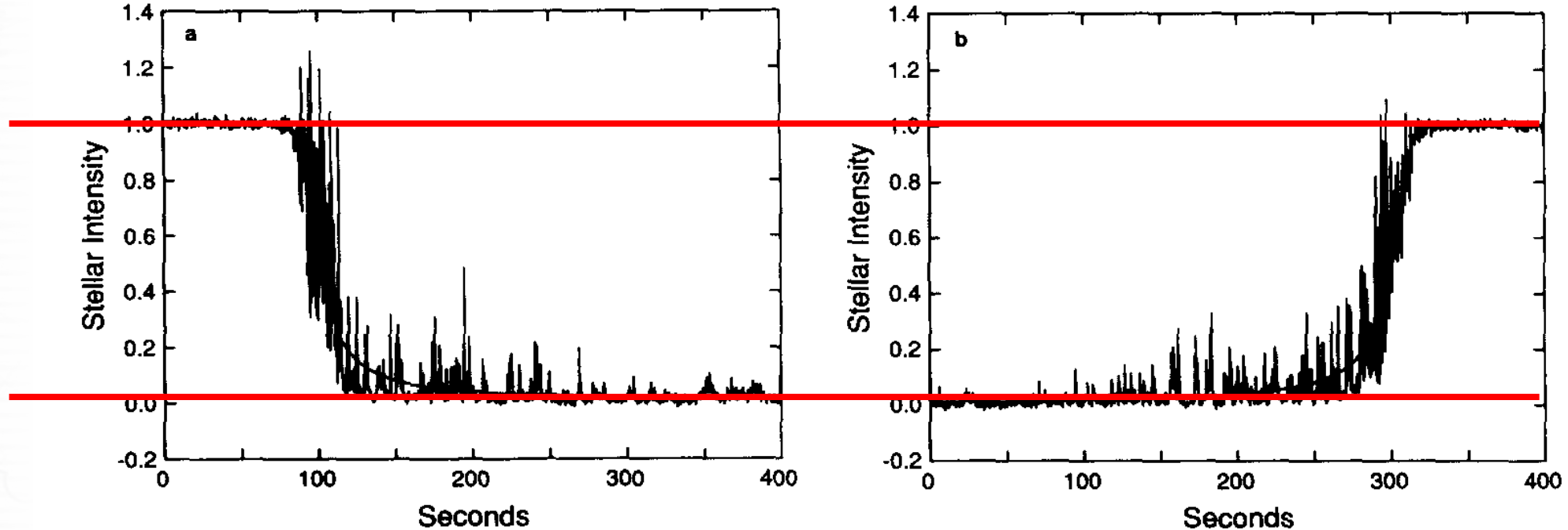
Total Δv required for two burn 180° phasing maneuver,
700km altitude circular orbit

Results/Knowledge Gained (2.1) Detector Sensitivity Challenge



Flux:
Uranus + Star

Uranus Only



Occultation Lightcurve measured by French, Jones and Hyland (1987)

The “Uranus Only” flux is only 10^{-14} W/m², which is $\sim 10^4$ photons m⁻² s⁻¹ in 2 μ m wavelength

- Detecting the flux is a challenge using a small telescope
- Even when the flux is detected, measurement is limited by shot-noise.

Results/Knowledge Gained (2.2) Occultation Sensitivity Study Needed (ongoing)

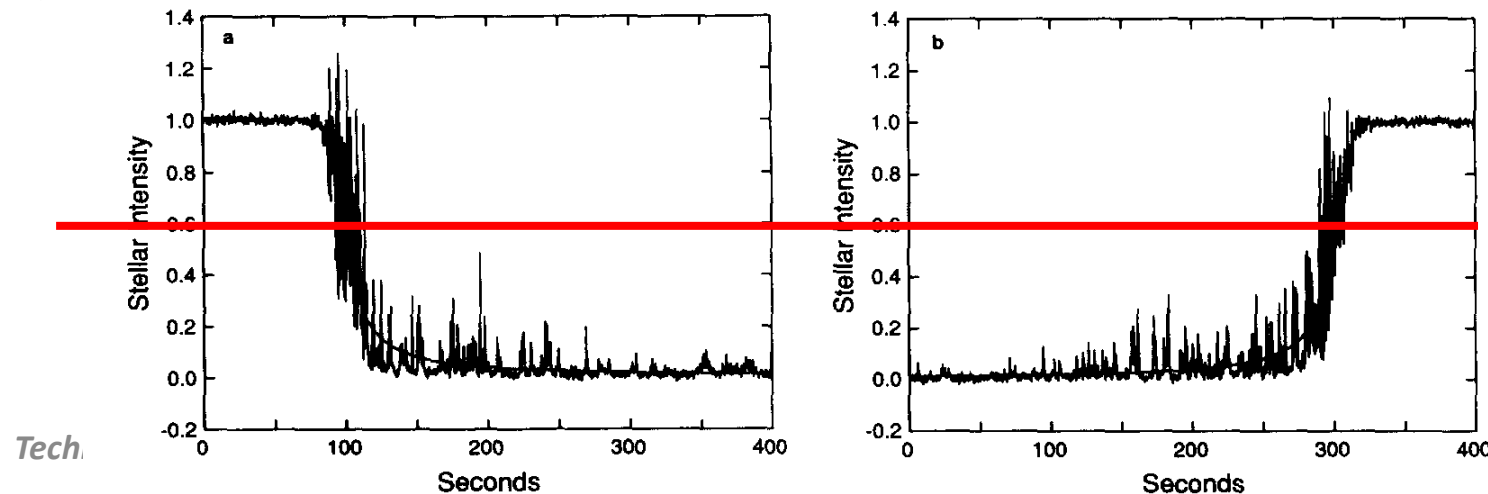


Question: Is detection of “Uranus Only” flux needed to perform T vs. p retrieval?

→ Sensitivity study needed

- Use latest Uranus GRAM profiles as “truth” (generated by Justin Garland)
- Use the Uranus GRAM profiles to perform forward modeling of Stellar Occultation to generate synthetic occultation lightcurve. (Will Saunders)
- Repeat forward modeling with small perturbation to the “truth” (Will Saunders)
- Generate Jacobian matrix for the sensitivity, and test the conjecture that occultation measurements can produce most of the necessary results by measuring the early/late portion of ingress/egress. (John Smith)

Conjecture: Stellar Occultation measurements do not depend on precisely measuring the Uranus-only flux.



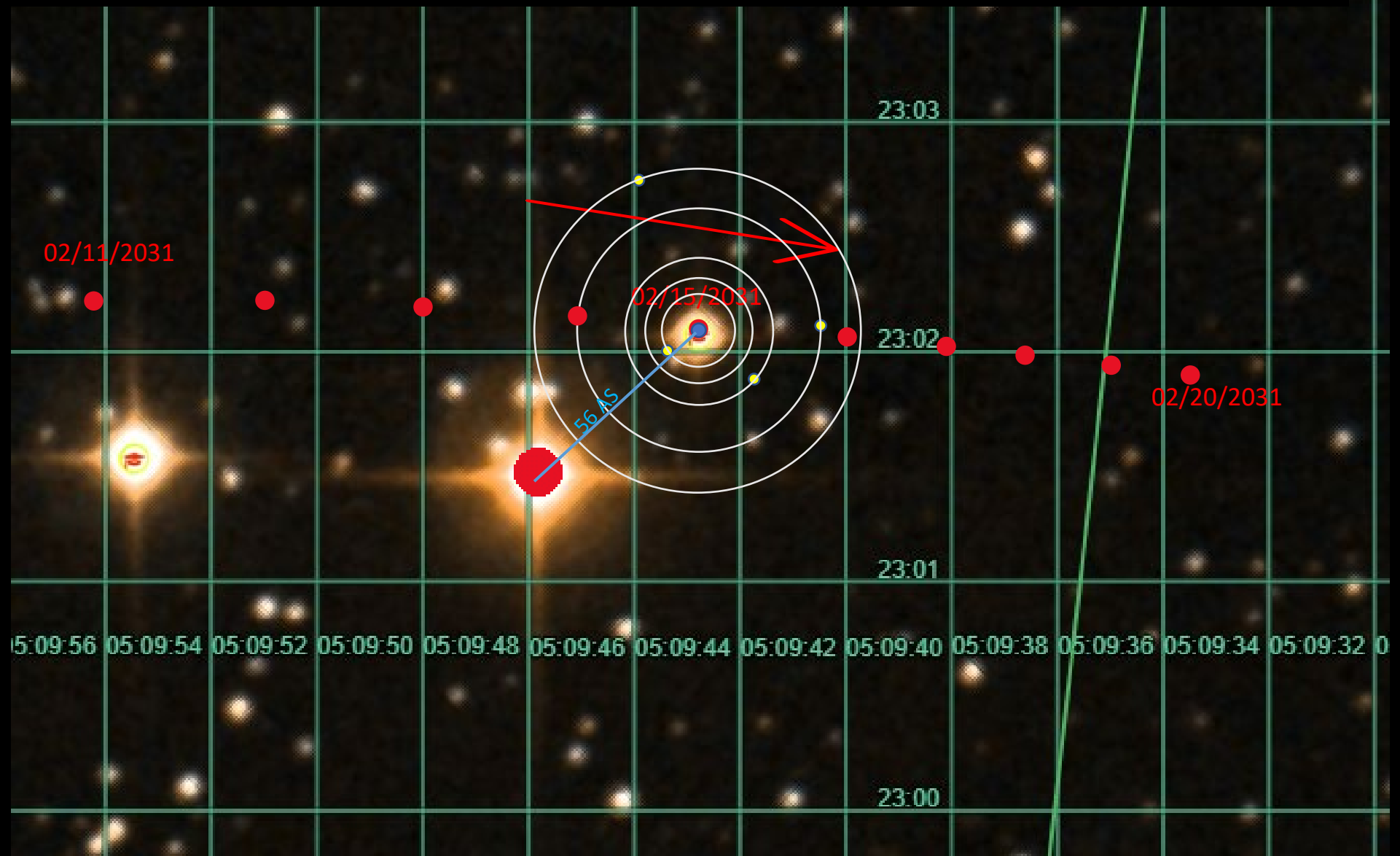
Background / Why this is important

- Shadow Chaser will likely adopt a photodetector rather than an imaging detector
- Photodetector measures the total incoming flux from the field of view, and does not inform what sources are present in the FoV
- We need to predict what objects will be in the FoV during the time of the occultation events, and size the FoV to minimize the flux from undesired sources
- FoV must be small enough that it excludes as many undesirable sources as possible, but must be large enough that sources do not wander in/out of field of view due to factors such as:
 - Orbital motion of Uranian Satellites
 - Spacecraft Pointing stability
- Categories of sources:
 - Star to be occulted (i.e. “signal”)
 - Uranus and its Rings (“noise”)
 - Uranian Moons
 - Other Stars in the background
- **Optimal FoV for Photodetector: 70 arcsec**

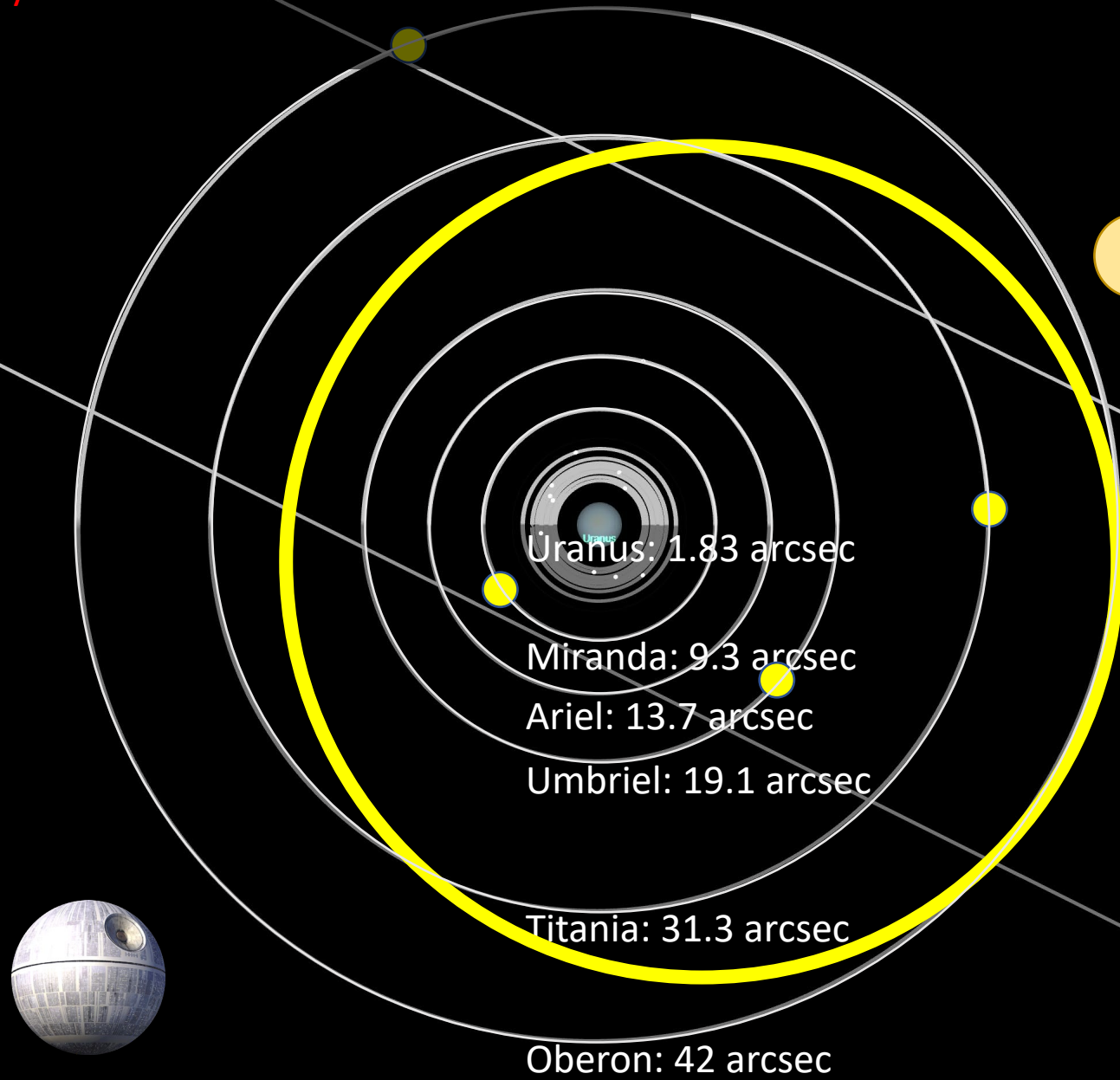
Background Starfield around the 2031-02-15 Uranus Occultation

A bright star exists 56 arcsec away from Uranus and occulted star on 2031-02-15

- Occulted star is 4.2 magnitude in 2-micron K band
- The “death star” (that’s no moon!) is 1.5 mag in 2-micron K band. X12 times brighter!!



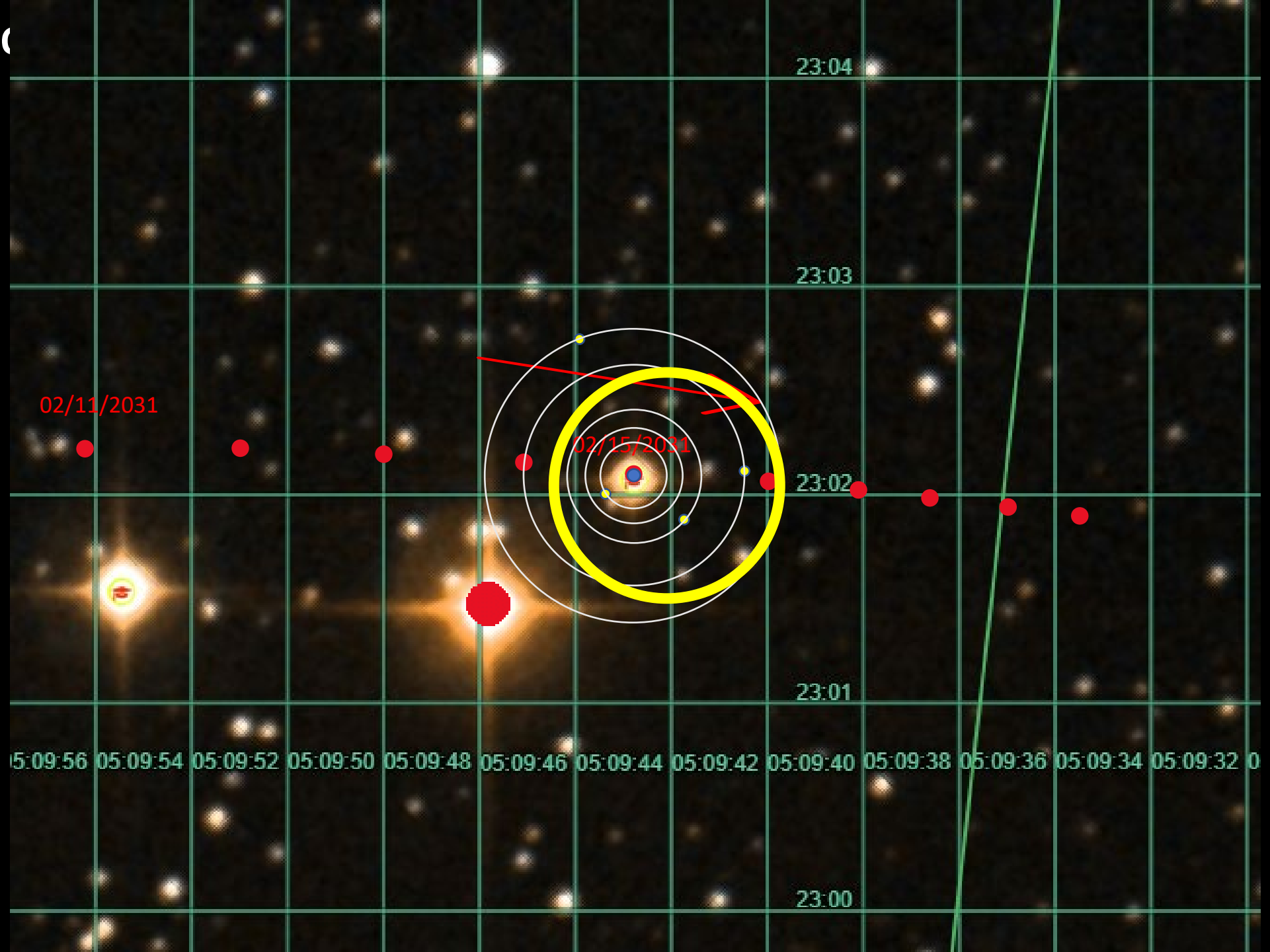
Potential Solution:
FoV 70 arcsec across will safely exclude Oberon and Death Star
during 2031-02-15 Event



Diffraction Limit of a
● 20-cm Aperture:
2.76 arcsec
● 7 arcsec pointing
stability

FOV: 70 arcsec across
Oberon Orb diam: 84 arcsec
Pointing Stability: 7 arcsec
X2 Diffraction limit: 6 arcsec

70 arcsec FO



Results/Knowledge Gained (2.4) Requirement for Optics



- FOV at Detector: 70 arcsec
- Sensor Area: 1 mm x 1 mm (assuming Teledyne PS3-2-71 or PS3-2-81)
- Plate Scale: 70 arcsec/mm
- Plate Scale Equation:

$$\text{PlateScale} = \frac{206265}{D \times f/\#} \text{ (arc sec onds / mm)}$$

- Where D is aperture diameter
- <https://supernova.lbl.gov/~sed/telescope/obsguide/platescale.html>
- If we assume $D = 300 \text{ mm} = 30 \text{ cm}$
- $f/\# = \frac{206265}{D \times \text{PlateScale}} = 9.8$
- (The notional telescope design by Tony Notari has $f/\# 6.0$, which is “in the same ballpark”)

Results/Knowledge Gained (2.4) Notional Optical Design



Preliminary Shadow Chaser Telescope specifications, 0.3 m diameter, F/6:

Material: TBD

Primary mirror

Diameter: 300 mm
Conic: parabola
RoC: 600 mm
Surface roughness: 10 nm rms

Secondary mirror

Diameter: 60 mm
Conic: -1.960
RoC: 120 mm
Obscuration: 5.6 %

Telescope

Focal length: 1800 mm (F/# 6.0)
BFL (from primary vertex): 50 mm
FS diameter: 0.890 mm
Field of View: 500 μ rad (103 arcsec)
Coating: Gold, ~97%R

WFE (total): 10 waves PV (0.6 μ m)
Blur circle 90%EE: 0.045 mm (~25 μ rad)
Focus tolerance: ± 25 μ m
Centration to FS: 1%
Pointing stability: < 1 μ rad

Environment

Operating temps: ??? deg C \\
Survival temps: ???
WFE distortion to vacuum: 100 nm rms

Mirror durability:

Humidity MIL-M-13508C
Temperature MIL-M-13508C
Durability MIL-M-13508C
Adherence MIL-M-13508C
Abrasion MIL-C-675C
Hardness MIL-M-13508C

Optical Workmanship:

Meets MIL-C-675C and MIL-O-13830

Storage

Cleanliness: CL300

Testing

Primary: WFE (hartmann, pentaprism)
Telescope: WFE, blur circle, FS transmission, alignment
Environmental: Thermal, vac
Mechanical: Vib, shock
Coating: Adhesion, durability, λ -shift in vac

Preliminary Shadow Chaser Telescope, 0.3 m diameter, F/6:
Ray-trace and Field stop

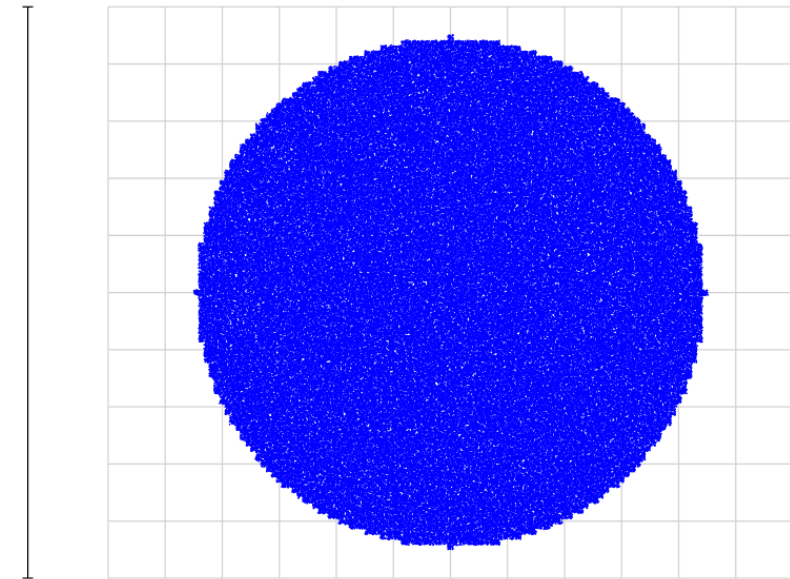
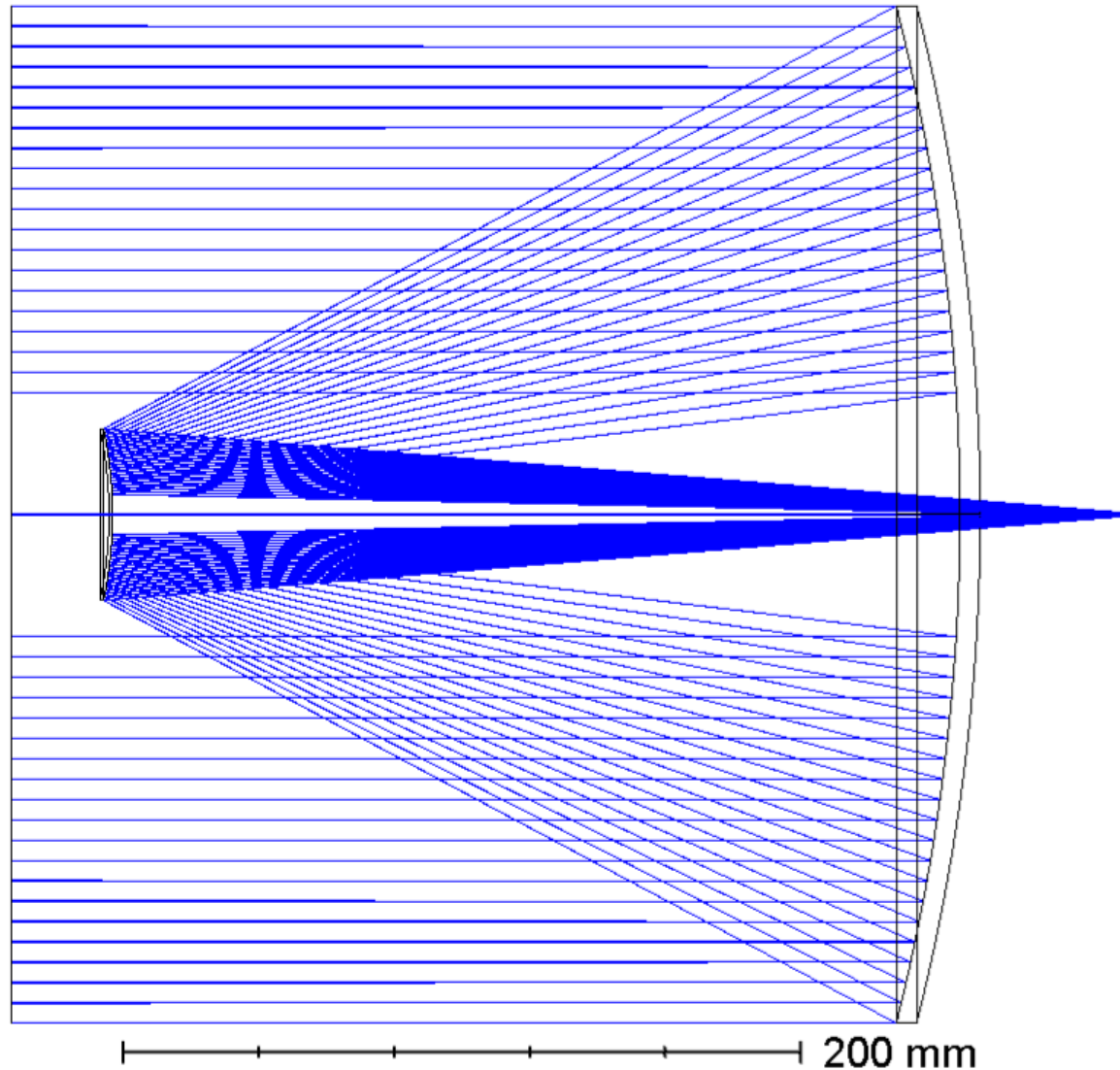
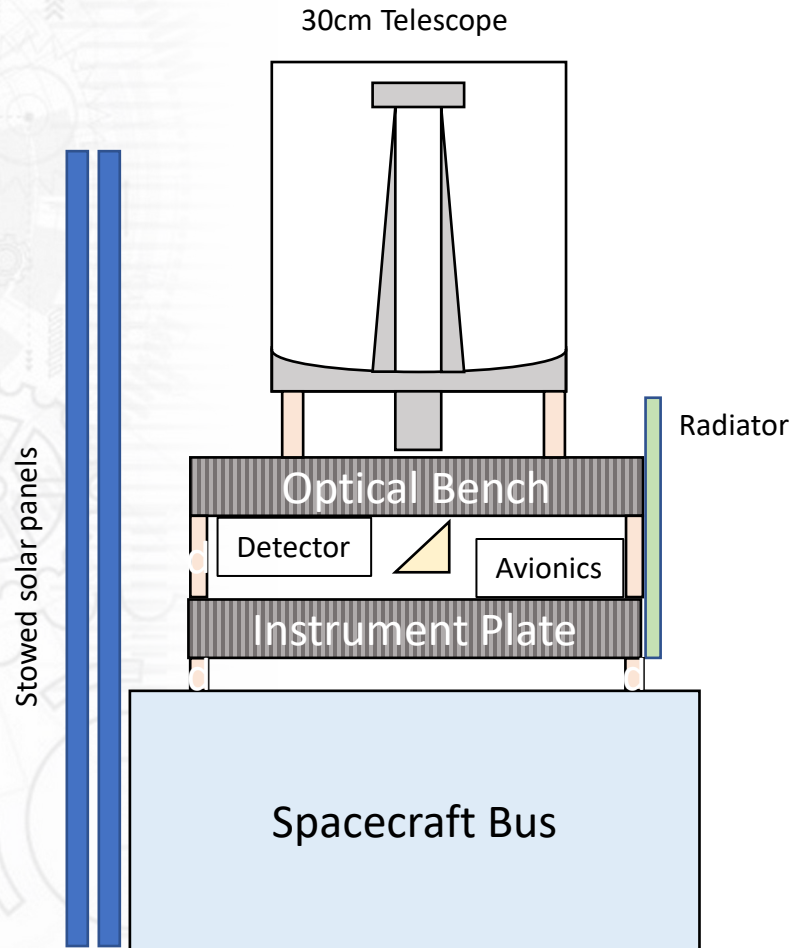


Image Diagram		
SC - telescope 8/23/2023 Scale bar is 1.0000 Millimeters. Field position: 0.0000, 0.0000 (deg) Efficiency : 89.197% Surface: 11		Zemax Zemax OpticStudio 19.4 SP2 SC-telescope.zos Configuration 1 of 1

Image at Field Stop for 500 μ rad FOV
Diameter $\sim$ 0.9 mm
Transmission including obscuration and reflectivity of
Gold mirror coatings = 89.2%

Results/Knowledge Gained (3.1) Notional Bus Layout



**20cm diameter F/10 has
200cm focal length**

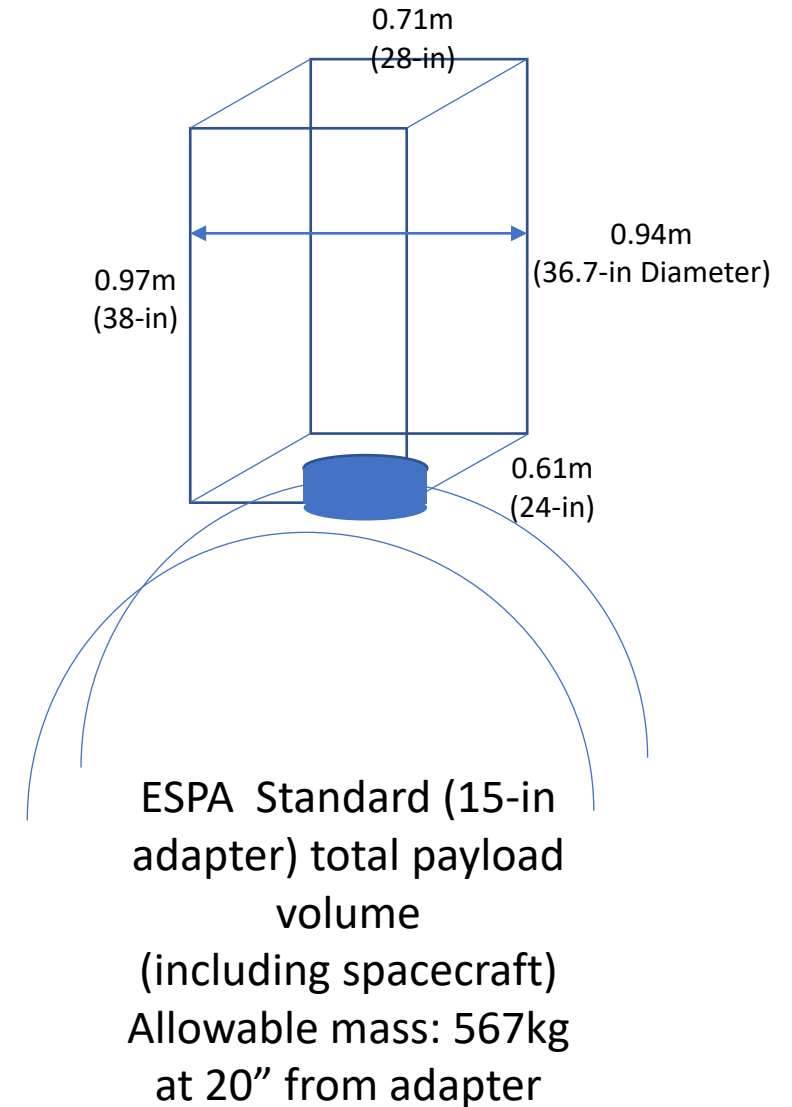
**30cm diameter F/6 has
180cm focal length**

Initial Notional ShadowChaser Instrument Layout

Results/Knowledge Gained (3.2) Launch Vehicle Constraints



- Assuming a 30-cm aperture instrument, ESPA Standard (15-inch adapter) should be adequate for Shadow Chaser
- See backup slides for vendor candidates





Results/Knowledge Gained (3.3) Cost

SSCM Small Satellite Cost Model

Inputs

SmallSat Cost Model (SSCM) Preliminary Results

Technical Parameter	Units	Value	Notes
Programmatic			
Fiscal Year for Estimate	YYYY	2023	
Inflation Methodology	---	NASA	
Development Time	months	60.0	
System			
Destination	---	Earth-Orbiting	
Design Life	months	24.0	
Satellite Wet Mass	kg	180.00	
Satellite Dry Mass	kg		
Spacecraft Bus Dry Mass	kg	52.00	look for clarification on dry mass
Number of Instruments	#		
Power			
Solar Cell Type	---	Gallium Arsenide	
Battery Type	---		
Power Subsystem Mass	kg	14.77	
BOL Power	W	200	
Structure			
Primary Structure Material	---	Composite	
Structure Subsystem Mass	kg	10.00	waiting for more detail
ADCS			
Star Tracker?	---	Yes	
ADCS Subsystem Mass	kg	10.00	
Pointing Control	deg	0.003	
Propulsion			
Monopropellant or Bipropellant?	---	Monopropellant	cost difference?
Propulsion Subsystem Dry Mass	kg	7.06	
TT&C/C&DH			
Communications Band	---		
TT&C/C&DH Subsystem Mass	kg	5.00	
Transmit Power	W	5	
Downlink Data Rate	kbps	500	
Thermal			
Thermal Subsystem Mass	kg	5.00	

Technical Parameter	Range				
	Low	Minimum	Value	Maximum	High
Development Time					
Design Life		0.2	24.0	96.0	
Satellite Dry Mass					
Spacecraft Bus Dry Mass		52.00	52.00	598.00	
Number of Instruments					
Power Subsystem Mass		14.77	14.77	201.00	
BOL Power (Power)		150	200	2200	
BOL Power (Structure)					
BOL Power (Thermal)		81	200	10500	
Structure Subsystem Mass		6.70	10.00	298.00	
ADCS Subsystem Mass		0.60	10.00	103.80	
Pointing Control		0.003	0.003	5.000	
Propulsion Subsystem Dry Mass		7.06	7.06	118.20	
TT&C/C&DH Subsystem Mass		4.70	5.00	115.40	
Transmit Power		1	5	100	
Downlink Data Rate		32	500	150000	
Thermal Subsystem Mass		0.70	5.00	53.00	

- Preliminary Spacecraft Cost: \$15M
 - (Not including instrument)
- Instrument may cost \$40M?
- Launch Cost: \$7M
- Current very rough estimate is about \$62M

	Estimate (FY23\$K)				% of Sub-level	% of Sys-level
	Non-Rec	Rec	Total	Std Error		
Spacecraft Bus Subsystems						
Power	1,802	2,770	4,572	1,715	20.4%	
Structure	880	808	1,688	754	7.5%	
ADCS	2,550	2,805	5,354	1,912	23.8%	
Propulsion	522	1,011	1,534	684	6.8%	
TT&C*	1,351	1,324	2,675	2,959	11.9%	
C&DH*	2,859	2,803	5,661		25.2%	
Thermal	504	466	970	424	4.3%	
Spacecraft Bus	10,467	11,987	22,454	4,070	100%	61.1%
IA&T*	2,346	2,749	5,095	2,896		13.9%
PM/SE	3,306	3,983	7,288	3,914		19.8%
LOOS*	0	1,933	1,933			5.3%
S/C Development & First Unit	16,118	20,651	36,770	6,346		100%

Accomplishments and Issues

Milestones: Accomplished

- For the 2031-02-15 event, a common A-Train SSO orbit offers good visibility
- Quantitatively characterized the challenges of measuring the lightcurve
- Notional Spacecraft Bus configuration drafted
- Rough cost: \$62M
(assuming 30-cm aperture with non-cryogenic detector is sufficient)

Issues

- Next SIMPLEx AO will descope Earth-orbiting concepts
 - March 2023 announcement by SMD descoped Earth-orbiting missions from next SIMPLEx
→ Tech Demo or Directed launch opportunity needed to fly
- Detector Sensitivity poses challenges – ongoing sensitivity study will explore new measurement approaches
- Lesson: Kickoff IDC2 session to identify challenges would have uncovered the detector sensitivity issue earlier in the study

Shadow-Chaser: A Small Satellite Concept to Probe Planetary Atmospheres Using Stellar Occultations

FY23 CIF IRAD Project

Principal Investigator: Cindy Young / Kunio Sayanagi

Annual Funding: \$ 125,000

National Aeronautics and
Space Administration



Problem and Impact to NASA

The Shadow Chaser smallsat mission will measure the middle+upper atmospheric temperatures of Uranus and Neptune through stellar occultation (SO) method from Earth orbit.

