JPL Team X Space-based Gravitational-Wave Observatory
OMEGA Report

Customer: Ron Hellings
September 6, 2012
Final report v.1.45a (public release version)

Jet Propulsion Laboratory, California Institute of Technology

This study was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

1281 OMEGA 2012-04 Study, Team X Final Report, 9/6/12

Customer: Ron Hellings, Ken Anderson, Tuck Stebbins & Jeff Booth

Facilitator: Keith Warfield

Sessions: April 3-5 & April 10, 2012

Study ID: 1281

Data Use Policy

- This document is intended to stimulate discussion of the topic described. All technical and cost analyses are preliminary. This document is not a commitment to work, but is a precursor to a formal proposal if it generates sufficient mutual interest.
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Institutional Cost Models

- **Cost estimates described or summarized in this document were generated as part of a preliminary concept study, are model-based, assume an out-of-house build, and do not constitute a commitment on the part of JPL or Caltech. References to work months, work years, or FTE's generally combine multiple staff grades and experience levels.**
- **JPL and Team X add appropriate reserves for development and operations. Unadjusted estimate totals may be conservative because JPL cost estimation models are based on experience from completed flight projects without extracting the historical contribution of expended project cost reserves.**

Table of Contents

Executive Report

(1281) OMEGA 2012-04
April 3 – 5 and 10, 2012

Author: Keith Warfield
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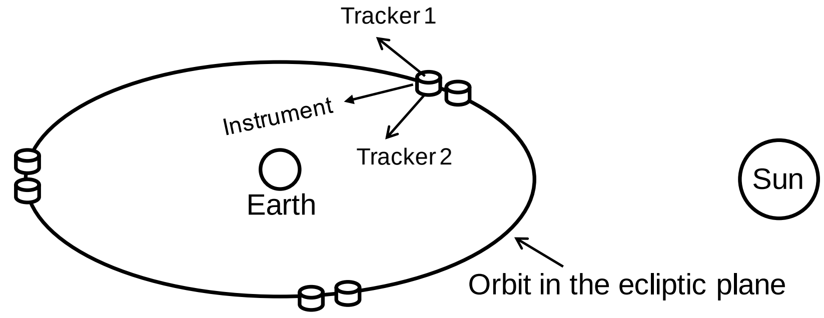
Study Overview

Study Purpose and History

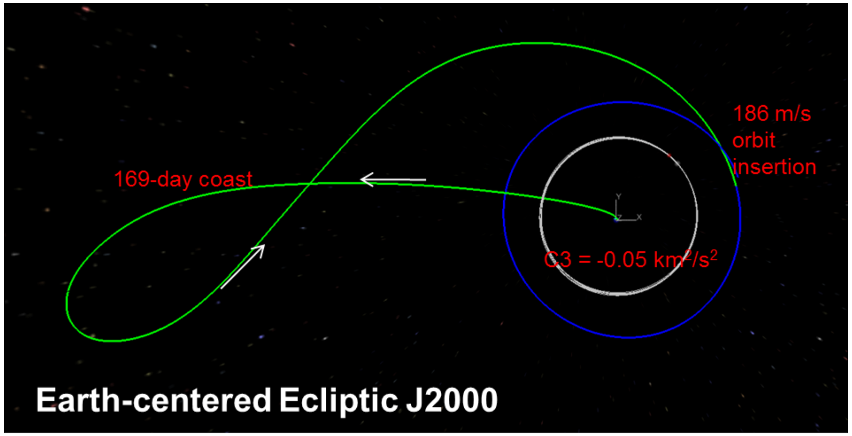
- The Omega Gravity Wave study was conducted over 4 sessions with a standard Team X Powerpoint report as output.
- This study looked at two variations on a 6 spacecraft high-Earth orbiting constellation using drag-free attitude control, micro-Newton thruster, and laser interferometry distance measurement technologies to measure gravitationally induced distortions of space.
- This work was one of three Gravity Wave studies conducted by Team X, in support of a NASA tradespace examination the cost/return of several key mission architectures selected by the Gravity Wave science community.

Mission Architecture

- The mission consist of 3 pairs of identical sciencecraft orbiting Earth at about 600,000 km. The pairs roughly form the vertices of an equilateral triangle.

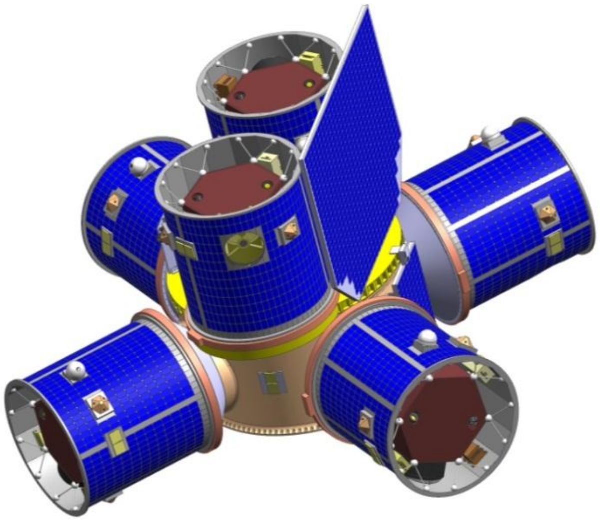


- Sciencecraft are transported to operating orbits on a single propulsive Carrier Craft
  - 169 day low-energy trajectory to orbit
  - 365 days from launch until all sciencecraft are in position
- 1 year science phase after all sciencecraft are in 600,000 km orbit



Executive Summary
Mission Architecture

- **Sciencecraft Architecture**
  - Cylindrical solar panel functions as a heatshield for the payload
  - Payload suspended in the heatshield on 12 thermally isolating bipods
    - Most avionics are attached to the inside of the cylindrical shield
  - Payload consists of laser/telescope distance measurement system and drag-free disturbance reduction system
  - Bus has heritage components but is not an off-the-shelf design
  - 3-axis stabilized
  - Micro-Newton In-FEEP thrusters
- **Propulsion Module**
  - Custom ESPA ring designed to carry all 6 sciencecraft at once
  - Monoprop blowdown propulsion system
  - Sciencecraft not functioning while in transport



Executive Summary
Study Guidelines

- **Contingency added to CBE values:**
  - 53% on mass, to compare masses estimated by MDL at GSFC.
  - 43% on power.
- **Other margins – follow JPL Design Principles**
- **Cost Reserves – 30% of Phases A-E (not including L/V)**
- **All Technology is at TRL 6**
  - Note where technology is not currently at TRL 6 and does not have a funded path to TRL 6 in time for this mission as a risk
- **NLS II Launch vehicles only**
- **Mission is Class B**
  - Functional redundancy in having 6 sciencecraft allows for Class C single-string sciencecraft
- **Selected spares**
- **6 testbeds**

Executive Summary
Overview of Options

- **The Team X design departed significantly from the Omega team's design assumptions in the area of accelerometer design (output from an earlier Team X Instrument design review) and development schedule. Team X and the Study Manager agreed to look at both cases to quantify the impact those two assumptions had on the overall mission cost.**

- **Option 1:**
  - JPL estimated accelerometer mass, power and cost
  - JPL estimated development schedule

- **Option 2:**
  - Omega team's supplied estimate for accelerometer mass, power and cost
  - Omega team's supplied estimate for development schedule

Major Trades/Conclusions

- **Team X vs. advocate schedule and accelerometer assumptions**
  - This was the primary trade of the study
  - Omega assumptions lowered costs by about $150M but raised significant risks
  - Still above the $1B target in both cases
- **A significant trade was conducted on designing a mission to avoid eclipse conditions throughout the mission**
  - Eclipses drive the sciencecraft array and battery sizing which, in turn, drive mass.
  - Eclipse-free design completed after the study; not included in either option.
- **Number of testbeds vs. schedule**
  - The I&T activities are constrained by the number of testbeds due to the parallel build plan. 6 testbeds shortened the schedule by 12 months

Executive Summary
Option Comparison

	Option 1	Option 2
Total Cost ($FY12)	$1.4B	$1.2B
Launch Mass (kg)	2376	2223
Sciencecraft Mass (kg)	218	196
Payload Mass (kg)	83.7	71.5
Sciencecraft Power (W)	258	220
Payload Power (W)	80	56
Phase A-D Schedule (months)	94	70
Phase E Schedule (months)	24	
Unfunded Technology Development Needed	FEEP Thrusters	FEEP Thrusters Accelerometers
Yellow Risks	3	6
Red Risks	0	0

Technical Findings

- **The Team X OMEGA estimate of $1.4B is the lowest cost of the three Gravity Wave studies conducted this year.**
  - It far exceeds the OMEGA Team's expectation of $0.4B
  - The Team X sciencecraft cost compares reasonably close to the Grail bus costs adjusted for four more units based on NASA CADRe data (see cost section)
  - The Team X instrument estimate ($69.3M 1st unit) is about $830k/kg
    - NICM historic instruments average about $600-700k/kg for Earth orbiting and $1.1-1.2M/kg for planetary so the Team X instrument cost is reasonably close to historic experience.
- **While the OMEGA assumptions lowered costs $150 M they added a new, unfunded technology development (accelerometers) and raised a number of schedule related risks.**
  - Even with these assumptions the mission cost exceeds the Study Manager's target of less than $1B
- **FEEP thrusters require technology development in both options**
  - Claimed heritage use was for charge control not attitude control
  - Qualification (and possible redesign) for attitude control is required

Executive Summary
Risk

- **Medium risks for both options:**
  - Staffing and destaffing difficulties for multiple parallel spacecraft builds
  - Short schedule lag of 2nd through 6th spacecraft builds following protoflight unit build does not offer much schedule protection against protoflight test and integration failure
  - FEEP development and qualification
- **Medium risks specific to Option 2 only:**
  - Inability to achieve sensitivity with baseline accelerometer will increase mass, power and cost of the instrument
  - Redesign effort due to inappropriate or missing requirements on early procurements of long lead items
  - Proposed schedule is too short for this class of mission
    - Not consistent with historic experience

1281 Omega 2012-04

Study Info

Customer: Jeff Booth, Ken Anderson, Ron Hellings

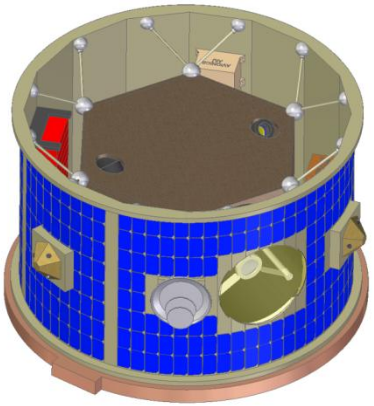
Partners: Surrey, SDL, MOOG

Study Type: Mission Study

Study Dates: April 3, 4, 5, and 10

Context: 4 sessions, Powerpoint report, written summary, risk report

Purpose: Point design for program architecture trades



Key Results

	Option 1	Option 2
Total Cost ($FY12)	$1.4B	$1.2B
Launch Mass (kg)	2376	2223
Sciencecraft Mass (kg)	218	196
Payload Mass (kg)	83.7	71.5
Sciencecraft Power (W)	258	220
Payload Power (W)	80	56
Phase A-D Schedule (months)	94	70
Phase E Schedule (months)	24	
Unfunded Technology Development Needed	FEEP Thrusters	FEEP Thrusters Accelerometers

Mission Summary

Launch Date: December 2013

Launch Vehicle: NLS II Contract

Target Body: HEO

Science: Gravitational Wave Astronomy

Instruments: Precision laser ranging, drag free accelerometer

Architecture: 6 identical sciencecraft, carrier spacecraft

Trades

Number of Options Studied: 2

Option 1: Team X estimated accelerometer and schedule

Option 2: Omega Team estimated accelerometer and schedule

Key subsystem trades: Cost vs. schedule and payload assumptions; power system mass vs. orbit characteristics; testbeds vs. schedule

Future Trades/Open Issues: accelerometer design specifics

Systems Report

1281 OMEGA 2012-04
April 2- 10, 2012

Author: George Sprague

Email: george.a.sprague@jpl.nasa.gov

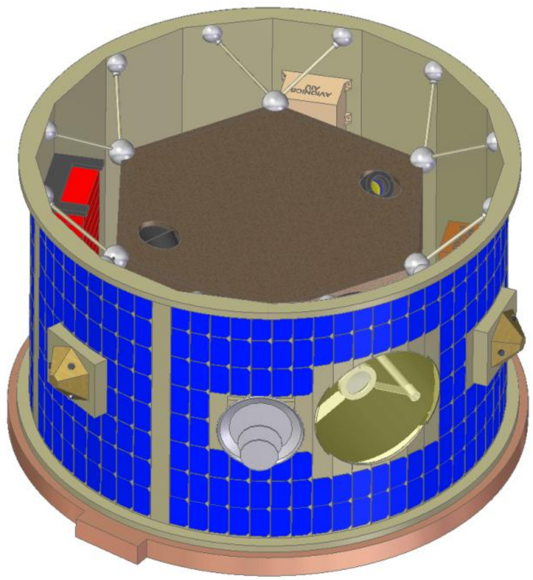
Phone: 818-393-1988

Table of Contents

Systems
Customer Overview on the Omega

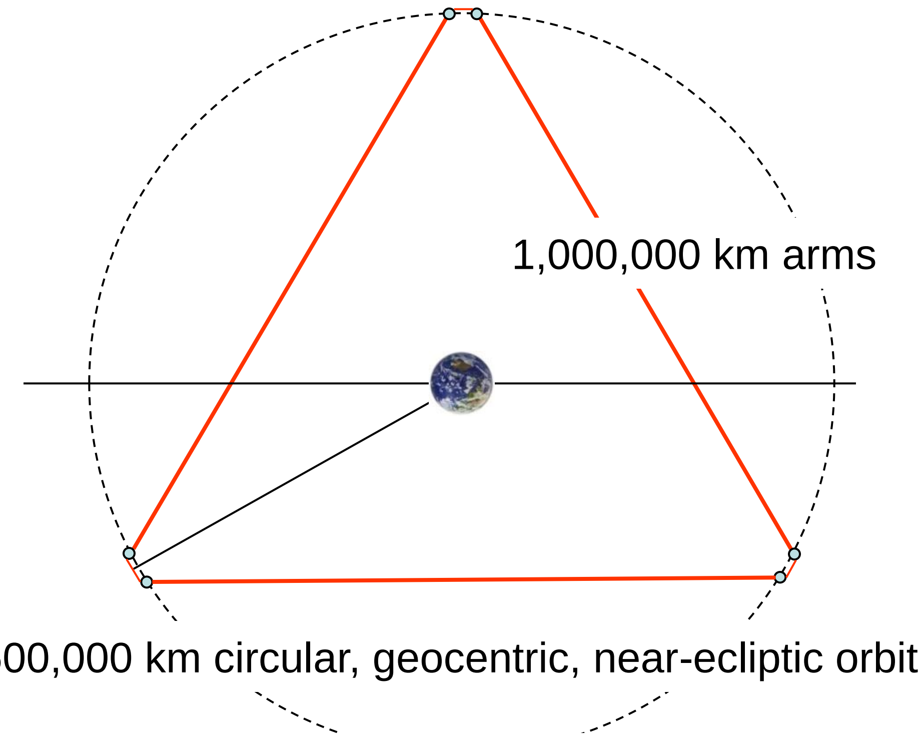
- **Six Microprobes measuring gravity waves in an earth orbit.**
  - All six probes are identical
  - Lifetime – 2 years
    - 1 year non-operating, 1 year mission
- **Delivered by a single carrier to**
  - Based on the ESPA (EELV Secondary Payload Adapter) Structure
  - TRL-9 hydrazine propulsion system
  - Smart carrier, all probes powered down until ejection
  - Full system redundancy
- **Microprobe Components**
  - Broadreach IAU
  - Composite cylindrical structure acting as sun shield
  - In-FEEP microthrusters
  - S-Band Transponder
  - Body-mounted solar array and ABSL Battery

Systems
Customer Overview



6 identical microprobes

- 110 Kg
- 101 watts
- 1 moving part



- Probes delivered in pairs
- 3-5 km separation in each pair
- 1 year science operations

Systems
Customer Overview - Redundancy

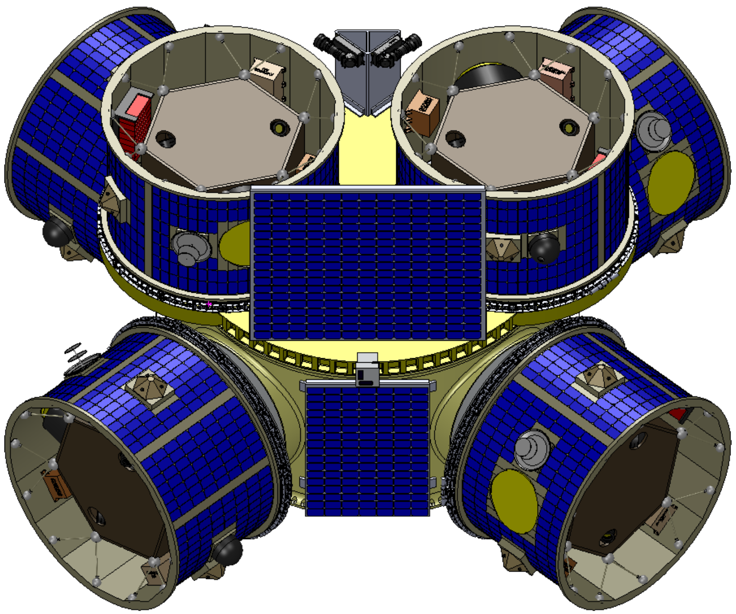
- OMEGA has two probes at each vertex of the detector

Failure type	3 Class A		6 Class C	
	Probes lost	Mission lost?	Probes lost	Mission lost?
Irrecoverable fatal design flaw	3	Yes	6	Yes
Recoverable fatal design flaw	1	Yes	1	No
Spacecraft-fatal random failure	1	Yes	1	No
Subsystem random failure	0	No	1	No

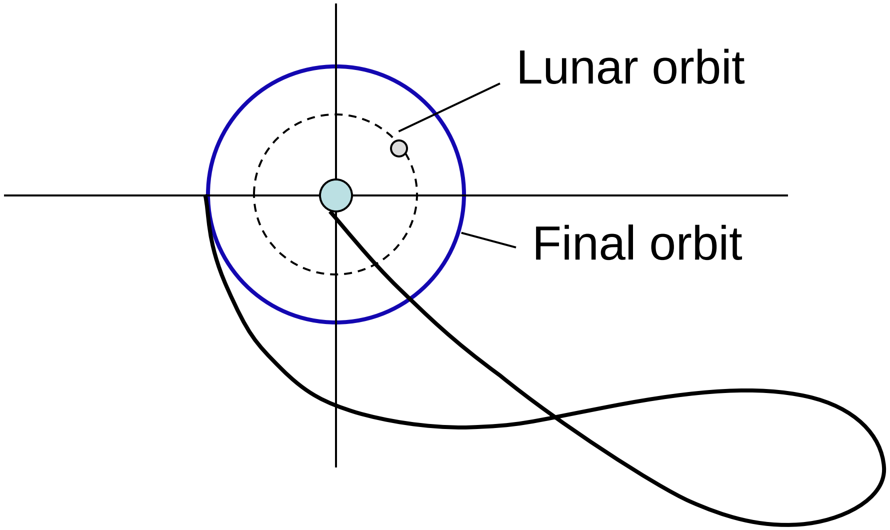
- OMEGA provides Class A mission reliability using Class C spacecraft. A single-point failure will only lead to a reduction in science, not to total mission failure.

Systems
Operational Scenario

- **Carrier Transports Probes Via a Weak Stability Boundary Trajectory**



- Single LV delivers all 6 probes
- De-orbit not necessary



- C3 = $-1.57\ km^2/s^2$
- 1 year constellation setup
- Total Δv = 501 m/s

Systems
Assumptions for the Omega Mission

- Assumptions
  - 53% contingency on CBE mass per Program Office guidelines
  - 30% margin on Phase E costs as opposed to a nominal 15%. Does not include launch vehicle.

- Power and other margins – follow JPL Design Principles
  - 43% contingency on power and 30% reserves on cost

- All Technology is at TRL 6

- NLS II Launch vehicles only

- Mission is Class B- the Functional redundancy in having 6 sciencecraft allows for Class C single-string sciencecraft

- Launch date for both options is September 2021.

Design Assumptions – Sciencecraft Option 1

Team X Study Guidelines

Omega Study 2012-04

Sciencecraft

Project - Study

Customer	Ken Anderson, Jeff Booth
Study Lead	Keith Warfield
Study Type	Space Physics Study
Report Type	PPT Slides

Project - Mission

Mission	Omega Study 2012-04
Target Body	High Earth Orbit to detect Gravity Waves coming from space
Science	Gravity Wave Detection
Launch Date	1-Sep-21
Mission Duration	24 months
Mission Risk Class	C
Technology Cutoff	2016
Minimum TRL at End of Phase B	6
Planetary Protection	Outbound: II, Inbound: N/A
Flight System Development Mode	Out-of-House

Project - Architecture

6 Microprobe Sciencecraft	on	Propulsion Module
Propulsion Module	on	Launch Vehicle

Trajectory	High Earth Orbit
L/V Capability, kg	2490 kg to a C3 of 0 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Systems

Design Assumptions – Sciencecraft Option 1

Spacecraft

Spacecraft	Sciencecraft
Instruments	Instrument,,,,,,,,,,,, etc
Potential Inst-S/C Commonality	Significant
Redundancy	Single
Stabilization	3-Axis
Heritage	None
Radiation Total Dose	10.8 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
Type of Propulsion Systems	In-FEEP microthrusters
Post-Launch Delta-V, m/s	0
P/L Mass CBE, kg	64.3 kg Payload CBE
P/L Power CBE, W	79.7
P/L Data Rate CBE, kb/s	1000
P/L Pointing, arcsec	30 arcsec in acquisition for control; 15 arcsec for knowledge
RSDO bus?	NO
Hardware Models	Protoflight S/C, EM instrument

Project - Cost and Schedule

Cost Target	$ 380 M
Mission Cost Category	Large - e.g. New Frontiers
FY$ (year)	2012
Include Phase A cost estimate?	Yes
Phase A Start	December 2013
Phase A Duration (months)	12
Phase B Duration (months)	15
Phase C/D Duration (months)	67
Review Dates	PDR - March 2016, CDR - September 2017, ARR - March 2019
Phase E Duration (months)	24
Phase F Duration (months)	24
New Development Tests	Yes
Project Pays Tech Costs from TRL	6
Spares Approach	Selected, 2 spare units
Parts Class	Commercial + Military 883B
Launch Site	Eastern Test Range

Design Summary – Sciencecraft Option 1

SYSTEMS WORKSHEET: ***Omega Study 2012-04***
Sciencecraft

Analyst: George Sprague | Start Date: 3/3/12 | Study Level: 1st point design with placeholders in MEL

Stabilization - cruise	3-Axis		Pointing Direction - cruise	Sun		Mission Duration	2.1	years
Stabilization - science	3-Axis		Pointing Direction - science	Sun		Max probe sun distance	0	AU
						Instrument Data Rate	1000	kbps (0)
Pointing Control	30	arcsec	Radiation Total Dose, krad	11		Daily Data Volume	0	Mbits average
Pointing Knowledge	15	arcsec	Redundancy	Single		Data Storage	0.0	Gb
Pointing Stability	0	arcsec/sec				Max Link Distance to Earth	0	AU
Determined by:	Star Tracker		Technology Cutoff	2016		Return Data Rate	0	kbps

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch	Mode 2 Power (W) Cruise	Mode 3 Power (W) Separation	Mode 4 Power (W) Communications	Mode 5 Power (W) Science	Mode 6 Power (W) Science in eclipse	Mode 7 Power (W) Science with Telecom	Mode 8 Power (W) Safe
Power Mode Duration (hours)					*1*	*24*	*1*	*4*	*24*	*4*	*2*	*24*
Payload on this Element												
Instruments	44%	64.3	30%	83.7	0	0	0	8	80	80	80	8
Payload Total	44%	**64.3**	30%	**83.7**	**0**	**0**	**0**	**8**	**80**	**80**	**80**	**8**
Spacecraft Bus			do not edit formulas below this line, use the calcualtions and override tables instead -->									
Attitude Control	1%	2.2	28%	2.8	0	0	10	10	10	10	10	10
Command & Data	3%	5.0	25%	6.3	0	0	25	25	25	25	25	25
Power	16%	23.6	30%	30.6	0	0	16	17	19	19	15	16
Propulsion1	3%	4.5	30%	5.9	0	0	6	6	6	6	6	6
Structures & Mechanisms	20%	29.2	30%	38.0	0	0	0	0	0	0	0	0
Cabling	5%	8.0	30%	10.4								
Telecom	2%	3.2	14%	3.6	0	0	40	40	5	5	40	40
Thermal	5%	6.8	0%	6.8	0	0	35	35	25	25	5	25
Bus Total		82.5	27%	104.4	0	0	132	133	90	90	101	122
Thermally Controlled Mass				104.4								
Spacecraft Total (Dry)		146.8	28%	188.0	0	0	132	141	170	170	181	130
Subsystem Heritage Contingency		41.2	28%	28%								
System Contingency		30.2	21%	21%	0	0	57	61	73	73	78	56
Spacecraft with Contingency		**218.2**	of total	w/o addl pld	**0**	**0**	**189**	**202**	**243**	**243**	**258**	**186**
Spacecraft Total (Wet)		**218.2**										

Design Assumptions – Propulsion Option 1

Team X Study Guidelines

Omega Study 2012-04

Propulsion Module with Rollup

Project - Study

Customer	Ken Anderson, Jeff Booth
Study Lead	Keith Warfield
Study Type	Space Physics Study
Report Type	PPT Slides

Project - Mission

Mission	Omega Study 2012-04
Target Body	High Earth Orbit to detect Gravity Waves coming from space
Science	Gravity Wave Detection
Launch Date	1-Sep-21
Mission Duration	12 months
Mission Risk Class	B
Technology Cutoff	2016
Minimum TRL at End of Phase B	6
Planetary Protection	Outbound: II, Inbound: N/A
Flight System Development Mode	Out-of-House

Project - Architecture

6 Microprobe Sciencecraft	on	Propulsion Module
Propulsion Module	on	Launch Vehicle

Trajectory	High Earth Orbit
L/V Capability, kg	2490 kg to a C3 of 0 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Systems

Design Assumptions – Propulsion Option 1

	Spacecraft
Spacecraft	Propulsion Module with Rollup
Instruments	None
Potential Inst-S/C Commonality	None
Redundancy	Dual (Cold)
Stabilization	3-Axis
Heritage	ESPA ring heritage
Radiation Total Dose	5.4 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
Type of Propulsion Systems	Monoprop
Post-Launch Delta-V, m/s	454
P/L Mass CBE, kg	0 kg Payload CBE
P/L Power CBE, W	0
P/L Data Rate CBE, kb/s	1000
P/L Pointing, arcsec	TBD
EDL Type	Select in Drop Down
RSDO bus?	NO
Hardware Models	Protoflight S/C, EM instrument
	Project - Cost and Schedule
Cost Target	$380 M
Mission Cost Category	Medium - e.g. Discovery, Scout, ESSP
FY$ (year)	2012
Include Phase A cost estimate?	Yes
Phase A Start	December 2013
Phase A Duration (months)	12
Phase B Duration (months)	15
Phase C/D Duration (months)	67
Review Dates	PDR - March 2016, CDR - September 2017, ARR - March 2019
Phase E Duration (months)	30
Phase F Duration (months)	24
New Development Tests	None
Project Pays Tech Costs from TRL	6
Spares Approach	Selected, 2 spare units
Parts Class	Commercial + Military 883B
Launch Site	Eastern Test Range

Systems

Design Summary – Propulsion Module Option 1

SYSTEMS WORKSHEET:		*Omega Study 2012-04* *Propulsion Module with Rollup*					
	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch	Mode 2 Power (W) Cruise	Mode 3 Power (W) Separation
Power Mode Duration (hours)					*1*	*24*	*1*
Additional Elements Carried by this Element							
Sciencecraft 1	13%	218.2	0%	218.2			
Sciencecraft 2	13%	218.2	0%	218.2			
Sciencecraft 3	13%	218.2	0%	218.2			
Sciencecraft 4	13%	218.2	0%	218.2			
Sciencecraft 5	13%	218.2	0%	218.2			
Sciencecraft 6	13%	218.2	0%	218.2			
Carried Elements Total	78%	**1309.5**	0%	**1309.5**	**0**	**0**	**0**
Spacecraft Bus			do not edit formulas below this line, use the calcualtions and overrid				
Attitude Control	0%	5.8	24%	7.1	22	22	22
Command & Data	1%	13.9	19%	16.6	40	40	40
Power	1%	17.3	30%	22.5	21	25	26
Propulsion1	4%	66.5	28%	84.9	25	1	25
Structures & Mechanisms	13%	210.7	30%	273.9	0	0	0
S/C-Side Adapter	1%	16.6	15%	19.1			
Cabling	1%	21.7	30%	28.3			
Telecom	0%	5.9	13%	6.7	40	40	40
Thermal	1%	15.3	0%	15.3	113	213	213
Bus Total		373.7	27%	474.3	261	341	366
Thermally Controlled Mass				474.3			
Spacecraft Total (Dry)		1683.2	6%	1783.8	261	341	366
Subsystem Heritage Contingency		100.6	6%	27%			
System Contingency		97.5	6%	26%	112	147	157
Spacecraft with Contingency		**1881**	of total	w/o addl pld	**373**	**487**	**524**
Propellant & Pressurant1	20%	465.5		For S/C mass =	2490.0		Delta-V, Sys 1
Spacecraft Total (Wet)		**2347**					
L/V-Side Adapter		29.5		Wet Mass for Prop Sizing	2490		
Launch Mass		**2376**		Dry Mass for Prop Sizing	1881		
Launch Vehicle Capability		**2490**	NLS II Contract				Additional
							Additior
Launch Vehicle Margin		**113.8**	5%				Ac

Assumptions for Option 2

- Slightly less power required by the instrument
- Slightly less mass required by the instrument
- Cost differs between options is largely due to Mission Phase length changes
  - Mainly in C/D. Went to 49 months (Option 2) from 67 months (Option 1.)

Systems
Design Assumptions – Sciencecraft Option 2

Team X Study Guidelines

Omega Study 2012-04

Sciencecraft Option 2

Project - Study

Customer	Ken Anderson, Jeff Booth
Study Lead	Keith Warfield
Study Type	Space Physics Study
Report Type	PPT Slides

Project - Mission

Mission	Omega Study 2012-04
Target Body	High Earth Orbit to detect Gravity Waves coming from space
Science	Gravity Wave Detection
Launch Date	1-Sep-21
Mission Duration	24 months
Mission Risk Class	C
Technology Cutoff	2016
Minimum TRL at End of Phase B	6
Planetary Protection	Outbound: II, Inbound: N/A
Flight System Development Mode	Out-of-House

Project - Architecture

6 Microprobe Sciencecraft	on	Propulsion Module
Propulsion Module	on	Launch Vehicle

Trajectory	High Earth Orbit
L/V Capability, kg	2490 kg to a C3 of 0 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Systems
Design Assumptions – Sciencecraft Option 2

Spacecraft

Spacecraft	Sciencecraft Option 2
Instruments	Instrument,,,,,,,,,,,, etc
Potential Inst-S/C Commonality	Significant
Redundancy	Single
Stabilization	3-Axis
Heritage	None
Radiation Total Dose	10.8 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
Type of Propulsion Systems	In-FEEP microthrusters
Post-Launch Delta-V, m/s	0
P/L Mass CBE, kg	55 kg Payload CBE
P/L Power CBE, W	54.0
P/L Data Rate CBE, kb/s	1000
P/L Pointing, arcsec	30 arcsec in acquisition for control; 15 arcsec for knowledge
RSDO bus?	NO
Hardware Models	Protoflight S/C, EM instrument

Project - Cost and Schedule

Cost Target	$ 380 M
Mission Cost Category	Large - e.g. New Frontiers
FY$ (year)	2012
Include Phase A cost estimate?	Yes
Phase A Start	December 2015
Phase A Duration (months)	9
Phase B Duration (months)	12
Phase C/D Duration (months)	49
Review Dates	PDR - September 2017, CDR - June 2018, ARR - March 2019
Phase E Duration (months)	24
Phase F Duration (months)	24
New Development Tests	Yes
Project Pays Tech Costs from TRL	6
Spares Approach	Selected, 2 spare units
Parts Class	Commercial + Military 883B
Launch Site	Eastern Test Range

Systems
Design Summary – Sciencecraft Option 2

SYSTEMS WORKSHEET: *Omega Study 2012-04*
Sciencecraft Option 2

Analyst: George Sprague | Start Date: 4/10/12 | Study Level: 1st point design with placeholders in MEL

Stabilization - cruise	3-Axis		Pointing Direction - cruise	Sun	Mission Duration	2.1	years
Stabilization - science	3-Axis		Pointing Direction - science	Sun	Max probe sun distance	0	AU
					Instrument Data Rate	1000	kbps (0)
Pointing Control	30	arcsec	Radiation Total Dose, krad	11	Daily Data Volume	0	Mbits averag
Pointing Knowledge	15	arcsec	Redundancy	Single	Data Storage	0.0	Gb
Pointing Stability	0	arcsec/sec			Max Link Distance to Earth	0	AU
Determined by:	Star Tracker		Technology Cutoff	2016	Return Data Rate	0	kbps

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch	Mode 2 Power (W) Cruise	Mode 3 Power (W) Separation	Mode 4 Power (W) Communi cations	Mode 5 Power (W) Science	Mode 6 Power (W) Science in eclipse	Mode 7 Power (W) Science with Telecom
Power Mode Duration (hours)					*1*	*24*	*1*	*4*	*24*	*4*	*2*
Payload on this Element											
Instruments	42%	55.0	30%	71.5	0	0	0	5	54	54	54
Payload Total	42%	**55.0**	30%	**71.5**	**0**	**0**	**0**	**5**	**54**	**54**	**54**
Spacecraft Bus	do not edit formulas below this line, use the calcualtions and override tables instead -->										
Attitude Control	2%	2.2	28%	2.8	0	0	10	10	10	10	10
Command & Data	4%	5.0	25%	6.3	0	0	25	25	25	25	25
Power	16%	21.4	30%	27.9	0	0	16	16	17	17	13
Propulsion1	3%	4.5	30%	5.9	0	0	6	6	6	6	6
Structures & Mechanisms	20%	26.1	30%	33.9	0	0	0	0	0	0	0
Cabling	6%	7.5	30%	9.7							
Telecom	2%	3.2	14%	3.6	0	0	40	40	5	5	40
Thermal	5%	6.8	0%	6.8	0	0	30	30	25	25	5
Bus Total		76.7	26%	96.8	0	0	127	127	88	88	100
Thermally Controlled Mass				96.8							
Spacecraft Total (Dry)		131.7	28%	168.3	0	0	127	133	142	142	154
Subsystem Heritage Contingency		36.7	28%	28%							
System Contingency		27.6	21%	21%	0	0	55	57	61	61	66
Spacecraft with Contingency		**196.0**	of total	w/o addl pld	**0**	**0**	**182**	**190**	**203**	**203**	**220**
Spacecraft Total (Wet)		**196.0**									
Launch Mass		**196.0**		Dry Mass for Prop Sizing	196						

Design Assumptions – Propulsion Option 2

Team X Study Guidelines

Omega Study 2012-04

Propulsion Module with Rollup Option 2

Project - Study

Customer	Ken Anderson, Jeff Booth
Study Lead	Keith Warfield
Study Type	Space Physics Study
Report Type	PPT Slides

Project - Mission

Mission	Omega Study 2012-04
Target Body	High Earth Orbit to detect Gravity Waves coming from space
Science	Gravity Wave Detection
Launch Date	1-Sep-21
Mission Duration	12 months
Mission Risk Class	B
Technology Cutoff	2016
Minimum TRL at End of Phase B	6
Planetary Protection	Outbound: II, Inbound: N/A
Flight System Development Mode	Out-of-House

Project - Architecture

6 Microprobe Sciencecraft	on	Propulsion Module
Propulsion Module	on	Launch Vehicle

Trajectory	High Earth Orbit
L/V Capability, kg	2490 kg to a C3 of 0 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Systems
Design Assumptions – Propulsion Option 2

Spacecraft

Spacecraft	Propulsion Module with Rollup Option 2
Instruments	None
Potential Inst-S/C Commonality	None
Redundancy	Dual (Cold)
Stabilization	3-Axis
Heritage	ESPA ring heritage
Radiation Total Dose	5.4 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
Type of Propulsion Systems	Monoprop
Post-Launch Delta-V, m/s	454
P/L Mass CBE, kg	0 kg Payload CBE
P/L Power CBE, W	0
P/L Data Rate CBE, kb/s	1000
P/L Pointing, arcsec	TBD
EDL Type	Select in Drop Down
RSDO bus?	NO
Hardware Models	Protoflight S/C, EM instrument

Project - Cost and Schedule

Cost Target	$380 M
Mission Cost Category	Medium - e.g. Discovery, Scout, ESSP
FY$ (year)	2012
Include Phase A cost estimate?	Yes
Phase A Start	December 2015
Phase A Duration (months)	9
Phase B Duration (months)	12
Phase C/D Duration (months)	49
Review Dates	PDR - September 2017, CDR - June 2018, ARR - March 2019
Phase E Duration (months)	30
Phase F Duration (months)	24
New Development Tests	None
Project Pays Tech Costs from TRL	6
Spares Approach	Selected, 2 spare units
Parts Class	Commercial + Military 883B
Launch Site	Eastern Test Range

Systems

Design Summary – Propulsion Module Option 2

SYSTEMS WORKSHEET: *Omega Study 2012-04*
Propulsion Module with Rollup Option 2

Stabilization - cruise	3-Axis		Pointing Direction - cruise	Sun
Stabilization - science	3-Axis		Pointing Direction - science	Sun
Pointing Control	360	arcsec	Radiation Total Dose, krad	5
Pointing Knowledge	180	arcsec	Redundancy	Dual (Cold)
Pointing Stability	10	arcsec/sec		
Determined by:	Insertion		Technology Cutoff	2016

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch	Mode 2 Power (W) Cruise	Mode 3 Power (W) Separation
Power Mode Duration (hours)					1	24	1
Additional Elements Carried by this Element							
Sciencecraft 1	13%	195.9	0%	195.9			
Sciencecraft 2	13%	195.9	0%	195.9			
Sciencecraft 3	13%	195.9	0%	195.9			
Sciencecraft 4	13%	195.9	0%	195.9			
Sciencecraft 5	13%	195.9	0%	195.9			
Sciencecraft 6	13%	195.9	0%	195.9			
Carried Elements Total	76%	**1175.6**	0%	**1175.6**	**0**	**0**	**0**
Spacecraft Bus		do not edit formulas below this line, use the calcualtions and overrid					
Attitude Control	0%	5.8	24%	7.1	22	22	22
Command & Data	1%	13.9	19%	16.6	40	40	40
Power	1%	17.3	30%	22.5	21	25	26
Propulsion1	4%	66.5	28%	84.9	25	1	25
Structures & Mechanisms	13%	200.0	30%	260.0	0	0	0
S/C-Side Adapter	1%	16.2	15%	18.6			
Cabling	1%	20.7	30%	27.0			
Telecom	0%	5.9	13%	6.7	40	40	40
Thermal	1%	15.2	0%	15.2	113	208	208
Bus Total		361.6	27%	458.6	260	335	360
Thermally Controlled Mass				458.6			
Spacecraft Total (Dry)		1537.2	6%	1634.2	260	335	360
Subsystem Heritage Contingency		97.0	6%	27%			
System Contingency		94.6	6%	26%	112	144	155
Spacecraft with Contingency		**1729**	of total	w/o addl pld	**372**	**479**	**515**
Propellant & Pressurant1	21%	465.5		For S/C mass =	2490.0		Delta-V, Sys 1
Spacecraft Total (Wet)		**2194**					
L/V-Side Adapter		28.3		Wet Mass for Prop Sizing	2490		
Launch Mass		**2223**		Dry Mass for Prop Sizing	1729		
Launch Vehicle Capability		**2490**	NLS II Contract				Additional
							Additior
Launch Vehicle Margin		**267.3**	11%				Ac

Power Modes – Omega Option 1 & 2

Power Mode	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Name	Launch	Cruise	Separation	Communications	Science	Science in eclipse	Science with Telecom	Safe
Duration (hrs)	1	24	1	4	24	4	2	24

- **The power modes are coordinated between the propulsion module and microprobes**
- **Launch until light is on the prop module array is nominally to last 1 hour.**
- **Cruise is 24 hours for the prop module.**
- **Separation is nominally an hour with telecomm transmitting.**
- **Communications is nominally a 4 hour pass to become established.**
- **Science with telecomm off is the nominal mode 24 hrs/day**
- **Science with telecomm is nominally 2 hours.**
- **Safe mode puts the instruments on standby.**

Systems
Additional Comments – Mass Margins

- ***Note:*** *Technical resource margins exist to deal with uncertainties, e.g. those known and others yet to be discovered, and to facilitate the design integration performed by system engineering. JPL's margin guidelines are experienced-based, and have been borne out in a variety of mission/system applications.*
- **JPL Design Principles Margin: >/=30% for projects in development prior to PDR**
- **Definitions**
  - **% JPL Design Principles Margin =** Dry Mass Margin / Dry Mass Allocation
    - **Dry Mass Allocation** = LV Capability – Total Carried Elements (CBE + Contingency) - Propellant Mass
    - **Dry Mass Margin** = Dry Mass Allocation - Dry Mass Current Best Estimate (CBE)
  - **% LV Mass Margin** = LV Mass Margin / LV Capability
    - **LV Mass Margin** = (LV - Capability Total Carried Elements (CBE + Contingency))– (Dry Mass CBE + Contingency + Propellant Mass)

	LV capability (kg)	Propellant mass (kg)	Science-craft dry mass CBE (kg)	Propulsion module mass CBE (Kg)	Wet Mass with Conting. (Kg)	JPL Design Principles margin (%)	LV Margin (kg)	LV Margin (%)
Option 1	2490	465.5	146.8	373.7	2347	36%	113.8	5%
Option 2	2490	465.5	131.7	361.6	2194	37%	267.3	11%

Conclusions

- **From the aspect of the mission, the OMEGA design closes.**
  - The six microprobes fit inside an NLS-II faring with adequate throw weight.
  - Propulsion Module has adequate Delta V to inject all of the microprobes into the desired orbits.
  - Mission is very doable but the expected savings will tend to be elusive.
    - Microprobes are very sensitive to change with a factor of six in cost.
  - Schedule for Option 2 is very aggressive.
- **Instrument Design Strengths**
  - Use of catalog items (with minor changes)
  - Utilization of LISA Pathfinder seed laser technology.
- **Instrument Design Weaknesses**
  - As expected at this stage of development, some of the design is incomplete.
  - Baseline MEL contains mass and power for analog units that do not in all cases include needed functionality/interfaces/performance (e.g. accelerometer for drag free)
  - Technology modifications to detectors to meet mass/power/cost constraints of Microprobe mission are currently at low TRL.
  - The design approach is to push most of the thermal control to the boundary of the instrument. The boundary condition requirements on the instrument, and the forcing environment applied has not yet been determined.

