Jet Propulsion Laboratory
California Institute of Technology

In-Space Assembled Telescope (iSAT) Study Meeting

Day 1

Oct 2-4, 2018
NASA LaRC

Nick Siegler
Chief Technologist, NASA Exoplanet Exploration Program
NASA Jet Propulsion Laboratory, California Institute of Technology

Harley Thronson
Senior Scientist, Advanced Concepts
NASA Goddard Space Flight Center

Rudra Mukherjee
Robotics Technologist
NASA Jet Propulsion Laboratory, California Institute of Technology

CL#18-5787

National Aeronautics and
Space Administration

NASA Langley Research Center Welcome Guide

In-Space Assembled Telescope Study Workshop III

October 2-4, 2018

And Now a Word from our Sponsor…

Dr. Paul Hertz
Director
Astrophysics Division
NASA Headquarters

Exoplanet Science Strategy Recommendation

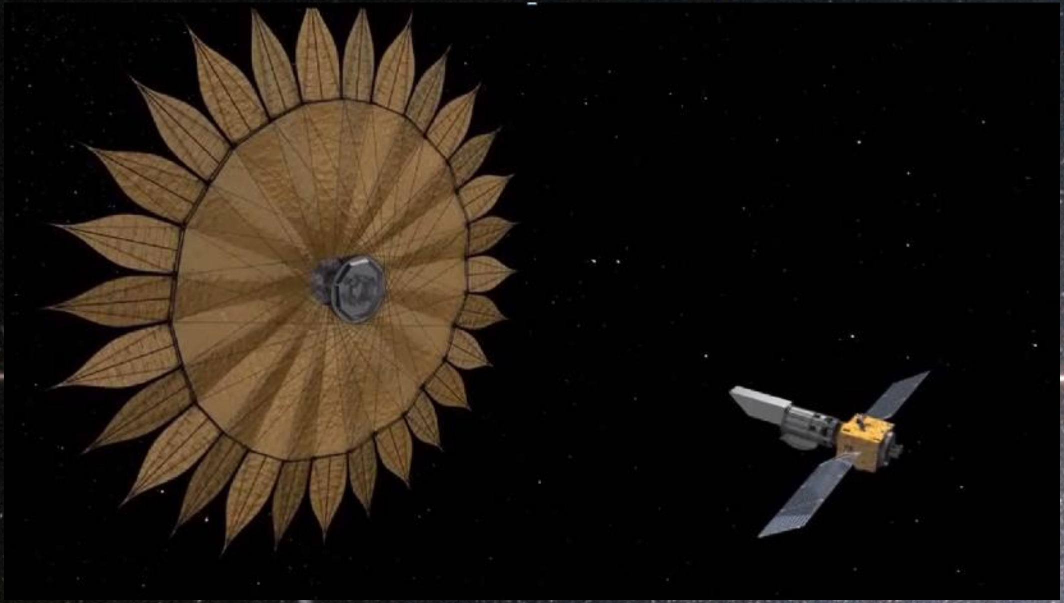
Released September 5, 2018 by the National Academies

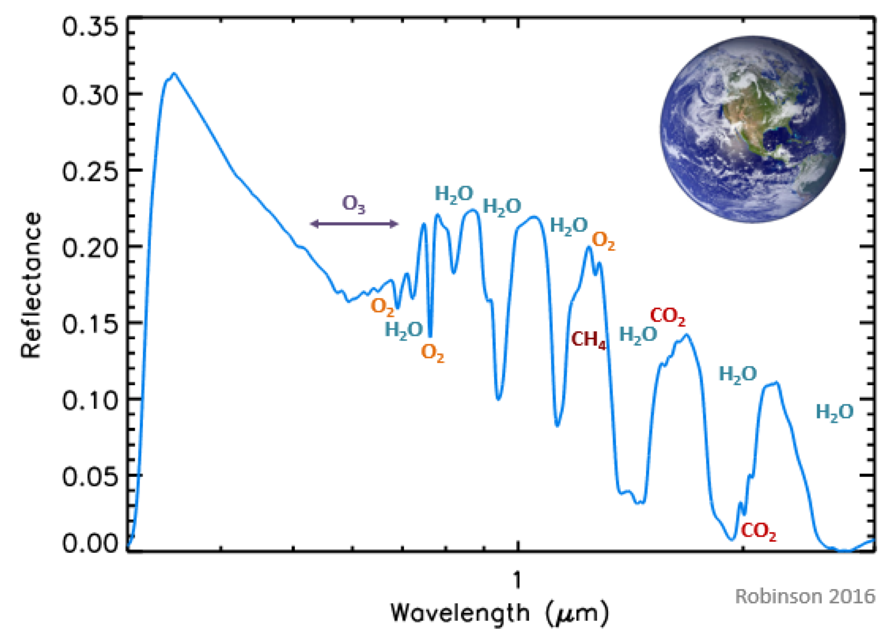
Recommendation #1:

NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.

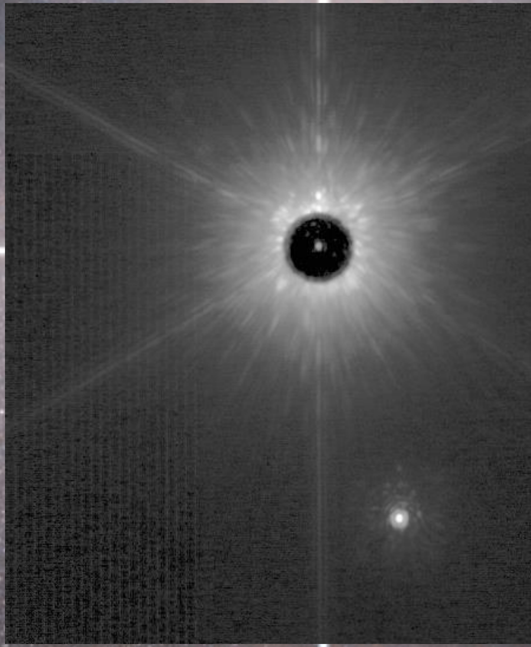
David Charbonneau (Harvard) Scott Gaudi (Ohio State University)

External Occulters (Starshades)

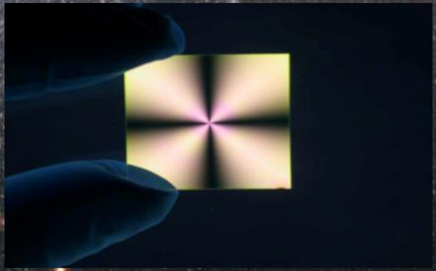




Robinson 2016

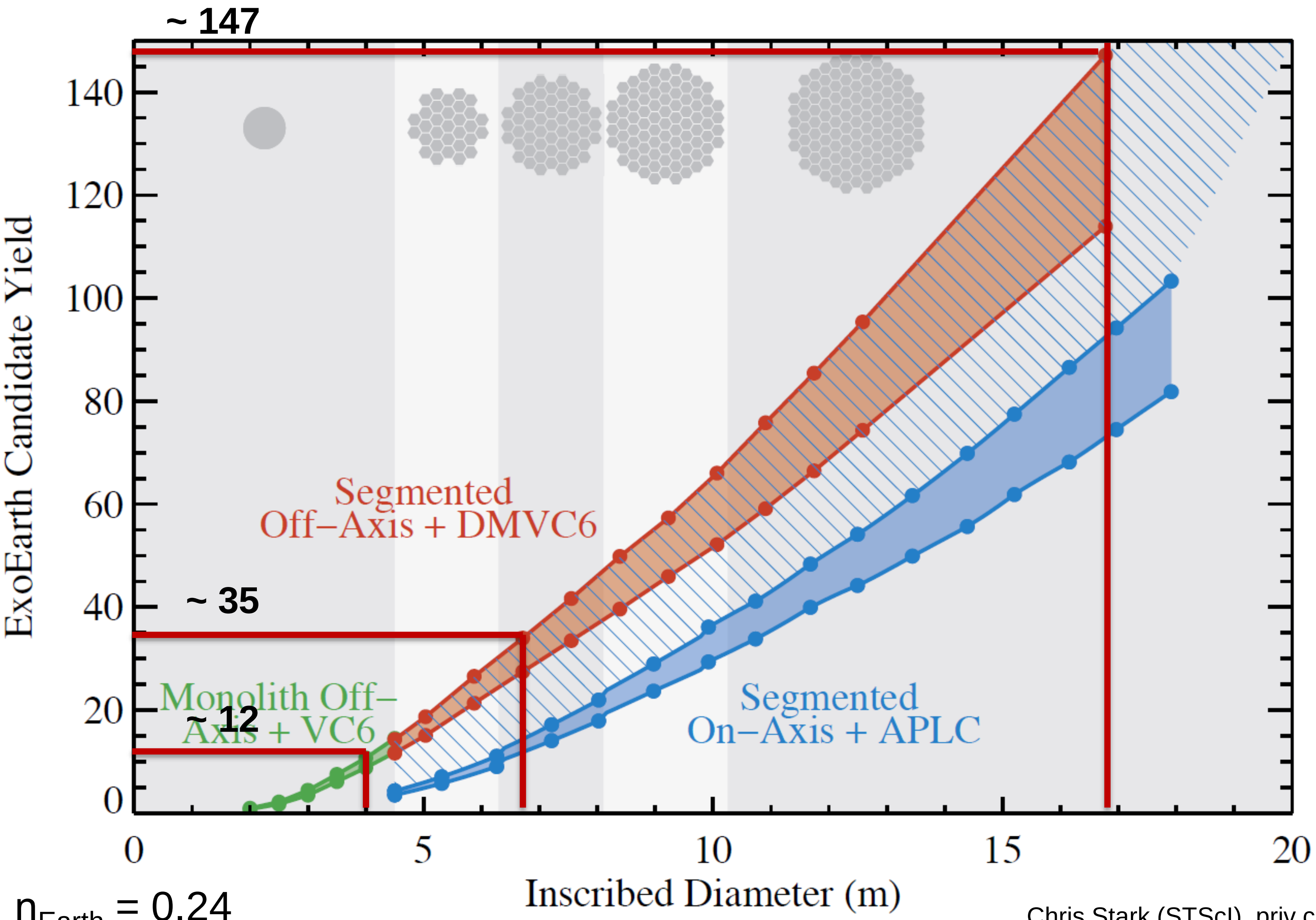


Internal Occulters (Coronagraphs)



Exo-Earth Model Predictions

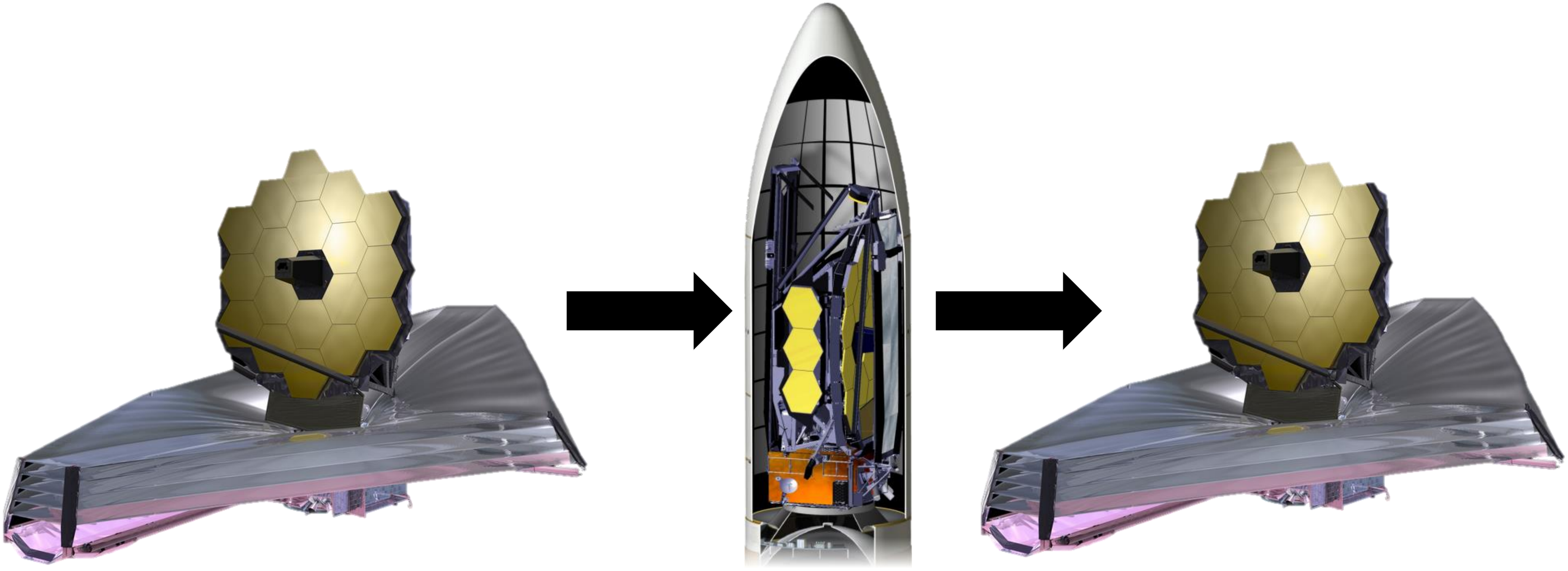
As a function of telescope aperture size; coronagraph architecture



$\eta_{Earth} = 0.24$

Chris Stark (STScI), priv comm

The Current Paradigm



$$$

- **Currently, no existing LV to fly an 8 m segmented telescope**
    - Not even a 4 m monolith
    - LVs in the works such as SLS, BFR, New Glenn

- 40 deployable structures
- 178 release mechanisms

In-Space Assembly and Servicing Workshop

70+ participants from government, industry, and academia

- 30 NASA Centers
- 29 Industry
- 7 NASA HQ
- 4 academia
- 4 STScI
- 1 DARPA

Planning Chair: Harley Thronson (NASA GSFC)
Co-chair: Nick Siegler (NASA JPL)
November 1-3, 2017
NASA GSFC

A Possible Vision for Large Space Telescopes

1) **Assembled in space**

2) **Serviced in space to extend their utility by:**
    - replacing the instrument payloads with newer more advanced ones
    - upgrading spacecraft subsystems as they wear and age
    - refueling to extend their lifetimes,
    - repairing when needed, and
    - incrementally enlarging the apertures over time

These potential benefits of iSSA of large future telescopes require study.