Address the Planetary Decadal Survey Priority Question "Q7. Giant planet structure and evolution: What processes influence the structure, evolution, and dynamics of giant planet interiors, atmospheres, and magnetospheres?"

Tackles the scientific needs to understand the unexpectedly hot but highly uncertain upper atmospheric temperatures of Uranus and Neptune found by Voyager 2, termed the "thermospheric energy crisis."

SO measurements from ground are unlikely to resolve the thermospheric energy crisis.



Goal/Objective

To develop a SmallSat mission concept to observe multiple SO events that could fit in an ~\$80M SIMPLEx-class budget.

Objectives for FY23:

- Determine orbit
- Determine radiation effects on spacecraft
- Determine delta-V requirements
- Design instrument
- Design spacecraft bus

Strategic Motivation:

- This project has the potential to open more doors for small satellites and LaRC in the planetary science market.



Innovation

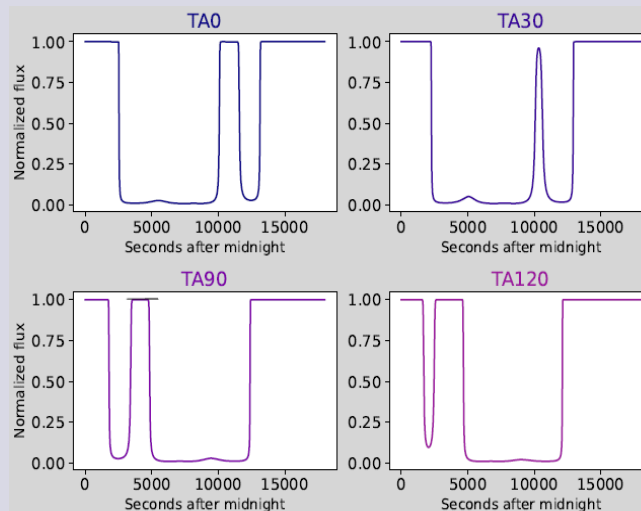
Our project will develop a small satellite mission concept that will make stellar occultation measurements from Earth orbit.

New Research & Development during FY23:

- Goal 1: Determine orbits that enable targeting multiple predicted events
- Goal 2: Determine the instrument telescope size and detector
- Goal 3: Design spacecraft bus that satisfy delta-V and payload requirements

February 15, 2031 Simulated Measurement of Uranus occultation

- Duration: 86.3 minutes
- 700km altitude SSO orbit
- Spacecraft dips in/out of occultation shadow twice in this configuration



Technical Approach

Determine orbit optimized for science measurements

- Using simulation tool developed in FY22

Determine radiation effects

- Performed by high school intern using open access tools

Determine delta-V requirements

- Using simulation tool developed in FY22

Design instrument

- Define trade space in spacecraft bus design

Design Spacecraft Bus

- Define trade space in spacecraft bus design

Partnerships:

William R. Saunders (Boston University)

Michael J. Person (MIT)

Paul Withers (Boston University)



Key Milestones/Deliverables

End of Year Deliverables

- A-Train SSO orbit offers good visibility of 2031-02-15 event
- Characterized the challenges of measuring the lightcurve
- Notional Spacecraft Bus configuration drafted
- Rough cost: \$62M
(assuming 30-cm aperture with non-cryogenic detector)

Next Steps:

- Characterize measurement sensitivity
- Refine instrument design
- Primary Tech Area: TX08.2

Shadow-Chaser: A Small Satellite Concept to Probe Planetary Atmospheres Using Stellar Occultations

FY23 CIF IRAD Project

Principal Investigator: Cindy Young / Kunio Sayanagi

Annual Funding: \$ 125,000

National Aeronautics and
Space Administration



Description and Customer

- **Concept:** Measure upper atmos structure of Uranus and Neptune from Earth Orbit from SmallSat using Stellar Occultation Technique
- **Opportunity:** High-quality Uranus event on 2031-02-15
- **Customer:** Uranus Orbiter and Probe (UOP) Stakeholders -- Reducing upper atmospheric uncertainty alleviate risk of future aerocapture maneuver for Uranus Orbiter and Probe (UOP) that should arrive Uranus by 2049

Partnership / Alignment

- **Partnership:** SMD/PSD – aerocapture enables faster interplanetary transfer to Uranus, and allow UOP to be launched later and still arrive Uranus by 2049, which may alleviate budget pressure
- **Partnership:** Science Community – advocate for the need to arrive Uranus sooner than possible using non-aerocapture orbit insertion options
- **Partnership:** Stellar Occultation measurement SMEs, e.g. Mike Person (MIT), Will Saunders (Boston U)

Scope, Resources and Risks

- **Scope:** Mission Design, Development & Management
- **Resources:** Mission and Instrument Design capabilities in ED and RD
- **Risk:** Whether Shadow Chaser can improve upper atmospheric uncertainty to sufficiently reduce aerocapture risks remains unproven
- **Risk:** If UOP does not incorporate aerocapture, Shadow Chaser is not needed

Actions Required

- **Mature Concept:** Measurement technique and instrument design require further development
- **Demonstrate Benefit:** Quantify anticipated benefit of Shadow Chaser to aerocapture design
- **Need flight opportunity:** Pursue Tech Demo or Directed opportunity – Originally targeted SIMPLEx, but the next AO will only solicit concepts for to be launched with DAVINCI, not compatible with Shadow Chaser.
- **Nurture/Recruit SMEs:** Stellar Occultation measurement expertise is rare; Need to nurture/recruit SMEs



BACKUP MATERIALS

Shadow Chaser



a SmallSat concept to determine the middle and upper atmospheric structures of Uranus and Neptune through stellar-occultation measurements from Earth orbit

Kunio M. Sayanagi (NASA Langley Research Center)

**Team: Cindy Young, Jonathan Chrono, Katherine McBrayer, Vianni Ricano Cadenas, Joshua Carden (NASA Langley Research Center)
William R. Saunders, Paul Withers (Boston University)
Michael J. Person, (Massachusetts Institute of Technology)
Madison Hanrahan (Deep Creek High School, Chesapeake, VA)**

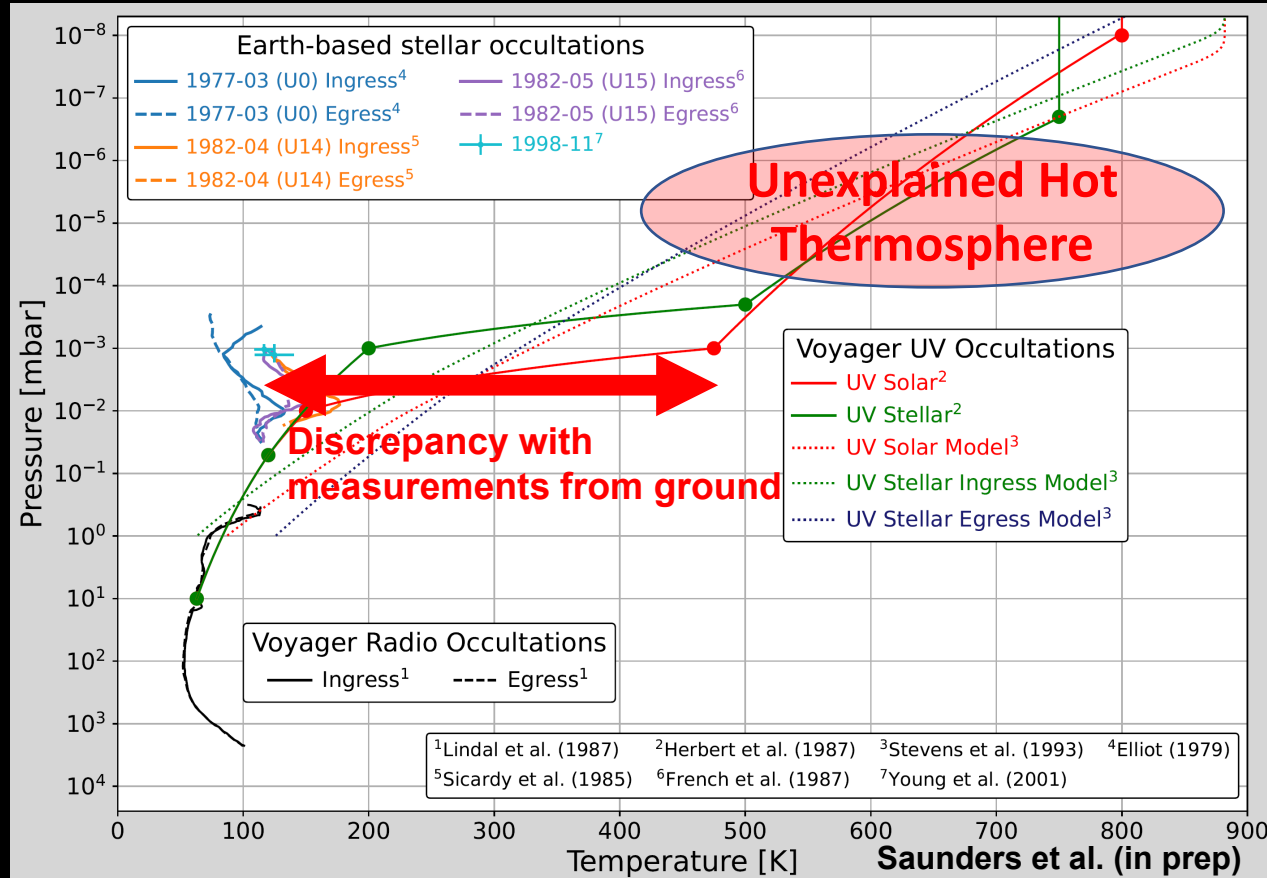
AGU Fall Meeting: December 16, 2022

Need to Characterize Mid/Upper Atmospheres of Uranus and Neptune

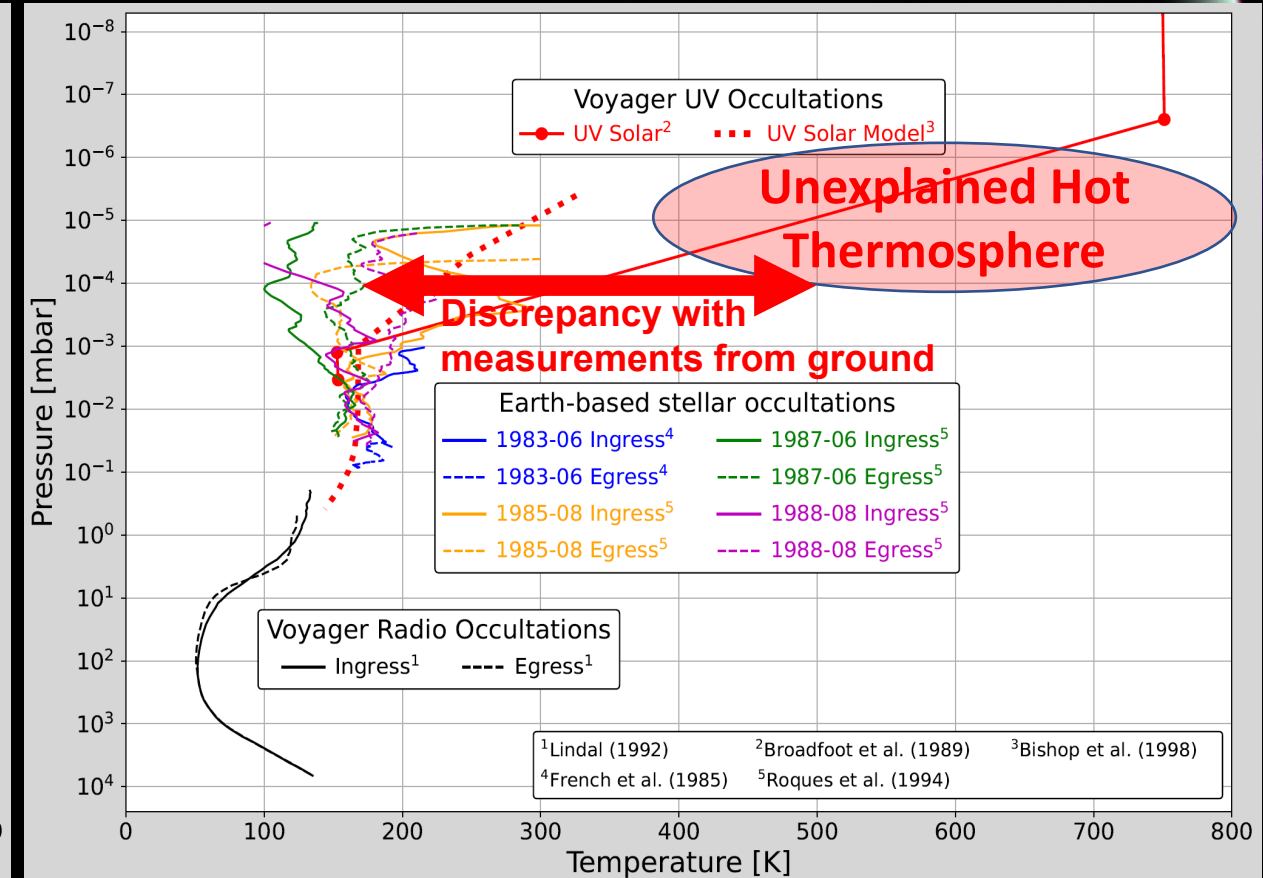
- Highly uncertain hot thermospheres measurements by Voyager 2 are inconsistent with theories
- Ground-based measurements show cooler thermosphere, but also hampered by Earth atmosphere
- Also see poster: W. Saunders P32E-1860 - Uranus' Lower Thermosphere is Cooler than Previously Thought

→ Space-based measurements required

Uranus



Neptune





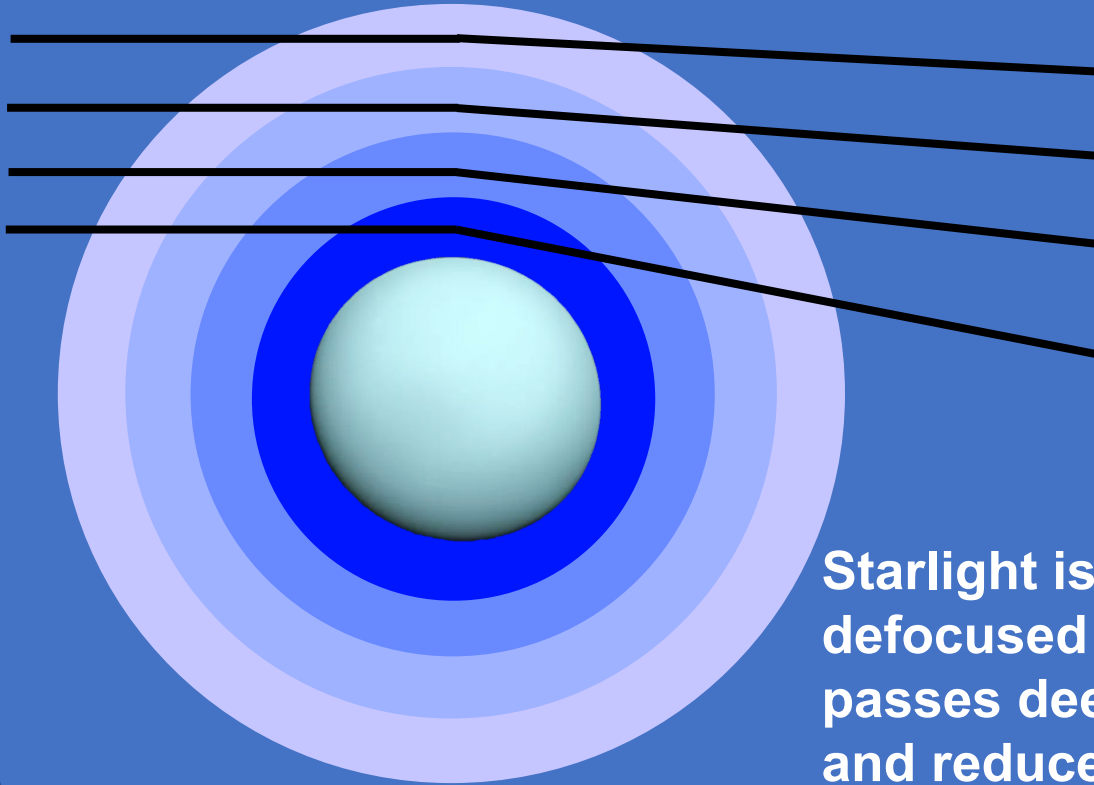
Shadow Chaser: a Stellar Occultation Mission

- Measure the middle and upper atmospheric temperature and density of Uranus and Neptune through stellar occultation (SO) technique from Earth orbit.



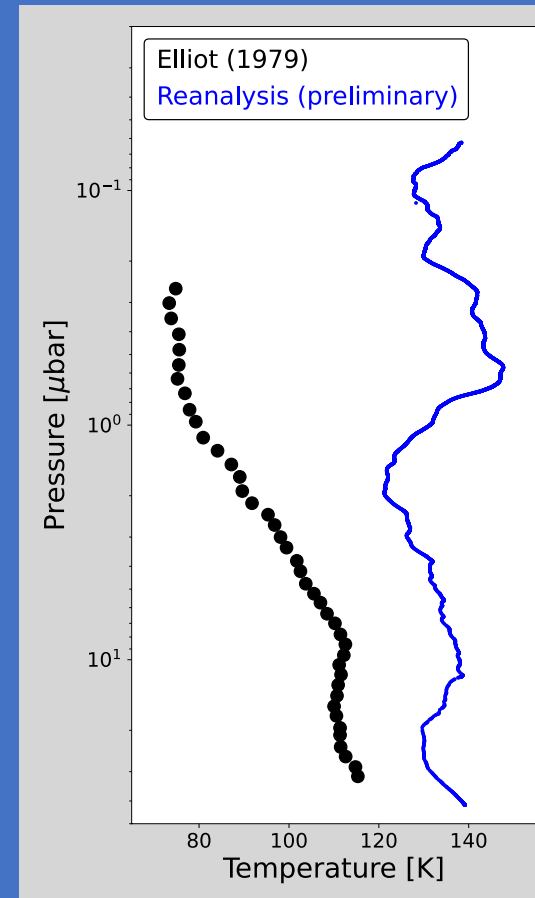
Stellar Occultation Measurement Method

Light path is refracted while the star goes behind the planet (i.e. “ingress”) and when the star re-emerges (“egress”)



Starlight is refractively defocused when it passes deeper layers, and reduces intensity seen from (near) Earth.

Solve an inverse problem: temperature, pressure, number density





Shadow Chaser: Science Goals and Objectives

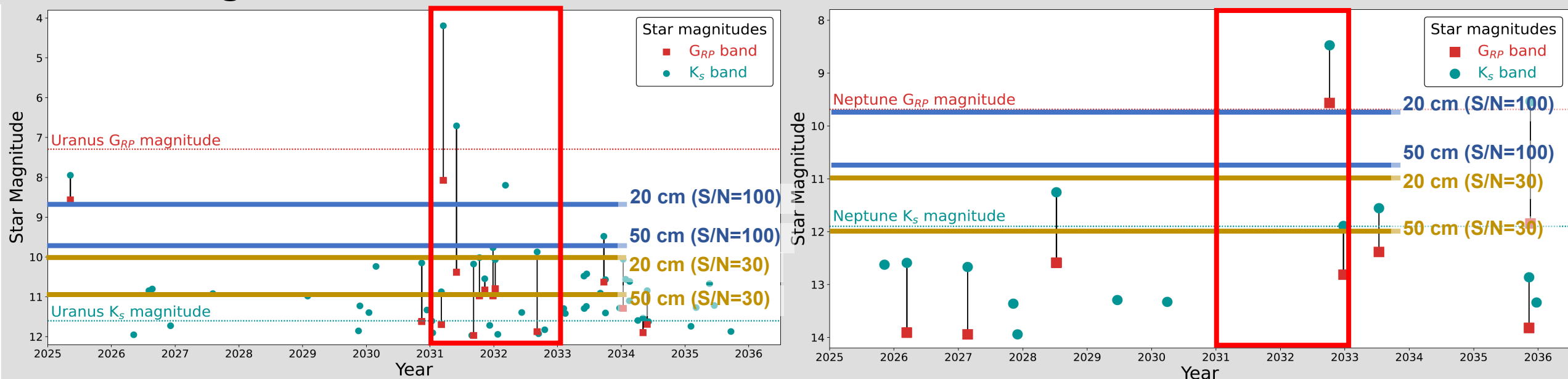
- Goal: Understand Energy Balance in the Upper Atmospheres of Uranus and Neptune
- Science Objectives:
 1. Definitively measure the upper atmospheric temperature and pressure as a function of altitude
 2. Determine the latitudinal structure of Uranus and Neptune's upper atmosphere
 - Need multiple Occultations to sample multiple latitudes
 3. Characterize seasonal variabilities in the upper atmospheres of Uranus and Neptune
 - Need multiple occultations sampling Northern & Southern hemispheres
- Reduce design margins of future Aerocapture Missions to Uranus and Neptune
- Opportunity: SIMPLEx
- Decadal Survey Relevance:

Address the Planetary Decadal Survey Priority Question “Q7. Giant planet structure and evolution: What processes influence the structure, evolution, and dynamics of giant planet interiors, atmospheres, and magnetospheres?”

Stellar Occultation Predictions

- Predicted 56 Uranus and 14 Neptune Occultations between 2025-2035
- 20 Uranus and 6 Neptune occultations are observable from the ground
→ Demonstrated the value of future orbital mission
- Instrument Requirement: Threshold aperture size of 20 cm to measure vertical structure
- 2031-2033 period has multiple viable SO events
- Published as Saunders et al (2022, Planetary and Space Science)

Magnitudes of occulted stars for Predicted SO events in 2025-2035

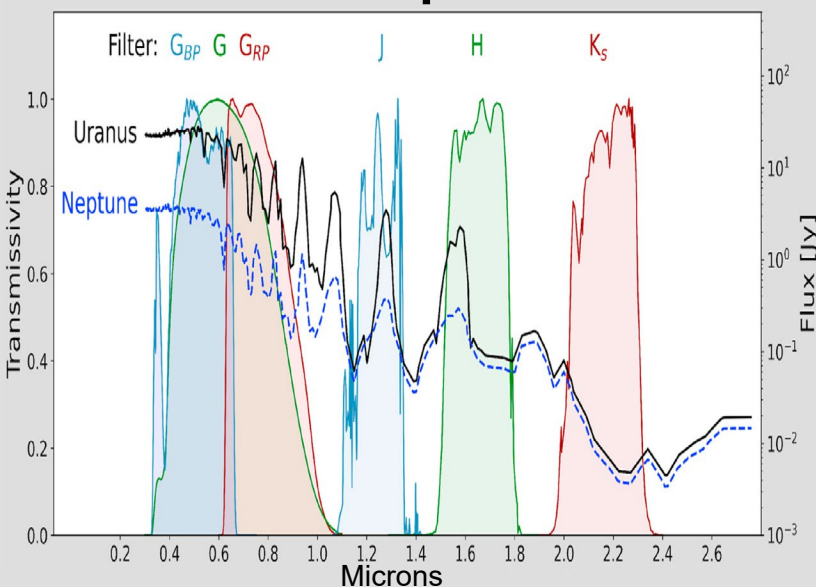


(Saunders et al. 2022, Planetary and Space Science)

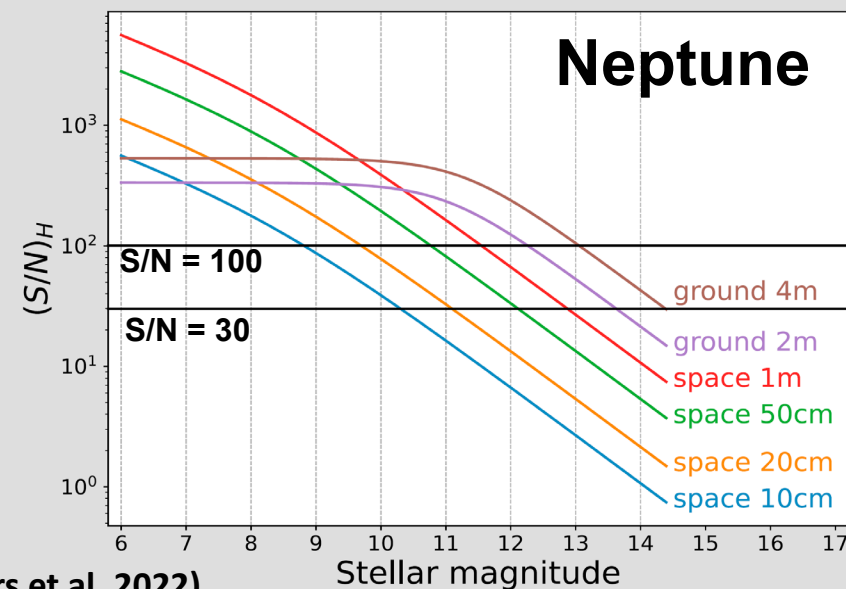
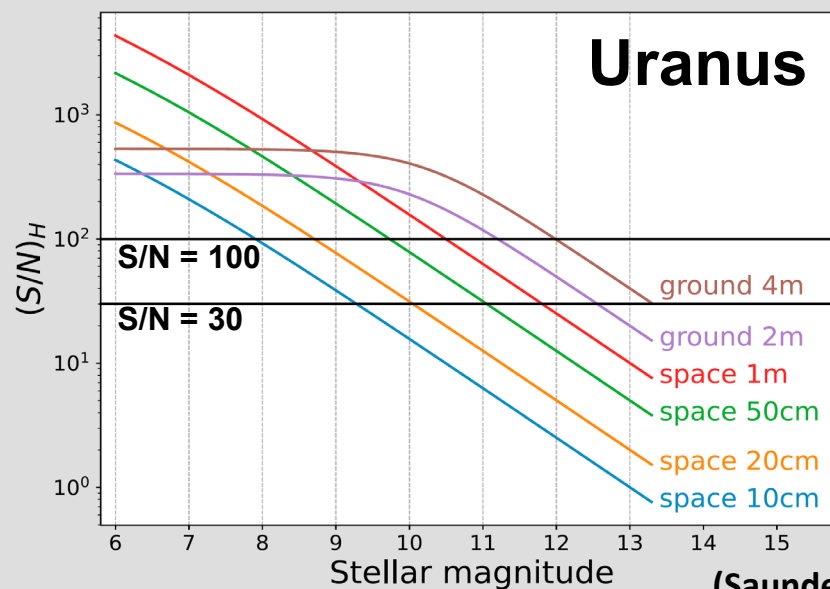
Instrument Requirements

- Observing in 2.2-micron Ks band reduces the noise from Uranus/Neptune.
- $S/N > 100$ is needed to retrieve atmos. structure w/ 1 scale height vert. resolution
- $S/N > 30$ is needed to retrieve average temperature of upper atmos.
- Best SO events have 4-9th mag stars for Uranus, and 9-12th mag for Neptune
- S/N Analysis for 20-cm aperture in space: 6th-mag SO could achieve higher S/N than 4m-aperture on the ground for both U&N
- For 10th-mag SO, 50-cm aperture in space is needed to achieve $S/N > 100$

Uranus + Neptune Flux



Comparison of SO S/N for space & ground telescopes



(Saunders et al. 2022)



Stellar Occultation Orbital Observation Modeling

- Each SO-event often requires >1-hour observing time
→ 90-minute Low-Earth Orbit (LEO) does not work
- GTO-like Orbits allow stable viewing geometry

February 15, 2031 Uranus Event

- Duration: 86.3 minutes
- S/N = 1983.5 (20 cm aperture in Ks band)

February 6, 2032 Uranus Event

- Duration: 38.8 minutes
- S/N = 205.7 (20 cm aperture in Ks band)



Delta-V Requirements

Assumption:

Spacecraft is delivered to a 12-hour Geosynchronous Transfer Orbit (GTO) through ride-share opportunity

Observations should happen around GTO apoapsis.

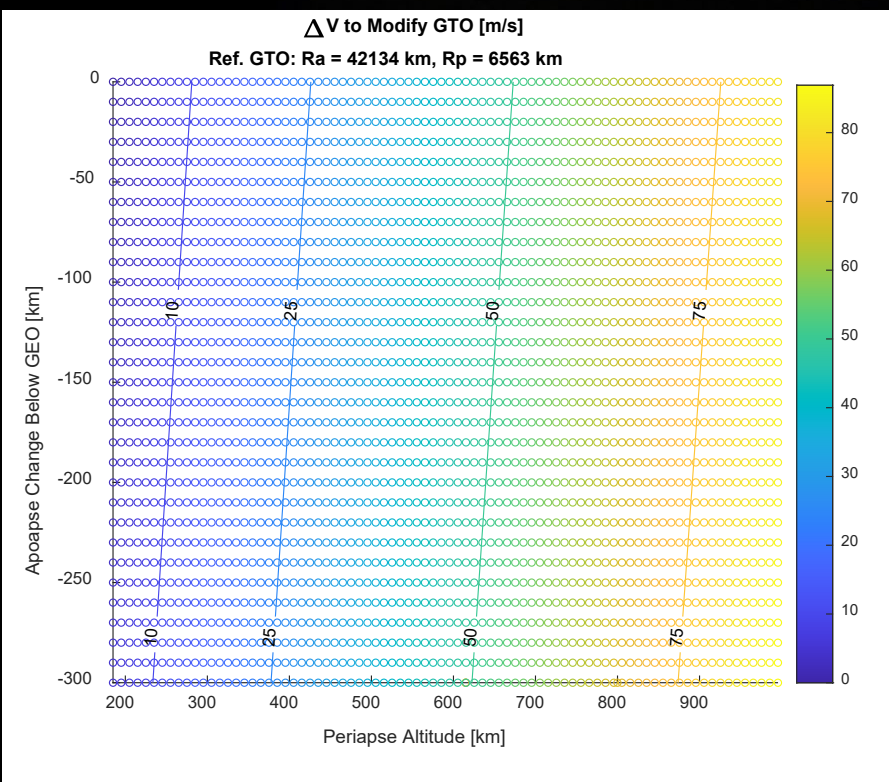
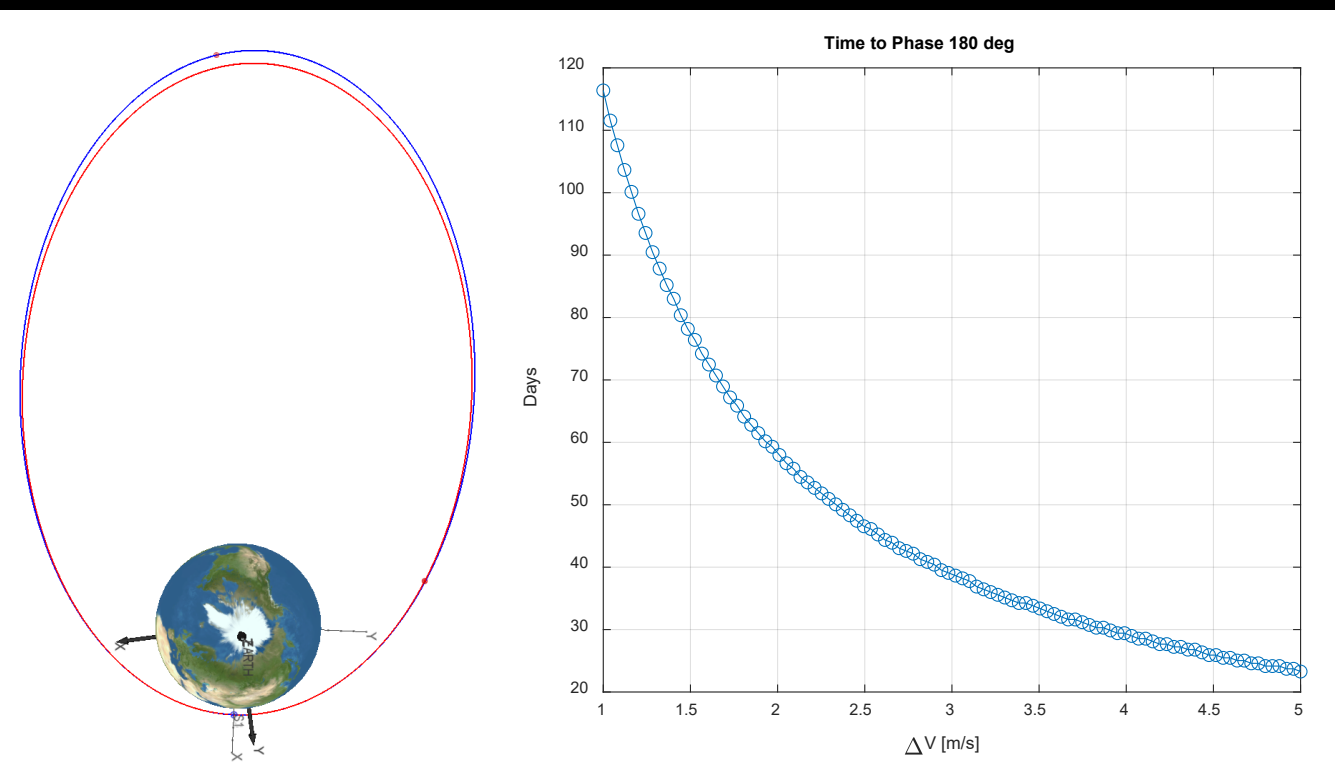
→ Orbital phase needs to be adjusted

→ Delta-V of 5 m/s is sufficient for each event

Total Mission Delta-V estimate after GTO insertion

- Raise periapsis to 800 km: 63 m/s
- Lower apoapsis to 300 km below GEO: 5 m/s
- Phase adjustment: 5 m/s per event x5 = 25 m/s
- Deorbit: 63 m/s