Systems
Subsystems Highlights

- **Mission:**
  - 6 microprobes at 3 equidistant locations (1 million km spacecraft-spacecraft distance aka “baseline”) in a distant retrograde Earth orbit.
    - With the pair of microprobes concept: good redundancy.
- **ACS: Microprobe knowledge for acquisition drives the choice of star tracker.**
  - All stellar attitude determination for acquisition and science
  - Attitude control: 3-axis stabilized using FEEP thrusters. No reaction wheels.
  - ACS Propulsion stage: Stellar inertial attitude determination using star tracker and gyros and attitude control using hydrazine thrusters.
- **C&DH: Options**
  - For the CDS Option 1 and Option 2 have the same hardware set (MEL)
  - Cost differs between options is due to Mission Phase length changes

Subsystems Highlights

- **Propulsion**
  - The Propulsion Stage optimized design for low cost permitted a simple blowdown monopropellant system for the Carrier
  - The microprobe low thrust and stability requirements led to a FEEP thruster design.
- **Power:**
  - Propulsion stage design is based on a mission class “B” with moderate to low complexity and full functional redundancy for electronics.
  - Microprobe design is based on mission class “C” with moderate to low complexity.
    - Science craft solar array sizing and battery sizing is based on power requirements for nominal science on-station with 4 hour eclipse.
      - Fixed-body array mounted on radial S/C geometry.

Subsystems Highlights

Structure

- Microprobe bus is a cylindrical shell with the solar arrays fixed to the outside. Electronics boxes are mounted on the inside of the shell. A series of struts attached to the inside of the shell support the instrument. The instrument is mounted in a hexagonal structure. The separation from the propulsion module is at one end of the cylinder.
- The Propulsion Module is a cylindrical structure with four Sciencecraft mounted radially on the outer cylinder wall and two mounted on the top deck. The general design of the cylindrical structure is an ESPA ring. The Solar Array is mounted to a fixed panel and the panel is mounted to the top deck.

Telecom system description

- Microprobes: Each vehicle has a single string S-band system with 4 body-fixed patch LGAs
- Propulsion Module: The carrier has a redundant S-band system with 4 body-fixed LGAs

Systems
Subsystems Highlights

- **Thermal: The key design drivers are**
  - To keep the optical system of the probe thermally stable, 1μK/100s
  - To keep the survival heater power for the instrument and engineering equipment low.
- **Ground system**
  - Separation distance within science craft pair is key and will require operator intervention to approve, otherwise little else is possible beyond on/off and communications coordination
- **Assessment of the Software**
  - Complex, capability-rich probes with full command and telemetry channels, some complex instruments, and their own guidance and navigation.
  - Moderately complex carrier with power, communication, attitude control capabilities
- **Programmatics**
  - Protoflight unit will be integrated first, additional units will be integrated during testing of protoflight.
  - Vendor will be integrating the microprobes and the propulsion stage which is a different paradigm from the vendor’s usual practice of controlling most of the manufacturing.

Systems
Risks for Omega

- **There are several major risks that affect the mission: Option 2**
  - Staffing and destaffing for multiple spacecraft build, which would be difficult for a large scale contractor
  - Proposed schedule is significantly too short for this class of mission. Not consistent with any NASA historic experience
- **There are several medium risk that may affect the mission:**

  Both Options
  - Short schedule time between protoflight and SC flight builds allows insufficient time to make changes if protoflight system test fails
  - FEEP must undergo new development and qualification because it is being repurposed and it is not planned for nor funded

  Option 2
  - Inability to achieve sensitivity with baseline accelerometer
  - Phase A/B too short, which could cause significant redesign due to inappropriate or missing requirements on early procurements of long lead items
- **There is a minor risks that may be border line yellow:**
  - Design Principle Violation - Lack of communication with probes prior to release
- **There is also one proposal risks that requires special attention when proposing the mission**
  - Inability to “test-as-we-fly” due to large spacecraft architecture

Instruments Report

1281 OMEGA 2012-04

April 2- 10, 2012

Author: Alfred E Nash

Email: Alfred.E.Nash@JPL.NASA.Gov

Phone: X 3-2639

Objectives and Technical Findings

- **Objectives**
  - Red-Team Review of Customer Baseline Design and identification of missing functionality, mass, power, data volume and/or cost
- **The results are summarized below:**

	Customer's Baseline	Team-X Instrument Study (= Mission Study Option 1)	Mission Study Option 2
Mass (kg) CBE	54	75	55
Power (W) CBE	49	85	54
Data Rate (kbps) CBE	0.596	0.596	0.596
Mission Life (months)	30	30	25
Cost ($M FY12) CBE (6 unit total)	-	234	198

- **For mission study**
  - Thermal mass, power & cost "book kept" with S/C (not instrument)
  - $ 69M ($ FY12) for "Instrument" first unit & $ 29M for each additional unit (2-6) = $ 214M total (Option 1)
  - Option 2 assumes 5.9M less expensive accelerometer

Instrument Summary
Strengths, Weaknesses, Opportunities & Threats

- **Design Strengths**
  - Use of catalog items (with minor changes) for laser components
  - Utilization of LISA Pathfinder seed laser technology
- **Design Weaknesses**
  - Some customer design incomplete (particularly software architecture)
  - Baseline MEL contains mass and power for analog units that do not in all cases include needed functionality and/or interfaces and/or performance (e.g. accelerometer for drag free)
  - Technology modifications to detector to meet mass/power/cost constraints of Microprobe mission are currently at low TRL
  - It's not clear that algorithms are really at TRL 6, particularly charge control and phase measurement.
  - The design approach is to push all or most of the thermal control to the boundary of the instrument; i.e., onto the spacecraft or spacecraft—instrument interface. However, it does not appear that the boundary condition requirements on the instruments have been determined, nor has the forcing environment applied by the spacecraft been determined. This reviewer is skeptical that adequate thermal control (considering all conditions) can either be achieved as simply as is proposed, or that the cost of doing so will be less than a technically more-complicated approach.

Instrument Summary
Strengths, Weaknesses, Opportunities & Threats

- **Future Opportunities**
  - “Build to Print” / “Commercial off the shelf” / “Catalog” items can be used (only) if the full set of OMEGA functions, interfaces, and performance requirements are met by the component.
- **Future Threats**
  - Internal disturbances (e.g., from AFT mirror, thermal disturbances, etc.) may be higher than estimated and may degrade performance from LISA levels.
  - The needed reduction in accelerometer noise from GOCE type levels (3×10^{-12} ms^{-2}Hz$^{-1/2}$) for a 320 g test mass single axis accelerometer without upgrades needed for OMEGA (caging, optical interface, etc.,) to the required OMEGA levels (3×10^{-15} ms^{-2}Hz$^{-1/2}$) for the needed multiple axis sensitivity, will require additional mass, power and cost resources.
    - These have been estimated using the LISA / SGO High Mass and Power for the “GRS” as requiring ~ 28 kg, 35 W & and 14 FY 12 $M for the first unit (all numbers w/out contingency – costs from NICM system model for a “fields” type instrument)
    - OMEGA “GRS” baseline was ~ 7.6 kg, 5 W and 7 FY 12 $M for the first unit (all numbers w/out contingency – costs from NICM system model for a “fields” type instrument)

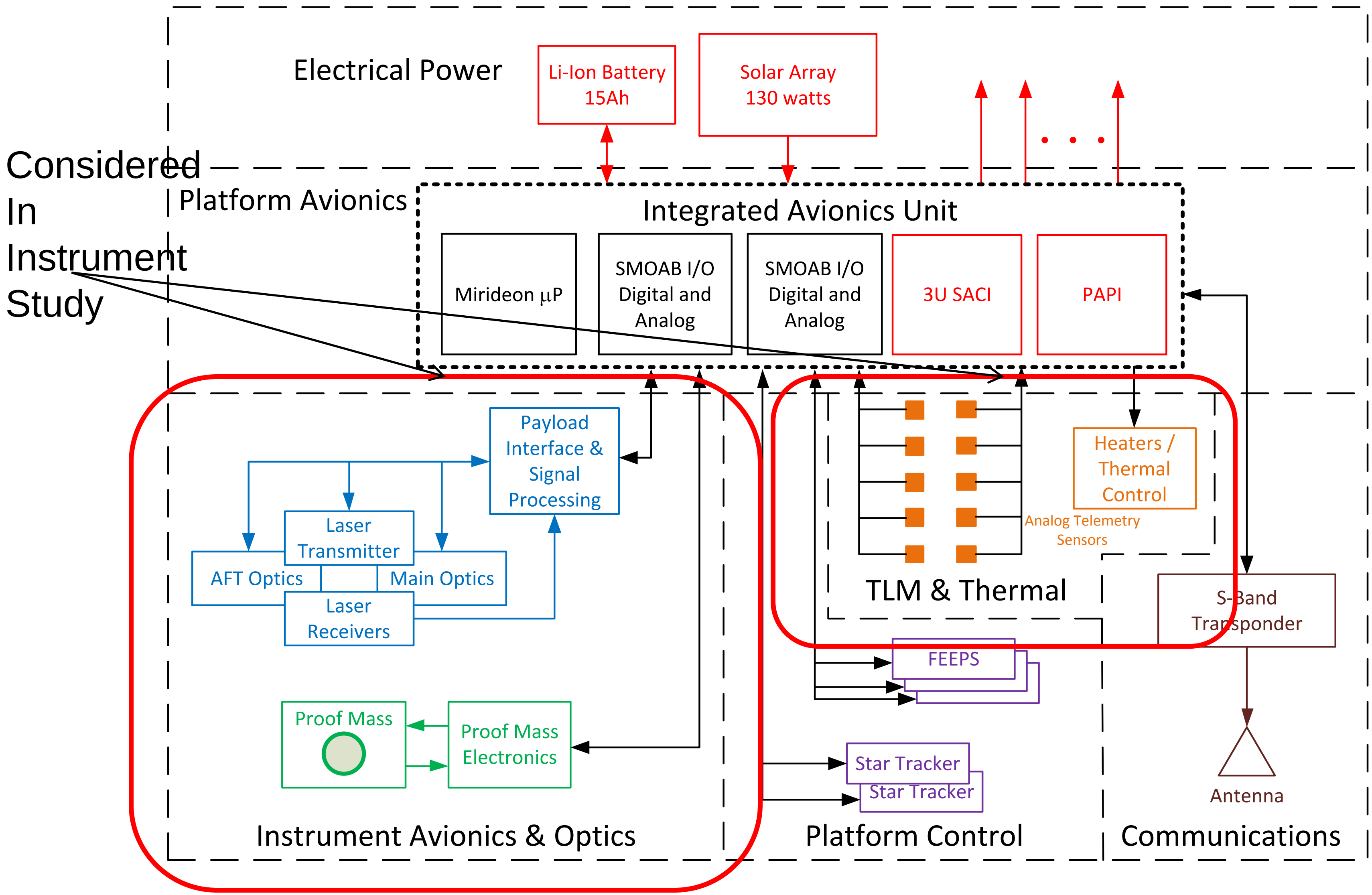
Requirements

- **Drag-free requirements (1 sigma)**
  - Accelerometer noise: 3×10^{-15} $ms^{-2}Hz^{-1/2}$
  - Position control: 1×10^{-9} m
- **Laser tracking system requirements (1 sigma)**
  - Phase readout noise: 7×10^{-12} m $Hz^{-1/2}$
  - Pointing accuracy: 4×10^{-7} rad
  - Pointing jitter: 5×10^{-10} rad $Hz^{-1/2}$
- **Optical bench and telescope requirements (1 sigma)**
  - CTE: 1×10^{-6}
  - Thermal stability: 10^{-5} K $Hz^{-1/2}$

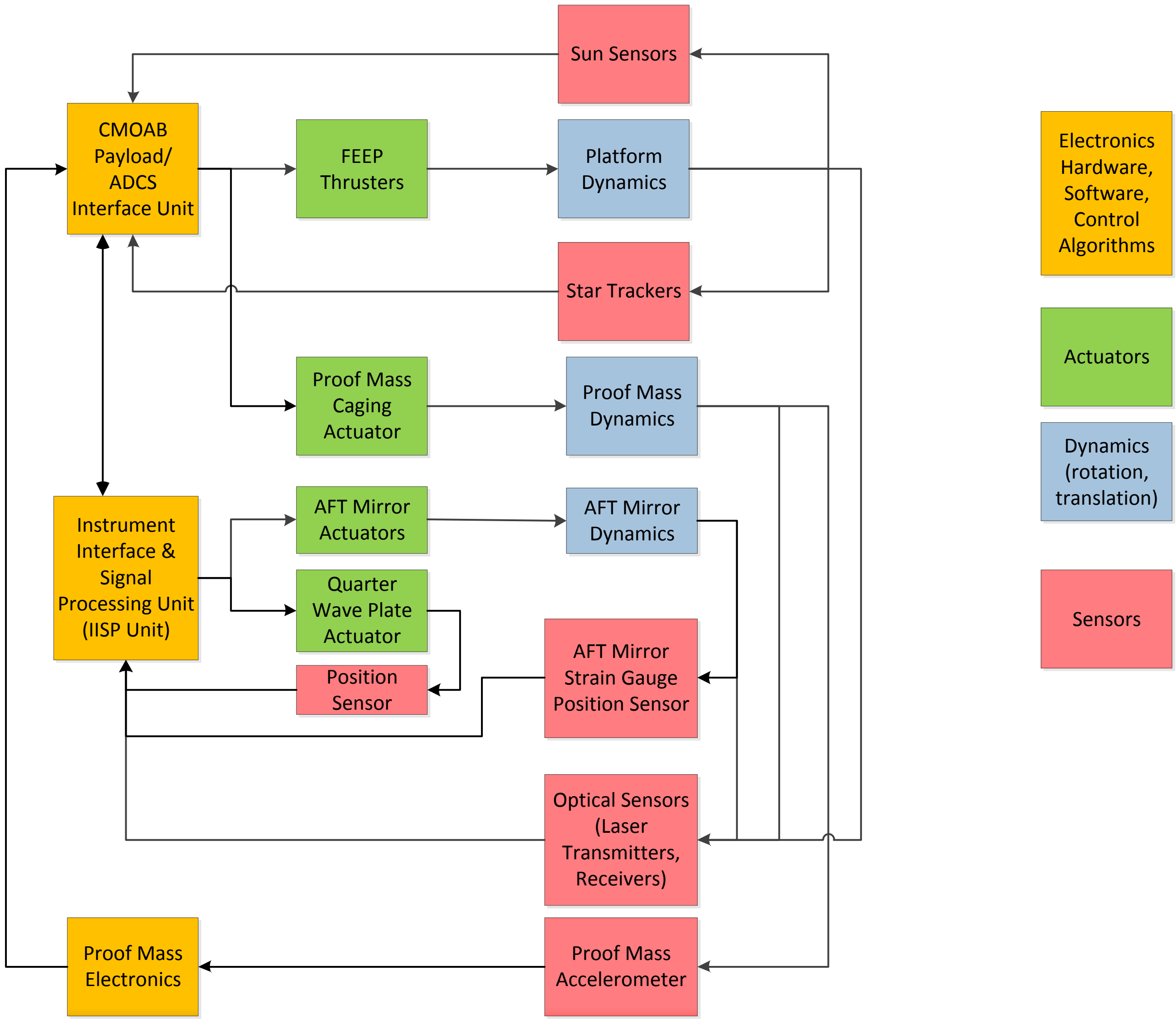
Preliminary Articulated Fine Tracker (AFT) Requirements

AFT Steering Mirror	Requirement
Mirror diameter (mm)	15
Maximum mechanical angle (millirad)	±22
Average velocity (millirad/sec)	very slow
Resolution (microrad)	TBD
Accuracy (microrad)	TBD
Power dissipation (W)	TBD (low)
Bandwidth (Hz)	1
Minimum temperature (K)	240
Launch load (G's)	20
NASA Risk Classification	C
Non-magnetic	Yes

Microprobe Block Diagram



Instrument Avionics & Controls



Instruments
Design Summary

- **Main Transmit and Receive Optics**
  - 25 cm aperture Cassegrain telescope
- **AFT Transmit and Receive Optics**
  - 12mm aperture Lens
- **Quad Photo Diode Detectors (part of phase locked loop Main and AFT Optics)**
- **Two Mechanisms (Articulated Fine Tracker (AFT) and ¼ λ Plate Mechanism)**
- **Distributed processing and control loops (interferometry, gravitational referencing, optical comm between S/C)**
- **Passive thermal control (presented baseline)**

Instruments

Technical Resources (Mass, Power, Data) per S/C

- **Customer Baseline Estimate**
  - Mass
    - 54 kg CBE, 70 kg MEV
  - Power
    - 48.9 W CBE, 63.6 W MEV
- **Team-X Estimate (GRS like Accelerometer)**
  - Mass
    - 75 kg CBE, 97 kg MEV
  - Power
    - 85 W CBE, 110 W MEV

Data Budget		
Science Data rate	512	bps
Engineering Data	84	bps
Science Data + Engineering Data	51494400	bits per day
Total Data per day	6.139	MB per day
Total Data per week	42.970	MB per week
Raw Phase Samples	3.000	MB per week
Total Data + Raw Phase Samples	45.970	MB per week
Total Data per week	367.762	Mb per week
Downlink: Once per week		
Data Rate	0.050	Mbps
Downlink Time	2.043	hours

Discussion

- Need to know relative position of corners +/- 200 m; 2 DOF from mirror; third from differential tracking or cross correlation of laser phase noise; 5 km nominal separation
- Required to reference their lasers' phase
- Need it to take out the relative noise of the two lasers;
- Each laser is free running and just measure the relative phase
- Locked within a 200 MHz (a fairly challenging requirement); there is a low-noise amplifier, mix RF with local oscillator tied to local clock, beat it down to a few kHz and then they sample.
- Need to know relative velocity "to a gnat's eyelash"; Doppler is tiny
- There are separate Local Oscillators for local and distant microprobes; "episodic" adjustments(?); SC needs to make determination

Instruments
Discussion

- **Since the OMEGA accelerometer is operating ~300K the materials in its vacuum (e.g., the test mass) are constantly outgassing (and for a very long time) – degrading the quality of the vacuum. A getter is used by ONERA to remove those evolved gasses.**
- **At some point the number of surface binding sites on the getter diminish to a point where the getter needs to be refreshed.**
- **When nonevaporative getters' (made from rare-earth alloys) surface sites have been filled, they are heated; at elevated temperatures the materials bound on the surface diffuse into the bulk of the getter and are trapped.**
- **Two thermal switches are proposed to allow the heating of the getter and then to accelerate the cool-down of the isolated accelerometer**
  - SDL's CLIC – cryogenic latching Instrument Connector
- **Europeans could find no getter large enough to evacuate all of the material they anticipated**
  - They vent to space – creates thermal challenge

Science Report

1281 OMEGA 2012-04
April 2- 10, 2012

Author: Curt Cutler
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Cost II

Bottom line:

Total Science Cost ~ $32.7M (compared to ~$45M for SGO-mid and Lagrange).

Table of Contents

Science Goals & Implementation

- **Science – First detection of gravitational waves (GWs) from space.**

  Source populations and rates very similar to LISA, including ~18,000 Galactic WD binaries, ~30/yr Merging Massive Black Hole binaries out to redshifts z ~15, and inspirals of stellar-mass compact objects into Massive Black Holes out to z~1.

- **Implementation – Omega can be thought of as "in-between" LISA and SGO-Mid. Omega/LISA/SGO-mid would have 1.e6/5.e6/1.e6 km arms, 30/40/25cm mirrors and 1.2/1.2/0.7 watts laser power. Main differences are 6 science-craft and geocentric orbits (Omega) vs. 3 science-craft and heliocentric orbits (LISA and SGO). Also, Omega is budgeting for only 1 year of science data taking, LISA/SGO plan for 5 and 2yrs, resp.**

Design Assumptions

Instrument

- Complex
- The “instrument” is the entire 6-satellite constellation, including gravitational reference sensors and laser metrology.
- The main science data is 3 independent time-series of so-called TDI variables, which effectively cancel laser phase noise and optical bench motion.

Operations

- Operations are extremely simple. There is no pointing, since the observatory has all-sky sensitivity. Data is taken continuously. Each S/C generates ~0.81 kb/s (of which 0.5 kb/s are science data and 0.31 are housekeeping), and each downloads its data to DSN once per week, for 1.82 hours. There are very few operational decisions to be made in phase E. The main exception is schedule changes near the times of massive black hole mergers. These special times will typically be known (from earlier GW data from the inspiral) some weeks to months in advance of these events.
- All data processing and analysis is done on the ground.

Operations:

From the point of view of science, operations are rather simple, since data taking is all-sky (no pointing) and continous except for short intervals when, e.g., a S/C passes thru the Earth's shadow.

(Note: these eclipses can take ~4 hours, and this thermal perturbation might render the data almost useful for those ~4 hours of cool- down, and the subsequent ~4 hours of warm-up.)

Science
Cost Assumptions

- We have assumed a 1.5-yr phase F, consistent with space missions of this level of data-analysis complexity, such as Planck or WMAP.
- The Project's science team receives Level 0 data, and then produces Level 1, 2 and 3 data products, including: the TDI variables, data quality flags, and the final source catalog.
- A Guest Observer Program ($9 M) is funded to do additional science investigations during phase E, such as inferring the stellar population densities near massive black holes in galactic nuclei, investigating mass transfer in degenerate binaries, and constraining alternative theories of gravitation (not GR). A Guest Observer Program, in which external (i.e., outside the Project) scientists interact with the Project and its science team, is highly recommended to insure a) that proper understanding and use of the Level 1,2,3 data products, and b) that the obviously available science is harvested with some efficiency.
- We assume that the basic algorithms for the data analysis have already been developed. Indeed, much of the necessary software has already been developed under the aegis of the Mock LISA Data Challenges.
- Data storage is trivial; the total science data is ~ 19 GB.
- Parts of the analysis could require a ~100-Teraflop cluster. But. especially by any plausible launch date, the computing cost should be small compared to manpower costs, and so we are neglecting it here.

Science
Cost Inputs

For purposes of Science costing, we term an instrument "complex" NOT if it's complex to build,

but rather if either 1) the science team has to make many decisions about how to use it (e.g.,

which rocks should the Mars rovers should pick up?), or 2) the data analysis for the instrument is complex. The latter holds for Omega – mostly since thousands of discrete sources all "overlap" in data time-series and must be disentangled.

We assume a 1.5-yr phase F, partly because the different data sub-analyses

(e.g., searches for EMRIs and searches for WD binaries) end up having significant cross-talk.

For both SGO-Mid and Lagrange, we assumed a 2-year phase F. We have cut that to 18 months for Omega because of its shorter phase E. But we do not cut phase F in half, since there are one-time costs, such as debugging the software, writing the final papers, and setting up a data server. (Note that assuming a 1-yr phase F would save only ~$1.1M.)

Cost II

We assumed $9M for a Guest Observer Program during science operations. (To compare apples to apples, we have assumed $9M/yr for SGO-Mid and Lagrange, too, meaning $18M total for their Guest Observer Programs.) The Guest Program will do related science using the Level-3 data products; e.g., look for electromagnetic counterparts or infer constraints on general relativity. In addition, the total cost for the Project's science team is $23.7M, divided as follows: $1.4M in A/B, $12.5M C/D, $9.8M in E/F. Total science cost of $32.7 is ~2-3% of total mission cost, which is on the low side for typical class B missions, however it is in line with the ~$45M science costs for SGO-Mid and Lagrange. The low costs partly reflects the fact that a great deal of software development has already been done via the Mock LISA Data Challenges, with, e.g., NASA ROSES funding. We expect that this form of data analysis software development would continue in the future.

Science
Cost: possible savings or increases

- **Potential Cost Uppers:**
  - **Unexpected systematics that must be “fitted out” (ala GP-B) could significantly complicate and stretch out the data analysis**

- **Potential savings: For SGO and Lagrange, moderate savings would be possible by decreasing science ops from 2 years to 1 year. However, for Omega, this savings is already incorporated into the mission. It is hard to see realistic possibilities for savings on science costs (without international partners).**

"Delta" study with shorter phases B/C

Using the JPL science cost model, the science cost decreases from $32.7M to $30.3M. The $2.3M savings comes mostly from the reduced management and science office costs that result from a shorter timeline.

Science
Risk

- **List of Risks**

  The science risk is that event rates and/or number densities in Nature are significantly lower than estimated, for one or two of the source types. Omega's planned sensitivity is excellent, so this is a minor risk.

A note on data rates

- During science ops, each probe generates 512 bps (science) + 300 bps (engineering) = 812bps = 8.77 MB/day-probe = 61.4 MB/wk-probe

- Each probe downlinks data 1/ week. Downlink rate is 0.075 Mbs,

so downlink time = 61.4x8/(.075x3600) = 1.82 hrs.

Total data for 12-month science ops = 8.77x6x365 MB = 19.2 GB

= 154 Gbits.

Implementation II: a comment on latency

From a science standpoint one advantage of Omega's geocentric orbit is that each satellite can "see" a DSN radio telescope at practically all times, since the probes' transmitters have a FOV of ~50 degrees. Therefore at "special times" around the moments of massive black hole mergers (which will often be known at least weeks in advance), it will be possible for reduce the latency down to ~4 hours: the time for each vertex probe-pair to transmit all its stored data to the ground, using 3 DSN sites simultaneously), and perhaps down to ~2 hours if telecom is set up with capacity for both probes at a vertex to transmit at the same time (at slightly different carrier frequencies).

Low latency means that optical astronomers can get very "up-to-date" info on the sky location of the source, which can improve dramatically over the final day prior to merger.

Mission Design Report

1281 OMEGA 2012-04
April 2- 10, 2012

Mark S. Wallace
with significant contributions by Jeffery Parker
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x4-4236

Mission Design
Table of Contents

Design Requirements

- **Mission:**
  - 6 microprobes at 3 equidistant locations (1 million km spacecraft-spacecraft distance aka “baseline”) in a distant retrograde Earth orbit
  - 600,000 km near-circular retrograde in the ecliptic plane
  - Sept 1, 2022 launch
- **Mission Design**
  - Use low-energy GRAIL-like trajectory to achieve orbit
  - Carrier vehicle builds up the constellation over 1 year
  - 1 year science phase
- **Launch Vehicle**
  - NLS II Contract desired by customer
- **Option 1 and Option 2 are identical from a design perspective and are not differentiated in this report, except for cost.**

Mission Design

Design Assumptions

- **An example low-energy trajectory is sufficient to size the DV and timeline for that phase.**
  - The DV and timeline do not change with launch date
  - Changes in the target (e.g. specific phasing used to determine low-energy trajectory) do not significantly impact the DV and timeline.
- **A conic analysis of the constellation establishment phase is sufficient.**
  - Lunar perturbations can be designed around.
  - Added 10% to the conic analysis DV to cover clean-ups and the differences between a conic and an integrated trajectory
- **An integrated trajectory, neglecting non-grav forces, but including the major gravity sources (Sun, Earth, Moon, and other 7 planets) is sufficient to demonstrate the constellation feasibility.**
  - Further assumed that the initial date of the integration does not materially impact the constellation parameters (e.g. baseline variation) if the initial conditions are re-converged for the different initial date.