Key Workshop Suggestions to NASA

✓ 1. **Commission a design study to understand how large-aperture telescopes could be assembled and serviced in space**
   - Initiate the study in time for initial results to be available to Gateway and robotics designers before end 2019.

✓ 2. **Provide input to the 2020 Decadal Survey about iSA as a potential implementation approach for future large apertures.**

Study Objective and Deliverables

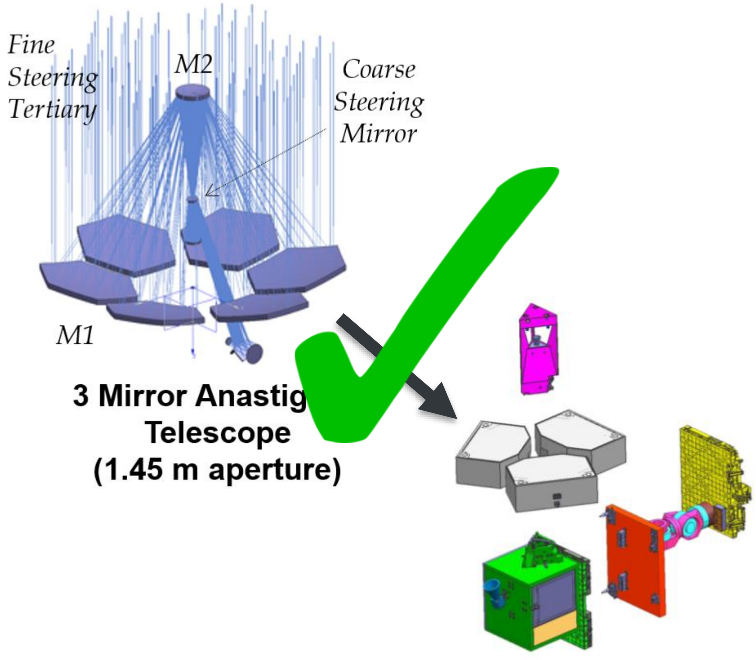
- **The in-Space Assembled Telescope (iSAT) Study is chartered by the NASA APD Director and the SMD Chief Technologist to deliver, by the goal of June 2019, a Decadal Survey Whitepaper assessing:**
  - ***"When is it advantageous assembling space telescopes in space rather than building them on the Earth and deploying them autonomously from individual launch vehicles?"***

Study Process

Activity 3: Deliver a whitepaper in behalf of NASA’s Astrophysics Division to the 2020 Decadal Survey Committee

Activity 2: Estimate the costs and assess the risks of a reference iSAT

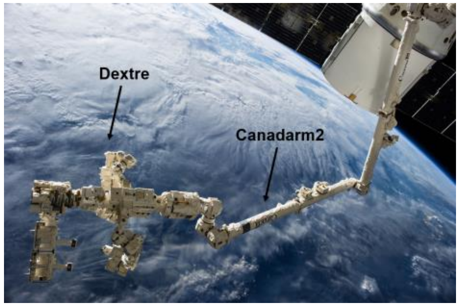
Activity 1a: Modularization and Testing

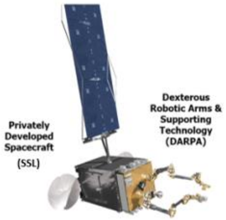


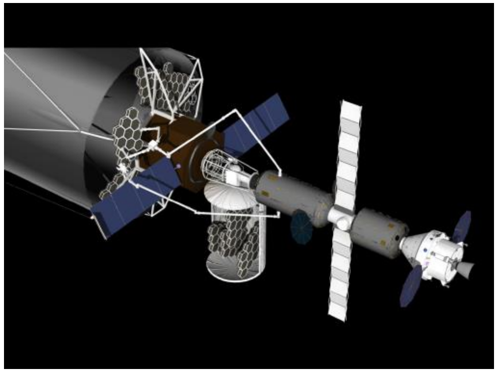
3 Mirror Anastig
Telescope
(1.45 m aperture)

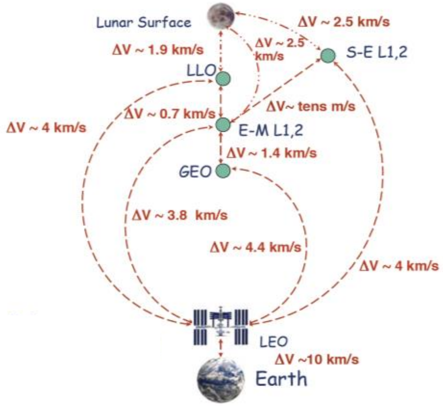
6 launch modules for assembly

Activity 1b: Assembly and Infrastructure









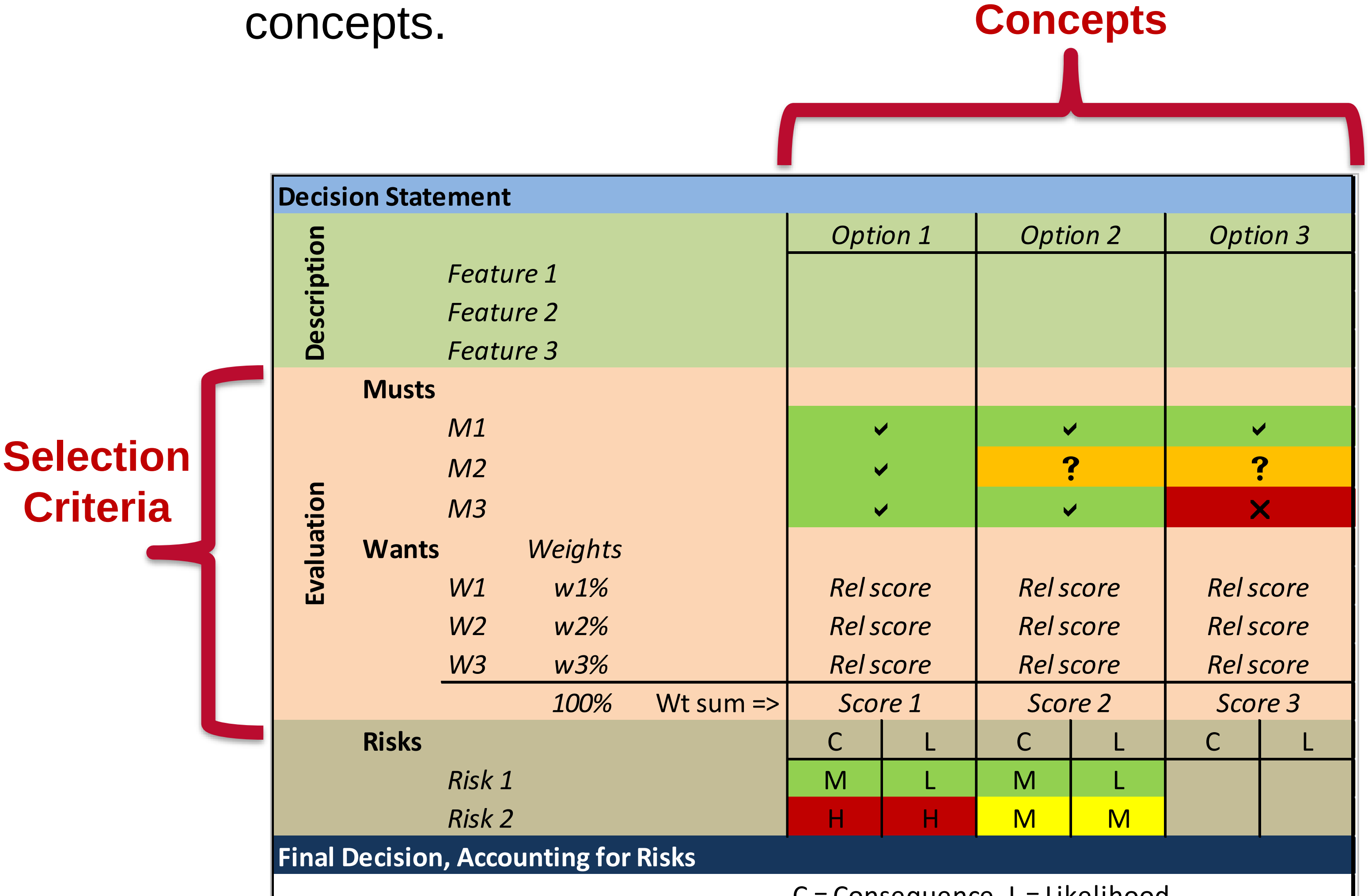
Telescope Assembly and Infrastructure Face-to-Face Meeting

NASA Langley Research Center, Oct 2-4, 2018

- **Expecting ~ 60 Study Members and Observers; local guests**
  - ❖ 5 NASA Centers
  - ❖ 14 private companies
  - ❖ 4 gov't agencies
  - ❖ 4 universities

Objectives of this Face-to-Face Meeting

1. Generate concepts to assemble the reference telescope and define its needed infrastructure
2. Advance the selection criteria in which we will prioritize these concepts.



Decision Statement									
Description				*Option 1*		*Option 2*		*Option 3*	
	Feature 1								
	Feature 2								
	Feature 3								
Evaluation	**Musts**								
	M1			✓		✓		✓	
	M2			✓		?		?	
	M3			✓		✓		✗	
	Wants	*Weights*							
	W1	*w1%*		*Rel score*		*Rel score*		*Rel score*	
	W2	*w2%*		*Rel score*		*Rel score*		*Rel score*	
	W3	*w3%*		*Rel score*		*Rel score*		*Rel score*	
		100%	Wt sum =>	*Score 1*		*Score 2*		*Score 3*	
	Risks			C	L	C	L	C	L
	Risk 1			M	L	M	L		
	Risk 2			H	H	M	M		
Final Decision, Accounting for Risks									