Total Delta-V Requirement = 156 m/s



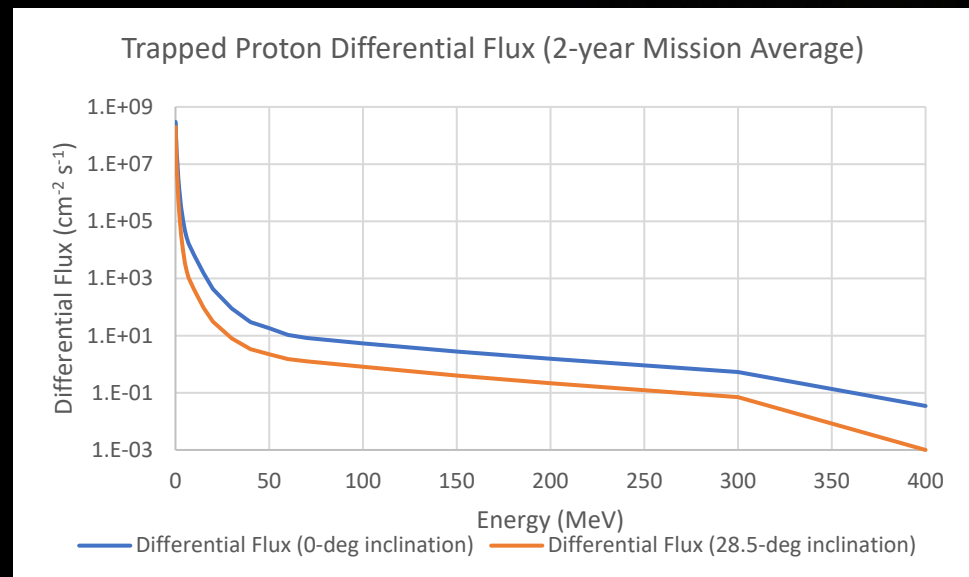
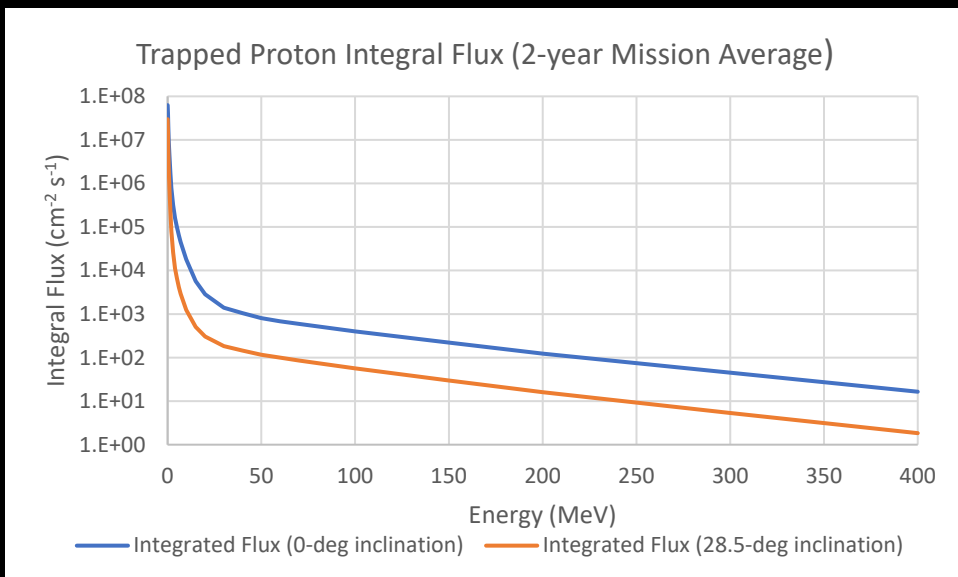
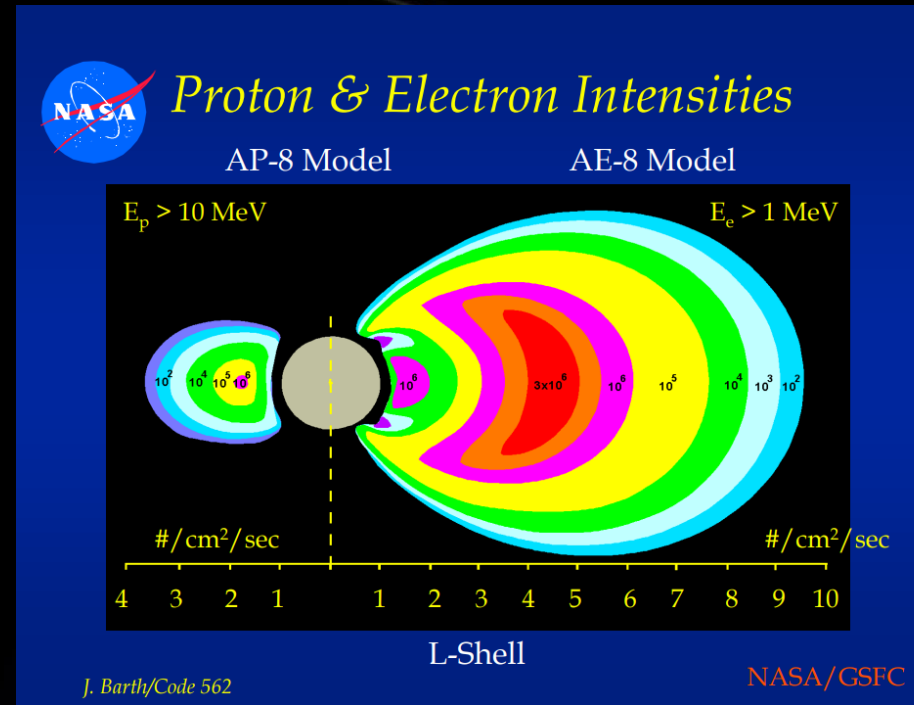
Radiation Environment

GTO goes through Van Allen radiation belt

→ Radiation mitigation may be needed

- GTO can have:
 - 28.5-deg inclination (KSC launch before plane change maneuver)
 - 0-deg inclination (after plane change maneuver)

Higher-inclination GTO receives lower radiation exposure



Calculated using
the SPENVIS tool
<https://www.spENVIS.oma.be/>



Shadow Chaser Mission Concept: Summary

- Stellar Occultation Measurements of Uranus and Neptune's Upper & Middle Atmospheric Structures
- Many Stellar Occultation Events exist in 2025-2035
- Notional mission duration: 2 years
→ 2031-3033 window covers many events!
- SmallSat Ride-share on GTO launch enables transformational measurements
- Aperture Size Requirement: 20 cm
- Mission Delta-V requirement: 156 m/s (for 5 events)
- Reduce risks to *Future Aerocapture Missions* to Uranus and Neptune
- Targeting next SIMPLEX AO

Take-home message:

**High-value Outer Planets Measurements are possible
from a SIMPLEX-class SmallSats in Earth orbit**

Also see poster by W. Saunders et al.:
P32E-1860 - Uranus' Lower Thermosphere is Cooler than Previously Thought



INTEGRATED DESIGN &
COLLABORATION CENTER



IDC² Study Session: Shadow Chaser Mission: Point Design Session Dates: August 21st – 24th

Kunio Sayanagi, Principal Investigator
Andrew Hunt, Facilitator



What is the IDC²



The IDC² is an incubator for concepts, technical maturation, missions, and structured ideation in a facilitated collaborative environment.

- Provides Facilitation, Coordination, and access to Subject Matter Experts matrixed from disciplines across LaRC
- Design space configured for optimal collaboration across different medias
- Efficient use of time and resources maximizing uninterrupted team focus
- Customer determines design goals, participates throughout the process, and helps define the products
- Inclusive of all organizations within NASA and our partners

The graphic is a vertical rectangular poster for the IDC² Integrated Design & Collaboration Center. At the top, it features the NASA logo and the IDC² logo, followed by the text 'INTEGRATED DESIGN & COLLABORATION CENTER'. Below this, there are three diamond-shaped images: the first shows a group of people in a meeting room, the second shows two people looking at a screen, and the third shows a person presenting to a group. The text 'Vision | The IDC² is an incubator for concepts, technical maturation, missions, and other structured ideation in a facilitated collaborative environment.' is followed by 'Objective | The IDC² facilitates rapid development utilizing an integrated approach with dedicated uninterrupted focus from Subject Matter Experts.' and 'New IDC² Model | Broadens the application of the IDC² sessions to include technical, programmatic, and organizational concept elements.' A large orange circle on the right contains the text 'FREE! in FY23'. At the bottom, it says 'The future of Design, Development, and Innovation begins at the NASA Langley IDC²!' and includes a QR code, the text 'Schedule a Session https://eds.larc.nasa.gov/', and the contact information 'Lisa Rippy: lisa.o.rippy@nasa.gov'.

FREE! in FY23

Schedule a Session
<https://eds.larc.nasa.gov/>
Lisa Rippy: lisa.o.rippy@nasa.gov

What is Shadow Chaser?



Shadow Chaser: A Stellar Occultation Mission

Shadow Chaser Description: Shadow Chaser is a SmallSat concept to measure the upper atmospheric structure of Uranus and Neptune from Earth orbit using the stellar occultation technique.

Shadow Chaser Science Objectives: Definitively measure the upper atmosphere temperature and pressure vs altitude. Determine the latitudinal structure of Uranus and Neptune's upper atmosphere.

Shadow Chaser IDC² Goals: Initial point-design of spacecraft bus and the mission from launch, science orbit insertion, science operation, and disposal. Understand the Earth Balance in the Upper Atmosphere of Uranus and Neptune

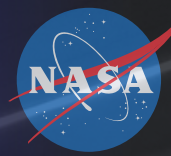
Shadow Chaser SME list



Shadow Chaser Mission: Point Design
IDC2 Session Dates: August 21st – 24th

SME List	Organization	Personnel	Contact
Principal Investigator, Customer	E302	Kunio Sayanagi	kunio.m.sayanagi@nasa.gov
LSE/CE	D208	Tory Scola	Salvatore.scola@nasa.gov
SE	D208	Adam Horn Katie Bebb	adam.c.horn@nasa.gov Kaitlyn.m.bebb@nasa.gov
SE	D208	Ted Holtz	Ted.Holtz@nasa.gov
Mechanical (on Call)	D202		
Electronics (on Call)	D203	Steve Bowen	stephen.c.bowen@nasa.gov
Thermal	D206		
Science			
Optics / Optical Engineer		Angela Harrivel	Angela.r.Harrivel@nasa.gov
Launch Options			
Propulsion Systems			
Spacecraft Bus			
Software	D207		
Cyber Security	D208	Andy Ramlatchan	andy.ramlatchan@nasa.gov
Power/Avionics	D203	Steve Bowen	stephen.c.bowen@nasa.gov
Schedule	B603B	Anish Parikh	anish.parikh@nasa.gov
Cost	B602C	Stephanie Primeaux	stephanie.j.primeau@nasa.gov
Risk	B602D		
External - Boston University		Will Saunders	wsaund@bu.edu
Facilitator, support	D208	Andrew Hunt	andrew.l.hunt@nasa.gov
Shadowchaser Team:	E402	Jonathon Chrone	jonathon.d.chrone@nasa.gov
	E402	Joshua Carden	joshua.f.carden@nasa.gov

Where is it located?



Location

- Building 2102, Room 209
 - Second floor of the Integrated Engineering Services Building (IESB)

Facility Technological Amenities

- Multiple workstations to support individual assessments
- Two large screens in the front and two on the side of the room for projecting multiple displays
- High quality audio and video conferencing for remote participants
- White Board space throughout the room for brainstorming activities

Shadow Chaser – IDC² Objectives



1. Determine optimal launch opportunity to observe the February 2031 Occultation Event

GTO:

- Pro: Ingress+Egress visible from single satellite with little orbital constraints
- Con: High delta-V requirement
- Con: Radiation Concern
- Con: Dearth of NASA Launch Opportunities

LEO / Sun Sync

- Pro: Launches and ride-share opportunities are relatively common
- Pro: Certain Sun Sync configurations go in/out of occultation shadow twice, multiplying the value of each occultation opportunity
- Con: Occultation visibility is obstructed by Earth,
May require multiple satellites
Observations may be compatible with a narrow range of orbital inclinations

2. Design a bus that accommodates a 20-cm aperture telescope, and sufficient delta-V capability for the mission

- Likely need an ESPA-class bus to accommodate a 20-cm aperture

3. Identify COTS instrument options that satisfies the 20-cm aperture requirement

- 20-cm aperture req is driven to satisfy sensitivity and SNR

Shadow Chaser – Instrument Requirements



1. Observing in 2.2-micron Ks band reduces the noise from Uranus/Neptune.
2. $S/N > 100$ is needed to retrieve atmos. structure w/ 1 scale height vert. resolution
3. $S/N > 30$ is needed to retrieve average temperature of upper atmos.
4. Best SO events have 4-9th mag stars for Uranus, and 9-12th mag for Neptune
5. S/N Analysis for 20-cm aperture in space: 6th-mag SO could achieve higher S/N than 4m-aperture on the ground for both U&N
6. For 10th-mag SO, 50-cm aperture in space is needed to achieve $S/N > 100$

- GTO Feasibility:
 - Can a Class-D SmallSat have sufficient radiation tolerance to operate in GTO to adjust its orbit and make measurements?
 - Can we find suitable launch opportunity/opportunities to observe the February 2031 occultation event?
- LEO / Sun Sync Feasibility:
 - How compatible are LEO / SSO with Occultation Observations? Can observing from multiple satellite solve visibility issues?
 - What are the delta-V requirements to observe SOs from LEO/SSO
- Instrument:
 - Do COTS options for optics (20-cm aperture) and detectors (2.2 micron) exist that satisfy sensitivity requirements?

Proposed IDC² Session Deliverables



- Determine the optimal launch opportunity
- Bus design that accommodates a 20-cm aperture telescope,
- Delta-V capability for the mission
- COTS instrument options that satisfies the 20-cm aperture requirement
- System requirements, functions, performance metrics, interfaces, and relevant environments used to inform design trades.
- Risks & Technical Challenges Identified.
- Cost and Schedule discussions.
- Notes from the meeting discussions.
- Audio recordings of the meeting sessions.
- Each SME provides key take-aways, risks, and project lessons learned from each SME at the completion of the session.
- Summary out brief through as a slide deck.

Schedule Day 1 (Afternoon)



DAY 1 (Monday) Afternoon – 08/21/2023

1:00 - 1:15: Introductions, logistics, explanation of room technology, General IDC² guidelines

1:15 - 1:30: Why are we all here/what should we be thinking about

1:30 - 2:30: Shadow Chaser Overview

2:30 - 3:30: Identify Primary/Priority and Secondary Use Cases

- Target Technical Objective – Purpose of Technology
- Technical functional Description
- Generic/Specific Environment
- Technology Performance metrics (mass, power, cost, vol etc.)
- Key Driving Requirements and Key Performance Parameters
- Target location and duration
- Identify Stakeholders

3:30 - 3:45: Break

3:45 - 4:30: Operational Requirements: At a high Level, describe functions to be performed and how well they need to be performed to produce the target application

•Environments

- Operational Environments (Min and Max)
 - Temperature, Pressure, Structures and Material Strength, Static Loads, Vibration-Sine, Vibration Transient, Shock, Planetary Dust, Contamination, Radiation, Plasma, Purge, Electromagnetic Effects, gravity_
- Non-Operational Environments (Min and Max)
- Relevant Environment (Min and Max)
- Technical Maturation Environment and Justification
- Define Key Critical Technical Elements (KCTE)
- Any Applicable Documents

Schedule Day 2



Day 2 (Tuesday) Morning– 08/22/2023 **Tentative**

9:00 – 9:15: Recap/Questions

9:15-10:15: **Launch Opportunity Discussion**

2:15-3:00: Key Critical Technical Elements – Provide context for the level at which the technology in question resides within a particular system’s architecture.

- Identify the Key Critical Technical Elements (KCTE) and description
- Identify Technical Objectives
- Identify Challenges
- Knowledge Gaps and scope
- Impacted Capabilities

3:00-4:00: Identify Driving Interfaces: Power interface, physical interfaces with Rover/Lander, Software interface.

4:00-4:30: Access Readiness Levels (RL) and Advanced Degree of Difficulty (AD2) (Risk)

- Identify Technology Readiness Levels (TRL)
- Identify Manufacturing Readiness Levels (MRL)
- Identify Software Readiness levels (SRL)
- Identify Modeling Readiness Levels (MoRL)

4:30: Conclusion of Day 2

Schedule Day 3



DAY 3 (Wednesday) – 08/23/2023 **Tentative**

9:00 – 9:15:	Recap Day 2
9:15 – 10:00:	Review trades for predesign work.
10:00 – 11:00	Define design analysis cycle
11:00 – 12:00:	Working Session
12:00 – 1:00:	Lunch
1:00 - 4:00:	Cost & Schedule + Working session/Open topic Breakout
4:00pm	Conclusion of Day 3

Schedule Day 4

(Subject to Change)



DAY 4 (Thursday) – 08/24/2023

9:00 – 9:15:	Recap Day 3
9:00 – 10:00:	
10:00 – 12:00	
12:00 – 1:00:	Lunch
1:00 – 2:00:	
2:00 – 3:00:	Cost & Schedule Part 2
3:00 – 3:30pm	Revisit any topics
3:30pm	Conclusion of Day 4



Shadow Chaser IDC2 Session Measurement ConOps Considerations / Rough Draft

Ted Holtz (LARC-D208)

Process	Description	Details	ConOps Impact & Questions
Step 1	Calibrate Detector	Calibrate the detector while imaging the full Uranian system while the target star is not in view. Take measurement of that flux and store it. 10 orbits prior to event for calibrating the detector to get the total flux of the Uranian system. Calibrate CCD. Is it helpful to take a calibration measurement of a black body or something else to help get a flux number on background?	Attitude control (pointing stability), Data Routing, Data Storage, Commands, etc. Does the L1 Requirement of 1-hour observation apply here?
	Calibrate Pointing		
Step 1.5	On-board processing (Given)	Number crunching to calculate flux, store value/data storage.	

Process	Description	Details	ConOps Impact & Questions
Step 2	Measure Wandering Star Flux	Well before ingress, obtain a measurement of a wandering star's flux before it gets near the planet.	Attitude control (pointing stability) Does the L1 Requirement of 1-hour observation apply here?
Step 2.5	On-board processing (Given)	Number crunching to calculate flux, store value.	
Step 3	Store baseline flux.	Baseline flux is comprised of 1) full uranium system without star, and 2) star is in view but far away from uranium system.	Does the L1 Requirement of 1-hour observation apply here?
Step 3.5	On-board processing (Given)	Number crunching to calculate flux, store value.	

Process	Description	Details	ConOps Impact & Questions
Step 4	Take measurement prior to Ingress	Use photometry to calculate total flux and separate flux.	Is there a proven algorithm that can already do this or something similar that can be tailored to your project? When will the calculations occur? Will the calculations occur after each image capture? Does the L1 Requirement of 1-hour observation apply here?
Step 4.5	On-board processing (Given)	Number crunching to calculate flux, store value.	Data storage
Step 5	Take measurements during eclipse	How many measurements during this sub-15 minute period?	Does the L1 Requirement of 1-hour observation apply here?
Step 5.5	On-board processing (Given)	Number crunching to calculate flux, store value.	Data storage

Process	Description	Details	ConOps Impact & Questions
Step 6	Take measurement during Egress		Does the L1 Requirement of 1-hour observation apply here?
Step 6.5	On-board processing (Given)	Number crunching to calculate flux, store value/data storage.	Data storage
Step 7	On-board post-processing (Given)	Prior to downlink, explore any lite-duty post-processing needs?	Does the L1 Requirement of 1-hour observation apply here?
Step 7.5	Prepare data for Downlink		
Step 8	Down Link		What stations? Look into AWS ground station solutions as options?
Step 9	Ground post-processing?		



Shadow Chaser IDC2 Session Mission ConOps Considerations

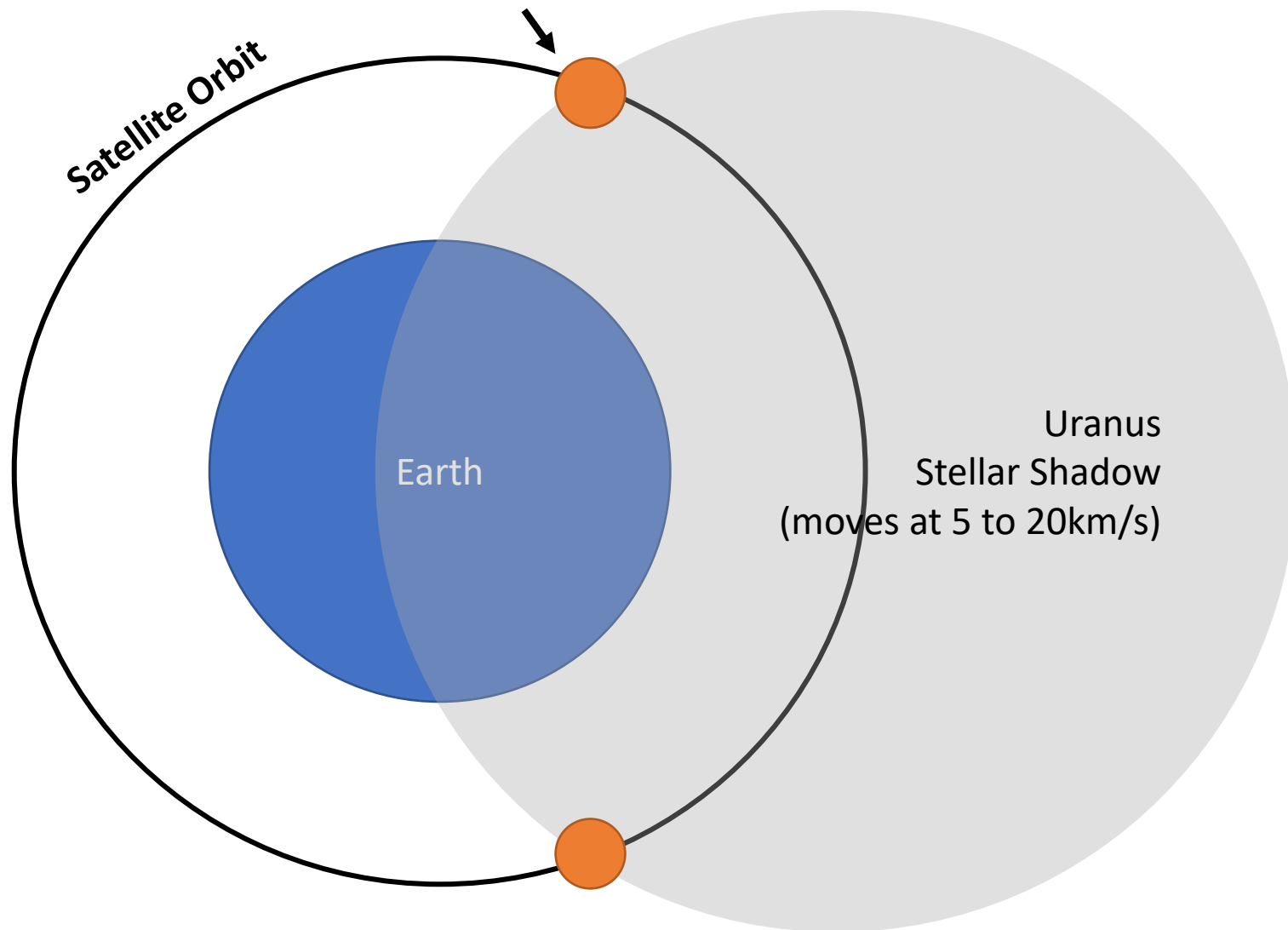
Ted Holtz (LARC-D208)

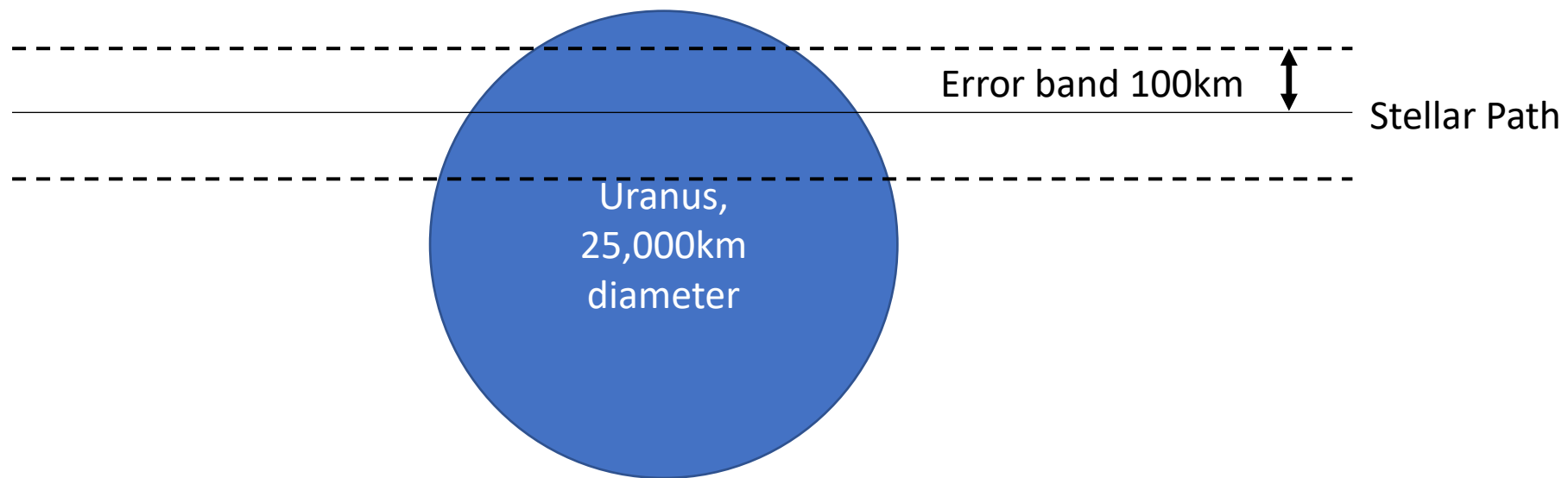
ShadowChaser Mission Concept of Operations

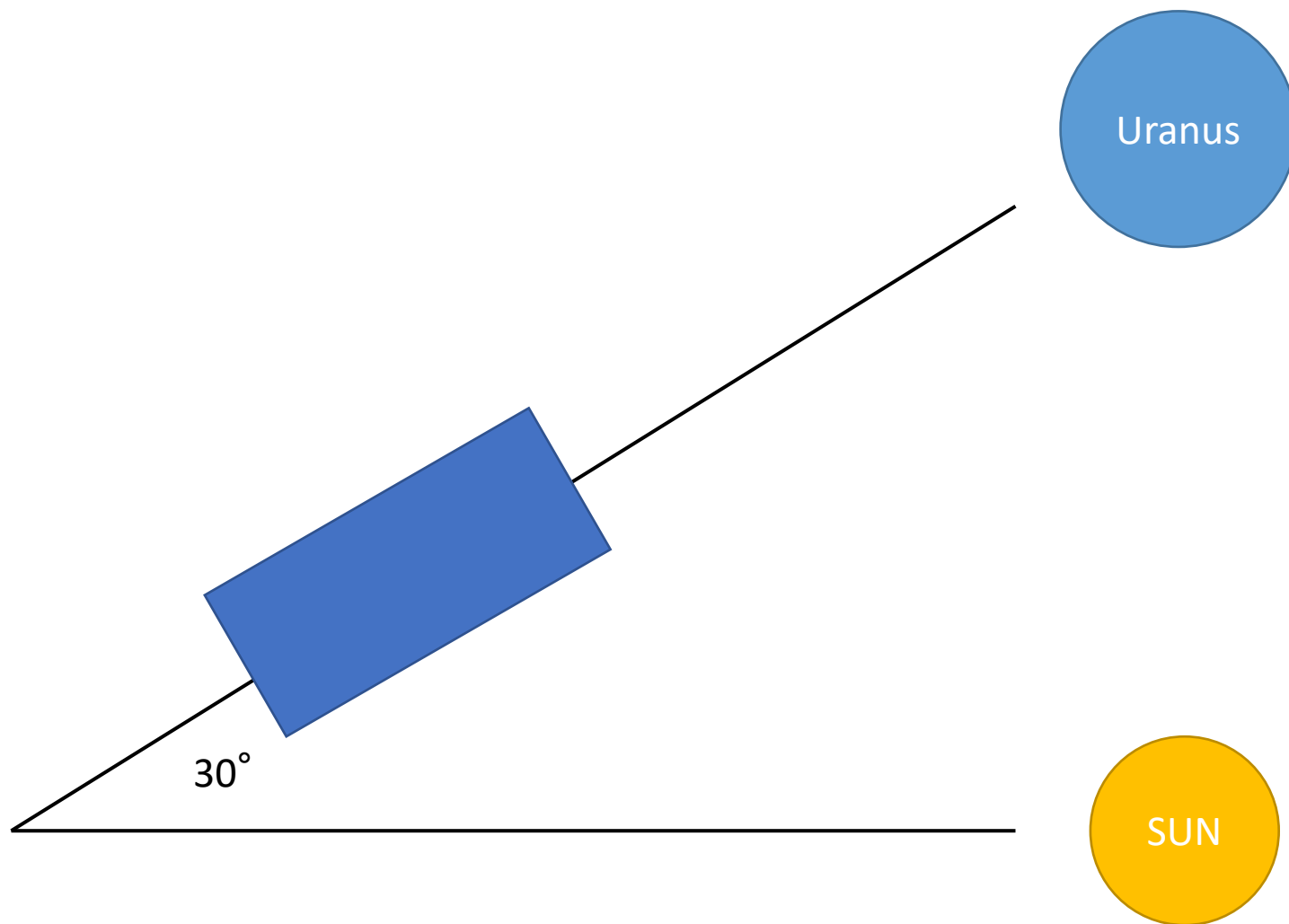


- Launch/On-orbit Checkout
 - Secondary launch on ESPA ring on deployable SmallSat to LEO (Sunsync orbit)
 - Final orbit maneuver burns
 - Spacecraft/instrument checkout
 - Test regular calibrations/measurements of stars/Uranus in advance to tune instrument
 - Put instrument into Safe mode until next measurement
- Occultation Measurement (Day in the Life)
 - Calibrate Detector 24 (TBR) hours prior
 - Download calibration data for analysis
 - Point Spacecraft to Target (Uranus)
 - Take occultation measurement over 20-30 (TBR) minutes
 - Downlink Science Data to ground stations
 - Put instrument into Safe mode until next measurement (weeks to months)

Spacecraft Positions for occultation
measurement (intersection of
shadow with orbit plane)









GTO Feasibility Analysis

Orbital Analysis: Josh Carden & Jon Chrono (E402)

Radiation Analysis: Madison Hanrahan (Deep Creek High School / Intern D206)

Radiation Interpretation: Chris Mertens (D309)



Event Visibility from GTO

- Each SO-event often requires >1-hour observing time
GTO-like Orbits allow stable viewing geometry around the apogee

February 15, 2031 Uranus Event

- Duration: 86.3 minutes
- S/N = 1983.5 (20 cm aperture in Ks band)

February 6, 2032 Uranus Event

- Duration: 38.8 minutes
- S/N = 205.7 (20 cm aperture in Ks band)



GTO Delta-V Requirements



Assumption:

Spacecraft is delivered to a 12-hour Geosynchronous Transfer Orbit (GTO) through ride-share opportunity

Observations should happen around GTO apoapsis.

