JPL Team X Space-based Gravitational-Wave Observatory (SGO) Mid and High Study Report

Customer: Jeffrey Livas
September 2012
Final report v.2.4 (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.

1279 SGO-Mid 2012-03 Study, Team X Final Report, 4/13/12

TEAM X
Jet Propulsion Laboratory

Customer: Jeffrey Livas, Jeff Booth
Facilitator: Cate Heneghan
Sessions: March 5-8, 2012
Study ID: 1279

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- 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.

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Executive Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Cate Heneghan
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Executive Summary

Study Overview

- **Team X examined 2 existing designs for the SGO mission**
- **The SGO options were originally designed and costed at GSFC as part of the LISA project effort.**
- **Team X was to check the feasibility of the designs and costs and make changes as needed.**
- **SGO is one of 3 Gravitational Wave experiment missions Team X will review this Spring**
  - For consistency, certain assumptions about margins and reserves will be made for all three studies

Executive Summary
Mission Architecture and Assumptions

- **Mission Architecture**
  - Three flight systems, each is a sciencecraft contained in a propulsion stage
  - Stack of three flight systems is launched on a single launch vehicle
  - Propulsion stage delivers the sciencecraft to the desired orbit then releases it and drops away
  - Three sciencecraft are placed in a helio-centric orbit, in a plane 60 degrees off sun, equidistant from each other
  - Instrument is fully integrated into the craft, thus the nomenclature “sciencecraft”
  - Each sciencecraft contains two lasers that can lock on each of the other sciencecraft.
- **Assumptions**
  - All three flight systems are identical
  - Selected spares – don’t necessarily carry 3 spares for 3 flight systems
  - 53% contingency on mass and 43% contingency on power
  - 30% reserves on cost
  - NLS II Launch Vehicle

Executive Summary

Overview of Options

- **Option 1 – SGO Mid**
  - Smaller sciencecraft / instrument (twin 25-cm telescopes w/lasers)
  - Helio-centric, Earth-trailing, drift away orbit
  - 1 million km spacing between each sciencecraft
  - 45 months for Phase E

- **Option 2 – SGO High**
  - Larger sciencecraft / instrument (twin 40-cm telescopes w/lasers)
  - Helio-centric, Earth-trailing, stable orbit
  - 5 million km spacing between each sciencecraft
  - 81 months for Phase E

Executive Summary

Major Trades/Conclusions – Option 1

- **One HGA instead of two HGAs**
  - Cut down on power, complexity and cost
- **Mono-prop instead of bi-prop**
  - Mono-prop saves complexity and cost

Executive Summary
Major Trades/Conclusions – Option 2

- **One HGA instead of two HGAs**
  - Cut down on power, complexity and cost
- **Mono-prop vs bi-prop**
  - Bi-prop was needed to accommodate the large distances the flight systems must travel
- **Light weighting the two Prop Stages on the top of the launch stack**
  - Quick calculations showed that not enough mass would be saved to fit the stack within the launch mass capability

- **Option 2 did not converge to fit within the LV mass constraints**
  - Opt. 2 was expected to converge because the customer's design converged.
  - It seems the customer underestimated the mass of the propulsion stages and, in turn, the delta V required.
  - This design cannot converge within the given constraints. However if some of these were relaxed, it might be possible to close the design.
    - Use a non NLS II LV like the Falcon 9 Heavy
    - Use a smaller mass contingency and light weight the top two propulsion stages

Executive Summary

Option Comparison

- **Note that mass and costs are not valid for Option 2 as it did not converge. The numbers given here are for reference only.**

	Telescope size (cm)	Prop System on Prop Stage	Science-craft mass (kg)	Cruise-craft mass, dry (kg)	3-stack mass, wet (Launch mass) (kg)	Mission cost ($B)
SGO Mid	25	Mono-Prop	717.5	1378	4553	1.9
SGO High	40	Bi-Prop	797.1	1641	5822	2.1

Executive Summary
Technical Findings

- **Option 1 fit within the LV constraints of volume and mass**
  - Design seems feasible with minor risks
  - Each Sciencecraft is 717.5 kg
  - Each Prop Stage with Sciencecraft is 1378 kg dry
    - Requiring 139.5 kg Hydrazine monopropellant
  - Total launch mass for 3-stack is 4553 kg, leaving 26% margin on LV capability
  - Cost of mission is $1.9B
- **Option 2 did not converge to fit within the LV mass constraints**
  - Team X proceeded with design as though an appropriately sized LV existed.
  - Each Sciencecraft is 797.1 kg
  - Each Prop Stage with Sciencecraft is 1641 kg dry
    - Requiring 299.4 kg Biprop
  - Total launch mass for 3-stack is 5938 kg, leaving 2% margin on LV capability
  - Cost of mission is $2.1B (assumed LV cost equaled that of an AtlasV 551)

Executive Summary

Risk

- The SGO High design is too massive for the largest launch vehicle in the NLS II database.

- There is a moderate risk that the lifetime of the colloidal thrusters is not long enough to survive the SGO High mission. This risk and several other minor risks are detailed in the Risk section of this report.

Systems Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: George Sprague

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

Systems
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- Conclusions for SGO High
- Option Comparison
- Risks

Systems
Options Overview

- **SGO Mid**
  - Three Earth trailing spacecraft in an equilateral triangle formation consisting of a Sciencecraft and Propulsion Module: Together they are called the Cruisecraft
    - 1 million km baseline
    - 2 years in science formation
  - Twin 25 cm telescopes (each) with lasers.
  - Arrive on-station 6/1/2022, Launch ~18 months prior
  - 45 mos for Phase E
- **SGO High**
  - The same as MID except
    - 5 million km baseline
    - 5 years in science formation
  - Twin 40 cm telescopes (each) with lasers.
  - Arrive on-station 6/1/2022, Launch ~18 months prior
  - 81 mos for Phase E

Mission Design

Scenario – SGO Mid

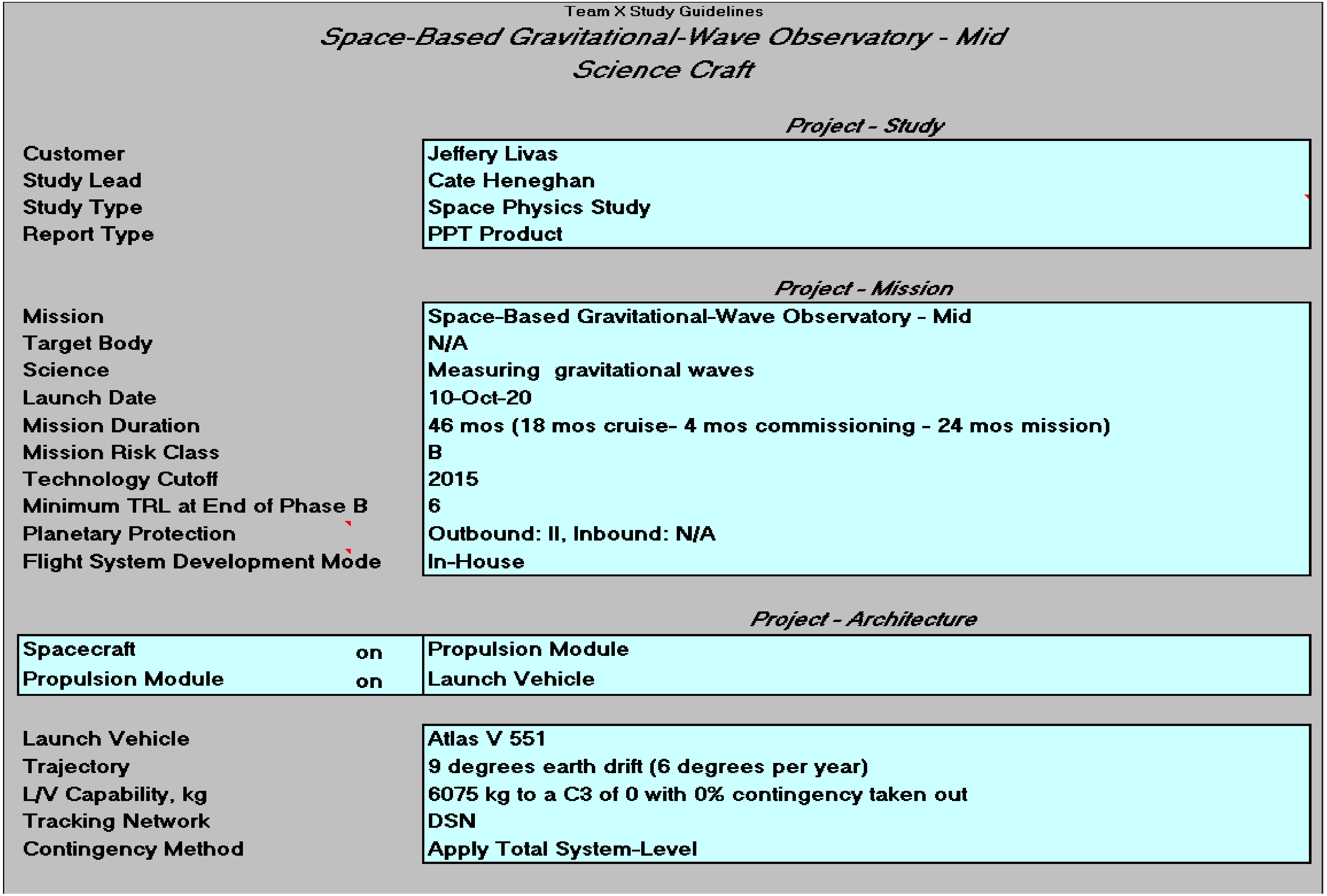
- **Mission Design**
  - Drift-away at ~ 5.5 deg/year (start at 9 deg, move to 21 deg)
- **Rationale**
  - The center of the constellation was chosen as the launch target because it captured the main common features of all three spacecraft and should minimize the DV required post-launch for each spacecraft.
  - The single most important common feature was the average drift-away rate.

Systems
Assumptions on SGO Mid

- Assumptions
  - 53% contingency on mass (in order to compare masses assumed by MDL at GSFC)
  - 43% contingency on power
  - 30% reserves on cost
  - 30% margin on Phase E costs as opposed to a nominal 15%.
  - Three identical Sciencecraft designed to be separated from the propulsion module.
  - Identical Propulsion Modules with identical structures
    - All three modules were sized to take launch loads stacked with three Cruisecraft (Sciencecraft and propulsion modules together.)
  - Clamp band incorporates the electrical connections between Sciencecraft and Propulsion Module.
  - Delta V was assumed to be 200 m/s for all three Cruisecraft.
  - A policy of selected spares was assumed
  - Customer provided MEL was used with only the modifications thought necessary by the chairs to update the design and save costs.

Systems

Mission Level Requirements for Sciencecraft



Team X Study Guidelines

Space-Based Gravitational-Wave Observatory - Mid

Science Craft

Project - Study

Customer	Jeffery Livas
Study Lead	Cate Heneghan
Study Type	Space Physics Study
Report Type	PPT Product

Project - Mission

Mission	Space-Based Gravitational-Wave Observatory - Mid
Target Body	N/A
Science	Measuring gravitational waves
Launch Date	10-Oct-20
Mission Duration	46 mos (18 mos cruise- 4 mos commissioning - 24 mos mission)
Mission Risk Class	B
Technology Cutoff	2015
Minimum TRL at End of Phase B	6
Planetary Protection	Outbound: II, Inbound: N/A
Flight System Development Mode	In-House

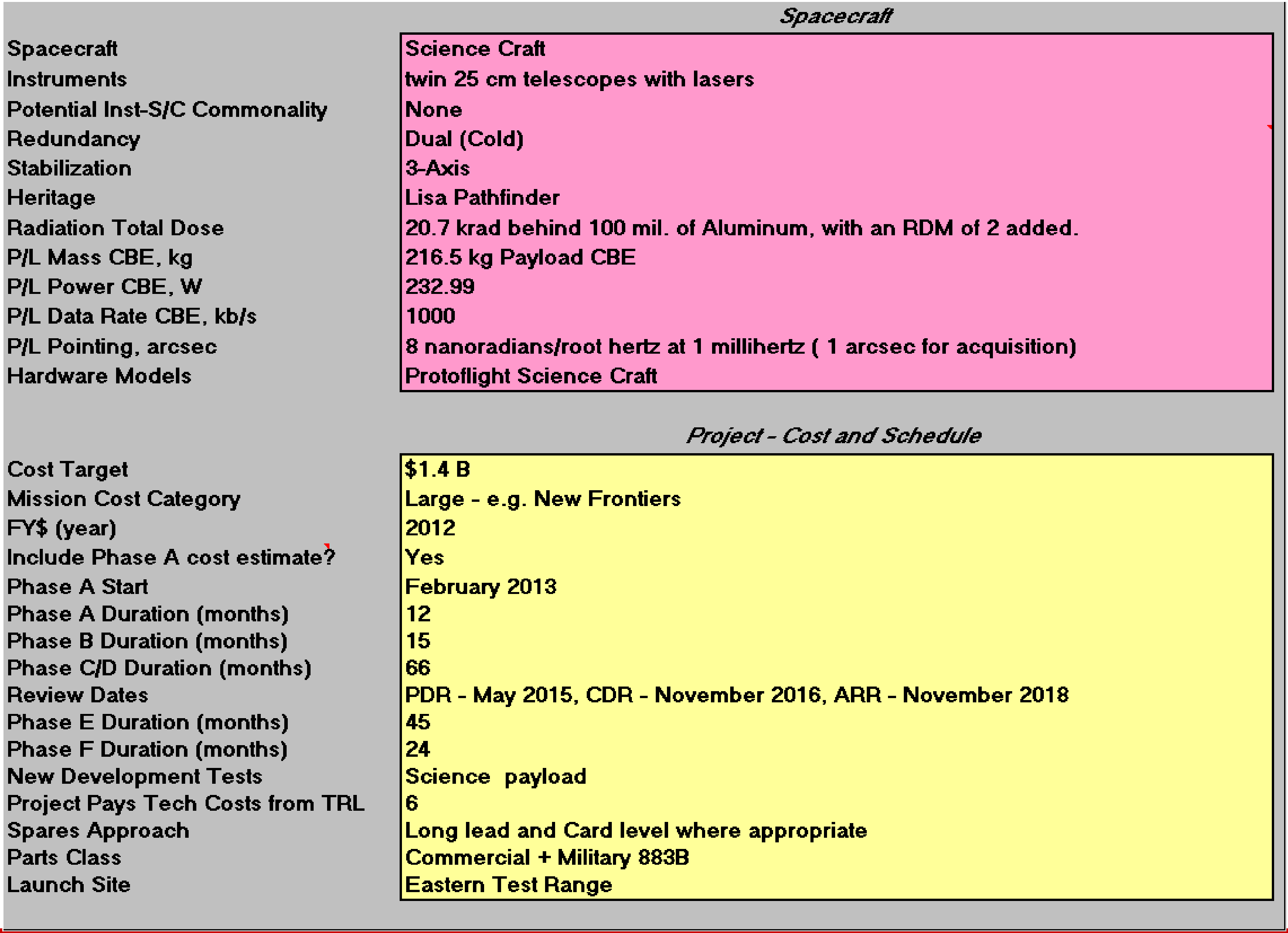
Project - Architecture

Spacecraft	on	Propulsion Module
Propulsion Module	on	Launch Vehicle

Launch Vehicle	Atlas V 551
Trajectory	9 degrees earth drift (6 degrees per year)
L/V Capability, kg	6075 kg to a C3 of 0 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Systems