Design: Timeline and Delta V Budget

Event	Rel. Time	Delta V (m/s)	# Maneuvers
Cruise TCMs	Launch to L+169d	20 m/s	5 (1 deterministic)
600,000 km orbit injection	L + 169 day	186 m/s	1
Release 2 probes			
Reduce Periapsis	L + 177 day	55 m/s	1
Circularize + Clean-up	L + 263 day	67 m/s	3 (1 @ 55 m/s)
Release 2 probes			
Reduce Periapsis	L + 269 day	55 m/s	1
Circularize + Clean-up	L + 355 day	67 m/s	3 (1 @ 55 m/s)
Release last 2 probes			
Remove Carrier from science orbit	L + 365 day	4 m/s	2 (1 ea. @ 2 m/s)
Total		454 m/s	16

Design

- **Low-energy trajectory designed by Jeffery Parker using an arbitrary 600,000 km semi-major axis orbit as the target and a launch date of 11/1/2020.**
  - -0.05 km^2/s^2 launch energy (C3) out of 28.5 deg inclination parking orbit
  - 186 m/s injection DV following 169 day transfer
- **The constellation initial conditions (below) were arrived at by minimizing the variation of the baseline from a 1 million km value over a two year integration.**
  - Maximum angular variation: 4.9 deg (62.5 deg – 57.6 deg)
  - Maximum range variation: 49,527 km (1,026,693 - 977,166 km)

Element (1-JAN-2025)	SC-1/-2	SC-3/-4	SC-5/-6
Semi-major Axis (km)	5.642030475447640e+05	5.785957314531232e+05	6.060348517870137e+05
Eccentricity	2.538063000534380e-02	2.626825640064612e-02	6.050034777667967e-02
Inclination (deg)	1.794175569972753e+02	1.784028332530828e+02	1.770712616332796e+02
Lon. of Node (deg)	-1.095775245209930e+00	5.736290362453956e+01	-5.915036105033782e+01
Arg. of Periapsis (deg)	1.977725927321673e+02	6.263875004127930e+01	2.106110650841421e+02
True Anomaly (deg)	1.611759411881538e+02	1.179755313201745e+02	-2.998974279822347e+01

- **Transfer between nodes of the constellation sized using 600,000 km semi-major axis science orbit and conic analyses**
  - 55.2 m/s to drop into orbit with 5/6th the period
  - Sized to match customer timeline (see Trades)

Design

- **Baseline design has long, mostly penumbral, eclipses in 1st year (2025):**
  - S/C-1/-2:
    - Feb: 249 minutes
    - Mar: 215 minutes
    - Apr: 253 minutes
    - Jun: 315.6 minutes total (includes 131.4 minutes in umbra)
  - S/C-3/-4:
    - Jul: 209 minutes
  - S/C-5/-6:
    - Jan: 58 minutes
    - Feb: 85 minutes
    - Sep: 112 minutes
    - Nov: 204 minutes
- **This was a driver for power and thermal designs**

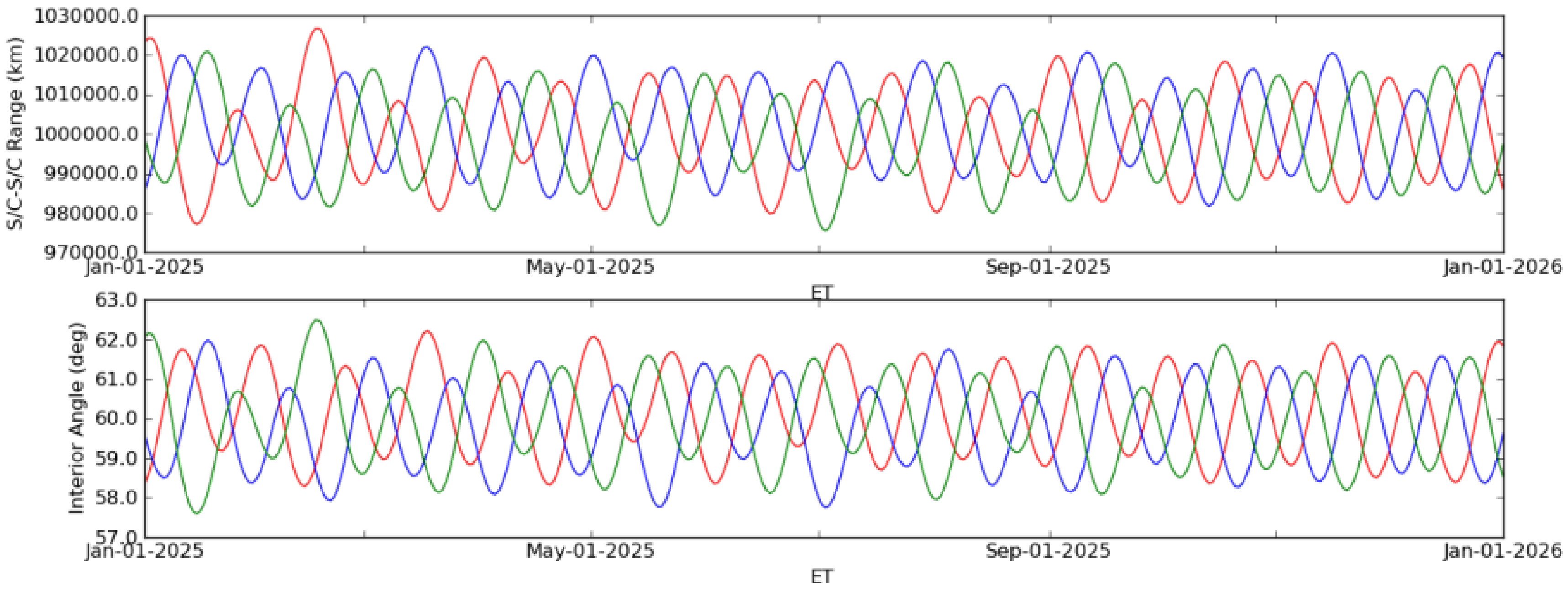
Mission Design
Design: LV

- **All values from NLS-II contract.**
- **NLS II Contract vehicle was desired by customer**
  - Final mass of the system (Carrier + 6 microprobes) was compatible with this vehicle.
  - NLS II Contract selected

Parameter	Value	Unit
Launch Vehicle	NLS II Contract	
Fairing Diameter	4.6	m
Max DLA	28	deg
C3	-0.05	km^2/s^2
Performance Mass	2490	kg

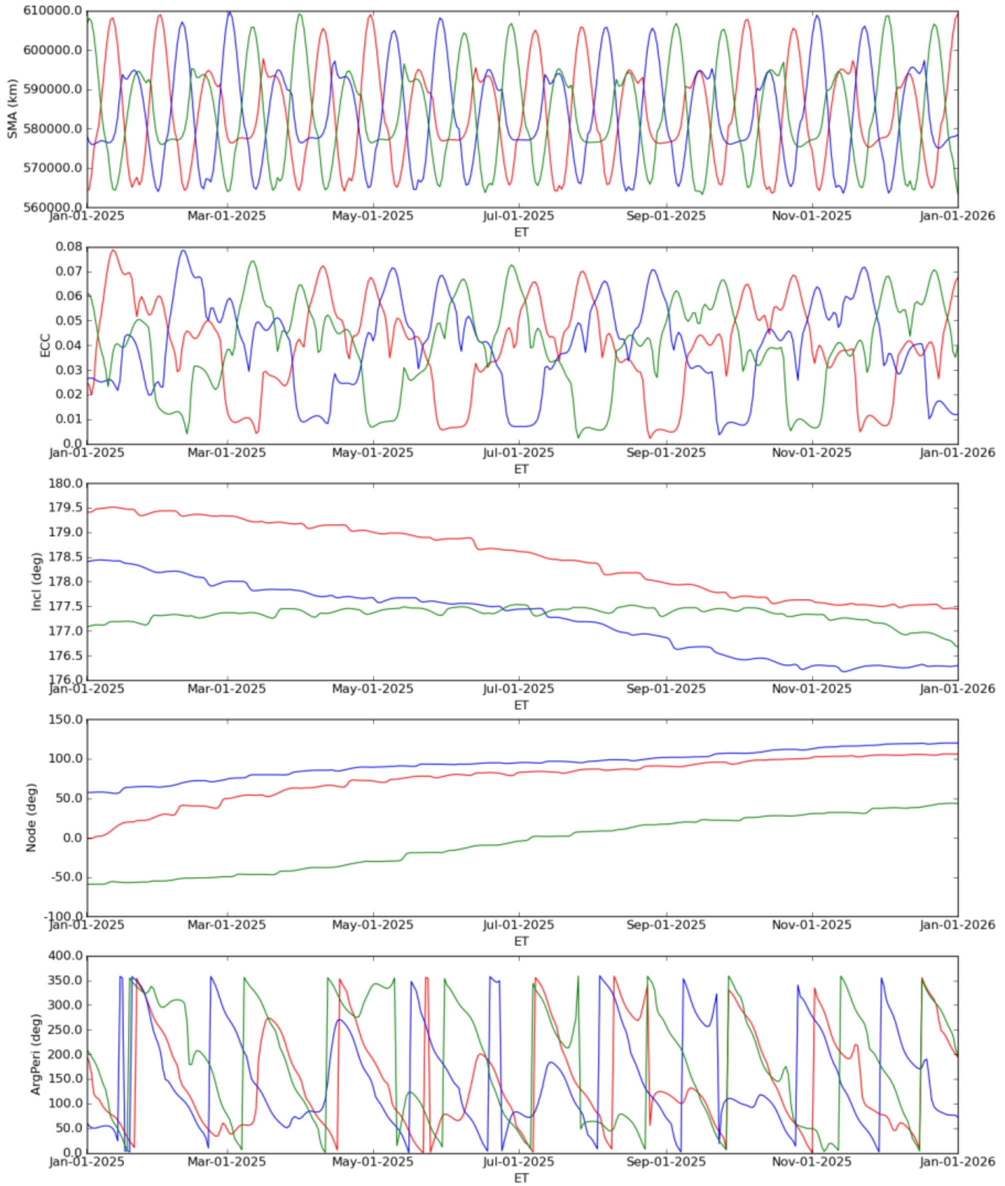
Mission Design
Plots

- **The initial conditions of the three spacecraft were optimized to minimize the average spacecraft-spacecraft range deviation from 1,000,0000 km**
  - Maximum angular variation: 4.9 deg (62.5 deg – 57.6 deg)
  - Maximum range variation: 49,527 km (1,026,693 - 977,166 km)

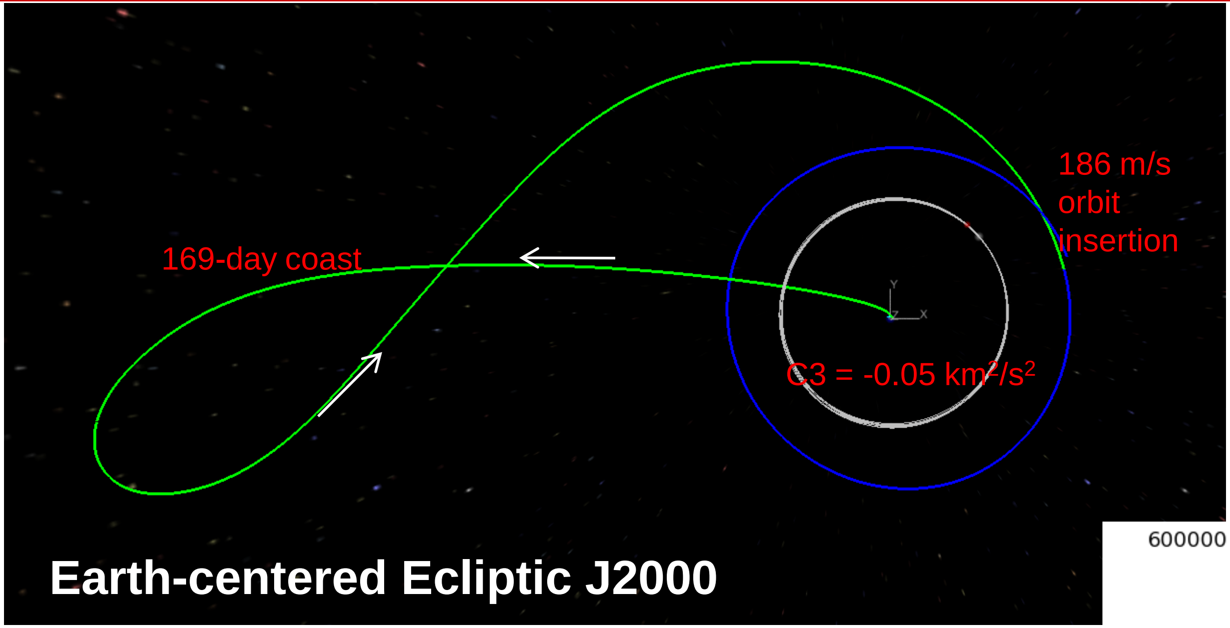


Plots

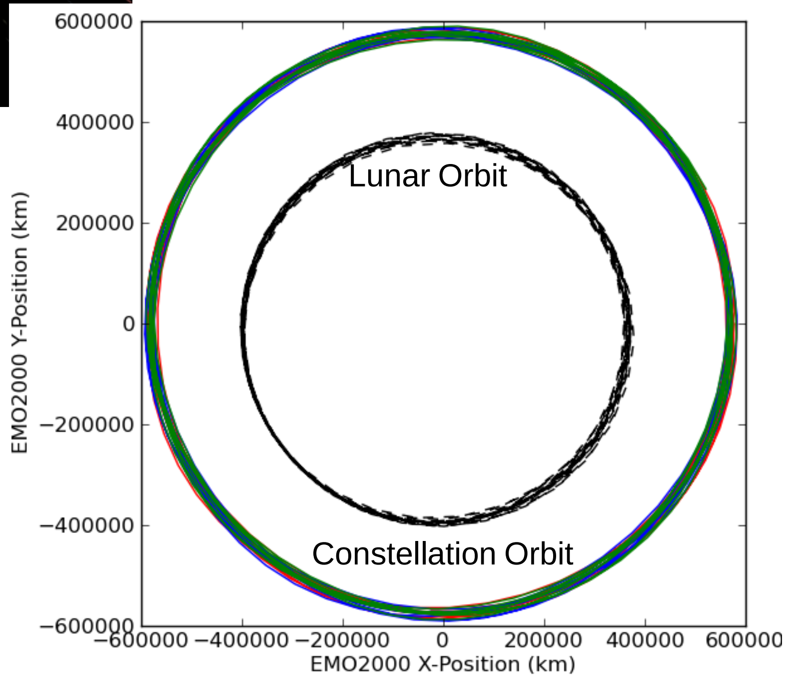
- **Each color represents the evolution of a single pair of spacecraft**
- **The orbit evolves under the influence of gravitational perturbations from various sources**
  - Sun, Moon
  - Jupiter
  - Other planets
- **Note the apparently secular drift in the inclination, longitude of node, and argument of periapsis.**



Mission Design
Visualization



- **Cruise trajectory and graphic by Jeffery Parker**



Cost Assumptions

- NAIF/SPICE software costs are assumed “complex” due to the number of independently flying spacecraft
- Navigation requirements assumed to be consistent with standard-level nav staffing
- Modeled as if all 6 microprobes were flying independently, as model doesn’t handle spacecraft doing different things at the same time (but does do multiple spacecraft doing the same thing at the same time)
  - Slight over-costing of the cruise phase & under costing of the constellation establishment phase

Cost Drivers

- Largest cost driver is the size of the constellation and the assumed navigation requirements
- The schedule differences between the two Options is a driver.

Potential Cost Savings

- None identified

Potential Cost Uppers

- The navigation staffing during the science phase seems a bit light to me.
  - The model wasn't validated for designing/operating this large of a constellation.
  - Phase E costs could be as much as 50% low

Risk

- **No risks identified. This is a complex mission at a low maturity level, but nothing is terribly time-critical or unusual.**

Option Comparison

- **Only difference between the two options is the development schedule.**
  - Option 2 is significantly shorter, which leads to lower costs and somewhat increased risk, as there is no difference in scope between Option 1 and 2

Option	Delta V (m/s)	Cost($M)	Orbit/Trajectory	Comments
1	454	22.3	Low Energy into DRO	94-month development
2	454	19.1	Low Energy into DRO	70-month development

ACS Report

(1281) OMEGA 2012-03

Dates: 3-5, 10 April 2012

Author: Bob Kinsey

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Table of Contents

Design Requirements for Sciencecraft (1 of 3)

- **Knowledge for acquisition drives the choice of star tracker.**
  - Spacecraft needs to provide accurate knowledge of its orientation to support the scan strategy used to locate and lock onto other spacecraft.
- **Spacecraft before and during acquisition:**
  - Control was not explicitly specified.
    - Propose 30 arcsec (3σ) for instrument LOS pointing.
    - See the next chart.
  - Knowledge based on preliminary top-level acquisition budget.
    - Propose 15.4 arcsec (3σ) for instrument LOS pointing.
    - See the next chart.
  - Stability was not explicitly specified.
    - Propose 0.3 arcsec/sec (3σ) per axis as a working requirement.
    - May do much better, but no need to over-constrain the system.

Design Requirements for Sciencecraft (2 of 3)

- **Table 1 below is a top-level acquisition budget for LISA.**
  - Tupper Hyde, NASA GSFC, "Technical Note: Acquisition with Scan and Defocus Methods: LISA Project," 10 February 2005.
- **Pointing budget for outgoing beam LOS.**
- **LISA assumed 25 km relative position knowledge.**
  - 5 µrad at 5 x 10^6 km range
  - 25 µrad at 1 x 10^6 km range
- **OMEGA needs 5 km relative position knowledge to meet a similar budget.**
  - Split DSN tracking between 2 ground stations (e.g., 4 hrs. each) for < 5 km.
  - ΔDOR is another alternative that can potentially achieve < 1 km.
- **Proposed OMEGA top-level pointing budget is on the next chart.**
  - Similar structure to Table 1, but relaxed requirements.

Table 1 Acquisition Cone Budget (3 sigma)

Spacecraft relative position knowledge [a]	± 5µrad
Star tracker accuracy [b]	± 5µrad
Star tracker vs. LOS calibration accuracy [c]	± 1µrad
LOS vs. outgoing optical axis [d]	± 1µrad
RSS	± 7.2µrad

Design Requirements for Sciencecraft (3 of 3)

- **Proposed budget for the far sciencecraft.**

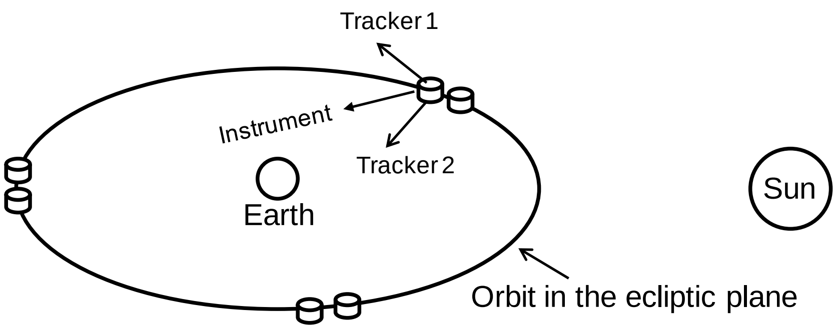
Acquisition Cone Budget
(half cone angles in μrad, 3 sigma)

Spacecraft relative pointing knowledge[1]	5.0	
Star tracker accuracy[2]	12.7	
Star tracker vs. LOS calibration accuracy	5.0	Suggested
LOS vs. outgoing optical axis	5.0	Suggested
RSS	15.4	
Margin (summed)	14.6	48.8% 100 x (Margin/Allocation)
Candidate Allocation	30.0	

[1]Assume DSN tracking split between two ground stations (e.g., 4 hours each), for < 5 km relative knowledge.
[2]Pitch and yaw knowledge within 3 arcsec, 1 sigma; multiply by 3 and RSS pitch and yaw.

Design Assumptions for Sciencecraft

- **Star tracker performance**
  - Vendor's spec is 3 arcsec (1σ) in pitch and yaw, 25 arcsec in roll.
  - 2 heads with both in operation during science.
  - Canted relative to the instrument boresight.
    - Assume each star tracker boresight 45 degrees off instrument boresight.
    - Assume 90 degrees between star tracker boresights.
    - Assume star trackers canted above/below ecliptic plane for sun avoidance.
    - Can achieve 3 arcsec (1σ) in all 3 spacecraft axes.
  - Leads to 12.7 arcsec (3σ) knowledge in direction of instrument boresight.
    - RSS of instrument pitch and yaw directions, with each at 9 arcsec (3σ).
- **Orbit characteristics**
  - Assume that 600,000 km circular orbits for the six spacecraft all lie in the ecliptic plane, as shown below.
  - Star tracker heads canted as shown.



ACS
Architecture for Sciencecraft

- **All stellar attitude determination for acquisition and science:**
  - Two vendor star camera heads.
    - Vendor star processing software will be run in the Broadreach processor.
- **Attitude determination in a high rate (> 6°/sec) failure scenario.**
  - Set of 8 coarse sun sensors.
- **Attitude control:**
  - 3-axis stabilized using FEEP thrusters. No reaction wheels.
- **Instrument has the capability to**
  - Sense the direction of incoming beams.
  - Point the outgoing beam to the near spacecraft.
  - Maintain the orientation of the proof mass.
- **Pointing algorithms used after acquisition provide**
  - Position and orientation commands to the spacecraft for shielding the proof masses from external disturbances.
  - Commands needed to maintain the proof mass orientation and point the outgoing beams.

Architecture for Carrier

- **Stellar inertial attitude determination using star tracker and gyros.**
  - Redundant pair of 2-head star cameras.
  - Redundant pair of IMUs.
  - Pair of coarse sun sensors, for initial deployment and for safe mode.

- **Attitude control using hydrazine thrusters.**
  - Set of eight 1-N thrusters and four 22-N main engines.
  - See the Propulsion section of the report for more detail.

ACS
Design

- **Attitude determination hardware on Sciencecraft:**
  - Vendor's star camera heads → Same as customer MEL.
    - 2 heads canted above and below the ecliptic plane for sun avoidance.
    - Performance 9 arcsec (3σ) in 3 axes, using 2 heads, tracking many stars.
  - coarse sun sensors: 8 units → Not included in customer MEL.
    - Oriented so that the set provides 4 pi sr coverage.
    - Single axis analog with ±5 deg accuracy, 120 deg FOV.
- **Attitude determination hardware on Carrier:**
  - Pair of coarse sun sensors → Change from customer MEL.
    - Two axis analog, 0.13 kg, no power, 1 deg accuracy, 2 pi sr, ~$40K ea.
    - 2-Axis DMC: 0.3 kg, 1 deg accuracy, 50 deg FOV, ~$46K ea.
  - Pair of vendor 2-head star cameras → Same as customer MEL.
    - Each unit has 2 heads; star processing done in main processor.
  - Pair of IMUs → Change from customer MEL.
    - 0.75 kg, 12 Watts, 3 deg/hr (3σ) per axis, max 1000 deg/sec, ~$250K.
    - Vendor: 1.8 kg, 4 Watts, unknown performance, unknown cost.
    - For reference: Vendor: 1.8 kg, 5 Watts, 10 deg/hr, 8 deg/sec, ~$85K.

Cost Assumptions for Sciencecraft (1 of 3)

- **Level of heritage**
  - **Completely New**
  - **Similar with Major Mods** ⟵ **Selected**
    - **80% new; 20% heritage**
  - **Similar with Minor Mods**
    - **40% new; 60% heritage**
  - **Identical**
    - **5% new; 95% heritage**
  - **Hardware Only**

New algorithms for pointing during and after acquisition.

Heritage spacecraft pointing functions (e.g., attitude determination, inertial pointing).

- **Level of pointing performance**
  - **1 degree**
  - **0.1 degree**
  - **0.01 deg; < 2 arcsec/sec**
  - **<0.01 deg; < 0.2 arcsec/sec** ⟵ **Selected**

- **Optional ACS control functions: Target-relative tracking.**
- **Non-standard costs manually added:** None

Cost Assumptions for Sciencecraft (2 of 3)

- **Star tracker cost assumptions**
  - Vendor's costs published online:
    - $500K for 1 data processing unit (DPU) and 1 camera head unit (CHU).
    - $860K for 1 DPU and 2 CHUs.
    - Difference is $360K for 1 CHU.
  - Assuming CHU cost of $360K before procurement burden.
    - Flight spares same; engineering models at 80% of flight unit costs.
  - No volume discount assumed.
  - Note that the cost may fluctuate due to exchange rates.
- **Star tracker total for 6 sciencecraft: $6.3M in FY 2012.**
  - 12 flight heads; two per sciencecraft.
  - 3 spare heads; square root of 12 is 3.46; round down.
  - Set of 2 EM heads, plus one spare EM.
  - Before procurement burden.

Cost Assumptions for Sciencecraft (3 of 3)

- **Spares for the sciencecraft:**

Item	Spares	Comments
Star camera heads	3	Square root of 12 total = 3.46, rounded down.
Sun sensors	7	Square root of 48 total = 6.93, rounded up.

- **EMs for the sciencecraft:**

Item	EMs	Comments
Sun sensor	11	Set of 8, plus 3 spare EMs.
Star camera heads	3	Set of 2, plus 1 spare EM.

ACS
Sciencecraft Cost – Option 1

- **Cost Estimate in FY 2012 $M**
  - Non-Recurring (NRE): 11.31   Recurring (RE): 3.95
  - Total = 1 x NRE + 6 x RE = $35.01M

Cost Assumptions for Carrier (1 of 2)

- **Level of heritage**
  - **Completely New**
  - **Similar with Major Mods**
    - **80% new; 20% heritage**
  - **Similar with Minor Mods** ← **Selected** Heritage spacecraft pointing functions (e.g., attitude determination, inertial pointing).
    - **40% new; 60% heritage**
  - **Identical**
    - **5% new; 95% heritage**
  - **Hardware Only**
- **Level of pointing performance**
  - **1 degree**
  - **0.1 degree** ← **Selected**
  - **0.01 deg; < 2 arcsec/sec**
  - **<0.01 deg; < 0.2 arcsec/sec**
- **Optional ACS control functions:** None
- **Non-standard costs manually added:** None

Cost Assumptions for Carrier (2 of 2)

- **Spares for the Carrier:**

Item	Spares	Comments
Sun sensors	1	1 spare for 2 flight units.
Star camera heads	1	1 spare for 2 flight units.
IMUs	1	1 spare for 2 flight units.

- **EMs for the Carrier:**

Item	EMs	Comments
Sun sensor	2	Test as you fly; No spare EM.
Star camera heads	2	Test as you fly; No spare EM.
IMUs	2	Test as you fly; No spare EM.

Carrier Cost – Option 1

- **Cost Estimate in FY 2012 $M**
  - Non-Recurring (NRE): 7.96   Recurring (RE): 4.56

Total Cost – Option 1

- **Total ACS cost is estimated at $47.53M in FY 2012.**
- **Cost Drivers**
  - Effort for design, analysis, and subsystem level system engineering accounts for $14.17M (30%).
  - Hardware costs are the bulk of the remainder.
- **Rule of thumb based on ACS chair experience over 400+ studies is that ACS is usually at least 5% of the total mission cost.**
  - Team X mission cost for Option 1 is $1.393B; 5% is $69.7M.
  - ACS estimate of $47.53M is 3.4% of $1.393B.
- **Suggests that the ACS cost estimate is low.**
  - On the other hand, most of the 400+ studies were 1st units, as opposed to constellations.
  - The 5% rule of thumb is overly conservative for a constellation, particularly for a constellation with 6 sciencecraft.
    - 1 x NRE + 6 x RE inherently leads to improved cost efficiency.

Sciencecraft Cost – Option 2

- **Cost Estimate in FY 2012 $M**
  - Non-Recurring (NRE): 10.27   Recurring (RE): 2.79
  - Total = 1 x NRE + 6 x RE = $27.01M

Carrier Cost – Option 2

- **Cost Estimate in FY 2012 $M**
  - Non-Recurring (NRE): 6.97   Recurring (RE): 3.59

ACS
Total Cost – Option 2

- **Total ACS cost is estimated at $37.57M in FY 2012.**
- **Cost Drivers**
  - Effort for design, analysis, and subsystem level system engineering accounts for $12.19M (32%).
  - Hardware costs are the bulk of the remainder.
- **Rule of thumb based on ACS chair experience over 400+ studies is that ACS is usually at least 5% of the total mission cost.**
  - Team X mission cost for Option 2 is $1.223B; 5% is $61.2M.
  - ACS estimate of $37.57M is 3.1% of $1.223B.
- **Suggests that the ACS cost estimate is low.**
  - On the other hand, most of the 400+ studies were 1st units, as opposed to constellations.
  - The 5% rule of thumb is overly conservative for a constellation, particularly for a constellation with 6 sciencecraft.
    - 1 x NRE + 6 x RE inherently leads to improved cost efficiency.

Risk – Both Options

Sun sensors for the sciencecraft:

- Original customer baseline had only 2 star trackers for each sciencecraft.
- Star trackers can track at rates up to 6 deg/sec.
  - Good for a star tracker, but 6 deg/sec (1 RPM) is still a relatively low rate.
  - Assuming that star trackers provide no useful information above 6 deg/sec.
- Baseline had the risk of loss of a sciencecraft in the event of off-nominal separation from the Carrier (e.g., with a rate of 7 deg/sec).
  - Since the Carrier would separate two sciencecraft at a time, the worst case would be a scenario in which both are tumbling with a rate > 6 deg/sec.
  - That scenario would result in loss of the mission.
  - Carrier thruster stuck on during the separation interval could lead to rate well in excess of 6 deg/sec (e.g., tens of deg/sec).
- Mitigated the risk by adding a set of coarse sun sensors.
  - Use these to sense sun direction; differentiate to estimate rate.
  - Possible to recover from relatively large tumbling rate given enough time, so long as there is sufficient sun on the body mounted solar arrays.

ACS
Option Comparison

- Same Sciencecraft and Carrier designs for both options.
- Cost estimates for Option 1 are higher due to longer schedule.

Element	CBE Mass (kg)	Cost ($M)	Architecture	Comments
Science-craft 1	2.16 CBE 2.76 with contingency	35.01	3-axis stabilized using FEEP thrusters.	Cost total for all 6 sciencecraft, including spares and EMs.
Carrier 1	1.06 CBE 1.17 with contingency	12.52	3-axis stabilized using hydrazine thrusters.	Cost total including spares and EMs.
Science-craft 2	2.16 CBE 2.76 with contingency	27.01	3-axis stabilized using FEEP thrusters.	Cost total for all 6 sciencecraft, including spares and EMs.
Carrier 2	1.06 CBE 1.17 with contingency	10.56	3-axis stabilized using hydrazine thrusters.	Cost total including spares and EMs.

ACS
Additional Comments

- **Sun sensors were added to the sciencecraft for both options.**
  - For sensing attitude and angular velocity if separation from the Carrier results in tumbling at a rate higher than 6 deg/sec (star tracker max rate).
- **Requires a rate-nulling control mode that is not entirely standard.**
  - Rate-nulling based on gyros measurements would be standard.
  - Algorithms and software would be needed to estimate the angular velocity based on sampled sun sensor measurements.
  - Not difficult, but requires some level of effort for design and analysis.
- **ACS cost estimate already includes $8M to $9M for developing algorithms and software related to sciencecraft pointing.**
  - May be enough that the cost of the above is already captured.
- **There is some possibility of a cost upper since there was no specific allowance for a sun-sensor based rate nulling mode.**
  - Likely to be < $1M for the added effort.

CDS Report

(1281) OMEGA 2012-04
April 3 – 5 & 10, 2012

Dwight Geer

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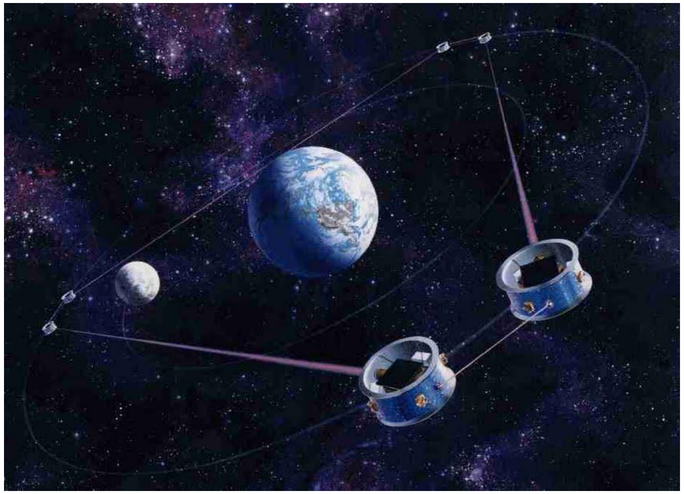
CDS
Table of Contents

Design Requirements

- **Mission:**
  - OMEGA is the third of three space-based gravity-wave observatories
    - Measures gravity waves using three spacecraft-pairs in a constellation
    - OMEGA uses pairs of spacecraft for redundancy lowering the Mission Class to “C” (a loss impacts science slightly)
- **Data Volumes**
  - The data volume over the week downlink period is about 490 Mbits per Science Craft – more than half being science data
  - To insure storage for at least a missed downlink pass 980 Mb (123 MB) storage is required



Design Requirements

Interfaces

- A shown in the Science Craft block diagram provided by the customer the CDS interfaces to the standard avionics (power, telecom, attitude control, propulsion) and the payload
- And as shown in the Carrier Craft block diagram, also provided by the customer and slightly updated, the CDS interfaces to the standard avionics and the payload (in this case the six Science Crafts – for checkouts and Science mission initiation)
- Broad Reach Engineering (BRE) hardware was identified in the block diagrams and, for a Class C Mission, is appropriate
  - BRE hardware selected provides the standard interfaces (1553, RS422, LVDS, discretes, analog interfaces including temperature measurements logic)
  - This is adequate for both the spacecraft interfaces and payload interfaces

Radiation

- Hardware is suitable for the 10.8 krad TID (this includes the RDF)

Design Options

- There is no hardware difference between Option 1 and Option 2

CDS
Design Assumptions

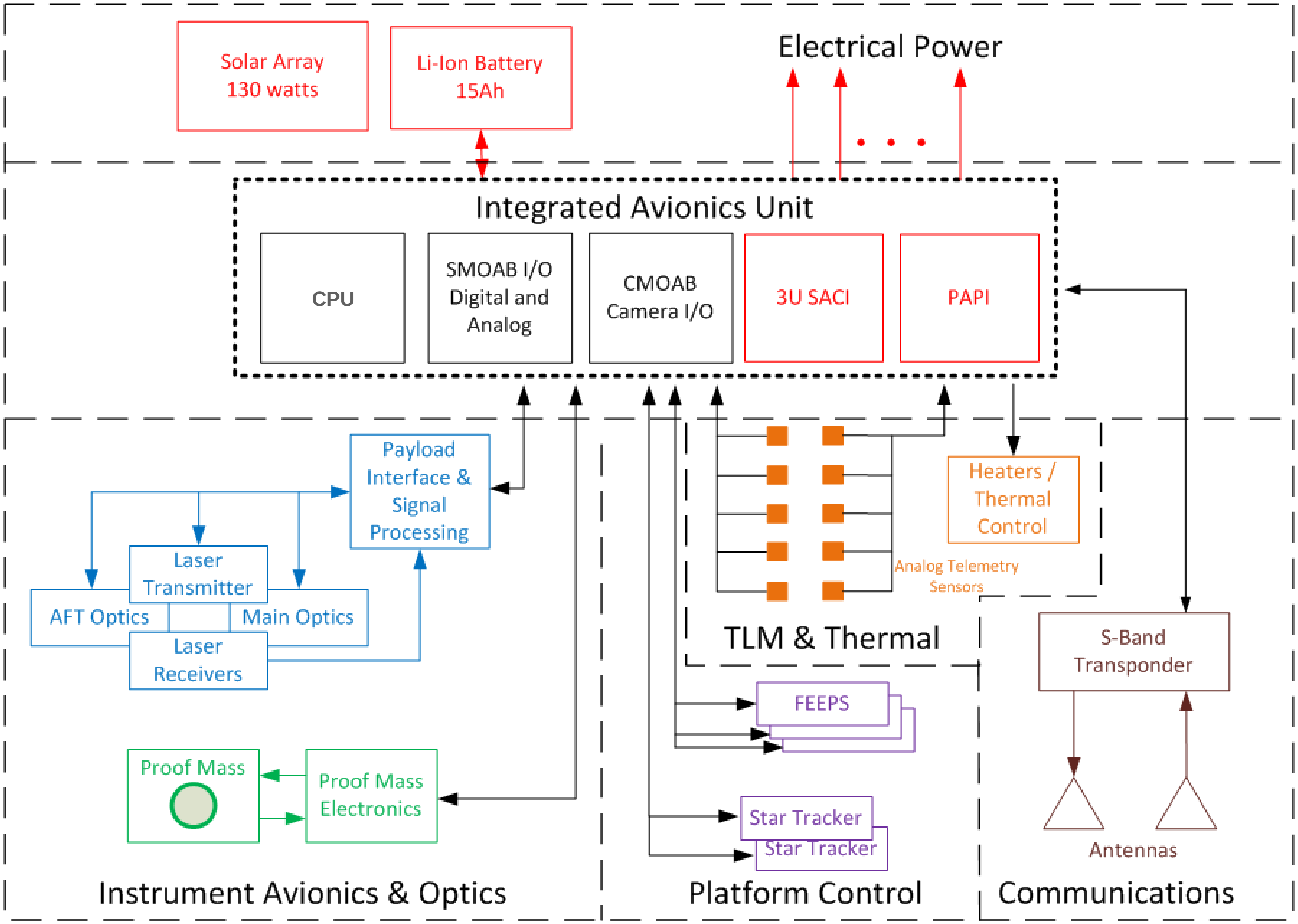
- **Selection of a Integrated Avionics Unit (IAU)**
  - This customer proposal for using an IAU is appropriate for this Mission as is selected for this Team X study
  - The boards chosen (again, per block diagrams) are appropriate
  - The dual string (cold sparing) Carrier Craft requires the a Redundancy Management Unit (RMU) to manage the redundancy and so is included in the Carrier Craft designs (Option 1 and Option 2)
- **Science Craft**
  - The Science Craft CDS is single string
  - Doubling the spacecraft at each of the three nodes provides redundancy
- **Carrier Craft**
  - The Carrier Craft CDS has dual string redundancy (using cold sparing)
  - A separate box, the RMU, provides redundancy management
- **FM Spares Plan**
  - Two FM spares are included (given 8 total FM units required)
- **GSE Plan**
  - Six sets of GSE is costed to support testing of the Science and Carrier S/Cs

Design

- **Hardware**
  - The Science Craft has one IAU (single string)
    - The components are listed in the first table on the following page
  - The Carrier Craft has two IAU's and one RMU (dual string)
    - The components are listed in the second table on the following page
  - Power Subsystem Boards in the IAU
    - Both the Science and Carrier Craft IAUs include Power Subsystem boards
      - SACI: Solar Array and Charging Interface
      - PAPI: Propulsion and Payload Power Interface
    - See Power Subsystem study report if additional information on these are needed
  - Storage
    - The data storage requirements is low and adequate storage is available in the two MOAB boards
      - SMOAB: Standard Multi-Operations Avionics Board
      - CMOAB: Camera Multi-Operations Avionics Board
  - Processing Capability
    - The Single Board Computer can operate at 133MHz with performance at 2 MIPS/MHz or 266MIPS with L1 and 256 kB of L2 cache

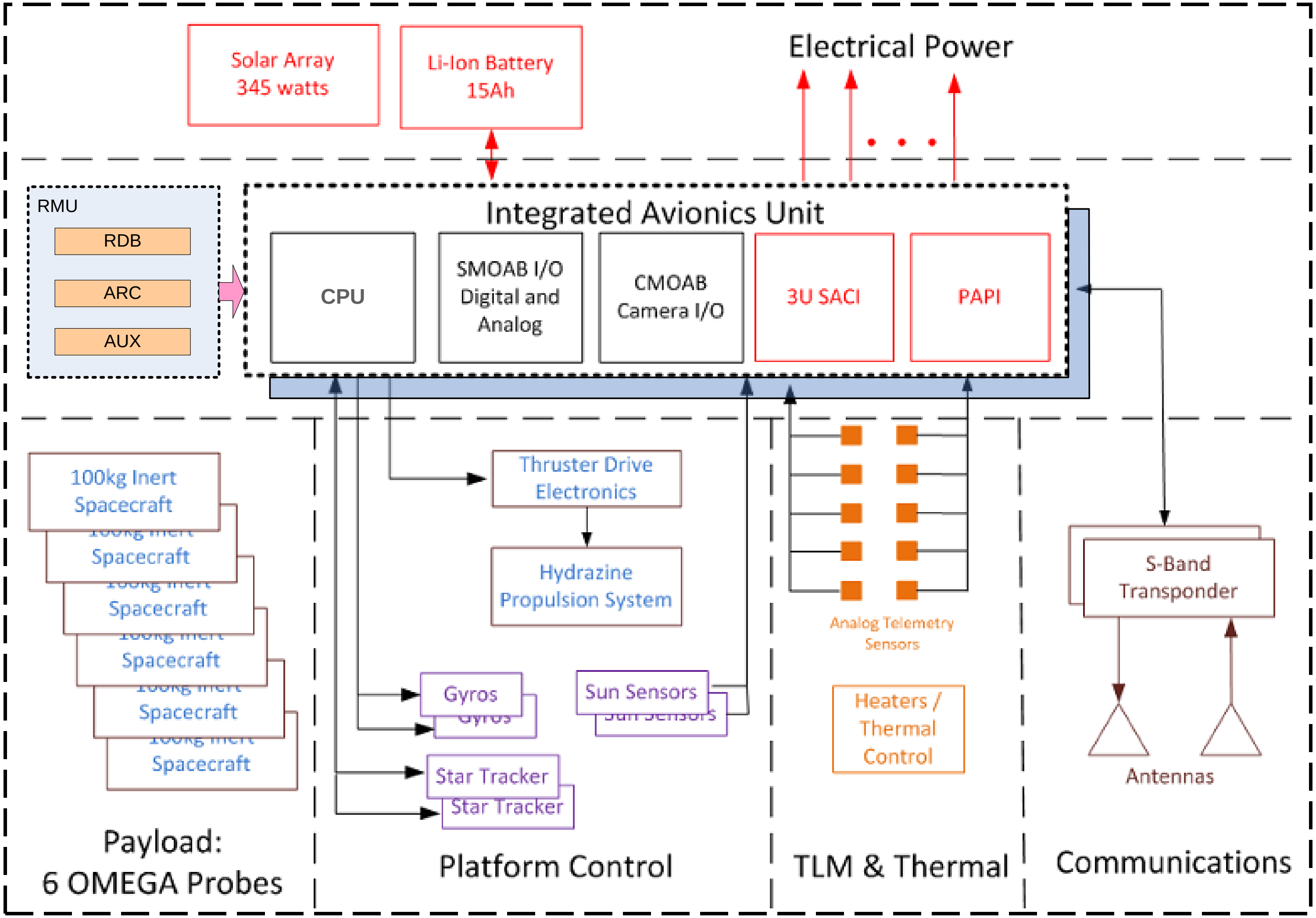
Block Diagram – Science Craft

- This is the customer block diagram with the same Integrated Avionics Unit (IAU)



Block Diagram – Carrier Craft

- **This is the customer block diagram but with dual string IAU's and a RMU**
  - The BRE Redundancy Management Unit (RMU) is a required to manage the two IAU strings



CDS
Cost Assumptions

- **Management and Subsystem Engineering**
  - The Management and Subsystem Engineering labor costs are carried in Science Craft CDS workbook
- **Flight Spares**
  - Two FM Spares appropriate for the 8 FM IAUs (6 Science S/C, 2 in Carrier)
    - The Science CDS workbook is set to 0.25 FM Spares
    - The Carrier CDS workbook is set to 0.5 FM Spares
    - The Carrier workbook was overridden to have one FM spare RMU
- **BTE (Bench Test Equipment)**
  - Two BTE sets are adequate for testing individual boards as needed
    - The Science workbook is set to 1/3 BTE
    - The Carrier workbook is set to 0 BTE (an override was included for the RMU)
- **GSE (Ground Support Equipment)**
  - Six GSE sets were requested
    - The Science workbook is set to 1 GSE (to get 6)
    - The Carrier workbook is set to 0 GSE (an override was included for the RMU)

Science Craft Cost – Option 1

- **1ST Unit Cost : $14.7M**
- **Nth Unit Cost: $5.1M (NRE Cost: $9.7M)**
  - For the six Science Crafts the total CDS cost is $40.0M

Carrier Craft Cost – Option 1

- **1ST Unit Cost : $11.0M**
- **Nth Unit Cost: $9.7M (NRE Cost: $1.3M)**
  - For the dual string Carrier Craft the total CDS cost is $11.0M

Science Craft Cost – Option 2

- **1ST Unit Cost : $12.5M**
- **Nth Unit Cost: $5.1M (NRE Cost: $7.4M)**
  - For the six Science Crafts the total CDS cost is $37.7M

Carrier Craft Cost – Option 2

- **1ST Unit Cost : $11.0M**
- **Nth Unit Cost: $9.7M (NRE Cost: $1.3M)**
  - For the dual string Carrier Craft the total cost is $11.0M

Cost – Options 1 and 2

Options

- For the CDS Option 1 and Option 2 have the same hardware set (MEL)
- Cost differs between options is due to Mission Phase length changes
  - With management and subsystem engineering carried in the Science spacecraft only this cost estimate (the Science S/C) changes between options
- For both options NRE was eliminated for the Carrier S/C
  - There were a few exceptions
    - Mechanical, Thermal, and Reliability analyses are included in the Carrier costs
    - The different environments require these analyses to be reviewed and updated

Potential Cost Savings

- Quantity Buys
  - Vendor has a breakpoint with some or all of their hardware at 10
    - The quantities are 6 Science IAU's & 2 Carrier IAU's plus 2 Spares – 10 total IAU's
    - The cost estimates in this study do not include this potential cost savings

Cost – Options 1 and 2 continued

- **Potential Cost Savings, continued**
  - Option 1 Phase C1 (design) may be long for mostly build-to-print set of H/W
    - But the time can not be reduced too much such that interface changes required by other long lead subsystems and instruments cannot be accommodated
- **Potential Cost Uppers**
  - Option 2 Phase C2 and C3 (fab and test) times may be too short
    - Once the design is frozen 9 months is often required due to parts procurement
    - Subsystem test time of 4 months for this large set of hardware is likely too short

CDS
Cost Table – Options 1 and 2

OMEGA Study 2012-04			QTY	CDS Unit Cost	Subtotal Cost	Constellation CDS Cost
Option 1						
	Science S/C	1st IAU	1	$14.7M	$14.7M	
		nth IAU	5	$5.1M	$25.3M	$40.0M
	Carrier S/C	Dual IAU and RMU	2	$11.0M	$11.0M	$11.0M
	Option 1 CDS Mission Cost					**$51.0M**
Option 2						
	Science S/C	1st IAU	1	$12.5M	$12.5M	
		nth IAU	5	$5.1M	$25.3M	$37.7M
	Carrier S/C	Dual IAU and RMU	2	$11.0M	$11.0M	$11.0M
	Option 2 CDS Mission Cost					**$48.7M**

Risk, Option Comparison, & Additional Comments

Potential Cost Uppers

- Option 2 Phase C2 and C3 (fab and test) times may be too short
    - Once the design is frozen 9 months is often required due to parts procurement
    - Subsystem test time of 4 months for this large set of hardware is likely too short

Option Comparison

- There are no hardware differences between option 1 and 2
- There is a cost difference due to Mission Phase length differences

Additional Comments

- Power Boards
    - The SACI and PAPI boards are not considered CDS boards but are included in this IAU design
        - Cost, Mass, and Power are carried in the CDS workbooks

Power Report

1281 OMEGA 2012-04
April 2- 10, 2012

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Power

Table of Contents

Power
Design Requirements – Option 1,2

- **Mission:**
  - Space physics mission using gravity wave instrument payload based on LISA science goals.
  - Six cylindrical science craft delivered via single carrier craft.