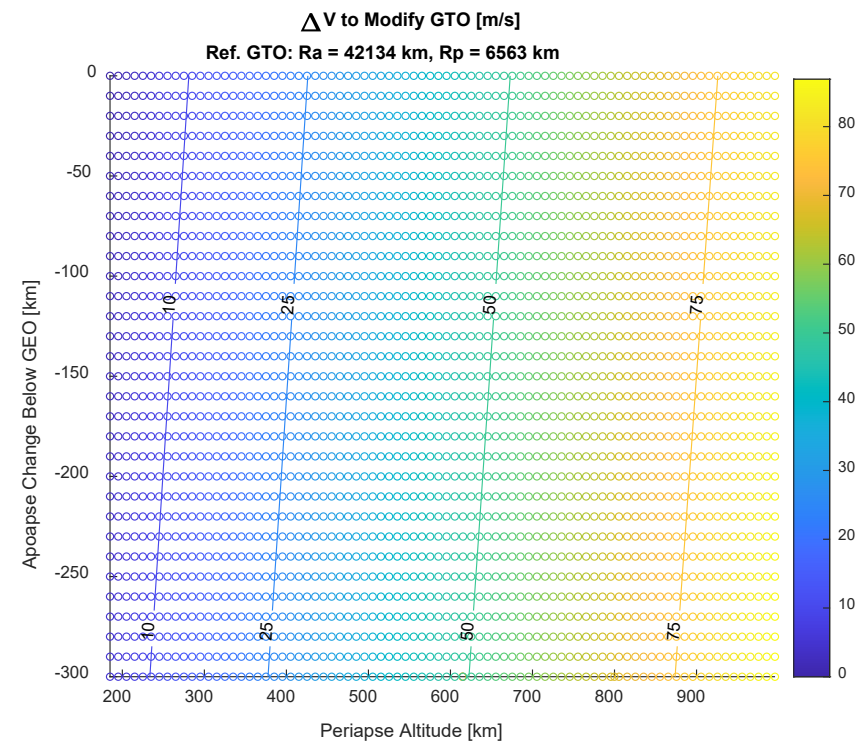
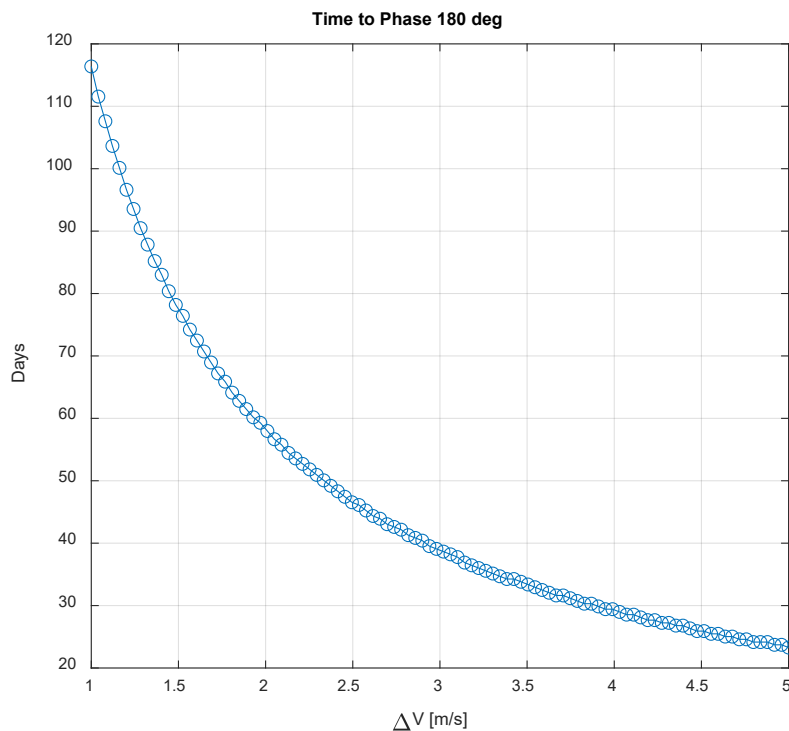
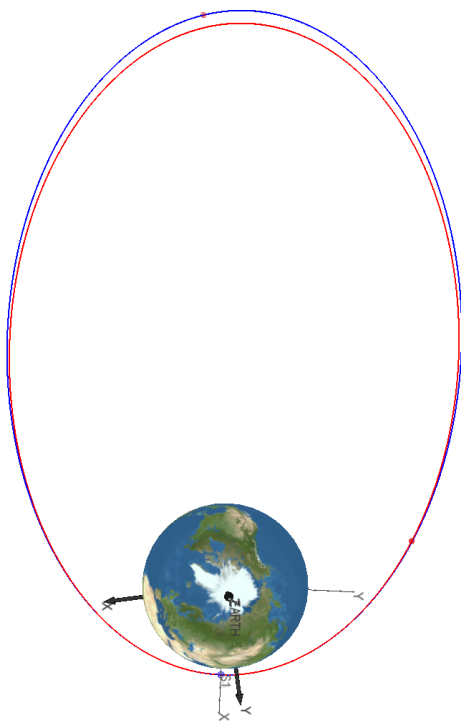
→ Orbital phase needs to be adjusted

→ Delta-V of 5 m/s is sufficient for each event

Total Mission Delta-V estimate after GTO insertion

- Raise periapsis to 800 km: 63 m/s
- Lower apoapsis to 300 km below GEO: 5 m/s
- Phase adjustment: 5 m/s per event x5 = 25 m/s
- Deorbit: 63 m/s

Total Delta-V Requirement = 156 m/s



GTO Radiation Dosage

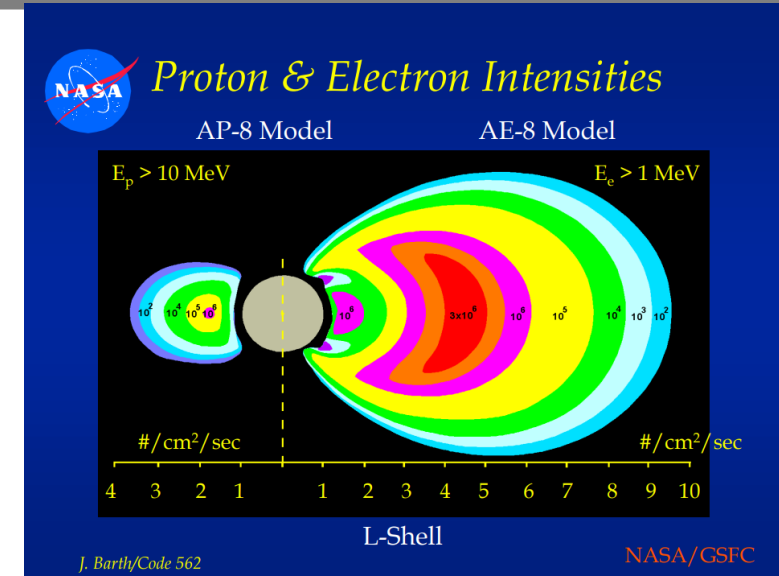
GTO goes through Van Allen radiation belt

- GTO can have:
 - 28.5-deg inclination (KSC launch before plane change maneuver)
 - 0-deg inclination (after plane change maneuver)

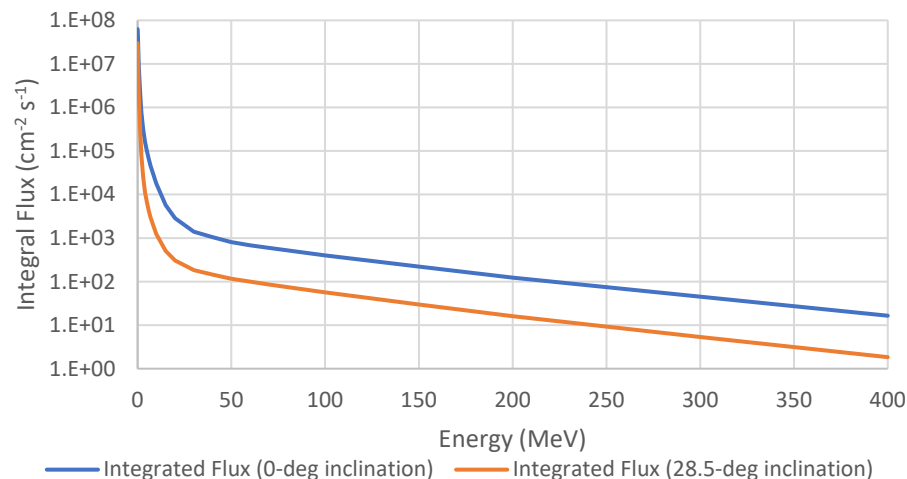
Higher-inclination GTO receives lower radiation exposure

Regardless of inclination, radiation flux too high for a low-cost spacecraft to stay in GTO for 2 years.

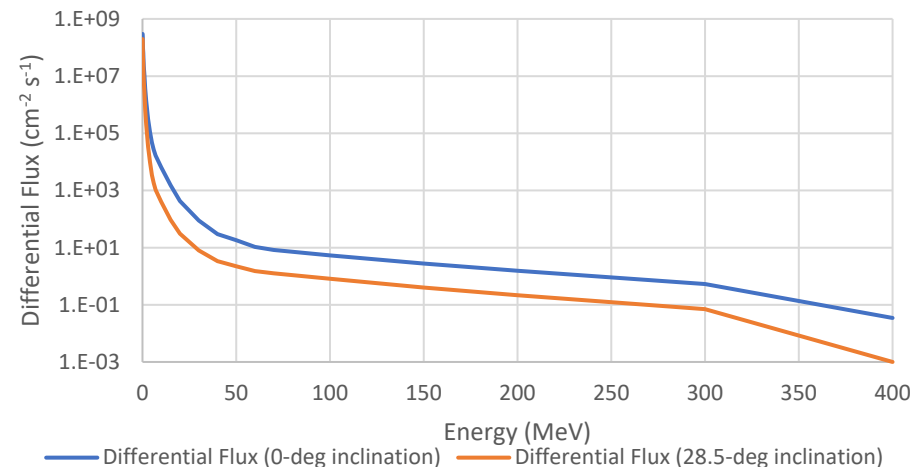
The radiation issue rules out GTO for Shadow Chaser



Trapped Proton Integral Flux (2-year Mission Average)



Trapped Proton Differential Flux (2-year Mission Average)



Calculated using
the SPENVIS tool
<https://www.spENVIS.oma.be/>



SSO Sensitivity Analysis

Josh Carden (E402)

Jonathan Chrono (E402)

Objective



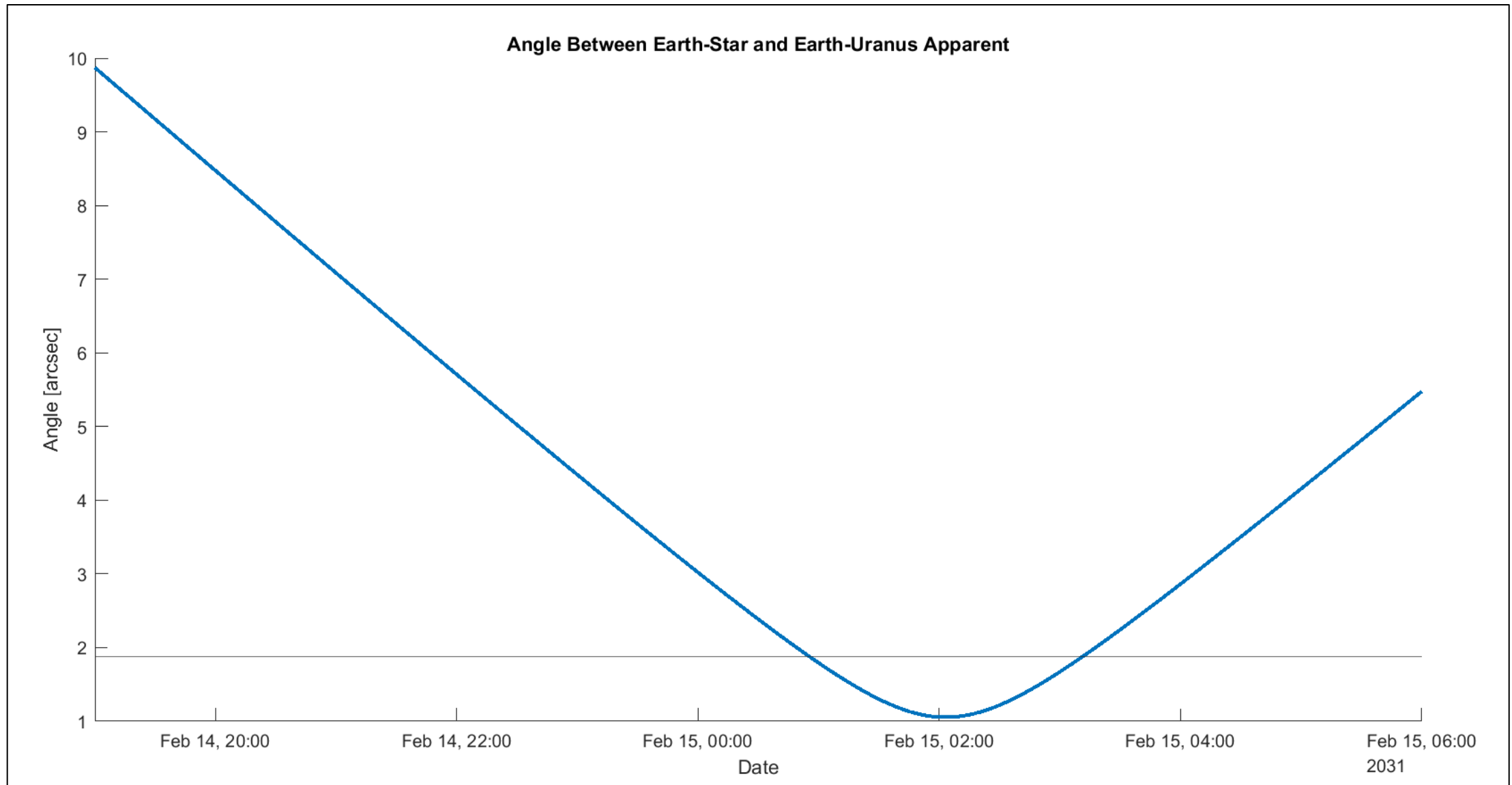
SPACE MISSION ANALYSIS BRANCH

- Orient the sun-synchronous orbit to get desired view of occultation
 - Ideal configuration is to align the orbit plane to be perpendicular to the viewing vector
 - The closer the angle is to perpendicular, the less chance there is for Earth to obstruct the view
 - This also increases the chance to observe the occultation multiple times
- Determine the sensitivity of sun-synchronous orbit parameters to capture the desired behaviors
 - Use occultation event on 02/15/2031 as the case for this analysis
 - Vary right ascension of ascending node (RAAN), true anomaly, and altitude of orbit to determine orientation, temporal, orbit velocity sensitivities

Occultation as Viewed From Earth



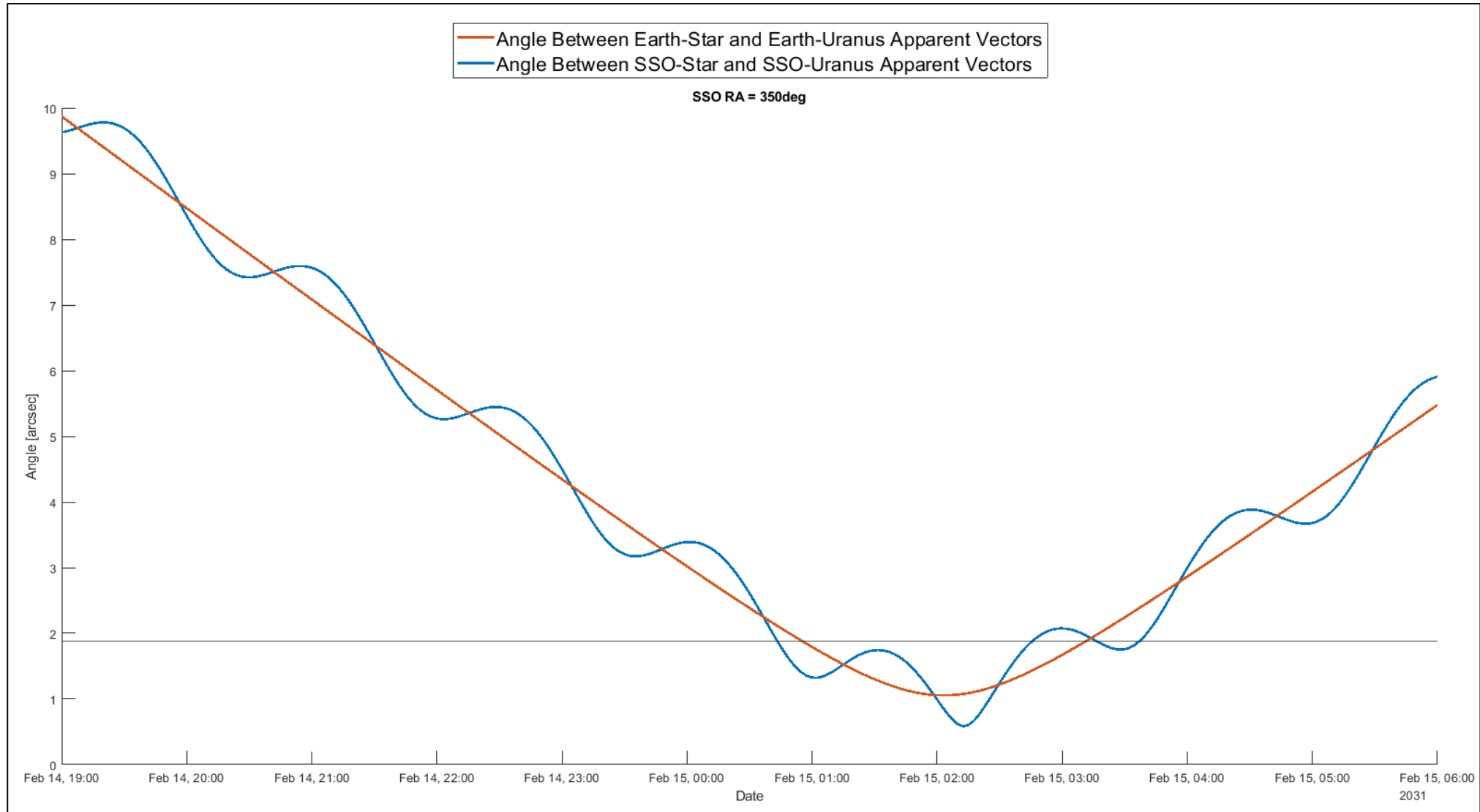
SPACE MISSION ANALYSIS BRANCH



Occultation as Viewed from SSO (500km)



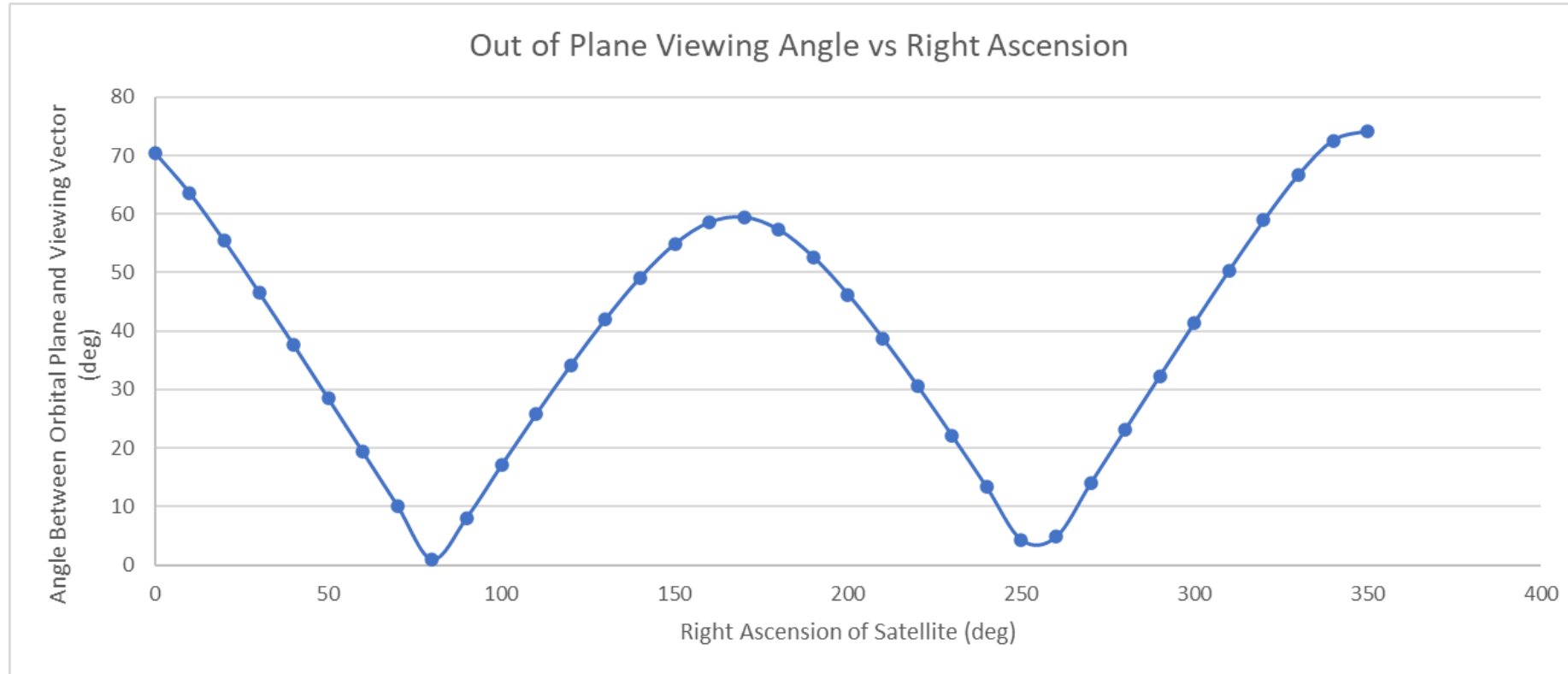
SPACE MISSION ANALYSIS BRANCH



RAAN Impact on Out of Plane Viewing Angle (500km)



SPACE MISSION ANALYSIS BRANCH

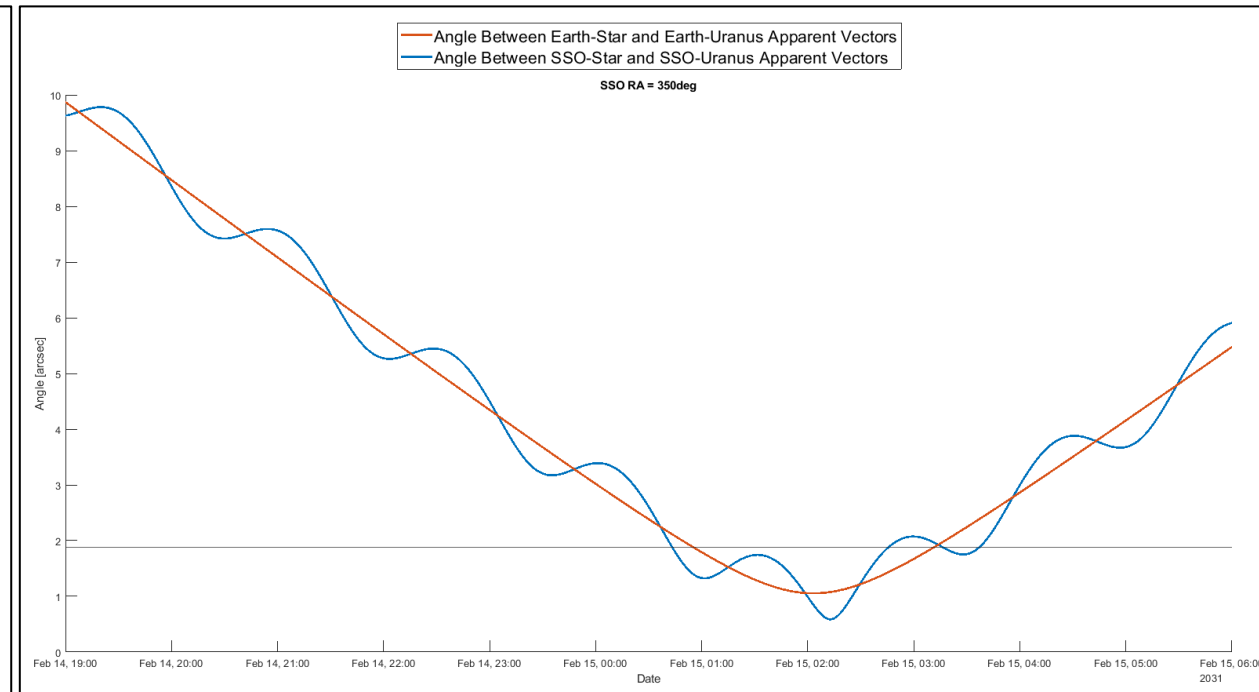
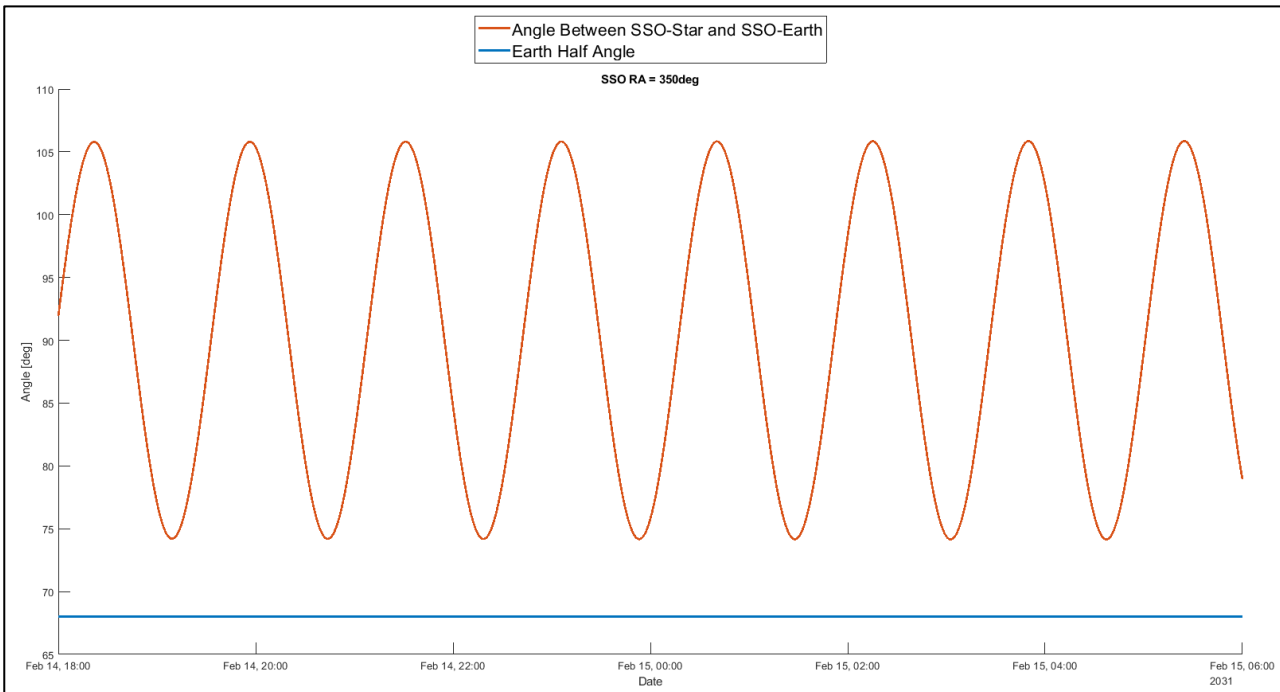


- RAANs of 350 and 170 yield max Out of Plane Viewing Angle
 - Minimums occur at 80 and 250

Max Out of Plane Viewing Angle (RAAN = 350, 500km)



SPACE MISSION ANALYSIS BRANCH



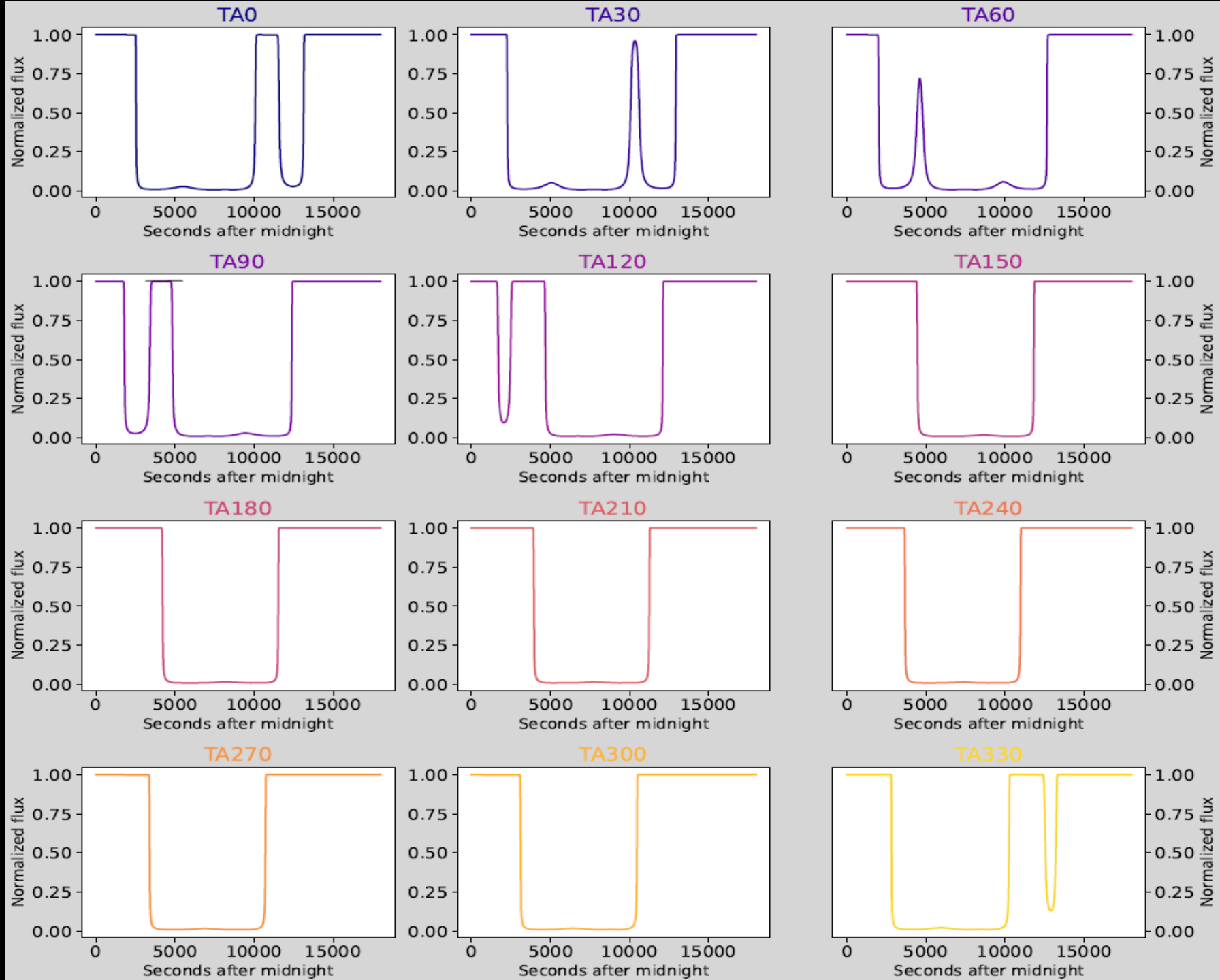
- Viewing is not obstructed by Earth throughout the duration of the occultation
- Multi occultation behavior is present (will depend on epoch)

LEO/SSO Benefit:

Right: Simulated light curves for SSO observations

SSO can offer multiple occultation observations per event.

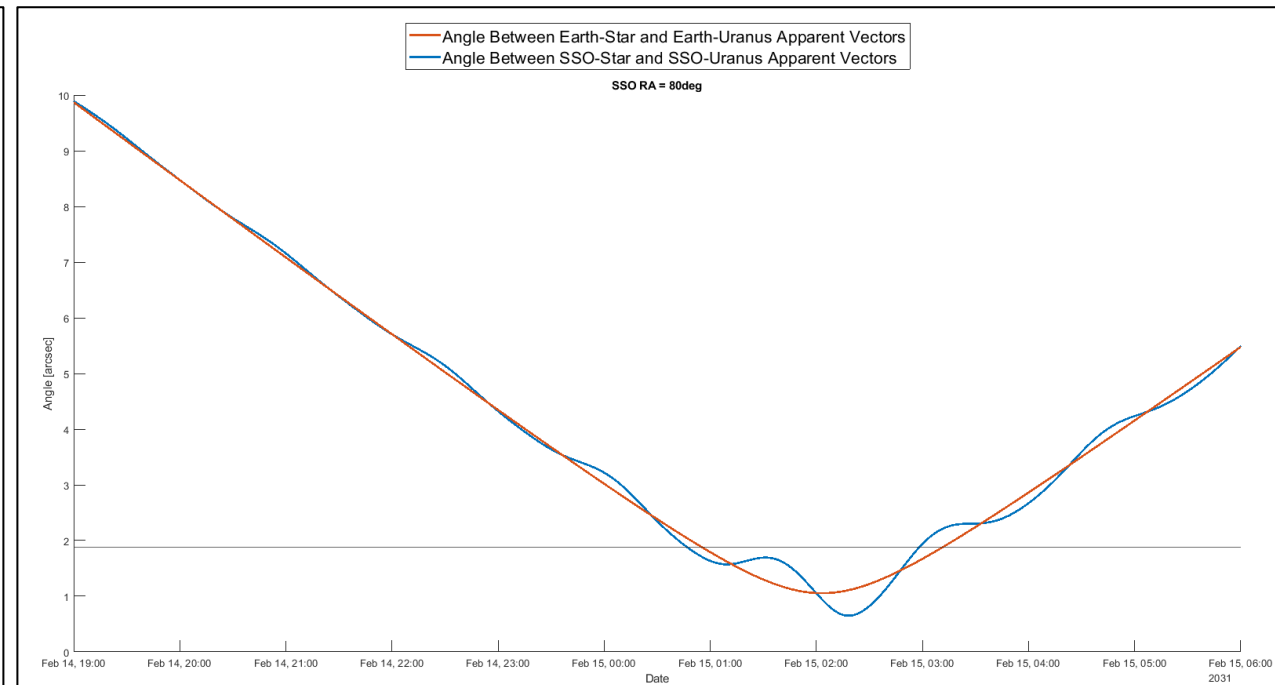
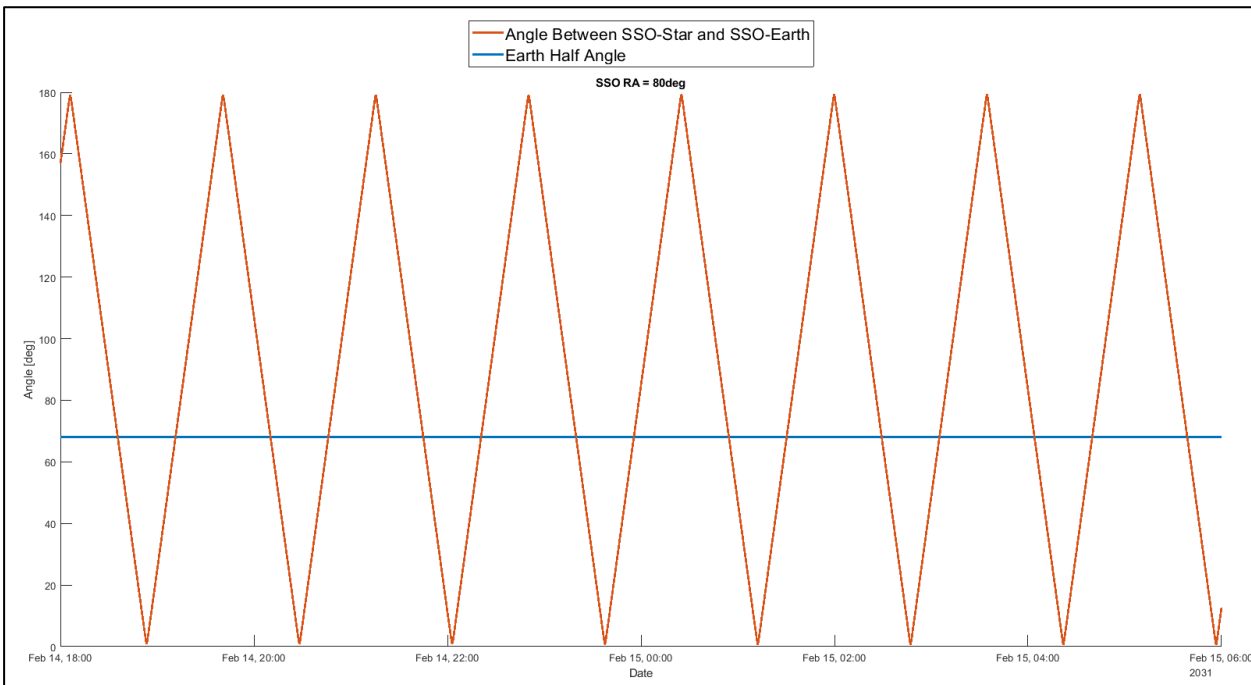
Shadow Chaser



Min Out of Plane Viewing Angle (RAAN = 80)



SPACE MISSION ANALYSIS BRANCH



- Viewing is heavily obstructed by Earth throughout the duration of the occultation
- Multi occultation behavior is removed

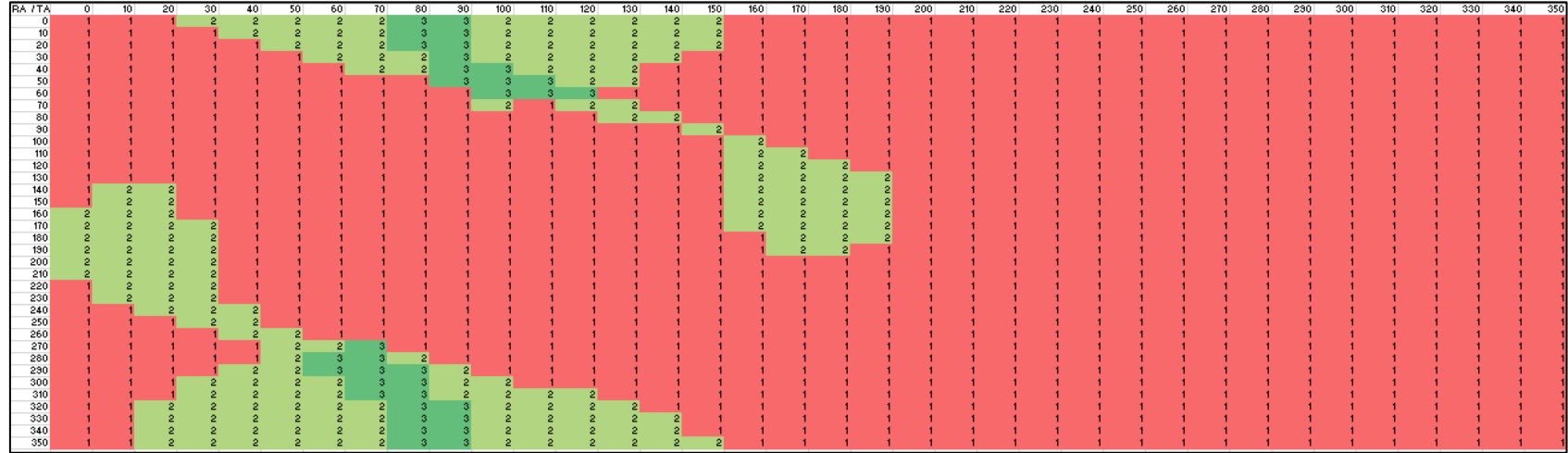
- Use MATLAB to cycle through STK orbits through the timing of occultation
 - Vary the RAAN from 0 to 350 (LTAN variation)
 - Vary the True Anomaly from 0 to 350
 - Vary the altitude from 400km to 800km
- Visibility improves with increasing altitude, increasing altitude increases the range of 100% visibility cases
- Multi-occultation behavior remains through higher altitudes
 - Higher sensitivity to changes in orientation