Mission Level Requirements for Sciencecraft



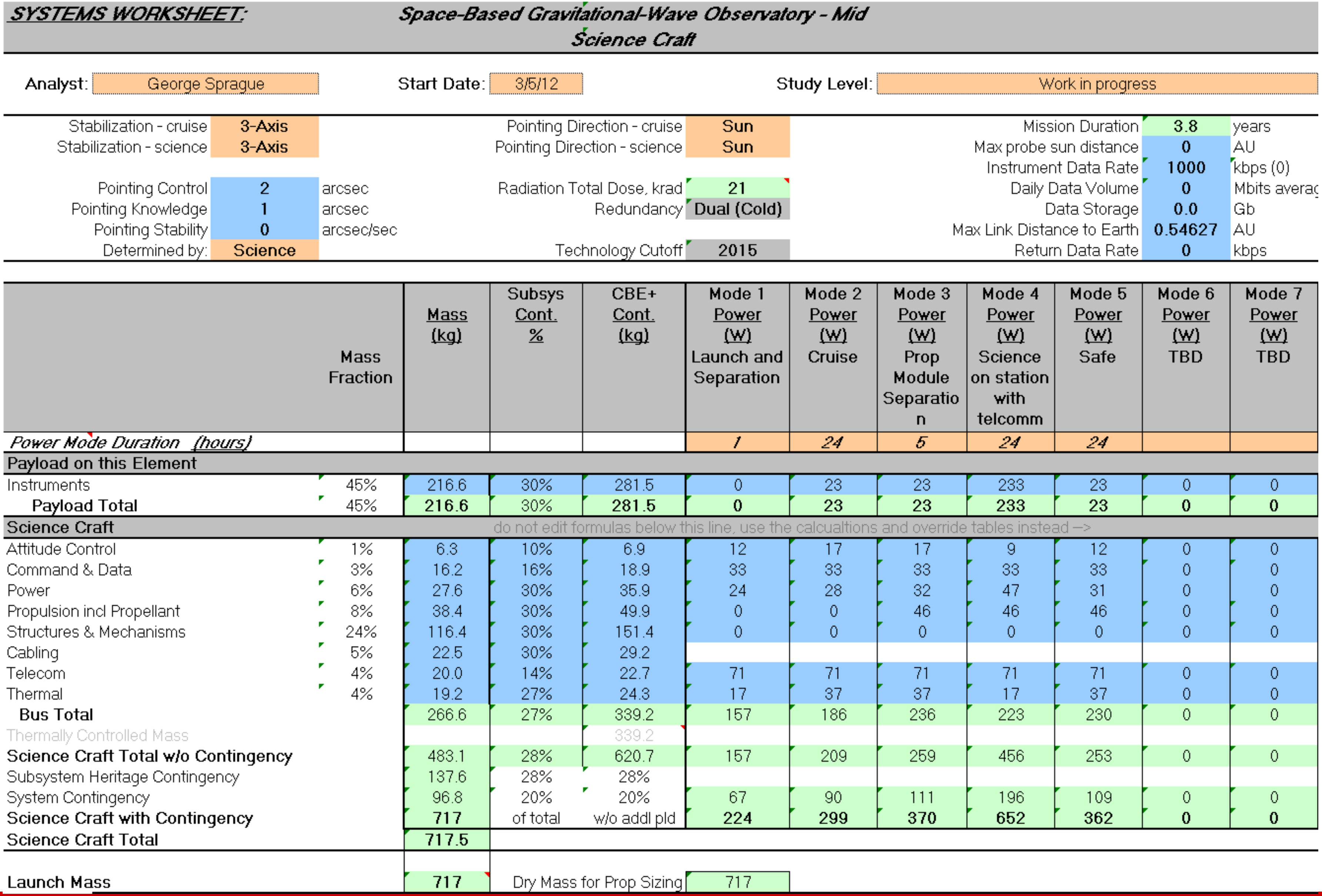
Spacecraft

Spacecraft	Science Craft
Instruments	twin 25 cm telescopes with lasers
Potential Inst-S/C Commonality	None
Redundancy	Dual (Cold)
Stabilization	3-Axis
Heritage	Lisa Pathfinder
Radiation Total Dose	20.7 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
P/L Mass CBE, kg	216.5 kg Payload CBE
P/L Power CBE, W	232.99
P/L Data Rate CBE, kb/s	1000
P/L Pointing, arcsec	8 nanoradians/root hertz at 1 millihertz (1 arcsec for acquisition)
Hardware Models	Protoflight Science Craft

Project - Cost and Schedule

Cost Target	$1.4 B
Mission Cost Category	Large - e.g. New Frontiers
FY$ (year)	2012
Include Phase A cost estimate?	Yes
Phase A Start	February 2013
Phase A Duration (months)	12
Phase B Duration (months)	15
Phase C/D Duration (months)	66
Review Dates	PDR - May 2015, CDR - November 2016, ARR - November 2018
Phase E Duration (months)	45
Phase F Duration (months)	24
New Development Tests	Science payload
Project Pays Tech Costs from TRL	6
Spares Approach	Long lead and Card level where appropriate
Parts Class	Commercial + Military 883B
Launch Site	Eastern Test Range

Systems
Sciencecraft Subsystems with Power Modes



SYSTEMS WORKSHEET: **_Space-Based Gravitational-Wave Observatory - Mid Science Craft_**

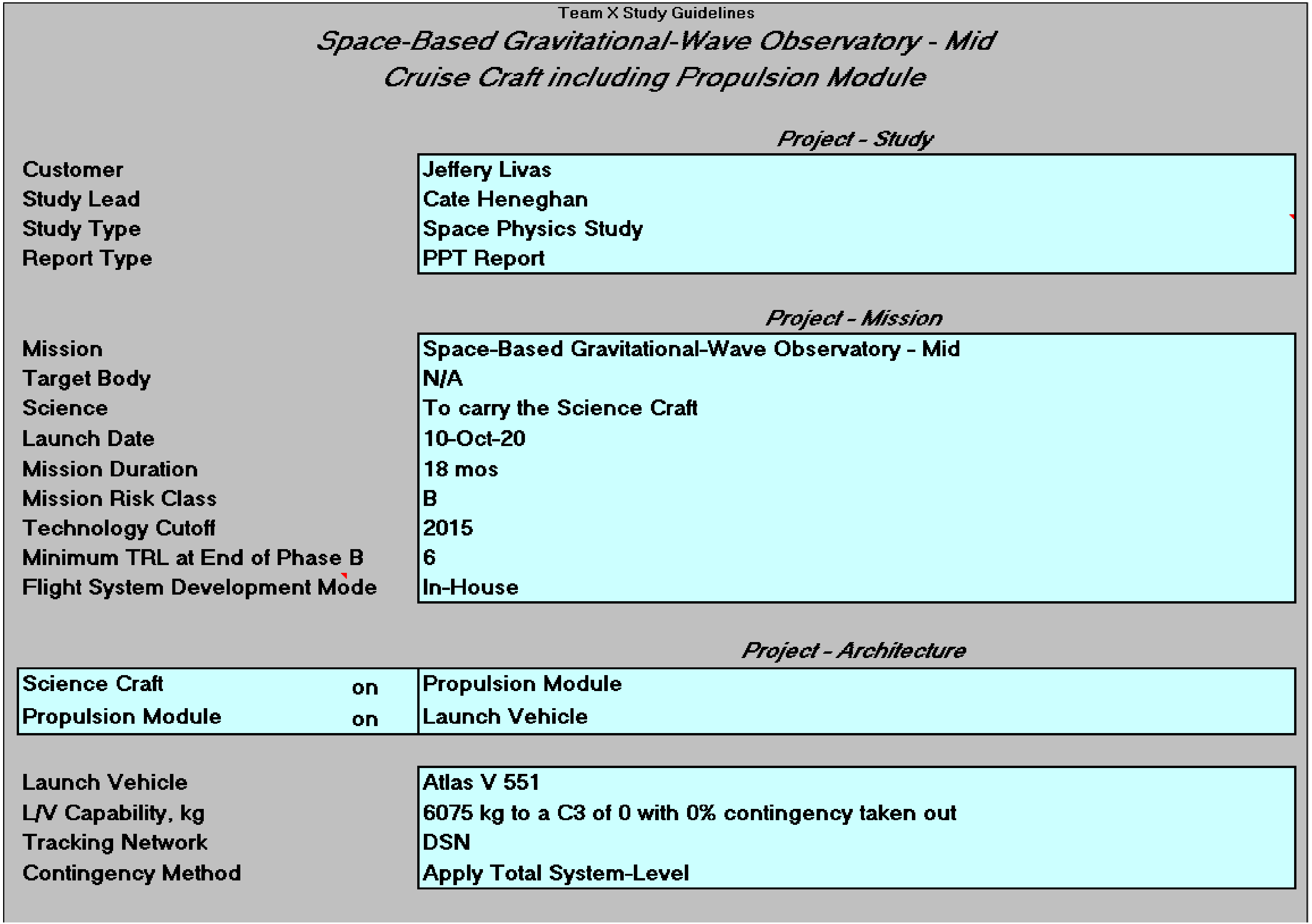
Analyst:	George Sprague	Start Date:	3/5/12	Study Level:	Work in progress

Stabilization - cruise	3-Axis		Pointing Direction - cruise	Sun	Mission Duration	3.8	years
Stabilization - science	3-Axis		Pointing Direction - science	Sun	Max probe sun distance	0	AU
					Instrument Data Rate	1000	kbps (0)
Pointing Control	2	arcsec	Radiation Total Dose, krad	21	Daily Data Volume	0	Mbits averag
Pointing Knowledge	1	arcsec	Redundancy	Dual (Cold)	Data Storage	0.0	Gb
Pointing Stability	0	arcsec/sec			Max Link Distance to Earth	0.54627	AU
Determined by:	Science		Technology Cutoff	2015	Return Data Rate	0	kbps

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch and Separation	Mode 2 Power (W) Cruise	Mode 3 Power (W) Prop Module Separation	Mode 4 Power (W) Science on station with telcomm	Mode 5 Power (W) Safe	Mode 6 Power (W) TBD	Mode 7 Power (W) TBD
Power Mode Duration (hours)					*1*	*24*	*5*	*24*	*24*		
Payload on this Element											
Instruments	45%	216.6	30%	281.5	0	23	23	233	23	0	0
Payload Total	45%	**216.6**	30%	**281.5**	**0**	**23**	**23**	**233**	**23**	**0**	**0**
Science Craft			do not edit formulas below this line, use the calcualtions and override tables instead -->								
Attitude Control	1%	6.3	10%	6.9	12	17	17	9	12	0	0
Command & Data	3%	16.2	16%	18.9	33	33	33	33	33	0	0
Power	6%	27.6	30%	35.9	24	28	32	47	31	0	0
Propulsion incl Propellant	8%	38.4	30%	49.9	0	0	46	46	46	0	0
Structures & Mechanisms	24%	116.4	30%	151.4	0	0	0	0	0	0	0
Cabling	5%	22.5	30%	29.2							
Telecom	4%	20.0	14%	22.7	71	71	71	71	71	0	0
Thermal	4%	19.2	27%	24.3	17	37	37	17	37	0	0
Bus Total		266.6	27%	339.2	157	186	236	223	230	0	0
Thermally Controlled Mass				339.2							
Science Craft Total w/o Contingency		483.1	28%	620.7	157	209	259	456	253	0	0
Subsystem Heritage Contingency		137.6	28%	28%							
System Contingency		96.8	20%	20%	67	90	111	196	109	0	0
Science Craft with Contingency		**717**	of total	w/o addl pld	**224**	**299**	**370**	**652**	**362**	**0**	**0**
Science Craft Total		**717.5**									
Launch Mass		**717**		Dry Mass for Prop Sizing	717						

Systems

Propulsion Module Requirements



Team X Study Guidelines

Space-Based Gravitational-Wave Observatory - Mid

Cruise Craft including Propulsion Module

Project - Study

Customer	Jeffery Livas
Study Lead	Cate Heneghan
Study Type	Space Physics Study
Report Type	PPT Report

Project - Mission

Mission	Space-Based Gravitational-Wave Observatory - Mid
Target Body	N/A
Science	To carry the Science Craft
Launch Date	10-Oct-20
Mission Duration	18 mos
Mission Risk Class	B
Technology Cutoff	2015
Minimum TRL at End of Phase B	6
Flight System Development Mode	In-House

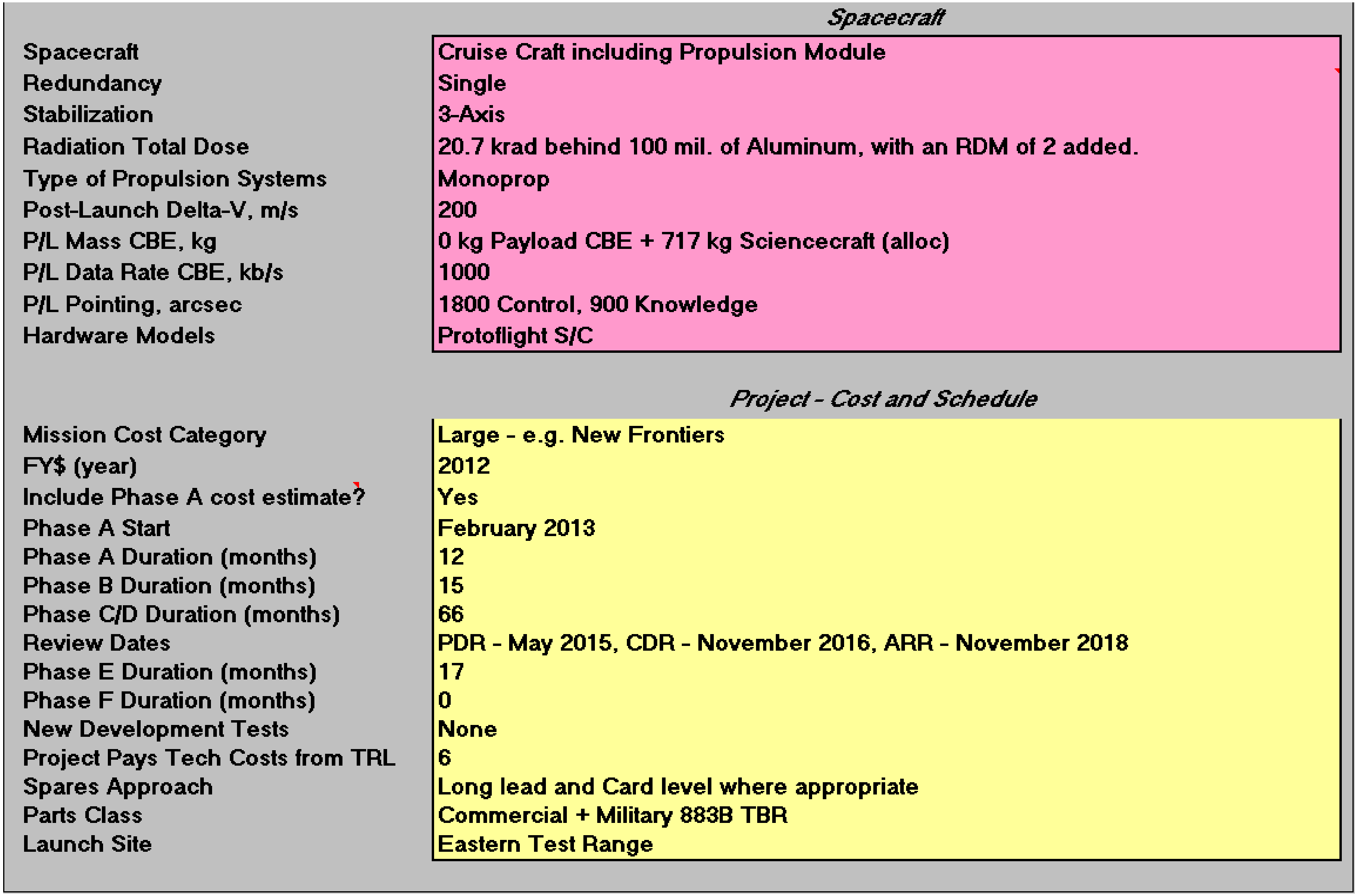
Project - Architecture

Science Craft	on	Propulsion Module
Propulsion Module	on	Launch Vehicle

Launch Vehicle	Atlas V 551
L/V Capability, kg	6075 kg to a C3 of 0 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Systems

Propulsion Module Requirements



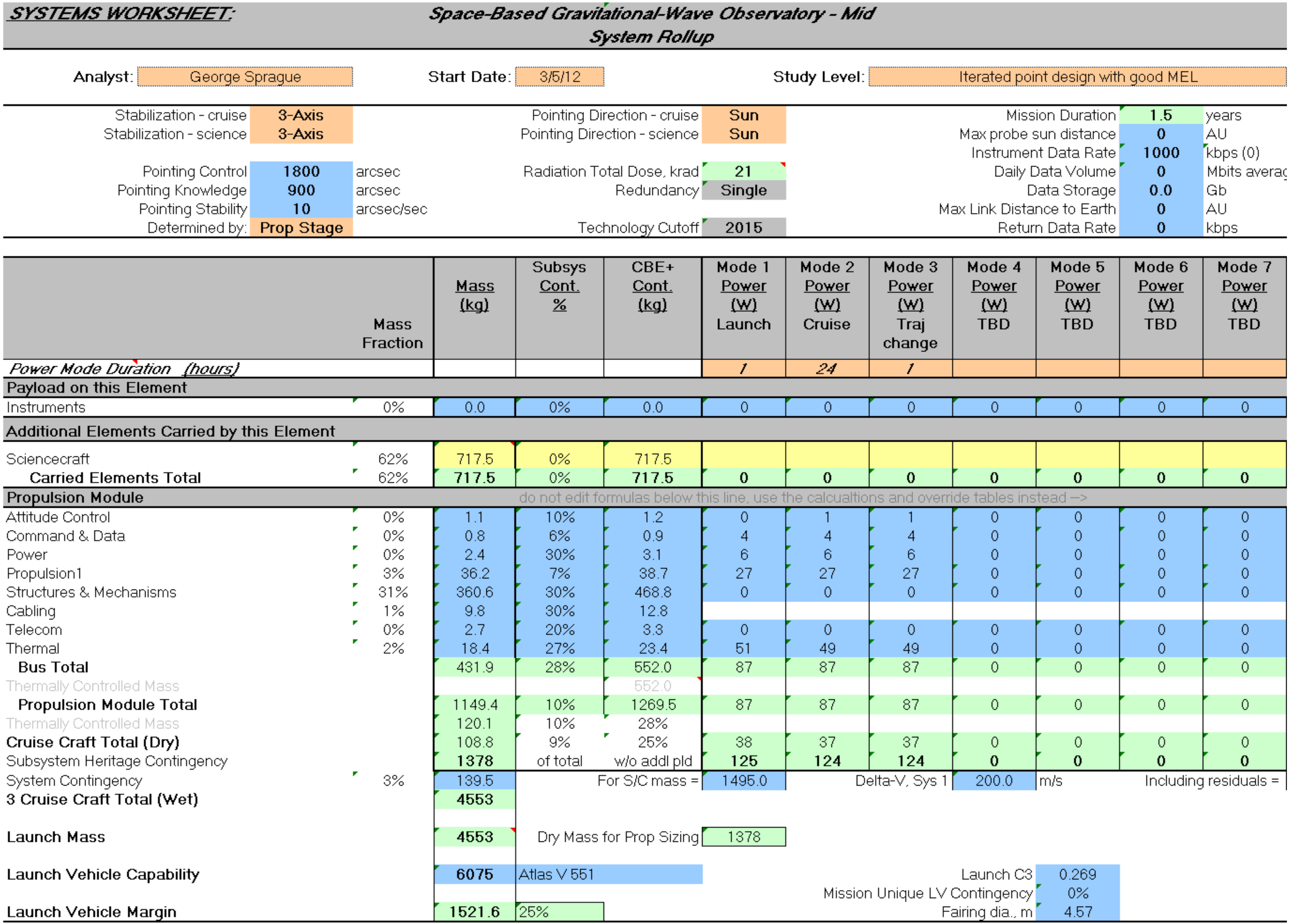
Spacecraft

Spacecraft	Cruise Craft including Propulsion Module
Redundancy	Single
Stabilization	3-Axis
Radiation Total Dose	20.7 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
Type of Propulsion Systems	Monoprop
Post-Launch Delta-V, m/s	200
P/L Mass CBE, kg	0 kg Payload CBE + 717 kg Sciencecraft (alloc)
P/L Data Rate CBE, kb/s	1000
P/L Pointing, arcsec	1800 Control, 900 Knowledge
Hardware Models	Protoflight S/C