C = Consequence, L = Likelihood

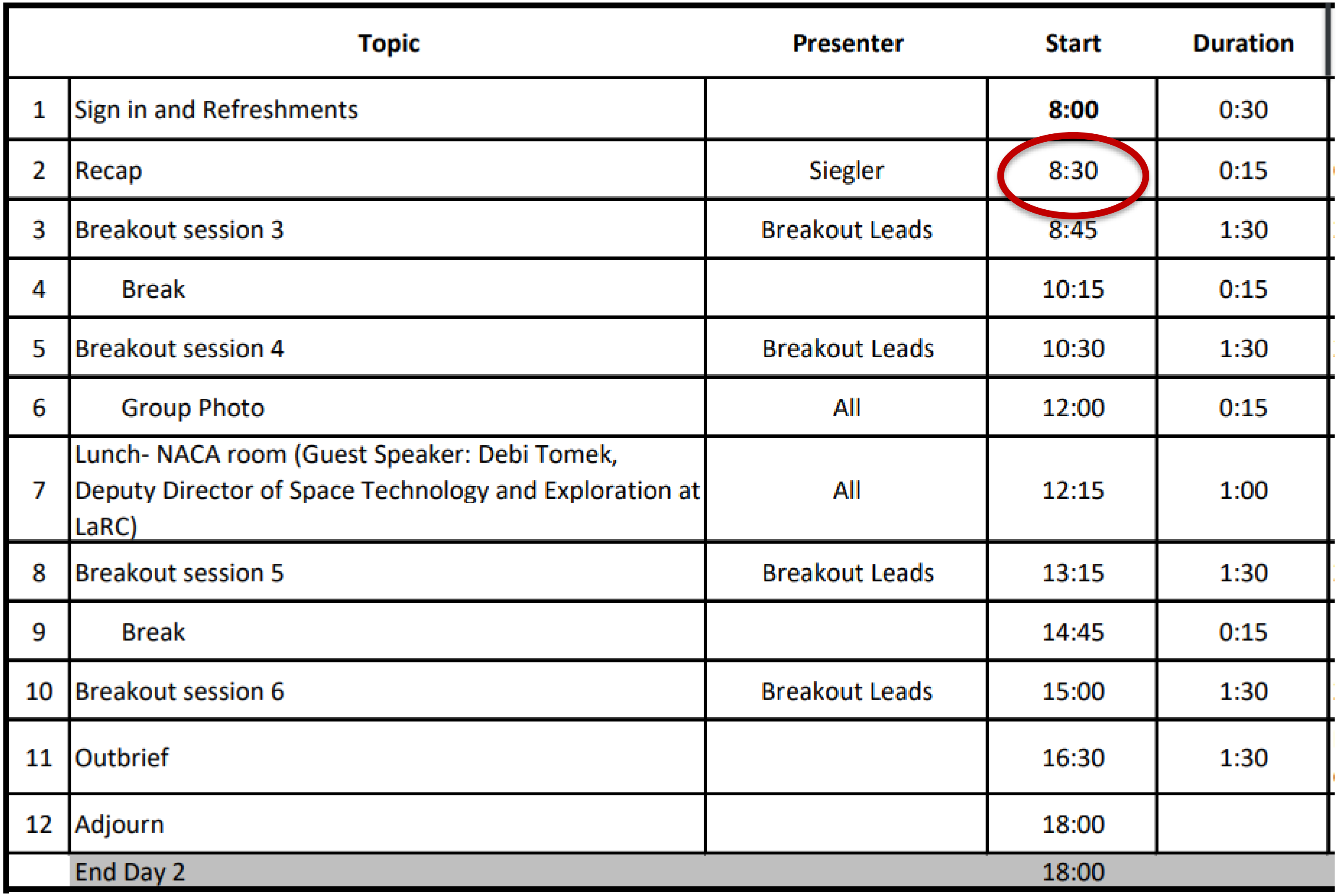
Agenda

Day 1 Agenda

Gateway Discussion by Kandyce Goodliff

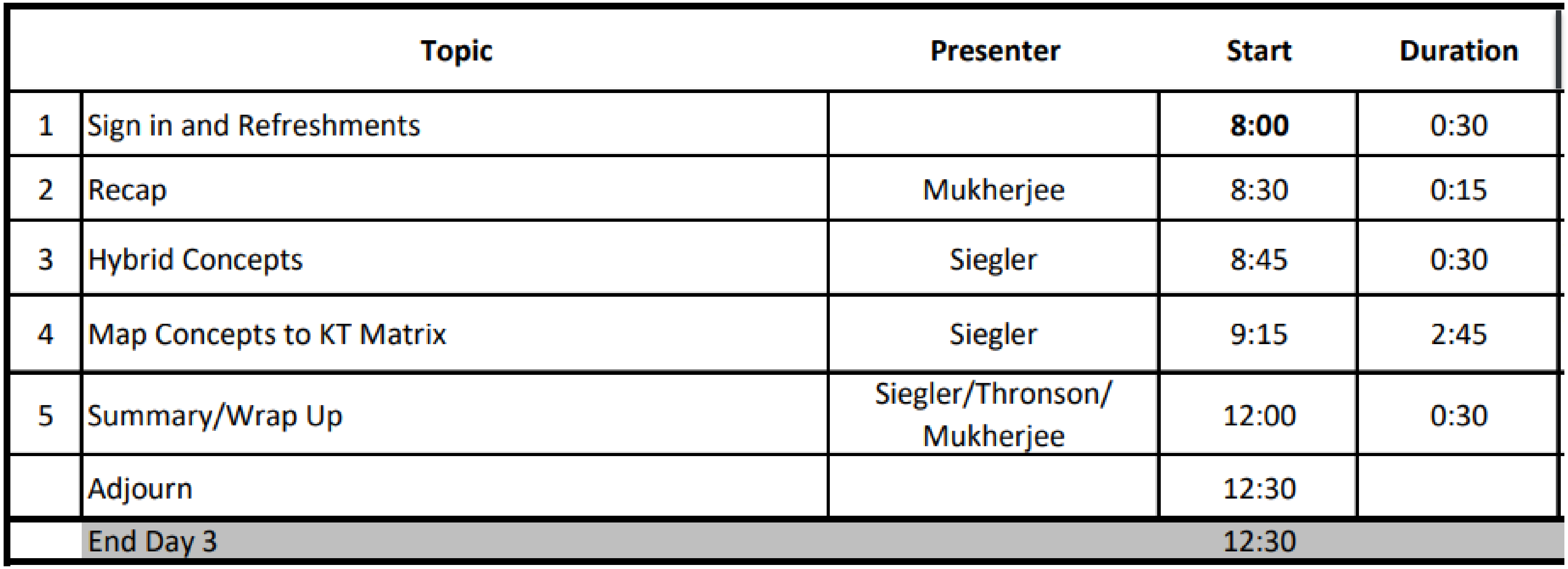
	Topic	Presenter	Start	Duration
1	Sign in and Refreshments		**8:30**	0:30
2	Welcome	Nick Siegler	9:00	0:05
3	Logistics overview	Lynn Bowman	9:05	0:05
4	LaRC Welcome	Cathy Mangum	9:10	0:05
5	Sponsor Comments	Paul Hertz (remotely)	9:15	0:10
6	Opening Remarks	Nick Siegler	9:25	0:20
7	Introductions	All	9:45	0:15
8	Technical Overview	Rudra Mukherjee	10:00	1:00
9	Musts and Wants Overview	Nick Siegler	11:00	0:45
10	Lunch- NACA room	All	11:45	1:15
11	Environments Overview	Dave Miller	13:00	0:45
12	Introduction to Breakout sessions	Rudra Mukherjee	13:45	0:15
13	Breakout Session 1	Breakout Leads	14:00	1:45
14	Break		15:45	0:15
15	Breakout Session 2	Breakout Leads	16:00	1:45
16	Outbrief	Breakout Leads	17:45	0:15
17	Adjourn		18:00	0:00
	End Day 1		18:00	
18	No Host Group Dinner @ "The Vanguard"		19:30	

Day 2 Agenda



	Topic	Presenter	Start	Duration
1	Sign in and Refreshments		**8:00**	0:30
2	Recap	Siegler	8:30	0:15
3	Breakout session 3	Breakout Leads	8:45	1:30
4	Break		10:15	0:15
5	Breakout session 4	Breakout Leads	10:30	1:30
6	Group Photo	All	12:00	0:15
7	Lunch- NACA room (Guest Speaker: Debi Tomek, Deputy Director of Space Technology and Exploration at LaRC)	All	12:15	1:00
8	Breakout session 5	Breakout Leads	13:15	1:30
9	Break		14:45	0:15
10	Breakout session 6	Breakout Leads	15:00	1:30
11	Outbrief		16:30	1:30
12	Adjourn		18:00	
	End Day 2		18:00	

Day 3 Agenda



	Topic	Presenter	Start	Duration
1	Sign in and Refreshments		**8:00**	0:30
2	Recap	Mukherjee	8:30	0:15
3	Hybrid Concepts	Siegler	8:45	0:30
4	Map Concepts to KT Matrix	Siegler	9:15	2:45
5	Summary/Wrap Up	Siegler/Thronson/ Mukherjee	12:00	0:30
	Adjourn		12:30	
	End Day 3		12:30	

Introductions

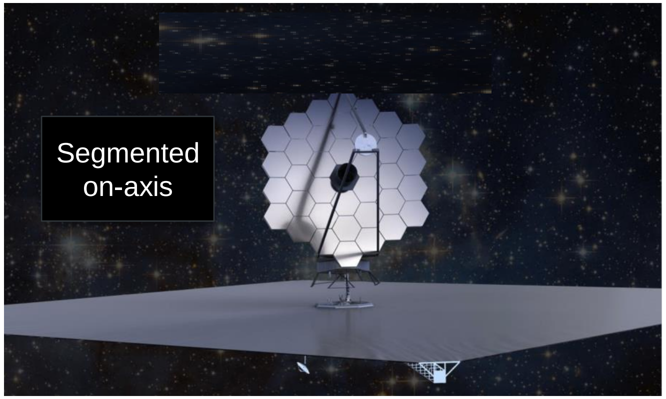
- **US Persons Only**
- **Study Leads:**
  - Nick Siegler, Harley Thronson, Rudra Mukherjee
- **Logistics:**
  - Christina Williams, Jennifer Gregory
- **Breakout Facilitators:**
  - David Miller, John Grunsfeld, Gordon Roesler
- **Recorders**
  - Ron Polidan, Doug McGuffey, Eric Mamajek
- **Participants (including those on the phone)**
  - Name, institution, area of expertise in this study

Telescope Modularization Workshop

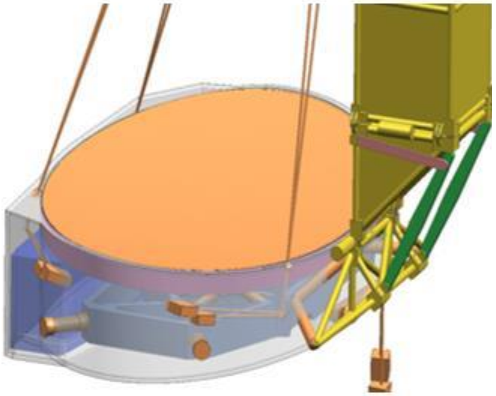
Caltech, June 5-7

47 invited participants from government, industry, and academia spanning the fields of astrophysics, engineering, and robotics.

Telescope Concepts Considered

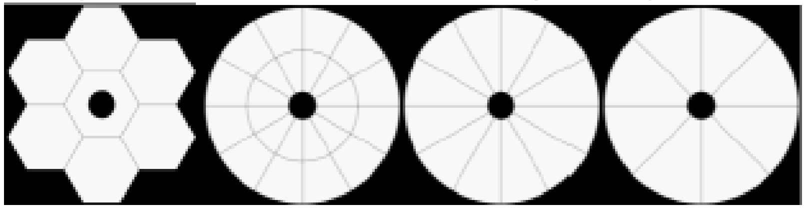


Elliptical, off-axis

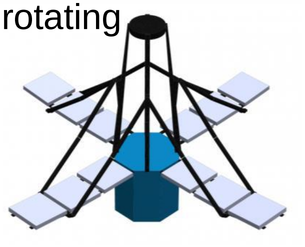


5 m segments

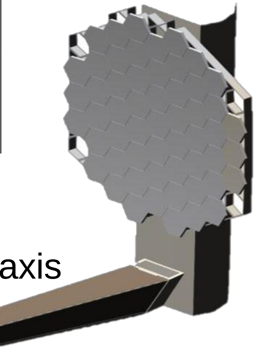
Pie-shaped segments



Sparse, rotating

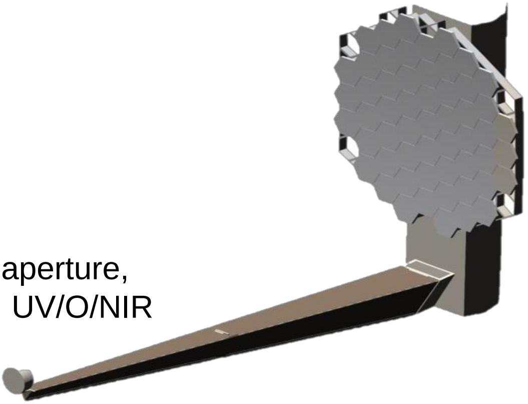


Segmented, off-axis

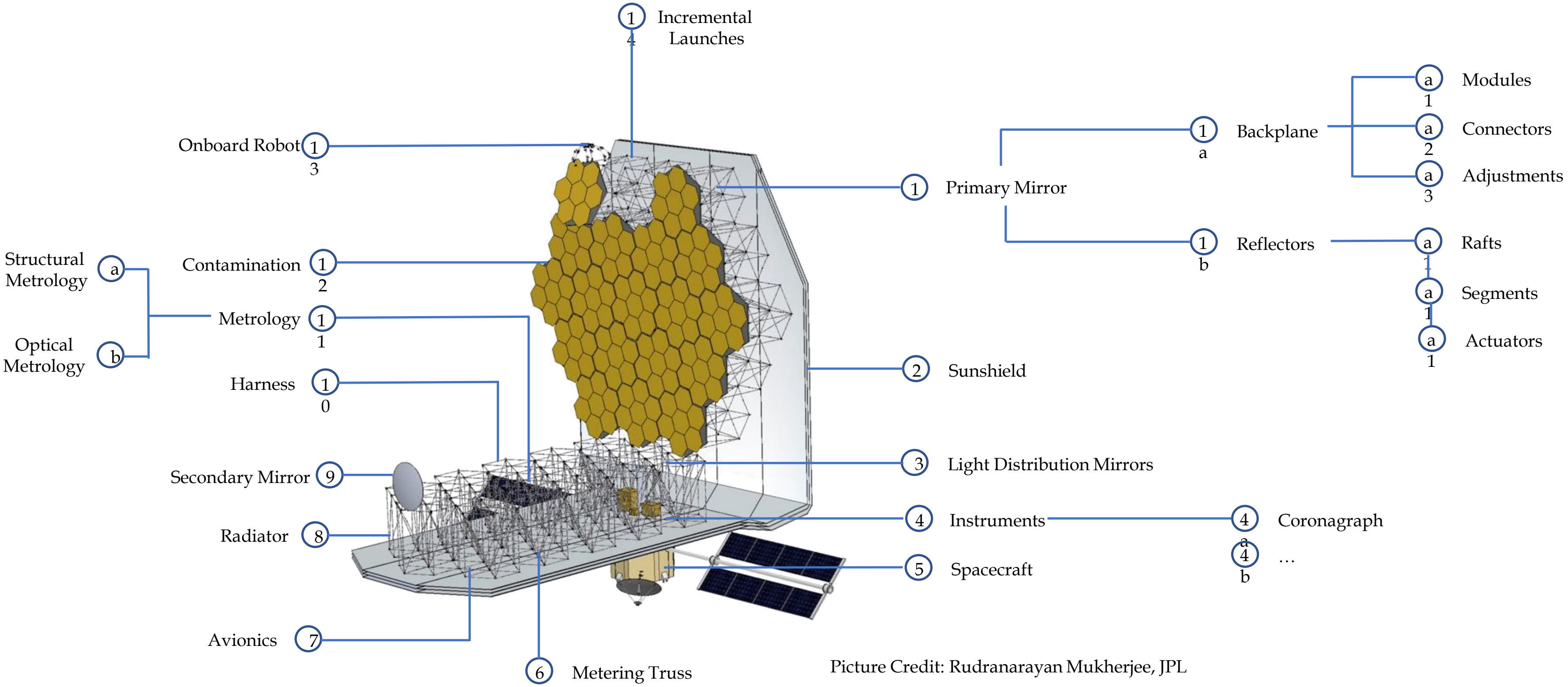


Telescope Modularization Concepts

- **A 20 m off-axis f/2 telescope would serve as a good reference for the Study**
- **No better compelling alternatives for this study.**
- **No major show stoppers were found.**
- **The consensus was that modularizing this reference telescope would be feasible with current and anticipated technology and processes.**