600 km Multi-Occultation and Visibility Behavior

SPACE MISSION ANALYSIS BRANCH

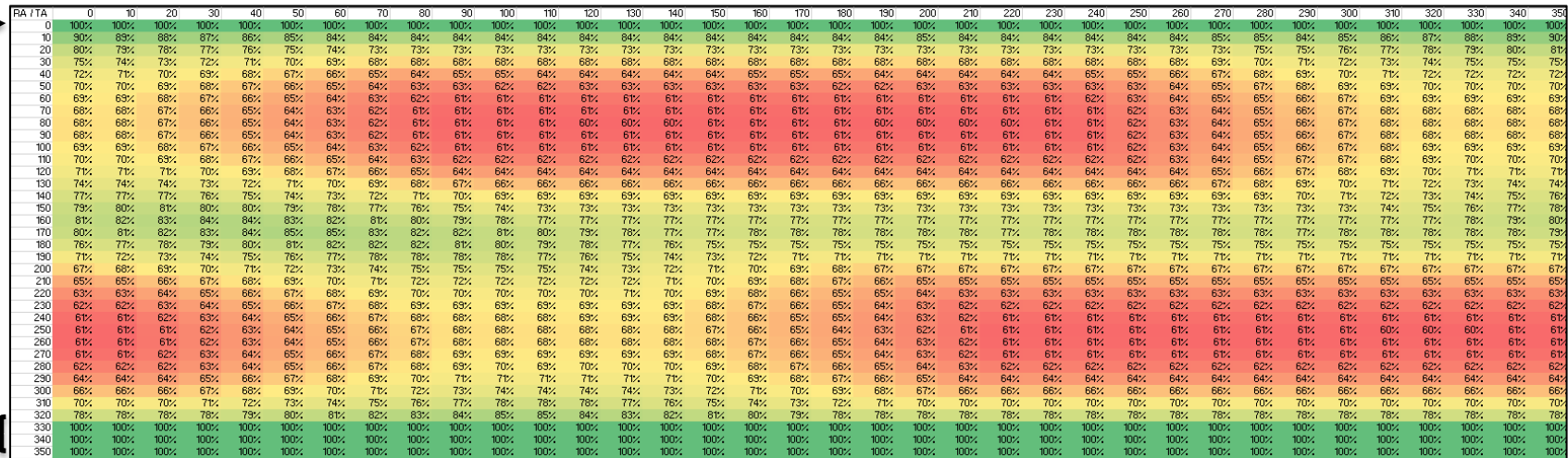
- X axis – true anomaly
- Y axis – right ascension
- Right ascensions with increased visibility also have increased multi-occultation viewing opportunities as expected
- Even with perfect visibility, the orbit must be phased properly to view multiple occultations

Multi-Occultation Behavior



True anomaly range required for multi-occultation viewing

Visibility Behavior



Right ascension range for 100% visibility

Altitude Affects on Visibility



SPACE MISSION ANALYSIS BRANCH

- Lowering the chance of Earth obstruction at higher altitude greatly increases the orbit configurations where the occultation vector is 100% not obstructed

Visibility at 400km

RA / TA	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350		
0	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	95%	95%	96%	95%	95%	94%	94%	94%	94%	94%	
10	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	77%	78%	79%	79%	79%	79%	79%	79%	78%	77%	76%	76%	76%	76%	
20	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	70%	71%	72%	72%	72%	72%	72%	72%	72%	71%	70%	63%	63%	63%	63%	
30	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	68%	67%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	67%	66%	65%	65%	
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50	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	31%	42%	43%	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	43%	42%	41%	41%	
60	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	32%	31%	30%	30%	
70	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	22%	22%	22%	22%	22%	22%	22%	22%	22%	22%	22%	22%	21%	20%	19%	19%	
80	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	14%	13%	12%	12%	
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100	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	6%	5%	4%	4%	
110	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	4%	3%	2%	2%
120	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	3%	2%	1%	1%
130	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	2%	1%	0%	0%
140	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	1%	0%	0%	0%
150	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
160	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
170	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
180	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
190	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
200	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
210	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
220	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
230	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
240	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
250	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
260	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
270	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
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300	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
310	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
320	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
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350	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%

Visibility at 800km

RA / TA	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350
0	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
10	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
20	81%	82%	83%	84%	85%	85%	85%	85%	85%	84%	82%	81%	80%	79%	78%	77%	77%	77%	77%	77%	77%	77%	77%	77%	77%	77%	77%	77%	77%	77%	77%	77%	78%	79%	80%	
30	75%	76%	77%	78%	79%	80%	80%	80%	79%	78%	77%	76%	75%	74%	73%	72%	71%	70%	69%	68%	67%	66%	65%	64%	63%	62%	61%	60%	59%	58%	57%	56%	55%	54%	53%	52%
40	72%	73%	74%	75%	76%	77%	77%	76%	75%	74%	73%	72%	71%	70%	69%	68%	67%	66%	65%	64%	63%	62%	61%	60%	59%	58%	57%	56%	55%	54%	53%	52%	51%	50%	49%	48%
50	70%	71%	72%	73%	74%	75%	75%	74%	73%	72%	71%	70%	69%	68%	67%	66%	65%	64%	63%	62%	61%	60%	59%	58%	57%	56%	55%	54%	53%	52%	51%	50%	49%	48%	47%	46%
60	69%	70%	70%	72%	73%	74%	74%	73%	72%	71%	70%	69%	68%	67%	66%	65%	64%	63%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%
70	68%	69%	70%	71%	72%	73%	74%	73%	71%	70%	69%	68%	67%	66%	65%	64%	63%	62%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%
80	67%	69%	70%	71%	72%	73%	73%	72%	71%	70%	69%	68%	67%	66%	65%	64%	63%	62%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%
90	67%	68%	70%	71%	72%	73%	73%	73%	72%	71%	70%	69%	67%	66%	65%	64%	63%	62%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%	61%
100	68%	69%	70%	71%	72%	73%	74%	74%	73%	71%	70%	69%	68%	67%	66%	65%	64%	63%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%
110	68%	70%	71%	72%	73%	74%	75%	75%	74%	73%	72%	71%	70%	69%	68%	67%	66%	65%	64%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%
120	69%	70%	72%	73%	74%	75%	76%	76%	75%	74%	73%	72%	71%	70%	69%	68%	67%	66%	65%	64%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%
130	71%	72%	73%	74%	75%	76%	77%	78%	78%	77%	76%	75%	74%	73%	72%	70%	69%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
140	73%	74%	75%	77%	78%	78%	80%	81%	81%	81%	80%	79%	78%	77%	76%	75%	73%	72%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%
150	76%	77%	78%	79%	80%	81%	82%	83%	84%	84%	84%	84%	84%	83%	82%	81%	80%	79%	78%	77%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%
160	81%	81%	81%	81%	82%	84%	85%	85%	86%	87%	87%	87%	87%	87%	87%	86%	85%	84%	83%	82%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%
170	82%	82%	82%	82%	82%	83%	84%	85%	86%	87%	88%	88%	88%	88%	88%	88%	87%	86%	85%	84%	83%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%
180	82%	82%	82%	82%	82%	83%	84%	85%	86%	87%	88%	88%	88%	88%	88%	88%	87%	86%	85%	84%	83%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%
190	83%	83%	83%	83%	83%	83%	84%	85%	86%	87%	88%	88%	88%	88%	88%	88%	87%	86%	85%	84%	83%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%
200	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
210	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%
220	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%
230	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%
240	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%
250	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%
260	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%
270	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%
280	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%	83%
290	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
300	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%
310	74%	74%	74%	74%	74%	74%	74%	74%	74%	74%	75%	76%	77%	78%	79%	80%	81%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	
320	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%
330	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
340	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
350	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

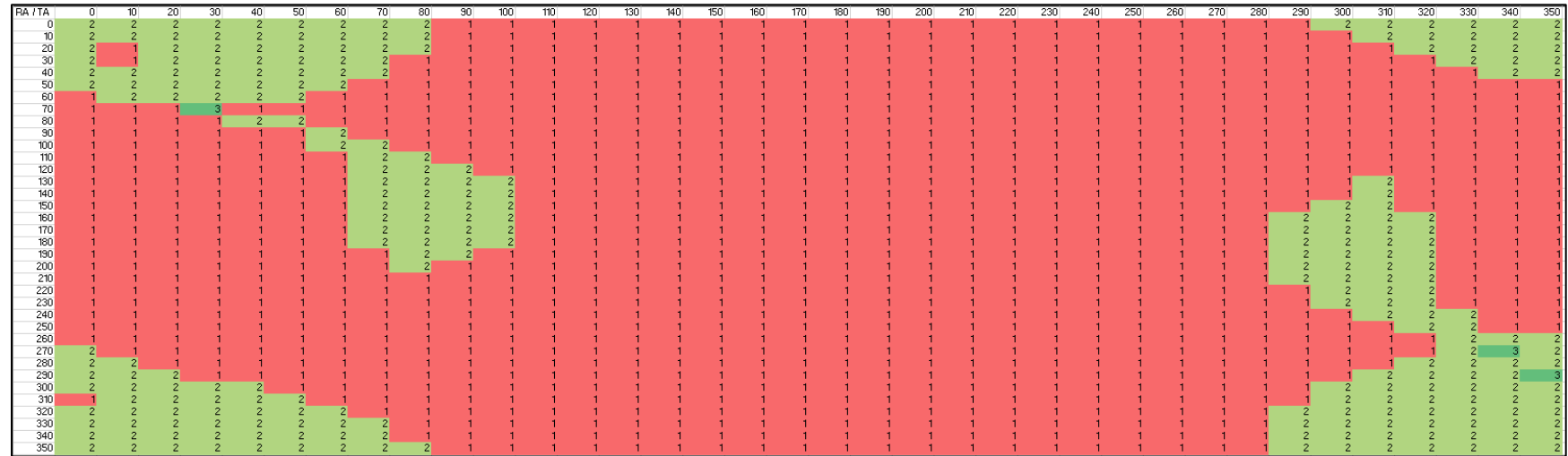
Altitude Affects on Multi-Occultation Behavior



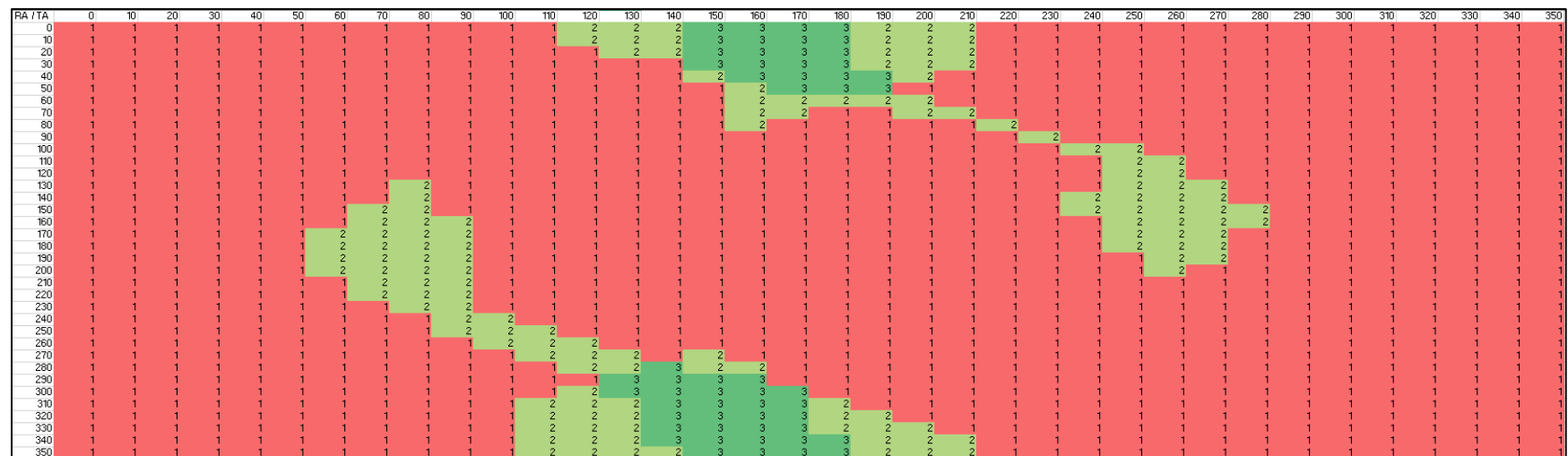
SPACE MISSION ANALYSIS BRANCH

- Increasing altitude does not have a high impact on ranges in which multiple occultations are observed
- There are 3 observation cases possible, but these are cases in which the spacecraft very slightly exits the shadow

Multi-Occultation behavior at 400km



Multi-Occultation behavior at 800km



Conclusions



SPACE MISSION ANALYSIS BRANCH

- There are right ascension ranges in which the viewing is never obstructed
 - These ranges are increased at higher altitudes
- Multi-occultation behavior is not greatly impacted by altitude
 - True anomaly phasing may be required to obtain the desired behavior

Shadow Chaser SSO Phasing Δv Analysis

Josh Carden

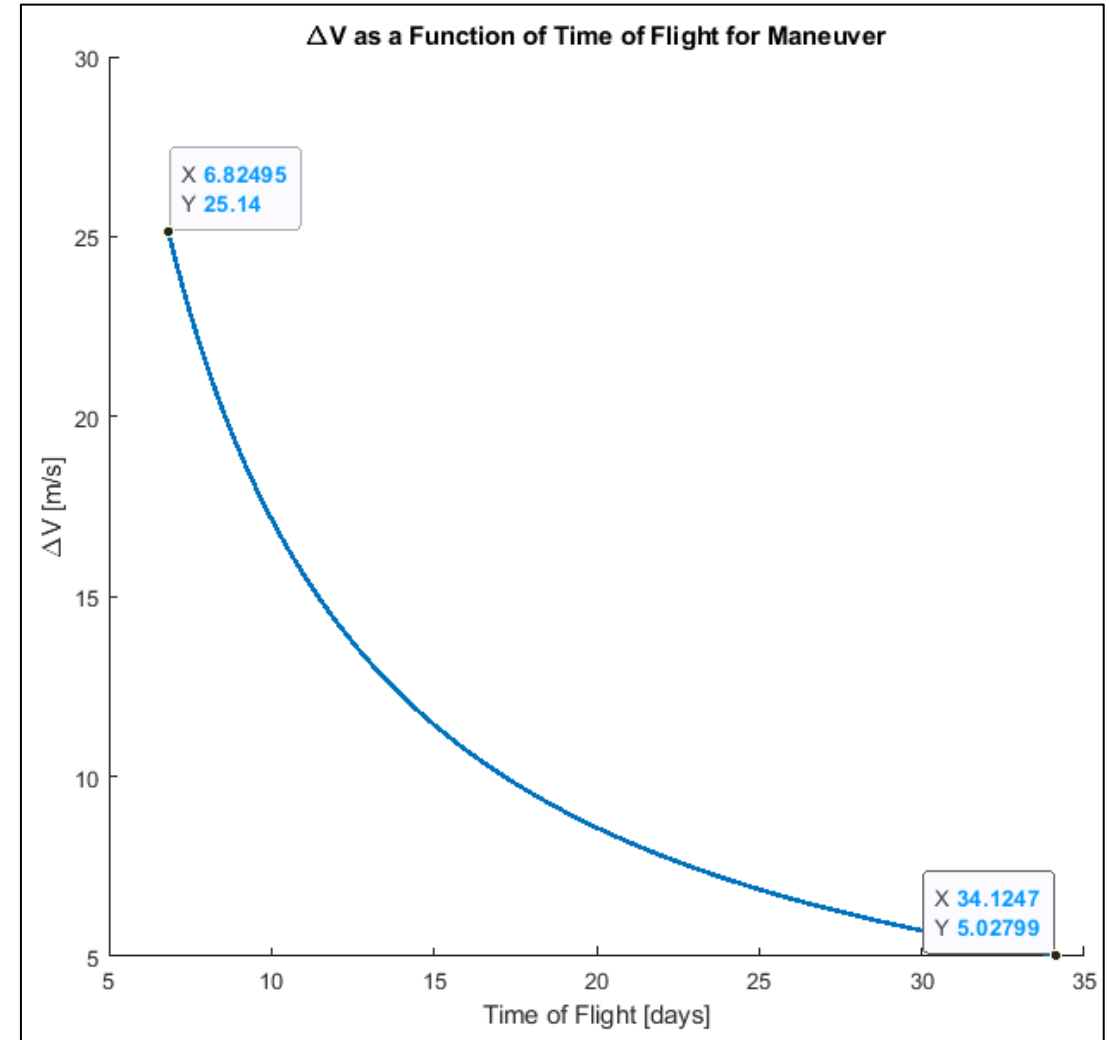
- Calculate the potential Δv needed to phase the orbit into a true anomaly in which visibility or multi-occultation viewing is optimal
- Assume the worst-case magnitude for phase change (180°)
- Use low-fidelity calculators, drag perturbations are not considered
- Determine the range of Δv required for:
 - Orbits at different altitudes
 - Time needed to complete the maneuver

Single Case Behavior



SPACE MISSION ANALYSIS BRANCH

- Two burns are required for the phasing maneuver
 - Burn 1 increase/ decreases the altitude to offset orbital period
 - Burn 2 returns the spacecraft to the original orbit when it is rephased such that the spacecraft is at the desired true anomaly
- The burn magnitude depends heavily on how long the spacecraft stays in the transfer orbit (i.e., how many revolutions in transfer orbit)
- The transfer orbit changes depending on the duration of time allowed to remain in the orbit
- If 6.8 days are spent in a transfer orbit (100 revolutions) the required Δv is 25.1 m/s
- The magnitude of Δv decays exponentially with time spent in transfer orbit
 - After 34 days the Δv is decreased to 5m/s

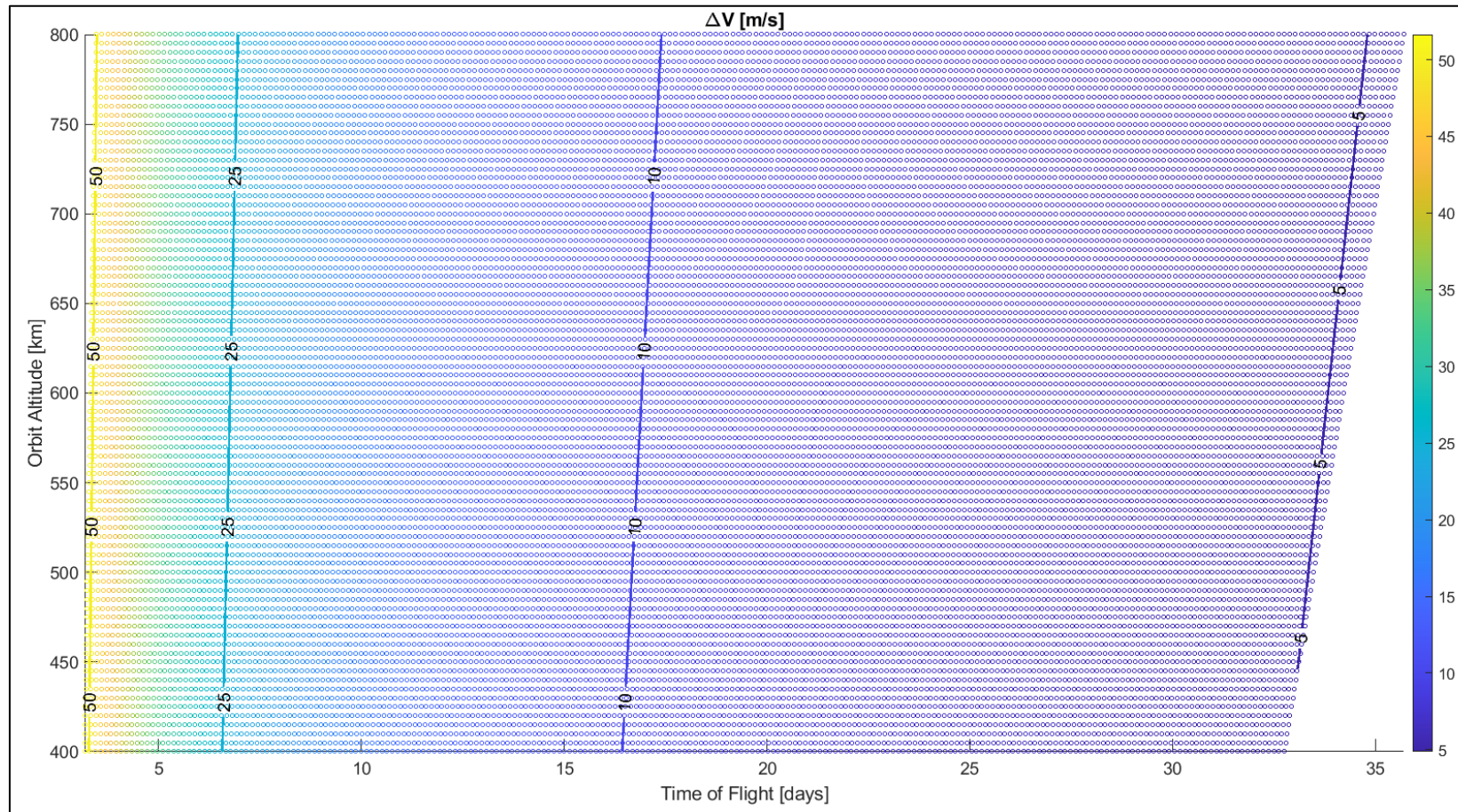


Total Δv required for two burn 180° phasing maneuver, 700km altitude circular orbit

Altitude and Time of Flight Variance



SPACE MISSION ANALYSIS BRANCH



- Varied altitude of orbit between 400km and 800km in 5km steps
- Varied orbit revolutions from 50 to 510 in 2 rev steps (revolutions are converted to time on x axis)
- Δv requirements do not vary as much with orbit altitude, time of flight has a more significant impact

Key Takeaway



SPACE MISSION ANALYSIS BRANCH

- Altitude variance is not a major driver in Δv magnitude for phasing
- Time spent in phasing orbit greatly affects the required Δv
 - 5 days in a transfer orbit will require ≈ 32 m/s of Δv
 - 1 month in a transfer orbit requires ≈ 5 m/s of Δv
- Given that occultation events are known much further in the future, low Δv magnitude phasing maneuvers are feasible



Shadow Chaser IDC2 Session Background Star Analysis during Uranus Occultation Events

Madison Hanrahan
(Student Intern D206 / Deep Creek highschool)

Question: What other stars might come near Uranus?

- Adopting photodetector rather than imaging detector means photometric measurements sense all sources in the FoV
- We need to know whether there are other stars near the occulted star.
- Analyzed the star field around the following Uranus events:
 - 2031-02-15
 - 2031-04-30
 - 2031-11-26
 - 2032-02-06
 - 2032-08-05
- Knowledge of background stars is also needed to design calibration ConOps later (e.g. flux from calibration FoV need to be predicted)

Background Star Search Procedure



From 2023-10-23 email from Madi Hanrahan <madihanrahan@gmail.com>

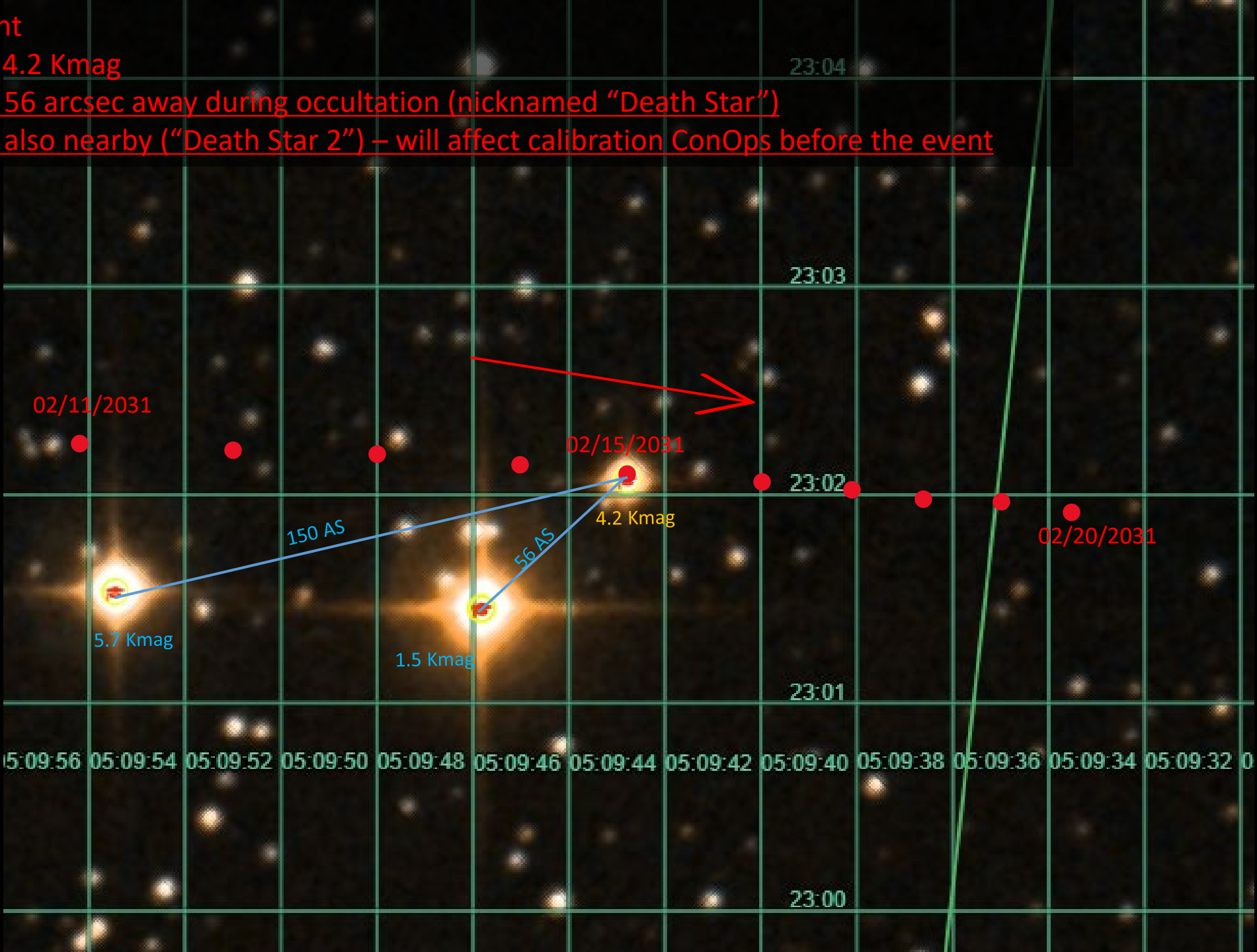
1. Use SIMBAD ([SIMBAD Astronomical Database - CDS \(Strasbourg\) \(u-strasbg.fr\)](https://simbad.u-strasbg.fr/simbad/)) to query celestial bodies that would be within a 200 arcsecond radius range from uranus' center position on 02-15-2031 at 00:00 UTC.
SIMBAD: <https://simbad.u-strasbg.fr/simbad/>
2. Take note of the stars within 200 arcsec for the event (e.g. the 2031-02-15 event had two stars: our "Death star" HD 241108 and "Death Star 2" TYC 1846-1777-1. Use SIMBAD to measure their angular separation from uranus as well as the magnitudes of their fluxes in the k band.
3. Take note of the coordinates of the occulted star of from SIMBAD and placed them in the visualization tool ESASky ([ESASky 5.3.0: https://sky.esa.int/](https://sky.esa.int/)
4. Use the JPL Horizons system ([Horizons System \(nasa.gov\) https://ssd.jpl.nasa.gov/horizons/app.html#/\) to output daily ephemeris at 00:00 UTC for uranus approx. 10 days before and after our events of interest. I took these coordinates for uranus and hand-plotted them across the star map given to me by ESASky.](https://ssd.jpl.nasa.gov/horizons/app.html#/)
5. The rest of what you see on the star maps should be fairly self explanatory, it is all data that can be found using the above three sources as well as the GAIA Archives ([Gaia Archive \(esa.int\)](https://gaia.esa.int/)).
6. There is plenty of "playing around" you can do with these sources, especially the visualization tool, ESASky, so if you need me to go more into detail about the parameters and settings I used for each source, I can try my best to remember!

2031-02-15 Event

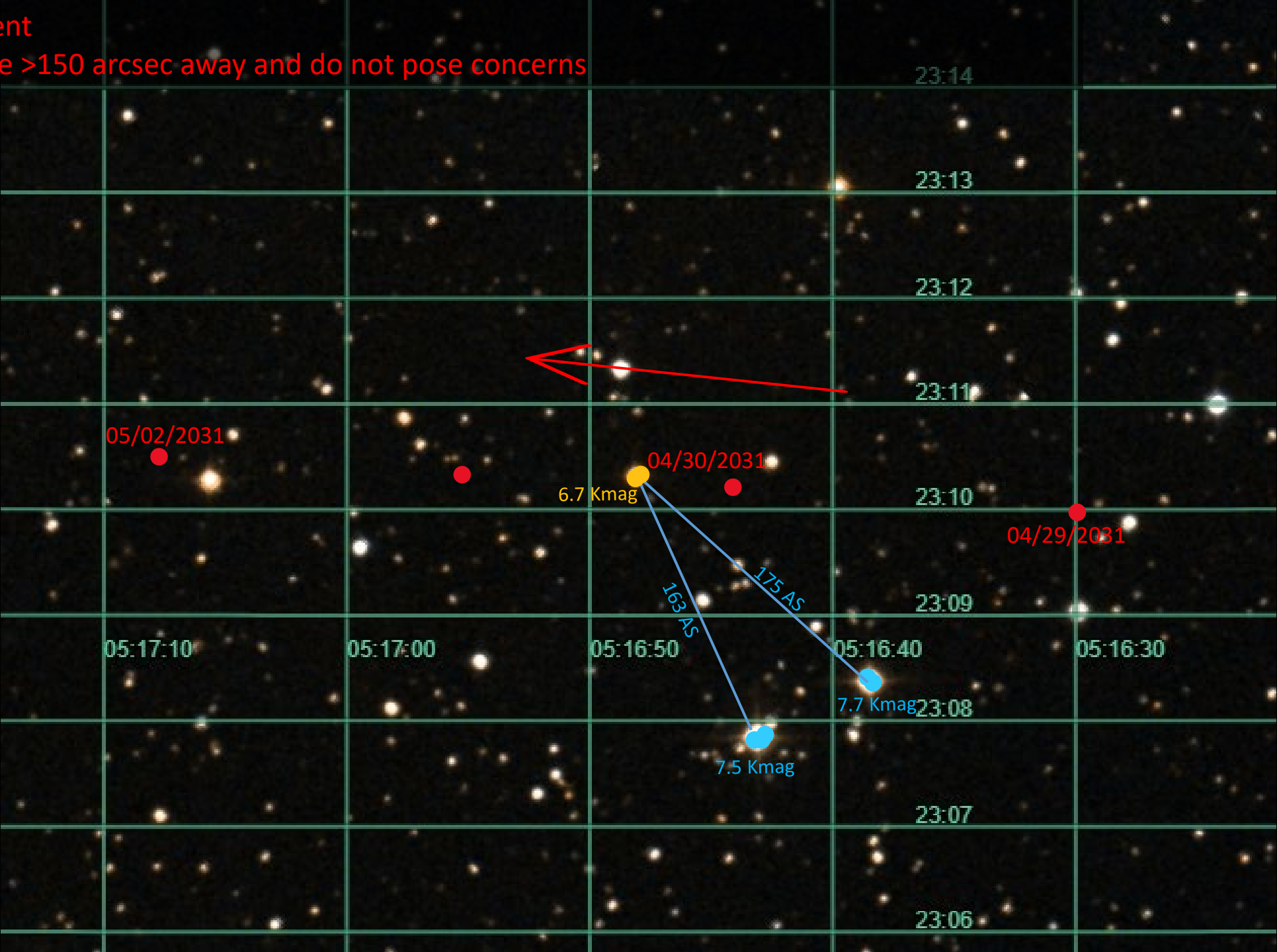
Occulted Star is 4.2 Kmag

1.5 Kmag star is 56 arcsec away during occultation (nicknamed “Death Star”)

5,7 Kmag star is also nearby (“Death Star 2”) – will affect calibration ConOps before the event



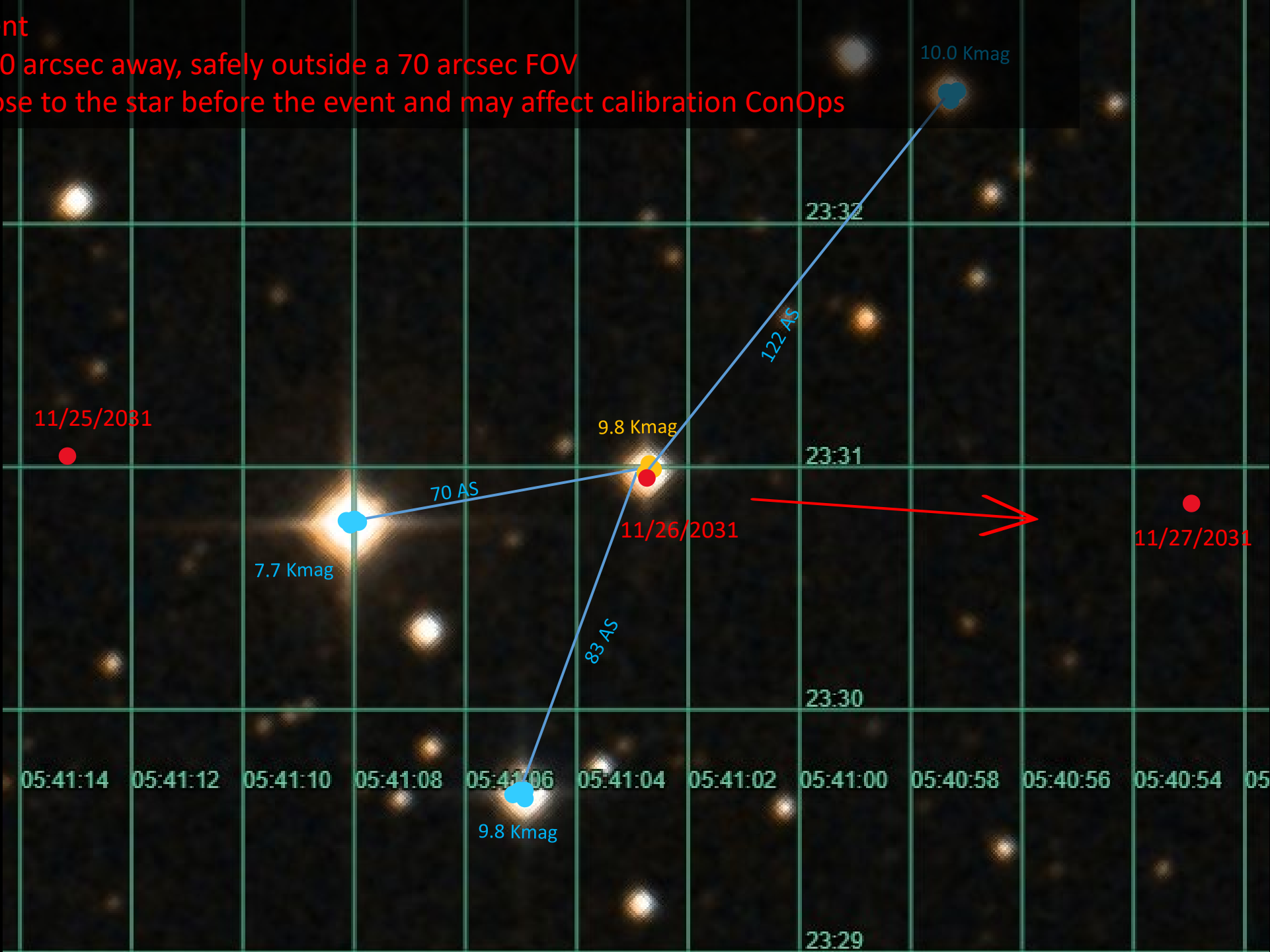
2031-04-30 Event
Closest stars are >150 arcsec away and do not pose concerns