- **Stabilization: 3-Axis stabilized for science crafts.**

- **Two Options based science/carrier craft delta:**
  - Option 1 science craft: science goals based on LISA science goals.
  - Option 2 science craft: shortened C/D schedule phases along with lower power draw on science instrument.
  - Option 1 vs. 2 carrier craft: shortened C/D schedule for option 2.

Power
Design Assumptions – Options 1,2 science/carrier crafts

- **BRE solar array and propulsion electronics for both carrier and science craft (SACI, PAPI).**
  - These electronics are carried by CD&H subsystem.
- **Carriercraft design is based on mission class "B" with moderate to low complexity.**
  - Full functional redundancy for electronics
- **Science craft design is based on mission class "C" with moderate to low complexity.**
  - Partial spares only for electronics.
- **Science craft solar array sizing is based on power requirements for nominal science on-station with 4 hour eclipse.**
  - Fixed-body array mounted on radial S/C geometry.
- **Science craft battery sizing is also based on power requirements for nominal science on-station during 4 hour eclipse.**
  - No requirement for charge duration.

Power
Summary – Option 1 Science craft

Power Summary Chart

Subsystem/Instrument		Power [W]									
		Launch	Cruise	Separation	Communications	Science	Science in eclipse	Science with Telecom	Safe	TBD	TBD
ACS		0.0	0.0	10.0	10.0	10.0	10.0	10.0	10.0	0.0	0.0
C&DH		0.0	0.0	24.6	24.6	24.6	24.6	24.6	24.6	0.0	0.0
Instruments		0.0	0.0	0.0	8.0	79.7	79.7	79.7	8.0	0.0	0.0
Other Elements		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Propulsion System 1		0.0	0.0	6.3	6.3	6.3	6.3	6.3	6.3	0.0	0.0
Propulsion System 2		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Propulsion System 3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Structures		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Telecomm		0.0	0.0	40.4	40.4	5.4	5.4	40.4	40.4	0.0	0.0
Thermal		0.0	0.0	35.0	35.0	25.0	25.0	5.0	25.0	0.0	0.0
Power Subsystem		0.0	0.0	16.1	16.8	18.9	18.9	14.7	15.9	4.3	4.3
TOTALS		**0.0**	**0.0**	**132.4**	**141.0**	**169.9**	**169.9**	**180.7**	**130.2**	**4.3**	**4.3**
Systems Contingency	%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%
Calculated Contingency	%	0%	0%	43%	43%	43%	43%	43%	43%	43%	43%
Subsysem Contingency	W			**56.9**	**60.6**	**73.1**	**73.1**	**77.7**	**56.0**	**1.9**	**1.9**
ACS	W			4.3	4.3	4.3	4.3	4.3	4.3		
C&DH	W			10.6	10.6	10.6	10.6	10.6	10.6		
Instruments	W				3.4	34.3	34.3	34.3	3.4		
Other Elements	W										
Propulsion System 1	W			2.7	2.7	2.7	2.7	2.7	2.7		
Propulsion System 2	W										
Propulsion System 3	W										
Structures	W										
Telecomm	W			17.4	17.4	2.3	2.3	17.4	17.4		
Thermal	W			15.1	15.1	10.8	10.8	2.2	10.8		
Power Subsystem	W			6.9	7.2	8.1	8.1	6.3	6.9	1.9	1.9
Subsystems with Contingency		**0.0**	**0.0**	**189.3**	**201.6**	**243.0**	**243.0**	**258.4**	**186.2**	**6.2**	**6.2**
Systems with Contingency		0.0	0.0	189.3	201.6	243.0	243.0	258.4	186.2	6.2	6.2
Duration (published by Systems, **hours**)		1.0	24.0	1.0	4.0	24.0	4.0	2.0	24.0	0.0	0.0

- **Science + eclipse power mode is sizing mode for both solar array and battery.**

Power
Summary – Option 2 Science craft

Power Summary Chart

Subsystem/Instrument		Power [W]									
		Launch	Cruise	Separation	Communications	Science	Science in eclipse	Science with Telecom	Safe	TBD	TBD
ACS		0.0	0.0	10.0	10.0	10.0	10.0	10.0	10.0	0.0	0.0
C&DH		0.0	0.0	24.6	24.6	24.6	24.6	24.6	24.6	0.0	0.0
Instruments		0.0	0.0	0.0	5.4	54.0	54.0	54.0	5.4	0.0	0.0
Other Elements		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Propulsion System 1		0.0	0.0	6.3	6.3	6.3	6.3	6.3	6.3	0.0	0.0
Propulsion System 2		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Propulsion System 3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Structures		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Telecomm		0.0	0.0	40.4	40.4	5.4	5.4	40.4	40.4	0.0	0.0
Thermal		0.0	0.0	30.0	30.0	25.0	25.0	5.0	25.0	0.0	0.0
Power Subsystem		0.0	0.0	15.7	16.1	16.8	16.8	13.4	15.7	4.3	4.3
TOTALS		**0.0**	**0.0**	**127.0**	**132.8**	**142.1**	**142.1**	**153.7**	**127.4**	**4.3**	**4.3**
Systems Contingency	%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%
Calculated Contingency	%	0%	0%	43%	43%	43%	43%	43%	43%	43%	43%
Subsysem Contingency	W			**54.6**	**57.1**	**61.1**	**61.1**	**66.1**	**54.8**	**1.9**	**1.9**
ACS	W			4.3	4.3	4.3	4.3	4.3	4.3		
C&DH	W			10.6	10.6	10.6	10.6	10.6	10.6		
Instruments	W				2.3	23.2	23.2	23.2	2.3		
Other Elements	W										
Propulsion System 1	W			2.7	2.7	2.7	2.7	2.7	2.7		
Propulsion System 2	W										
Propulsion System 3	W										
Structures	W										
Telecomm	W			17.4	17.4	2.3	2.3	17.4	17.4		
Thermal	W			12.9	12.9	10.8	10.8	2.2	10.8		
Power Subsystem	W			6.8	6.9	7.2	7.2	5.8	6.8	1.9	1.9
Subsystems with Contingency		**0.0**	**0.0**	**181.6**	**189.9**	**203.2**	**203.2**	**219.8**	**182.2**	**6.2**	**6.2**
Systems with Contingency		0.0	0.0	181.6	189.9	203.2	203.2	219.8	182.2	6.2	6.2
Duration (published by Systems, **hours**)		1.0	24.0	1.0	4.0	24.0	4.0	2.0	24.0	0.0	0.0

- **Science + eclipse power mode is still sizing mode for both solar array and battery.**

Summary – Option 1, 2 Carrier craft

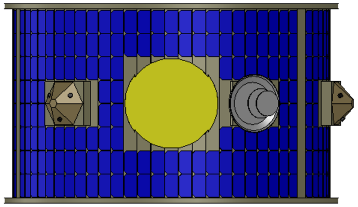
Power Summary Chart for launch, separation, and cruise mode.

Subsystem/Instrument		Launch	Cruise	Separation
ACS		22.0	22.0	22.0
C&DH		39.5	39.5	39.5
Instruments		0.0	0.0	0.0
Other Elements		0.0	0.0	0.0
Propulsion System 1		24.7	0.7	24.7
Propulsion System 2		0.0	0.0	0.0
Propulsion System 3		0.0	0.0	0.0
Structures		0.0	0.0	0.0
Telecomm		40.4	40.4	40.4
Thermal		114.4	214.4	214.4
Power Subsystem		20.7	24.9	26.3
TOTALS		**261.7**	**341.9**	**367.3**
Systems Contingency	%	43%	43%	43%
Calculated Contingency	%	43%	43%	43%
ACS (Override)	%			
C&DH (Override)	%			
Instruments (Override)	%			
Other Elements (Override)	%			
Propulsion System 1 (Override)	%			
Propulsion System 2 (Override)	%			
Propulsion System 3 (Override)	%			
Structures (Override)	%			
Telecomm (Override)	%			
Thermal (Override)	%			
Power Subsystem (Override)	%			
Subsysem Contingency	W	**112.5**	**147.0**	**157.9**
ACS	W	9.5	9.5	9.5
C&DH	W	17.0	17.0	17.0
Instruments	W			
Other Elements	W			
Propulsion System 1	W	10.6	0.3	10.6
Propulsion System 2	W			
Propulsion System 3	W			
Structures	W			
Telecomm	W	17.4	17.4	17.4
Thermal	W	49.2	92.2	92.2
Power Subsystem	W	8.9	10.7	11.3
Subsystems with Contingency		**374.2**	**488.9**	**525.2**
Systems with Contingency		367.5	474.5	510.5
Duration (published by Systems, **hours**)		1.0	24.0	1.0

- **Launch is battery sizing mode and cruise is the solar array sizing model.**

Design – Option 1 Science craft – Array

- **Cylindrically mounted solar array**
  - Non spinning
    - High operating temperature > 90^{o}C (array rear side view is into spacecraft)
  - Packing factor is customer effective area on projected area, then PF = 0.85
  - Total array area is 2x projected area
  - 10 degree off pointing angle due to radial cell layout
  - 8% total degradation from BOL to EOL
    - 2% UV, 6% radiation



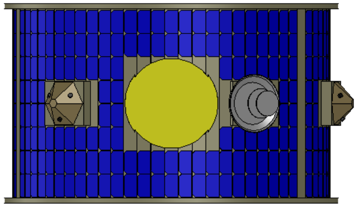
(Projected area)

- **Sizing mode is science in eclipse mode**
  - Assume battery recharge can be achieved in greater than 10 days

Power

Design – Option 2 Science craft – Array

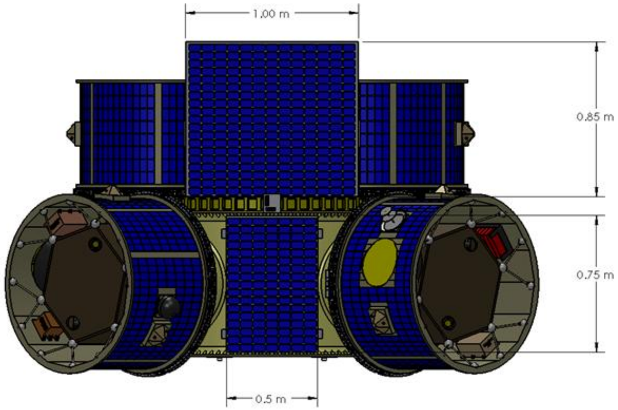
- **Cylindrically mounted solar array**
  - Non spinning
    - High operating temperature > 90^{o}C
  - Packing factor is customer effective area on projected area, then PF = 0.80
  - Total array area is 2x projected area
  - 20 degree off pointing angle due to radial cell layout
  - 8% total degradation from BOL to EOL
    - 2% UV, 6% radiation
- **Sizing mode is science in eclipse mode**
  - Assume battery recharge can be achieved in approximately 1 week



(Projected area)

Design – Option 2 Carrier craft– Array

- **Cylindrically mounted solar array**
  - Non spinning
    - High operating temperature > 90°C
  - Packing factor = 0.85
  - 0 degree off pointing angle
  - 6% total degradation from BOL to EOL
    - 2% UV, 4% radiation
- **Sizing mode is cruise mode**
- **SA design identical for both option 1 & 2:**



Design – Option 1 Science craft - Batteries

Li-Ion secondary battery

- Sized to science in eclipse case
  - Assume >50% DOD
    - Few per year
- Will also use during science with telecom power mode at low DOD
  - 2 hour duration
  - ~ Once per week
  - Eliminates need for larger array
- ABSL small cells, 60A-hr nameplate

Flight Batteries	
Chemistry	Li-ION
Capacity (A-Hr)	30
Cells / Battery	8
Prime Flight Batteries	2
Redundant Flight Batteries	
Total Flight Batteries	2

Flight Battery Capabilities

	Cell	Single Battery	Flight Batteries Prime	Flight Batteries Redundant	Flight Batteries Total
		1	2	0	2
Voltage (V)	3.60	28.80			
Rated Energy (W-Hr)		864.00	1,728.00	-	1,728.00
Mass (Kg)		7.88	15.76	-	15.76
Volume (Liters)		5.40	10.80	-	10.80
Depth of Discharge -User Def Launch			0%	0%	0%
Depth of Discharge - Array Sizing			58%	0%	0%
Depth of Discharge - Max Custom Case			56%	0%	56%

Power
Design – Option 2 Science craft- Batteries

- **Li-Ion secondary battery**
  - Sized to science in eclipse case
    - Assume >50% DOD
      - Few per year
  - Will also use during science with telecom power mode at low DOD
    - 2 hour duration
    - ~ Once per week
    - Eliminates need for larger array
  - ABSL small cells, 60A-hr nameplate

Flight Batteries	
Chemistry	Li-ION
Capacity (A-Hr)	26
Cells / Battery	8
Prime Flight Batteries	2
Redundant Flight Batteries	
Total Flight Batteries	2

Flight Battery Capabilities

	Cell	Single Battery	Flight Batteries		
			Prime	Redundant	Total
		1	2	0	2
Voltage (V)	3.60	28.80			
Rated Energy (W-Hr)		748.80	1,497.60	-	1,497.60
Mass (Kg)		6.90	13.81	-	13.81
Volume (Liters)		4.68	9.36	-	9.36
Depth of Discharge -User Def Launch			0%	0%	0%
Depth of Discharge - Array Sizing			56%	0%	0%
Depth of Discharge - Max Custom Case			54%	0%	54%

Design – Option 1, 2 Carrier craft - Batteries

- **Li-Ion secondary battery**
  - Sized to launch case
    - Assume ~40% DOD
  - ABSL small cells, 30A-hr nameplate

Flight Batteries	
Chemistry	Li-ION
Capacity (A-Hr)	30
Cells / Battery	8
Prime Flight Batteries	1
Redundant Flight Batteries	
Total Flight Batteries	1

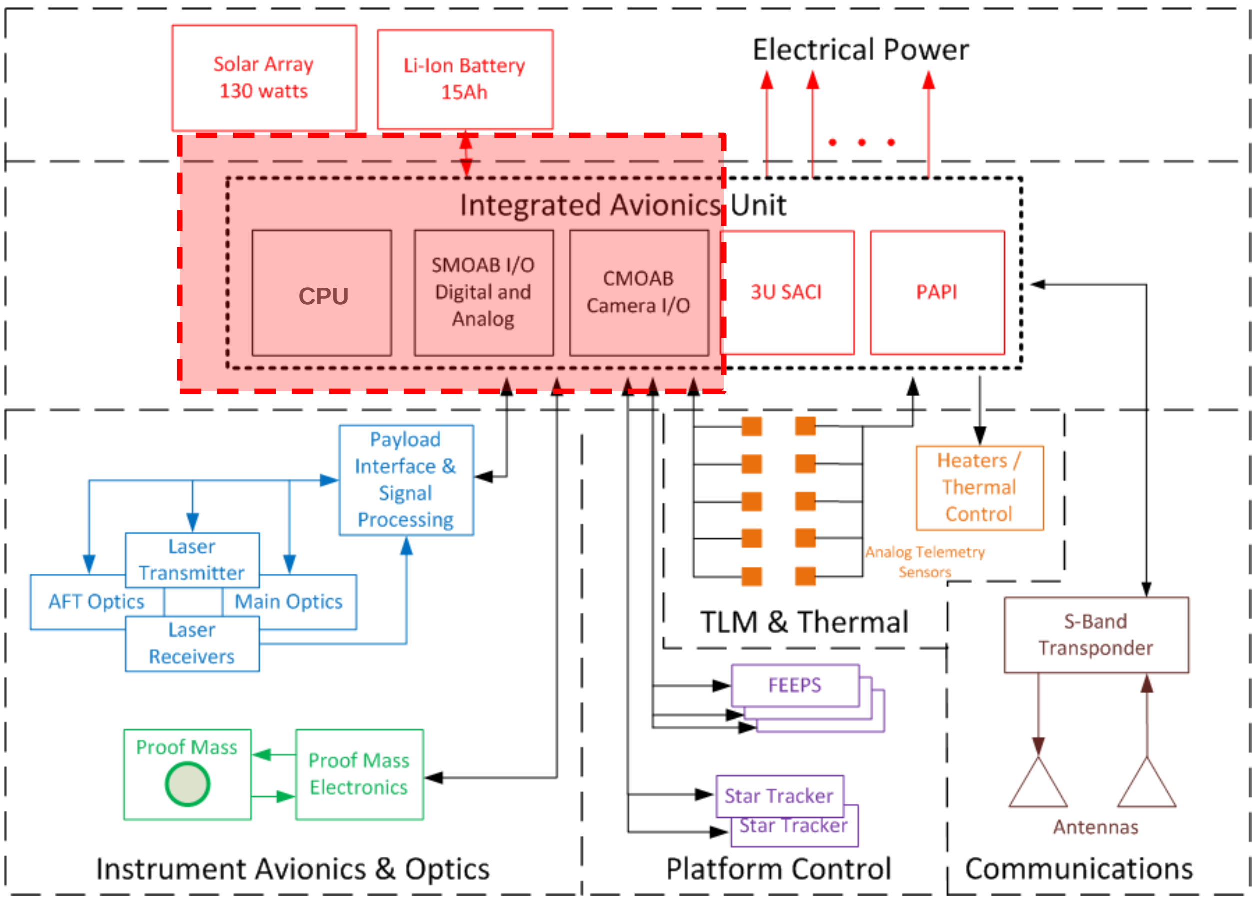
Flight Battery Capabilities					
		Single Battery	Flight Batteries		
			Prime	Redundant	Total
	Cell	1	1	0	1
Voltage (V)	3.60	28.80			
Rated Energy (W-Hr)		864.00	864.00	-	864.00
Mass (Kg)		7.88	7.88	-	7.88
Volume (Liters)		5.40	5.40	-	5.40
Depth of Discharge -User Def Launch			0%	0%	0%
Depth of Discharge - Array Sizing			0%	0%	0%
Depth of Discharge - Max Custom Case			43%	0%	43%

Design – Option 1, 2 – Science/Carrier Electronics

- **SACI and PAPI BRE cards for solar array and propulsion interface electronics.**
  - These BRE cards are accounted by CD&H subsystem.
- **Only house-keeping electronics cards are added to support power subsystem.**
  - No need for propulsion and solar array interface cards.
  - Only 2 spares for all 6 science craft.
  - Full spares for carrier craft.

Design – Option 1, 2 – Science/Carrier Electronics

- **Power block diagram for both science and carrier craft**
  - SACI and PAPI cards are carried by CD&H subsystem



Cost Assumptions – Option 1, 2 Science craft

- **Carriercraft design is based on mission class "C" with moderate to low complexity.**

Cost Assumptions – Option 1, 2 Carrier craft

- **Carriercraft design is based on mission class “B” with moderate to low complexity.**

Cost – Option all options

- **See Cost Summary in the Cost Section.**

- **Cost Drivers**
  - 4 hour eclipse during primary on-station primary mission operations.

- **Potential Cost Savings**
  - None.

- **Potential Cost Uppers**
  - Increasing projected solar array area to for science craft beyond 1m^2.

Risk

- **List of Risks**
  - Battery DoD during science + eclipse power mode is higher than nominal at 60%. If battery degraded severely, limited power margin will be available.
    - Low risk for primary mission, but may significantly impact extended missions.
  - For Option 1 of science craft, SA power output is based on rough estimate of required projected cell area from circular geometry using packing factor = 0.85 and 10^{o} cosine angle in order to maintain total solar array area < 1m^2. Actual power output from SA may not meet power requirements during science + eclipse mode.

Power
Additional Comments

- **The 4 hour eclipse during on-station primary science operations has a substantial impact on battery sizing and mass. The science craft battery sizing goes down to minimum 15-20Ahr nameplate as appose to 60Ahr nameplate design with the eclipse.**
  - Without eclipse, the mass savings of the battery is more than 10 kg alone.
- **Solar array stringing shall be from top to bottom of cylindrical science craft to keep all cells at approximately same generated current. Stringing along cylinder circumference will have lower current cells combining with higher current cells. String current will be limited by lowest cells.**

Propulsion Report

(1281) Omega Study
Date 4/10/2012

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Table of Contents

Propulsion
Design Requirements

- **Mission:**
  - Gravity wave determination from changes to location of 6 science spacecraft (probes) in a geocentric orbit of 600,000 km near the eliptic
- **Mission Design**
  - Delta-v of 454 m/s for cruise to final 600,000 km radius geocentric near-ecliptic orbit
    - Propulsion system to deliver probes to station
    - 2 probes released , transit to new station, 2 probes released, transit to new station
- **ACS**
  - Moog system used for ACS for transit to final science orbits
  - Micro delta-v for station keeping using FEEPs once at science orbits
- **Configuration**
  - Science orbit requires extremely low spacecraft jitter, so a typical hydrazine system with propellant slosh is not an option

Propulsion
Design Assumptions

- Assume any style propulsion system for the cruise stage that lowers cost and meets the requirements while still fitting within the launch vehicle capability
- Assume an indium FEEP propulsion system at TRL-6 for each probe to meet the ACS and station keeping requirements

Propulsion
Design Option 2

- **Hardware**
  - 6 ea Science Spacecraft using indium FEEP propulsion system
    - 3 FEEPs per cluster, 1.95 kg CBE per cluster including 30% contingency
    - 3 clusters per science craft, 5.9 kg CBE per sciencecraft including 30% contingency
  - Propulsion Stage 1 is a simple blowdown Hydrazine monopropellant system, 550.5 kg CBE including 30% contingency
    - Four each special development Titanium diaphragm tanks
    - Four 5N primary thrust engines
    - Eight 1N ACS engines

- **Functionality**
  - Science spacecraft FEEP propulsion system provides low jitter station keeping and attitude control for mission duration
  - Propulsion Stage 1 provides delta-v required to get to science orbits and ACS for cruise to science orbits

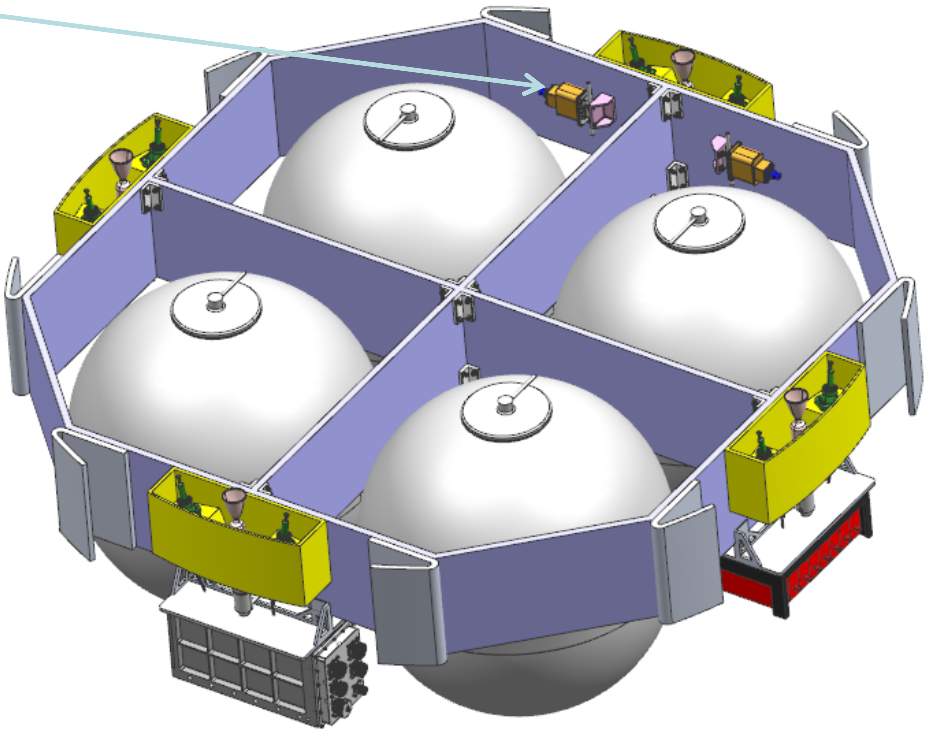
Carrier Thrusters and Tanks

<u>Bottom View</u>

- Tanks require new development
- Thrusters in production over 40 years, flown numerous times

Torque Motor Isolation Valves

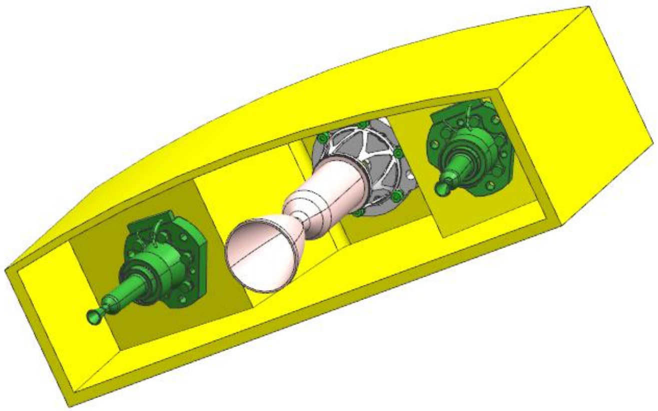
Not Shown:
Pressure Transducers
Plumbing
Harnesses
Mounting Hardware
Thruster Shields
etc…

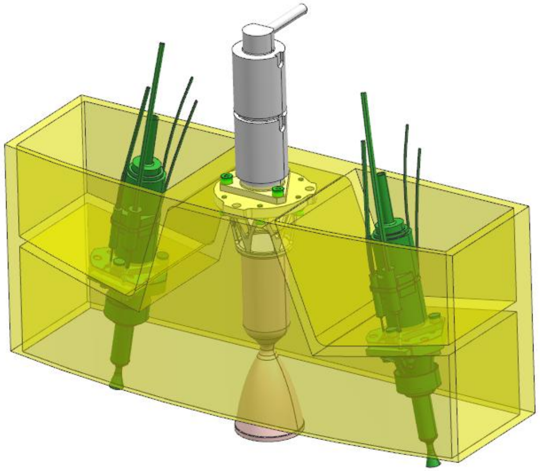


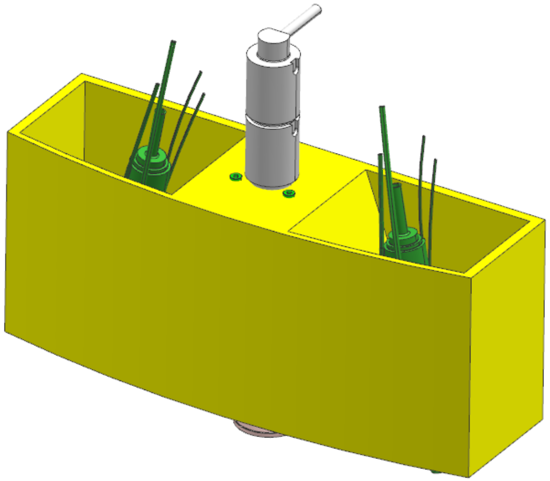
Carrier Propulsion

Rocket Engine Module (REM)

- 1N Thrusters (qty 2 per side)
- 5N Thruster



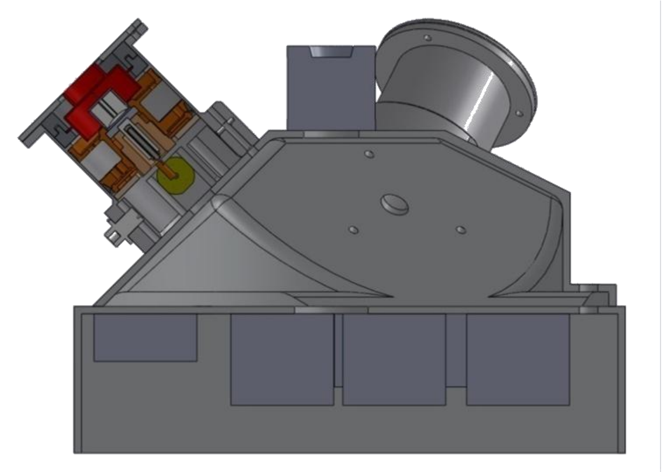




Propulsion
Design – FEEP Clusters

- Tantalum-capillary 3 µN average thrust emitters
- TRL 6 design with established manufacturing process
- COTS highly miniaturized electronics – MILSTAR approved
- TRL8 Carbon Nanotube Neutralizer
- 3 Thrusters and 1 Neutralizer per Cluster
- FEEPs require modifications and life tests to reach TRL-8
    - Structural and electrical modifications
    - Only 1,300 hours operating life tested to date

Parameter	OMEGA-FEEP with Electronics
Cluster-Volume	165x165x120 mm
Cluster-Mass	1.5 kg



Design – Propulsion Stage 1 Option 2

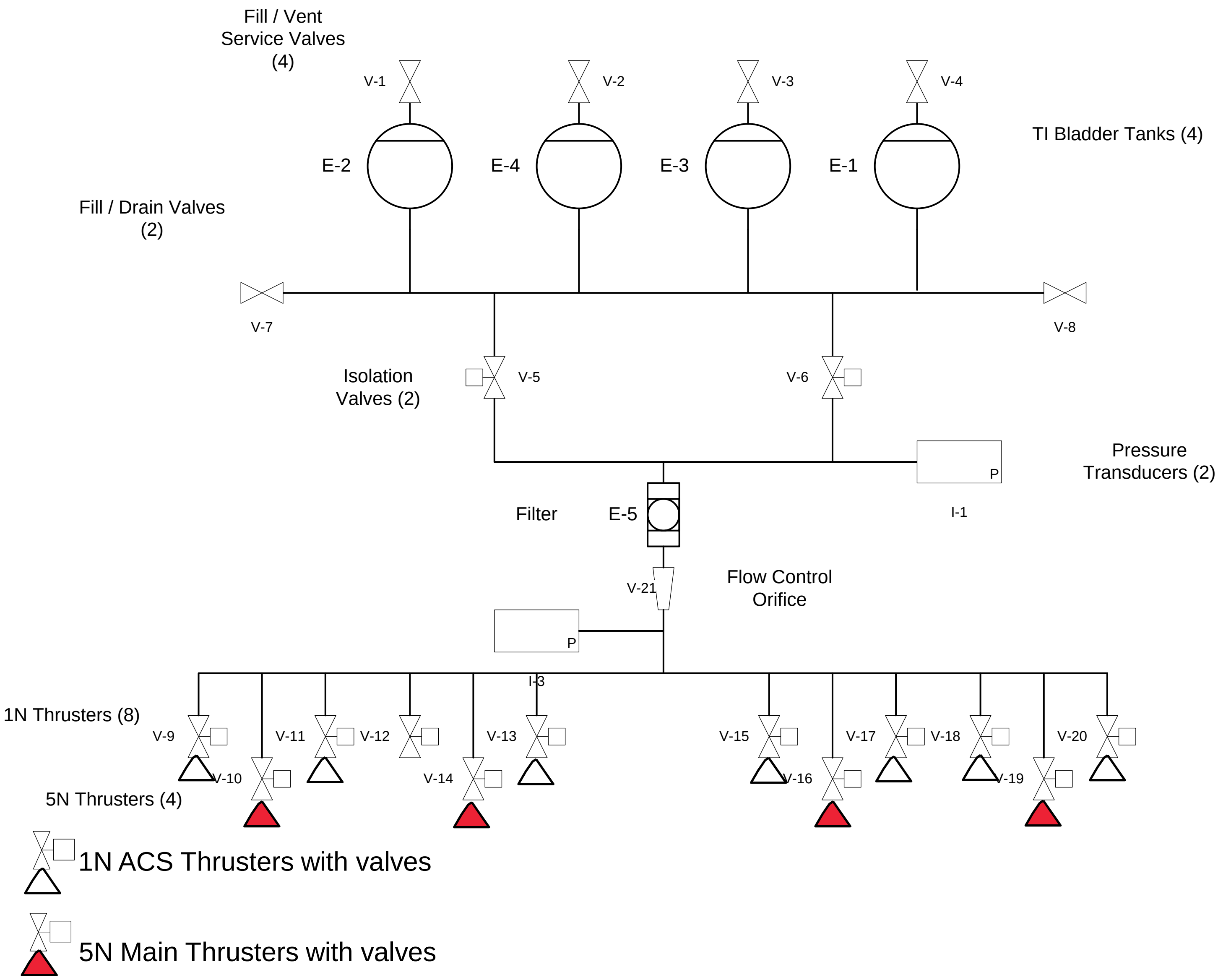
Propellant

- Hydrazine: 465 kg for Prop Stage 1
- 454 m/s delta-v for 2195 kg final mass for Prop Stage 1

Propulsion Stage 1 Delta-V

Mission Description	Maneuver Type		ADD, JET, ACS, or SEP	Delta V	Impulse	Engine Selection			
Event Name, Description	Assign Propellant To System:	Event Type	Mass (kg)	Delta V (m/s)	Impulse (N-sec)	Use engines on System #:	Pointing offset (deg)	Specific Engine from equipment list	# of Engines Firing
Trans-orbit TCMs	1	DV		20		1		Monoprop Main Engine	4
600k km orbit insertion	1	DV		186		1		Monoprop Main Engine	4
Release 2 probes	1	DV		0		1		Monoprop Main Engine	4
Reduce Periapsis	1	DV		61		1		Monoprop Main Engine	4
Circularize	1	DV		61		1		Monoprop Main Engine	4
Release 2 probes	1	DV		0		1		Monoprop Main Engine	4
Reduce Periapsis	1	DV		61		1		Monoprop Main Engine	4
Circularize	1	DV		61		1		Monoprop Main Engine	4
Release 2 probes	1	DV		0		1		Monoprop Main Engine	4
Small DVs to dispose	1	DV		4		1		Monoprop Main Engine	4
ACS	1	ACS	5			1		Monoprop Thrusters 1	2

Block Diagram – Propulsion Stage 1 Option 2



Cost Assumptions – Option 2

- In-FEEP 3-engine cluster, 3 clusters each for the Science spacecraft propulsion system
- Cost reduction is a design driver
- Spares for each component per standard practice
- Workforce adjusted for shortened phase C/D duration

Cost

Cost Drivers

- Shortened phase duration C/D drives costs lower
- Indium FEEPs not sufficiently developed to TRL-8 drives cost up

Potential Cost Savings

- Utilization of off-the-shelf propellant tanks save cost if tanks can be found to fit within the volume constraints

Potential Cost Uppers

- Delta-qualification of the FEEP thruster for increased mission life and propellant through-put along with structure/electronics modifications adds cost, and if problems arise during development to TRL-8 costs can increase more than baselined for this study, especially due to the accelerated schedule
- Custom design propellant tank fits within the Carrier but adds cost

Risk

- Delta-qualification of the FEEP thruster for increased mission life and propellant through-put on Science spacecraft 2 will add moderate risk
- Modifications to FEEP structure and electronics adds minimal additional risk
- For the propulsion stage risk is low when using flight proven components
    - Assumption is the four each carrier hydrazine tanks that have to be designed and developed is minimal risk

Propulsion Element Comparison

- Mass, cost, and count is per spacecraft

Element	Mass (kg)	Cost ($M)	Thrusters	Tank Size (m)	Propellant mass (kg)	Comments
Carrier Prop Stage	550.5 CBE incl. 3% contingency	$14.4M	4 – 5N main 8- 1N TVC	0.55 dia x 0.79 long 4 ea	N2H4: 464.9	
Indium FEEP system	TBD	$12.0M	3 Thrusters per cluster, 3 clusters per spacecraft	Included within dimensions defined for the FEEPs	TBD	

Propulsion
Additional Comments

- Continued micro-thruster development is required both for the thruster and system to account for longer lifetime requirements and fuel capacity required over existing hardware. This includes modifications to the structure and electronics, and most importantly to FEEP lifetime, which currently has been demonstrated to 1,300 hours compared to an Omega mission requirement of about 26,000 hours.
- There is large uncertainty in the ability of the current FEEP thruster design to match performance and environmental requirements for the OMEGA mission. Micro-thruster cost appears to have been severely underbid. To reduce uncertainties, a joint development program with the vendor FOTEC is proposed. This program should address thruster performance characterization and leverage ST-7 experiences, including stability and lifetime testing, PPU/DCIU redesign and characterization, thruster cluster mechanical and thermal design, and micro-thruster system integration with spacecraft systems (C&DH, avionics, software and thermal). Given the criticality of this thruster design to the mission, only a complete understanding of this technology and its' delivered performances and risk can ensure mission success, requiring detailed contract monitoring, including either witnessing or actually performing critical thruster and PPU tests. ST-7 thruster technology may be considered as a back-up option.