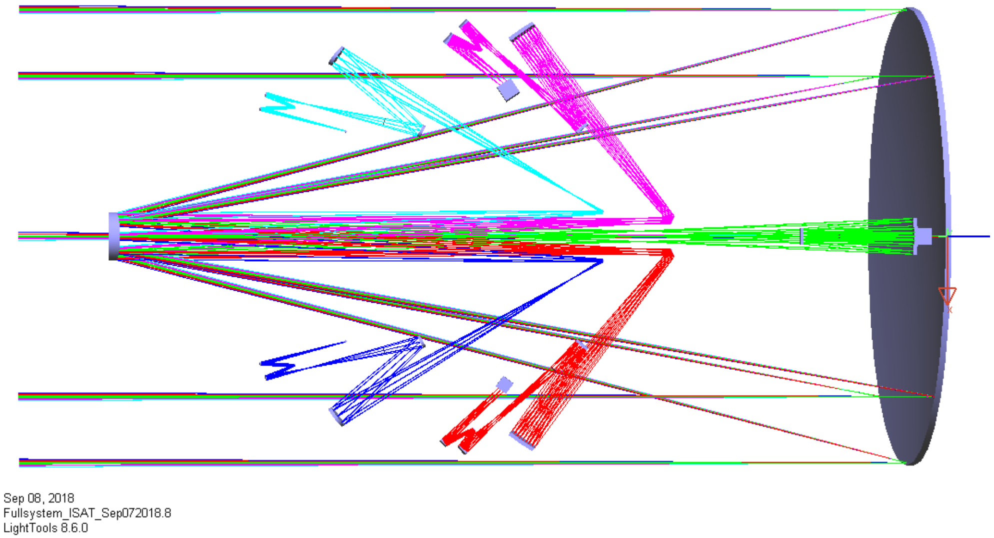


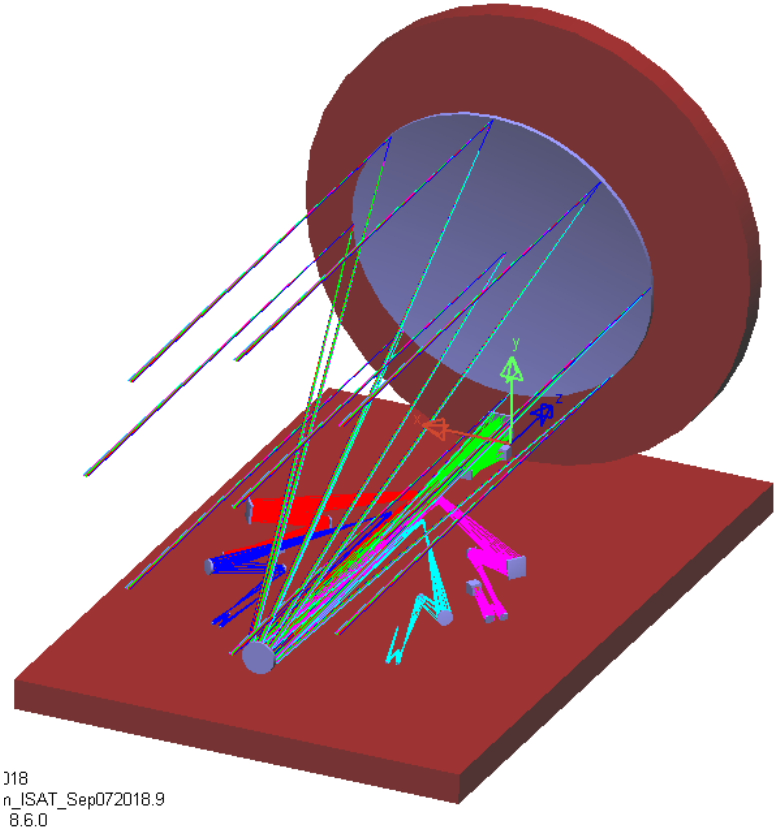
20 m, f/2, off-axis,
segmented, filled-aperture,
with coronagraph, UV/O/NIR

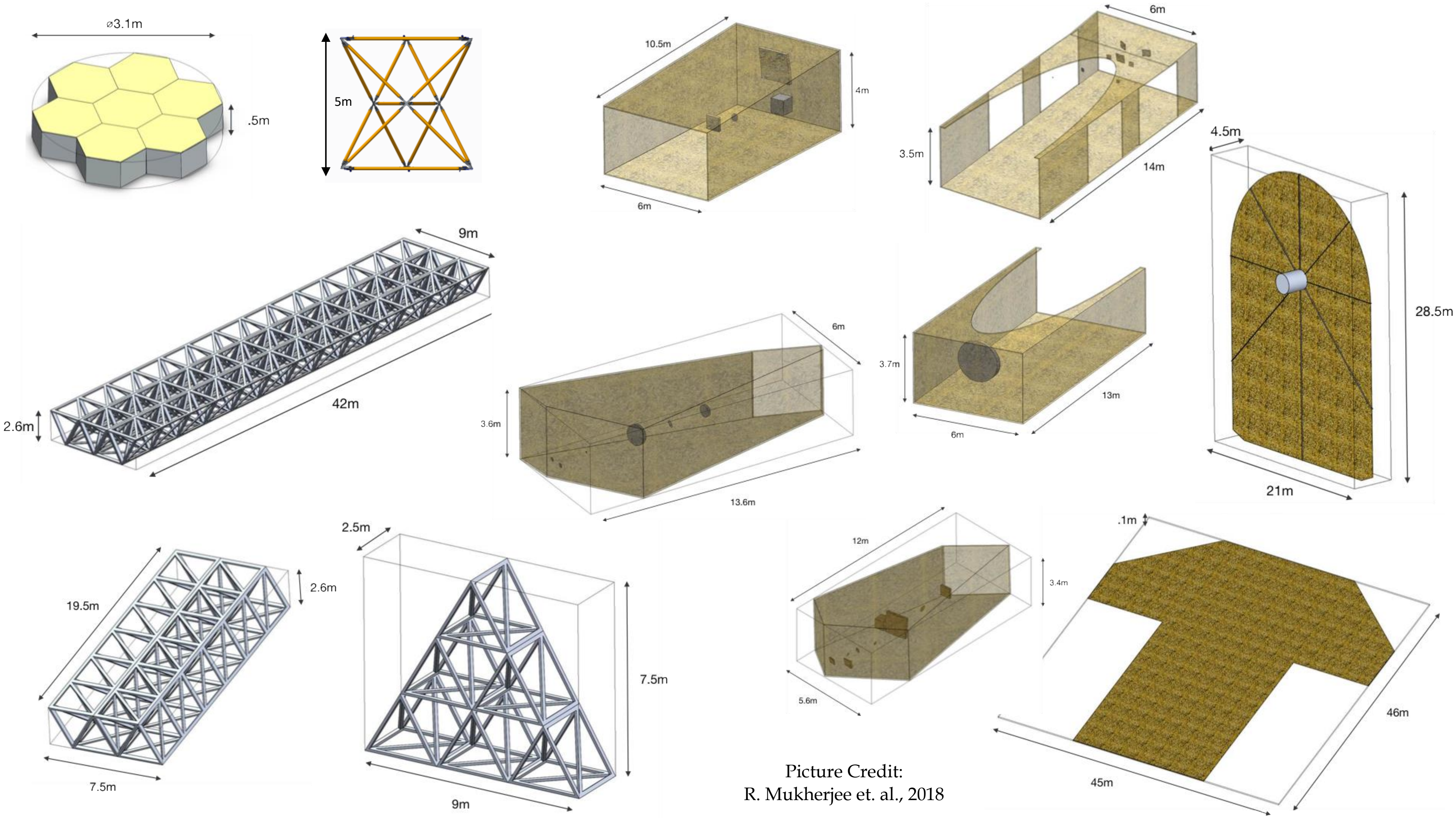


Picture Credit: Rudranarayan Mukherjee, JPL

Optical Design

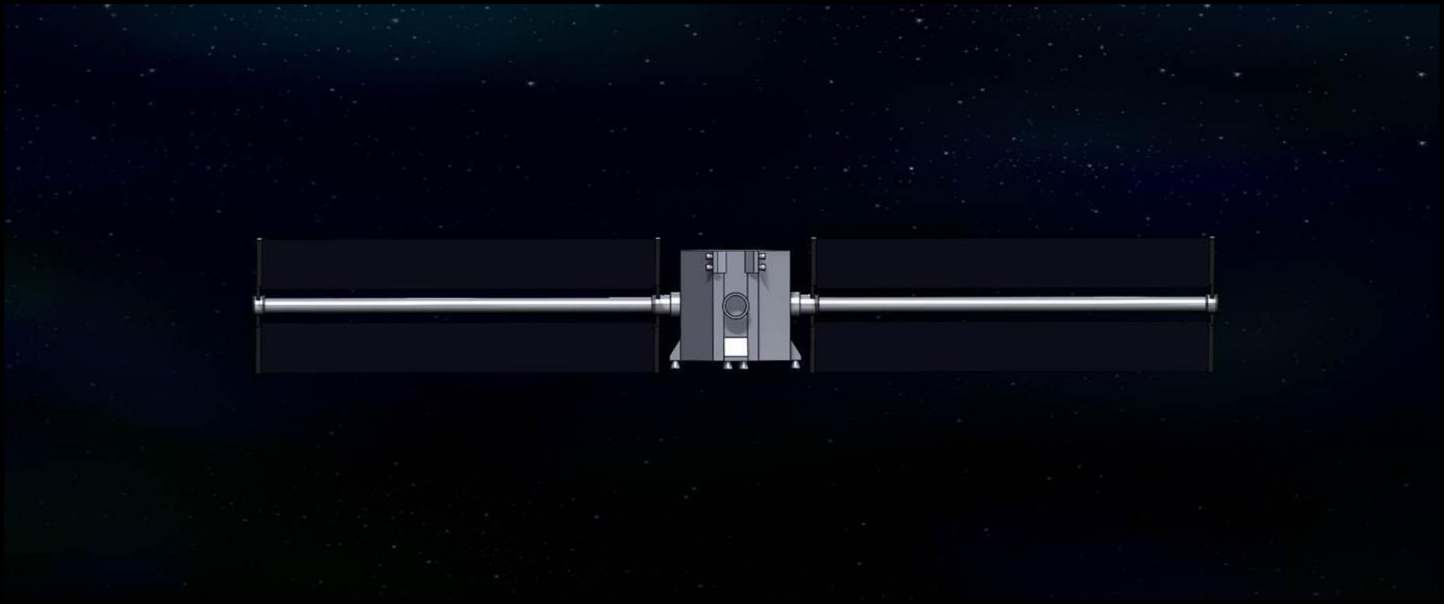




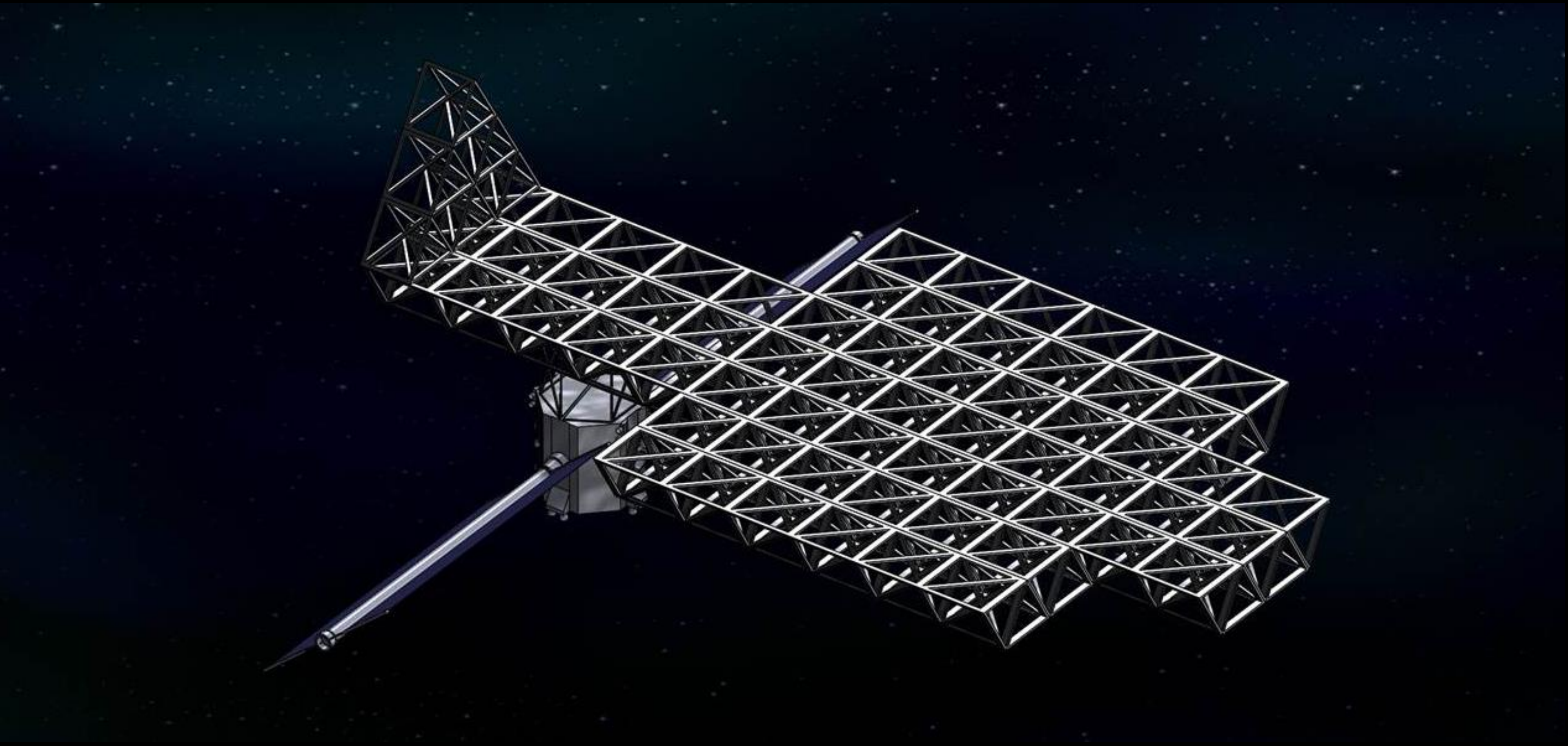


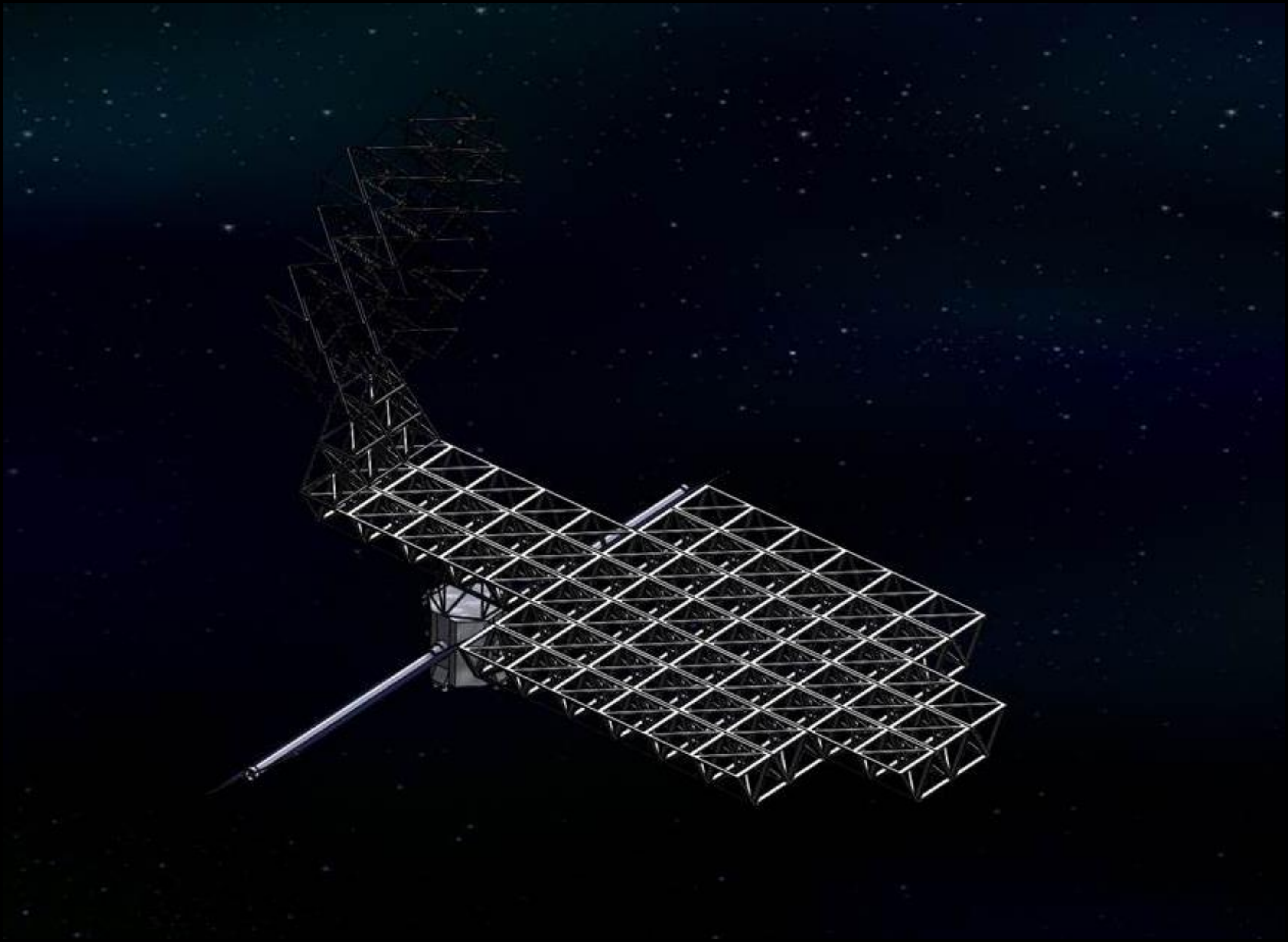
Picture Credit:
R. Mukherjee et. al., 2018

