

## **Team X Study Summary for ASMCS Theia**

***Jet Propulsion Laboratory,  
California Institute of Technology***

**with contributions from the Theia Team**

P. Douglas Lisman, NASA Jet Propulsion Laboratory  
David Spergel, Princeton University  
Ben Parvin, NASA Jet Propulsion Laboratory  
Paul Scowen, Arizona State University  
Daniel Stern, NASA Jet Propulsion Laboratory

This study was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The series of Team X studies for ASMCS Theia began with two instrument studies in August and September of 2008. The August study set out to scope a large CCD array star formation survey camera (SFC) for integration with a 4-meter telescope at Sun-Earth L2. The study goals included capturing the cost, mass and instrument requirements placed on the spacecraft and overall mission. The September study estimated the scope and cost the eXtrasolar Planet Characterizer (XPC) payload, which consists of two cameras, two coronagraph arms with one Integral Field Unit spectrograph each. The results from the instrument studies were fed into a first Team X mission study done in October 2008.

The October mission study focused on scoping and cost-estimating a 2-spacecraft formation flying mission at L2. One spacecraft supported a 4-meter telescope with a coronagraph (XPC), survey camera (SFC), and UV spectrograph. The other spacecraft carried a 45-meter diameter occulter. The telescope spacecraft pivots from target to target while the occulter spacecraft slews to reposition in front of the telescope. The slewing is done with solar electric propulsion (SEP). The separation between the two spacecraft is 62,700 km.

In January 2009, there was a follow-up study of the SFC instrument. The purpose was to estimate the mass and cost changes due to the addition of an on-board calibration system and raising the detector operating temperature from 133K to 175K. In February 2009, there was a one-session final mission study to address a number of small changes to the design, including some modifications to the XPC instrument design.

The primary objective of the Theia mission is the direct observation and characterization of exoplanets. Planets would be found by blocking light from the star with a combination of an external occulter and a coronagraph. The primary mission would be 5 years (after on-orbit checkout) and there would be consumables for 10 years. Targeting a new star requires moving the occulter a large distance, which is done using electric propulsion. While the occulter is moving to prepare for observations of a new target, the telescope

is used for other astrophysics observations involving the star formation camera and/or the UV spectrograph.

The spacecraft would be launched separately, with each on its own EELV (Atlas V 551) with direct injection to an Earth-Sun L2 halo orbit. Once in position, the two systems would form one large observatory. Relative positioning between the spacecraft is obtained through a laser ranging system and an IR camera, with positional information shared over an S-band link, and course positioning achieved with the spacecraft ACS subsystems. Fine pointing is handled with an actuated secondary mirror in the telescope and actuated mirrors within the instruments. The baseline spacecraft and mission parameters are summarized in the table below. Key design features are:

- **Telescope** – 4m on-axis Cassegrain design, with actuated secondary mirror, operating from 200nm to 1100nm.
- **Instruments:**
  - **SFC** – Wide field star formation survey camera. Camera has two 0.6m X 0.6m passively cooled focal planes.
  - **XPC** – eXtrasolar Planet Characterizer. IR and visible Lyot coronagraphs for direct planet imaging. Each can be redirected to a corresponding spectrometer. Instrument also contains the IR camera used for formation flying and an ozone camera.
  - **UVS** – Ultra-violet Spectrometer. Instrument design was supplied by customer.
- **ACS:**
  - **Occluder** – Mostly conventional – reaction wheels, precision star trackers, and IMUs – but also includes laser ranging system for formation flying
  - **Telescope** – Redundant star trackers, IMUs, 6 reaction wheels. Also includes active vibration isolation for improved pointing.
- **Structure:**
  - **Occluder** – Proprietary bus design including a deployable 45m diameter light shield. Deployable, articulated solar arrays.
  - **Telescope** – The spacecraft bus is a hexagonal box structure with the passive vibration isolation mounts for the reaction wheels and active struts on the telescope. Solar arrays and the HGAs are articulated. A deployable solar sail is also included.
- **Propulsion** – Both spacecraft use a monoprop blowdown system for L2 insertion, reaction wheel unloading, and in the case of the occulter, station keeping. In addition, the occulter also has a SEP system for slewing between observation targets.