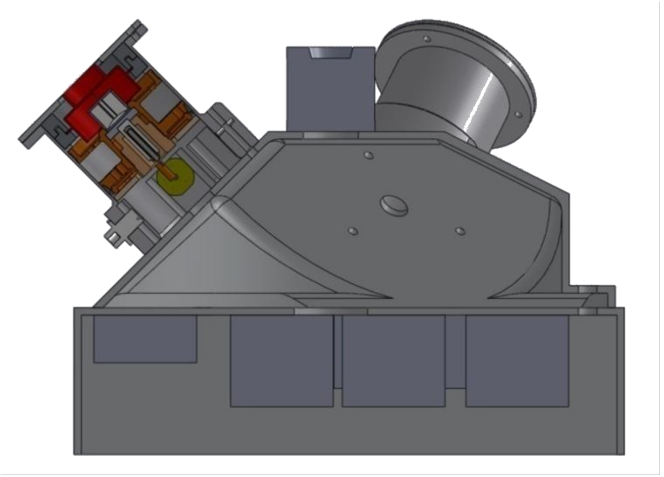
Propulsion
Additional Comments

- **Based on this information, the following approach is recommended:**
  - Total FEEP operating time requirement is about 25 times the demonstrated operating time for the FEEPs. Recommend considering the colloidal thrust system or the Italian FEEPs on ST7
  - Perform life testing as soon as possible, at least beginning at the start of Phase B, to mitigate lifetime concerns and discovery of “unknown unknowns”
  - Other FEEP risks include the fact that substantial modifications to the FEEPs have been made:
    - Switched to Ta capillary emitters
    - Reservoir material changed to Ta
    - Assumption is that emitter hermetic sealing is no longer required, and is based on a 12-month storage test of 6 emitters with the result that “In ALMOST all cases the operating voltage was unchanged…”; the amount of testing seems insufficient to assume that long-term FEEP operation is unchanged due to air exposure
    - New emitter thermal isolation material
    - New emitter-extraction electrode distance
    - New plume shields
    - New PPU electronics

FEEP Thruster Clusters

- Tantalum-capillary 3 μN average thrust emitters
- TRL 8 MMS design with established manufacturing process
- COTS highly miniaturized electronics – MILSTAR approved
- TRL8 Carbon Nanotube Neutralizer
- 3 Thrusters and 1 Neutralizer per Cluster

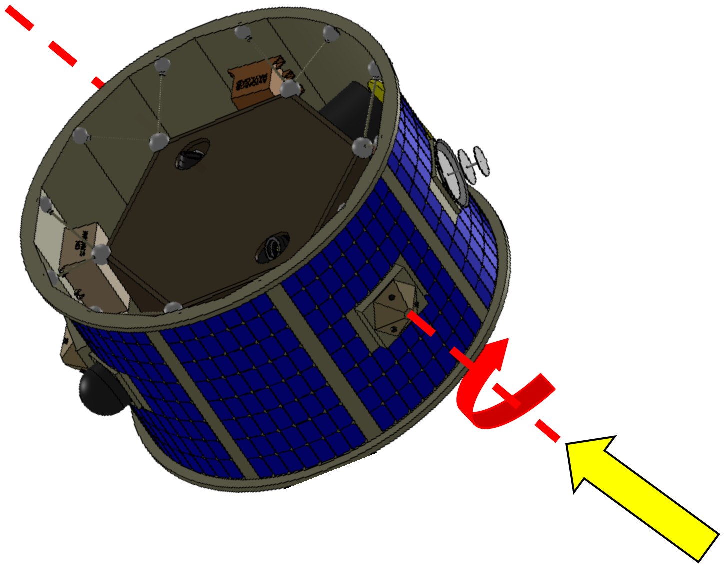
Parameter	OMEGA-FEEP with Electronics
Cluster-Volume	165x165x120 mm
Cluster-Mass	1.5 kg



Microprobe Deployment

- Post ejection reorientation
  - Assumes no array input until orthogonal to ecliptic plane
  - Sufficient energy in battery
- Other separation factors
  - Maximum tip-off rotation rates resulting from
    - Microprobe COM position
    - Separation system imbalances
    - Carrier residual rotation rates
  - System performance requirements will ensure controllable tip-off rate

Parameter	Value
Total MOI (platform/instrument)	<16.99kgm^2
FEEP max thrust	10μN
Thruster lever arm	0.5m
Time for 90° turn	77min
Battery DOD	21%



Mechanical Report

(1281) Omega 2012-04
April 3-5, 2012

Author: Chris Landry

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Phone: 818-354-3180

Table of Contents

Mechanical
Design Requirements

- **Mission:**
  - Earth Orbiting
  - Six (6) deployable spacecraft (Sciencecraft) with one (1) carrier/dispenser (Propulsion Module)
- **Launch Vehicle: NLS II Contract**
- **Stabilization: 3-Axis**
- **Payload:**
  - Instrument on the Sciencecraft
- **Option 1**
  - Instrument mass = 64.3 kg
- **Option 2**
  - Instrument mass = 55.0 kg

Design Assumptions

- **Customer brought their own design with mass list.**
  - The customer masses were not input directly. This was a design study where the design concept was retained.

- **Separation system for each of the Sciencecraft is book kept (mass and cost) entirely on the Propulsion Module. It is not split between the two elements.**

Mechanical
Design – Sciencecraft

- **Design**
  - Bus is a cylindrical shell with the Solar Arrays fixed to the outside. Electronics boxes are mounted on the inside of the shell. A series of struts attached to the inside of the shell support the instrument. The instrument is mounted in a hexagonal structure. The separation from the Propulsion Module is at one end of the cylinder.
  - Total Solar Array area is 2.0 m^2 for both options.
- The customer provided CAD model has the primary structure weighing over 200 lbs based on the volume. Most likely this was just a representation. An appropriate structure would be a thin aluminum ribbed structure or a honeycomb cylindrical structure.

- **Mechanisms and Deployments**
  - The Sciencecraft does not have any deployables or mechanisms outside of the instrument.

Mechanical
Design – Propulsion Module

Design

- The Propulsion Module is a cylindrical structure with four Sciencecraft mounted radially on the outer cylinder wall and two mounted on the top deck. The general design of the cylindrical structure is an ESPA ring.
- Total Solar Array area for Option 1 is 2.1 m^2 and for Option 2 is 2.2 m^2. The Solar Array is mounted to a fixed panel and the panel is mounted to the top deck.

Mechanisms and Deployments

- The Propulsion Module has six (6) lightband separation systems, one for each Sciencecraft.

Mechanical
Mass – Sciencecraft Option 1

- **Detailed Mass List**
  - Total Mechanical Mass = 29.2 kg CBE
  - Total Cabling Mass = 8.0 kg CBE

Mass – Propulsion Module Option 1

Detailed Mass List

- Total Mechanical Mass = 254.1 kg CBE
- Total Cabling Mass = 21.7 kg CBE

Mass – Sciencecraft Option 2

Detailed Mass List

- Total Mechanical Mass = 26.1 kg CBE
- Total Cabling Mass = 7.4 kg CBE

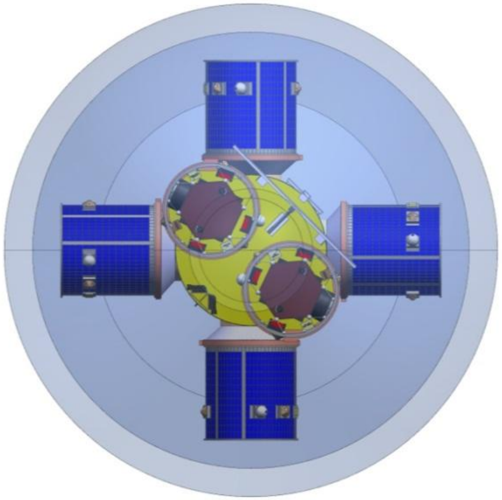
Mass – Propulsion Module Option 2

Detailed Mass List

- Total Mechanical Mass = 242.0 kg CBE
- Total Cabling Mass = 20.7 kg CBE

Configuration Drawings – Stowed

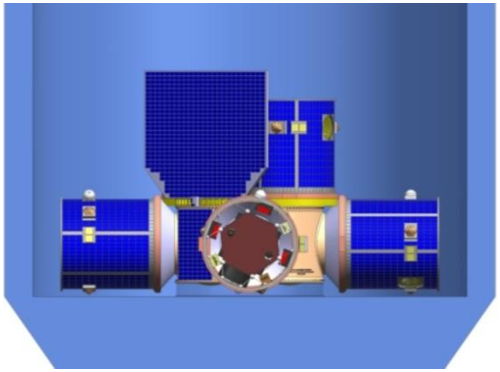
- Options 1 and 2 have very similar configuration.



Top View of Spacecraft in Fairing

Full Spacecraft in Fairing

Iso View in Fairing

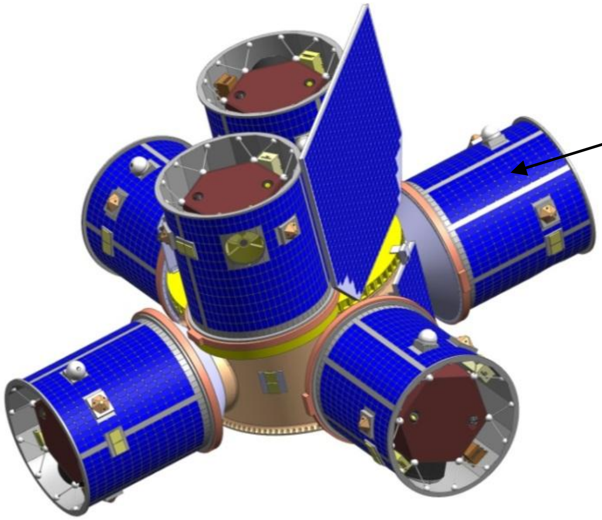


Closer View of Spacecraft in Fairing

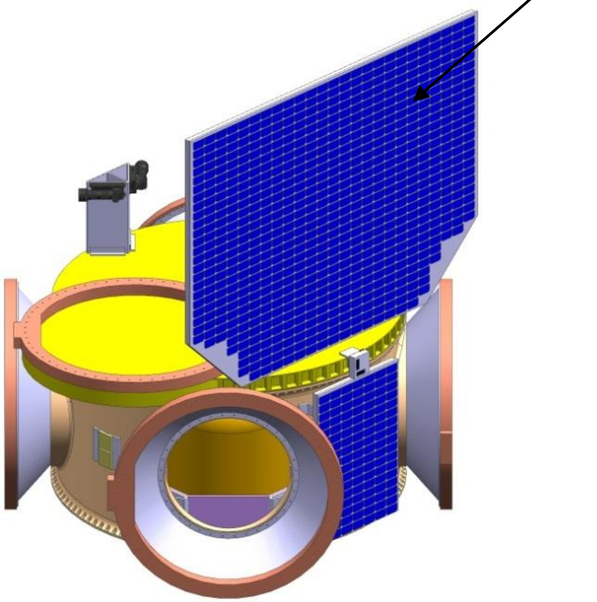
Configuration – Spacecraft

Configuration Drawings – Deployed

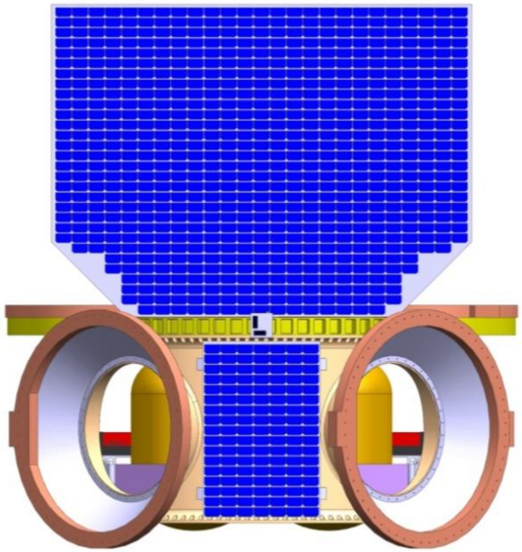
- Options 1 and 2 have very similar configuration.



Spacecraft in Flying Configuration



Propulsion Module with Sciencecraft Deployed

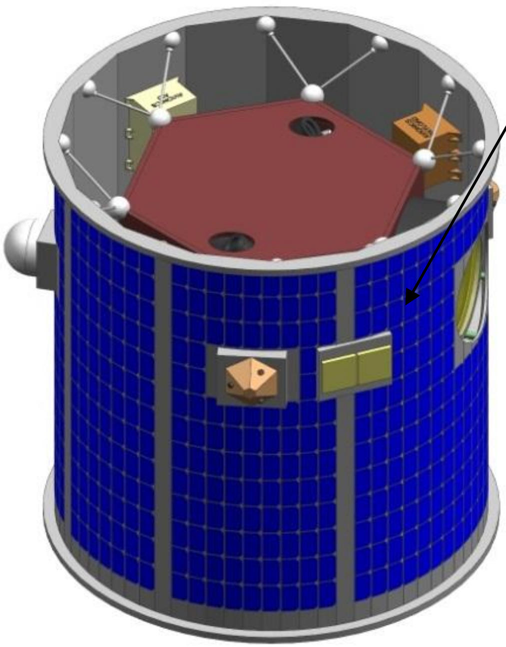


Side View of Propulsion Module

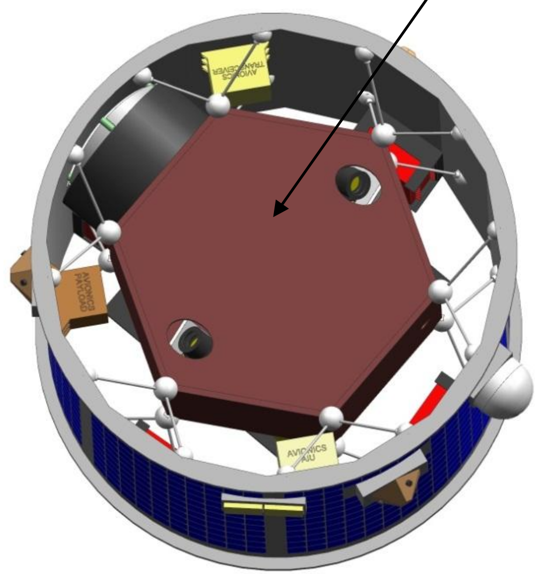
- **Configuration Drawings – Stowed/Deployed**
  - Options 1 and 2 have very similar configuration.

Fixed Solar Panel

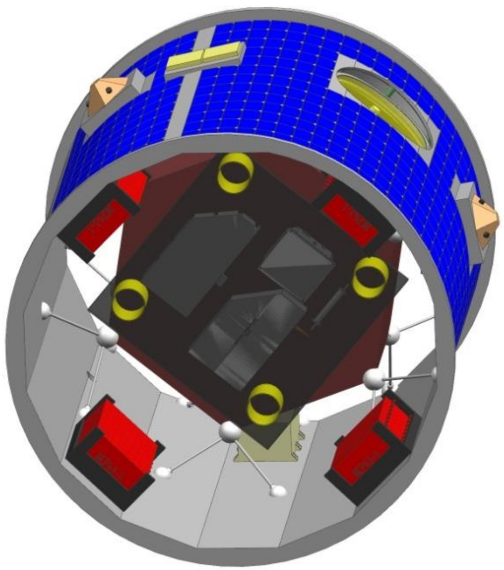
Instrument



Sciencecraft in Flight Configuration



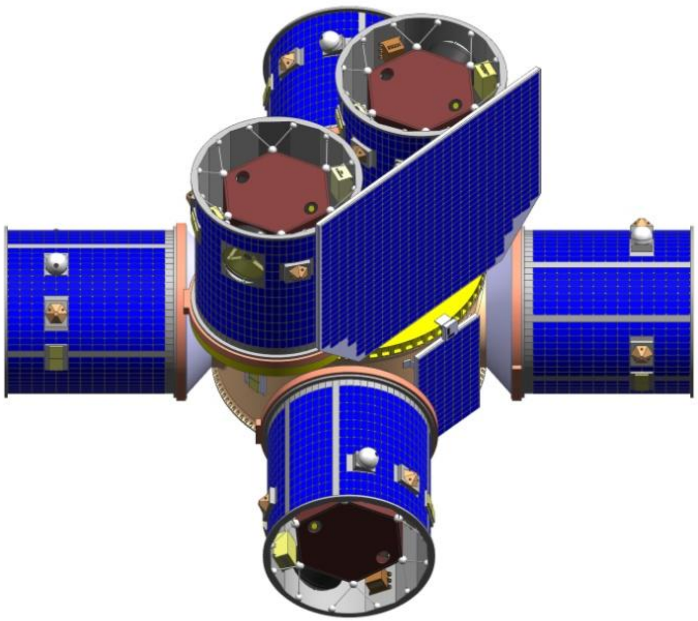
Top of Sciencecraft



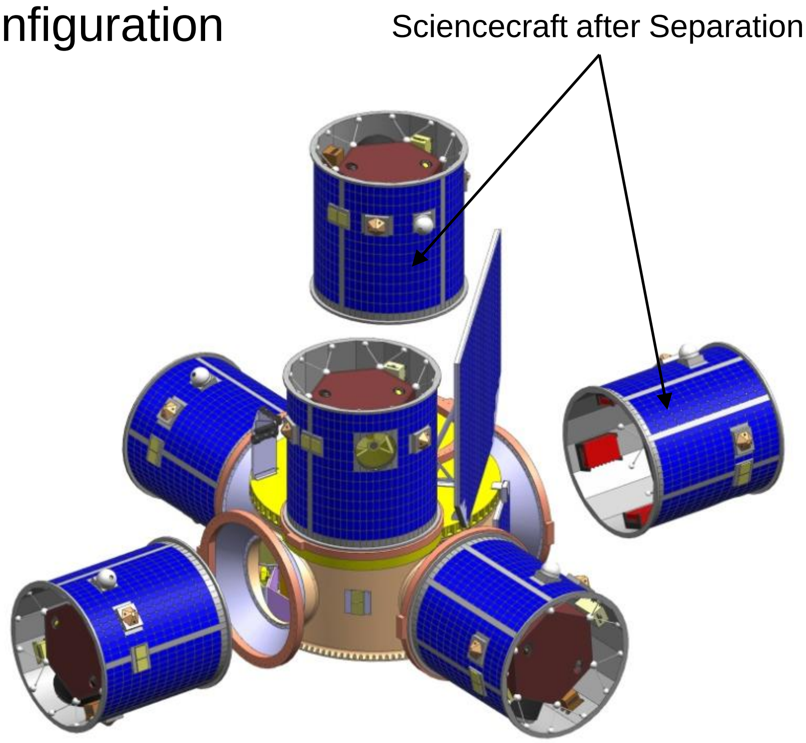
Bottom of Sciencecraft

Configuration Drawings – Stowed

- Options 1 and 2 have very similar configuration



Propulsion Module before Sciencecraft Separation



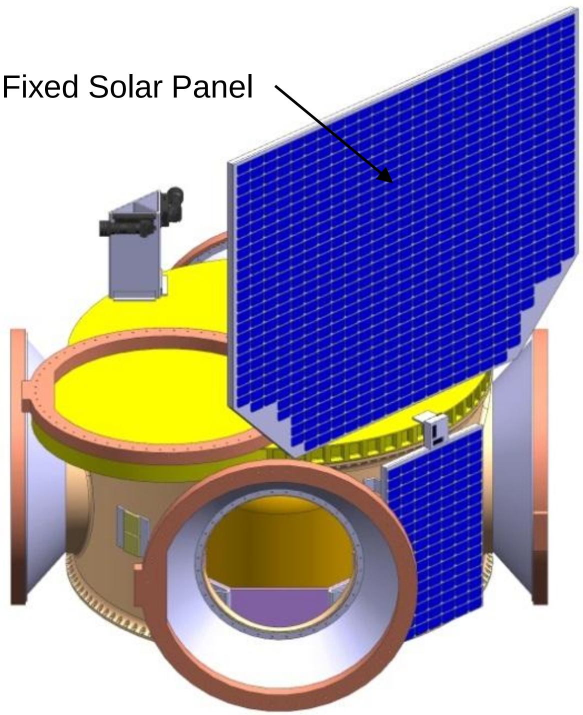
Propulsion Module showing Sciencecraft Separation

Mechanical
Configuration – Propulsion Module

Configuration Drawings – Deployed

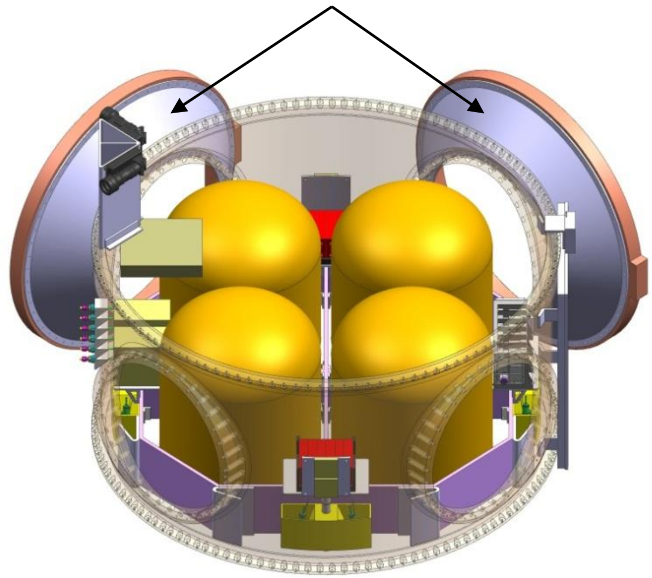
- Options 1 and 2 have very similar configuration

Fixed Solar Panel



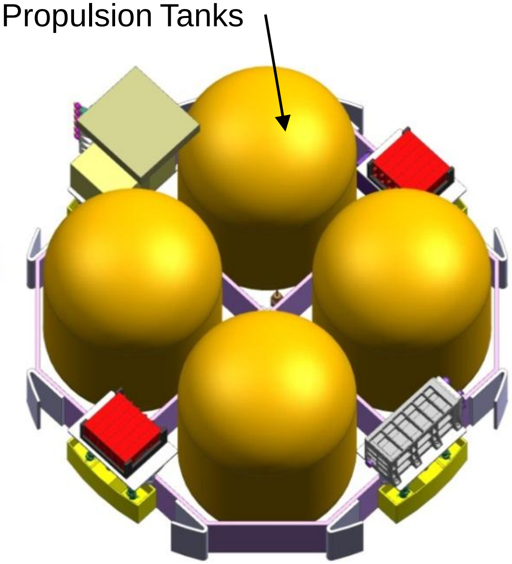
Propulsion Module after all Sciencecraft Separations

Sciencecraft Separation Cone



View Inside of Propulsion Module

Propulsion Tanks



Inside of Propulsion Module

Mechanical
Cost Assumptions

- Mechanical Systems Engineering costs are included in the Sciencecraft.
- Contamination Control for the entire mission is included in the Sciencecraft.
- Cost for the lightband in entirely included in the Propulsion Module and not split between the two elements.

Cost – Sciencecraft Option 1

Cost Summary by Hardware Element

- Mechanical (Including I & T): $17.60M
- Cabling: $2.48M
- Materials & Processes: $0.62M
- Contamination Control: $1.08M

Cost – Propulsion Module Option 1

Cost Summary by Hardware Element

- Mechanical (Including I & T): $14.59M
- Cabling: $3.01M
- Materials & Processes: $0.73M
- Contamination Control: $0.00M

Cost – Sciencecraft Option 2

Cost Summary by Hardware Element

- Mechanical (Including I & T): $15.16M
- Cabling: $1.83M
- Materials & Processes: $0.62M
- Contamination Control: $0.88M

Cost – Propulsion Module Option 2

Cost Summary by Hardware Element

- Mechanical (Including I & T): $14.42M
- Cabling: $2.17M
- Materials & Processes: $0.73M
- Contamination Control: $0.00M

Mechanical

Cost – Comments

- **Cost Drivers**
  - The major cost driver is the spacecraft structure. Aside from the separation systems, there are no mechanisms on the spacecraft.

- **Potential Cost Savings**
  - The only method of saving cost is to design a “cheap” structure. This would most likely be a basic metallic structure that uses well known manufacturing procedures and does not require much testing.
  - Using separation nuts instead of Lightbands mat reduce cost. This is a less expensive separation system and there are six needed for this mission.

- **Potential Cost Uppers**
  - A complicated structure made from composite may cost more as manufacturing processes can be more expensive. Composite structures require more testing mostly for workmanship. This additional testing would be a cost upper.

Risk

- **Sciencecraft on Top needs to clear Propulsion Module Solar Array**
  - During separation from the Propulsion Module the Sciencecraft on the top may hit the Propulsion Module Solar Panel.
  - Verify through analysis and design that the separation will not impact the Solar Panel.

Option Comparison

- **The only difference between the two options is the mass and power of the instrument.**
  - The numbers in the mass and cost column represent the Sciencecraft and Propulsion Module

Option	Mass (kg)	Cost ($M)	Configuration	Comments
1	29.2 kg 254.1 kg	$17.60M $14.59M	Six Sciencecraft mounted on a propulsion Module	Instrument Mass = 64.3 kg
2	26.1 kg 242.0 kg	$15.16M $14.42M	Six Sciencecraft mounted on a propulsion Module	Instrument Mass = 55.0 kg

Configuration Report

(1281) Omega 2012-04
April 3-5, 2012

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Table of Contents

Design Requirements and Assumptions

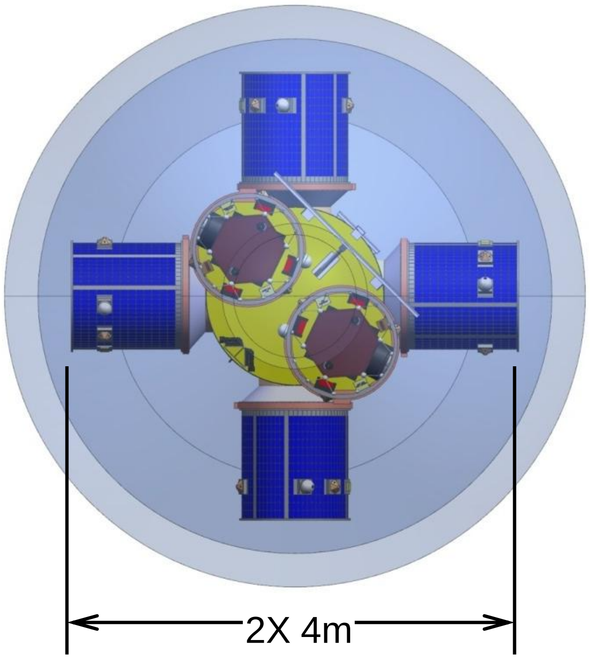
Requirements

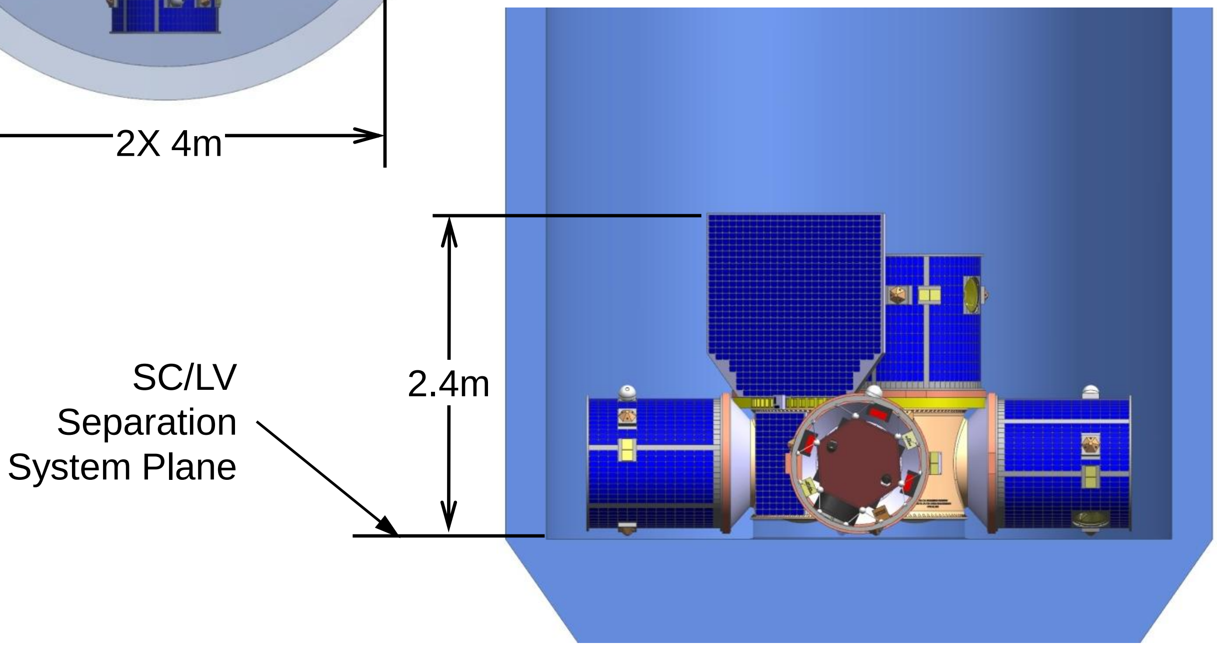
- Microprobe accommodates 1 instrument. Carrier accommodates 6 microprobes at launch for insertion of microprobes into High Earth Orbit.
- Launch Vehicle: NLS II Contract
- Payload:
  - OMEGA Instrument

Assumptions

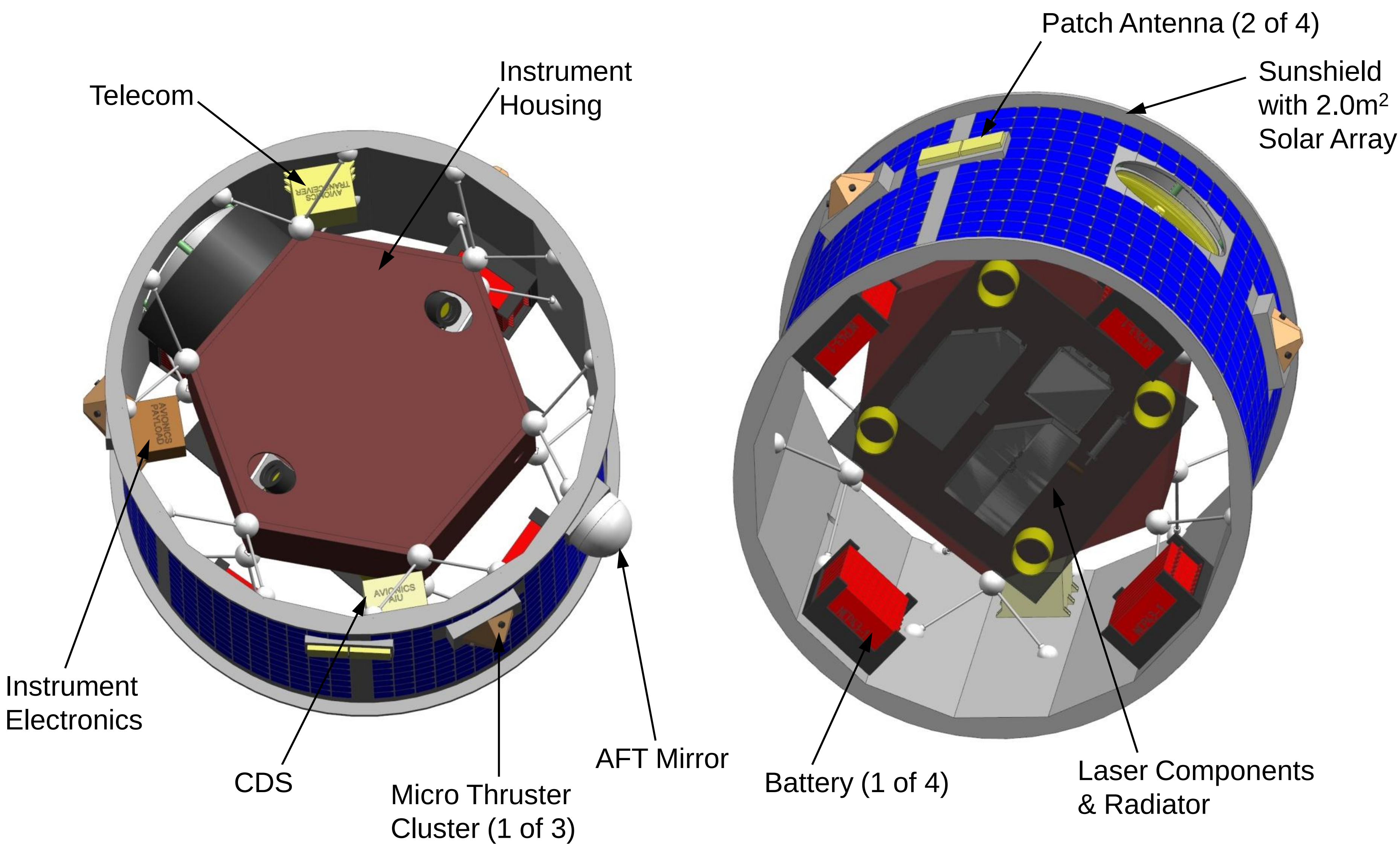
- Customer-provided configuration files are complete.
- Option 2 instrument volume identical to Option 1.