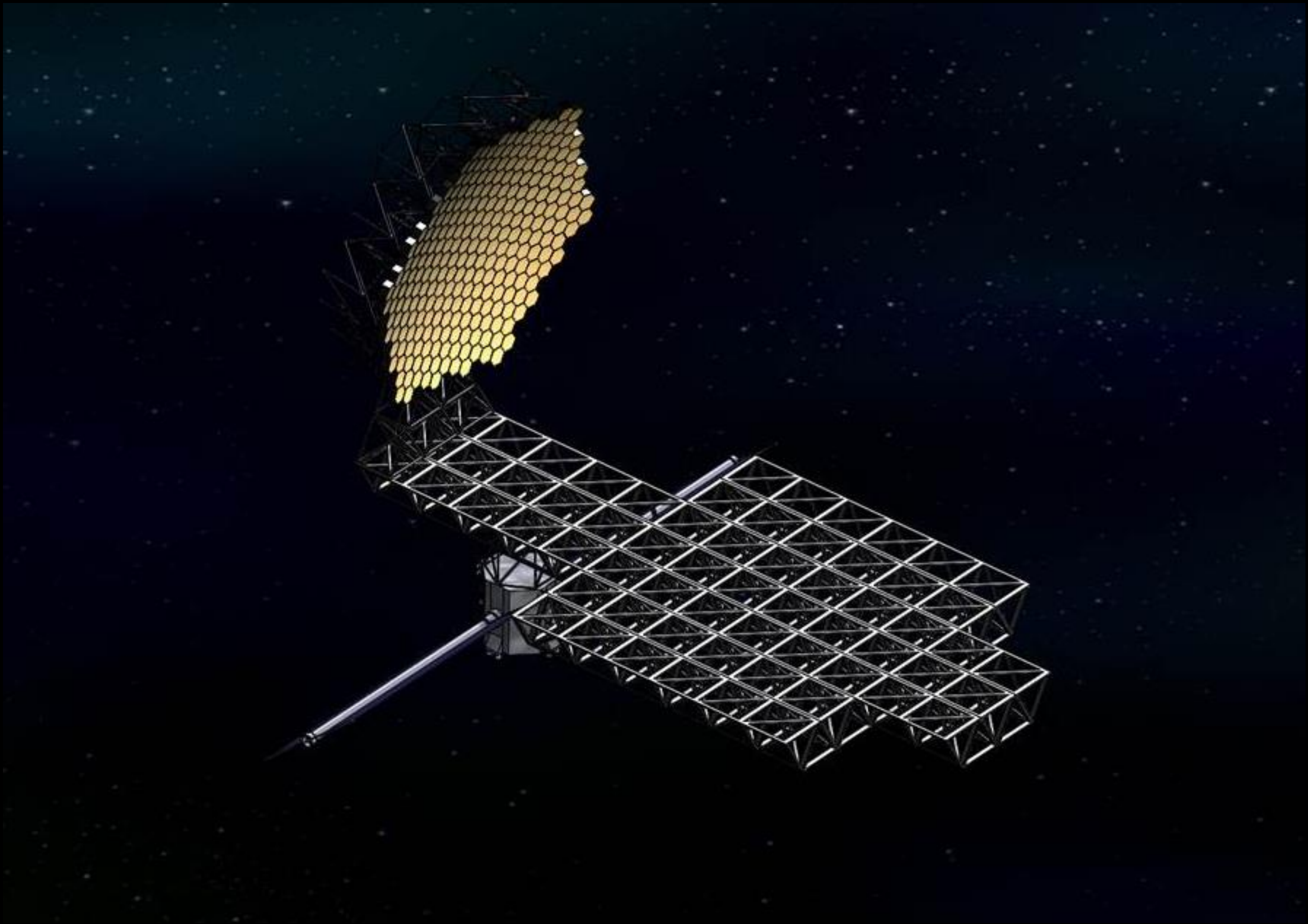
Telescope Bus and Solar Arrays

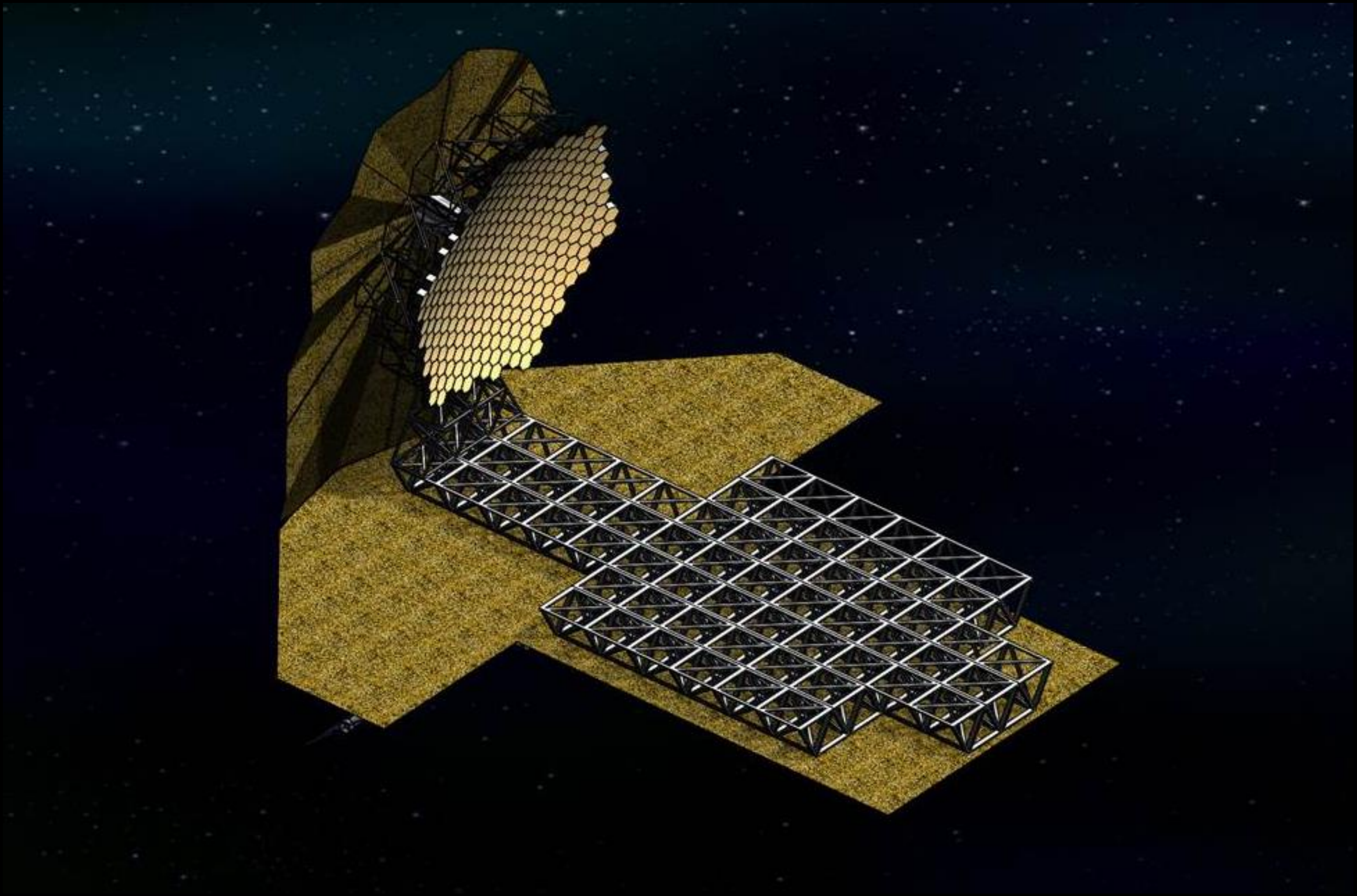


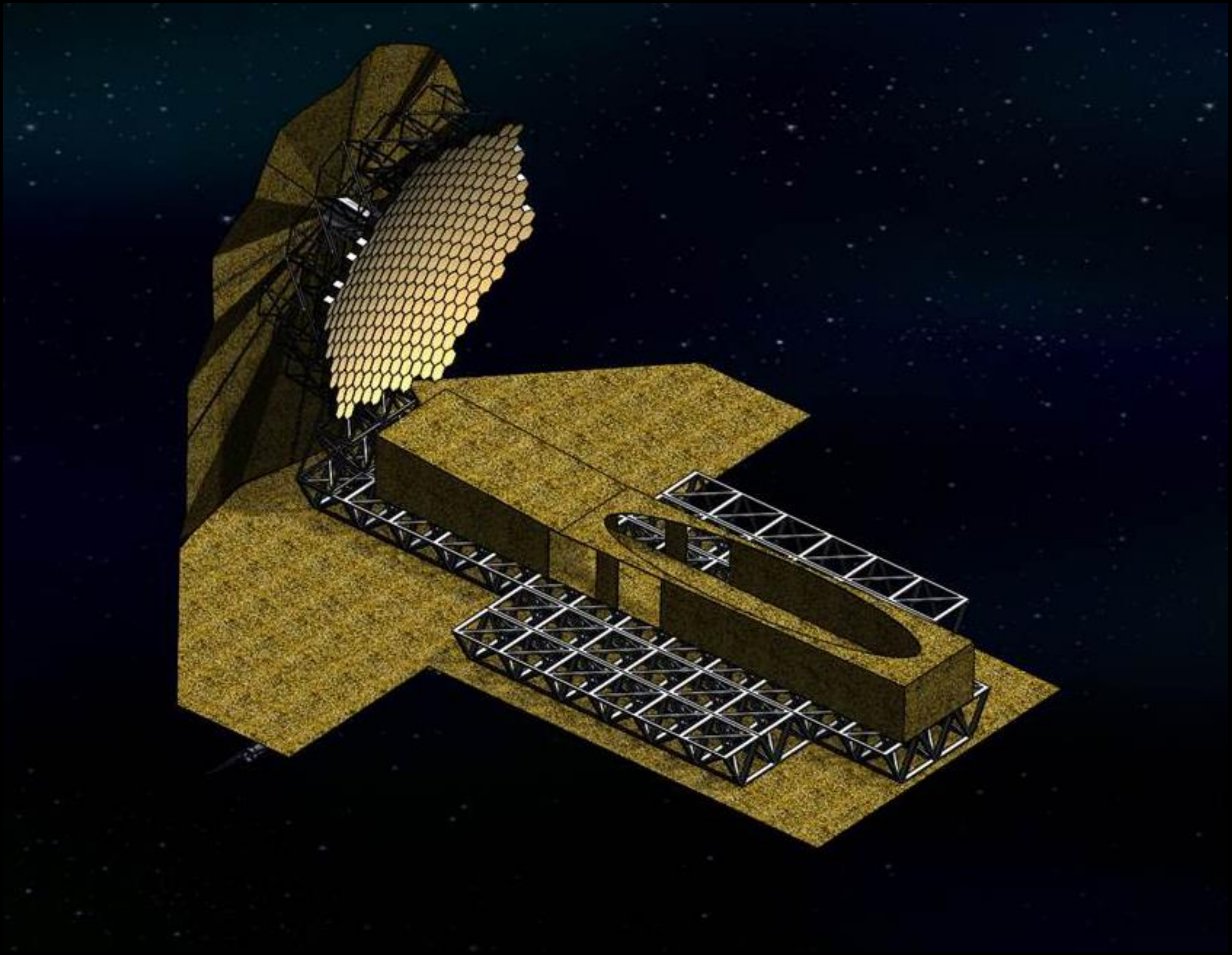
Following drawings all come from R. Mukherjee et al. 2018