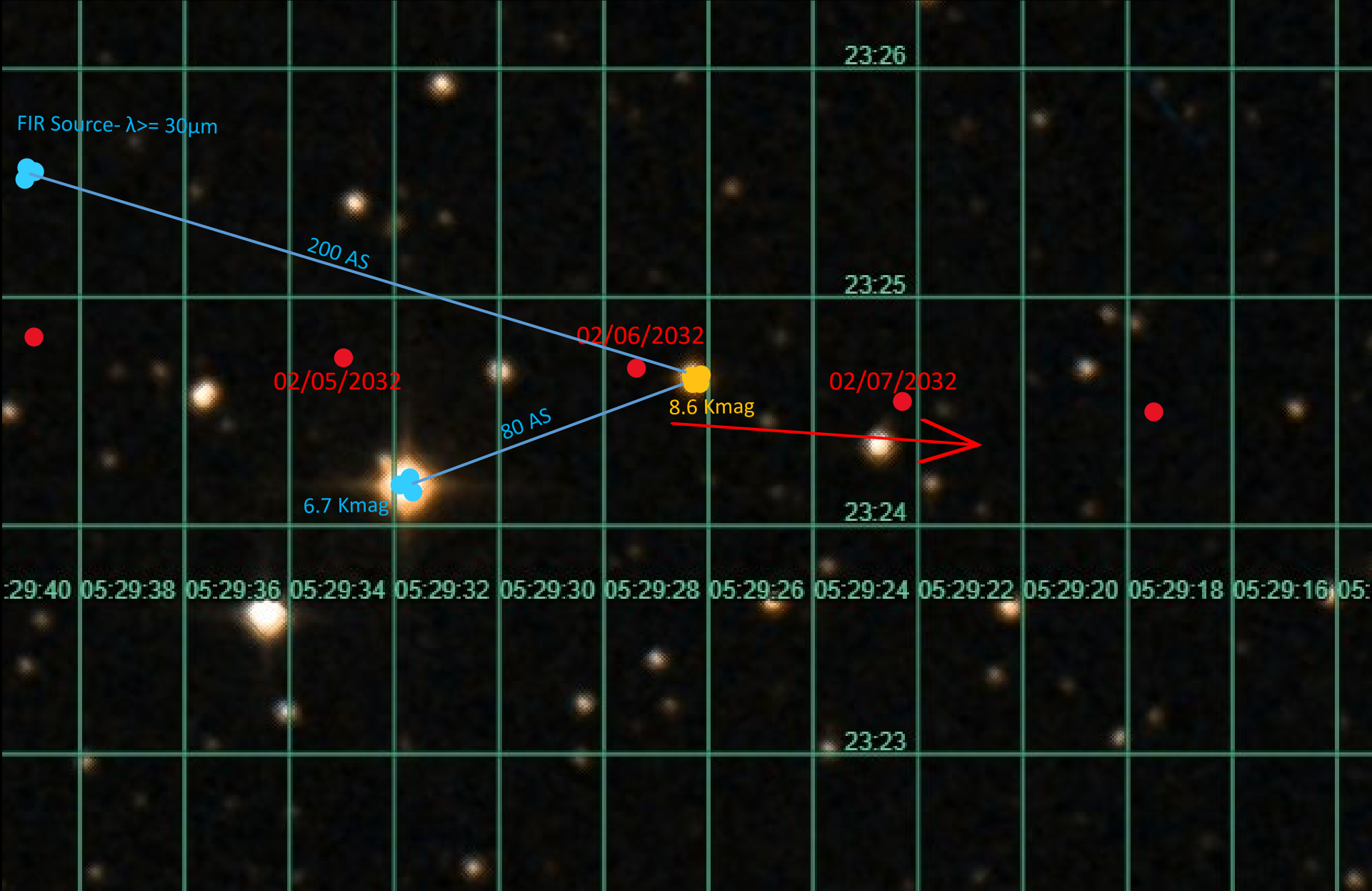
2031-11-26 Event

Closest star is 70 arcsec away, safely outside a 70 arcsec FOV

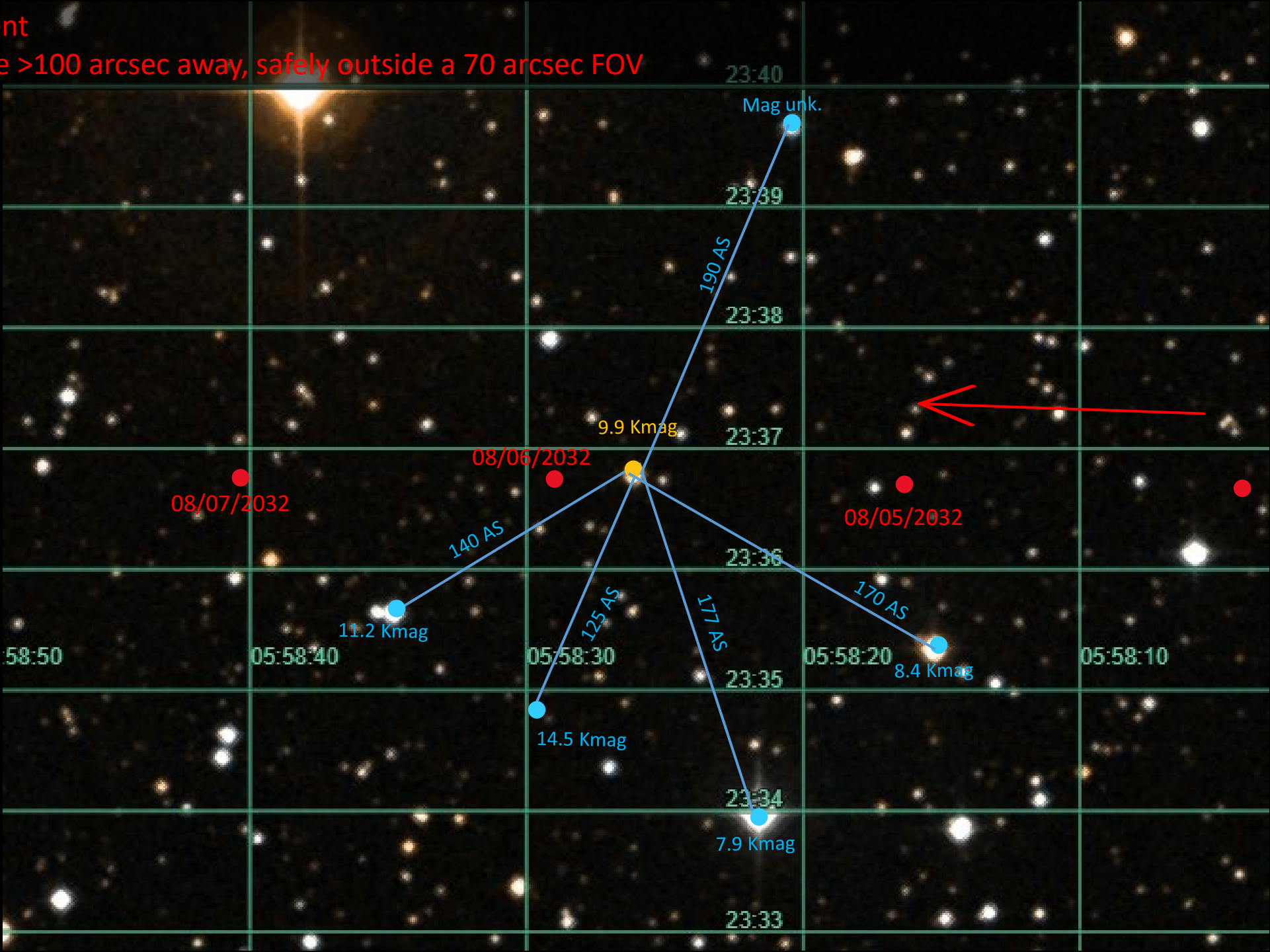
Uranus goes close to the star before the event and may affect calibration ConOps



2032-02-06 Event
Closest star is 80 arcsec away, safely outside a 70 arcsec FOV
Uranus goes close to the star after the event and may affect calibration ConOps



2032-08-06 Event
Closest stars are >100 arcsec away, safely outside a 70 arcsec FOV





Shadow Chaser

Instrument Field of View Considerations

Kunio Sayanagi

2023-08-23

Background / Why this is important



- Shadow Chaser will likely adopt a photodetector rather than an imaging detector
- Photodetector measures the total incoming flux from the field of view, and does not inform what sources are present in the FoV
- We need to predict what objects will be in the FoV during the time of the occultation events, and size the FoV to minimize the flux from undesired sources
- FoV must be small enough that it excludes as many undesirable sources as possible, but must be large enough that sources do not wander in/out of field of view due to factors such as:
 - Orbital motion of Uranian Satellites
 - Spacecraft Pointing stability
- Categories of sources:
 - Star to be occulted (i.e. “signal”)
 - Uranus and its Rings (“noise”)
 - Uranian Moons
 - Other Stars in the background



JWST View of Uranian System

Things to note:

- Rings are bright and VERY close to the planet
- Satellites are also bright
- Other sources come and go near Uranus!

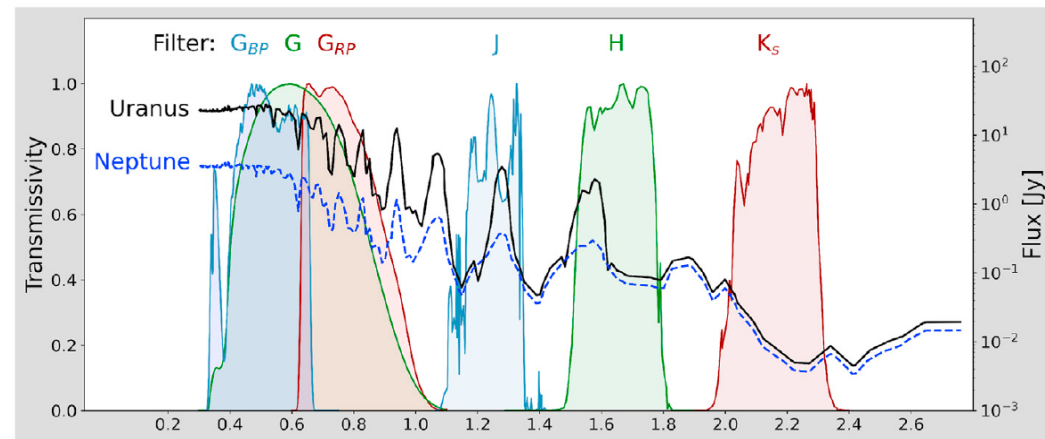


Fig. 2. Uranus and Neptune composite spectra (solid black and dashed blue lines corresponding to right y-axis) overlaid with bandpasses of the seven filters used in this study (shaded regions corresponding to left y-axis). See Section 3.1 for explanation of how these spectra were produced.

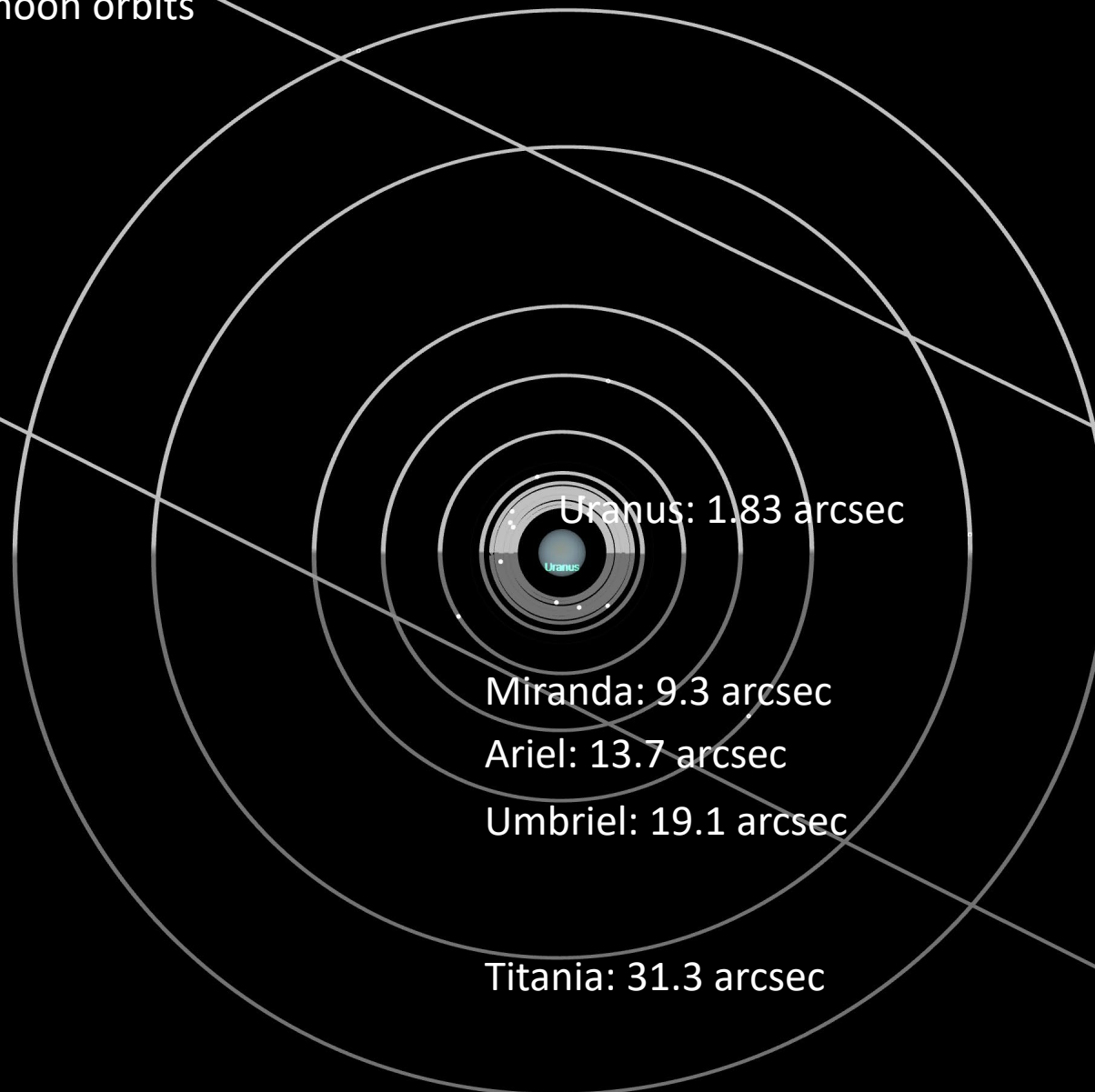
JWST View of Uranus System



Uranus System Seen from Earth

Apparent Radius of Uranus and moon orbits

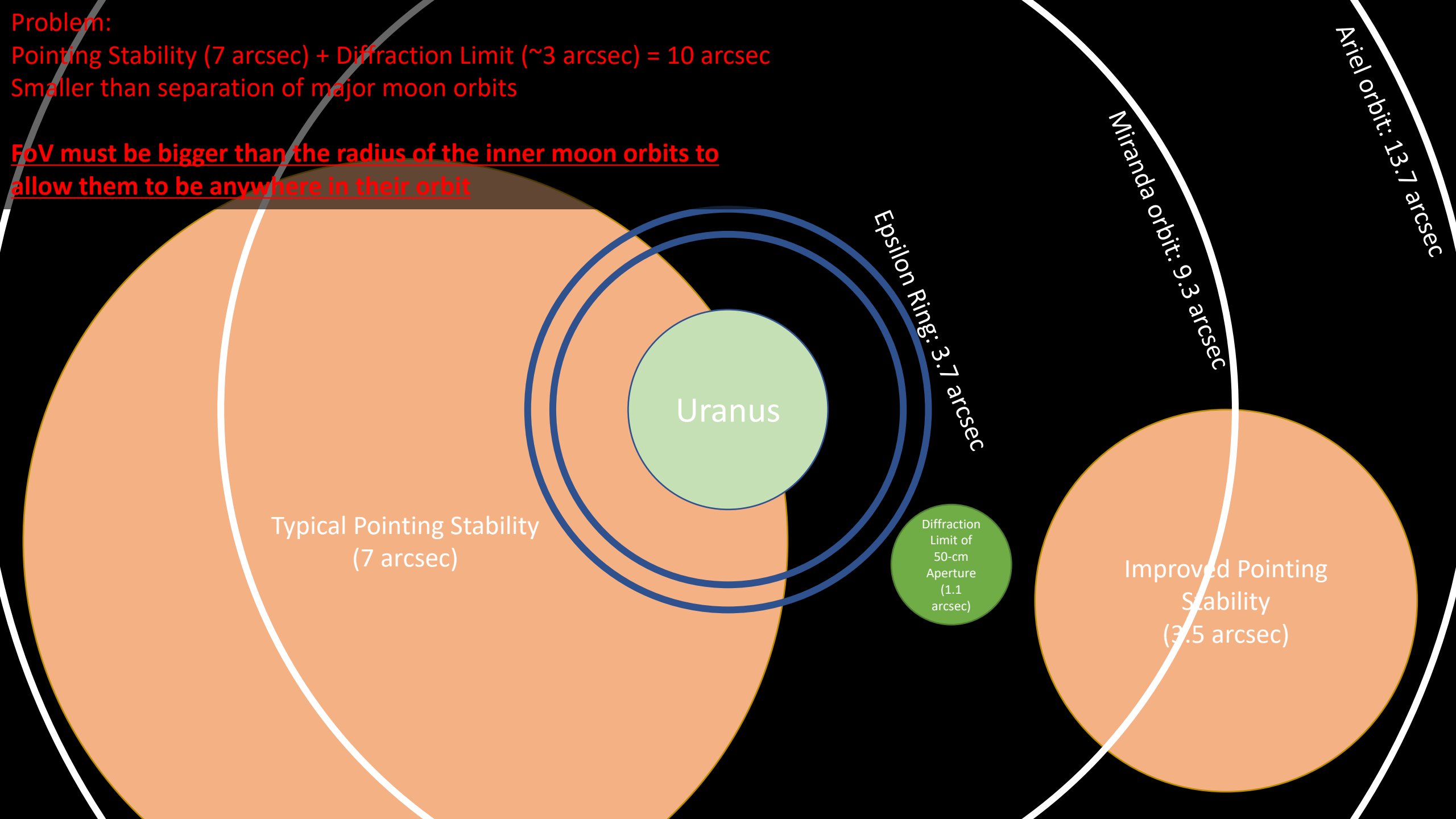
(2031-02-15 02:04UTC)



Diffraction Limit of a
● 20-cm Aperture:
2.76 arcsec

Problem:
Pointing Stability (7 arcsec) + Diffraction Limit (~3 arcsec) = 10 arcsec
Smaller than separation of major moon orbits

FoV must be bigger than the radius of the inner moon orbits to allow them to be anywhere in their orbit



Consideration:

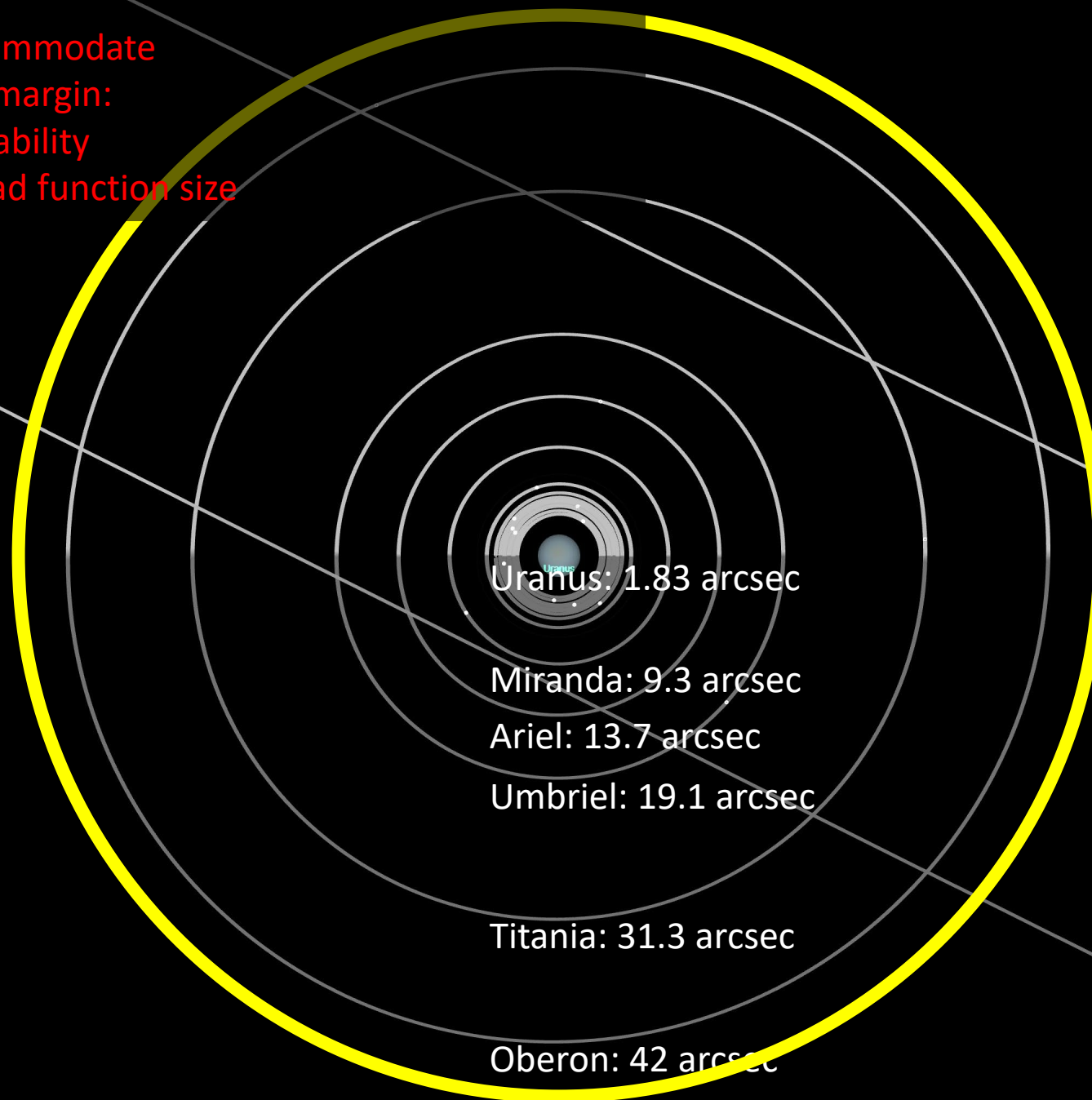
FoV 97 arcsec across will accommodate
all moons with the following margin:

7 arcsec pointing stability

6 arcsec point-spread function size

Diffraction Limit of a

● 20-cm Aperture:
2.76 arcsec

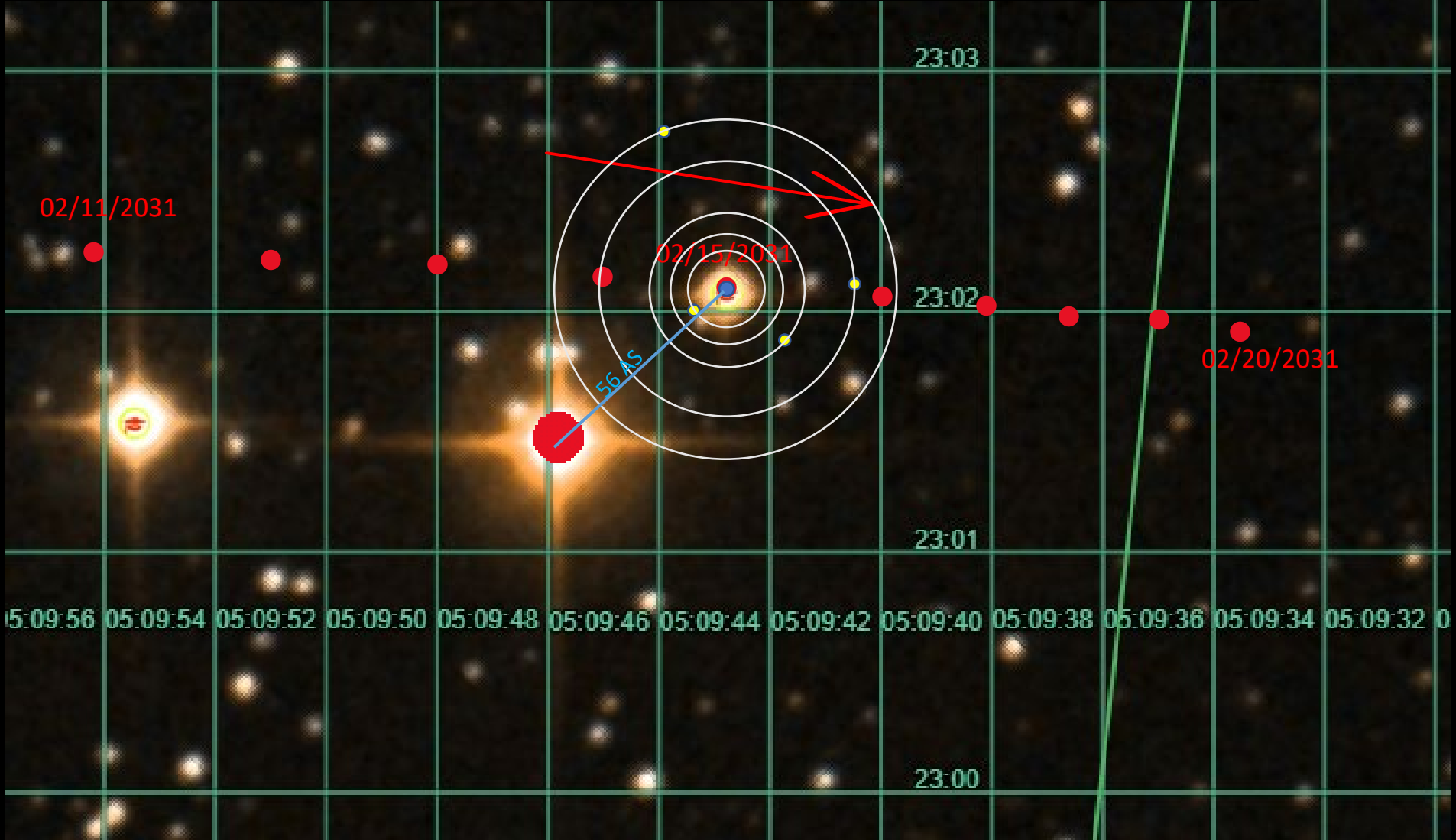


FoV: 97 arcsec across
Oberon Orb diam: 84 arcsec
Pointing Stability: 7 arcsec
X2 Diffraction limit: 6 arcsec

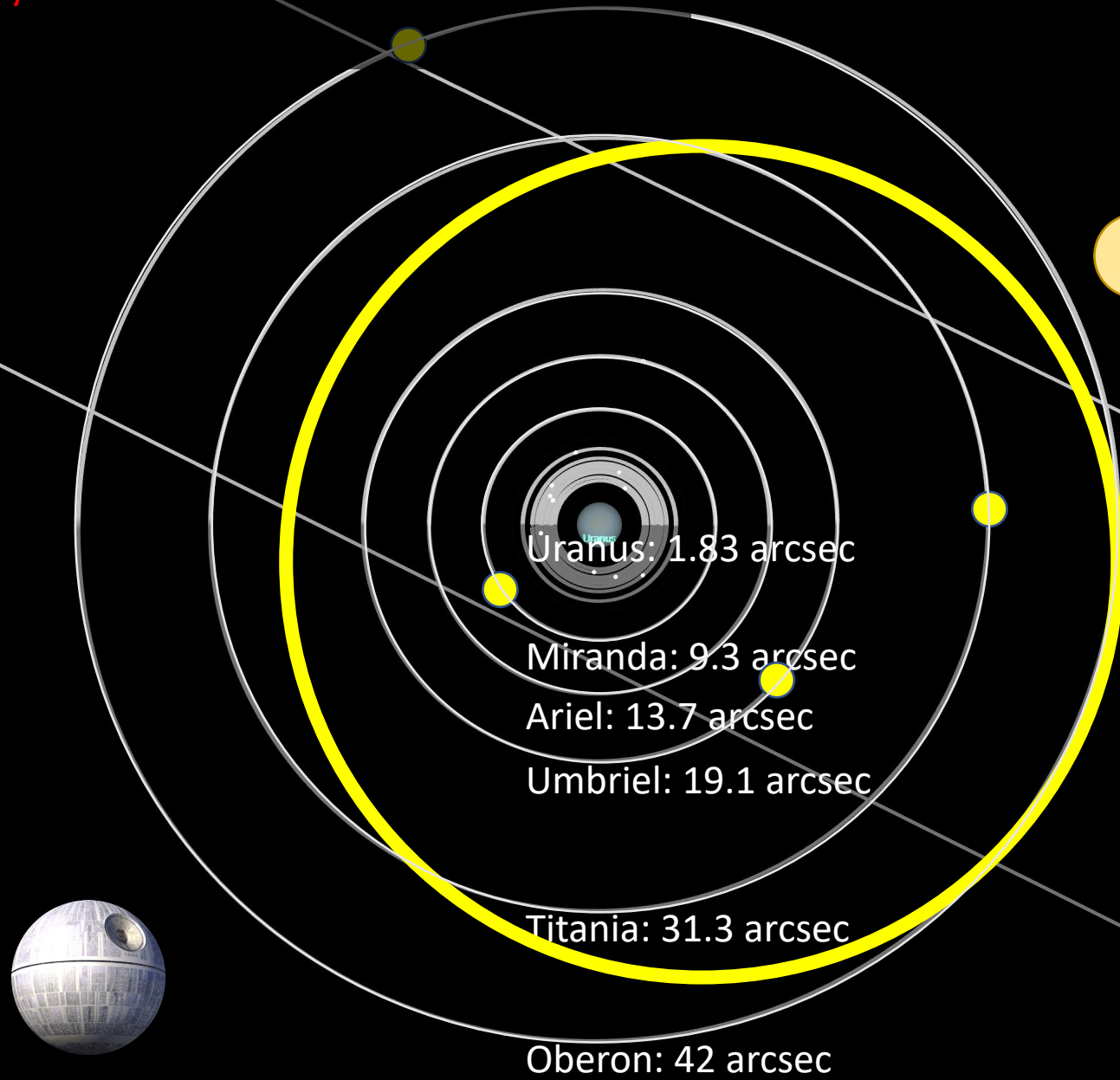
Background Starfield around the 2031-02-15 Uranus Occultation

A bright star exists 56 arcsec away from Uranus and occulted star

- Occulted star is 4.2 magnitude in 2-micron K band
- The “death star” (that’s no moon!) is 1.5 mag in 2-micron K band. X12 times brighter!!



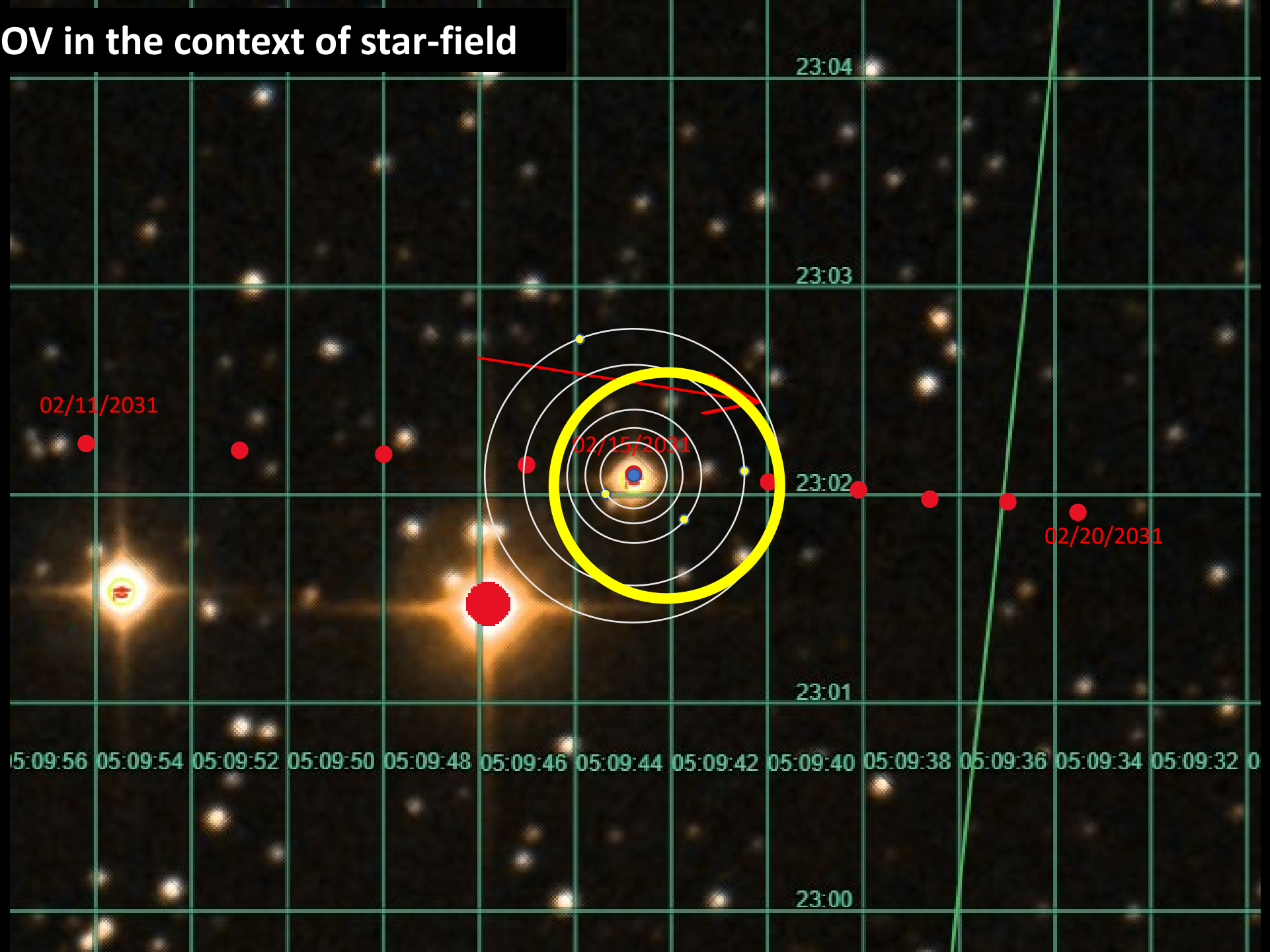
Potential Solution:
FoV 70 arcsec across will safely exclude Oberon and Death Star
during 2031-02-15 Event



Diffraction Limit of a
● 20-cm Aperture:
2.76 arcsec
● 7 arcsec pointing
stability

FOV: 70 arcsec across
Oberon Orb diam: 84 arcsec
Pointing Stability: 7 arcsec
X2 Diffraction limit: 6 arcsec

70 arcsec FOV in the context of star-field



How do we determine the FoV?