Project - Cost and Schedule

Mission Cost Category	Large - e.g. New Frontiers
FY$ (year)	2012
Include Phase A cost estimate?	Yes
Phase A Start	February 2013
Phase A Duration (months)	12
Phase B Duration (months)	15
Phase C/D Duration (months)	66
Review Dates	PDR - May 2015, CDR - November 2016, ARR - November 2018
Phase E Duration (months)	17
Phase F Duration (months)	0
New Development Tests	None
Project Pays Tech Costs from TRL	6
Spares Approach	Long lead and Card level where appropriate
Parts Class	Commercial + Military 883B TBR
Launch Site	Eastern Test Range

Systems
Prop Module with Rollup to Cruisecraft



SYSTEMS WORKSHEET:

Space-Based Gravitational-Wave Observatory - Mid
System Rollup

Analyst: George Sprague   Start Date: 3/5/12   Study Level: Iterated point design with good MEL

Stabilization - cruise	3-Axis		Pointing Direction - cruise	Sun		Mission Duration	1.5	years
Stabilization - science	3-Axis		Pointing Direction - science	Sun		Max probe sun distance	0	AU
						Instrument Data Rate	1000	kbps (0)
Pointing Control	1800	arcsec	Radiation Total Dose, krad	21		Daily Data Volume	0	Mbits averag
Pointing Knowledge	900	arcsec	Redundancy	Single		Data Storage	0.0	Gb
Pointing Stability	10	arcsec/sec				Max Link Distance to Earth	0	AU
Determined by:	Prop Stage		Technology Cutoff	2015		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) Traj change	Mode 4 Power (W) TBD	Mode 5 Power (W) TBD	Mode 6 Power (W) TBD	Mode 7 Power (W) TBD
Power Mode Duration (hours)					*1*	*24*	*1*				
Payload on this Element											
Instruments	0%	0.0	0%	0.0	0	0	0	0	0	0	0
Additional Elements Carried by this Element											
Sciencecraft	62%	717.5	0%	717.5							
Carried Elements Total	62%	**717.5**	0%	**717.5**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Propulsion Module			do not edit formulas below this line, use the calcualtions and override tables instead -->								
Attitude Control	0%	1.1	10%	1.2	0	1	1	0	0	0	0
Command & Data	0%	0.8	6%	0.9	4	4	4	0	0	0	0
Power	0%	2.4	30%	3.1	6	6	6	0	0	0	0
Propulsion1	3%	36.2	7%	38.7	27	27	27	0	0	0	0
Structures & Mechanisms	31%	360.6	30%	468.8	0	0	0	0	0	0	0
Cabling	1%	9.8	30%	12.8							
Telecom	0%	2.7	20%	3.3	0	0	0	0	0	0	0
Thermal	2%	18.4	27%	23.4	51	49	49	0	0	0	0
Bus Total		431.9	28%	552.0	87	87	87	0	0	0	0
Thermally Controlled Mass				552.0							
Propulsion Module Total		1149.4	10%	1269.5	87	87	87	0	0	0	0
Thermally Controlled Mass		120.1	10%	28%							
Cruise Craft Total (Dry)		108.8	9%	25%	38	37	37	0	0	0	0
Subsystem Heritage Contingency		**1378**	of total	w/o addl pld	**125**	**124**	**124**	**0**	**0**	**0**	**0**
System Contingency	3%	139.5		For S/C mass =	1495.0		Delta-V, Sys 1	200.0	m/s	Including residuals =	
3 Cruise Craft Total (Wet)		**4553**									
Launch Mass		**4553**		Dry Mass for Prop Sizing	1378						
Launch Vehicle Capability		**6075**	Atlas V 551					Launch C3	0.269		
								Mission Unique LV Contingency	0%		
Launch Vehicle Margin		**1521.6**	25%					Fairing dia., m	4.57		

Cleared for public release. For discussion purposes only.

Systems

Subsystems Highlights for the Mid Option

- **ACS**

  Attitude control hardware on the Sciencecraft: Colloidal thrusters with a thrust range of 4 to 150 µN. Attitude control hardware on the SGO-Mid prop module: hydrazine thrusters. Instrument and star tracker measurements used in pointing algorithms. Responsibility for pointing beams and spacecraft shifts to the payload during science operations.

- **CDS**

  - The C&DH subsystems for both options (SGO-Mid and -High) are identical. The Sciencecraft includes most of the C&DH hardware including the computer. The Prop Module has a MREU that resides in the Power Chassis. The Propulsion modules' CD&H subsystems are single string.

- **Power**

  - Array: Driving power mode - Science on station with telecommunications. Batteries: Driving power mode – Launch and separation. Redundancy met with use of ABSL design with its inherent series/parallel design. Allowing for additional strings. Electronics: Redundant boards.

- **Propulsion**

  - Sciencecraft Options 1 & 2 have a colloidal propulsion system based on ST7 design /heritage. Prop. Stage MID = blowdown Hydrazine monopropellant system (change from BiProp,). Prop. Stage HIGH.= regulated Hydrazine/NTO bi-propellant system.

Systems

Subsystems Highlights for the MID Option

- **Structure**
  - The materials utilized to construct the Primary Structure of the Sciencecraft for both the Mid and High options were a combination of machined aluminum and titanium with flat panels constructed of metallic honeycomb composite. The materials utilized to construct the Primary Structure of the Propulsion Stage for the Mid option were a combination of machined aluminum with flat panels constructed of metallic honeycomb composite. Due to the stacked launch configuration, additional material has be added for all propulsion stages.
- **Telecommunications**
  - The nominal design from the customer had a Ka-Band downlink for the science data and X-Band communications via LGAs for cruise and low rate engineering data. The science data rate is only 90 kbps – Ka-Band is not needed. To save money, the design was changed to remove the Ka-Band equipment as well as the second HGA.
- **Thermal**
  - Passive design is necessary due to strict stability requirements. Active heaters cycling on and off would disturb the system. Environment is steady, 60 degree inclination results in one revolution per year for the Sciencecraft.

Systems
Conclusions for the Mid Option

- **Mission Design**
  - Appears to be very doable.
- **Instrumentation and methodology**
  - Appears to be complete and well thought-out.
- **Strengths**
  - Low data rate from payload to ground.
  - Graceful degradation as links are lost from 6 to 4 (only with loss of 3 links is science threshold floor crossed.)
- **With the original approach and MEL: SGO Mid**
  - The design closes comfortably. The concept of placing the Sciencecraft inside of the load bearing Propulsion Module appear to be very viable. The drawback is that to save cost, the mass structure of the stack of 3 spacecraft is not optimized. A trade should be done in order to either find a different side by configuration or to optimize the structures and see if the stack will fit in a smaller launch vehicle.

Systems

Conclusions for the Mid and High Options

- **An ATLAS 551 can comfortably launch the entire SGO mid Cruisecraft stack**
  - 26% Margin over and above the 53% contingency applied to the total launch mass.
- **Power from the Solar Arrays for both Options should be closely monitored if any subsystems show any growth in power demand.**
  - 90% packing factor with the HGA promising to cast a shadow.
- **Suggested Changes to SGO Mid Option MEL to save costs**
  - Change from BiProp to a Monoprop blowdown system
  - Telecom change from Ka band to X band and removal of 1 HGA.
- **Risks**
  - Initial Assessment of SGO MID and HIGH only points at number of minor risks with one risk being rate as moderate for the HIGH option.
    - Lifetime thruster issues.

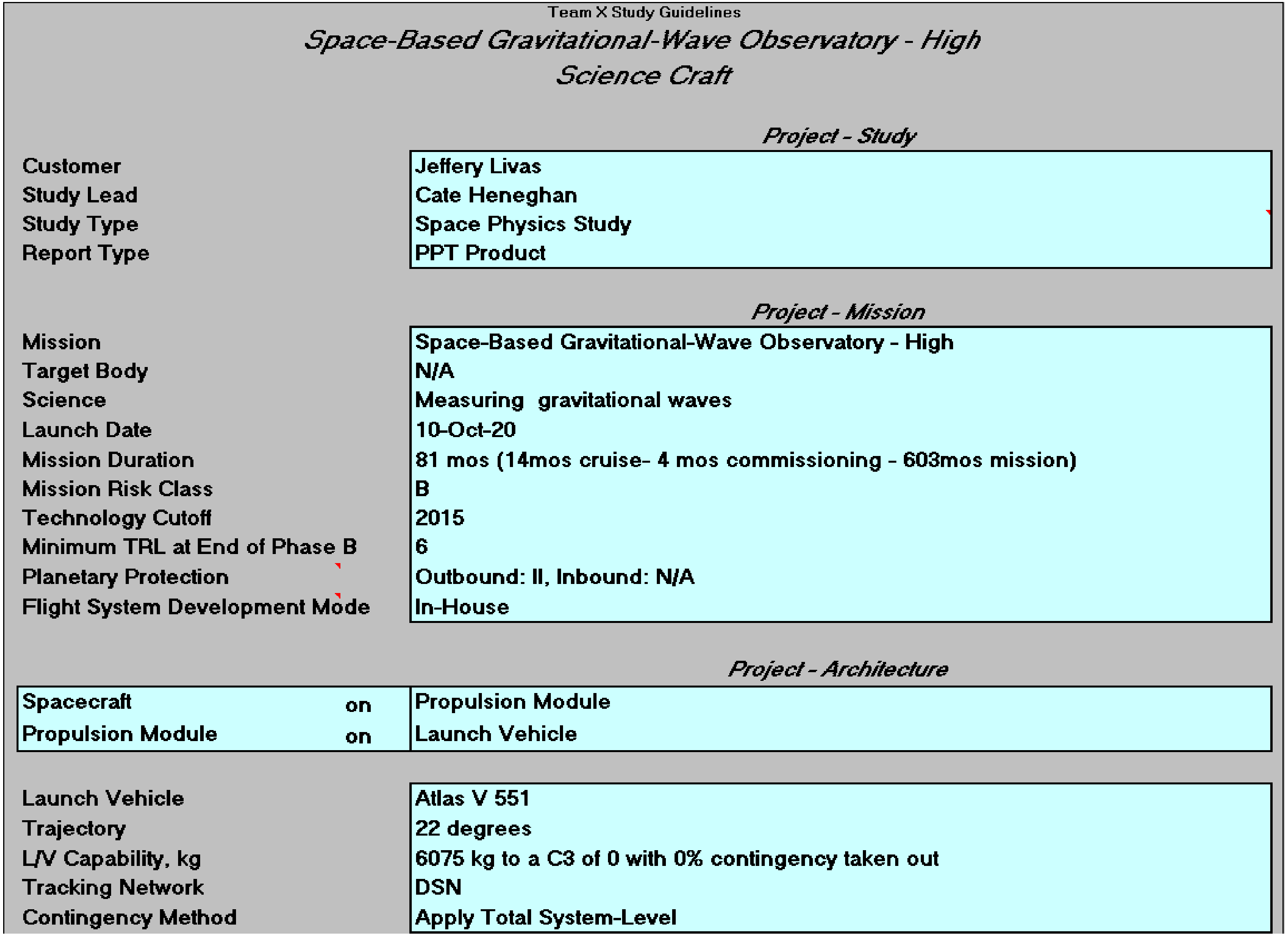
Systems

Assumptions on SGO High

- Assumptions on SGO High – similar to SGO Mid except for
    - 40 cm Telescopes
    - Longer baseline and mission.
    - Delta V required is about 1096 m/sec. Switch to BiProp vs Monoprop for propulsion and control.
- Standard Assumptions similar to SGO Mid.
    - 53% contingency on mass (in order to compare masses assumed by MDL at GSFC)
    - 43% contingency on power and 30% reserves on costs
    - 30% margin on Phase E costs as opposed to a nominal 15%.
    - Three identical Sciencecraft designed to be separated from the propulsion module.
    - Identical Propulsion Modules with identical structures.
    - Clamp band incorporates the electrical connections between Sciencecraft and Propulsion Module.
    - Chosen launch vehicle adapter is highly efficient.
    - Customer provided MEL was used with only the modifications thought necessary by the chairs to update the design and save costs.

Systems

Requirements for Sciencecraft for High Option



Team X Study Guidelines

Space-Based Gravitational-Wave Observatory - High

Science Craft

Project - Study

Customer	Jeffery Livas
Study Lead	Cate Heneghan
Study Type	Space Physics Study
Report Type	PPT Product

Project - Mission

Mission	Space-Based Gravitational-Wave Observatory - High
Target Body	N/A
Science	Measuring gravitational waves
Launch Date	10-Oct-20
Mission Duration	81 mos (14mos cruise- 4 mos commissioning - 603mos mission)
Mission Risk Class	B
Technology Cutoff	2015
Minimum TRL at End of Phase B	6
Planetary Protection	Outbound: II, Inbound: N/A
Flight System Development Mode	In-House

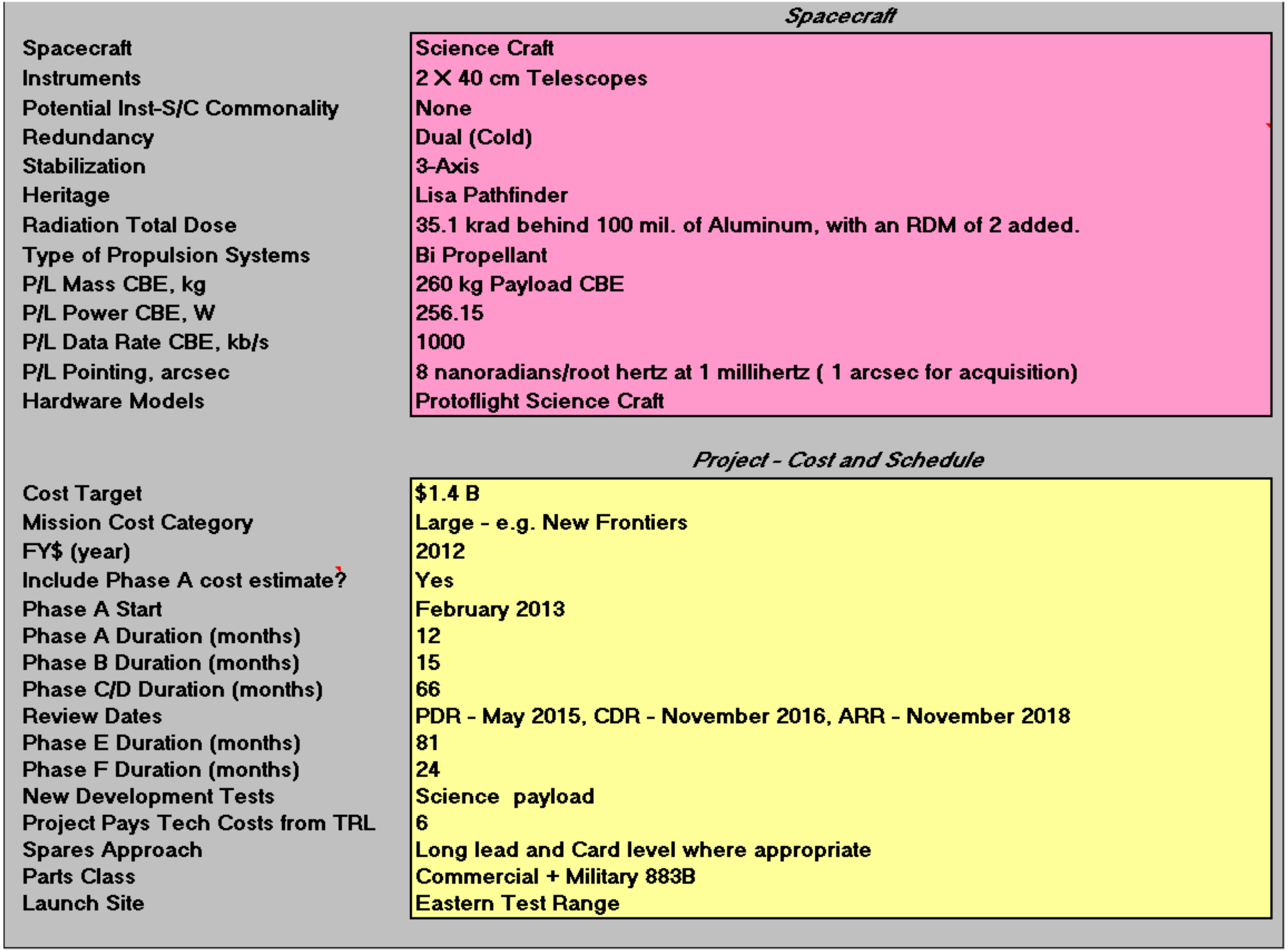
Project - Architecture

Spacecraft	on	Propulsion Module
Propulsion Module	on	Launch Vehicle

Launch Vehicle	Atlas V 551
Trajectory	22 degrees
L/V Capability, kg	6075 kg to a C3 of 0 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Systems