- **Thermal** – MLI, radiators and heaters on both spacecraft. Telescope has a “sugar scoop” insulating sun shade on the telescope.
- **Telecom:**
  - **Occulter** – Fully redundant system with S band downlinks, up-links, and relay links. The system includes 3 LGAs. Redundant Ka band receivers and LGAs were added for RF tracking of the occulter.
  - **Telescope** – Fully redundant system with S and Ka-band downlinks, and S band up-links and relay links. The system includes two 1m gimbaled S/Ka HGA. Redundant Ka band receivers were added for RF tracking of the occulter.

System	Launch Mass (kg)		
	Occulter	5878	
	Observatory	6276	
	Spacecraft Power (W)		
	Occulter	16873	
	Observatory	2289	
Total Mission Cost (\$M FY08)			
Radiation TID (krad)		19	
Science	Science Goals		
	Detecting and Characterizes Earth-like exoplanets		
	Key Measurements	Spectral analysis of exo-planets and a panchromatic broad and key narrow band emission-line imaging of all high mass star formation sites	
	No. of Scientists	21	
Total Data Volume (Gbits)		6.6 PBytes (assuming 2:1 lossless compression)	
Mission Design	Launch Date		
	1-Aug-23		
	Launch Vehicle		
	Occulter	Atlas V 551	
	Observatory	Atlas V 551	
	Launch Mass Allocation (kg)		
	Occulter	6377	
	Observatory	6390	
	Target Body		
	Exo-Planets		
Trajectory/Orbit Type			
L2 Halo Orbit			
Mission Duration (months)			
60 (with consumables for 60 month extension)			
Key Mission Phases		Launch, Trajectory Correction Manuevers, Halo insertion, and Formation Flying	
Instruments	Telescope	Type	On-axis Cassegrain
		Size	4m
		Frequency Range	200nm -- 1100nm
	No. of Instruments		
	Occulter	4	
	Observatory	1	
	Instrument Types		
	Occulter	Star Shade	
	Observatory	Exoplanet Characterizer, Star Formation Camera, Ultraviolet Spectrograph, Fine Guidance, Telescope	
	Payload Mass (kg) - CBE		
	Occulter	1040	
	Observatory	3196.6	
	Payload Power (W)		
	Occulter	0	
	Observatory	471	
	Payload Data Rate (Mbps)		
	Occulter	0	
Observatory	1640		
Operating Temperature (K)			
Occulter	-		
Observatory	293		
ACS	Pointing Control (arcsec)		
	Occulter	7200	
	Observatory	1	
	Pointing Knowledge (arcsec)		
	Occulter	1800	
	Observatory	1	
	Pointing Stability (arcsec)		
	Occulter	10	
	Observatory	10	
	Stabilization Type (3-axis, spin, gravity grad.)		
	Occulter	3-axis	
	Observatory	3-axis	
Pointing Technologies			
Occulter	Sun Sensors, Star Trackers, IMU, SEP Accelerometer, Reaction Wheels		
Observatory	Sun Sensor, Star Tracker, IMU, Reaction Wheels, Various Control Algorithms		
CDH	Processor Type		
	Occulter	RAD 750	
	Observatory	RAD 751	
	Redundancy (hot, cold, single string)		
	Occulter	Cold	
	Observatory	Cold	
Data Storage (Gbytes)			
Occulter	32		
Observatory	12000		

Telecom	Bands	
	Occulter	Ka and S-Band
	Observatory	Ka and S-Band
	Antenna Types	
	Occulter	Two LGAs and three LGA Helix
	Observatory	Two 1.0m HGAs and two LGA Helix
	Uplink Rate (kbps)	
	Occulter	2
	Observatory	2
	Downlink Rate (kbps)	
	Occulter	20
	Observatory	1000000
	Gimballed? (Y/N)	
	Occulter	No
Observatory	Yes	
Power	Solar Array Area (m <sup>2</sup> )	
	Occulter	60
	Observatory	7.5
	Solar Array Type	
	Occulter	GaAs TJ Rigid
	Observatory	GaAs TJ Rigid
	Articulated SA? (Y/N)	
	Occulter	Yes
	Observatory	Yes
	EOL Power (W)	
	Occulter	17023
	Observatory	2163
	Battery Storage Size(s) (A-hrs)	
	Occulter	50
Observatory	40	
Battery Type(s)		
Occulter	Li-ION	
Observatory	Li-ION	
Propulsion	No. of Prop Systems	
	Occulter	2
	Observatory	1
	Type(s) of System(s)	
	Occulter	Monoprop Blowdown and SEP
	Observatory	Monoprop Blowdown
	Propellant Mass(es) (kg)	
Occulter	1005.9 Hydrazine and 1158 Xenon	
Observatory	224.3	
Structures	Primary Structural Mass (kg) - CBE	
	Occulter	362.4
	Observatory	240.8
	No. of Mechanisms	
	Occulter	3
Observatory	9	
Thermal	Active/Passive	
	Occulter	Passive
	Observatory	Passive
	Key Operating Temperature(s) (K)	
	Occulter	-
	Observatory	300
	Thermal Stability (mK/hr)	
	Occulter	-
Observatory	-	
Thermal Control Technologies		
Occulter	MLI, heaters, thermistors, and radiator	
Observatory	MLI, heaters, thermistors, and radiator	
Ground System	Ground Antenna(s)	DSN 34m
	Average Pass Duration (hrs)	8
	Links/week	7 passes for each spacecraft except during Calibration (1 pass) and Slew (2 passes)