Design Configuration Stowed – Option 1 & 2



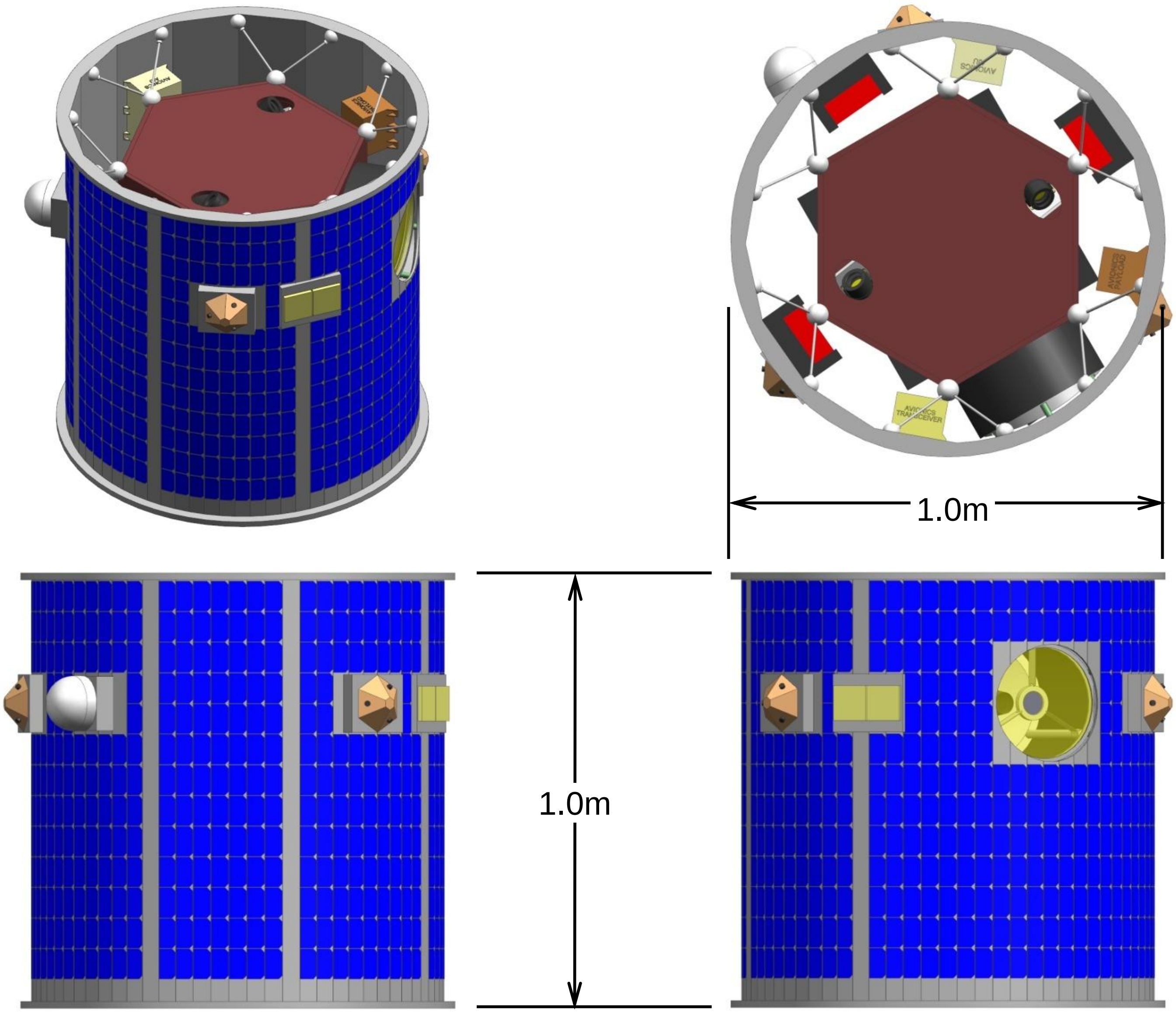


Design Configuration Sciencecraft – Option 1 & 2

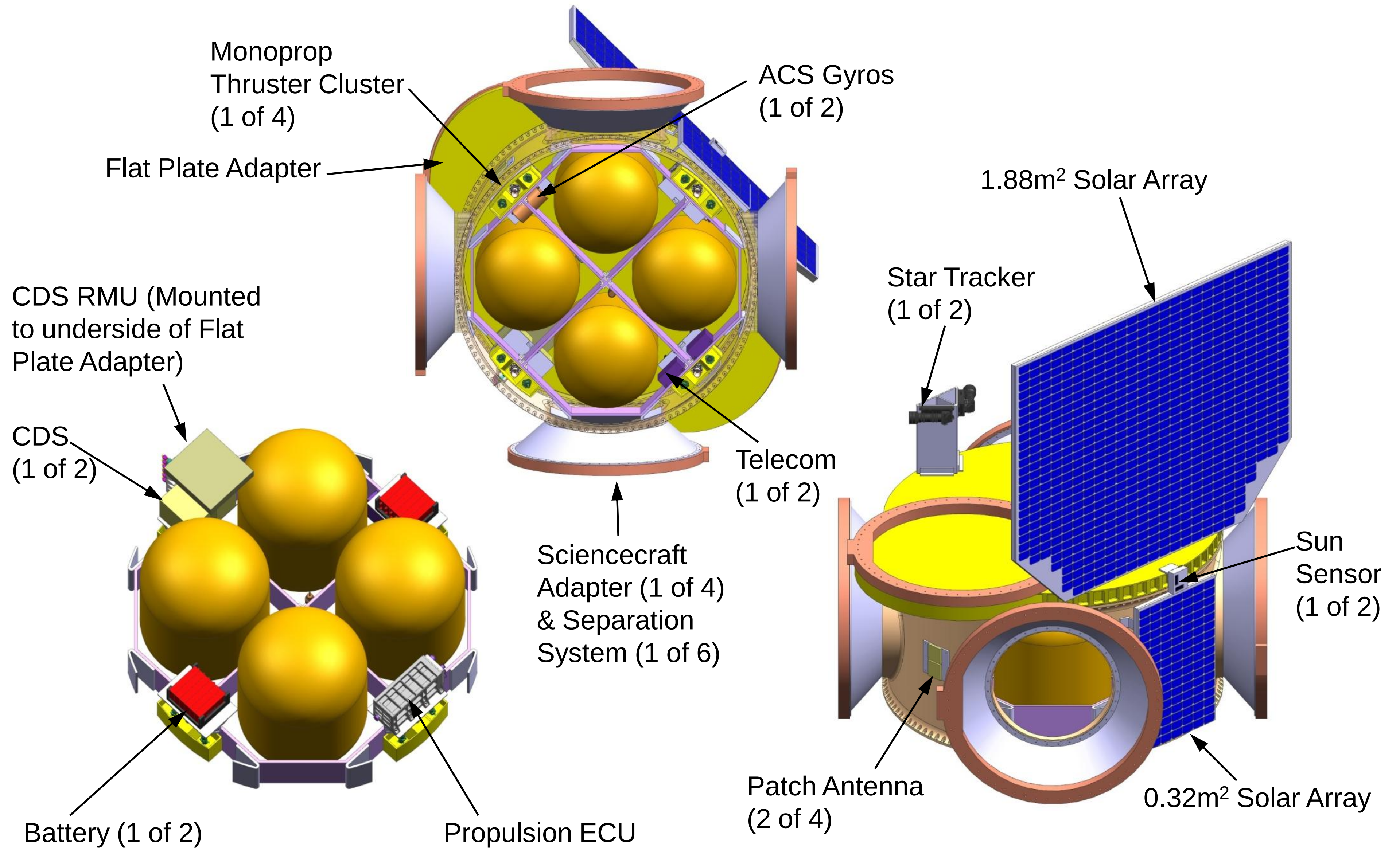


Configuration

Design Configuration Sciencecraft – Option 1 & 2

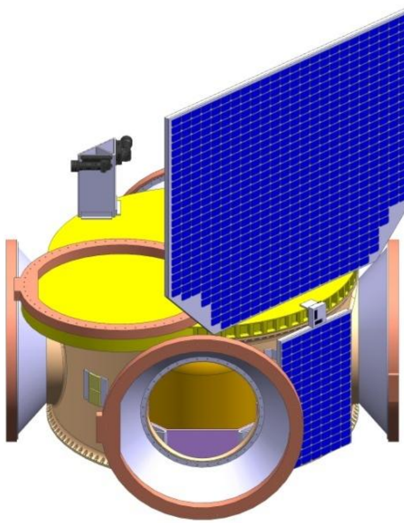


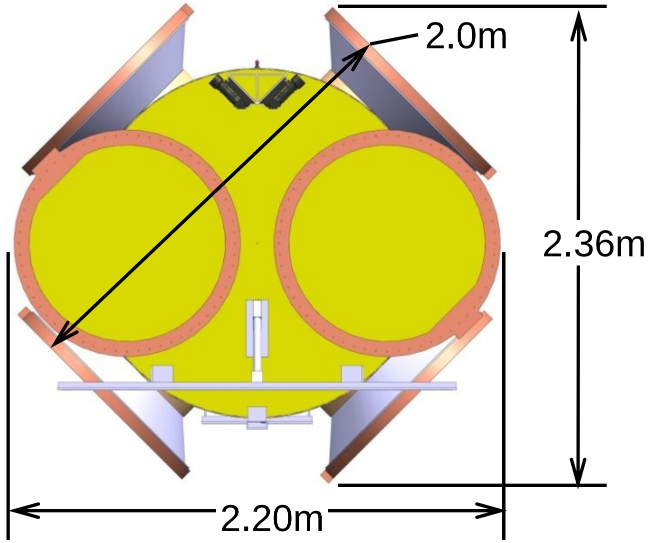
Design Configuration Carrier – Option 1 & 2

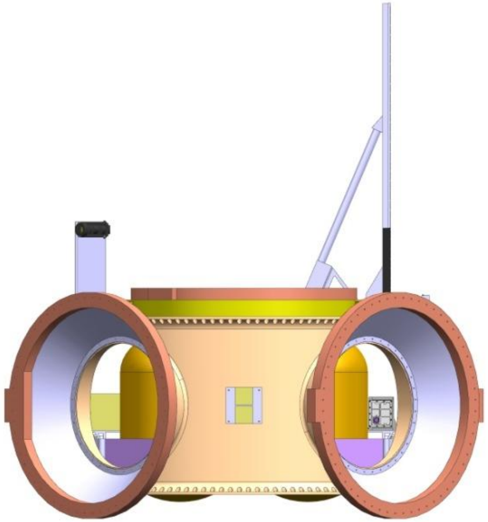


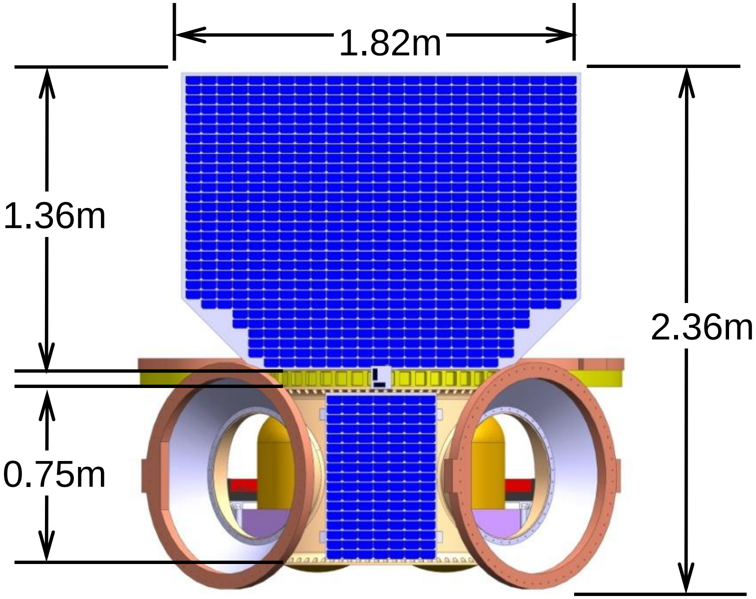
Configuration

Design Configuration Carrier – Option 1 & 2

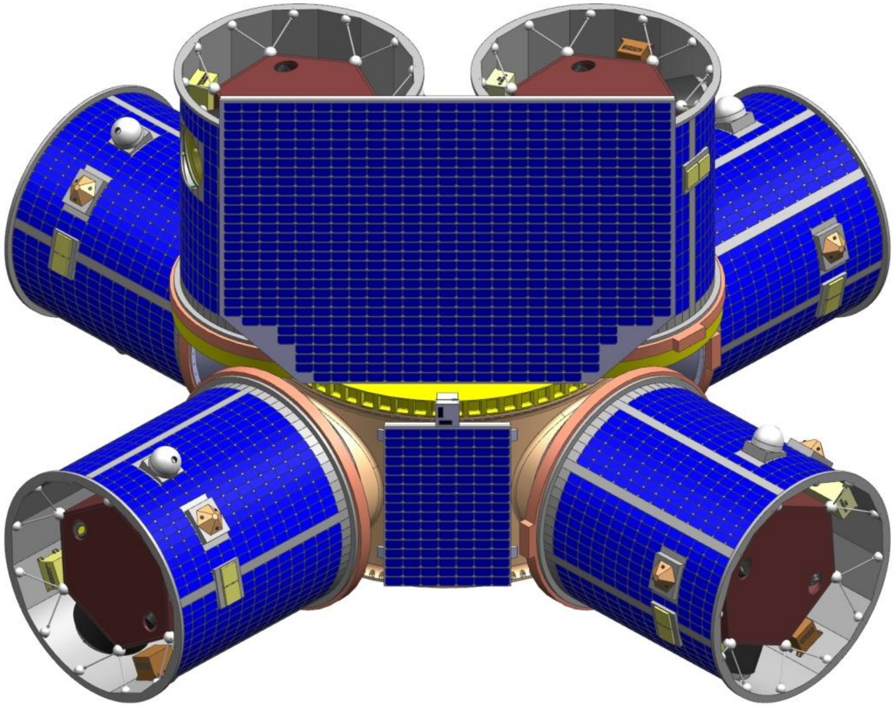


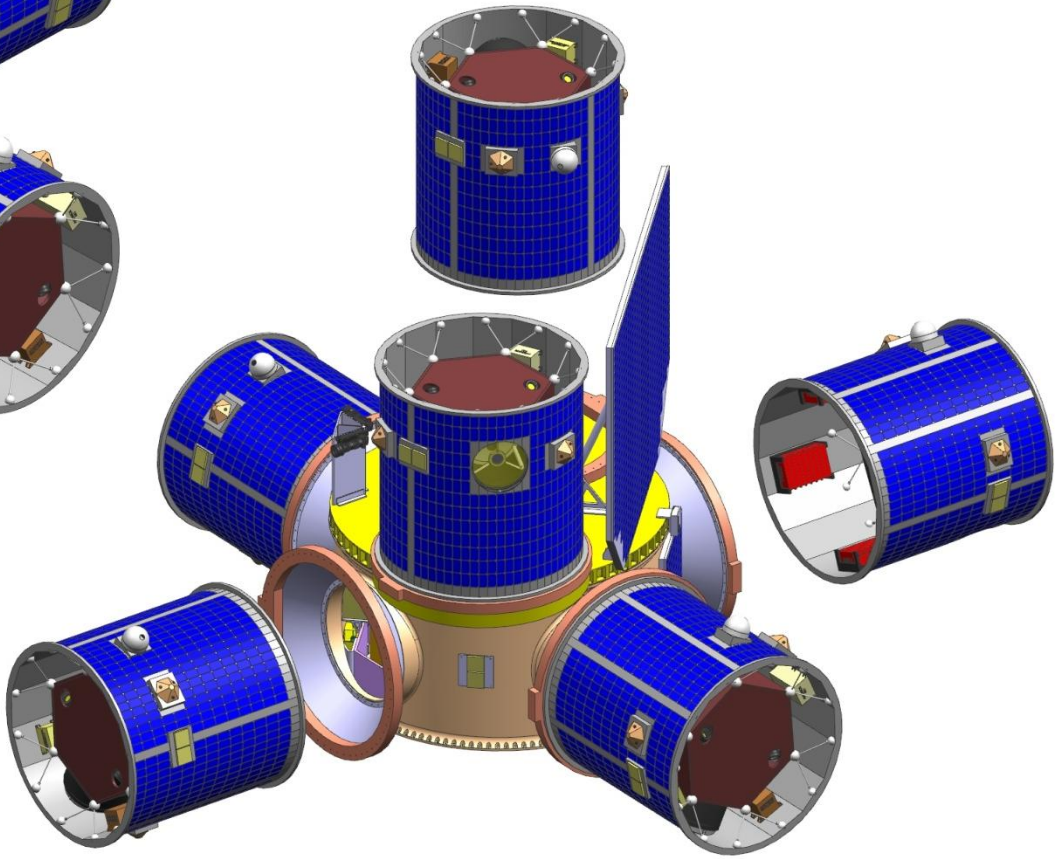






Design Configuration Carrier with Probes– Option 1 & 2





Configuration
Option Comparison

- **Option 1 instrument design is as provided in customer CAD configuration files. Option 2 instrument design is smaller in mass but no configuration files were available.**
- **Additional subsystem level differences between Options 1 & 2 are too subtle to warrant distinct configuration models under the study's time constraints.**

Option	LV	Configuration	Comments
1	NLS II Contract	Baseline	Carrier with 6 microprobes.
2	NLS II Contract	Reduced Instrument	No configuration changes at Prop Module or Sciencecraft level, only instrument. Option 2 Instrument CAD not available.

Configuration
Additional Comments

- Location of avionics and other subsystem hardware may need to be optimized appropriately per stress and mass properties requirements.
- Secondary support structure (e.g. prop tank supports, etc.), cabling and prop line routing not shown in configuration, but need to be accommodated.
- Packaging of the configuration depicted herein within the NLS II Contract fairing is feasible with significant height margin.

Thermal Report

(1281) Omega 2012-04
April 3-5, 10, 2012

Author: Gaj Birur
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Phone:818-354-4762

Thermal
Table of Contents

Thermal
Design Requirements – Science Craft

- **Mission:**
  - Space Physics, Gravity wave science mission orbiting earth
  - Lifetime – 2 years, one year non-operating, one year science mission
  - 4 hours eclipse, three times during the science part of the mission
- A total of six identical probes paired and stationed at three locations in the 1M km orbit around earth
- Each probe has an instrument with an optical assembly thermally isolated from the rest of the probe; the probe has its own avionics, power, and telecom subsystems
- Carrier provides survival heater power during cruise before the probe is jettisoned into orbit around earth

Design Assumptions – Science Craft

- **Temperature requirements for the Science Craft are**:
  - Telecom: -35 C to 50 C
  - Avionics: -40 C to +55 C
  - Battery: -20 to +30 C
  - Instrument: -40 C to 50 C
- **Thermal Environment**
  - Earth orbiting probes
  - Three eclipses of about four hour duration
- **Interface assumptions**
  - The sciencecraft (probe) is thermally isolated from the Carrier during cruise
  - The instrument in the probe is thermally isolated from the rest of the probe
  - The avionics, power, and telecom boxes are mounted on the sunshade but thermally isolated from the sunshade and have their own radiators and survival heaters

Thermal
Summary – Science Craft – Option 1

Power Thermal Summary Chart

	Suggested	Input/Override	Used
Thermal Design Inputs			
Thermally Controlled Mass	123.8 kg		123.8 kg
Spacecraft Dry Mass Density	200.0 kg/m3	220.0 kg/m3	220.0 kg/m3
Spacecraft Wet Mass Density	200.0 kg/m3	220.0 kg/m3	220.0 kg/m3
Thermal Power/Controlled Mass	0.05 W/kg	0.00 W/kg	0.00 W/kg
Conduction Ctrl Mass/Ctrlled Mass	0.001 kg/kg		0.001 kg/kg
Bus Geometry Approximation	Cube		Cube
Multi-Layer Insulation			
MLI Type	Interlayered		Interlayered
Number of Layers	20		20
Specific Mass	0.75 kg/m2		0.75 kg/m2
Specific Area	0.50 m2/blanket		0.50 m2/blanket
Propulsion Heater Power			
Tank Heaters	2.5 W		2.5 W
Line Heaters	0.5 W		0.5 W
Thermal Design Calculations			
Thermally Controlled Surface Area	4.1 m2		4.1 m2
Total Propulsion Tank Surface Area	0.0 m2		0.0 m2

Subsystems	Mass			Power Modes									
	CBE	Cont.	PBE	Launch 1.0 hr.	Cruise 24.0 hr.	Separation 1.0 hr.	Communications 4.0 hr.	Science 24.0 hr.	Science in eclipse 4.0 hr.	Science with Telecom 2.0 hr.	Safe 24.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.
Total Wet Stack (w/o Thermal)	154.9 kg	51%	234.2 kg	0.0 W	0.0 W	97.4 W	106.0 W	144.9 W	144.9 W	175.7 W	105.2 W	4.3 W	4.3 W
Carried Elements	0.0 kg	0%	0.0 kg										
Wet Element (w/o Thermal)	154.9 kg	51%	234.2 kg	0.0 W	0.0 W	97.4 W	106.0 W	144.9 W	144.9 W	175.7 W	105.2 W	4.3 W	4.3 W
Pressurant & Propellant	0.0 kg	0%	0.0 kg										
Dry Element (w/o Thermal)	154.9 kg	51%	234.2 kg	0.0 W	0.0 W	97.4 W	106.0 W	144.9 W	144.9 W	175.7 W	105.2 W	4.3 W	4.3 W
Instruments	64.3 kg	30%	83.7 kg	0.0 W	0.0 W	0.0 W	8.0 W	79.7 W	79.7 W	79.7 W	8.0 W	0.0 W	0.0 W
Other Payload	0.0 kg	0%	0.0 kg										
Dry Bus (w/o Thermal)	90.6 kg	66%	150.6 kg	0.0 W	0.0 W	97.4 W	98.0 W	65.2 W	65.2 W	96.0 W	97.2 W	4.3 W	4.3 W
ADC	2.2 kg	28%	2.8 kg	0.0 W	0.0 W	10.0 W	10.0 W	10.0 W	10.0 W	10.0 W	10.0 W	0.0 W	0.0 W
CDH	5.0 kg	25%	6.3 kg	0.0 W	0.0 W	24.6 W	24.6 W	24.6 W	24.6 W	24.6 W	24.6 W	0.0 W	0.0 W
Power	23.6 kg	30%	30.6 kg	0.0 W	0.0 W	16.1 W	16.8 W	18.9 W	18.9 W	14.7 W	15.9 W	4.3 W	4.3 W
Propulsion	4.5 kg	30%	5.9 kg	0.0 W	0.0 W	6.3 W	6.3 W	6.3 W	6.3 W	6.3 W	6.3 W	0.0 W	0.0 W
Mechanical	52.1 kg	30%	67.8 kg	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Telecom	3.2 kg	14%	3.6 kg	0.0 W	0.0 W	40.4 W	40.4 W	5.4 W	5.4 W	40.4 W	40.4 W	0.0 W	0.0 W
Systems Contingency			33.6 kg										
Thermal	6.8 kg	0%	6.8 kg	0.0 W	0.0 W	35.0 W	35.0 W	25.0 W	25.0 W	5.0 W	25.0 W	0.0 W	0.0 W

Thermal
Summary – Science Craft – Option 2

- **Power Thermal Summary Chart**
- **Option 2 has lower powered instrument in the probe**

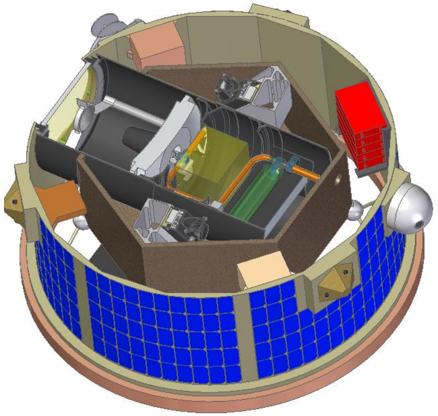
Thermal Design Inputs			
Thermally Controlled Mass	116.3 kg		116.3 kg
Spacecraft Dry Mass Density	200.0 kg/m3	220.0 kg/m3	220.0 kg/m3
Spacecraft Wet Mass Density	200.0 kg/m3	220.0 kg/m3	220.0 kg/m3
Thermal Power/Controlled Mass	0.05 W/kg	0.00 W/kg	0.00 W/kg
Conduction Ctrl Mass/Ctrlled Mass	0.001 kg/kg		0.001 kg/kg
Bus Geometry Approximation	Cube		Cube
Multi-Layer Insulation			
MLI Type	Interlayered		Interlayered
Number of Layers	20		20
Specific Mass	0.75 kg/m2		0.75 kg/m2
Specific Area	0.50 m2/blanket		0.50 m2/blanket
Propulsion Heater Power			
Tank Heaters	2.5 W		2.5 W
Line Heaters	0.5 W		0.5 W
Thermal Design Calculations			
Thermally Controlled Surface Area	3.9 m2		3.9 m2
Total Propulsion Tank Surface Area	0.0 m2		0.0 m2

Subsystems	Mass			Power Modes									
	CBE	Cont.	PBE	Launch 1.0 hr.	Cruise 24.0 hr.	Separation 1.0 hr.	Communications 4.0 hr.	Science 24.0 hr.	Science in eclipse 4.0 hr.	Science with Telecom 2.0 hr.	Safe 24.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.
Total Wet Stack (w/o Thermal)	139.8 kg	52%	212.1 kg	0.0 W	0.0 W	97.4 W	103.2 W	117.1 W	117.1 W	148.7 W	102.4 W	4.3 W	4.3 W
Carried Elements	0.0 kg	0%	0.0 kg										
Wet Element (w/o Thermal)	139.8 kg	52%	212.1 kg	0.0 W	0.0 W	97.4 W	103.2 W	117.1 W	117.1 W	148.7 W	102.4 W	4.3 W	4.3 W
Pressurant & Propellant	0.0 kg	0%	0.0 kg										
Dry Element (w/o Thermal)	139.8 kg	52%	212.1 kg	0.0 W	0.0 W	97.4 W	103.2 W	117.1 W	117.1 W	148.7 W	102.4 W	4.3 W	4.3 W
Instruments	55.0 kg	30%	71.5 kg	0.0 W	0.0 W	0.0 W	5.4 W	54.0 W	54.0 W	54.0 W	5.4 W	0.0 W	0.0 W
Other Payload	0.0 kg	0%	0.0 kg										
Dry Bus (w/o Thermal)	84.8 kg	66%	140.6 kg	0.0 W	0.0 W	97.4 W	97.8 W	63.1 W	63.1 W	94.7 W	97.0 W	4.3 W	4.3 W
ADC	2.2 kg	28%	2.8 kg	0.0 W	0.0 W	10.0 W	10.0 W	10.0 W	10.0 W	10.0 W	10.0 W	0.0 W	0.0 W
CDH	5.0 kg	25%	6.3 kg	0.0 W	0.0 W	24.6 W	24.6 W	24.6 W	24.6 W	24.6 W	24.6 W	0.0 W	0.0 W
Power	21.5 kg	30%	27.9 kg	0.0 W	0.0 W	16.1 W	16.5 W	16.8 W	16.8 W	13.4 W	15.7 W	4.3 W	4.3 W
Propulsion	4.5 kg	30%	5.9 kg	0.0 W	0.0 W	6.3 W	6.3 W	6.3 W	6.3 W	6.3 W	6.3 W	0.0 W	0.0 W
Mechanical	48.5 kg	30%	63.0 kg	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Telecom	3.2 kg	14%	3.6 kg	0.0 W	0.0 W	40.4 W	40.4 W	5.4 W	5.4 W	40.4 W	40.4 W	0.0 W	0.0 W
Systems Contingency			31.1 kg										
Thermal	6.8 kg	0%	6.8 kg	0.0 W	0.0 W	30.0 W	30.0 W	25.0 W	25.0 W	5.0 W	25.0 W	0.0 W	0.0 W

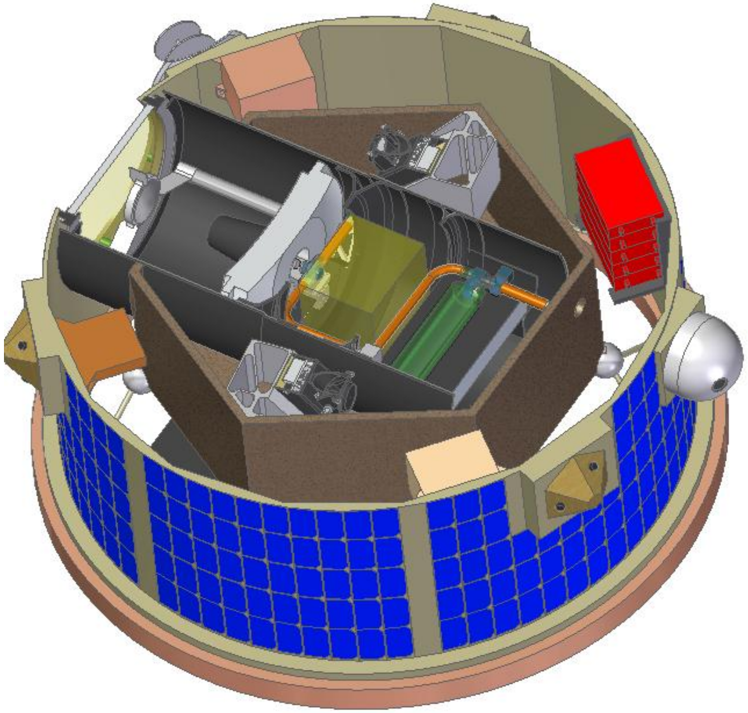
Design – Science Craft

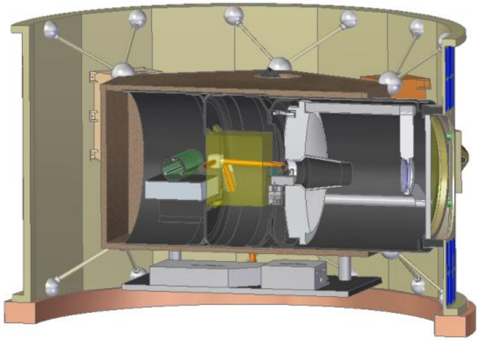
Design Details

- MLI on the inside of the Sun Shade (SS) for thermal isolation
- MLI between hexagonal composite structure and the Optics
- The microprobe avionics and telecom are thermally isolated from the SS
- Radiators on individual electronics boxes and battery for heat rejection
- The radiators are facing the same side as the instrument and laser box radiator
- Radiators with white paint
- Survival heaters on the instrument, avionics, and telecom boxes
- Temperature sensors, film heaters, mechanical thermostats etc.
- Thermal conduction control elements



Thermal
Design – Science Craft





Main Optics

Sun Filter

Proof Mass

IISP Unit

AFT Optics

AFT Mirror

Laser Components

Radiator

Thermal
Cost – Science Craft – Option 1

Cost Assumptions

- Class C probes

Thermal Control System Cost by Phase								Thermal Control System Cost	
A 12 mo.	B 15 mo.	C1 18 mo.	C2 9 mo.	C3 9 mo.	D1 27 mo.	D2 4 mo.	Total 94 mo.	NRE (A-C1) 45 mo.	RE (C2-D2) 49 mo.
$164.3 K	$451.9 K	$1222.5 K	$345.0 K	$246.5 K	$702.6 K	$54.8 K	$3187.6 K	**$1838.7 K**	**$1348.8 K**

Cost Drivers

- The length of the phases seem too long, this increases the cost due to WF need to be on the project (taxi meter effect).

Potential Cost Savings

- Reduce the duration of the phases

Potential Cost Uppers

- If the thermal stability requirement is not able to be met with the thermal design selected, additional design effort may be needed

Thermal
Cost – Science Craft – Option 2

Cost Assumptions

- Class C probes

Thermal Control System Cost by Phase								Thermal Control System Cost	
A 9 mo.	B 12 mo.	C1 9 mo.	C2 5 mo.	C3 4 mo.	D1 27 mo.	D2 4 mo.	Total 70 mo.	NRE (A-C1) 30 mo.	RE (C2-D2) 40 mo.
\$123.3 K	\$525.9 K	\$1049.9 K	\$372.2 K	\$219.1 K	\$702.6 K	\$54.8 K	\$3047.7 K	**\$1699.0 K**	**\$1348.6 K**

Cost Drivers

- The length of the phases seem too long, this increases the cost due to WF need to be on the project (taxi meter effect).

Potential Cost Savings

- Reduce the duration of the phases

Potential Cost Uppers

- If the thermal stability requirement is not able to be met with the thermal design selected, additional design effort may be needed

Risk – Science Craft

List of Risks

- The instrument requirement for stringent thermal stability of 1 micro K/100s may be difficult to achieve with traditional thermal hardware
  - During its orbit around earth the telescope window is exposed to the sun several times a year and affect its thermal stability
  - Additional operational heater control may be needed during these occasions to maintain the required stability

- The survival heaters for the instrument and engineering boxes will depend on the allowable non-op temperatures and may be large if the AFT low limit is not low enough (at or below -45 C)

CARRIER

Thermal
Design Requirements – Carrier

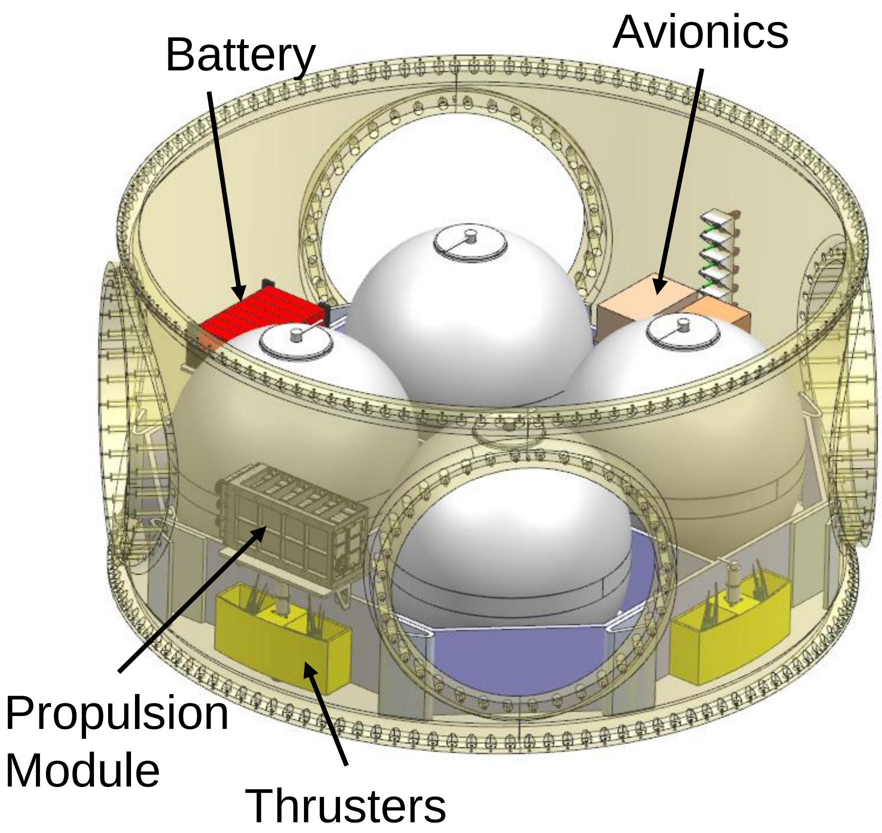
- **Mission:**
  - Space Physics, Gravity wave science mission orbiting earth
  - Lifetime – one year

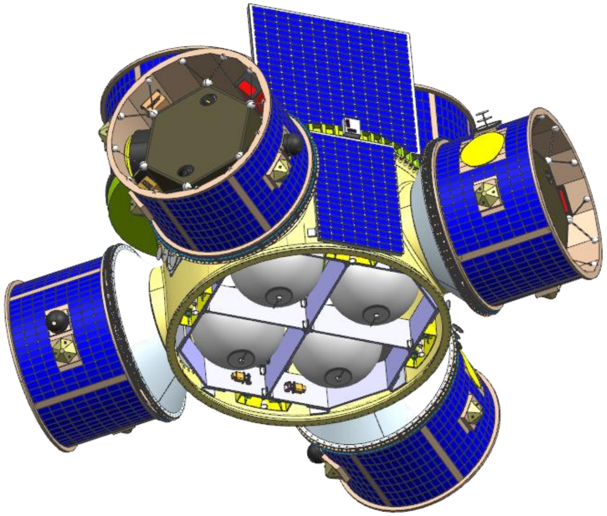
- Carrier has a payload of six microprobes
- Microprobes are jettisoned in pairs into a circular orbit around Earth. Carrier has its own power, avionics, and telecom subsystems
- Carrier provides survival heater power for the probes during cruise before they are jettisoned into orbit around Earth

Thermal
Design Assumptions – Carrier

- Temperature requirements for the carrier system are:
  - Propulsion tanks: 10 C to 40 C
  - Propellant lines: 10 C to 50 C
  - Avionics: -40 C to +55 C
  - Telecom: -35 C to 50 C
  - Battery: -20 C to 30 C
- Thermal Environment
  - Earth orbiting probes
- Interface assumptions
  - The sciencecrafts (microprobes) are thermally isolated from the Carrier during cruise
  - The avionics, power, and telecom boxes are mounted on the structure around the tanks and thermally isolated from the tanks

Thermal
Design – Carrier





Thermal
Summary – Carrier – Option 1

- **Power Thermal Summary Chart**

	Suggested	Input/Override	Used
Thermal Design Inputs			
Thermally Controlled Mass	487.9 kg		487.9 kg
Spacecraft Dry Mass Density	200.0 kg/m3		200.0 kg/m3
Spacecraft Wet Mass Density	200.0 kg/m3		200.0 kg/m3
Thermal Power/Controlled Mass	0.05 W/kg		0.05 W/kg
Conduction Ctrl Mass/Ctrlled Mass	0.001 kg/kg		0.001 kg/kg
Bus Geometry Approximation	Cube		Cube
Multi-Layer Insulation			
MLI Type	Interlayered		Interlayered
Number of Layers	20		20
Specific Mass	0.75 kg/m2		0.75 kg/m2
Specific Area	0.50 m2/blanket		0.50 m2/blanket
Propulsion Heater Power			
Tank Heaters	2.5 W		2.5 W
Line Heaters	0.5 W		0.5 W
Thermal Design Calculations			
Thermally Controlled Surface Area	10.9 m2		10.9 m2
Total Propulsion Tank Surface Area	9.3 m2		9.3 m2