Requirements for Sciencecraft for High Option



Spacecraft

Spacecraft	Science Craft
Instruments	2 X 40 cm Telescopes
Potential Inst-S/C Commonality	None
Redundancy	Dual (Cold)
Stabilization	3-Axis
Heritage	Lisa Pathfinder
Radiation Total Dose	35.1 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
Type of Propulsion Systems	Bi Propellant
P/L Mass CBE, kg	260 kg Payload CBE
P/L Power CBE, W	256.15
P/L Data Rate CBE, kb/s	1000
P/L Pointing, arcsec	8 nanoradians/root hertz at 1 millihertz (1 arcsec for acquisition)
Hardware Models	Protoflight Science Craft

Project - Cost and Schedule

Cost Target	$1.4 B
Mission Cost Category	Large - e.g. New Frontiers
FY$ (year)	2012
Include Phase A cost estimate?	Yes
Phase A Start	February 2013
Phase A Duration (months)	12
Phase B Duration (months)	15
Phase C/D Duration (months)	66
Review Dates	PDR - May 2015, CDR - November 2016, ARR - November 2018
Phase E Duration (months)	81
Phase F Duration (months)	24
New Development Tests	Science payload
Project Pays Tech Costs from TRL	6
Spares Approach	Long lead and Card level where appropriate
Parts Class	Commercial + Military 883B
Launch Site	Eastern Test Range

Systems
High Sciencecraft Subsystems with Power Modes

SYSTEMS WORKSHEET: ***Space-Based Gravitational-Wave Observatory - High Science Craft***

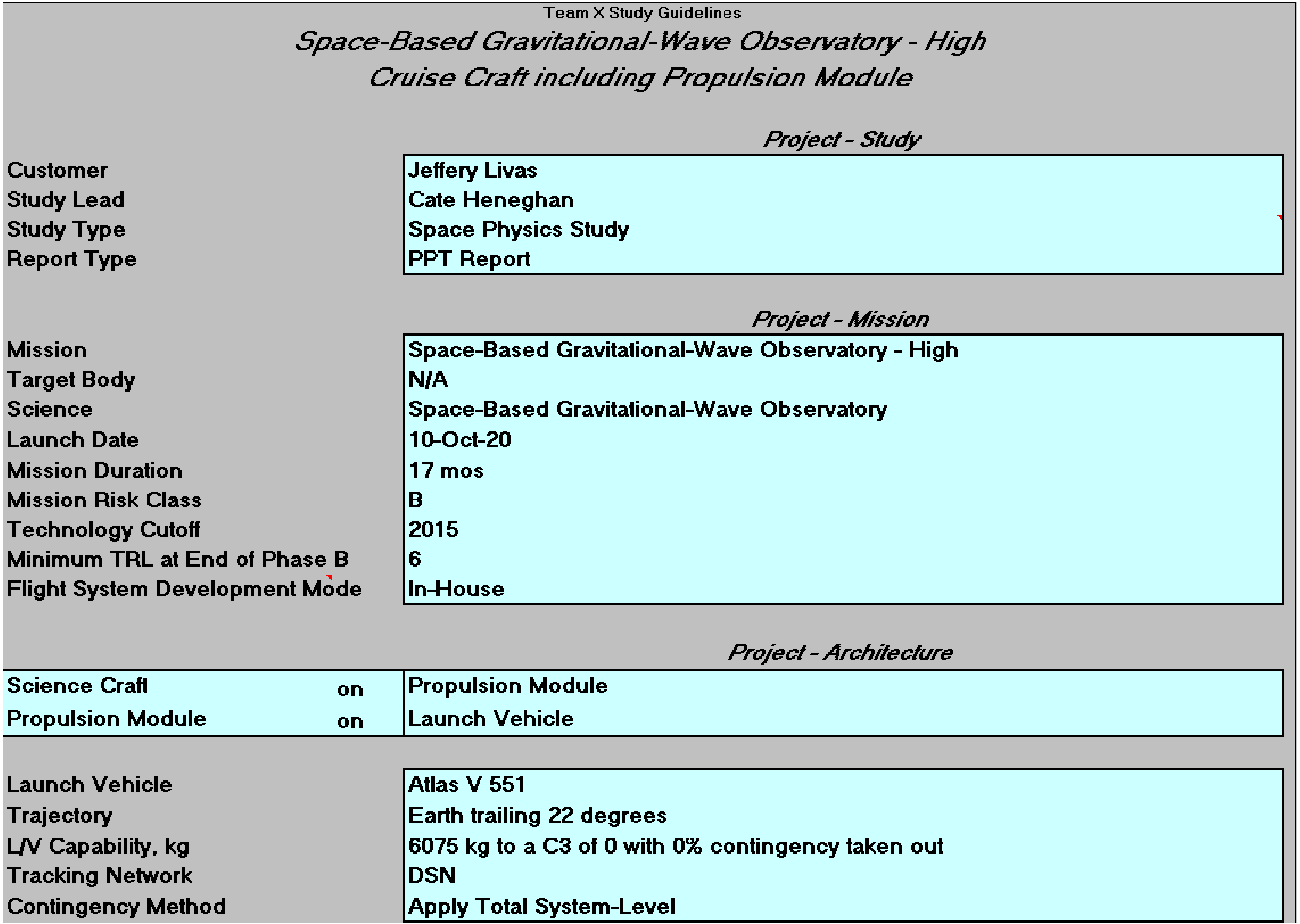
Analyst: George Sprague | Start Date: 3/5/12 | Study Level: Iterated point design with good MEL

Stabilization - cruise	3-Axis		Pointing Direction - cruise	Sun	Mission Duration	6.8	years
Stabilization - science	3-Axis		Pointing Direction - science	Sun	Max probe sun distance	0	AU
					Instrument Data Rate	1000	kbps (0)
Pointing Control	2	arcsec	Radiation Total Dose, krad	35	Daily Data Volume	0	Mbits averag
Pointing Knowledge	1	arcsec	Redundancy	Dual (Cold)	Data Storage	0.0	Gb
Pointing Stability	0	arcsec/sec			Max Link Distance to Earth	0	AU
Determined by:	Science		Technology Cutoff	2015	Return Data Rate	0	kbps

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch and Separatio	Mode 2 Power (W) Cruise	Mode 3 Power (W) Prop Module Separatio	Mode 4 Power (W) Science on station with	Mode 5 Power (W) Safe	Mode 6 Power (W) TBD	Mode 7 Power (W) TBD
Power Mode Duration (hours)					*1*	*24*	*5*	*24*	*24*		
Payload on this Element											
Instruments	48%	260.1	30%	338.1	0	26	26	256	26	0	0
Payload Total	48%	**260.1**	30%	**338.1**	**0**	**26**	**26**	**256**	**26**	**0**	**0**
Science Craft	do not edit formulas below this line, use the calcualtions and override tables instead -->										
Attitude Control	1%	6.3	10%	6.9	12	17	17	9	12	0	0
Command & Data	3%	16.2	16%	18.9	33	33	33	33	33	0	0
Power	5%	29.6	30%	38.4	24	29	33	50	32	0	0
Propulsion incl Propellant	7%	38.4	30%	49.9	0	0	46	46	46	0	0
Structures & Mechanisms	23%	124.8	30%	162.2	0	0	0	0	0	0	0
Cabling	4%	23.0	30%	29.8							
Telecom	4%	20.0	14%	22.7	71	71	71	71	71	0	0
Thermal	4%	19.7	27%	25.0	18	48	48	18	48	0	0
Bus Total		277.9	27%	353.9	157	198	247	225	241	0	0
Science Craft Total w/o Contingency		538.0	29%	692.0	157	223	273	481	267	0	0
Subsystem Heritage Contingency		154.0	29%	29%							
System Contingency		105.1	20%	20%	67	96	117	207	115	0	0
Science Craft with Contingency		**797**	of total	w/o addl pld	**224**	**319**	**390**	**689**	**381**	**0**	**0**
Science Craft Total		**797.1**									

Systems

High Propulsion Module Requirements



Team X Study Guidelines

Space-Based Gravitational-Wave Observatory - High
Cruise Craft including Propulsion Module

Project - Study

Customer	Jeffery Livas
Study Lead	Cate Heneghan
Study Type	Space Physics Study
Report Type	PPT Report

Project - Mission

Mission	Space-Based Gravitational-Wave Observatory - High
Target Body	N/A
Science	Space-Based Gravitational-Wave Observatory
Launch Date	10-Oct-20
Mission Duration	17 mos
Mission Risk Class	B
Technology Cutoff	2015
Minimum TRL at End of Phase B	6
Flight System Development Mode	In-House

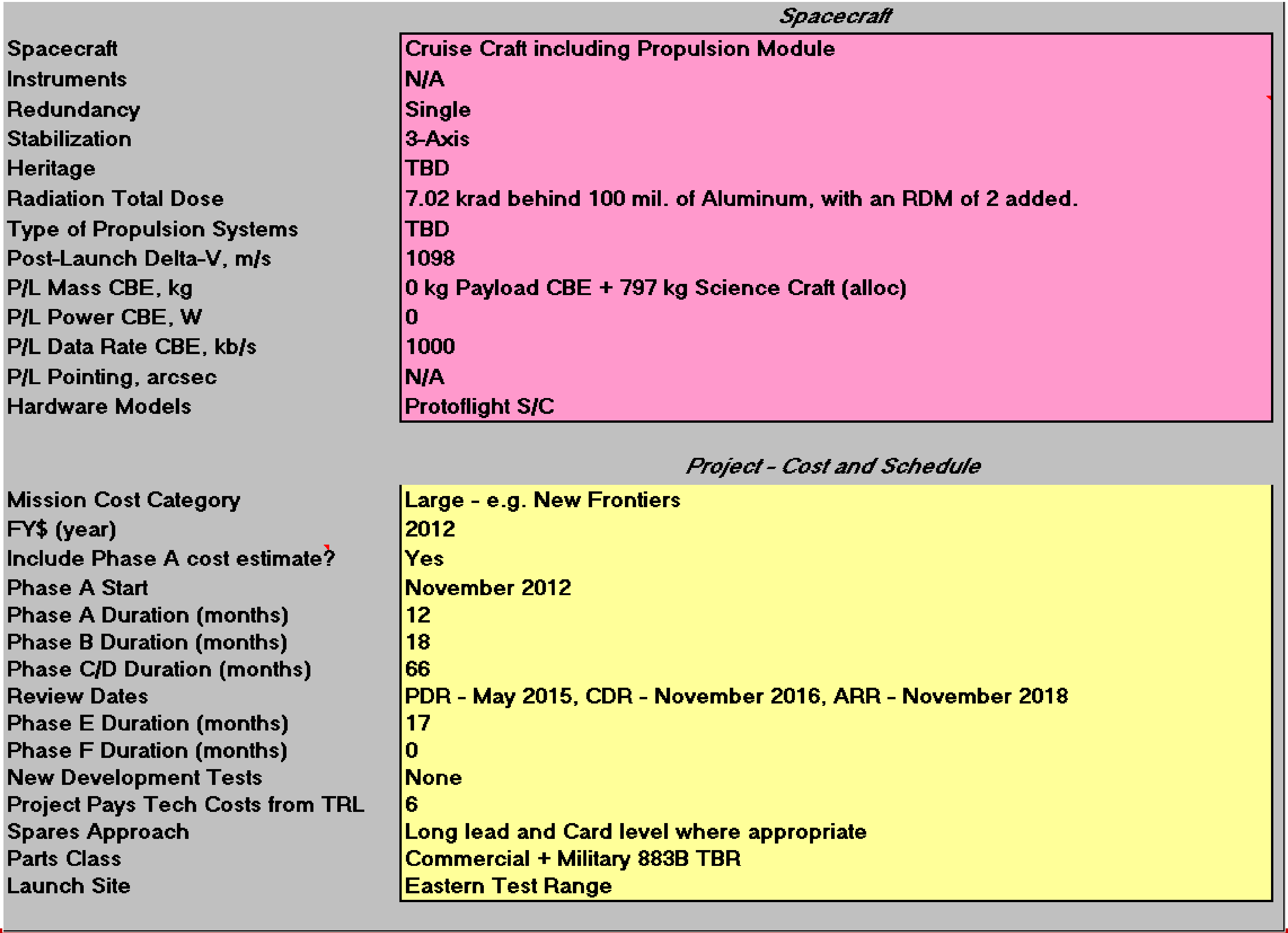
Project - Architecture

Science Craft	on	Propulsion Module
Propulsion Module	on	Launch Vehicle

Launch Vehicle	Atlas V 551
Trajectory	Earth trailing 22 degrees
L/V Capability, kg	6075 kg to a C3 of 0 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Systems

High Propulsion Module Requirements



Spacecraft

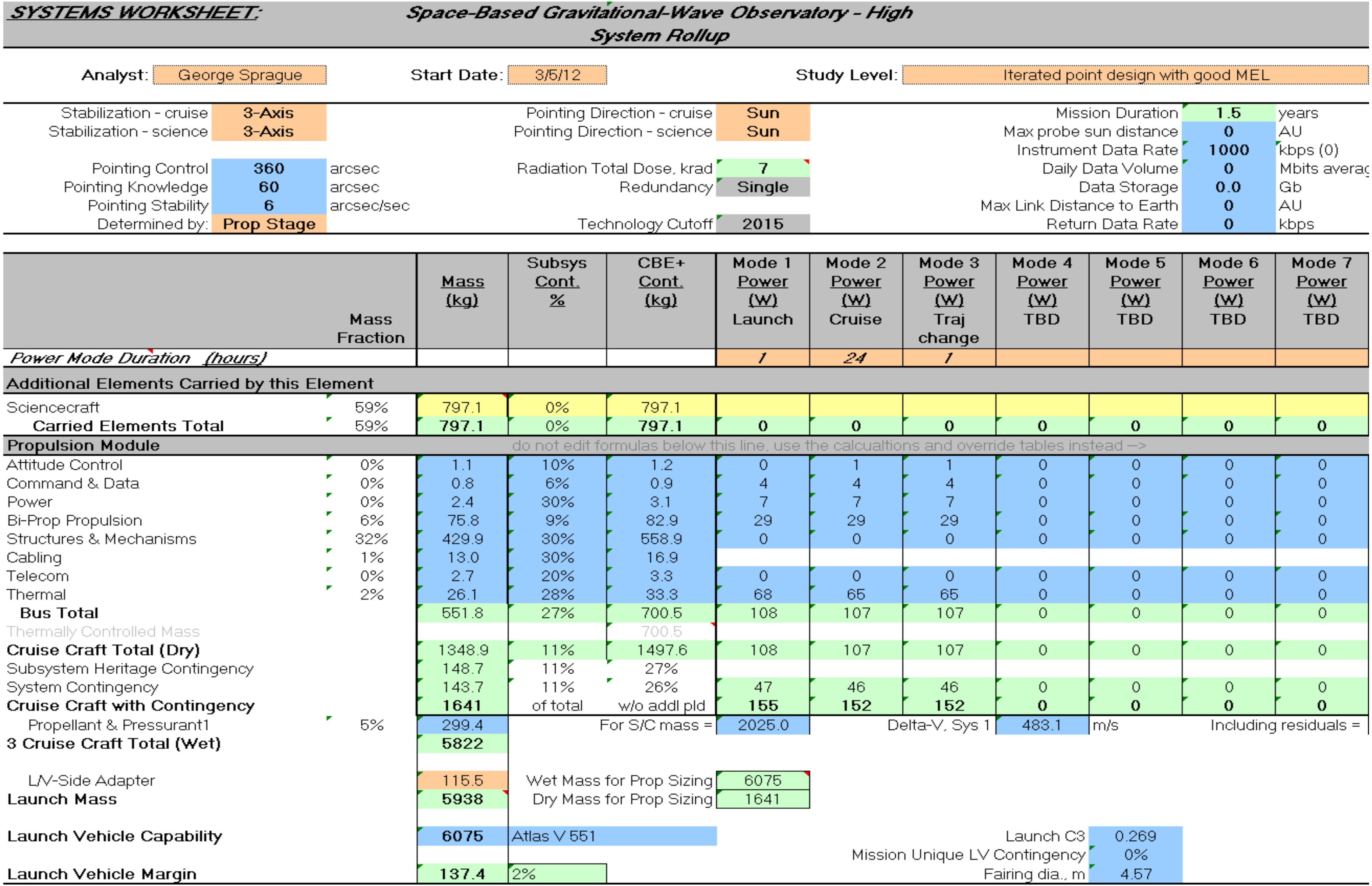
Spacecraft	Cruise Craft including Propulsion Module
Instruments	N/A
Redundancy	Single
Stabilization	3-Axis
Heritage	TBD
Radiation Total Dose	7.02 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
Type of Propulsion Systems	TBD
Post-Launch Delta-V, m/s	1098
P/L Mass CBE, kg	0 kg Payload CBE + 797 kg Science Craft (alloc)
P/L Power CBE, W	0
P/L Data Rate CBE, kb/s	1000
P/L Pointing, arcsec	N/A
Hardware Models	Protoflight S/C