- **Power:**
  - **Occluder** – The power system must support the large draw of the SEP system. Consists of: two 50 A-hr Li Ion batteries; about 60 m<sup>2</sup> solar array area on two deployable, articulated wings; dual string power electronics; and 100V bus for the SEP system.
  - **Telescope** – Includes: two 40 A-hr Li Ion batteries; about 7.5 m<sup>2</sup> solar array area on two deployable, articulated wings; and dual string power electronics.
- **CDH:**
  - **Occluder** – Cold spare redundant system based on JPL standard avionics architecture. The system includes a RAD 750 processor and 32 Gbit NVM.
  - **Telescope** – Cold spare redundant system based on JPL standard avionics architecture. The system includes a RAD 750 processor and 12 TByte SSR.

For uniformity in assumptions across all ASMCS studies, Team X assumed JPL built buses as the baseline.

## Key Trades

Several key trades were examined as part of the set of Team X studies. The most significant trades were:

- **Medium resolution positioning of Occluder with ground-based navigation vs. Telescope to Occluder laser metrology** – The possibility of using ground-based Doppler ranging to achieve the 10m occulter positional accuracy needed to hand over control to the telescope's fine pointing algorithm was explored in a white paper. The baseline laser ranging was retained due to open questions about data latency and the relative costs between the two options, but the possibility is promising and additional analysis is recommended.
- **Semi-cylindrical telescope solar array vs. deployed flat panels** – A semi-cylindrical solar array would avoid the deployment and low frequency vibration coupling issues associated with flat panels. This would simplify the telescope pointing control, but there may be a packaging issue in fitting the cylindrical array in the fairing. Further examination of this option is recommended.

## Cost Estimate Interpretation Policy, Reserves, and Accuracy

Team X guidelines for this study were to provide independent design and costing analysis for each mission concept. Project-provided designs were used, but not project-provided cost estimates. The cost estimates summarized in this document were generated as part of a Pre-Phase-A preliminary concept study, are model-based, were

prepared without consideration of potential industry participation, and do not constitute an implementation-cost commitment on the part of JPL or Caltech. The accuracy of the cost estimate is commensurate with the level of understanding of the mission concept, typically Pre-Phase A, and should be viewed as indicative rather than predictive. Team X typically adds 30% reserves for development (Phases A-D) and 15% for operations (Phase E).

## Cost Estimate

Project Cost is roughly \$6B FY09 with appropriate contingencies, including 5 years of science operations.

Item	Cost (\$M 2009)*	Notes
Management, Systems Engr., Mission Assurance	150	
Payload System	2960	1
-- Observatory - Exo Charac	150	
-- Observatory - Star Cam	400	
-- Observatory - UV Spec	200	
-- Observatory - Guid Sensors	80	
-- Observatory - Telescope	2000	
-- Occulter - Starshade	100	
-- Other	25	
Flight System	560	2
Mission Ops / Ground Data System	190	
Launch vehicle	445	2 Atlas V 551
Assembly, Test, Launch Operations	40	
Science	250	
Education and Public Outreach	45	
Mission Design	10	
Reserves	1200	
Total Project Cost	5850	

### Notes

\* Individual WBS elements have been rounded to 2 significant digit

1. Payload system includes instrument.
2. Includes observatory plus occulter flight systems.

**Phase Cost Table – Costs are in \$M FY2009**

Phase A	Phase B	Phase C/D	Phase E/F	Total
50.0	460.0	4,970.0	370.0	5850

**Technology Costing**

Team X does not provide technology development costing. Models are based on assuming TRL 6 by the end of Phase B. No additional estimates of technology development costs and schedule were generated for this study.

Copyright 2009 all rights reserved.