Step 1: Need detector's sensing area dimensions in unit of mm x mm

Step 2: FoV (in milli-radians) divided by sensing area dimension (mm) will give the plate-scale in milli-radians per mm

Step 3: Determine the focal length needed to give the plate-scale determined in Step 2.

What is the size of a typical detector?

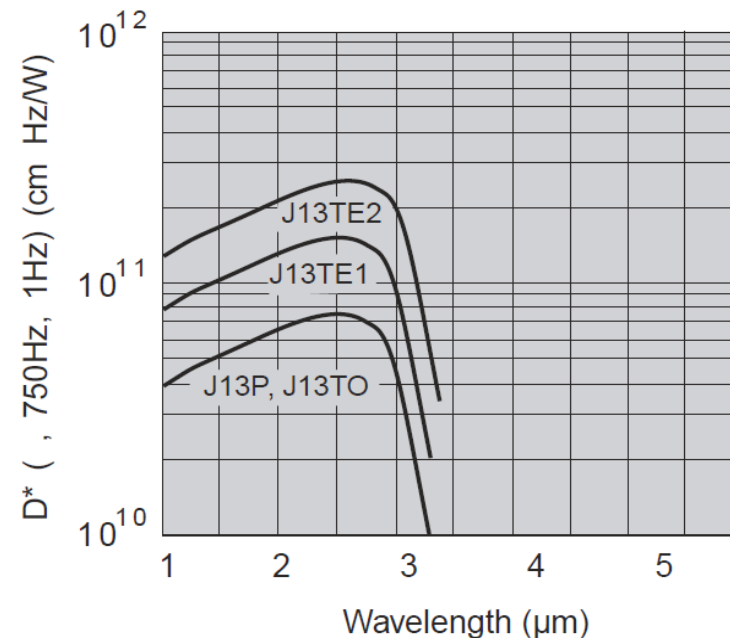
- Reference Photo Detector: Teledyne J13TE2 (PbS)
- https://www.teledynejudson.com/prods/Documents/PbSalt_shortform_Oct2002.pdf
- Has nominal sensitivity in 2-micron wavelengths

J13TE2 Series

2-Stage Thermoelectrically Cooled PbS Detectors

The J13TE2 Series detectors are high quality PbS photodiodes mounted on two-stage thermoelectric coolers with thermistors for control and stabilization of the detector element. At the standard operating temperature of -30°C , the wavelength peak is $2.6\mu\text{m}$.

Figure 18-1
Detectivity vs Wavelength for J13 Series PbS



Model Number	Part Number	Active Size	Wavelength p	D* (p, 750, 1) (min.) (cmHz ^{1/2} W ⁻¹)	Blackbody D* (500K, 750, 1) (min.) (cmHz ^{1/2} W ⁻¹)	Responsivity @ p (min.) (V/W)	Resistance (M)	Time Constant (μsec)	Operating Temperature (K)	Standard Package
		(mm)	(μm)							
J13P Series Room Temperature PbS										
PS3-0-01	1100012	1 x 1	2.5	7.7x10 ¹⁰	7.7x10 ⁸	3x10 ⁵	0.5 - 2.5	150 - 350	298	Plate
PS3-0-02	1100020	2 x 2				1.5x10 ⁵				
PS3-0-03	1100025	3 x 3				1x10 ⁵				
PS3-0-06	1100160	6 x 6				5x10 ⁴				
PS3-0-10	1100190	10 x 10				3x10 ⁴				
J13TO Series Room Temperature TO Package PbS										
PS3-0-51	1200045	1 x 1	2.5	7.7x10 ¹⁰	7.7x10 ⁸	3x10 ⁵	0.5 - 2.5	150 - 350	298	TO-5
PS3-0-52	1200075	2 x 2				1.5x10 ⁵				
PS3-0-53	1200090	3 x 3				1x10 ⁵				
PS3-0-86	1200135	6 x 6				5x10 ⁴				TO-8
J13TE Series Thermoelectrically Cooled PbS										
PS3-1-71	1200285	1 x 1	2.5	1.5x10 ¹¹	1.5x10 ⁹	7x10 ⁵	0.5 - 8	500 - 1000	253	Single Stage TO-37 TO-3
PS3-1-72	1200295	2 x 2				3.5x10 ⁵				
PS3-1-73	1200305	3 x 3				2.3x10 ⁵				
PS3-1-310	1200306	10 x 10				0.7x10 ⁵				
PS3-1-81	1200367	1 x 1	2.5	1.5x10 ¹¹	1.5x10 ⁹	7x10 ⁵	0.5 - 8	500 - 1000	253	One- Stage TO-8
PS3-1-82	1200368	2 x 2				3.5x10 ⁵				
PS3-1-83	1200369	3 x 3				2.3x10 ⁵				
PS3-2-71	1200325	1 x 1	2.6	2.5x10 ¹¹	2.3x10 ⁹	9x10 ⁵	1 - 10	700 - 1200	243	Two- Stage TO-37
PS3-2-72	1200345	2 x 2				4.5x10 ⁵				
PS3-2-73	1200365	3 x 3				3x10 ⁵				
PS3-2-81	1200328	1 x 1	2.6	2.5x10 ¹¹	2.3x10 ⁹	9x10 ⁵	1 - 10	700 - 1200	243	Two- Stage TO-8
PS3-2-82	1200338	2 x 2				4.5x10 ⁵				
PS3-2-83	1200358	3 x 3				3x10 ⁵				
PS3-3-31	1200371	1 x 1	2.7	3x10 ¹¹	1.8x10 ⁹	1x10 ⁶	2 - 25	2500 - 3500	208	Three- Stage TO-3
PS3-3-32	1200372	2 x 2				5x10 ⁵				
PS3-3-33	1200373	3 x 3				3.5x10 ⁵				

Sensing Area: 1 mm x 1 mm

F-number Calculation

- FOV: 70 arcsec
- Sensor Area: 1 mm x 1 mm (assuming Teledyne PS3-2-71 or PS3-2-81)
- Plate Scale: 70 arcsec/mm
- Plate Scale Equation:
$$\text{PlateScale} = \frac{206265}{D \times f/\#} \text{ (arc sec onds / mm)}$$
 - Where D is aperture diameter
 - <https://supernova.lbl.gov/~sed/telescope/obsguide/platescale.html>
- If we assume $D = 300 \text{ mm} = 30 \text{ cm}$
- $f/\# = \frac{206265}{D \times \text{PlateScale}} = 9.8$
- (The notional telescope design by Tony Notari has $f/\# 6.0$, which is “in the same ballpark”)



Shadow Chaser Detector Considerations

Kunio M. Sayanagi

Exploring Goddard Detectors:

- John Marketon (D211)m James Chevenak (GSFC-5530), David Franz (GSFC-5530), Murzy Jhabvala (GSFC-5500), Augustyn Waczynski (GSFC-5530)

Survey of COTS Detectors:

- Tamer Refaat (D211), John Smith (E304)

Predicting/Simulating Detector Performance during Occultation

- Will Smith (Boston U.), Justin Garland (E302/AMA. Hampton U.), John Smith (E304)

Notes for later reference – see following notes for details:

ShadowChaser_FluxCalc-Notes_2023-09-07_Kunio.docx

Note-photodetector-detectivity_2023-09-07kms.docx

Nature of the challenge: Weak flux from Uranus

Flux:

Uranus + Star

Uranus Only

Flux from Uranus is only 10^{-14} W/m^2 , which is $\sim 10^4 \text{ photons m}^{-2} \text{ s}^{-1}$.

Detecting the flux is a challenge, and even when the flux is detected, measurement is limited by shot-noise.

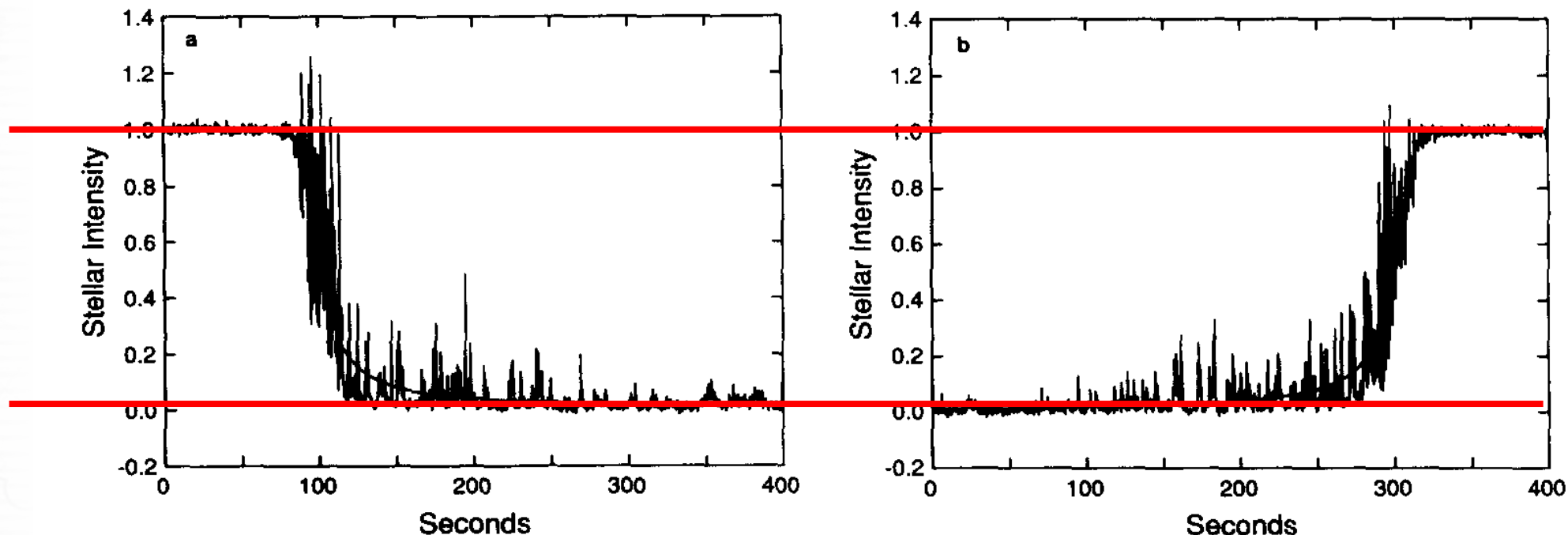


FIG. 6. (a) Immersion occultation lightcurve, plotted at 0.2 sec/point ($\lambda = 2.2 \mu\text{m}$). The solid line is the best-fitting isothermal atmospheric model curve. (b). Emersion occultation lightcurve, plotted at 0.2 sec/point ($\lambda = 2.2 \mu\text{m}$). The solid line is the best-fitting isothermal atmospheric model curve.

French, Jones and Hyland (1987)

How were past ground-based measurements made?



Occultation measurements were made in 2-micron bands in the 1980s.

- E.g. French et al. (1982), French, Jones and Hyland (1987) used a telescope with >2-meter aperture (>x100 larger light-collecting area than 20-cm envisioned for Shadow Chaser).
- Even with the larger aperture, measuring flux from Uranus should have required a detector with detectivity of $D^* = 4.5 \times 10^{14} \text{ cm Hz}^{1/2} \text{ W}^{-1}$, which is 3 orders of magnitude better than best detectors today with $D^* = 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$.

Examples of past occultations and their observations



U12. French et al. (1982)

Star: UCAC2 25096598

Observed on 1.9-meter telescope at Mount Stromlo Observatory in 2.2 microns (K band)

Star Magnitudes:

R 12.07

G 11.684

J 9.619

H 8.857

K 8.674

U15. French et al. (1987)

Star: UCAC2 23648038

Observed on 4.0-meter telescope at CTIO, 3.6-m at ESO, and 2.6-meter at CLCO, all in the K band.

Star Magnitudes:

R 10.63

G 10.479

J 8.113

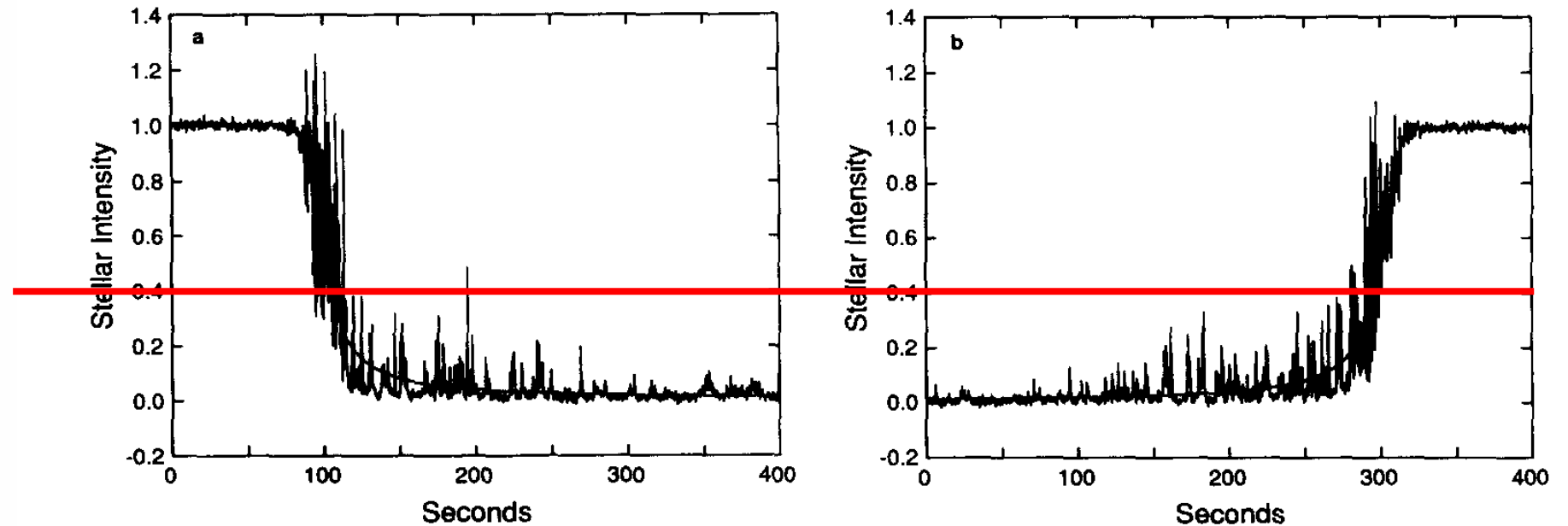
H 7.362

K 7.15

Occultation Sensitivity



Conjecture: Stellar Occultation measurements do not depend on precisely measuring the Uranus-only flux.



- Could the measurements be sensitive to only the early/late part of the ingress/egress light curve? (e.g. above the red line)
- Ground-based observations are relatively expensive, so their approach is to try taking data and see if it works. No detailed sensitivity study has been published.

Ongoing Study – characterize occultation sensitivity



- Use latest Uranus GRAM profiles as “truth” (generated by Justin Garland)
- Use the Uranus GRAM profiles to perform forward modeling of Stellar Occultation to generate synthetic occultation lightcurve. (Will Saunders)
- Repeat forward modeling with small perturbation to the “truth” (Will Saunders)
- Generate Jacobian matrix for the sensitivity, and test the conjecture that occultation measurements can produce most of the necessary results by measuring the early/late portion of ingress/egress. (John Smith)



Shadow Chaser Notional Telescope Specs

Anthony Notari (LARC-D211)

Preliminary Shadow Chaser Telescope specifications, 0.3 m diameter, F/6:

Material: TBD

Primary mirror

Diameter:	300 mm
Conic:	parabola
RoC:	600 mm
Surface roughness:	10 nm rms

Secondary mirror

Diameter:	60 mm
Conic:	-1.960
RoC:	120 mm
Obscuration:	5.6 %

Telescope

Focal length:	1800 mm (F/# 6.0)
BFL (from primary vertex):	50 mm
FS diameter:	0.890 mm
Field of View:	500 μrad (103 arcsec)
Coating:	Gold, ~97%R

WFE (total):	10 waves PV (0.6 μm)
Blur circle 90%EE:	0.045 mm (~25 μrad)
Focus tolerance:	±25 μm
Centration to FS:	1%
Pointing stability:	< 1 μrad

Environment

Operating temps:	??? deg C \
Survival temps:	???
WFE distortion to vacuum:	100 nm rms

Mirror durability:

Humidity	MIL-M-13508C
Temperature	MIL-M-13508C
Durability	MIL-M-13508C
Adherence	MIL-M-13508C
Abrasion	MIL-C-675C
Hardness	MIL-M-13508C

Optical Workmanship:

Meets	MIL-C-675C and MIL-O-13830
-------	----------------------------

Storage

Cleanliness:	CL300
--------------	-------

Testing

Primary:	WFE (hartmann, pentaprism)
Telescope:	WFE, blur circle, FS transmission, alignment
Environmental:	Thermal, vac
Mechanical:	Vib, shock
Coating:	Adhesion, durability, λ-shift in vac

Preliminary Shadow Chaser Telescope, 0.3 m diameter, F/6:
Ray-trace and Field stop

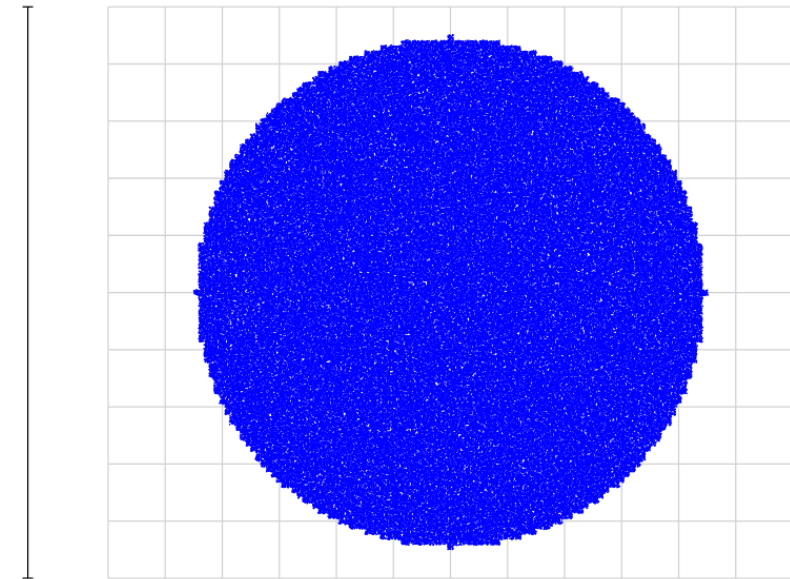
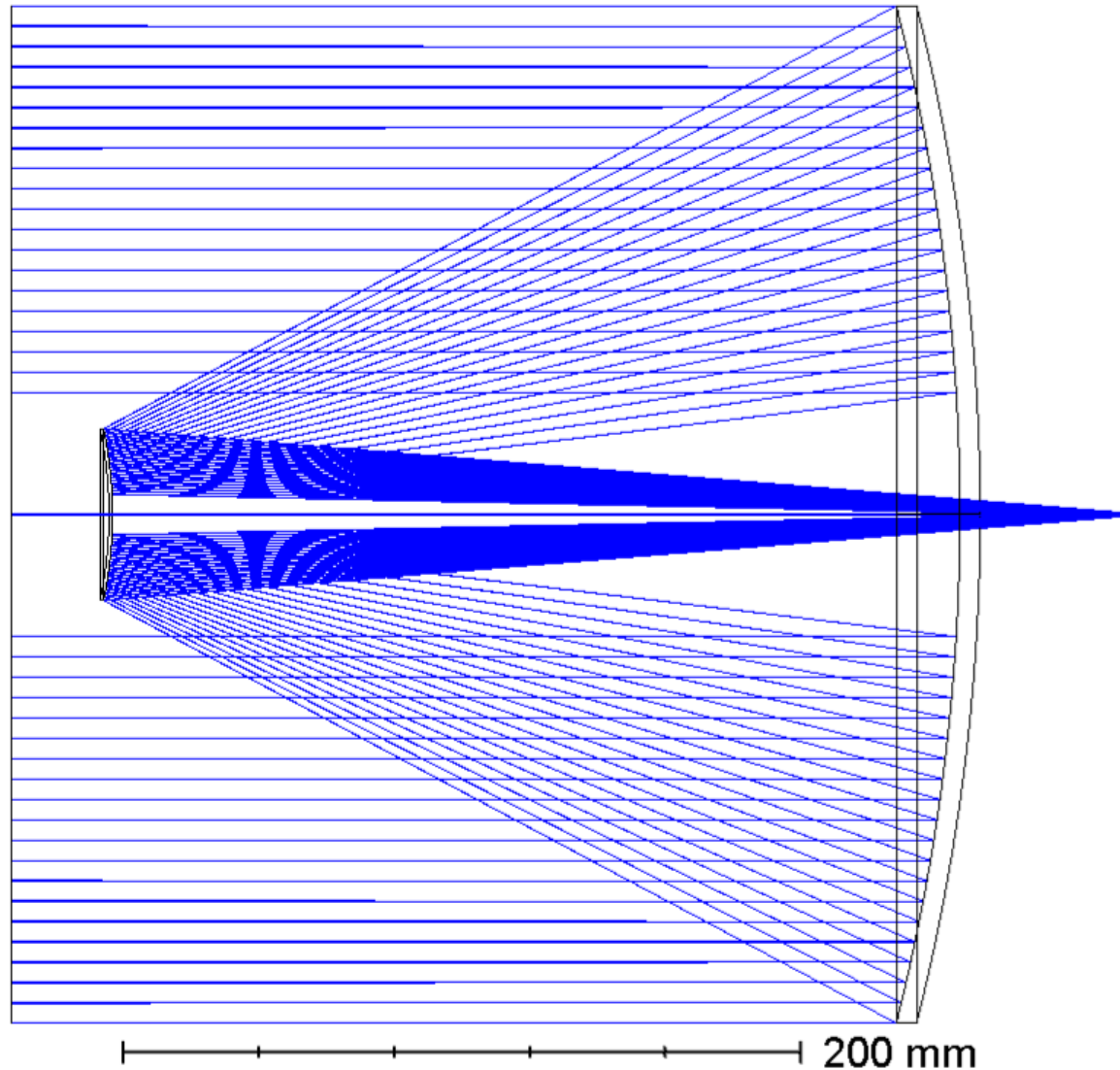


Image Diagram		
SC - telescope 8/23/2023 Scale bar is 1.0000 Millimeters. Field position: 0.0000, 0.0000 (deg) Efficiency : 89.197% Surface: 11		Zemax Zemax OpticStudio 19.4 SP2 SC-telescope.zos Configuration 1 of 1

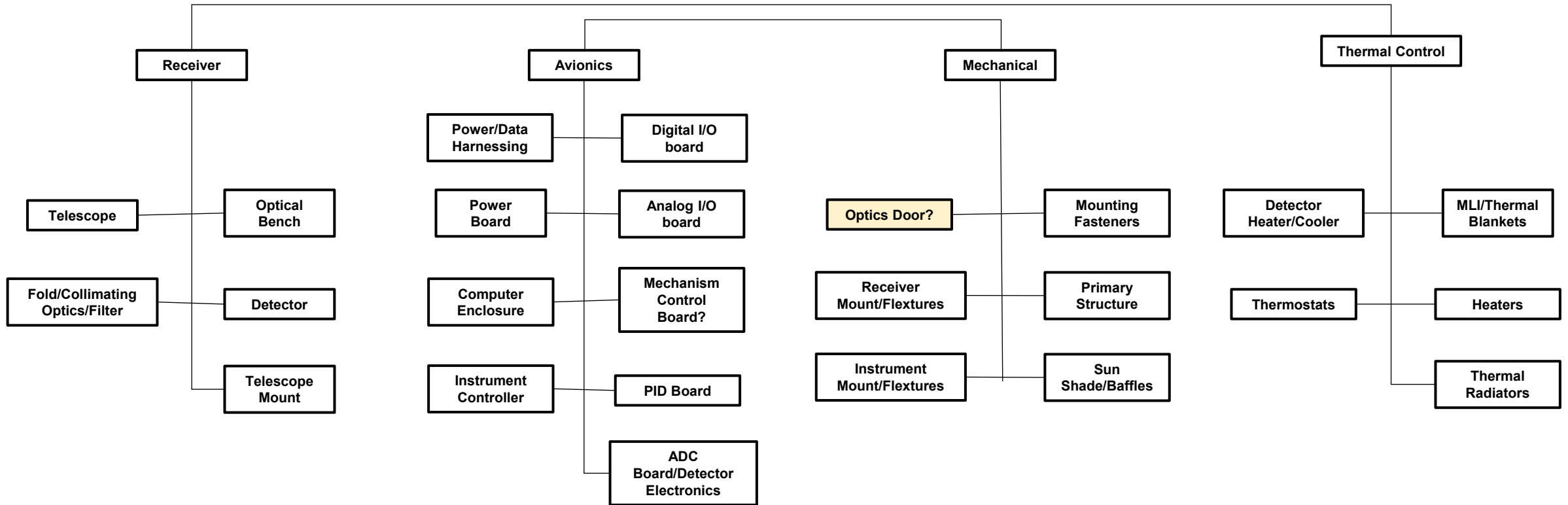
Image at Field Stop for 500 μ rad FOV
Diameter $\sim$ 0.9 mm
Transmission including obscuration and reflectivity of
Gold mirror coatings = 89.2%



Shadow Chaser System Block Diagram

Ted Holtz (LARC-D208)

ShadowChaser Instrument



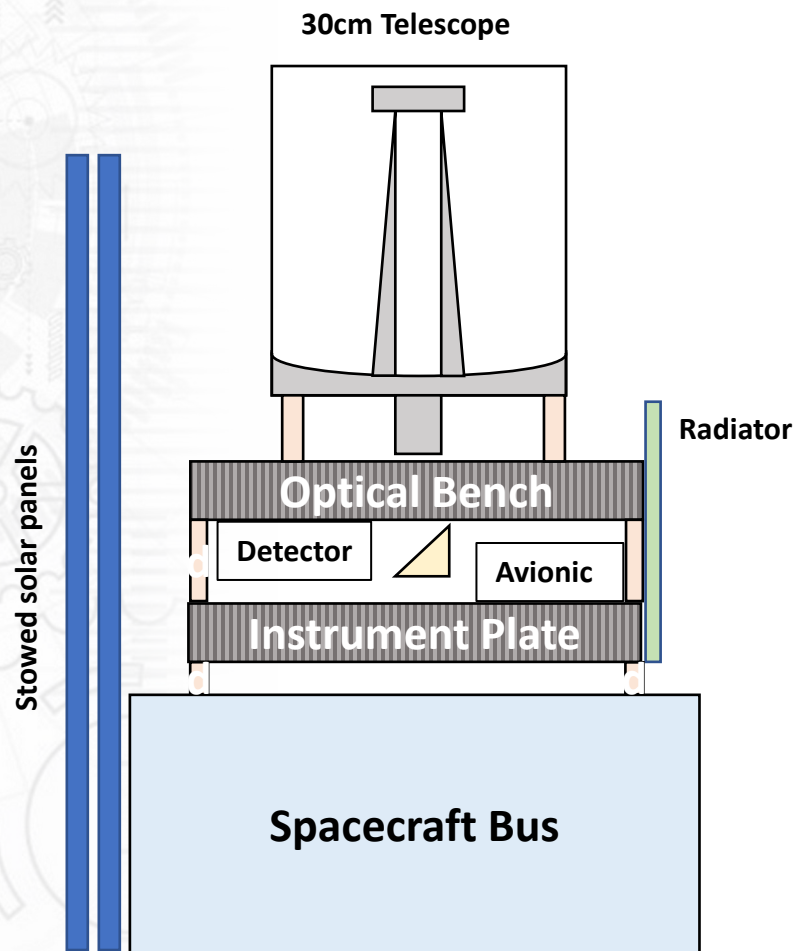
Assumes Data Storage, Downlink, and Power are supplied by the Spacecraft Bus



Shadow Chaser Spacecraft Notional Layout and Dimensions

Ted Holtz (LARC-D208)

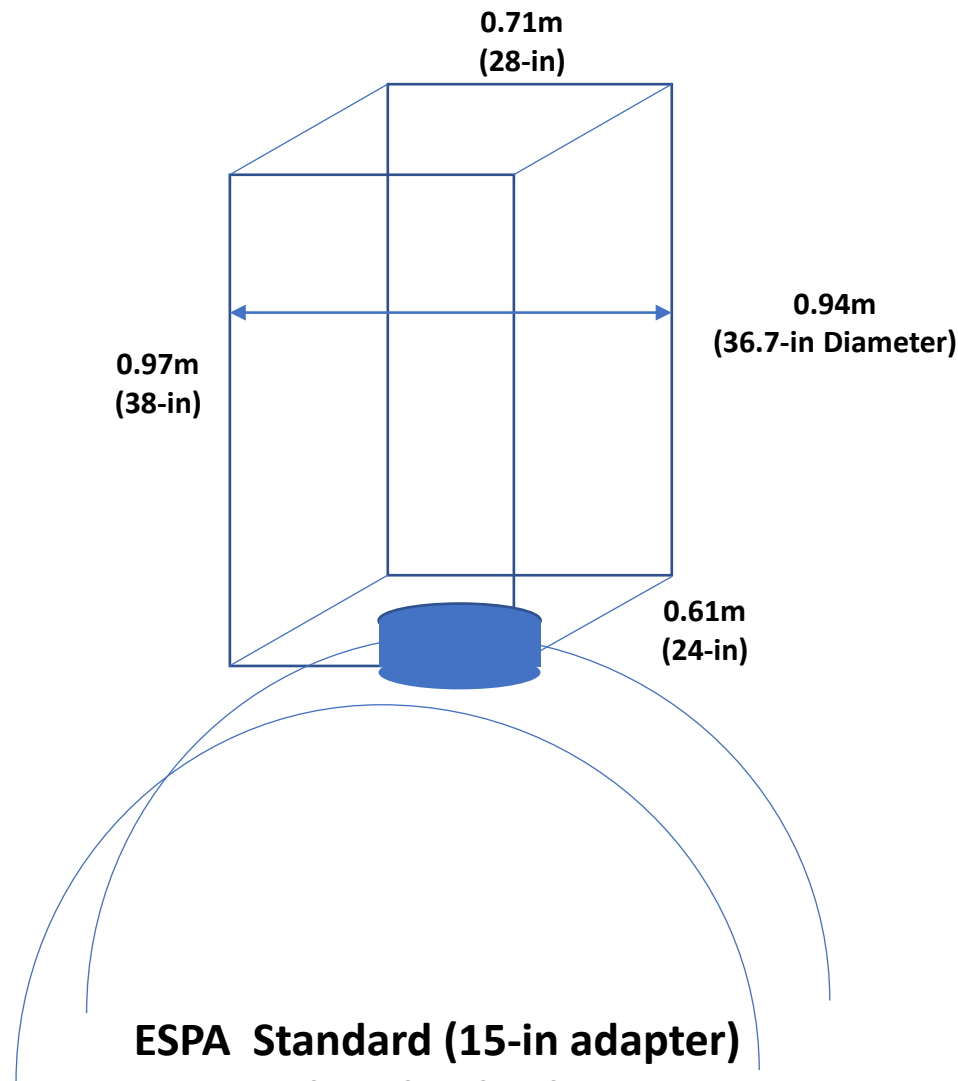
Notional Layout



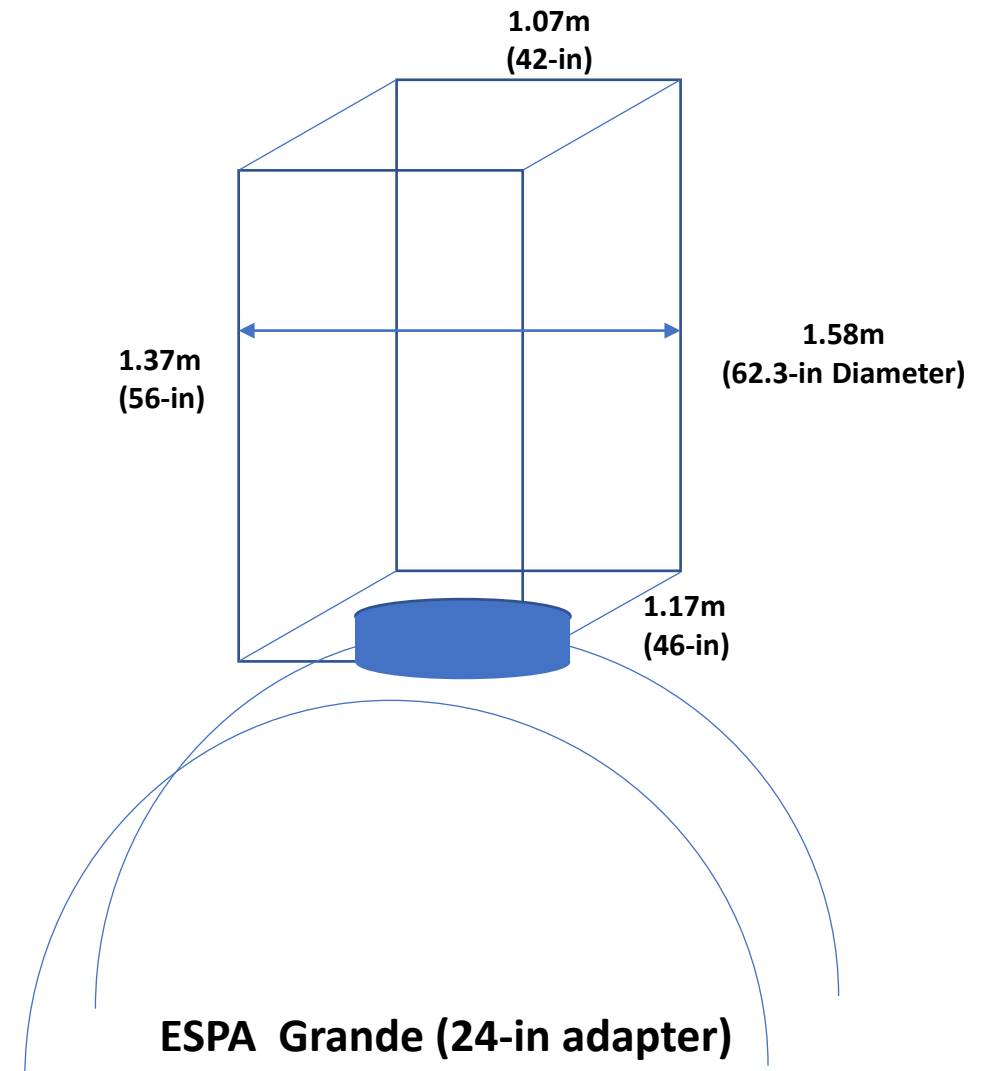
**20cm diameter F/10 has
200cm focal length**

**30cm diameter F/6 has 180cm
focal length**

Initial Notional ShadowChaser Instrument Layout



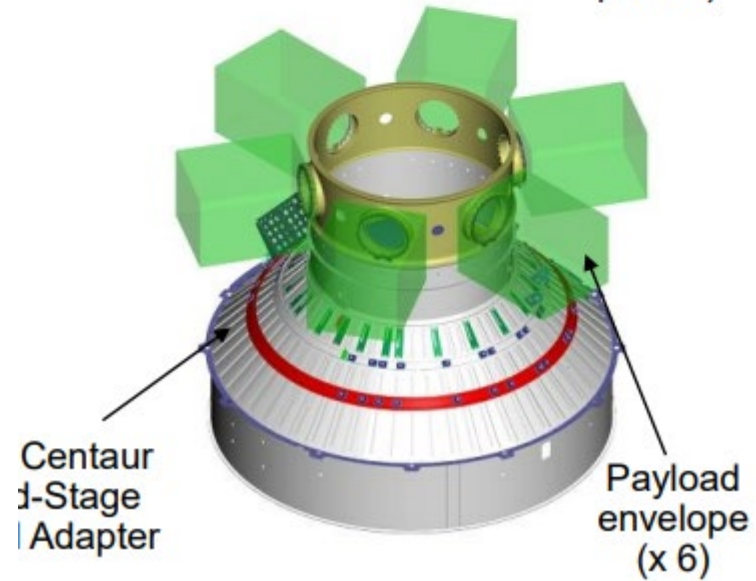
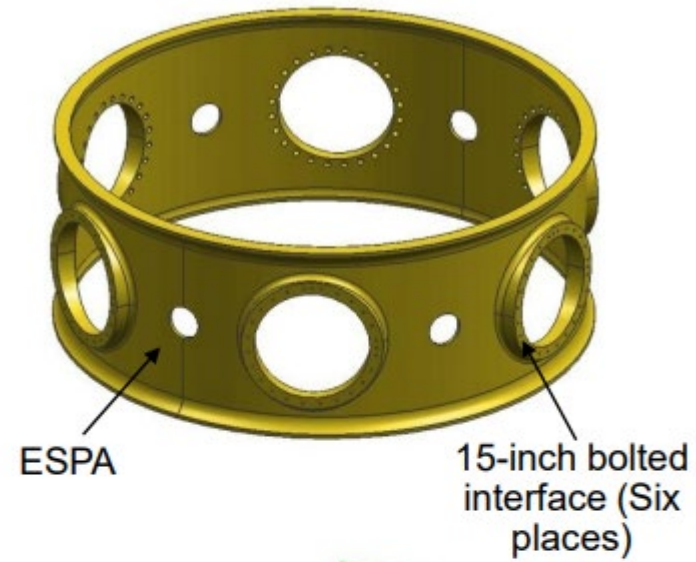
**ESPA Standard (15-in adapter)
total payload volume
(including spacecraft)
Allowable mass: 567kg at 20°
from adapter**



**ESPA Grande (24-in adapter)
total payload volume
(including spacecraft)
Allowable mass: 1543kg at 20°
from adapter**

This should be adequate for ShadowChaser

ESPA Ring Illustration





**Schmidt-Cassegrain
secondary mirror blockage**



**Ritchey-Chretien secondary mirror
blockage is larger due to hyperbolic, vs
spherical ground mirrors
(will need to factor this for a clear aperture
calculation).**



Shadow Chaser IDC2 Session VADR Launch Vehicle Candidates

Charles Pett, LaRC

August 22-24, 2023

Overview

- Which vendors can launch an ESPA Standard/ESPA Grande class spacecraft as a dedicated launch service?
- Where is there overlap between:
 - ESPA spacecraft volume constraints
 - ESPA allowable payload mass
 - Launch vehicle mass to orbit capabilities and fairing size
- **Analysis assumes spacecraft volume and mass to match that which ESPA ring allows**
 - Launch window and specific orbit not considered

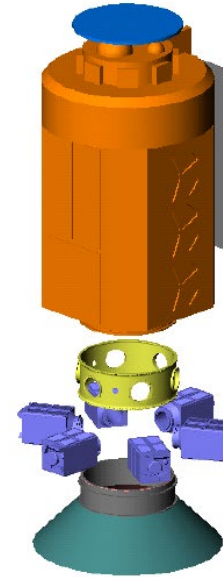


Figure 2. Left, ESPA and auxiliary payloads launching with primary spacecraft
Right, ESPA stack for ORBCOMM OG2 spacecraft

ESPA allowable payload volume

- **If we assume largest allowable ESPA volume, spacecraft is constrained by 56" dimension, to be conservative**
- **Thus, spacecraft volume constrains launch vehicle fairing to >1.42m**
- **Note: For rideshare with ESPA ring, >3.5-m fairing required**

- With a standard ESPA Ø15" port, the allocated payload volume is a 24" x 28" x 38" box as pictured in Figure 8.
- For the ESPA Grande with five Ø24" ports, the allocated volume is a 42" x 46" x 56" box also pictured in Figure 8. Note that these dimensions are for a 5-meter fairing. For a 4-meter fairing, the volume is 42" x 46" x 38".