Project - Cost and Schedule

Mission Cost Category	Large - e.g. New Frontiers
FY$ (year)	2012
Include Phase A cost estimate?	Yes
Phase A Start	November 2012
Phase A Duration (months)	12
Phase B Duration (months)	18
Phase C/D Duration (months)	66
Review Dates	PDR - May 2015, CDR - November 2016, ARR - November 2018
Phase E Duration (months)	17
Phase F Duration (months)	0
New Development Tests	None
Project Pays Tech Costs from TRL	6
Spares Approach	Long lead and Card level where appropriate
Parts Class	Commercial + Military 883B TBR
Launch Site	Eastern Test Range

Systems

High Prop Module Reqt. w/Rollup to Cruisecraft



SYSTEMS WORKSHEET: ***Space-Based Gravitational-Wave Observatory - High***
System Rollup

Analyst: George Sprague | Start Date: 3/5/12 | Study Level: Iterated point design with good MEL

Stabilization - cruise	3-Axis		Pointing Direction - cruise	Sun	Mission Duration	1.5	years
Stabilization - science	3-Axis		Pointing Direction - science	Sun	Max probe sun distance	0	AU
					Instrument Data Rate	1000	kbps (0)
Pointing Control	360	arcsec	Radiation Total Dose, krad	7	Daily Data Volume	0	Mbits averag
Pointing Knowledge	60	arcsec	Redundancy	Single	Data Storage	0.0	Gb
Pointing Stability	6	arcsec/sec			Max Link Distance to Earth	0	AU
Determined by:	Prop Stage		Technology Cutoff	2015	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) Traj change	Mode 4 Power (W) TBD	Mode 5 Power (W) TBD	Mode 6 Power (W) TBD	Mode 7 Power (W) TBD
Power Mode Duration (hours)					*1*	*24*	*1*				
Additional Elements Carried by this Element											
Sciencecraft	59%	797.1	0%	797.1							
Carried Elements Total	59%	**797.1**	0%	**797.1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Propulsion Module				do not edit formulas below this line, use the calcualtions and override tables instead -->							
Attitude Control	0%	1.1	10%	1.2	0	1	1	0	0	0	0
Command & Data	0%	0.8	6%	0.9	4	4	4	0	0	0	0
Power	0%	2.4	30%	3.1	7	7	7	0	0	0	0
Bi-Prop Propulsion	6%	75.8	9%	82.9	29	29	29	0	0	0	0
Structures & Mechanisms	32%	429.9	30%	558.9	0	0	0	0	0	0	0
Cabling	1%	13.0	30%	16.9							
Telecom	0%	2.7	20%	3.3	0	0	0	0	0	0	0
Thermal	2%	26.1	28%	33.3	68	65	65	0	0	0	0
Bus Total		551.8	27%	700.5	108	107	107	0	0	0	0
Thermally Controlled Mass				700.5							
Cruise Craft Total (Dry)		1348.9	11%	1497.6	108	107	107	0	0	0	0
Subsystem Heritage Contingency		148.7	11%	27%							
System Contingency		143.7	11%	26%	47	46	46	0	0	0	0
Cruise Craft with Contingency		**1641**	of total	w/o addl pld	**155**	**152**	**152**	**0**	**0**	**0**	**0**
Propellant & Pressurant1	5%	299.4		For S/C mass =	2025.0		Delta-V, Sys 1	483.1	m/s		Including residuals =
3 Cruise Craft Total (Wet)		**5822**									
L/V-Side Adapter		115.5		Wet Mass for Prop Sizing	6075						
Launch Mass		**5938**		Dry Mass for Prop Sizing	1641						
Launch Vehicle Capability		**6075**	Atlas V 551					Launch C3	0.269		
								Mission Unique LV Contingency	0%		
Launch Vehicle Margin		**137.4**	2%					Fairing dia., m	4.57		

Cleared for public release. For discussion purposes only.

Systems

Conclusions for the SGO High Option

- **The SGO high option did not close for Team X**
  - The combination of larger telescopes, more Delta V and the resulting impact on structures mass with the stack configuration led to a design spiral which placed it outside the L/V capability.
    - Note: The Atlas 551 has the maximum performance in the Team X database but the Falcon 9 Heavy is still an option.
- **A Propulsion switch was made on SGO-High to BiProp to save mass.**
- **Two initial suggestions were made for trades**
  - Cutting the contingency to 43% (changes the guidelines.) Preliminary trade not shown. Saves about 200 kg per vehicle - only about half of the necessary savings.
  - Cutting the Delta V to slightly less than half of the necessary 1.1 km/sec. Trade is shown in the sheet. Design closes but mission design chair indicated that the Delta V necessary would not change that much if the angle between earth and the constellation were shortened. The implication for the shortened angle is lessened lifespan for the constellation.

Systems
Conclusions for the SGO High Option

- **An approach to a trade.**
  - Build the bottom structure to take the full load, the middle structure to take the load from top spacecraft and the top spacecraft to take only the load for itself. This saves on mass but structure qualifications are necessary for 3 separate structures. Compare the costs of qualification to the cost of a larger launch vehicle.
  - Along the same lines, the optimization of the primary structure should be studied to settle on a single structure. The maturity of the design should lead to a decrease in structural mass and also cut the contingency.
- **Radiation dosage is higher for the High option because of the longer mission life.**
- **Power from the Solar Arrays should be closely monitored if any subsystems show any growth in power demand.**
  - 90% packing factor with the HGA promising to cast a shadow.

Executive Summary
Major Trades/Conclusions – HIGH

- **One HGA instead of two HGAs**
  - Reduction in power, complexity and cost.
    - Based on the low data rate.
- **Mono-prop vs bi-prop**
  - Bi-prop was needed to accommodate the large distances the flight systems must travel
- **Light weighting the two propulsion stages on the top of the launch stack**
  - Quick calculations showed that not enough mass would be saved to fit the stack within the launch mass capability

Systems

Option Comparison

Opt-ion	Each Science-craft (kg) with 53% conting.	Power (W) each Science craft with 43% conting.	Each Cruisecraft dry with 53% conting. (kg)	Total Launch Mass (kg) with 53% conting.	Comments
MID	717.5 kg	652 W maximum	1378 kg	4553 kg	This is the total stack mass of three cruisecraft.
HIGH	797.1 kg	689 W maximum	1641 kg	5822 kg	This is the stack mass with about half of the propellant loading. This design does not close. The Delta V for mission is ~1.1 km.

Systems

Risks

- **Number of minor risks that pose potential threats to the mission**
  - Event rates for massive black hole binary mergers and extreme-mass-ratio-inspirals
  - Low TRL photoreceivers
  - Technology inheritance from future missions
  - Star Tracker cost growth and manufacturing
  - Heritage software algorithms
  - Damage to proof mass in the event of a hard impact
  - Re-qualification of the Colloidal feed system
- **Two proposal risks**
  - Shock loads/cold welding of proof mass during launch
  - Inability to “test-as-we-fly” due to large spacecraft architecture
- **There is one moderate risk specific to the SGO-High mission**
  - Colloidal thrusters lifetime limitations.

Instruments Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Alfred Nash

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

Instruments

Table of Contents

- Design Requirements
- Design Assumptions
- Design
- Design Rationale
- Cost
- Design Analysis and Risk
- Option Comparison
- Additional Comments

Instruments
Design Requirements

- **Mission:**
  - 3 Spacecraft in Free Earth Trailing Orbits

- **Constraints**
  - Continuous Observing (after 18 month cruise and 4 month commissioning) in drift away orbit

- **Measurement**
  - Time-varying strain (ΔL/L) in spacetime typically ~10-21 /√Hz = 10 pm/10 Gm/√Hz
  - Variations are periodic or quasi-periodic between $3x10^{-5}$ and 1 Hz, observable for months to centuries

- **SGO-Mid Telescope diameter is reduced from 40 to 25 cm, and the laser power out of the telescope is reduced from 1.2 to 0.7 W (end of life) compared to SGO High**

Instruments

Design Assumptions

- **List of Assumptions made for the Designs**
  - Customer provided design/MEL for both Mid & High options

Instruments

Design – Schematic Block Diagram

Included

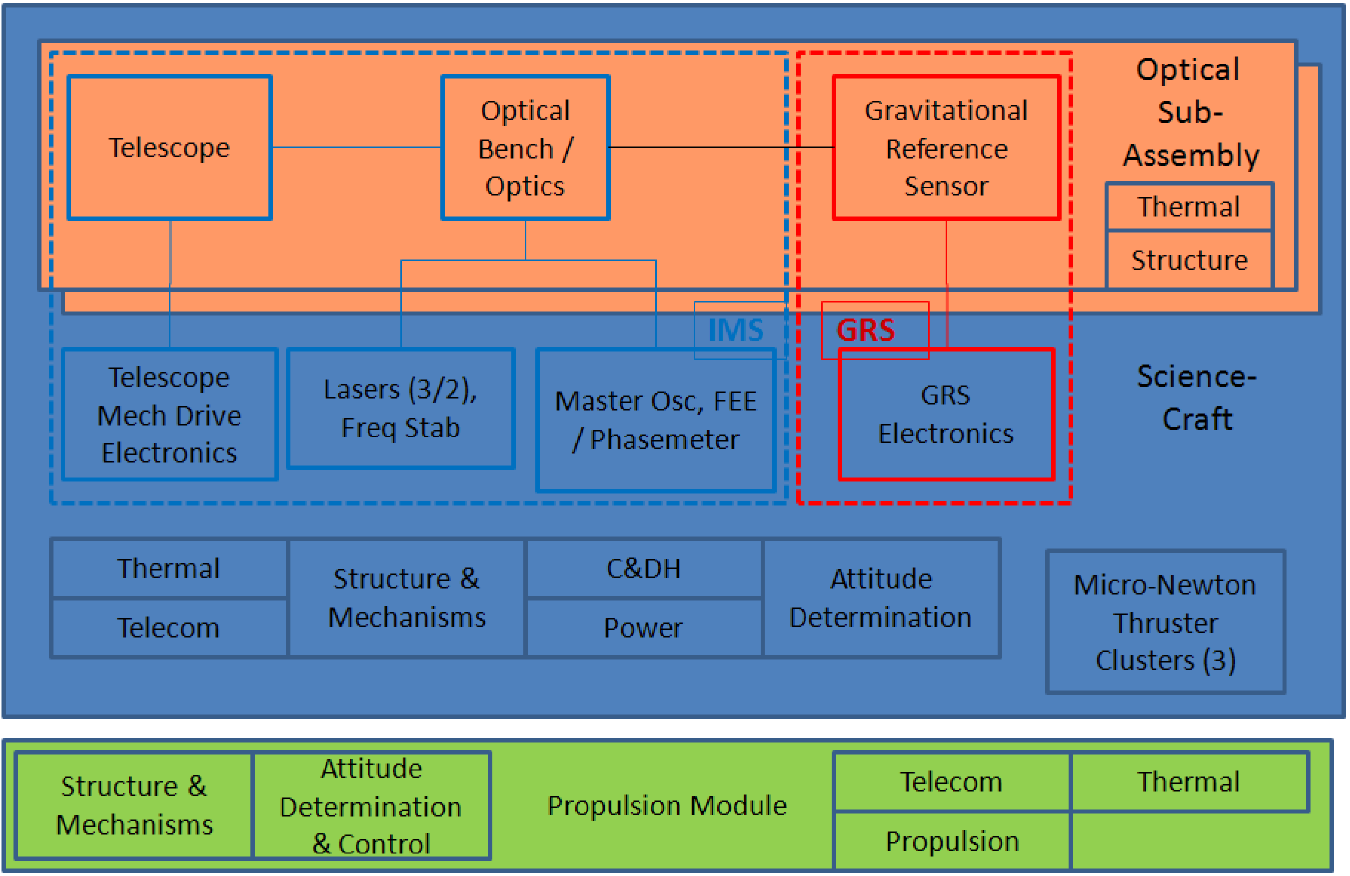
In

Instruments

NOT
Included

In

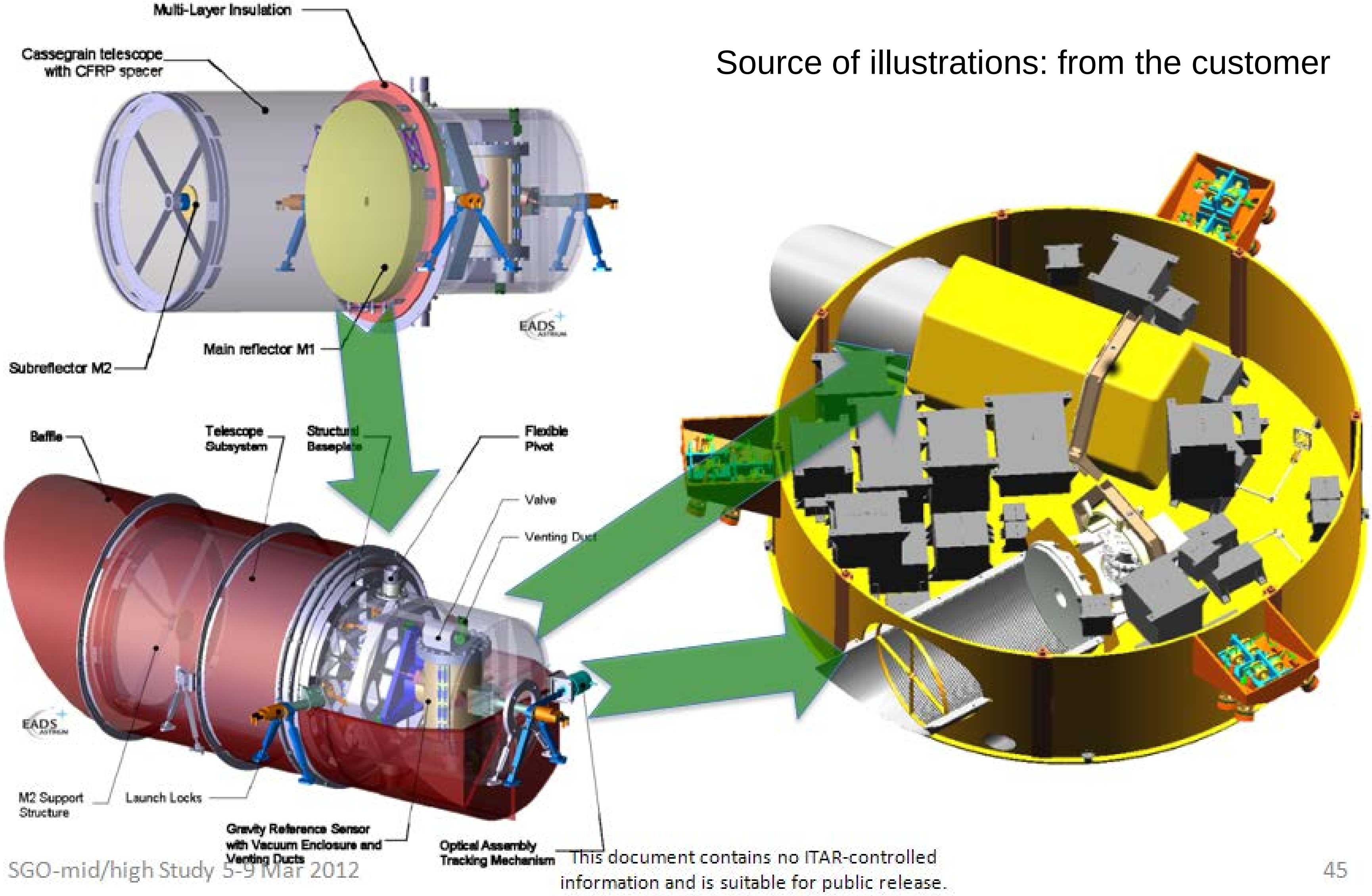
Instruments



SGO-mid/high Study 5-9 Mar 2012

Instruments
Design Overview

Source of illustrations: from the customer



SGO-mid/high Study 5-9 Mar 2012

This document contains no ITAR-controlled information and is suitable for public release.