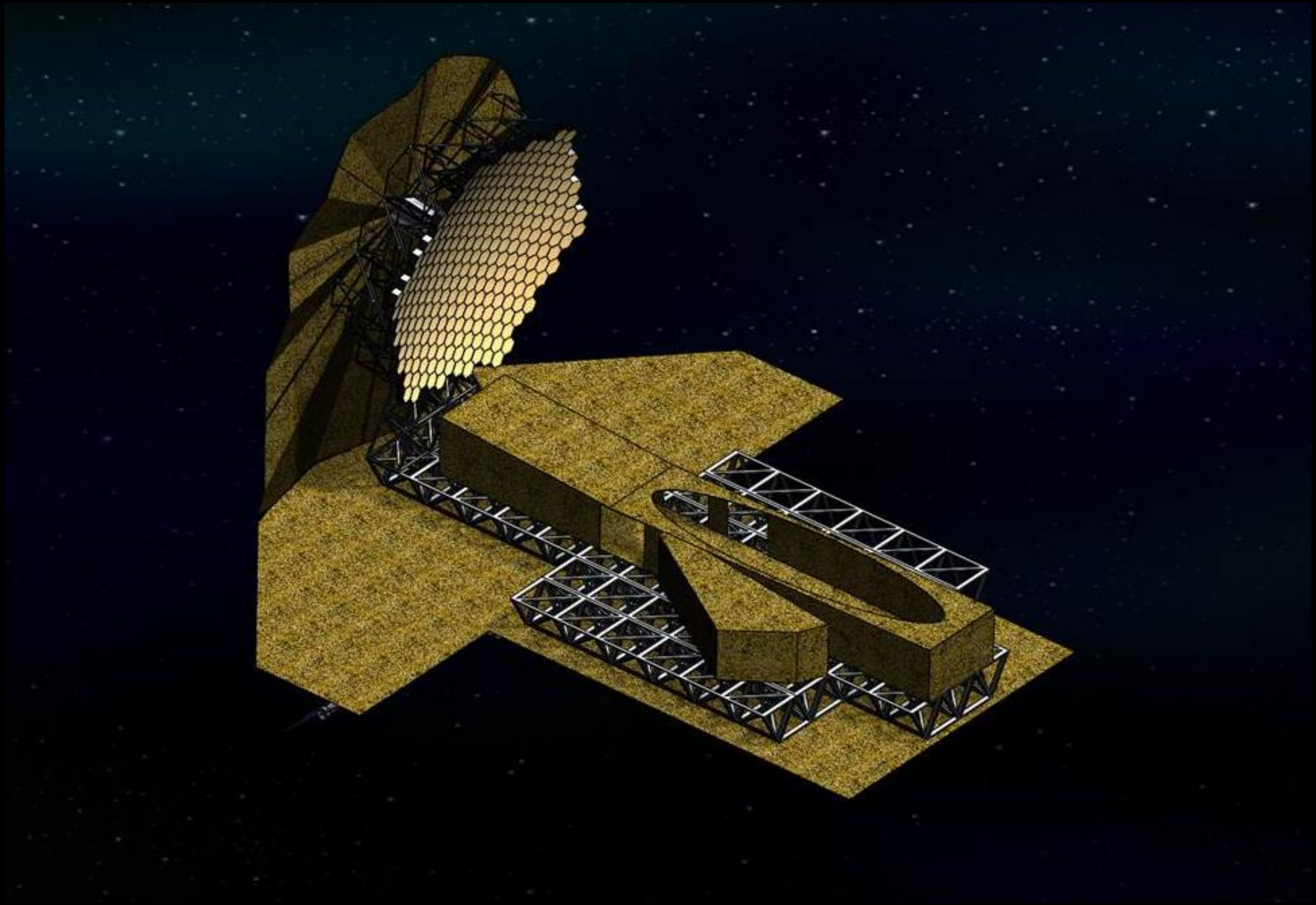


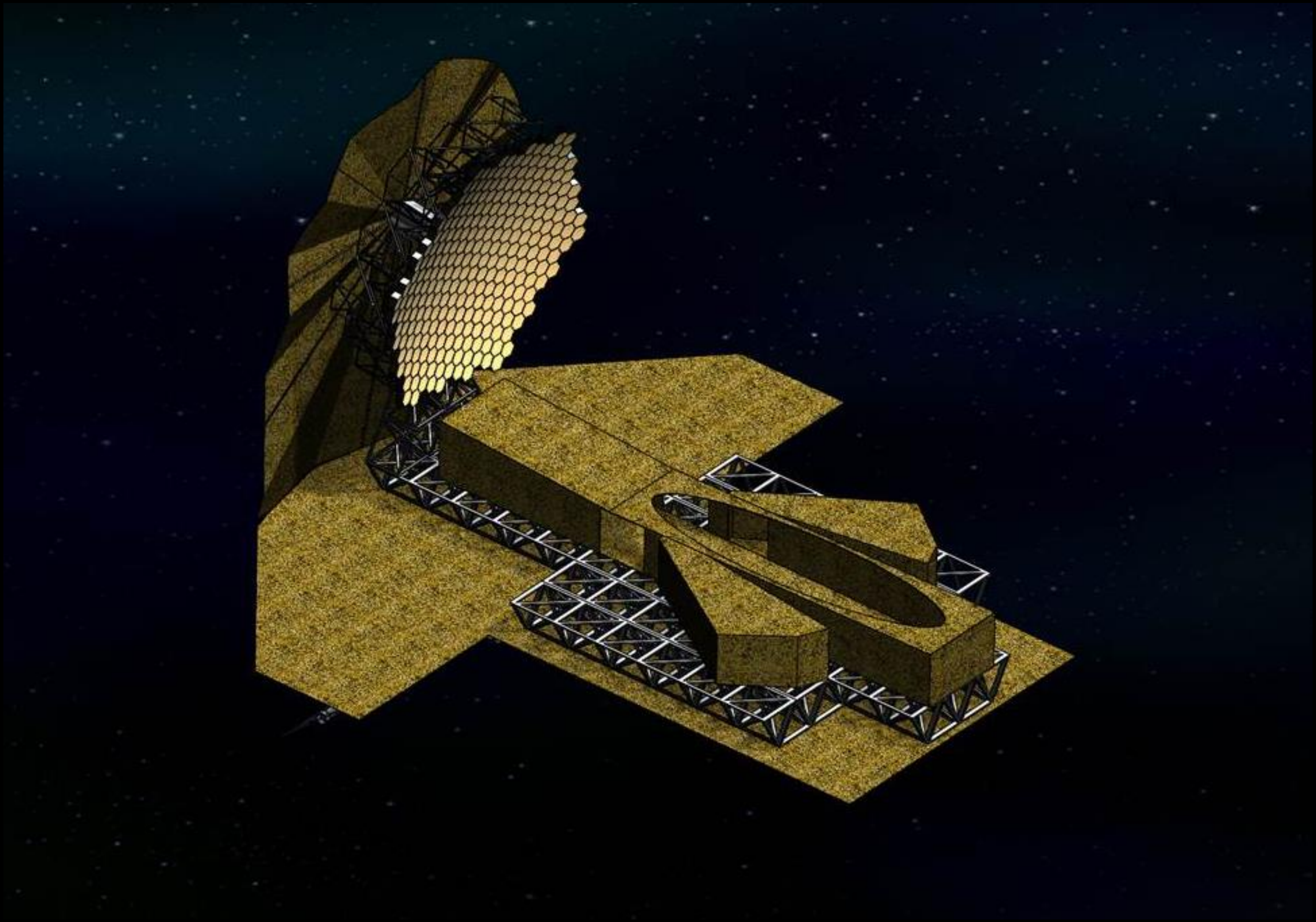


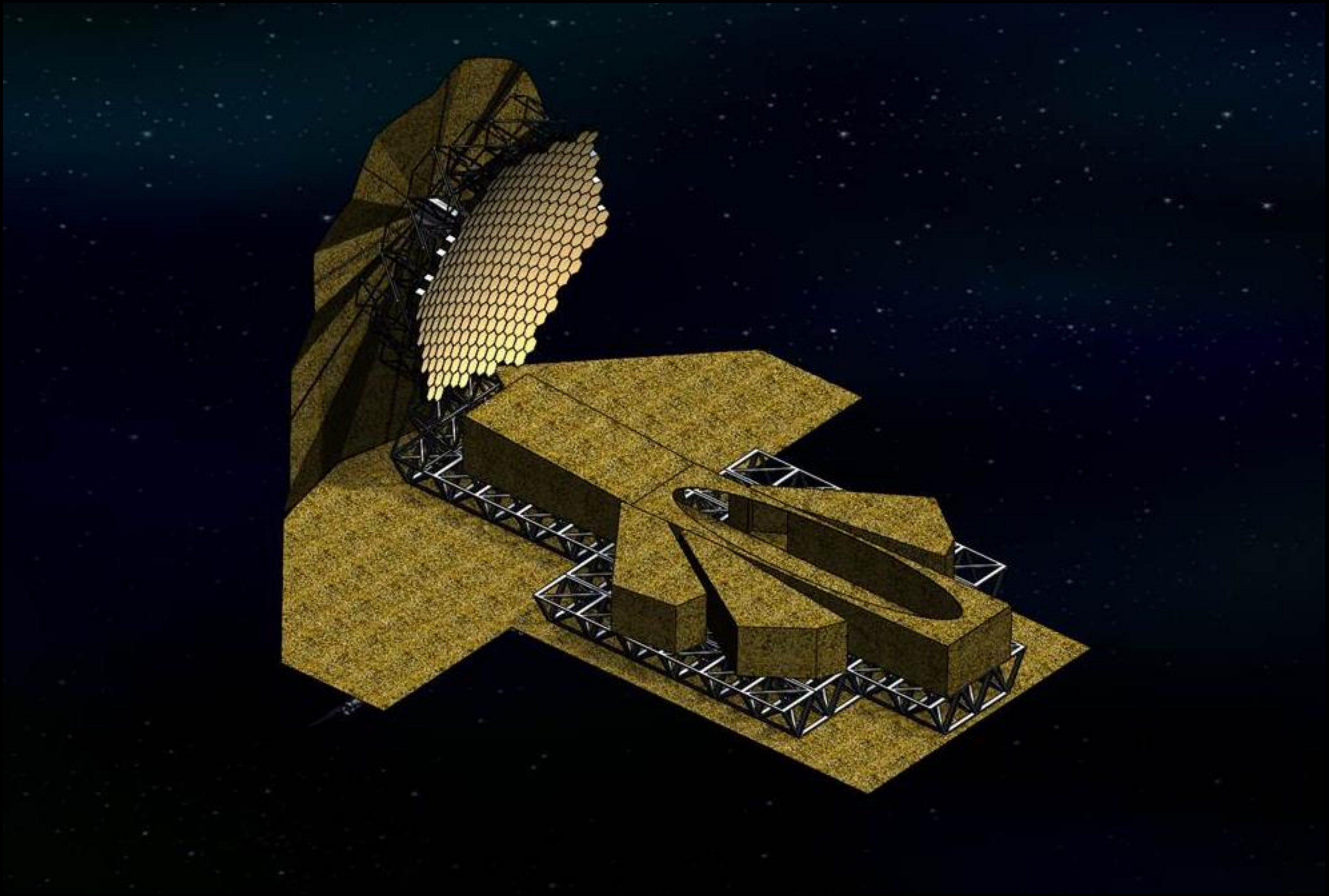


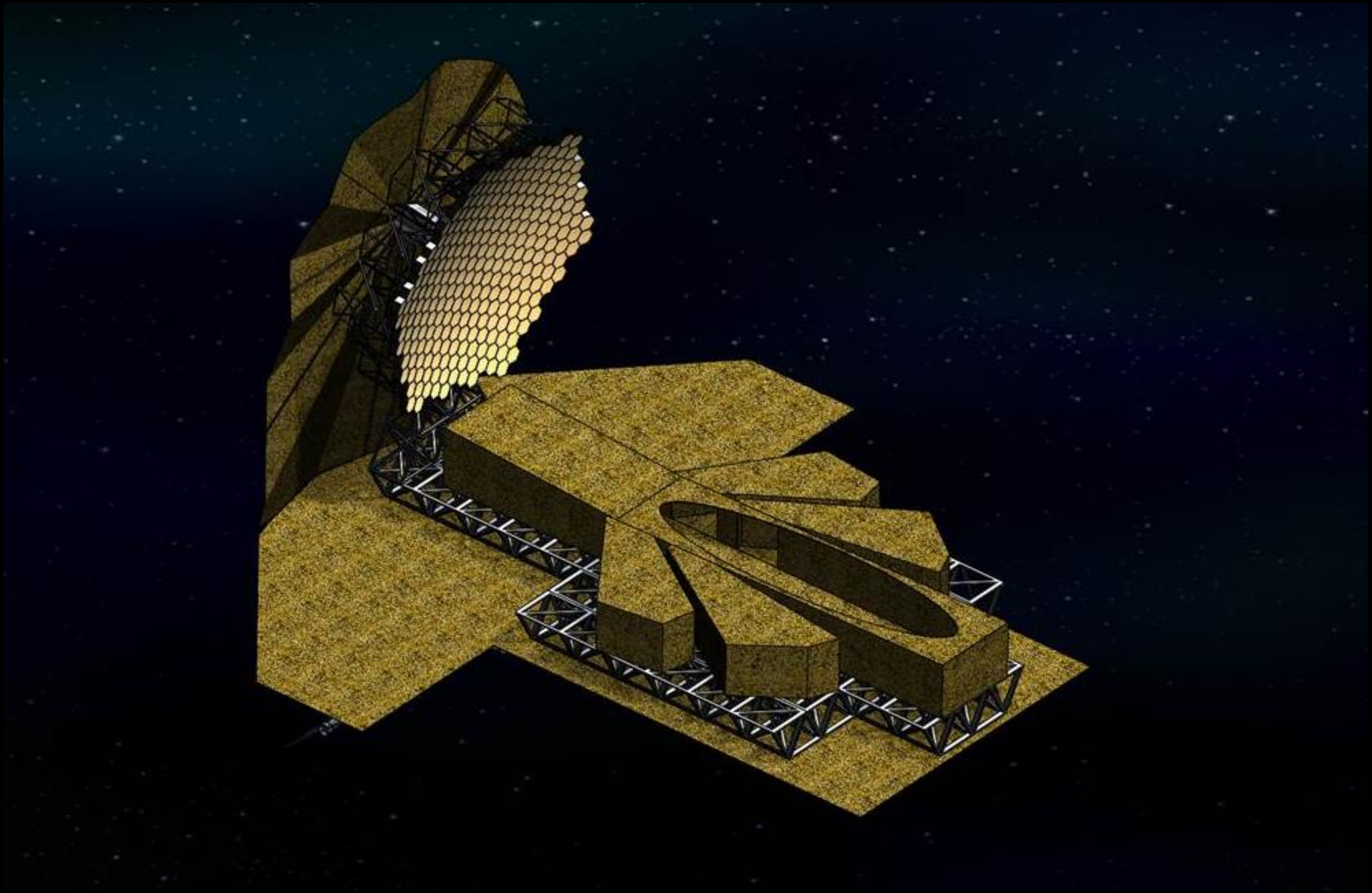












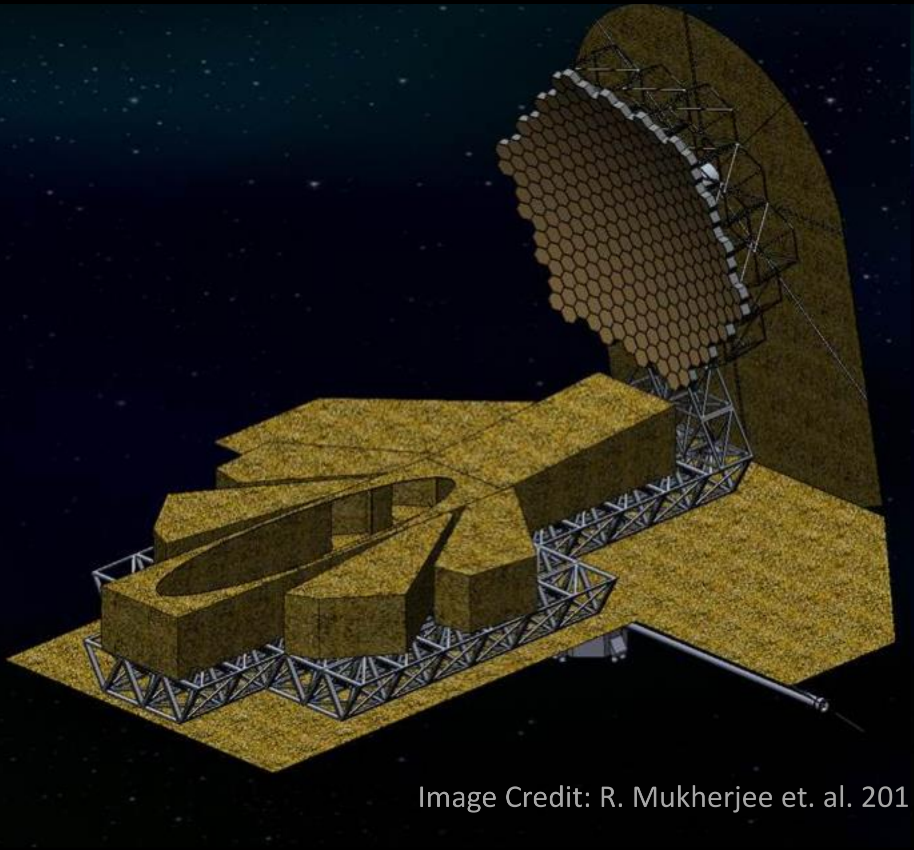


Image Credit: R. Mukherjee et. al. 201

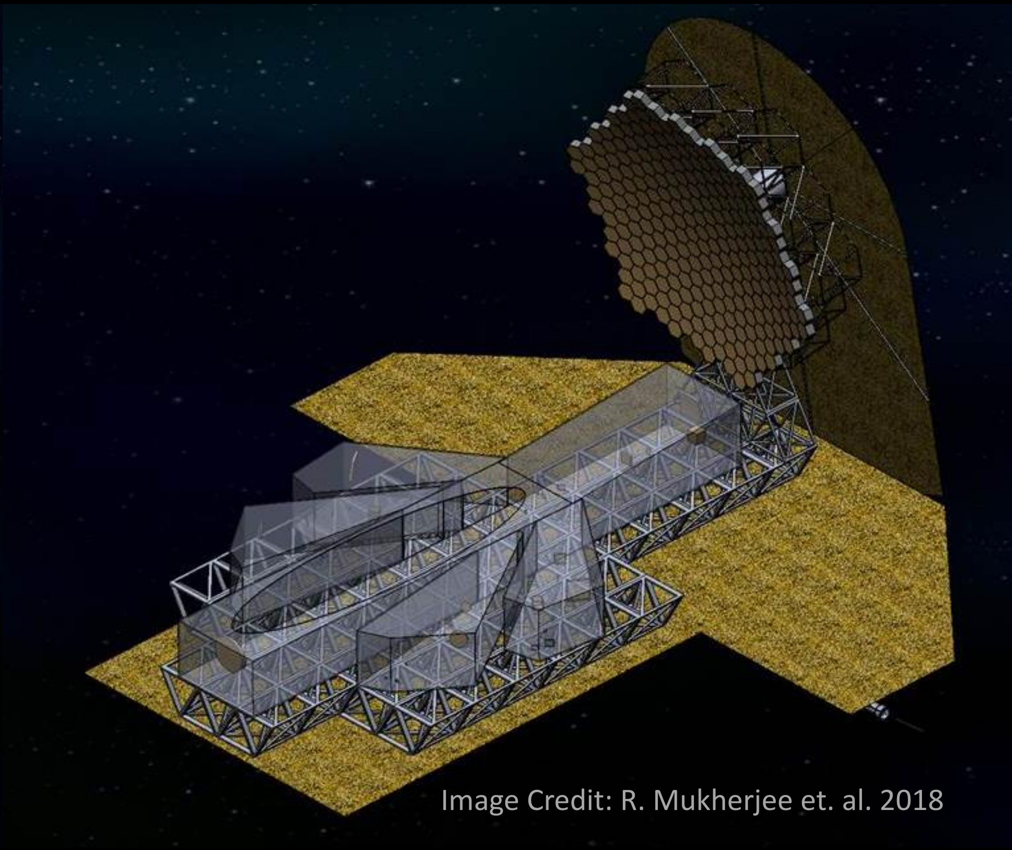
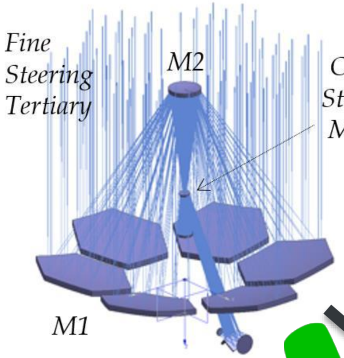


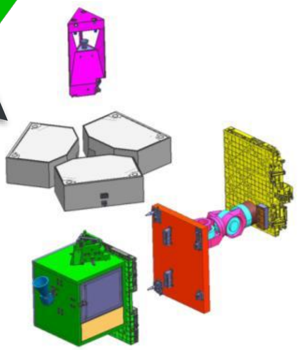
Image Credit: R. Mukherjee et. al. 2018

iSAT

Activity 1a: Modularization and Testing

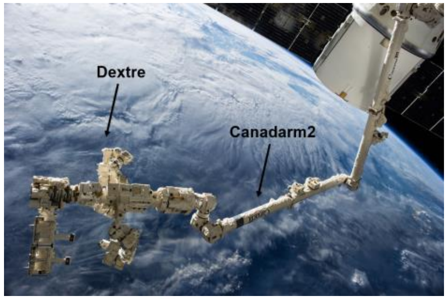


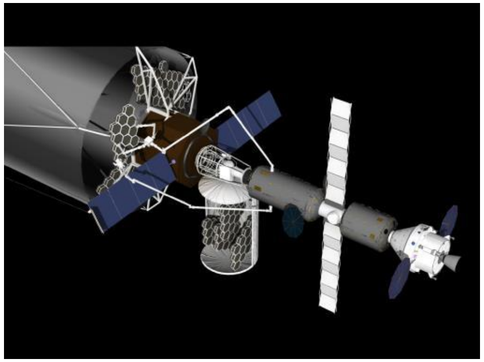
3 Mirror Anastig
Telescope
(1.45 m aperture)

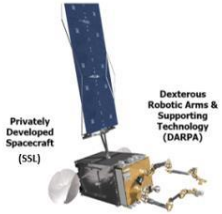


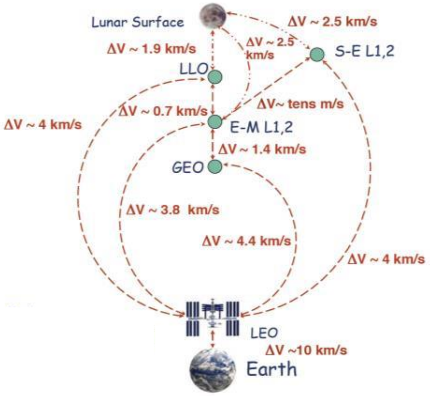
6 launch modules for assembly

Activity 1b: Assembly and Infrastructure









1. Observatory has to be **10nm** stable: structure has to be micro level stable
2. Interfaces between the instruments have to be **light sealing**
3. **2cm** maximum spacing between mirror rafts
4. Alignment: **micron** level
5. Build the structure first and show it meets optical requirements

Initial Conditions: Ignore far field rendezvous

Orbits

1. LEO
2. LEO – 2
3. HEO
4. GEO
5. Cis-Lunar (Gateway)
6. SE-L2

Assets

1. Free Flyer (e.g. RESTORE-L, RSGS)
2. Station and its robotics (e.g. ISS, Gateway)
3. Embedded Walking Robot (e.g. Canada Arm, Dragonfly)
4. Astronaut
5. Or combinations thereof

LEO	GEO	CIS LUNAR	L2
SLS	SLS	SLS	SLS
New Glenn	New Glenn	New Glenn	New Glenn
Delta 4 H	Delta 4 H	Delta 4 H	Delta 4 H
FH	FH	FH	FH
Vulcan	Vulcan	Vulcan	Vulcan
Ariane	Ariane	Ariane	Ariane
Atlas 5	Atlas 5	Atlas 5	Altas 5
F9	F9		
H3	H3		
Angara	Angara		
GSLV	GSLV		
Antares	Antares		
Pegasus			
Athena 1			
Athena 2c			
Firefly			
Vector			
Pegasus			
Electron			
Minotaur C			
Launcher One			
PSLV			

1. **Are there technical reasons why we cant do any of this today?**
2. **What are key upcoming milestones, pertinent to 1b, that make the case for ISA?**
3. **What can be done on the ground to make ISA job easier?**
4. **What can ISA do to make the job on the ground easier?**

ID	Consideration	Bulletized Comments or Descriptions. Also use to summarize justification, if any, for scores to	Technical challenge or Engineering complexity (tall tent pole) (-	Impact on assembly or servicing schedule	Impact on cost	Impact on Risk	Scalability: How well does this scale to smaller telescopes (5m-