Subsystems	Mass			Power Modes									
	CBE	Cont.	PBE	Launch 1.0 hr.	Cruise 24.0 hr.	Separation 1.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.
Total Wet Stack (w/o Thermal)	#######	11%	#######	142.6 W	117.4 W	142.6 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
Carried Elements	#######	0%	#######										
Wet Element (w/o Thermal)	835.0 kg	29%	#######	142.6 W	117.4 W	142.6 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
Pressurant & Propellant	465.5 kg	0%	465.5 kg										
Dry Element (w/o Thermal)	369.5 kg	66%	611.8 kg	142.6 W	117.4 W	142.6 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
Instruments	0.0 kg	0%	0.0 kg	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Other Payload	0.0 kg	0%	0.0 kg										
Dry Bus (w/o Thermal)	369.5 kg	66%	611.8 kg	142.6 W	117.4 W	142.6 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
ADC	5.8 kg	24%	7.1 kg	22.0 W	22.0 W	22.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
CDH	13.9 kg	19%	16.6 kg	39.5 W	39.5 W	39.5 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Power	13.9 kg	30%	18.0 kg	16.0 W	14.8 W	16.0 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
Propulsion	66.5 kg	28%	84.9 kg	24.7 W	0.7 W	24.7 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Mechanical	263.5 kg	44%	378.8 kg	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Telecom	5.9 kg	13%	6.7 kg	40.4 W	40.4 W	40.4 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Systems Contingency			99.7 kg										
Thermal	14.6 kg	0%	14.6 kg	114.4 W	214.4 W	214.4 W	38.4 W	38.4 W	38.4 W	38.4 W	38.4 W	38.4 W	38.4 W

Thermal
Summary – Carrier – Option 2

- Power Thermal Summary Chart
- Option 2 is the lower powered probe instrument

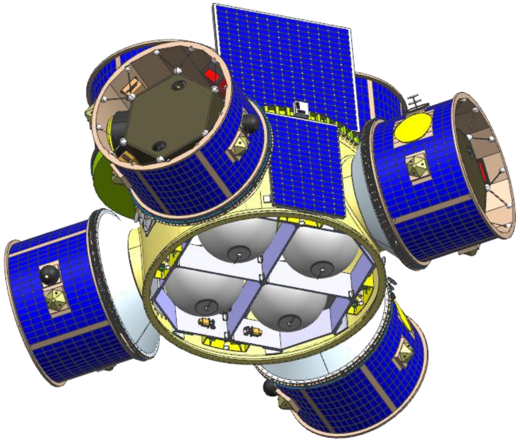
	Suggested	Input/Override	Used
Thermal Design Inputs			
Thermally Controlled Mass	458.4 kg		458.4 kg
Spacecraft Dry Mass Density	200.0 kg/m3		200.0 kg/m3
Spacecraft Wet Mass Density	200.0 kg/m3		200.0 kg/m3
Thermal Power/Controlled Mass	0.05 W/kg		0.05 W/kg
Conduction Ctrl Mass/Ctrlled Mass	0.001 kg/kg		0.001 kg/kg
Bus Geometry Approximation	Cube		Cube
Multi-Layer Insulation			
MLI Type	Interlayered		Interlayered
Number of Layers	20		20
Specific Mass	0.75 kg/m2		0.75 kg/m2
Specific Area	0.50 m2/blanket	1.00 m2/blanket	1.00 m2/blanket
Propulsion Heater Power			
Tank Heaters	2.5 W		2.5 W
Line Heaters	0.5 W		0.5 W
Thermal Design Calculations			
Thermally Controlled Surface Area	10.4 m2		10.4 m2
Total Propulsion Tank Surface Area	9.3 m2		9.3 m2

Subsystems	Mass			Power Modes									
	CBE	Cont.	PBE	Launch 1.0 hr.	Cruise 24.0 hr.	Separation 1.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.
Total Wet Stack (w/o Thermal)	########	11%	########	147.3 W	127.2 W	152.6 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
Carried Elements	########	0%	########										
Wet Element (w/o Thermal)	811.7 kg	28%	########	147.3 W	127.2 W	152.6 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
Pressurant & Propellant	465.5 kg	0%	465.5 kg										
Dry Element (w/o Thermal)	346.2 kg	66%	573.6 kg	147.3 W	127.2 W	152.6 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
Instruments	0.0 kg	0%	0.0 kg	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Other Payload	0.0 kg	0%	0.0 kg										
Dry Bus (w/o Thermal)	346.2 kg	66%	573.6 kg	147.3 W	127.2 W	152.6 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
ADC	5.8 kg	24%	7.1 kg	22.0 W	22.0 W	22.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
CDH	13.9 kg	19%	16.6 kg	39.5 W	39.5 W	39.5 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Power	17.3 kg	30%	22.5 kg	20.7 W	24.6 W	26.0 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W	6.2 W
Propulsion	66.5 kg	28%	84.9 kg	24.7 W	0.7 W	24.7 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Mechanical	236.8 kg	44%	341.2 kg	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Telecom	5.9 kg	13%	6.7 kg	40.4 W	40.4 W	40.4 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Systems Contingency			94.6 kg										
Thermal	15.2 kg	0%	15.2 kg	112.9 W	207.9 W	207.9 W	36.9 W	36.9 W	36.9 W	36.9 W	36.9 W	36.9 W	36.9 W

Design – Carrier

Design Details

- MLI cover all the four propellant tanks
- MLI on the inside of carrier covering the entire inside surface
- MLI covers both top and bottom of the carrier except for any opening for the radiators for the avionics, telecom boxes, and thrusters
- Radiators on individual electronics boxes and battery for heat rejection
- Operational heaters on propellant tanks & lines, battery, and survival heaters on avionics, & Telecom boxes
- Temperature sensors, film heaters, mechanical thermostats, etc.
- Radiators with white paint
- Thermal conduction control elements



Thermal
Cost – Carrier – Option 1

Cost Assumptions

Thermal Control System Cost by Phase								Thermal Control System Cost	
A 12 mo.	B 15 mo.	C1 18 mo.	C2 9 mo.	C3 9 mo.	D1 27 mo.	D2 4 mo.	Total 94 mo.	NRE (A-C1) 45 mo.	RE (C2-D2) 49 mo.
$164.3 K	$781.1 K	$1781.6 K	$974.8 K	$591.9 K	$1479.1 K	$0.0 K	$5772.8 K	**$2727.0 K**	**$3045.7 K**

Cost Drivers

- Long duration of the phases leads more to labor cost (taximeter)

Potential Cost Savings

- Reduce the duration of the phases

Potential Cost Uppers

- Discuss any issues that could drive the cost up (could also be cost risks)

Cost – Carrier – Option 2

- **Option 2 has lower powered instrument**
- **Cost Assumptions**

	Thermal Control System Cost by Phase							Thermal Control System Cost	
A 9 mo.	**B** 12 mo.	**C1** 9 mo.	**C2** 5 mo.	**C3** 4 mo.	**D1** 27 mo.	**D2** 4 mo.	**Total** 70 mo.	**NRE (A-C1)** 30 mo.	**RE (C2-D2)** 40 mo.
$123.3 K	$789.2 K	$1189.7 K	$789.9 K	$306.9 K	$1109.3 K	$0.0 K	$4308.3 K	**$2102.2 K**	**$2206.1 K**

- **Cost Drivers**
  - Long duration of the phases leads to more labor costs (taxi meter)
- **Potential Cost Savings**
  - Reduce the duration of the phases
- **Potential Cost Uppers**

Risk - Carrrier

List of Risks

- The survival heaters for the probes and engineering boxes will depend on the allowable non-op temperatures and may be large if the AFT low limit is not low enough (at or below -45 C)

Telecom Report

(1281) Omega 2012-04

April 3-5, 10, 2012

Author: D. Hansen

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Design Requirements

General Telecom Requirements
- Support a two-way link with Earth through all mission phases for both the prop stage and each sciencecraft
- Support contacts with each sciencecraft once/week

Downlink/Return Requirements
- Support a downlink rate of 75 kbps to a DSN BWG ground station during the science phase

Uplink/Forward Requirements
- Support an uplink CMD rate of 2 kbps

Link Quality Requirements
- BER of 1E-05 for CMD links
- FER of 1E-04 for TLM links
- Minimum 3 dB margin on all DTE links

Specific Requirements from Customer
- Two spares for the full complement of components for the 6 sciencecraft and carrier stage

Telecom
Design Assumptions – Options 1 & 2

- **Operational Assumptions**
  - Sciencecraft is 3-axis stabilized
  - Carrier stage drops off a pair of sciencecraft and then moves on to the next location
  - Sciencecraft telecom is off until separation from the prop stage
- **Antenna Assumptions**
  - Two LGAs will be positioned on opposite sides of both the prop stage and each sciencecraft to provide ~4 pi steradian antenna coverage
  - The primary LGA during science operations will be pointed closely at Earth
- **Ground Station Assumptions**
  - 34m BWG DSN ground stations with 100 W transmitters
    - Can use a higher transmit power (up to 20 kW) if needed
- **Carrier Telecom Assumptions**
  - 2 kbps uplink and downlink rate is sufficient
    - Can support higher rates if needed
- **Coding Assumptions**
  - Downlink uses a Convolutional 7, ½ code
  - Uplink is uncoded (as far as telecom is concerned, will use a standard BCH code that is decoded in the CDS)

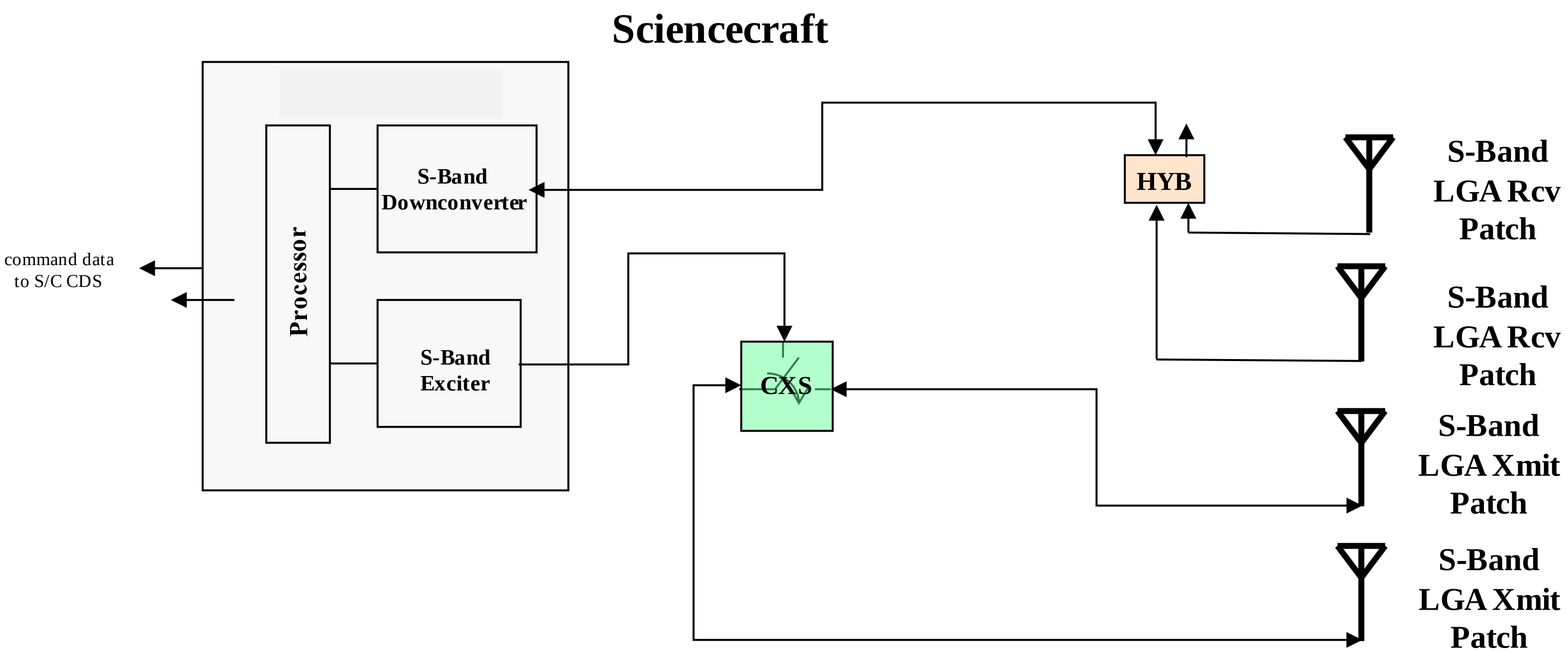
Telecom
Design – Options 1 and 2

- **Sciencecraft**
  - Each vehicle has a single string S-band system with 4 body-fixed patch LGAs
  - There are separate transmit and receive LGA patch antennas
    - They could be combined into single stacked patches which would require a diplexer on the transponder but reduce the cabling
  - The transmit LGAs are connected to the transponder through a switch and the receive LGAs are connected through a hybrid
- **Hardware Includes:**
  - Four S-band low gain patch antennas – two transmit and two receive
  - One S-band transponder
    - With built in 5 W SSPA and diplexer (if necessary)
  - Switch, hybrid and coax cabling
- **Estimated total mass of 3.2 kg**
- **Link margin for the 75 kbps downlink is 7.9 dB**
- **The command uplink margin is > 10 db with 100W transmit power**

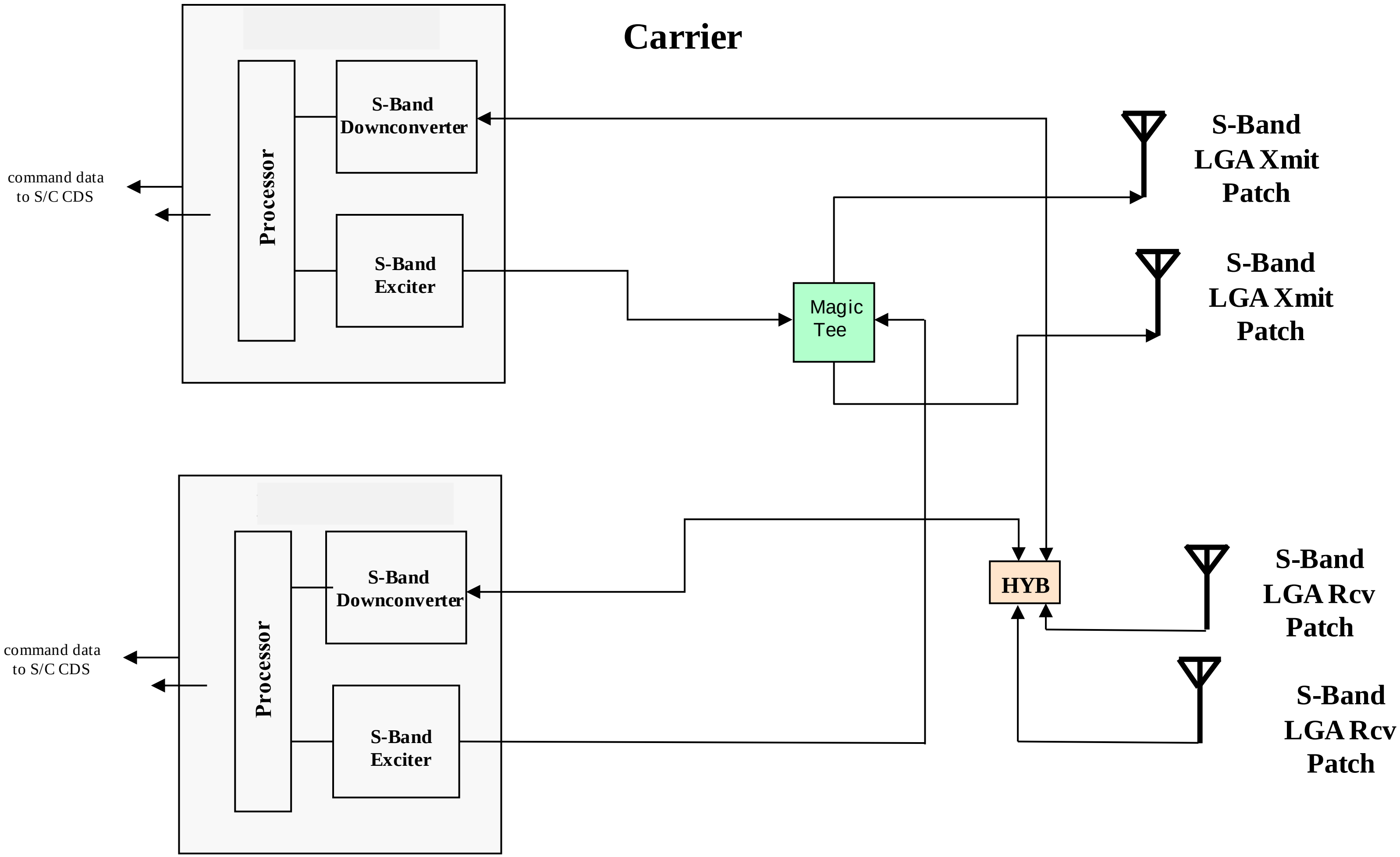
Telecom
Design – Options 1 and 2

- **Carrier**
  - The carrier has a redundant S-band system with 4 body-fixed LGAs
  - There are separate transmit and receive LGA patch antennas
    - They could be combined into single stacked patches which would require a diplexer on the transponder
  - The transmit LGAs are connected to the transponder through a Magic Tee to split the power and the receive LGAs are connected through a hybrid
- **Hardware Includes:**
  - Four S-band low gain patch antennas – two transmit and two receive
  - Two S-band transponders from
    - With built in 5 W SSPA and diplexer (if necessary)
  - Magic Tee, hybrid and coax cabling
- **Estimated total mass of 5.9 kg**
- **Assuming data rates of 2 kbps both up and down for the carrier stage, the link margin is > 10 dB for both the CMD uplink and TLM downlink**

Sciencecraft Block Diagram – Options 1 and 2



Carrier Block Diagram – Options 1 and 2



Cost – Sciencecraft Option 1

Costing Assumptions

- Two spares for the complement of components for all of the spacecraft carried in the first sciencecraft
- Costs for telecom support to ATLO carried by systems chair
- No telecom hardware or support is included for testbeds

Sciencecraft - Option 1

- Total: $17,041 K NRE: $10,119 K RE: $6,922 K

Cost – Sciencecraft Option 2

- **Sciencecraft - Option 2**
  - Reduced schedule time
  - Total: $14,154 K NRE: $8,597 K RE: $5,556 K

Cost – Carrier Options 1 and 2

- **Carrier – Options 1 and 2**
  - Same cost for both options – cost is primarily hardware
  - Spares are carried by the 1st sciencecraft except for the Magic Tee and coax cabling
  - Total: $4,161 K NRE: $1,038 K RE: $3,123 K

Risk

- **Low telecom risk mission**
  - Simple near-Earth S-band design
  - All components have flight heritage
  - Redundancy achieved through multiple sciencecraft

Additional Comments

- **Design Trades**
  - On the carrier, can connect the transmit antennas with a switch or a Magic Tee
    - Using a Magic Tee means not having to flip a switch when the S/C angle to Earth changes
    - This is done for the receive antennas on the sciencecraft and carrier
    - Could consider using stacked patch LGAs with a diplexer on the transponder or use separate transmit and receive LGAs with no diplexer

Ground Systems Report

(1281) Omega 2012-04
April 3-5, 2012

Author: G. Welz

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Table of Contents

Ground Systems
Design Requirements

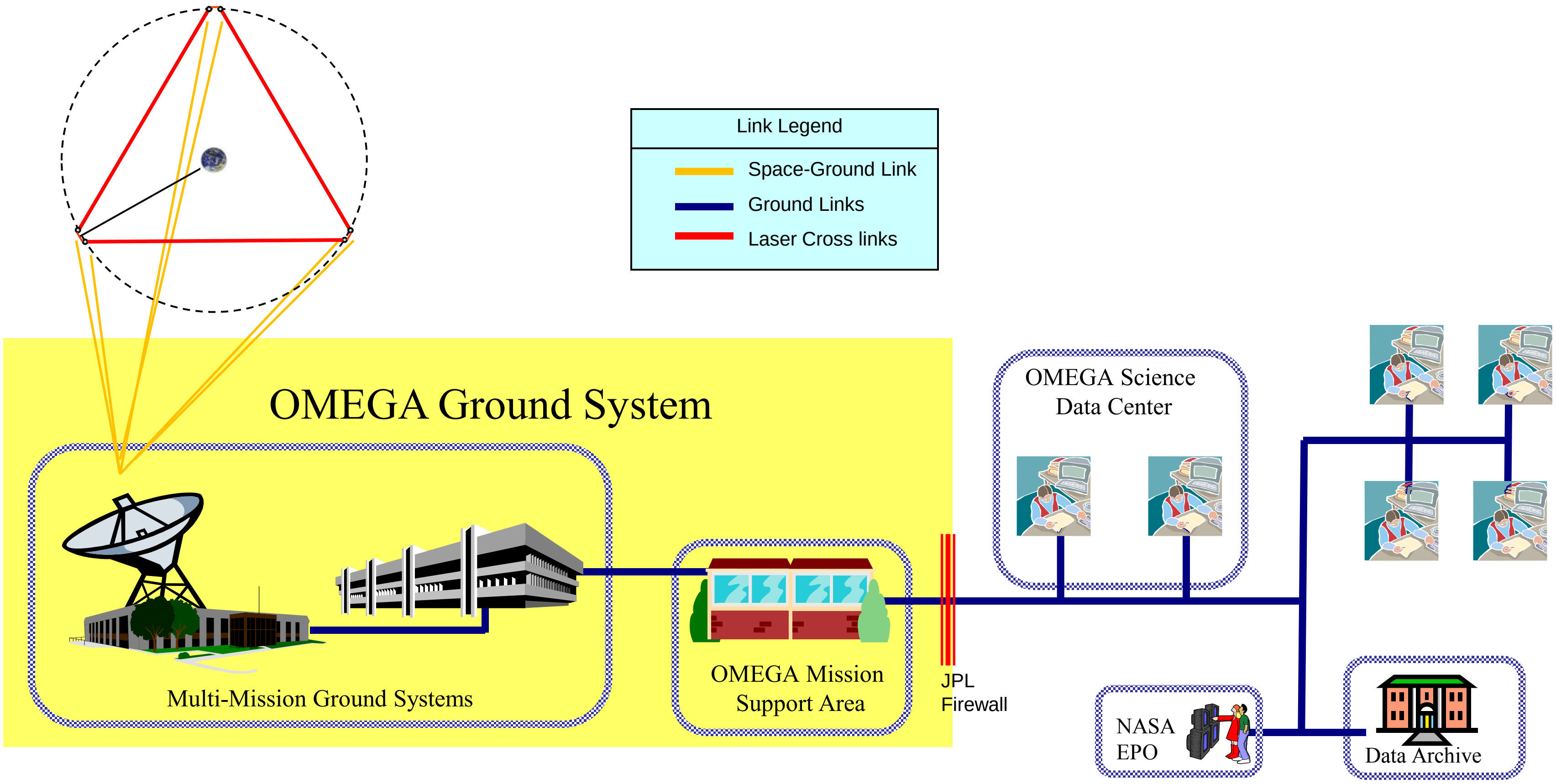
- **Mission:**
  - Constellation of 6 spacecraft is a 600,000 km high Earth orbit, roughly on the ecliptic
  - Constellation broken in to pairs,
    - Each pair at a different vertex of an equilateral triangle
    - The spacecraft in a pair are 3-5 km apart, distance maintained with minimal ground interaction
  - Carrier craft carries all elements to deployment points, after last deployment carrier is decommissioned
  - Once constellation fully deployed, relationship between spacecraft is what the science is all about, s/c maintain relationship autonomously
  - Periodic maneuvers made to maintain 3-5km separation (expected to be once a week)
- **Data Volumes**
  - 491 Mb/week per spacecraft

Ground Systems
Design Assumptions

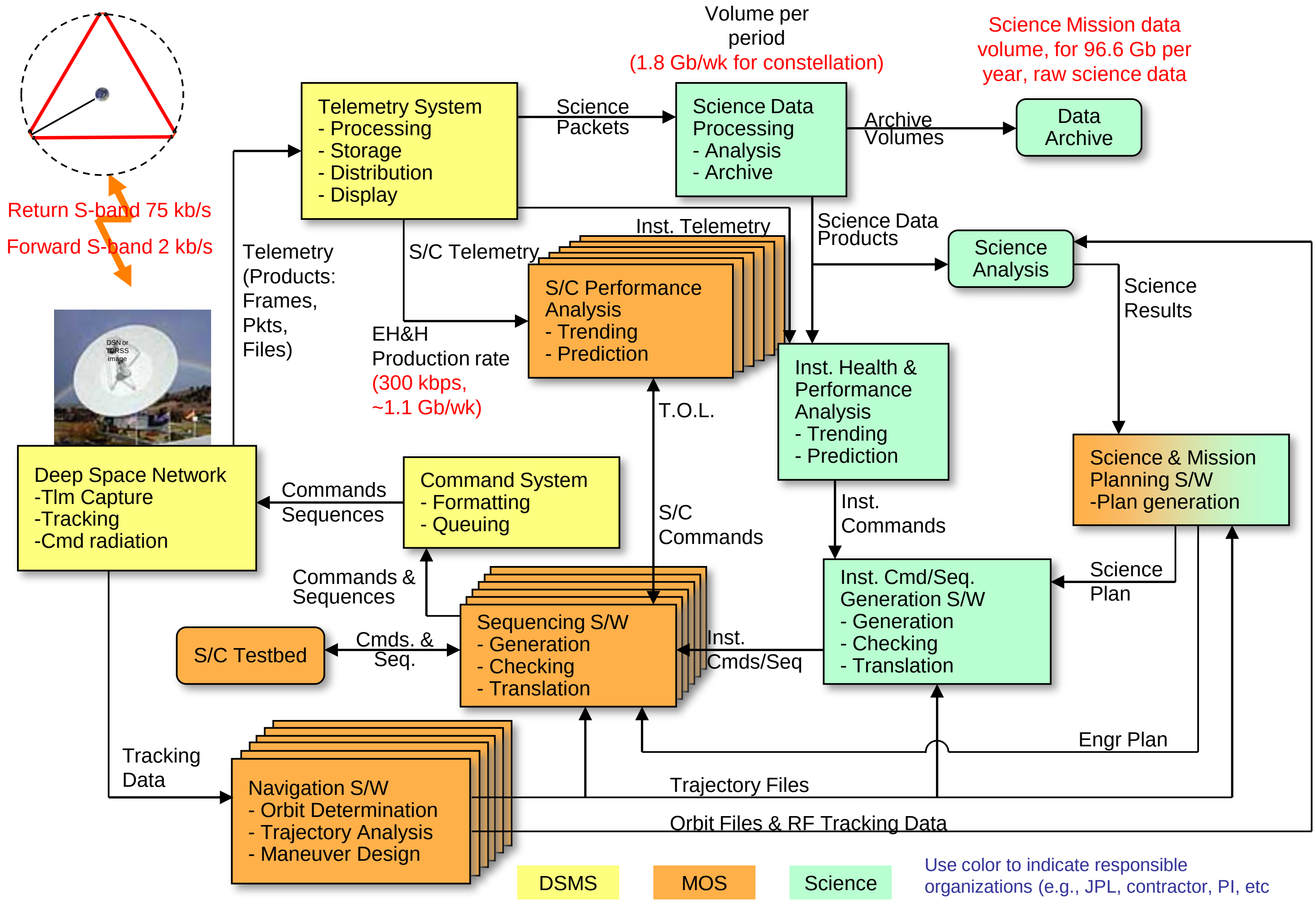
- **Assumptions**
  - Carrier deliveries 3 pair of science spacecraft to orbit locations
  - Science spacecraft are very simple, with high autonomy
  - Separation distance within science craft pair is key and will require operator intervention to approve, otherwise little else is possible beyond on/off and communications coordination
- **Ground system is based on a mission specific implementation of the standard JPL mission operations and ground data systems**
- **Phase E Activity Description**

	Launch and Operations		
Activity Number	Activity Name	Start Date	End Date
1	Launch and Operations	1-Sep-21	1-Oct-21
2	Cruise through final deployment	2-Oct-21	31-Aug-22
3	Constellation check out and calibration	1-Sep-22	1-Oct-22
4	Science phase	2-Oct-22	30-Sep-23

Operational View



Functional View



Design – Deep Space Network

- **Use DSN 34m BWG subnet,**
  - May need all 3 complexes at once, this can will present scheduling challenges
  - Use of MSPA for communicating with pairs
  - TCM – Trajectory Change Maneuver for the carrier uses a standard tracking profile around the maneuver, this is the minimum considered adequate for planning and verifying the maneuver
  - Track twice a week per pair to perform individual spacecraft calibration
  - Track 3x a week per pair for system calibration
  - Track 1x a week per pair for routine science

Downlink/Tracking Scenario

- Cruise
  - Most tracking is for navigation and housekeeping for carrier
    - Around each maneuver and deployment 14 tracks per week
  - For deployed science craft
    - For Each deployment, track recently deployed science craft 2-3x 4-hours per week to establish baseline separation, check-out and characterize science craft
    - Previously deployed science craft 1x 4-hours per week to continue managing separation and continue characterization
- During science:
  - Best case is downlink from each spacecraft once a week for 2 hours, this is adequate for planned science return
- Commanding would occur at least once per week to each spacecraft, possible every communication opportunity

Cost Assumptions

- **Mission concept doesn't fit well within model envelope.**
  - Multiple spacecraft operations assumes spacecraft require more management that these microsats will/should need
  - Development costs reflect multiple spacecraft, but may not be handling simplicity of individual elements or commonality across elements well
  - Recognize potential for model estimate to be high, but not significantly (<25%)
  - Spacecraft operations for science craft should be trivial, there is little that an operator or analyst can do if a problem occurs. Staffed science craft accordingly. Assumed sharing of s/s analyst across all science craft.
  - Carrier is slightly more complicated than the science craft, assume early on we can share subsystem analyst with science craft. Added additional SE support for carrier to handle any additional complexity.

Ground Systems
Cost

Difference between options, that impact ground system is schedule.

- Option 1: 27 month A/B, 67 month C/D
- Option 2: 21 month A/B, 49 month C/D

Option	MOS Dev ($M)	MOS Ops ($M)	GDS Dev ($M)	GDS Ops ($M)	Tracking Dev ($M)	Tracking Ops ($M)	EEIS ($M)	Total ($M)
1	26.7	14.3	30.1	2.9	1.2	6.9	1.6	83.7
2	21.9	14.3	24.6	2.9	1.2	6.9	1.1	73.3

Cost Drivers

- 1 carrier + 6 Science craft, with separation management between pairs drives GDS and MOS costs. Development costs seem higher than what I expected, but walking through the elements having trouble finding much fat.

Software Report

(1281) Omega

April 3 – 5, 2012, April 10, 2012

Author: Karen Lum

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Software
Table of Contents

Software
Design Requirements – All Options

- **Mission:**
  - 6 identical microprobes (sciencecraft) on a carrier (propulsion module)
  - High circular geocentric orbit
- **Microprobes:**
  - Single string
  - FSW processor controls the steering of the AFT mirror
  - ACS flight software responsible for processing and controlling the tracking and pointing of the probes
- **Carrier:**
  - Dual string, cold sparing
  - Deployment of the probes in pair
- **Out-of-House Flight Software development**
  - Vendor will probably outsource the FSW development

Software
Design Assumptions – All Options

- **Complex, capability-rich probes with full command and telemetry channels, some complex instruments, and their own guidance and navigation**
- **Moderately complex carrier with power, communication, attitude control capabilities**
- **The Flight Software Subsystem includes the following:**
  - Command and data Handling software, which includes the flight computer operating system, device drivers, on-board file and data management, interprocess communications, on-board sequencers
  - Guidance and Navigation Software, which includes design of algorithms for attitude determination, guidance, on-board navigation and control, deployment and control of mechanisms
  - Engineering Applications software, which includes interfacing engineering devices (power, pyro, thermal, telecom, etc.) with the spacecraft, commanding, telemetry collection, data gathering and conversion, fault monitoring, and subsystem control
  - Payload Accommodation software for interfacing payload devices with the spacecraft, providing payload-specific data processing, payload fault protection, payload command and telemetry, and payload control
  - System Services software, which includes system fault protection, event recording, mode management, task arbitration, constraint management, health management, resource monitoring and management, and mission clock
- **Fully co-located, highly experienced flight software development organization**

Software
Design – All Options

- **ACS Features**
  - Probes: Highly complex ACS system with very challenging attitude control requirements driven by precision pointing
    - FSW has to process accelerometer/interferometer data for determining pointing control
    - Low rates of change in direction of thrust, but high accuracy requirements
  - Carrier: Standard 3-axis control system with high level of pointing accuracy
    - Carrier has to orient itself before deploying the probes
    - Low rates of change in direction of thrust
    - Sequenced deployment of the six probes in pairs
- **CDS Features**
  - Little onboard storage and data manipulation required
    - Packetization is performed by the instruments
  - Moderate radiation environment (high Earth orbit) will require some software recovery/prevention
    - Well-known architectural design and implementation of fault protection software for this environment
  - Carrier is dual string, cold sparing
  - Probes each are single string

Software
Design – All Options

- **Engineering Subsystems**
  - Moderate thermal control requirements: Control of simple heaters and thermostats
  - Simple power control requirements: acquire and report data from battery mounted array and battery
  - Simple Telecom control: direct downlink to earth of the probe science data
    - The probes don't have to communicate (relay) with each other
- **The carrier will not perform any onboard science data analysis**
- **Some onboard data analysis will be performed by the Probe FSW to analyze and maintain precision pointing**
  - This data processing is critical to the achievement of the mission goals
- **Payload Accommodation**
  - The carrier interfaces to the probes will be simple
    - Pass through commands and receive and store telemetry
  - The probe FSW interfaces to the IISP and the Accelerometer are moderately complex
    - FSW controls the mirror through IISP loose real time
      - infrequent adjustments made to keep mirrors pointed at other spacecraft
    - The accelerometer also requires loose real time control and data processing in order to maintain precision pointing

Software
Cost Assumptions – All Options

- **Costed in FY2012 Dollars**
- **The estimate includes**
  - includes Phase A through Phase D flight software development costs
  - System Concept Phase
  - Proposal-level software requirements
  - The development of software requirements through the software integration and test phase
  - Software management
  - Software system engineering
  - Detailed design, code and unit testing
  - Informal software QA by SW development team
  - Informal CM
  - Software documentation
  - System administration
  - Flight software system test (pre-ATLO software to software integration)
  - Minor bug fixes during ATLO
  - Simulation software under flight software testbed, but excludes the procurement of the flight-like test set
  - FSW procurements (RTOS, CM tool, excluding Testbed)

Software
Cost Assumptions – All Options

- **The estimate does not include**
  - Testbed procurement
  - Phase E
  - Formal Software QA by a separate organization
  - System-Level Engineering functions
  - ATLO support (carried in WBS 10.0)
  - Hardware testbed development
  - Maintenance
  - High-level Program Management
  - Hardware management
  - Independent Verification and Validation
  - Project Software System Engineer (carried in WBS 2.0)
  - Reserves (held at higher level by the Cost Chair)

Cost – Probes FSW Option 1

- **Microprobes**
  - NRE: $16.4M
  - RE: $0.9M
  - 1st Unit cost of probes: $17.2M
  - Total cost of all 6 probes: $21.5M

Cost – Carrier FSW Option 1

- **Carrier**
  - NRE:$10.6M
  - RE: $0.6M
  - Total Carrier: $11.2M

Cost – Total FSW Cost Option 1

- **Total FSW Cost of the Mission**
  - All Probes: $21.5M
  - Carrier: $11.2M
  - **Total FSW Cost: $32.7M**

Cost – Probes FSW Option 2

- **Microprobes**
  - NRE: $16.2M
  - RE: $0.9M
  - 1st Unit cost of probes: $17.0M
  - Total cost of all 6 probes: $21.3M

Cost – Carrier FSW Option 2

- **Carrier**
  - NRE:$10.4M
  - RE: $0.5M
  - Total Carrier: $11.0M

Cost – Total FSW Cost Option 2

- **Total FSW Cost of the Mission**
  - All Probes: $21.3M
  - Carrier: $11.0M
  - **Total FSW Cost: $32.3M**

Software
Cost Comments – All Options

- **Cost Drivers**
  - Major cost driver is the very challenging attitude control requirements

- **Potential Cost Savings**
  - None

- **Potential Cost Uppers**
  - Overly optimistic inheritance assumptions

Risk

- Design assumes reuse of flight software of the generic core spacecraft software. This software has been used in satellite programs. Most missions have specific software needs that may need to be developed for the mission. The application needs of this mission may not match the application needs of prior missions, leading to much larger software modification than expected. Unrealized heritage could impact the mission by $10M or more.

Software
Option Comparison

- **Instrument mass and power change between the two options does not affect software**
  - No change in number of interfaces
  - No change in functionality of the instruments
- **Schedule is the only difference that affects software between the two options**

Option	Cost ($M)	Functionality/Complexity	Comments
1	$32.7M		Longer Phase A-D schedule duration
2	$32.3M	Change in instruments' mass and power (but does not affect number of interfaces nor functionality of the instruments)	Decreased Phase A-D scheduled duration

Programmatics Report

Study Title: (1281) Omega mission

Date 4/3-4/5/2012

Author: Jared Lang

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Table of Contents

Schedule Requirements

- **Launch Date: September 1, 2021**
- **Phase E Duration: 24 months (12 months prime science)**
- **Partners: GSFC, SSTL**
- **Major Schedule Constraints**
  - Schedule durations are driven by the number of spacecraft (6 units)
  - Long lead items (Accelerometer and FEEP thruster) require procurement in the Early phases of the mission (Phase A for the accelerometer, Phase B for the thrusters
  - Technology Development Cutoff: 03/01/2016
- **Schedule Reserves**
  - 1 month per year
  - ATLO has 2 month

Programmatics
Schedule Assumptions

- **Implementation Mode: In-House**
- **Mission Timeline**
  - Cruise: 12 months for the carrier to distribute the constellation
  - Commissioning: 3 months
  - Science operations: 12 months
- **Location of assembly/testing**
  - S/C: In-House
  - Instruments: In-House
- **The assumption is that the mission will meet the TRL cutoff date with the elements that are part of technology development.**

Programmatics

Schedule – Option 1

- **Key Dates:**
  - Phase A start: 12/1/2013
    - PMSR - 12/1/2014
  - Phase B start: 12/7/2014
    - PDR - 3/1/2016
  - Phase C start: 3/1/2016
    - CDR – 9/1/2017
  - Phase D start: 3/1/2019
    - PSR - 6/1/2021
  - Launch: 9/1/2021

Phase	*Duration (months)*
A	12
B	15
C/D	67
C Design	18
Fab	18
D I&T	27
D Launch	3
D: L + 30	1
E	24
A-D	94

Programmatics

Schedule

Sample Schedule for Omega Study 2012-04

Basic Mission (Mostly inherited HW & SW, some new technology, etc.)