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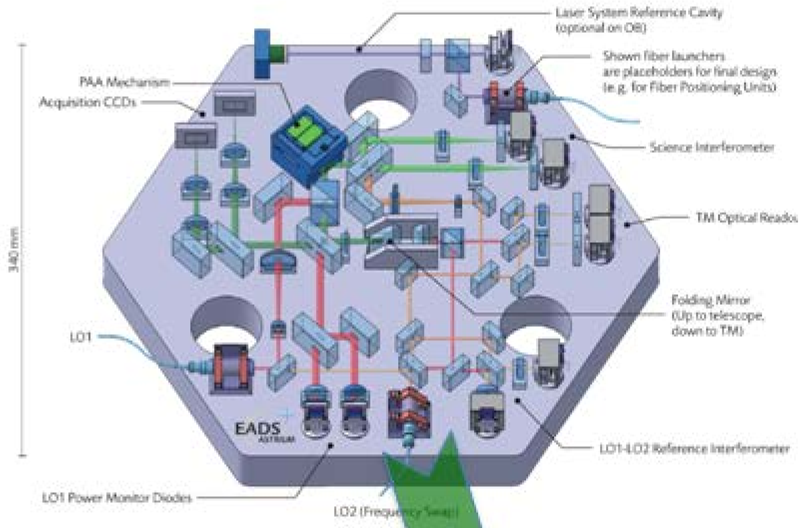
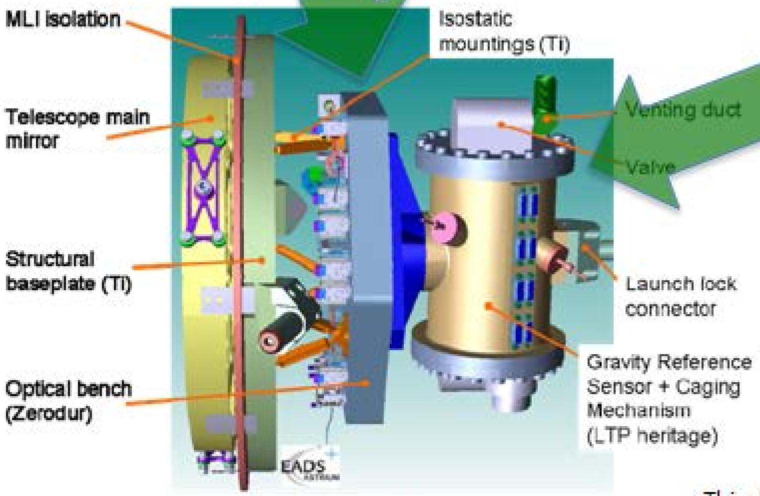
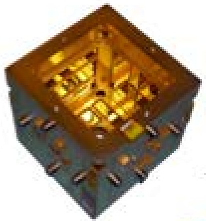
Instruments
Design – Details

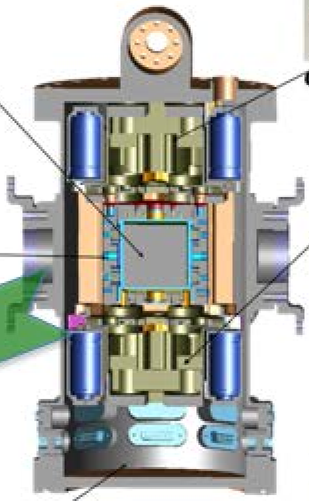


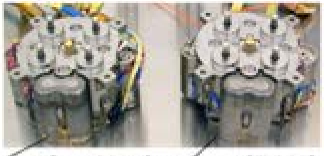


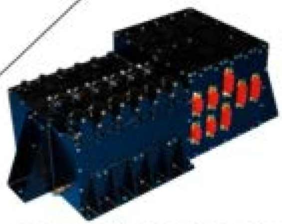

Test Mass

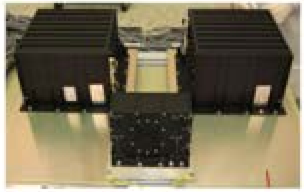

Electrode Housing


Vacuum Chamber (EM)

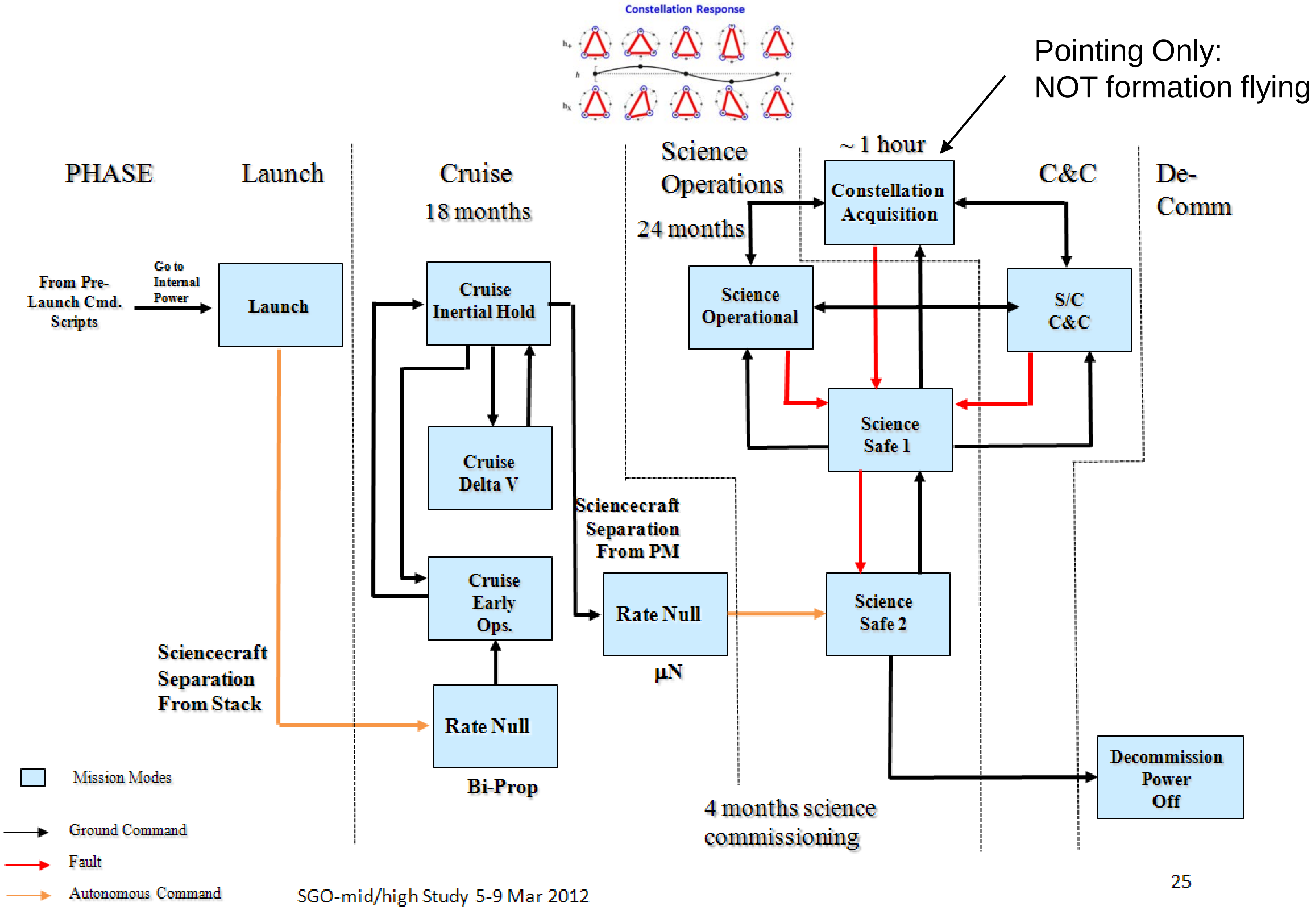



Caging Mechanism (EQM)


Charge Management


Front End Electronics

Instruments
Design – Modes



Pointing Only:
NOT formation flying

SGO-mid/high Study 5-9 Mar 2012

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Instruments

Design – SGO MID Option

- **Essentially 2 Instruments / Spacecraft (“Science Compliment” in Customer Supplied MEL)**
  - **25 cm** telescope (in field guiding)
  - **0.7 W** EOL Laser Power
  - **Mass = 216.55/2 = 108 kg** CBE per “instrument”
  - **Power = 232.99/2 = 116 W** CBE per “instrument”
  - Data Rate = 2.5 kbps per “instrument” (5 kbps per payload on each S/C)
  - Measures spacetime strain

Instruments
Design – SGO HIGH Option

- **Essentially 2 Instruments / Spacecraft (“Science Compliment” in Customer Supplied MEL)**
  - **40 cm** telescope (articulates as unit)
  - **1.2 W** EOL Laser Power
  - **Mass = 260.08/2 = 130 kg** CBE per “instrument”
  - **Power = 256.15/2 = 128 W** CBE per “instrument”
  - Data Rate = 2.5 kbps per “instrument” (5 kbps per payload on each S/C)
  - Measures spacetime strain

Instruments
Design Elements Held By Other Chairs

- **Thrusters held by propulsion.**
- **ACS Algorithms held by ACS, computing done within C&DH H/W**

- **Design Rationale**
  - Customer provided designs (Mid & High)

Instruments
Cost – All Options

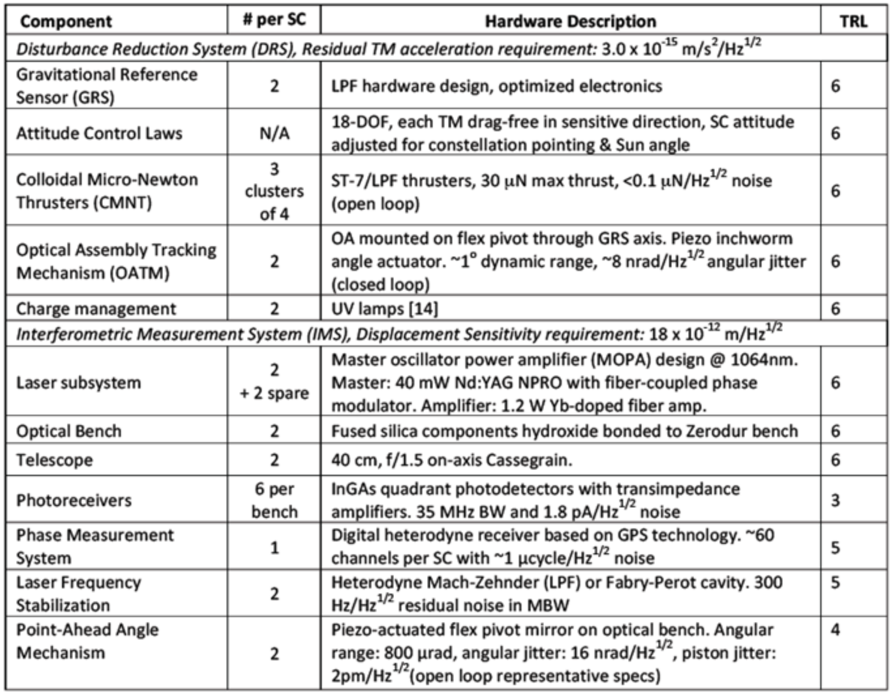
- **Cost Drivers**
  - Mass and Power drive cost (perceptions, at least).

- **Potential Cost Savings**
  - 3 Spacecraft with 4 links
    - 2 spacecraft with 2 links not sensitive enough to detect even biggest events

- **Potential Cost Uppers**
  - Low TRL Items (e.g., photoreceivers, point ahead angle system, phase measurement system, laser frequency stabilization)
  - Systematics larger than estimated or more difficult to suppress than estimated.

Instruments
Design Analysis and Risk

- **Strengths**
  - Low data rate from payload to ground
  - Technology demonstrations to date (LISA ground demonstrations)
  - Smaller telescope than MOLA, HiRISE
  - Graceful degradation as lose links from 6 to 4 (only with loss of 3 links is threshold floor crossed)
- **Opportunities**
  - SIM technology development inheritance?
- **Weaknesses**
  - Number of < TRL 6 items > 1
  - “internal”/control loop/data processing data rates may scare some reviewers and lead them to question estimates of electronics mass & power.
- **Threats**
  - JWST (lack of budget for a $B mission)
  - Comparisons to SIM (Co$t/Risk)
    - Pointing telescopes
    - Interferometry
    - Stringent dimensional stability
  - Reluctance to fund an observatory for a regime of no *direct* detections (of gravity waves - to date).
  - GP-B legacy (cost / science return)



Component	# per SC	Hardware Description	TRL
Disturbance Reduction System (DRS), Residual TM acceleration requirement: 3.0 x 10^{-15} m/s^2/$Hz^{1/2}$			
Gravitational Reference Sensor (GRS)	2	LPF hardware design, optimized electronics	6
Attitude Control Laws	N/A	18-DOF, each TM drag-free in sensitive direction, SC attitude adjusted for constellation pointing & Sun angle	6
Colloidal Micro-Newton Thrusters (CMNT)	3 clusters of 4	ST-7/LPF thrusters, 30 μN max thrust, <0.1 μN/$Hz^{1/2}$ noise (open loop)	6
Optical Assembly Tracking Mechanism (OATM)	2	OA mounted on flex pivot through GRS axis. Piezo inchworm angle actuator. ~1° dynamic range, ~8 nrad/$Hz^{1/2}$ angular jitter (closed loop)	6
Charge management	2	UV lamps [14]	6
Interferometric Measurement System (IMS), Displacement Sensitivity requirement: 18 x 10^{-12} m/$Hz^{1/2}$			
Laser subsystem	2 + 2 spare	Master oscillator power amplifier (MOPA) design @ 1064nm. Master: 40 mW Nd:YAG NPRO with fiber-coupled phase modulator. Amplifier: 1.2 W Yb-doped fiber amp.	6
Optical Bench	2	Fused silica components hydroxide bonded to Zerodur bench	6
Telescope	2	40 cm, f/1.5 on-axis Cassegrain.	6
Photoreceivers	6 per bench	InGAs quadrant photodetectors with transimpedance amplifiers. 35 MHz BW and 1.8 pA/$Hz^{1/2}$ noise	3
Phase Measurement System	1	Digital heterodyne receiver based on GPS technology. ~60 channels per SC with ~1 μcycle/$Hz^{1/2}$ noise	5
Laser Frequency Stabilization	2	Heterodyne Mach-Zehnder (LPF) or Fabry-Perot cavity. 300 Hz/$Hz^{1/2}$ residual noise in MBW	5
Point-Ahead Angle Mechanism	2	Piezo-actuated flex pivot mirror on optical bench. Angular range: 800 μrad, angular jitter: 16 nrad/$Hz^{1/2}$, piston jitter: 2pm/$Hz^{1/2}$(open loop representative specs)	4

Instruments

Option Comparison

Option	Mass (kg)	Cost ($M)	Instruments	Comments
Mid	216.55 kg CBE	$ 175 M FY 12 w/o reserve	"Science Compliment"	25 cm telescope (in field guiding) 0.7 W EOL Laser Power
High	260.08 kg CBE	$ 197 M FY 12 w/o reserve	"Science Compliment"	40 cm telescope (articulates as unit) 1.2 W EOL Laser Power

Science Report

Study Title: Space-based Gravitational Wave Observatory: MID

Date 3/7/2012

Author: Curt Cutler

Email: cjcutler@jpl.nasa.gov

Science
Table of Contents

- Science Goals & Implementation
- Design Assumptions
- Design
- Cost Assumptions: Mid
- Cost: Mid
- Cost Assumptions: High
- Cost: High
- Risk
- Additional Comments

Science

Science Goals & Implementation

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

Sources include: ~4e3 Galactic WD binaries, ~1-100 Merging Massive Black Hole binaries out to redshifts z ~14, inspirals of stellar-mass compact objects in Massive Black Holes out to z~0.2. Could measure a stochastic background of GWs from the early universe down to rho_{GW}/rho_{tot} ~ 1.e-9.

- **Implementation – very similar to former "LISA" mission, but with**

5x shorter arms, smaller telescope, and shorter lifetime. SGO-Mid's sensitivity would be ~5x worse than LISA's through most of the sensitivity band below ~20 mHz (but somewhat better sensitivity than LISA's above ~30 mHz).

Science
Design Assumptions – Option MID

- **Instrument**
  - Complex
  - The "instrument" is the entire constellation, including gravitational reference sensors and laser metrology.
  - The main science data is 3 independent time-series of so-called TDI variables, which is effectively 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 5 kb/s (of which ~4 kb/s are housekeeping), and downloads its data to DSN for 8 hour intervals every 6 days. Therefore the download bit rate has to be 18x the data collection rate, or 90 kb/s. The 3-S/C constellation downloads for 8 hours every 2 days.
  - 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.

- **Science team**
  - SGO-Mid is not an observatory in the usual sense of "pointing" the telescope in the direction requested by the observer. Thousands of individually identifiable source signals are all "on" simultaneously in the 3 output data streams. Therefore the large "Guest Observer" program is absolutely necessary for extracting the science, and close coordination of their activities by the Project Scientist is also crucial.

Science

Design – Option MID

- Science Operational View
- Operations are rather simple. Data taking is all-sky (no pointing) and continuous except for short intervals when, e.g., the communication radio antennae are re-pointed towards DSN dishes. (This will cause vibrations that are expected to swamp the gravitational-wave signal.)

Science

Cost Assumptions – Option MID

- We have assumed a 2-yr phase F, consistent with space missions of this level of data-analysis complexity, such as Planck or WMAP.

- The Project generates Level 0, 1, 2 and 3 data products, including the final source catalog. A Guest Observer Program ($9 M/yr) is funded to do additional science investigations with the level-3 data products, 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).

- 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 ~ 0.12 Byte.
- 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 – Option Mid

•Per input from the Customer, we assumed $9M/yr for the Guest Observer Program; this Program will do related science using the Level-3 data products; e.g., look for electromagnetic counterparts or infer constraints on general relativity.

•Total cost for the Project's science team is $26.1M, divided as follows:
$1.6M in A/B, $8.7M C/D, $11.0M in E, and $4.8M in F.

> •Total science cost of $44.1M is ~2-3% of total mission cost, which is on the low side for typical class B missions. However 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 – Option Mid

- **Cost Drivers—only way to significantly decrease/increase science cost is to decrease/increase mission data-taking lifetime.**
- **Potential Cost Uppers**
  - Unexpected systematics that must be “fitted out” (ala GP-B) could significantly complicate and stretch out the data analysis

Science
Risk and Additional Comments

- **List of Risks**

  The major 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.