Q1	What is the impact of the thermal environment on the assembly process?						
Q2	What is the impact of sun position changes (lighting conditions, slew etc.) on the assembly process?						
Q3	What are other disturbance sources (e.g. gravity gradient) and their impact on the assemblage?						
Q4	What is the MMOD environment and its impact on the assemblage?						
Q5	What are the mission assurance issues specific to the orbit (e.g. Material choices)?						
Q6	Is the orbit easy to access and resupply (time between launches, number of vehicles, cost etc.), and its impact?						
Q7	What is the delta V for transport of the observatory from assembly to operational location and its impact (e.g. ruggedization, mass margins and accelerations to observatory)?						
Q8	What is the impact of orbit choice on spacecraft control/agility and fuel needs?						
Q9	Does the orbit present an opportunity for human intervention (high bandwidth telerobotics or EVA)?						
Q10	What is the impact of orbit choice on need for low bandwidth (supervised autonomy) vs high bandwidth (joystick) telerobotics?						
Q11	What is the impact of the orbit on complexity of communications? E.g. do we have constant contact, need a relay, time delay and data size etc.						
Q12	Does the orbit enable leveraging existing infrastructure (E.g. ISS, gateway, Commercial Free-Flyer)?						

Notional Function Based Phase Space

	Free Flyer	Station	Embedded Robot	Astronaut
LEO	R, A, T, I, S	V	A, I	V, A, I
GEO	V, (RATIS)*		(AI)*	
Cislunar	R, A, T, I, S	V	A, I	V, A, I
SE-L2	R, S		A, M, I	

Ref: Gordon Roesler

R = rendezvous and capture of upcoming payloads, handoff to embedded robots
A = assembly of telescope from component modules
M = in-service maintenance, upgrade
V = verification of assembly concepts, robotics, etc. (risk reduction prior to go-ahead)
I = inspection of assembled systems/subsystems
T = tugging of components, subassemblies, or fully assembled telescope between orbits
S = station-keeping, attitude adjustment, wheel desaturation
* The starred options represent assembly in GEO by renting a commercial free-flyer there.