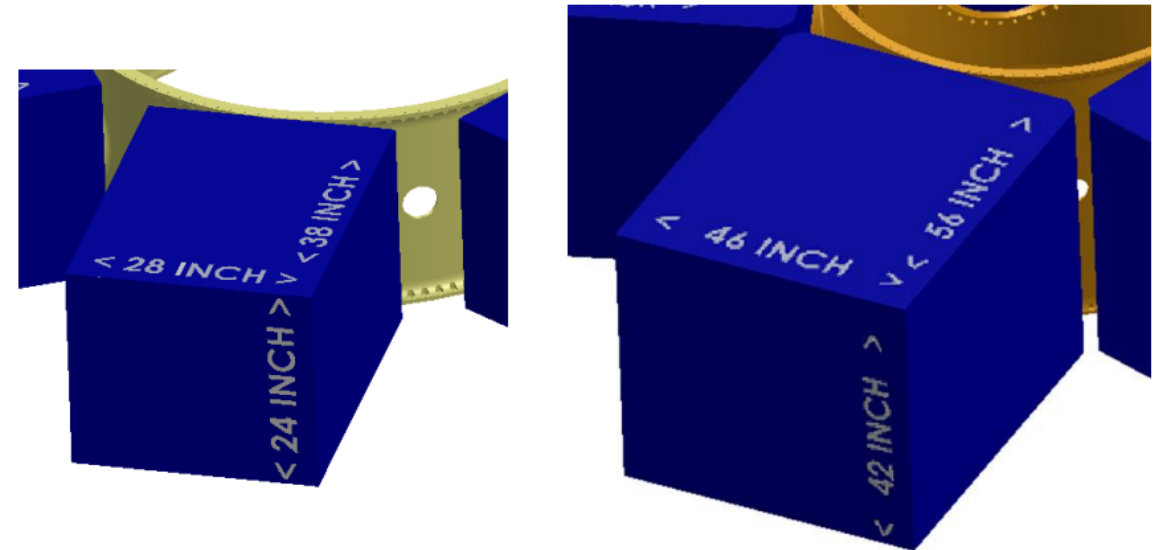


Figure 8. Left, Standard ESPA payload volume; Right, ESPA Grande payload volume for 5-meter fairing

ESPA allowable payload mass *per port*

- To be conservative, assuming a distance from bolt circle interface to payload center of gravity (CG) of 16 inches
- Assuming ESPA Grande allowable mass of ~2000lb, or 910kg for mass constraint

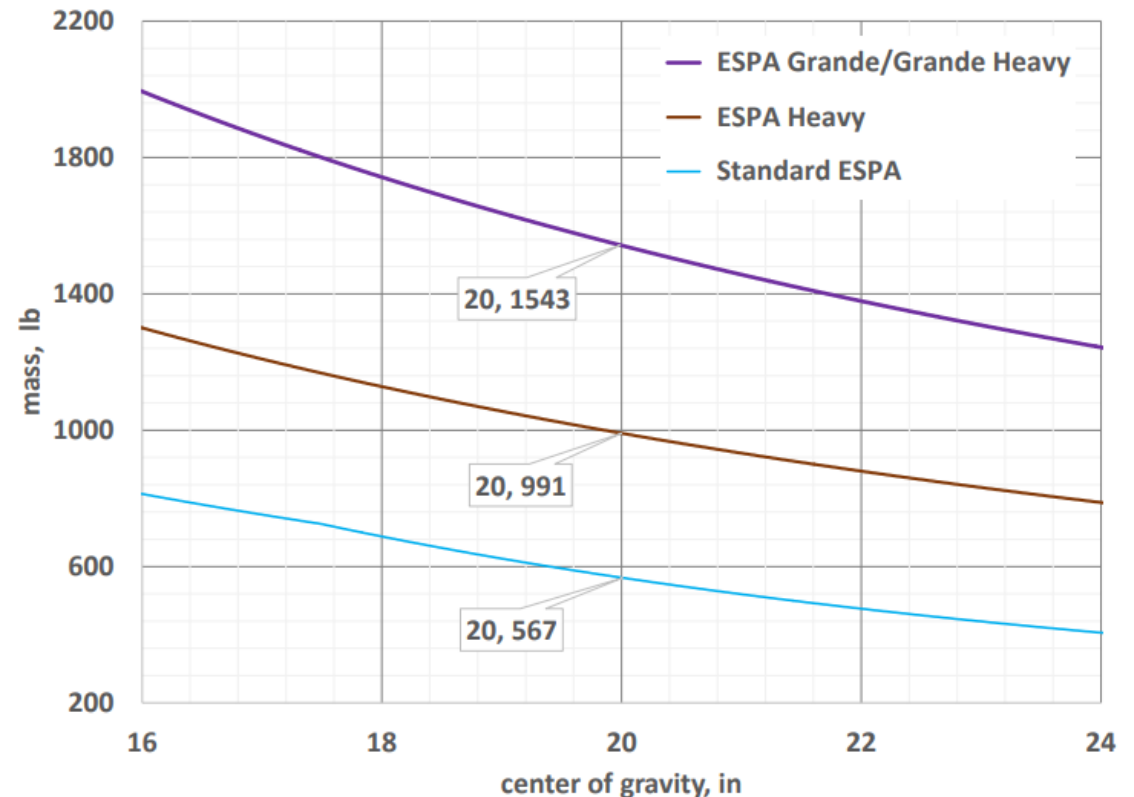


Figure 7. ESPA payload mass allowable vs distance from interface plane to payload center of gravity

Venture-Class Acquisition of Dedicated and Rideshare (VADR) Selections

- [ABL Space Systems](#) of El Segundo, California
- [Astra Space Inc.](#) of Alameda, California
- [Blue Origin Florida LLC](#) of Merritt Island, Florida
- L2 Solutions LLC of Houston – need data
- [Northrop Grumman Systems Corporation](#) of Chandler, Arizona
- [Phantom Space Corporation](#) of Tucson, Arizona
- [Relativity Space Inc.](#) of Long Beach, California
- [Rocket Lab USA Inc.](#) of Long Beach, California
- Spaceflight Inc. of Seattle – need data
- [Space Exploration Technologies Corp.](#) (SpaceX) of Hawthorne, California
- [United Launch Services LLC](#) of Centennial, Colorado
- Virgin Orbit LLC of Long Beach, California – need data
- [Firefly Space Transport Services](#) of Cedar Park, Texas

Is launch vehicle fairing >1.4m?

Vendor	Launch vehicle	Payload to LEO	Fairing	Meets fairing constraint?
ABL Space Systems	RS1	0.8-1 t (1200-200km SSO)	2 m	Yes
			2.7 m	Yes
Astra Space	Rocket 4	0.6 t (500km)	1.7 m	Yes
Blue Origin	New Glenn	45 t	7 m	Yes
Northrop Grumman	Antares	8 t	3.9 m	Yes
	Pegasus	0.5 t	1.1 m	No
Phantom Space	Daytona	0.5 t	1.5 m	Yes
	Laguna	1.2 t	2 m	Yes
Relativity Space	Terran R	23.5 t	5 m	Yes
Rocket Lab	Electron	0.3 t	1.2 m	No
	Neutron	13 t	7 m	Yes
SpaceX	Falcon 9	22.8 t	3.7 m	Yes
	Falcon Heavy	63.8 t	12.2 m	Yes
United Launch Alliance	Atlas V	8.08 t	4-5 m	Yes
	Vulcan	9.2 t	5.4 m	Yes
	Delta IV	10.2 t	5 m	Yes
Firefly Space	Alpha	1 t (300km)	5 m	Yes
	MLV	16 t	5 m	Yes

Can fairing constrained launch vehicles deliver 0.91t to orbit?

Vendor	Launch vehicle	Payload to LEO	Fairing	Meets mass constraint?	Mass margin
ABL Space Systems	RS1	0.8-1 t (1200-200km SSO)	2 m 2.7 m	No/Yes	-0.11 t/+0.09t
Astra Space	Rocket 4	0.6 t (500km)	1.7 m	No	-0.31 t
Blue Origin	New Glenn	45 t	7 m	Yes	44.1 t
Northrop Grumman	Antares	8 t	3.9 m	Yes	7.1 t
Phantom Space	Daytona Laguna	0.5 t 1.2 t	1.5 m 2 m	No Yes	-0.41 t 0.29 t
Relativity Space	Terran R	23.5 t	5 m	Yes	22.6 t
Rocket Lab	Neutron	13 t	7 m	Yes	12.1 t
SpaceX	Falcon 9	22.8 t	3.7 m	Yes	21.9 t
	Falcon Heavy	63.8 t	12.2 m	Yes	62.9 t
United Launch Alliance	Atlas V	8.08 t	4-5 m	Yes	7.2 t
	Vulcan	9.2 t	5.4 m	Yes	8.3 t
	Delta IV	10.2 t	5 m	Yes	9.3
Firefly Space	Alpha	1 t (300km)	5 m	Yes	0.09 t
	MLV	16 t	5 m	Yes	15.1 t

Vendor candidates

Tight mass budgets:

- ABL Space – RS1
- Phantom Space – Laguna
- Firefly Space – Alpha

Vendor	Launch vehicle	Payload to LEO	Fairing	Mass margin
ABL Space Systems	RS1	1 t (200km SSO)	2 m 2.7 m	0.09t
Blue Origin	New Glenn	45 t	7 m	44.1 t
Northrop Grumman	Antares	8 t	3.9 m	7.1 t
Phantom Space	Laguna	1.2 t	2 m	0.29 t
Relativity Space	Terran R	23.5 t	5 m	22.6 t
Rocket Lab	Neutron	13 t	7 m	12.1 t
SpaceX	Falcon 9	22.8 t	3.7 m	21.9 t
	Falcon Heavy	63.8 t	12.2 m	62.9 t
United Launch Alliance	Atlas V	8.08 t	4-5 m	7.2 t
	Vulcan	9.2 t	5.4 m	8.3 t
	Delta IV	10.2 t	5 m	9.3
Firefly Space	Alpha	1 t (300km)	5 m	0.09 t
	MLV	16 t	5 m	15.1 t

Preliminary conclusions and considerations

- Many VADR launch vehicles can deliver ESPA payloads to LEO
- Caution: The constraints here were based on ESPA max allowable port volume and so good vendor candidates may have been weeded out, such as RocketLab Electron. This may be a good option for a spacecraft with different size and mass constraints
- This was a high-level analysis assuming spacecraft mass and volume to be equal to ESPA volume and mass capabilities. More refined analysis will zero in on specific ESPA configuration, considering:
 - Refined spacecraft volume and mass
 - Payload CG location if using ESPA ring
 - LEO orbital elements
 - Launch schedule
 - Dedicated vs. Rideshare
 - Launch & integration cost

References

- Moog ESPA User Guide
- VADR launch provider websites and user guides



Rideshare options with ESPA ring

Charles Pett, LaRC

August 22-24, 2023

Table 2. Summary of common ESPA configurations

	Interface	Max Port Count	ESPA Height	Port Interface Fastener Size	Port Payload Capacity	ESPA Mass	Guideline Payload Volume
ESPA Standard	Ø 15"	6	24"	1/4" Fasteners	567 lb * (257 kg)	293 lb (133 kg)	24"x28"x38"
ESPA Heavy				5/16" Fasteners	991 lb * (450 kg)	293 lb (133 kg)	
ESPA Grande	Ø 24"	5	42"	1/4" Fasteners 5/16" Fasteners	1543 lb * (700 kg)	465 lb (211 kg)	42"x46"x56" **
ESPA Standard Variant	4-Point Mount	6	24"	1/4" Fasteners	400 lb (181 kg)	295 lb (134 kg)	24"x28"x38"
ESPA Standard Variant	Ø 11.7"	12	24"	1/4" Fasteners	300 lb (136 kg)	263 lb (119 kg)	TBD

M7 or M8 fasteners can replace 1/4" or 5/16" fasteners.

Port payload capacities assume payload center of gravity at 20 inches (50.8 cm).

* Capacities decrease to 485 lb, 710 lb, and 1026 lb (220 kg, 322 kg, and 465 kg) if utilizing the heritage ESPA load factors (8.5g/8.5g) regardless of APL mass.

** Volume shown is for 5-meter fairing; replace 56" with 38" for 4-meter fairing

Do launch vehicles meet fairing constraint?

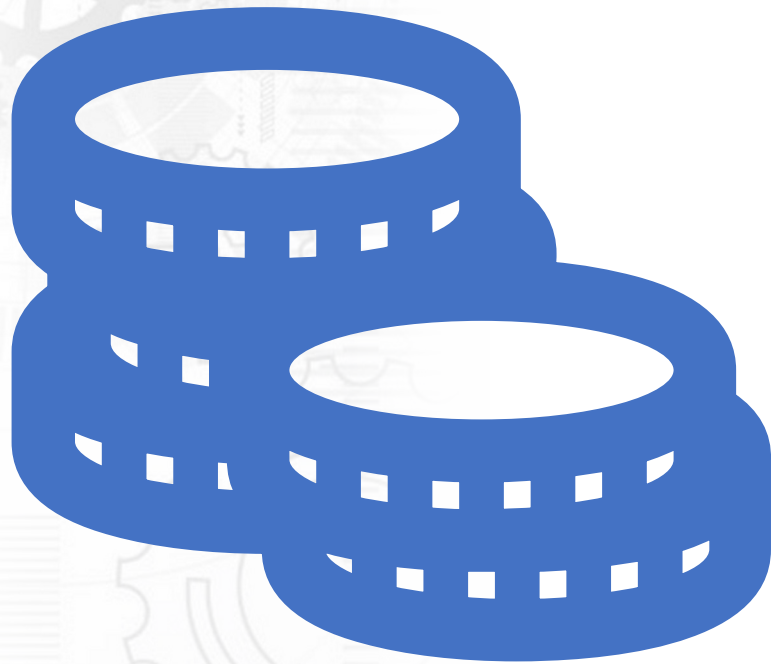
Provider	Launch vehicle	Payload to LEO	Fairing	Meets fairing constraint?
ABL Space Systems	RS1	0.8-1 t (1200-200km SSO)	2 m 2.7 m	No No
Astra Space	Rocket 4	0.6 t (500km)	1.7 m	No
Blue Origin	New Glenn	45 t	7 m	Yes
Northrop Grumman	Antares Pegasus	8 t 0.5 t	3.9 m 1.1 m	No ESPA Grande (56") No
Phantom Space	Daytona Laguna	0.5 t 1.2 t	1.5 m 2 m	No No
Relativity Space	Terran R	23.5 t	5 m	Yes
Rocket Lab	Electron Neutron	0.3 t 13 t	1.2 m 7 m	No Yes
SpaceX	Falcon 9 Falcon Heavy	22.8 t 63.8 t	3.7 m 12.2 m	No ESPA Grande (56") Yes
United Launch Alliance	Atlas V Vulcan Delta IV	8.08 t 9.2 t 10.2 t	4-5 m 5.4 m 5 m	Yes Yes Yes
Firefly Space	Alpha MLV	1 t (300km) 16 t	5 m 5 m	Yes Yes



Can fairing constrained launch vehicles meet mass to orbit constraint?

Provider	Launch vehicle	Payload to LEO	Fairing	Meets fairing constraint?	Meets mass constraint?	Smallest margin for primary payload*
Blue Origin	New Glenn	45 t	7 m	Yes	Yes	44.1 t
Northrop Grumman	Antares	8 t	3.9 m	No ESPA Grande (56")	Yes	7.1 t
Relativity Space	Terran R	23.5 t	5 m	Yes	Yes	25.6 t
Rocket Lab	Neutron	13 t	7 m	Yes	Yes	12.1 t
SpaceX	Falcon 9	22.8 t	3.7 m	No ESPA Grande (56")	Yes	21.9 t
	Falcon Heavy	63.8 t	12.2 m	Yes		62.9 t
United Launch Services	Atlas V	8.08 t	4-5 m	Yes	Yes	7.2 t
	Vulcan	9.2 t	5.4 m	Yes	Yes	8.3 t
	Delta IV	10.2 t	5 m	Yes	Yes	9.3
Firefly Space	Alpha MLV	1 t (300km)	5 m	Yes	Yes	89 kg
		16 t	5 m	Yes	Yes	15.1 t

***To be conservative, assumes largest ESPA ring mass + largest payload mass at 20-in CG**



Cost Findings for IDC2: ShadowChaser

Cost Analyst: Stephanie Primeaux

NASA Instrument Cost Model (NICM)

Overview

Using the normalized database, statistical analysis and data mining techniques were applied to develop:

- Cost Estimating Relationships (CERs) at the subsystem and system levels
- Schedule Estimating Relationships (SERs) at the System Level
- Phase B-D
- FY\$

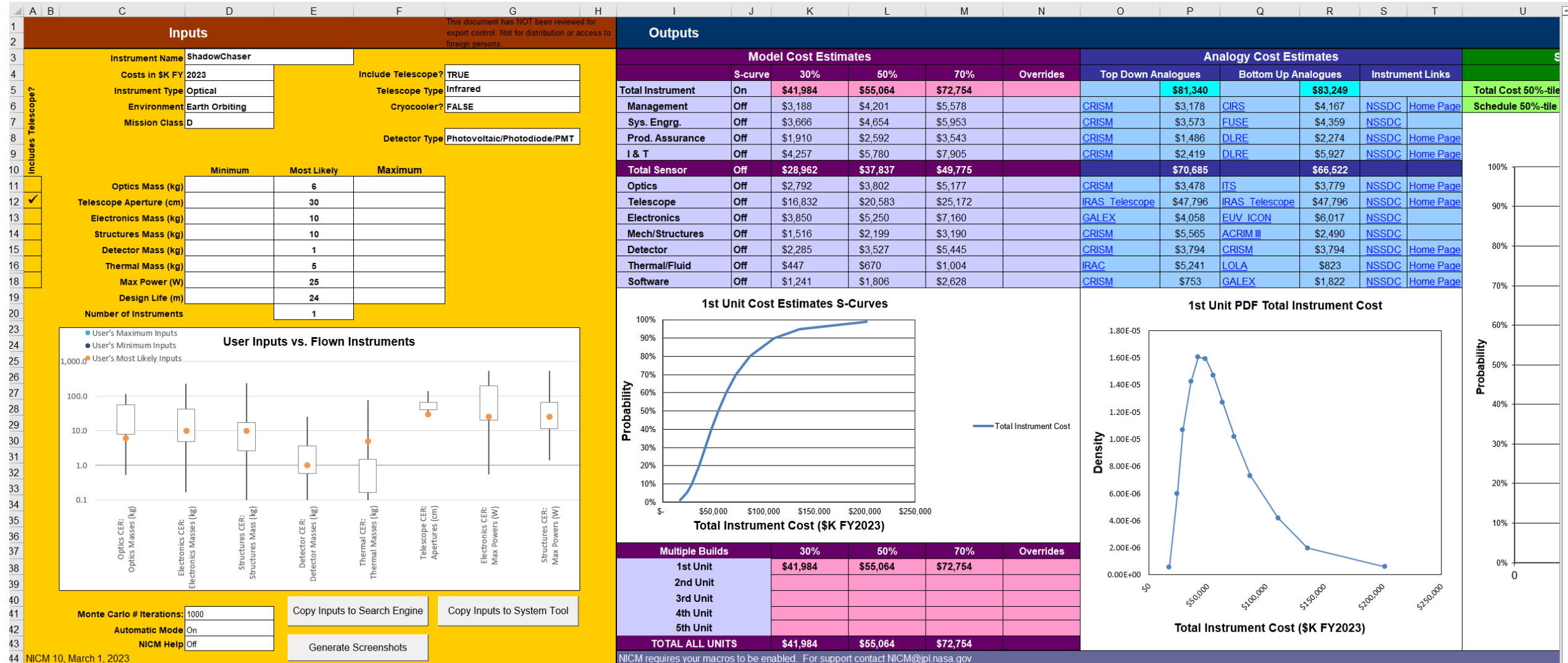
Subsystem Tool:

- Uses a variety of subsystem inputs to produce cost estimates at 30,50 and 70% confidence levels.
- Each subsystem CER was based on its identified technical and programmatic cost drivers, whose significance were determined by statistical analysis.

System Tool:

- Uses system level inputs to produce cost estimates at 30,50 and 70% confidence levels.
- The empirical relationships between the system level costs and the database technical and programmatic parameters (or characteristics) were determined by using cluster analysis and PCA regression. The CERs were then validated using bootstrap cross-validation methods. Please see section 8.1 for a description of cluster analysis, PCA regression and bootstrap cross-validation.

NICM- Subsystem Cost Estimates



SmallSat Cost Model (SSCM) Overview

SSCM employs a parametric methodology for estimation of program cost. It is best suited to the early, conceptual development phase of a spacecraft program when cost and performance trades can be easily performed. A collection of cost-estimating relationships is included that estimate the costs of developing and producing a spacecraft system with the following subsystems:

- **Attitude determination and control subsystem (ADCS)**
- **Propulsion**
- **Power**
- **Telemetry, tracking, and command**
- **Command and data handling (C&DH)**
- **Structure**
- **Thermal**

SSCM generates an estimate for Phases C and D of the spacecraft development, yet the funding profile spreads costs over Phases B, C, and D. Therefore, the SSCM estimate must be augmented to account for the amount of funding spent in

Phase B. According to the NASA Systems Engineering Handbook, the costs in Phase B should typically be between six and 10 percent of the development costs [14]. Based on this, SSCM adds 10 percent to the Phase C/D estimate prior to generating the funding profile

SmallSat Cost Model (SSCM) Preliminary Results



Inputs

Technical Parameter	Units	Value	Notes
Programmatic			
Fiscal Year for Estimate	YYYY	2023	
Inflation Methodology	---	NASA	
Development Time	months	60.0	
System			
Destination	---	Earth-Orbiting	
Design Life	months	24.0	
Satellite Wet Mass	kg	180.00	
Satellite Dry Mass	kg		
Spacecraft Bus Dry Mass	kg	52.00	look for clarification on dry mass
Number of Instruments	#		
Power			
Solar Cell Type	---	Gallium Arsenide	
Battery Type	---		
Power Subsystem Mass	kg	14.77	
BOL Power	W	200	
Structure			
Primary Structure Material	---	Composite	
Structure Subsystem Mass	kg	10.00	waiting for more detail
ADCS			
Star Tracker?	---	Yes	
ADCS Subsystem Mass	kg	10.00	
Pointing Control	deg	0.003	
Propulsion			
Monopropellant or Bipropellant?	---	Monopropellant	cost difference?
Propulsion Subsystem Dry Mass	kg	7.06	
TT&C/C&DH			
Communications Band	---		
TT&C/C&DH Subsystem Mass	kg	5.00	
Transmit Power	W	5	
Downlink Data Rate	kbps	500	
Thermal			
Thermal Subsystem Mass	kg	5.00	

Technical Parameter	Range				
	Low	Minimum	Value	Maximum	High
Development Time					
Design Life		0.2	24.0	96.0	
Satellite Dry Mass					
Spacecraft Bus Dry Mass		52.00	52.00	598.00	
Number of Instruments					
Power Subsystem Mass		14.77	14.77	201.00	
BOL Power (Power)		150	200	2200	
BOL Power (Structure)					
BOL Power (Thermal)		81	200	10500	
Structure Subsystem Mass		6.70	10.00	298.00	
ADCS Subsystem Mass		0.60	10.00	103.80	
Pointing Control		0.003	0.003	5.000	
Propulsion Subsystem Dry Mass		7.06	7.06	118.20	
TT&C/C&DH Subsystem Mass		4.70	5.00	115.40	
Transmit Power		1	5	100	
Downlink Data Rate		32	500	150000	
Thermal Subsystem Mass		0.70	5.00	53.00	

	Estimate (FY23\$K)				% of	% of
	Non-Rec	Rec	Total	Std Error	Sub-level	Sys-level
Spacecraft Bus Subsystems						
Power	1,802	2,770	4,572	1,715	20.4%	
Structure	880	808	1,688	754	7.5%	
ADCS	2,550	2,805	5,354	1,912	23.8%	
Propulsion	522	1,011	1,534	684	6.8%	
TT&C*	1,351	1,324	2,675	2,959	11.9%	
C&DH*	2,859	2,803	5,661		25.2%	
Thermal	504	466	970	424	4.3%	
Spacecraft Bus	10,467	11,987	22,454	4,070	100%	61.1%
IA&T*	2,346	2,749	5,095	2,896		13.9%
PM/SE	3,306	3,983	7,288	3,914		19.8%
LOOS*	0	1,933	1,933			5.3%
S/C Development & First Unit	16,118	20,651	36,770	6,346		100%

IRAD Required Slides

Goal 1: Determine orbits that enable targeting multiple predicted events

- Analyzed and ruled out GTO due to radiation concerns
- Determined that SSO offers good event visibility
- Discovered SSO enables dipping in/out of occultation shadow multiple times per event

Goal 2: Determine the instrument telescope size and detector

- Unanticipated difficulty to formulate method to measure Radiative flux from Uranus
- Ongoing: Measurement Sensitivity study to develop measurement method
- Promising optical design and detector identified, still must prove measurement works

Goal 3: Design spacecraft bus that satisfy delta-V and payload requirements

- ESPA bus satisfies requirements assuming 30-cm aperture and non-cryogenic instrument

Impact on the State of the Art

- New Discovery: SSO enables dipping in/out of occultation shadow multiple times per event, and multiply value of each event
- Ongoing sensitivity study will also improve design of ground-based stellar occultation measurements

Shadow Chaser FY23 Progress



Team Progress

- Orbit Characterization
- Background Stars in FoV
- Instrument Design/Analysis
 - Detector Considerations
- Measurement Approach/Design

IDC2 Topics

- Radiation Risk Analysis
- Measurement ConOps
- Mission ConOps
- Instrument Design
 - Telescope + Detector
- Systems Integration
- Launch Vehicle/Config Options
- Cost



• Conference Proceedings

- Sayanagi et al. (2022) “Shadow Chaser: a SmallSat concept to determine the middle and upper atmospheric structures of Uranus and Neptune through stellar-occultation measurements from Earth orbit” AGU Fall Meeting 2022
- Sayanagi et al. (2023) “Shadow Chaser: a smallsat concept to determine the middle and upper atmospheric structures of Uranus and Neptune through stellar-occultation measurements from Earth orbit” NASA SMD Technology Showcase 2023
- Sayanagi et al. (2023) “Shadow Chaser: a SmallSat for stellar-occultation measurements of Uranus and Neptune’s thermospheres from Earth orbit” Japan Geoscience Union Annual Meeting 2023
- Sayanagi (2023) “Outer Planets Exploration: Considerations for International Cooperation” JAXA/ISAS Planetary Exploration Workshop 2023

• Peer Reviewed Publication

- Saunders et al. 2022. “Assessment of the feasibility of space-based stellar occultation observations of Uranus and Neptune.” Planetary and Space Science 213, 105431. <https://doi.org/10.1016/j.pss.2022.105431>

• PhD Dissertation

- Will Saunder’s PhD Dissertation Chapter

Future/upcoming work and opportunities



Upcoming Work (FY24):

- Left over procurement funding committed to RSES contract
- Analyze occultation sensitivity
- Design instrument

PM Tool Dashboard Image



Project Management Dashboard - Shadow-Chaser

[Go to Input Sheet](#) [Go to Master Dash](#)

Objective: Shadow Chaser is a SIMPLEx mission concept that measures thermospheric densities of Uranus and Neptune (U&N) from Earth orbit via the stellar occultation (SO) technique. Our objective is to investigate the surprisingly hot thermospheres of U&N found by Voyager 2 (V2). The high

Target Completion: 8/31/2023 ● Project Funding: \$125,000 ● Total FTE + Expense: \$ 123,000 ● Project Deliverables: 0% ● Overall Health: 60% ●

OVERALL PROGRESS



Unobligated expense: \$ 73,600

RESOURCES

Name	Planned FTE	Outlook FTE
Kunio Sayanagi	0.00	0.00
Cindy Young	0.00	0.00
Jonathan Chrono	0.00	0.00
Josh Carden	0.30	?
0	0.00	0.00
0	0.00	0.00
0	0.00	0.00
0	0.00	0.00
0	0.00	0.00
0	0.00	0.00
Totals:	0.30	0.30

EXPENSES

Item	Planned \$	Outlook \$	Obligated
Contractors	\$75,600	\$75,600	\$0
AGU Fall Meeting Travel (	\$2,000	\$0	\$2,000
0	\$0	\$0	\$0
0	\$0	\$0	\$0
0	\$0	\$0	\$0
0	\$0	\$0	\$0
0	\$0	\$0	\$0
0	\$0	\$0	\$0
0	\$0	\$0	\$0
0	\$0	\$0	\$0
Totals:	\$77,600	\$75,600	\$2,000

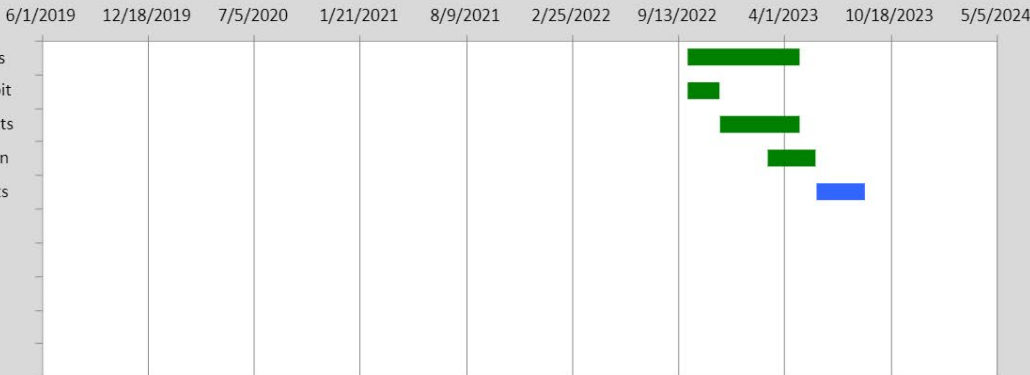
TASK COMPLETION

Milestone/Task	Planned End	Projected End	% Complete
Determine orbits that en	4/30/2023	4/30/2023	100%
Determine radiation dose	11/30/2022	11/30/2022	100%
Determine the propulsion	4/30/2023	4/30/2023	100%
Determine the instrumen	5/30/2023	5/30/2023	100%
Design spacecraft bus th	8/31/2023	8/31/2023	100%
0	1/0/1900		
0	1/0/1900		
0	1/0/1900		
0	1/0/1900		
0	1/0/1900		
Total Project Schedule:	8/31/2023	8/31/2023	100%

KEY RISKS

- Risk A = a minor annoyance, not too worry ●
- Risk B = a definite issue but not too much impact ●
- Risk C = a potential show-stopper ●
- 0

CURRENT TASK SCHEDULES



TASK COMPLETION HISTOGRAM



KEY NOTES Status as of: 10/1/2022