Oct-13, Mar-14, Sep-14, Feb-15, Aug-15, Feb-16, Jul-16, Jan-17, Jun-17, Dec-17, May-18, Nov-18, May-19, Oct-19, Apr-20, Sep-20, Mar-21, Sep-21, Feb-22, Aug-22, Jan-23, Jul-23, Dec-23

Phase	Start Date	End Date
Omega Study 2012-04		
MCR	12/01/13	12/03/13
Ph A Project Definition	12/01/13	11/26/14
PMSR	12/01/14	12/03/14
Ph B Preliminary Design	12/07/14	03/01/16
CR/PDR/Tech Cutoff	03/01/16	03/04/16
Ph C Design	03/01/16	07/09/17
Margin	07/09/17	09/01/17
CDR	09/01/17	09/04/17
Ph C Fabrication	09/04/17	05/09/18
Margin	05/09/18	06/01/18
Ph C S/S I&T	06/01/18	02/03/19
Margin	02/03/19	03/01/19
ARR (ph D)	03/01/19	03/04/19
Proj I&T (ATLO)	03/04/19	01/07/21
Margin	01/07/21	06/01/21
PSR	06/01/21	06/04/21
Launch Ops	06/04/21	08/12/21
Margin	08/12/21	09/01/21
Launch	09/01/21	09/22/21
L+30-end Ph D	09/22/21	10/22/21
Phase E	10/22/21	10/12/23

Legend	
Normal Task	
Margin	
Long Lead Item	
Project Level Review	◆◆◆
PDR/Tech cutoff	◆◆◆
Launch	◆◆◆

Programmatics

Schedule – Option 2

- **Key Dates:**
  - Phase A start: 12/1/2015
    - PMSR - 9/1/2016
  - Phase B start: 9/7/2016
    - PDR - 9/1/2017
  - Phase C start: 9/1/2017
    - CDR – 6/1/2018
  - Phase D start: 3/1/2019
    - PSR - 6/1/2021
  - Launch: 9/1/2021

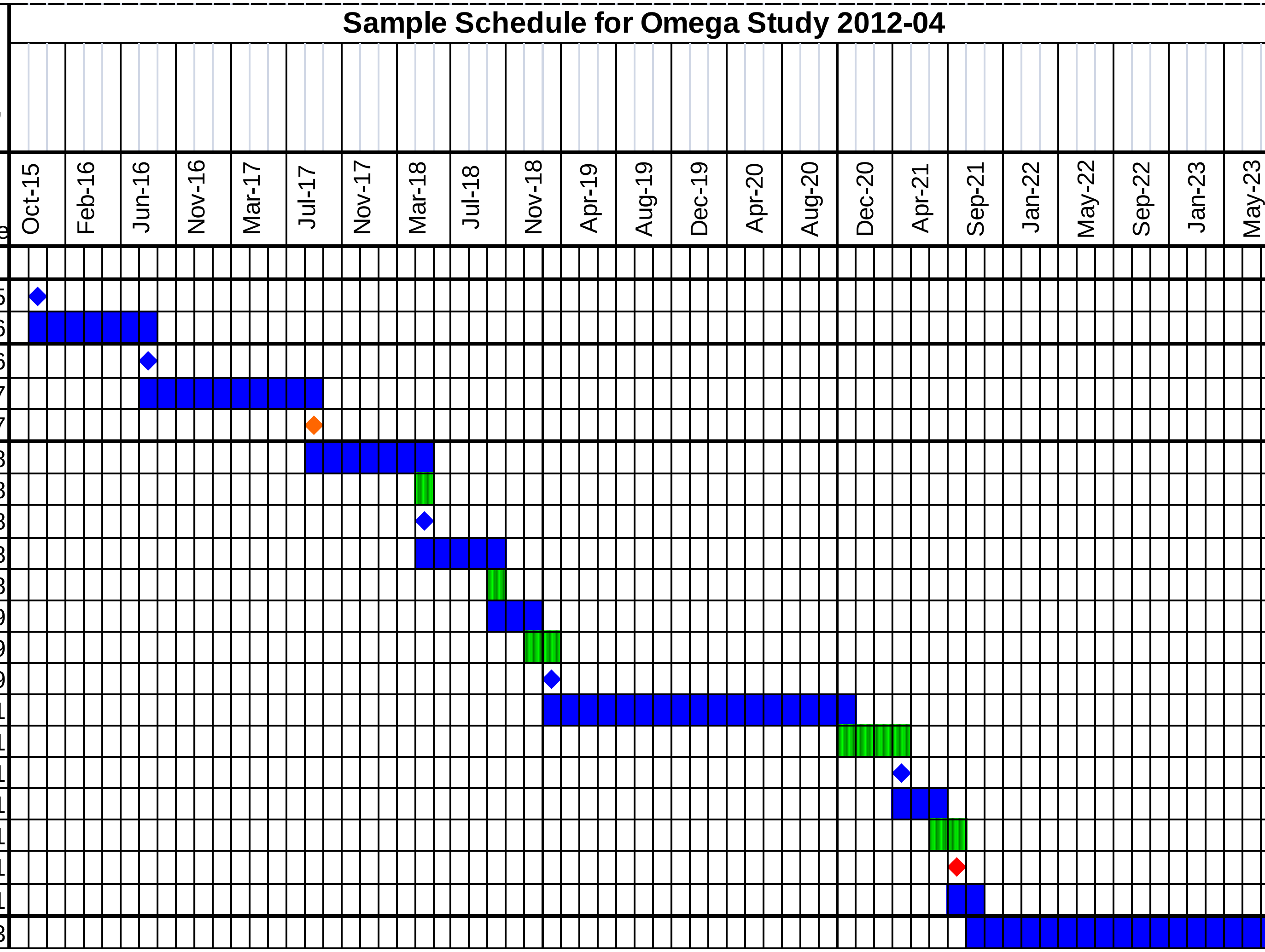
Phase	*Duration (months)*
A	9
B	12
C/D	49
C Design	9
Fab	9
D I&T	27
D Launch	3
D: L + 30	1
E	24
A-D	70

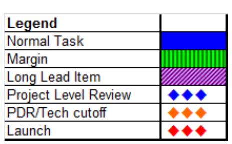
Programmatics

Schedule

Basic Mission (Mostly inherited HW & SW, some new technology, etc.)

Phase	Start Date	End Date
Omega Study 2012-04		
MCR	12/01/15	12/03/15
Ph A Project Definition	12/01/15	08/27/16
PMSR	09/01/16	09/03/16
Ph B Preliminary Design	09/06/16	09/01/17
CR/PDR/Tech Cutoff	09/01/17	09/04/17
Ph C Design	09/01/17	05/06/18
Margin	05/06/18	06/01/18
CDR	06/01/18	06/04/18
Ph C Fabrication	06/04/18	10/19/18
Margin	10/19/18	11/01/18
Ph C S/S I&T	11/01/18	02/19/19
Margin	02/19/19	03/01/19
ARR (ph D)	03/01/19	03/04/19
Proj I&T (ATLO)	03/04/19	01/07/21
Margin	01/07/21	06/01/21
PSR	06/01/21	06/04/21
Launch Ops	06/04/21	08/12/21
Margin	08/12/21	09/01/21
Launch	09/01/21	09/22/21
L+30-end Ph D	09/22/21	10/22/21
Phase E	10/22/21	10/12/23





Risk Report

(1281) OMEGA 2012-04
April 3 – 5 and 10, 2012

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Methodology
Risk Guidance

- Risk are scored on the NASA 5x5 Risk matrix

Mission Risks

Likelihood					
>25%					
10 - 25%					
5 - 10%					
1 - 5%					
0 - 1%					
	<10%	10 - 24%	25 - 49%	50 - 99%	100%
	Minimal Impact to Mission	Small Reduction in Mission Return	Moderate Reduction in Mission Return	Significant Reduction in Mission Return	Mission Failure

Impact

Implimentation Risks

Likelihood					
>70%					
50 - 70%					
30 - 50%					
10 - 30%					
0 - 10%					
	<10%	10 - 49%	50 - 99%	100 - 119%	>120%
	Minimal Reduction in Contingency	Small Reduction in Contingency	Significant Reduction in Contingency	Consume All Contingency, Budget and Schedule	Overrun Budget and Contingency, Cannot Meet Launch Date with Current Resources

Impact

Risk

System Level Risk Summary- Major Risks

Likelihood

		13 (Option 2) 14 (Option 2)		
8	12 (Option 1)	15 (Option 2)		
		7	9	
	3, 6	1, 2	4	
		5, 11		

Impact

- **There are several major risks that affect the mission:**

  Option 2

  - Staffing and destaffing for multiple (6) spacecraft build, which would be difficult for a large scale contractor (13)
  - Proposed schedule is significantly too short for this class of mission. Not consistent with any NASA historic experience (14)

Risk

System Level Risk Summary- Moderate Risks

Likelihood					
			13 (Option 2) 14 (Option 2)		
	8	12 (Option 1)	15 (Option 2)		
			7	9	
		3, 6	1, 2	4	
			5, 11		
	Impact				

- **There are several medium risk that may affect the mission:**

Both Options

- Short schedule time between protoflight and SC flight builds allows insufficient time to make changes if protoflight system test fails (4)
- FEEP must undergo new development and qualification because it is being repurposed and it is not planned for nor funded (7)

Option 2

- Inability to achieve sensitivity with Onera accelerometer (9)
- Phase A/B too short, which could cause significant redesign due to inappropriate or missing requirements on early procurements of long lead items (15)

System Level Risk Summary: Minor

- **There is a minor risks that may be border line yellow:**
  - Design Principle Violation - Lack of communication with probes prior to release (6)

- **There is also one proposal risks that requires special attention when proposing the mission**
  - Inability to “test-as-we-fly” due to large spacecraft architecture.

Major Risk Items

Risk #	Option	Risk Category	Title	Description of Risk	Likelihood	Impact
13	Option 2	Implementation	Staffing and Destaffing Issues (Option 2)	Due to the rapid development and construction of multiple units, the mission requires a significant increase in staffing in a short amount of time. Once done with construction, the large workforce required to build several units must now quickly destaff. There is a risk that the logistics of finding sufficient workers quickly will be very difficult, delaying the schedule. The estimated impact is from 6 to 12 months, which would threaten the launch date. Also at the end of construction, rolling employees off onto other tasks may take significant time, drawing out the schedule as well. This is especially an issue with Option 2 given its short schedule.	5	3
14	Option 2	Implementation	Current schedule is too short for this large of a mission (Option 2)	Typical missions of this type (size, new Technology development, and complexity) require more time to complete. There is a major concern that phases C and D will require extension, especially for Option 2. Since there will need to be such a large workforce to build several spacecraft, any small slip in schedule will result in a major cost impact.	5	3

Risk

Medium Risk Items

Risk #	Option	Risk Category	Title	Description of Risk	Likelihood	Impact
4	Both	Implementation	System Test Failure on Protoflight Spacecraft	The current design schedule assumes that the five additional spacecraft begin integration immediatly following the integration of the protoflight, prior to system testing. In the event of a system test failure or inability to meet the required capabilities as a system, integration of the five additional spacecraft will need to be postponed until the spacecraft team can resolve the failure. This would potentially cause a significant increase in phase D.	2	4
7	Both	Implementation	FEEP Development and Qualification	FEEP Development and Qualification: FEEP Thrusters require characterization and modification of original design. Thrusters have currently flown as charge controllers and will require significant thermal and structural engineering, PPU and DCIU characterization and modification, thruster characterization at different operating set point, and modeling to understand plume effects. A program to characterize and modify the thruster components is expected to take ~18 months. In addition to characterization, the thrusters will require a life test in it's operating mode of at least 1.5 years (50% more than the expected life). Due to schedule constraints, the characterization of the thrusters must start early in phase B (assuming that you can overlap some of the chracterization with the life test). There is very little schedule margin for this development program and a risk that any anomallies occuring with the thrusters will cause a significant slip in schedule.	3	3
9	Both	Implementation	Unable to achieve sensitivity with Accelerometer	There is currently no paper evidence that the Vendor can provide an accelerometer capable of the sensitivities required for the mission. If they are unable to do so, the mission will have to fall back to the GRS based architecture used by LISA, resulting in a significant mass, power and cost increase.	3	4
12	Option 1	Implementation	Staffing and Destaffing Issues (Option 1)	Due to the rapid development and construction of multiple units, the mission requires a significant increase in staffing in a short amount of time. Once done with construction, the large workforce required to build several units must now quickly destaff. There is a risk that the logistics of finding sufficient workers quickly will be very difficult, delaying the schedule. The estimated impact is from 6 to 9 months, which would threaten the launch date. Also at the end of construction, rolling employees off onto other tasks may take significant time, drawing out the schedule as well.	4	2
15	Option 2	Implementation	Redesign of spacecraft due to missing or mispecified requirements of long lead items (Option 2)	Long lead items such as the acceleromters and FEEP thruster require contract definition and procurement in the early phases of the mission, before many of the interface or system requirements have been defined. There is a risk that a redesign of the spacecraft subsystems to accomodate interface or requirement change may be required later in the manufacturing process. This would have an impact on the current schedule.	4	3

Risk

Minor Risk Items

Risk #	Option	Risk Category	Title	Description of Risk	Likelihood	Impact
1	Both	Mission	Event rate risk for massive black hole binary mergers (risk re what exists in Nature)	Best estimate of event rate for detected massive black hole mergers is ~17/yr, but almost all of these are at redshift z >> 1, and are based on poorly tested assumptions re event rate in early universe (z >7). The true rate could be factor ~10 lower, so one might possibly detect only order 1 source. One would really want at least several (~3-5) detections to have confidence in them and GR tests derived from them.	2	3
2	Both	Mission	Event rate for "extreme-mass-ratio-inspirals"	These are mostly inspirals ~10-solar-mass black holes into ~100,000 - 1000,000 solar-mass black holes in galactic nuclei. Current best estimate is that SGO-Mid will detect ~100/yr. However a pessimistic estimate of only order ~1/yr is not in conflict with known astronomy. At least a few events (~3-5) strongly desired to have confidence in the events and the corresponding tests of General Relativity.	2	3
3	Both	Implementation	Low-noise photoreceivers currently at TRL 3	The phasemeter photoreceivers with low-noise (1.8 pA/sqrt(Hz) considered to meet the noise requirements are currently at TRL 3 and have to be further matured. Use of existing photoreceiver technology (with lower performance) would require design changes to control noise and result in cost increase. Science return could be reduced if noise requirements are not met.	2	2
5	Both	Mission	Lack of Communication with MicroProbes Prior to Release	The current design assumes that the probes will be turned off during cruise and a seperation switch will be used to turn the probes on after seperation. There is a risk that with out communication during cruise, it will be impossible to checkout the spacecraft health prior to release and released spacecraft may not operate correctly. Though the loss of one spacecraft is tolerable without significant degredation in science, losing multiple may cause loss of mission.	1	3
6	Both	Implementation	Optimistic Software Heritage Assumptions	Design assumes reuse of flight software of the generic core spacecraft software. This software has been used in satellite programs . Most missions have specific software needs that may need to be developed for the mission. The application needs of this mission may not match the application needs of prior missions, leading to much larger software modification than expected.	2	2
8	Both	Implementation	Thermal stability requirement for the sciencecraft optical assembly	The sciencecraft has a thermal stability requirement of 1micro K/100 s for the optical assembly. During the probes orbit around earth, the the probe's telesciope window will see the sun and this will add heat into the optical assembly and affect thermal stability. Additional heater control may be needed in those conditions and may be difficult to maintain the stability	4	1
11	Both	Implementation	FEEP Manufacturing Process	Few FEEPs have been made or flown and as a result process may not be inplace to produce significant numbers of teh thrusters. OMEGA will require 56 thrusters, at least 18 PPUs, plus engineering models and spares. The large number of items may overwhelm the their manufacturing process, possibly causing schedule delays and/or impacting product quality.	1	3

Proposal Risk Items

Risk #	Option	Risk Category	Title	Description of Risk
10	Both	General System Risks	Inability to test system as we fly	Due to the size of the system architecture, it is impossible to test the capability to align the spacecraft at those distances on the ground. Testing can be done on the spacecraft individually and small scale alignments (for example, within the robodome at JPL), however testing the entire system as if it were flown on the ground is impossible. When proposing this mission special attention should be paid to identify and describe the testing, verification, and validation approach for the mission.

Cost Report

(1281) OMEGA
4/3/2012 – 4/5, 4/10/2012

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Cost
Table of Contents

Cost Assumptions - Option1

- **Fiscal Year: 2012**
- **Mission Class: B (Microprobes class C due to redundancy)**
- **Cost Category: Large**

- **Wrap Factors**
  - Phase A-D Reserves: 30% - Not calculated on LV and Tracking costs
  - Phase E-F Reserves: 30% - Not calculated on LV and Tracking costs
  - E&PO: 1%

Cost Assumptions - Option2

- **Fiscal Year: 2012**
- **Mission Class: B (Microprobes class C due to redundancy)**
- **Cost Category: Large**

- **Wrap Factors**
  - Phase A-D Reserves: 30% - Not calculated on LV and Tracking costs
  - Phase E-F Reserves: 30% - Not calculated on LV and Tracking costs
  - E&PO: 1%

Cost Assumptions

- **Management and Systems Engineering**
  - Project – Project level management and system engineering costs are book kept with the Microprobes.
  - Payload – The payload management and systems engineering costs are assumed to be included in the individual instrument costs since there is only one unique type of instrument.
  - Flight System – Flight system management and system engineering costs are book kept with the Microprobes.
- **ATLO**
  - Calculated separately for Microprobes and Propulsion Module.
- **Mission Assurance**
  - Calculated together for both units and book kept with the Microprobes.
  - Assuming Class C (due to the Microprobes) and elements built out-of-house.

Cost Assumptions

- **6 flight system testbeds.**
- **Assumed New Frontiers levels of staffing for program management and systems engineering.**
  - Based on customer team estimate of total cost started with Discovery levels of staffing, but increased the estimate since the total cost is over $1B.
- **NLS II Contract LV cost estimated at $125M.**
  - Goddard and KSC estimate the NLS II Contract cost at $125M after procurement and NASA costs
  - Customer estimate for NLS II Contract cost is $57M (increased to $67M by 18% procurement burden).
- **Option 1 – 12 month Phase A, 15 month Phase B, 67 month Phase C/D, 24 month Phase E**
- **Option 2 – 9 month Phase A, 12 month Phase B, 49 month Phase C/D, 24 month Phase E**

Cost

Cost Total - Option1

COST SUMMARY (FY2012 $M)	Generate ProPricer Input	Team X Estimate		
		CBE	Res.	PBE
Project Cost		$1086.2 M	26%	$1372.1 M
Launch Vehicle		$125.0 M	0%	$125.0 M
Project Cost (w/o LV)		$961.2 M	30%	$1247.1 M
Development Cost		$897.3 M	30%	$1166.1 M
Phase A		$12.4 M	30%	$16.1 M
Phase B		$55.1 M	30%	$71.6 M
Phase C/D		$829.8 M	30%	$1078.4 M
Operations Cost		$63.9 M	27%	$81.0 M

Cost

Cost AD - Option1

WBS Elements	NRE	RE	1st Unit	All Units
Project Cost (including Launch Vehicle)	$687.4	$173.3	$860.7	$1372.1 M
Development Cost (Phases A - D)	$492.4 M	$171.5 M	$663.9 M	$1166.1 M
01.0 Project Management	$20.9 M		$20.9 M	$20.9 M
02.0 Project Systems Engineering	$19.6 M	$0.2 M	$19.8 M	$20.8 M
03.0 Mission Assurance	$10.1 M	$2.9 M	$13.1 M	$27.8 M
04.0 Science	$13.9 M		$13.9 M	$13.9 M
05.0 Payload System	$40.2 M	$29.1 M	$69.3 M	$214.9 M
Microprobes	$40.2 M	$29.1 M	$69.3 M	$214.9 M
Instrument	$40.2 M	$29.1 M	$69.3 M	$214.9 M

06.0 Flight System	$174.2 M	$79.1 M	$253.3 M	$435.5 M
6.01 Flight System Management	$15.0 M		$15.0 M	$15.0 M
6.02 Flight System Systems Engineering	$20.5 M		$20.5 M	$20.5 M
Microprobes	$79.9 M	$33.5 M	$113.4 M	$280.9 M
6.04 Power	$6.4 M	$6.6 M	$13.0 M	$46.1 M
6.05 C&DH	$9.7 M	$5.3 M	$15.0 M	$41.5 M
6.06 Telecom	$10.1 M	$6.9 M	$17.0 M	$51.6 M
6.07 Structures (includes Mech. I&T)	$12.2 M	$5.4 M	$17.6 M	$44.7 M
6.08 Thermal	$1.8 M	$1.3 M	$3.2 M	$9.9 M
6.09 Propulsion	$9.6 M	$2.4 M	$12.0 M	$23.8 M
6.10 ACS	$11.3 M	$4.0 M	$15.3 M	$35.0 M
6.11 Harness	$1.8 M	$0.6 M	$2.5 M	$5.6 M
6.12 S/C Software	$16.4 M	$0.9 M	$17.2 M	$21.5 M
6.13 Materials and Processes	$0.6 M	$0.1 M	$0.6 M	$0.9 M
Propulsion Module	$49.9 M	$42.6 M	$92.6 M	$92.6 M
6.04 Power	$6.4 M	$6.9 M	$13.3 M	$13.3 M
6.05 C&DH	$2.5 M	$10.0 M	$12.6 M	$12.6 M
6.06 Telecom	$1.0 M	$3.1 M	$4.2 M	$4.2 M
6.07 Structures (includes Mech. I&T)	$8.7 M	$5.9 M	$14.6 M	$14.6 M
6.08 Thermal	$2.9 M	$2.9 M	$5.9 M	$5.9 M
6.09 Propulsion	$6.8 M	$7.9 M	$14.7 M	$14.7 M
6.10 ACS	$8.0 M	$4.6 M	$12.5 M	$12.5 M
6.11 Harness	$2.3 M	$0.7 M	$3.0 M	$3.0 M
6.12 S/C Software	$10.6 M	$0.6 M	$11.2 M	$11.2 M
6.13 Materials and Processes	$0.7 M	$0.1 M	$0.7 M	$0.7 M
6.14 Spacecraft Testbeds	$8.8 M	$2.9 M	$11.8 M	$26.5 M
07.0 Mission Operations Preparation	$30.9 M		$30.9 M	$30.9 M
7.0 MOS Teams	$26.7 M		$26.7 M	$26.7 M
7.03 DSN Tracking (Launch Ops.)	$1.2 M		$1.2 M	$1.2 M
7.06 Navigation Operations Team	$2.9 M		$2.9 M	$2.9 M
7.08 Mission Planning Team	$0.0 M		$0.0 M	$0.0 M
09.0 Ground Data Systems	$30.6 M		$30.6 M	$30.6 M
9.0 Ground Data System	$30.1 M		$30.1 M	$30.1 M
9.06 Navigation H/W & S/W Development	$0.5 M		$0.5 M	$0.5 M
10.0 ATLO	$23.0 M	$20.1 M	$43.1 M	$84.5 M
Microprobes	$18.6 M	$8.3 M	$26.9 M	$68.2 M
Propulsion Module	$4.4 M	$11.8 M	$16.2 M	$16.2 M
11.0 Education and Public Outreach	$1.4 M	$0.4 M	$1.8 M	$3.1 M
12.0 Mission and Navigation Design	$14.3 M		$14.3 M	$14.3 M
Development Reserves	$113.4 M	$39.6 M	$152.9 M	$268.8 M

Cost EF - Option1

Operations Cost (Phases E - F)	$69.9 M	$1.8 M	$71.8 M	$81.0 M
01.0 Project Management	$3.1 M		$3.1 M	$3.1 M
02.0 Project Systems Engineering	$0.0 M	$0.0 M	$0.0 M	$0.0 M
03.0 Mission Assurance	$0.2 M	$0.1 M	$0.3 M	$1.0 M
04.0 Science	$18.8 M		$18.8 M	$18.8 M
07.0 Mission Operations	$26.1 M		$26.1 M	$26.1 M
09.0 Ground Data Systems	$3.0 M		$3.0 M	$3.0 M
11.0 Education and Public Outreach	$4.2 M	$1.3 M	$5.5 M	$11.9 M
12.0 Mission and Navigation Design	$0.0 M		$0.0 M	$0.0 M
Operations Reserves	$14.5 M	$0.4 M	$15.0 M	$17.1 M
8.0 Launch Vehicle	$125.0 M		$125.0 M	$125.0 M

Cost

Cost Total - Option2

COST SUMMARY (FY2012 $M)	Generate ProPricer Input	Team X Estimate		
		CBE	Res.	PBE
Project Cost		$969.7 M	26%	$1220.6 M
Launch Vehicle		$125.0 M	0%	$125.0 M
Project Cost (w/o LV)		$844.7 M	30%	$1095.6 M
Development Cost		$782.1 M	30%	$1016.4 M
Phase A		$10.2 M	30%	$13.3 M
Phase B		$49.8 M	30%	$64.8 M
Phase C/D		$722.1 M	30%	$938.3 M
Operations Cost		$62.5 M	27%	$79.2 M

Cost AD - Option2

WBS Elements	NRE	RE	1st Unit	All Units
Project Cost (including Launch Vehicle)	$610.5	$155.5	$766.0	$1220.6 M
Development Cost (Phases A - D)	$416.4 M	$153.8 M	$570.2 M	$1016.4 M
01.0 Project Management	$15.7 M		$15.7 M	$15.7 M
02.0 Project Systems Engineering	$14.7 M	$0.2 M	$14.8 M	$15.7 M
03.0 Mission Assurance	$9.0 M	$2.7 M	$11.7 M	$25.5 M
04.0 Science	$11.5 M		$11.5 M	$11.5 M
05.0 Payload System	$36.8 M	$26.6 M	$63.4 M	$196.6 M
Microprobes	$36.8 M	$26.6 M	$63.4 M	$196.6 M
Instrument	$36.8 M	$26.6 M	$63.4 M	$196.6 M

06.0 Flight System	$150.3 M	$69.6 M	$219.9 M	$374.3 M
6.01 Flight System Management	$11.1 M		$11.1 M	$11.1 M
6.02 Flight System Systems Engineering	$15.1 M		$15.1 M	$15.1 M
Microprobes	$70.8 M	$28.3 M	$99.1 M	$240.6 M
6.04 Power	$4.9 M	$4.6 M	$9.5 M	$32.5 M
6.05 C&DH	$7.4 M	$5.3 M	$12.7 M	$39.2 M
6.06 Telecom	$8.6 M	$5.6 M	$14.2 M	$41.9 M
6.07 Structures (includes Mech. I&T)	$10.2 M	$4.9 M	$15.2 M	$39.8 M
6.08 Thermal	$1.7 M	$1.3 M	$3.0 M	$9.8 M
6.09 Propulsion	$9.6 M	$2.4 M	$12.0 M	$23.8 M
6.10 ACS	$10.3 M	$2.8 M	$13.1 M	$27.0 M
6.11 Harness	$1.3 M	$0.5 M	$1.8 M	$4.3 M
6.12 S/C Software	$16.2 M	$0.9 M	$17.0 M	$21.3 M
6.13 Materials and Processes	$0.6 M	$0.1 M	$0.6 M	$0.9 M
Propulsion Module	$45.5 M	$38.7 M	$84.2 M	$84.2 M
6.04 Power	$4.9 M	$5.0 M	$9.9 M	$9.9 M
6.05 C&DH	$2.5 M	$10.0 M	$12.6 M	$12.6 M
6.06 Telecom	$1.0 M	$3.1 M	$4.2 M	$4.2 M
6.07 Structures (includes Mech. I&T)	$8.6 M	$5.8 M	$14.4 M	$14.4 M
6.08 Thermal	$2.1 M	$2.2 M	$4.3 M	$4.3 M
6.09 Propulsion	$6.7 M	$7.8 M	$14.4 M	$14.4 M
6.10 ACS	$7.0 M	$3.6 M	$10.6 M	$10.6 M
6.11 Harness	$1.7 M	$0.5 M	$2.2 M	$2.2 M
6.12 S/C Software	$10.4 M	$0.5 M	$11.0 M	$11.0 M
6.13 Materials and Processes	$0.7 M	$0.1 M	$0.7 M	$0.7 M
6.14 Spacecraft Testbeds	$7.8 M	$2.6 M	$10.4 M	$23.3 M
07.0 Mission Operations Preparation	$26.0 M		$26.0 M	$26.0 M
7.0 MOS Teams	$21.9 M		$21.9 M	$21.9 M
7.03 DSN Tracking (Launch Ops.)	$1.2 M		$1.2 M	$1.2 M
7.06 Navigation Operations Team	$2.9 M		$2.9 M	$2.9 M
7.08 Mission Planning Team	$0.0 M		$0.0 M	$0.0 M
09.0 Ground Data Systems	$25.4 M		$25.4 M	$25.4 M
9.0 Ground Data System	$25.0 M		$25.0 M	$25.0 M
9.06 Navigation H/W & S/W Development	$0.5 M		$0.5 M	$0.5 M
10.0 ATLO	$19.3 M	$18.8 M	$38.1 M	$77.9 M
Microprobes	$16.0 M	$8.0 M	$24.0 M	$63.9 M
Propulsion Module	$3.3 M	$10.8 M	$14.1 M	$14.1 M
11.0 Education and Public Outreach	$1.2 M	$0.4 M	$1.6 M	$2.7 M
12.0 Mission and Navigation Design	$10.8 M		$10.8 M	$10.8 M
Development Reserves	$95.8 M	$35.5 M	$131.3 M	$234.3 M

Cost EF - Option2

Operations Cost (Phases E - F)	$69.2 M	$1.7 M	$70.8 M	$79.2 M
01.0 Project Management	$3.1 M		$3.1 M	$3.1 M
02.0 Project Systems Engineering	$0.0 M	$0.0 M	$0.0 M	$0.0 M
03.0 Mission Assurance	$0.2 M	$0.1 M	$0.3 M	$1.0 M
04.0 Science	$18.8 M		$18.8 M	$18.8 M
07.0 Mission Operations	$26.1 M		$26.1 M	$26.1 M
09.0 Ground Data Systems	$3.0 M		$3.0 M	$3.0 M
11.0 Education and Public Outreach	$3.6 M	$1.2 M	$4.8 M	$10.5 M
12.0 Mission and Navigation Design	$0.0 M		$0.0 M	$0.0 M
Operations Reserves	$14.4 M	$0.4 M	$14.7 M	$16.7 M
8.0 Launch Vehicle	$125.0 M		$125.0 M	$125.0 M

Cost Potentials

Potential Cost Savings

- Staffing as appropriate for a Discovery mission would reduce the total cost (including reserves) by $36M for Option 1, and by $24M for Option 2.
  - Reducing the staffing would introduce a risk of overrun or lack of oversight given the total cost of the mission.
- Goddard and KSC estimate for NLS II Contract has a lower bound of $100M. This number could be used with an accompanying risk.

Potential Cost Uppers

- JPL Mars program is estimating NLS II Contract cost at $133M, which is $8M higher than the estimate used in this study.

Risk

List of Risks

- Schedule delay due to problems with protoflight unit
    - For Option 1, a 6 month delay (with full staffing and constant Phase D burn rate) would cost an estimated $71M, which would use up 26% of the total Phase A-D reserves.
    - For Option 2, a 6 month delay (with full staffing and constant Phase D burn rate) would cost an estimated $88M, which would use up 37% of the total Phase A-D reserves.

Cost

Option Cost Comparison

- **Option 2 has a shorter schedule, which decreases the cost of FTE-driven line items.**
  - 11% less total cost.
  - Effects noticeable across every WBS item in phases A-D.

COST SUMMARY (FY2012 $M)	Option 1	Option 2
WBS Elements	All Units	All Units
Project Cost (including Launch Vehicle)	$1372.1 M	$1220.6 M
Development Cost (Phases A - D)	$1166.1 M	$1016.4 M
01.0 Project Management	$20.9 M	$15.7 M
02.0 Project Systems Engineering	$20.8 M	$15.7 M
03.0 Mission Assurance	$27.8 M	$25.5 M
04.0 Science	$13.9 M	$11.5 M
05.0 Payload System	$214.9 M	$196.6 M
06.0 Flight System	$435.5 M	$374.3 M
07.0 Mission Operations Preparation	$30.9 M	$26.0 M
09.0 Ground Data Systems	$30.6 M	$25.4 M
10.0 ATLO	$84.5 M	$77.9 M
11.0 Education and Public Outreach	$3.1 M	$2.7 M
12.0 Mission and Navigation Design	$14.3 M	$10.8 M
Development Reserves	$268.8 M	$234.3 M
Operations Cost (Phases E - F)	$81.0 M	$79.2 M
01.0 Project Management	$3.1 M	$3.1 M
02.0 Project Systems Engineering	$0.0 M	$0.0 M
03.0 Mission Assurance	$1.0 M	$1.0 M
04.0 Science	$18.8 M	$18.8 M
07.0 Mission Operations	$26.1 M	$26.1 M
09.0 Ground Data Systems	$3.0 M	$3.0 M
11.0 Education and Public Outreach	$11.9 M	$10.5 M
12.0 Mission and Navigation Design	$0.0 M	$0.0 M
Operations Reserves	$17.1 M	$16.7 M
8.0 Launch Vehicle	$125.0 M	$125.0 M
Launch Vehicle and Processing	$125.0 M	$125.0 M
Nuclear Payload Support	$0.0 M	$0.0 M

Generate ProPricer Input | WBS Dictionary

Cost

Option Flight System Cost Comparison

- **Flight System cost difference are also driven by schedule**
- **14% less for the Microprobes, and 9% less for the Propulsion Module**

COST SUMMARY (FY2012 $M)	Option 1	Option 2
WBS Elements	**All Units**	**All Units**
06.0 Flight System	**$435.5 M**	**$374.3 M**
6.01 Flight System Management	$15.0 M	$11.1 M
6.02 Flight System Systems Engineering	$20.5 M	$15.1 M
6.03 Product Assurance (included in 3.0)	$0.0 M	$0.0 M
Microprobes	$280.9 M	$240.6 M
6.04 Power	$46.1 M	$32.5 M
6.05 C&DH	$41.5 M	$39.2 M
6.06 Telecom	$51.6 M	$41.9 M
6.07 Structures (includes Mech. I&T)	$44.7 M	$39.8 M
6.08 Thermal	$9.9 M	$9.8 M
6.09 Propulsion	$23.8 M	$23.8 M
6.10 ACS	$35.0 M	$27.0 M
6.11 Harness	$5.6 M	$4.3 M
6.12 S/C Software	$21.5 M	$21.3 M
6.13 Materials and Processes	$0.9 M	$0.9 M
Propulsion Module	$92.6 M	$84.2 M
6.04 Power	$13.3 M	$9.9 M
6.05 C&DH	$12.6 M	$12.6 M
6.06 Telecom	$4.2 M	$4.2 M
6.07 Structures (includes Mech. I&T)	$14.6 M	$14.4 M
6.08 Thermal	$5.9 M	$4.3 M
6.09 Propulsion	$14.7 M	$14.4 M
6.10 ACS	$12.5 M	$10.6 M
6.11 Harness	$3.0 M	$2.2 M
6.12 S/C Software	$11.2 M	$11.0 M
6.13 Materials and Processes	$0.7 M	$0.7 M
6.14 Spacecraft Testbeds	$26.5 M	$23.3 M

Generate ProPricer Input

Cost
Comparison to GRAIL

- **GRAIL flight system costs from time of launch, in FY12 dollars.**
  - GRAIL was a two spacecraft mission.
  - GRAIL mission with six spacecraft estimated assuming GRAIL costs were 67% non-recurring cost and 33% recurring cost (from GRAIL PM estimate but not verified).

COST SUMMARY (FY2012 $M)	Generate ProPricer Input	Option 1	Option 2	Grail	Grail 6 unit
WBS Elements		All Units	All Units	2 Units	All Units
Microprobes		$280.9 M	$240.6 M	$116.4 M	$232.8 M
6.04 Power		$46.1 M	$32.5 M	$11.5 M	$22.9 M
6.05 C&DH		$41.5 M	$39.2 M	$27.2 M	$54.3 M
6.06 Telecom		$51.6 M	$41.9 M	$7.9 M	$15.9 M
6.07 Structures (includes Mech. I&T)		$44.7 M	$39.8 M	$17.3 M	$34.6 M
6.08 Thermal		$9.9 M	$9.8 M	$3.0 M	$5.9 M
6.09 Propulsion		$23.8 M	$23.8 M	$11.4 M	$22.8 M
6.10 ACS		$35.0 M	$27.0 M	$14.4 M	$28.7 M
6.11 Harness		$5.6 M	$4.3 M	$2.2 M	$4.4 M
6.12 S/C Software		$21.5 M	$21.3 M	$21.6 M	$43.2 M
6.13 Materials and Processes		$0.9 M	$0.9 M		