- **Additional Comments**
  - Science costs for SGO-Mid should be roughly the same for upcoming Lagrange and OMEGA studies, up to re-scaling for different data-taking lifetimes.

Mission Design Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Mark S. Wallace

Email: mark.s.wallace@jpl.nasa.gov

Mission Design

Table of Contents

- Design Requirements
- Design Assumptions
- Design
- Design Rationale
- Cost
- Risk
- Option Comparison
- Additional Comments

Mission Design

Design Requirements

- **Mission:**
  - Three Earth trailing spacecraft in an equilateral triangle formation
    - Mid:
      - 1 million km baseline
      - 2 years in science formation
    - High:
      - 5 million km baseline
      - 5 years in science formation
  - Arrive on-station 6/1/2022, Launch ~18 months prior
- **Mission Design**
  - Mid: Drift-away at ~ 5.5 deg/year (start at 9 deg, move to 21 deg)
  - High: Formation drifts to 22 deg behind Earth and stays there.
- **Launch Vehicle**
  - Customer desires a shared launch off a Falcon Heavy

Mission Design
Design Assumptions

- **MID:**
  - Customer provided a set of initial states and epochs for the spacecraft in the formation.
  - The launch date was optimized to minimize the launch energy (C3) with the following assumed constraints:
    - The launch target was the average of the given states (the center of the formation)
    - Ballistic trajectory to target (no maneuvers)
  - Launch period effects are identical as those for LISA
- **HIGH:**
  - Design assumed to be identical to the very mature LISA design.
  - Data in this report summarizes the data from three-customer provided reports:
    - (1) Hughes, S. “Alternative Cost and Constraint Functions Results for LISA.” 08/29/05
    - (2) Sweetser, Theodore H. “An end-to-end trajectory description of the LISA mission.” 28 April 2005
    - (3) Sweetser, Ted. “LISA Mission Description.” 2005-12-09

Mission Design

Design: Timeline and Delta V Budget – MID

- **Maneuvers were optimized for minimum delta-v given the assumed fixed launch target.**
- **Total Delta V:**
  - SC1: 154 m/s
  - SC2: 123 m/s
  - SC3: 180 m/s
  - An additional 20 m/s is allocated for:
    - Preliminary analysis of launch vehicle cleanup shows ~ 5 m/s required.
    - LISA launch period effects were ~ 9 m/s
    - The remaining 6 m/s is margin
- **The spacecraft achieve the formation 17 months after launch and 3 months before the specified state**

Event	**S/C**	**Date**	**Launch Relative**	**Delta V (m/s)**
Launch and LV separation	1, 2, and 3	10/10/2020	L = 0d	0
DSM1-1	1	3/14/2021	L + 155d	12
DSM3-1	3	4/20/2021	L + 192d	28
DSM2-1	2	6/14/2021	L + 247d	111
DSM3-2	3	7/22/2021	L + 285d	81
DSM1-2	1	8/26/2021	L + 320d	127
DSM3-3 and science orbit injection	3	11/12/2021	L + 398d	71
DSM2-2 and science orbit injection	2	11/18/2021	L + 404d	12
DSM1-3 and science orbit injection	1	3/9/2022	L + 515d (17 mo.)	15
Science Orbit Target	1, 2, and 3	6/1/2022	L + 599d (20 mo.)	0
Total				

Mission Design

Design: Timeline and Delta V Budget – HIGH

- **From Ref (2) derived from the LISA Project.**
- **The launch date should have minimal effect on the delta-v**

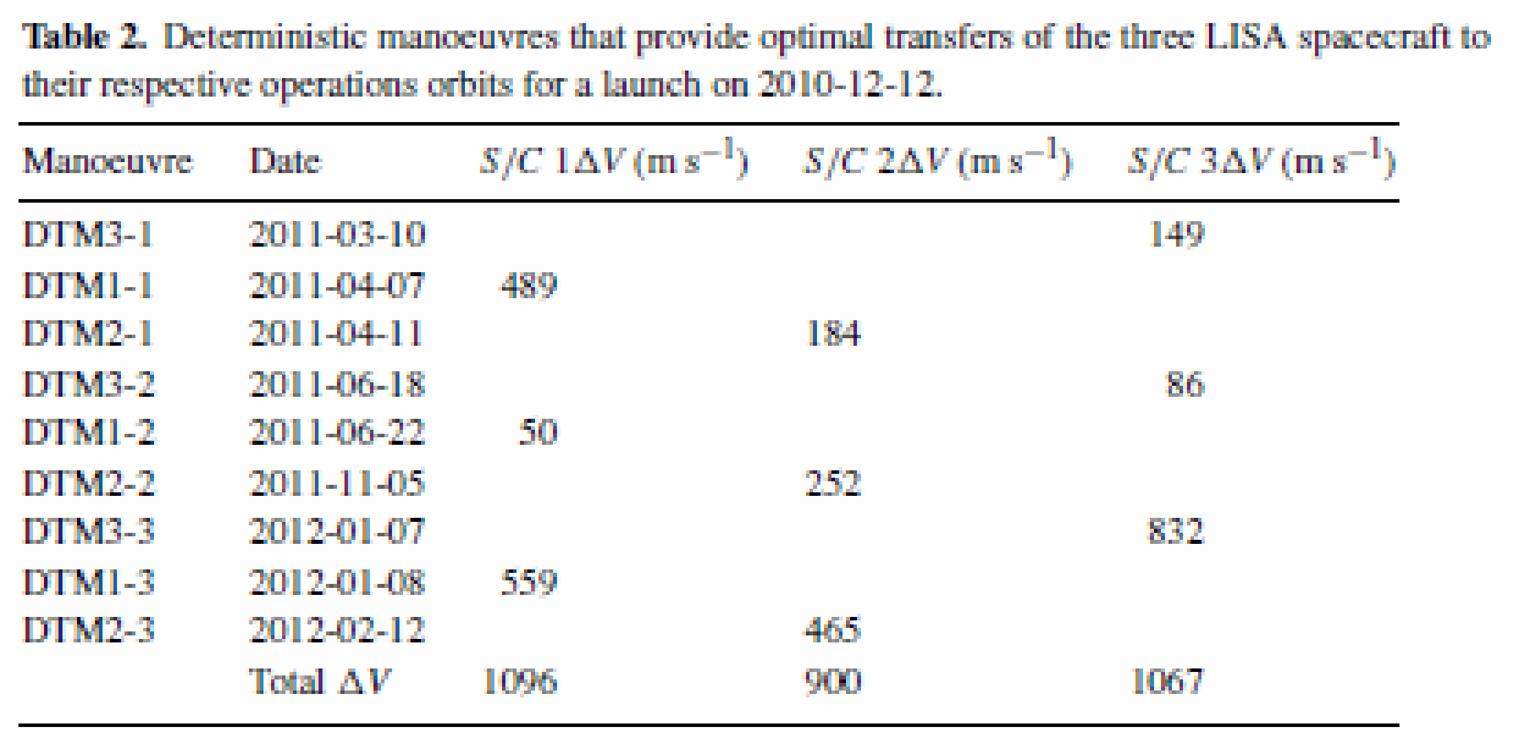


Table 2. Deterministic manoeuvres that provide optimal transfers of the three LISA spacecraft to their respective operations orbits for a launch on 2010-12-12.

Manoeuvre	Date	S/C 1ΔV (m s^{-1})	S/C 2ΔV (m s^{-1})	S/C 3ΔV (m s^{-1})
DTM3-1	2011-03-10			149
DTM1-1	2011-04-07	489		
DTM2-1	2011-04-11		184	
DTM3-2	2011-06-18			86
DTM1-2	2011-06-22	50		
DTM2-2	2011-11-05		252	
DTM3-3	2012-01-07			832
DTM1-3	2012-01-08	559		
DTM2-3	2012-02-12		465	
	Total ΔV	1096	900	1067

Mission Design
Design – MID

Injection (relative to Earth, EME2000)		
Epoch	08-OCT-2020 05:27:38.2599 UTC	
C3	0.268997287	km2/s2
Outbound Dec.	6.078164018	deg
Outbound RA.	10.67815734	deg
Time From Periapsis	600	sec
Inclination	30	deg
Periapsis Altitude	185	km

SC2 Orbit Definition (relative to Sun, EMO2000)		
Epoch	31-MAY-2022 23:59:59.0000 UTC	
Semi-Major Axis	1.008353102	AU
Eccentricity	0.003253356	deg
Inclination	0.190186518	
Longitude of Node	-90.12617818	deg
Argument of Periapsis	119.5304085	deg
True Anomaly	-150.008828	deg

SC1 Orbit Definition (relative to Sun, EMO2000)		
Epoch	31-MAY-2022 23:59:59.0000 UTC	
Semi-Major Axis	1.008332945	AU
Eccentricity	5.67239E-05	
Inclination	0.18975526	deg
Longitude of Node	149.6832758	deg
Argument of Periapsis	48.94048579	deg
True Anomaly	40.96115279	deg

SC3 Orbit Definition (relative to Sun, EMO2000)		
Epoch	31-MAY-2022 23:59:59.0000 UTC	
Semi-Major Axis	1.00835895	AU
Eccentricity	0.003280712	deg
Inclination	0.189411181	
Longitude of Node	29.89305249	deg
Argument of Periapsis	60.27277933	deg
True Anomaly	149.6071975	deg

Mission Design

Design – HIGH

- **From Ref (2) derived from the LISA Project.**

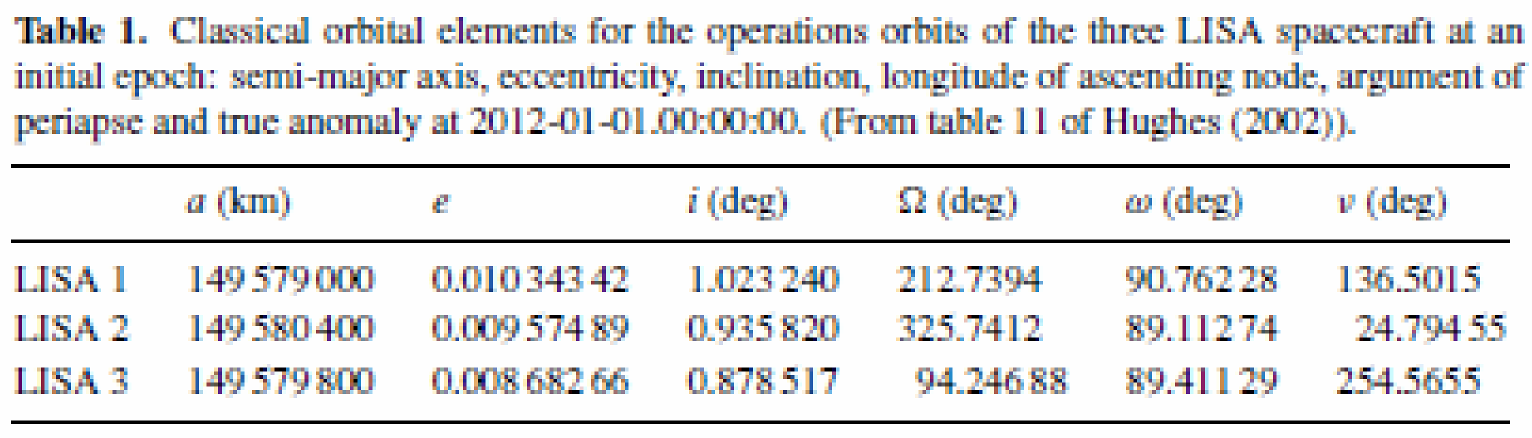
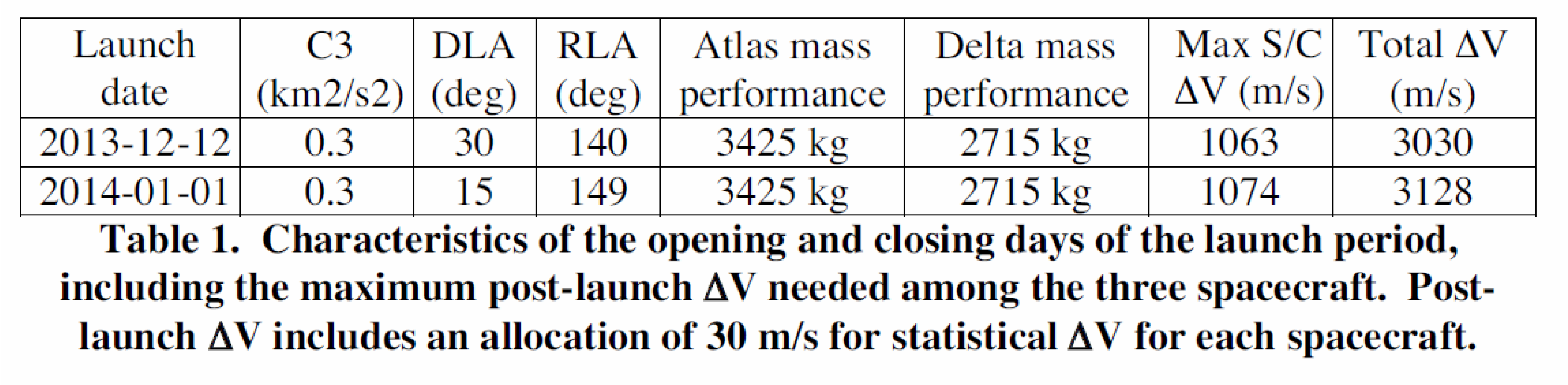


Table 1. Classical orbital elements for the operations orbits of the three LISA spacecraft at an initial epoch: semi-major axis, eccentricity, inclination, longitude of ascending node, argument of periapse and true anomaly at 2012-01-01.00:00:00. (From table 11 of Hughes (2002)).

	a (km)	e	i (deg)	Ω (deg)	ω (deg)	ν (deg)
LISA 1	149 579 000	0.010 343 42	1.023 240	212.7394	90.762 28	136.5015
LISA 2	149 580 400	0.009 574 89	0.935 820	325.7412	89.112 74	24.794 55
LISA 3	149 579 800	0.008 682 66	0.878 517	94.246 88	89.411 29	254.5655

- **From Ref (3) derived from the LISA Project.**



Launch date	C3 (km2/s2)	DLA (deg)	RLA (deg)	Atlas mass performance	Delta mass performance	Max S/C ΔV (m/s)	Total ΔV (m/s)
2013-12-12	0.3	30	140	3425 kg	2715 kg	1063	3030
2014-01-01	0.3	15	149	3425 kg	2715 kg	1074	3128

Table 1. Characteristics of the opening and closing days of the launch period, including the maximum post-launch ΔV needed among the three spacecraft. Post-launch ΔV includes an allocation of 30 m/s for statistical ΔV for each spacecraft.

Mission Design

Design: LV – Both Options

- **The launch vehicle targets for both options are essentially the same.**
- **Larger vehicles exist, but performance data is unavailable**
  - Delta IV Heavy was available under NLS-1 (9260 kg), but not NLS-2 and may have suffered similar USAF-driven performance degradation as the Atlas V
  - The SLS and Falcon Heavy do not exist except on paper but could be considered should they mature on a useful schedule.

Parameter	**Value**	**Unit**
Launch Vehicle	Atlas V 551	
Fairing Diameter	4.57	m
Max DLA*	30	
C3	0.3	km^2/s^2
Fairing Length	5.10	m
Performance Mass	6075	kg
Contingency	0	%
Launch Duration	Unknown	Min.