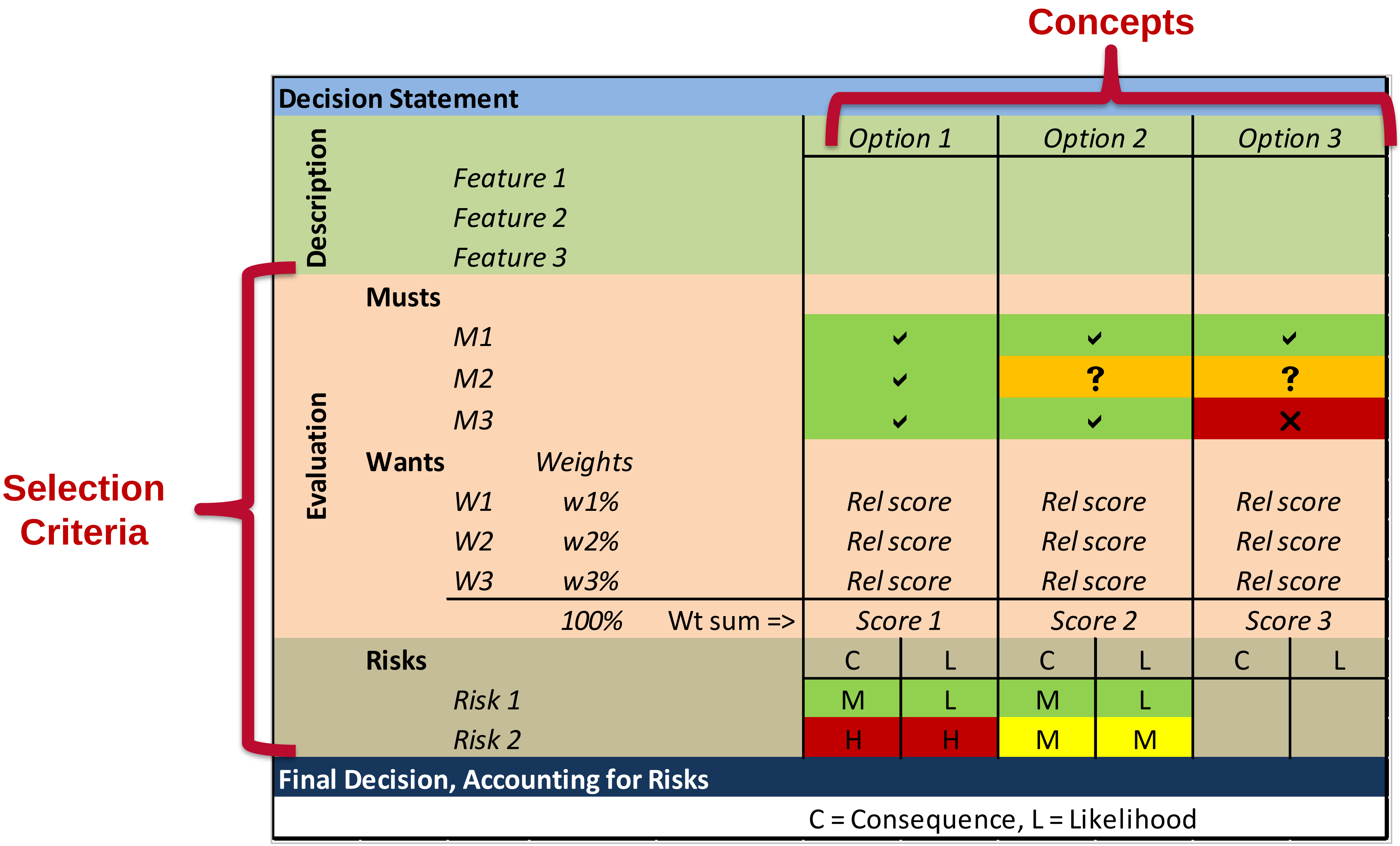
#	Question	Clarification
Q1.	Describe the RPO con-ops and requirements on the assembly agent, resupply vehicle, sensing and SC control authority	Assume resupply vehicle is 1-10km away from assemblage. What is the terminal capture scenario?
Q2.	Describe the assembly agent(s) and their roles	Think through the phases of resupply, berthing/docking, transfer from cargo bay to assembly location, and assembly steps
Q3	Describe the assembly sequence i.e. how do we go from the modules to the observatory	Pick a module, work through its assembly steps in some detail, and perhaps discuss how those steps may change or include new steps for other modules
Q4	Describe mobility or accessibility approach to different regions of the observatory for assembly – estimate precision and accuracy	Again, think through where all the agent needs to go for a representative module, and how that changes for other modules as the telescope starts to come together
Q5	Describe the manipulation approach envisioned including estimates for accuracy and precision: soft goods, hard goods, soft to hard interfaces; large modules vs small modules	Consideration may include addressing the desire to minimize disturbances (shock and handling loads), achieve desired precision, stiffness of connection, V&V, localization, perception among others
Q6	Estimate the disturbances injected during assembly and servicing to the observatory: soft goods, hard goods, soft to hard interfaces	Interfaces: Truss module to truss interface (hard), mirror raft to truss (hard), instrument to truss (hard), instrument to instrument (hard and soft)
Q7	Describe any space and size constraints for grapples	For e.g. the max spacing between the rafts is 2cm

#	Question	Clarification
Q8	Describe the role of autonomy and readiness of these capabilities	Where all do we need autonomy, are we able to do this today, what are the steps needed to get there?
Q9	Describe the joining and other interfacing approaches/requirements (reversible, adjustable, soft assembly followed by hardening or direct hard assembly etc) and features that aid the agent	Discussions rotate around kinds of joining options (permanent, reversible), the estimation of their ability to meet stiff, alignment etc. Also discuss features to simplify the assembling agent's job
Q10	Describe the approach for meeting contamination allocations	Discuss the contamination sources and possible mitigation approaches, their relative risks and costs
Q11	Describe the V&V approach (local and global) for the observatory	Local: Assembled one module – how to V&V that step? Global: Assembled all the trusses or the completed observatory – how to V&V that?
Q12	Describe calibration approach for agent	Perception, arm motion etc
Q13	Describe anomaly resolution approach	Beyond: Houston, we have a problem
Q14	Describe the SC control requirement and envisioned plan (attitude control)	There will be a lot of large modules being moved around. How will we control cm and not tumble
Q15	Estimate overall assembly time and servicing time	Ball park: days, months, years

Team A	Team B	Team C
Nick Siegler	Rudra Mukherjee	Harley Thronson
John Grunsfeld	**David Miller**	**Gordon Roesler**
Keith Havey	Bob Hellekson	Paul Lightsey
Howard MacEwen	David Redding	Kevin Patton
Paul Backes	Glen Henshaw	Erik Komendera
Adam Yingling	John Lymer	Michael Fuller
Al Tadros	Hsiao Smith	Kenneth Ruta
Diana Calero	Roger Lepsch	Keenan Albee
Kim Aaron	Allison Barto	Sharon Jefferies
Douglas McGuffey	Joseph Pitman	Phil Williams
William Doggett	John Dorsey	Jason Herman
Robert Briggs	Kevin DiMarzio	Rob Hyot
Alex Ignatiev	Nate Shupe	Bradley Peterson
David Folta	Bo Naasz	Kimberly Mehalick
Yu Wei	Carlton Peters	Michael Elsperman
Keith Belvin	Leslie Doggrell	Samantha Glassner
Blair Emanuel	Ryan Ernandis	Evan Linck
Hideshi Ishikawa	Beeth Keer	Josh Vander Hook
Alison Nordt	Michael Renner	
Lynn Bowman	**Ron Polidan**	**Eric Mamajek**

Kepner Tregoe Decision Matrix

Kepner-Tregoe Decision Matrix



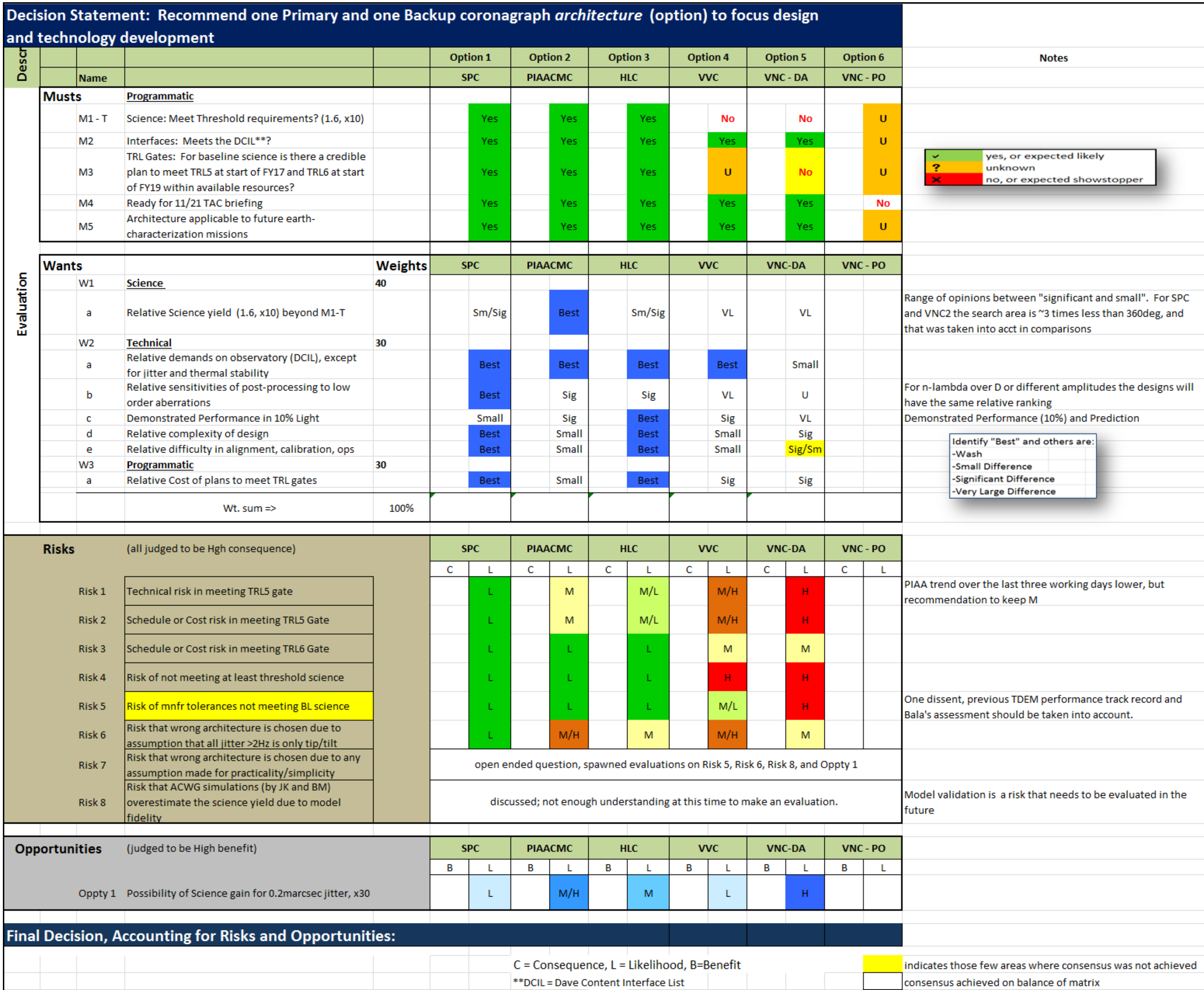
Concepts

Selection Criteria

Decision Statement										
Description					*Option 1*		*Option 2*		*Option 3*	
		Feature 1								
		Feature 2								
		Feature 3								
Evaluation	**Musts**									
		M1			✓		✓		✓	
		M2			✓		?		?	
		M3			✓		✓		✗	
	Wants		*Weights*							
		W1	*w1%*		*Rel score*		*Rel score*		*Rel score*	
		W2	*w2%*		*Rel score*		*Rel score*		*Rel score*	
		W3	*w3%*		*Rel score*		*Rel score*		*Rel score*	
			100%	Wt sum =>	*Score 1*		*Score 2*		*Score 3*	
	Risks				C	L	C	L	C	L
		Risk 1			M	L	M	L		
		Risk 2			H	H	M	M		
Final Decision, Accounting for Risks										

C = Consequence, L = Likelihood

Example of a Completed Trade Matrix



Decision Statement: Recommend one Primary and one Backup coronagraph *architecture* (option) to focus design and technology development

Descr	Name			Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Notes
				SPC	PIAACMC	HLC	VVC	VNC - DA	VNC - PO	
Musts		**Programmatic**								
	M1 - T	Science: Meet Threshold requirements? (1.6, x10)		Yes	Yes	Yes	No	No	U	
	M2	Interfaces: Meets the DCIL**?		Yes	Yes	Yes	Yes	Yes	U	
	M3	TRL Gates: For baseline science is there a credible plan to meet TRL5 at start of FY17 and TRL6 at start of FY19 within available resources?		Yes	Yes	Yes	U	No	U	✓ yes, or expected likely ? unknown ✕ no, or expected showstopper
	M4	Ready for 11/21 TAC briefing		Yes	Yes	Yes	Yes	Yes	No	
	M5	Architecture applicable to future earth-characterization missions		Yes	Yes	Yes	Yes	Yes	U	

Evaluation										
Wants			**Weights**	SPC	PIAACMC	HLC	VVC	VNC-DA	VNC - PO	
	W1	**Science**	40							
	a	Relative Science yield (1.6, x10) beyond M1-T		Sm/Sig	Best	Sm/Sig	VL	VL		Range of opinions between "significant and small". For SPC and VNC2 the search area is ~3 times less than 360deg, and that was taken into acct in comparisons
	W2	**Technical**	30							
	a	Relative demands on observatory (DCIL), except for jitter and thermal stability		Best	Best	Best	Best	Small		
	b	Relative sensitivities of post-processing to low order aberrations		Best	Sig	Sig	VL	U		For n-lambda over D or different amplitudes the designs will have the same relative ranking
	c	Demonstrated Performance in 10% Light		Small	Sig	Best	Sig	VL		Demonstrated Performance (10%) and Prediction
	d	Relative complexity of design		Best	Small	Best	Small	Sig		Identify "Best" and others are: -Wash -Small Difference -Significant Difference -Very Large Difference
	e	Relative difficulty in alignment, calibration, ops		Best	Small	Best	Small	Sig/Sm		
	W3	**Programmatic**	30							
	a	Relative Cost of plans to meet TRL gates		Best	Small	Best	Sig	Sig		
		Wt. sum =>	100%							

Risks		(all judged to be Hgh consequence)	SPC		PIAACMC		HLC		VVC		VNC-DA		VNC - PO		
			C	L	C	L	C	L	C	L	C	L	C	L	
	Risk 1	Technical risk in meeting TRL5 gate		L		M		M/L		M/H		H			PIAA trend over the last three working days lower, but recommendation to keep M
	Risk 2	Schedule or Cost risk in meeting TRL5 Gate		L		M		M/L		M/H		H			
	Risk 3	Schedule or Cost risk in meeting TRL6 Gate		L		L		L		M		M			
	Risk 4	Risk of not meeting at least threshold science		L		L		L		H		H			
	Risk 5	Risk of mnfr tolerances not meeting BL science		L		L		L		M/L		H			One dissent, previous TDEM performance track record and Bala's assessment should be taken into account.
	Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt		L		M/H		M		M/H		M			
	Risk 7	Risk that wrong architecture is chosen due to any assumption made for practicality/simplicity	open ended question, spawned evaluations on Risk 5, Risk 6, Risk 8, and Oppty 1												
	Risk 8	Risk that ACWG simulations (by JK and BM) overestimate the science yield due to model fidelity	discussed; not enough understanding at this time to make an evaluation.												Model validation is a risk that needs to be evaluated in the future

Opportunities		(judged to be High benefit)	SPC		PIAACMC		HLC		VVC		VNC-DA		VNC - PO	
			B	L	B	L	B	L	B	L	B	L	B	L
	Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30		L		M/H		M		L		H		

Final Decision, Accounting for Risks and Opportunities:

C = Consequence, L = Likelihood, B=Benefit

**DCIL = Dave Content Interface List

🟨	indicates those few areas where consensus was not achieved
☐	consensus achieved on balance of matrix

Current Status of the Matrix

Additional Slides

Jet Propulsion Laboratory
California Institute of Technology