* Declination of Launch Asymptote

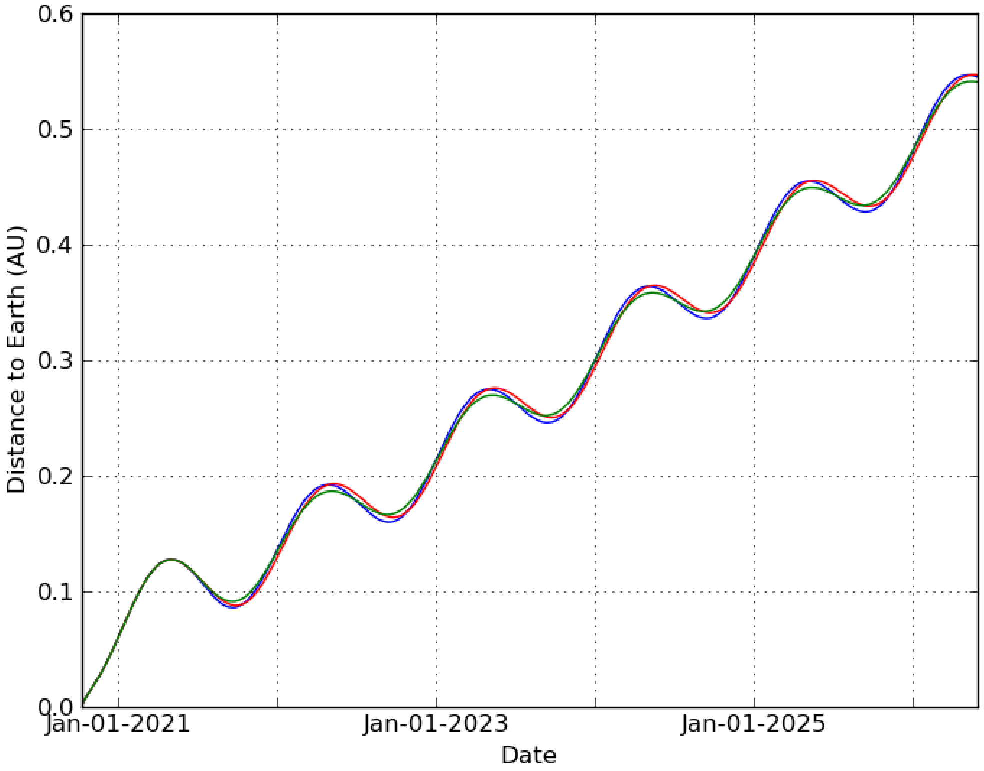
Mission Design

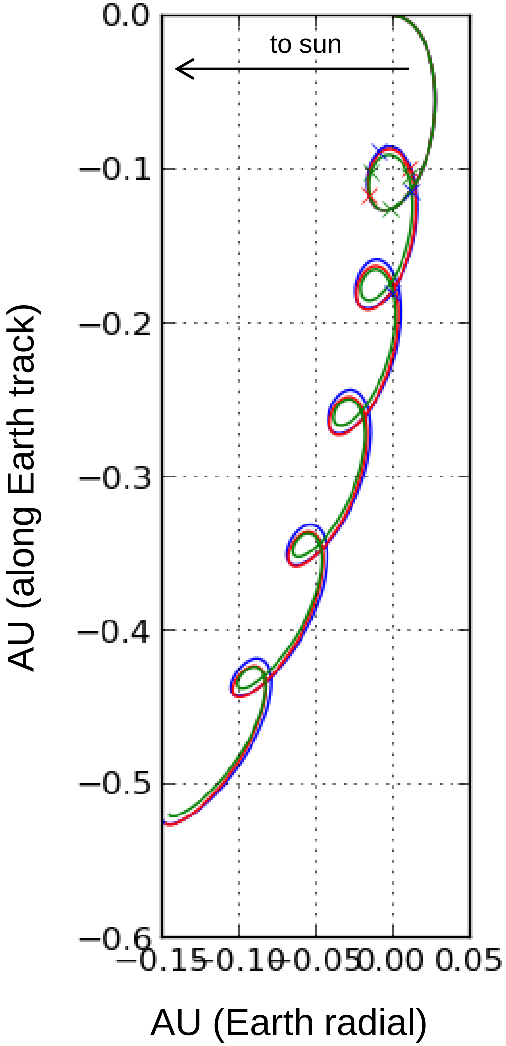
Plots – All Options

- **Plots of the various geometric constraints around which the constellations for both options were designed were supplied by the customer and are not repeated here.**

Mission Design
Visualization – MID

- **Colors:**
  - SC-1 = blue
  - SC-2 = red
  - SC-3 = green
- **X's on right-hand plot indicate maneuver locations**





Mission Design

Design Rationale

MID (Mid)

- **The center of the constellation was chosen as the launch target because it captured the main common features of all three spacecraft and should minimize the DV required post-launch for each spacecraft.**
  - The single most important common feature was the average drift-away rate, the maneuvers don’t need to execute large period changes.
  - The time required to find a true minimum-maximum delta-v launch target was prohibitive for a Team X level study.
- **Three maneuvers were used because that was the LISA baseline**

HIGH (High)

- **There was basically no Mission design work done in Team X for the SGO-High option.**
- **The customer provided all required information.**

Mission Design

Trades

- **HIGH did not converge with customer-provided delta-v budget**
  - Mechanical and Propulsion chairs determined that it could converge if the delta-v requirement could be cut to ~50% of the baseline (~**500 m/s** total).
  - It was postulated that the delta-v could be reduced by drifting away slower, to 14 deg in 18 months instead of 22 deg in 18 months.
  - A preliminary analysis indicated that **650 m/s** were required to target the center of the constellation with this drift-away rate and then stop with reasonable launch energies. The additional delta-v for inclination changes to establish the 5 Gm baseline were not included.
    - A much lower DV solution was found with a very small C3, but it was too small to ensure that the upper stage would escape in the presence of launch vehicle injection errors.
    - A higher C3 required overly-large changes in heliocentric inclination and/or eccentricity which had to be removed by the propulsion model post-launch.
  - Additional analyses, including a minimum-maximum delta-v launch target, may yield a feasible solution.
- **Another option would be to go to a baseline between the 1 Gm MID (200 m/s) and the 5 Gm HIGH (1100 m/s).**
  - The factor-of-five difference in both baseline and DV suggests that the inclination change required to achieve the baseline may be the driving difference in the DV budgets.
  - 2-3 Gm may be achievable for 500 m/s.

Mission Design

Cost – MID

- **Cost Assumptions**
  - Costed as a direct launch (no shared launch vehicle)
  - Navigation costs are typical of deep space cruise, not the Kepler-level communication-only costs
  - Treated the SPICE costs as “Complex” because there is no modification for multiple spacecraft in the model and the “Complex” setting accounts for multiple C-Kernels.
  - Costs include Section 343 MDN/SAS service centers
  - All costs are FY12

Mission Design

Cost – MID

- **Cost Drivers**
  - Navigation accuracy setting is the main driver
  - This level is necessary to establish and verify the formation

- **Potential Cost Savings**
  - If a Kepler-level “communication/reconstruction only” level of navigation is sufficient, $0.2M could be saved per month at that level (up to $4.8M for the entire science phase)

- **Potential Cost Uppers**
  - Sharing the launch vehicle could incur up to $0.08-$1.4M in additional launch vehicle specification costs, depending on the relationship to the co-manifest.
    - This does not include launch vehicle integration costs.

Mission Design

Cost – HIGH

- **Cost Assumptions**
  - Costed as a direct launch (no shared launch vehicle)
  - Navigation costs are typical of deep space cruise, not the Kepler-level communication-only costs
  - Treated the SPICE costs as “Complex” because there is no modification for multiple spacecraft in the model and the “Complex” setting accounts for multiple C-Kernels.
  - Costs include Section 343 MDN/SAS service centers
  - All costs are FY12

Mission Design

Cost – HIGH

- **Cost Drivers**
  - Navigation accuracy setting is the main driver
    - This level is necessary to establish and verify the formation
  - Phase E duration difference is the cause of the different costs between MID and HIGH.

- **Potential Cost Savings**
  - If a Kepler-level “communication/reconstruction only” level of navigation is sufficient, $0.2M could be saved per month at that level (up to $8.7M for the entire science phase)

- **Potential Cost Uppers**
  - Sharing the launch vehicle could incur up to $0.08-$1.4M in additional launch vehicle specification costs, depending on the relationship to the co-manifest.
    - This does not include launch vehicle integration costs.

Mission Design

Risk

- **No atypical Mission Design / Navigation risks identified.**

Mission Design
Option Comparison

- **Similarities**
  - Equilateral triangle formation/constellation in an Earth-trailing orbit
  - Propulsion module performs up to 3 maneuvers to establish each science-craft's position within the formation/constellation over 18 months.
- **Differences**
  - MID ("Mid")
    - 1 million km baseline, orbit drifts away, 2 year science phase
    - $17.5M cost
  - HIGH ("High")
    - 5 million km baseline, orbit "fixed" at 22 deg behind earth, 5 year science phase
    - **DID NOT COVERGE** with the specified DV, see "Trades" slides.
    - $21.5M cost

Option	Delta V (m/s)	Cost($M)	Orbit/Trajectory	Comments
1 ("Mid")	**200**	**$17.53M**	**1 Gm baseline, drifting away, 2 year science phase**	
2 ("High")	**1074**	**$21.53M**	**5 Gm baseline, fixed at 22 deg behind earth, 5 year science phase**	**System did not converge at this DV, no trajectory found to satisfy lower DV required for convergence.**

ACS Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Bob Kinsey

Email: Robert.J.Kinsey@jpl.nasa.gov

ACS
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- Design Requirements
- Design Assumptions
- Design
- Design Rationale
- Cost Assumptions
- Cost
- Risk
- Option Comparison
- Additional Comments

ACS

Design Requirements – Both Options (1 of 2)

- **The instrument has the following capabilities:**
  - Point outgoing beams as needed to direct them to other spacecraft.
  - Sense the direction of incoming beams relative to the spacecraft.
  - Provide position and orientation commands to the spacecraft for
    - Shielding the proof masses from external disturbances.
    - Adjusting orientation as needed to maintain lock on other spacecraft.
- **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 during acquisition:**
  - Control was not explicitly specified.
    - Assuming 2 arcsec (3σ) per axis to allow for thruster deadband.
  - Knowledge within 1 arcsec (3σ) per customer team initial briefing.
    - Technical note on the next chart suggests 0.707 arcsec per axis required, assuming RSS of pitch and yaw for 1 arcsec knowledge of boresight.
    - Already limited on choice of star tracker with 1 arcsec per axis.
  - Stability was not explicitly specified.
    - Assuming 0.1 arcsec/sec (3σ) per axis.

ACS

Design Requirements – Both Options (2 of 2)

- **Customer provided the following document, which has Table 1:**
  - Tupper Hyde, NASA GSFC, “Technical Note: Acquisition with Scan and Defocus Methods: LISA Project,” 10 February 2005.
- **Table 1 is 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
- **SGO-Mid 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.
  - ∆DOR is another alternative that can potentially achieve < 1 km.
- **Per customer, star tracker accuracy/cone budget can be relaxed.**
  - Acquisition simulations show 5 minutes required with 10 minute margin.
  - Allow 10 minutes. Accept star tracker accuracy of 8.8 µrad (6.2 pitch/yaw).

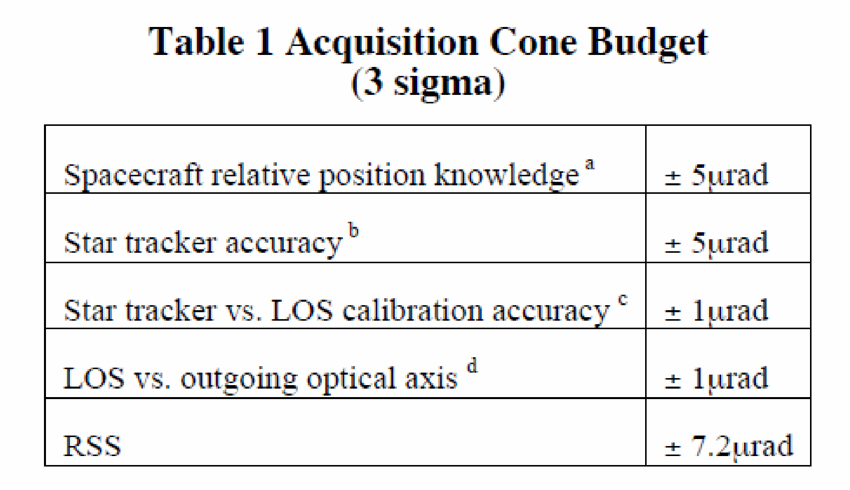

Table 1 Acquisition Cone Budget (3 sigma)

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

ACS
Design Assumptions – Both Options

- **Star tracker performance**
  - Star tracker spec is 0.7 arcsec (1σ) per axis
    - 4 heads with at least 2 in operation at a time.
    - End of life
  - From previous chart 6.2 µrad (3σ) or 0.41 arcsec (1σ) required.
    - Current spec exceeds requirement by 71%.
    - Actual performance may be better than the spec.
    - May be improvements in the star tracker before the tech cutoff date.
  - Assuming that an improved version of the tracker will be available, or another star tracker with the required performance.

ACS

Architecture – Both Options

- **Propulsion module**
  - 3-axis stabilized using thrusters:
    - Hydrazine system for Mid option; Bi-prop/dual mode system for High option.
  - Stellar-inertial attitude determination with algorithms run from sciencecraft.
    - Gyros, star tracker, sun sensors.
- **Sciencecraft during acquisition**
  - 3-axis stabilized using colloidal thrusters that provide 4 to 150 µN.
    - No reaction wheels onboard.
  - All stellar attitude determination:
    - Star tracker with multiple heads
    - Sun sensors for safe mode.
- **Sciencecraft during nominal science operations:**
  - Instrument and star tracker measurements used in pointing algorithms.
  - Responsibility for pointing beams and spacecraft shifts to the payload.
- **Attitude control during science operations:**
  - Colloidal thrusters.

ACS
Design – Both Options (1 of 2)

- **Attitude determination hardware on sciencecraft:**
  - Star tracker → Same as customer MEL.
    - 3 heads: one aligned with each telescope boresight, redundant unit aligned in-between the two.
    - Redundant power supplies and redundant electronics.
    - Performance 2.1 arcsec (3σ) in 3 axes, using 2 heads, tracking many stars.
  - coarse sun sensors: 12 units → Lower mass than customer MEL.
    - Single axis analog with 120 deg FOV; 5 deg accuracy.
  - IMU → Same as customer MEL.
    - Redundant units; each contains 3 gyros, 3 accelerometers.
    - Performance 1 deg/hr bias (1σ) per axis.
- **Attitude determination hardware on prop module:**
  - Star tracker: 2 heads → Same as customer MEL.
  - coarse sun sensors: 6 units → Lower mass than customer MEL.

ACS
Design – Both Options (2 of 2)

- **Attitude control hardware on the sciencecraft:**
  - Colloidal thrusters with a thrust range of 4 to 150 μN.
  - See the Propulsion section for details on thrusters.

- **Attitude control hardware on the prop module:**
  - SGO-Mid prop module: hydrazine thrusters.
  - SGO-High prop module: bi-prop/dual mode thrusters.
  - See the Propulsion section for details on thrusters.

ACS
Design Rationale – Both Options

- **Architecture based on LISA and LISA Pathfinder.**
- **Choice of attitude determination components:**
  - Star tracker was advertised as a 1 arcsec (3σ) star tracker ten years ago. More recently (2009), the vendor is claiming 2.1 arcsec (3σ).
  - Star tracker has a high degree of magnetic cleanliness, which is important for this mission.
  - The customer pointing budget calls for a 1 arcsec tracker.
  - The Star tracker was likely selected years ago during earlier concept studies, when it was advertised as a 1 arcsec tracker.
- **Choice of attitude control components:**
  - Colloidal thrusters provide the capability to cancel very small external disturbances in real time, making the system drag-free.
  - Colloidal thrusters provide fine pointing capability comparable to wheels.
  - Eliminates the need for reaction wheels; saves ACS mass, power, cost.
- **The design does not meet requirements using current star tracker.**
  - Assuming improvement or another tracker selected by the tech cutoff.

ACS
Trades – Both Options

- **Team X ACS did not perform any trades, but did discuss the choice of star tracker with the customer team.**
- **Star tracker in the baseline is not adequate to meet the customer requirement LOS knowledge during acquisition.**
  - Stated requirement is 0.707 arcsec (3σ) in pitch and yaw.
  - Tracker performance is 2.1 arcsec (3σ) in pitch and yaw.
- **Customer agreed that the requirement can be relaxed.**
  - Only using 5 minutes of 15-minute allocated time for acquisition.
- **Instead, allow 10 minutes for acquisition, 5 minute margin.**
  - In that case, RSS total in “Cone Budget” (Table 1 above) can be relaxed to 10.2 μrad instead of 7.2.
  - Meet this with 8.8 μrad allocation for RSS of star tracker pitch and yaw.
    - 6.2 μrad (1.24 arcsec) in pitch and yaw (3σ).
- **Star tracker exceeds 1.24 arcsec by 71%.**
  - Assuming that better performance will be demonstrated by tech cutoff date.
  - Alternative is to use a different tracker (e.g., Sodern Hydra).

ACS
Cost Assumptions – Both Options (1 of 3)

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

New system-level pointing design and analysis, but counting on savings from ST7 tech demo of some functions.

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:** None
- **Non-standard costs manually added:** None

ACS
Cost Assumptions – Both Options (2 of 3)

- **Star tracker cost assumptions**
  - Customer MEL includes star tracker with multiple heads.
  - star trackers prices have been very low compared to comparable products.
    - Cost may be heavily government subsidized.
    - If so, current state of European economy suggests the cost could go higher.
  - Star tracker 2009 spec is 2.1 arcsec (3σ) in all 3 axes, using multiple heads.
    - See Requirements section above. Need 0.707 arcsec per axis.
    - If the star tracker is improved to provide better performance, the cost could go higher.
  - Assuming the following costs, estimated by rough analogy to other high performance trackers. Hedge against not adequate/not available.
    - Flight unit: $300K per head; $500K for processing electronics/power supply.
    - Flight spares same; engineering models at 80% of flight unit costs.
- **Star tracker total before burden or CTM costs: $12.2M in FY 2012.**
  - 15 flight heads; 6 flight electronics/power supplies
  - 5 spare heads; 2 spare electronics/power supplies
  - 4 EM heads; 3 EM electronics/power supplies

ACS

Cost Assumptions – Both Options (3 of 3)

- **Spares for the sciencecraft:**

Item	Spares	Comments
Sun sensor	6	Flight total is 36 for 3 sciencecraft.
Star tracker	1	Includes 2 electronics/power supplies and 3 heads.
IMU	3	Flight total is 6 for the 3 sciencecraft.
Gimbal Drive Electronics	3	Flight total is 6 for the 3 sciencecraft.

- **EMs for the sciencecraft:**

Item	EMs	Comments
Sun sensor	3	2 plus 1 spare EM.
Star tracker	1.5	Full unit plus spare head and electronics/power supply.
IMU	3	2 units plus 1 spare EM
Gimbal Drive Electronics	3	2 units plus 1 spare EM

ACS

Cost – Both Options

- **Total ACS cost is estimated at $38.1M in FY 2012.**
- **Cost Drivers**
  - star trackers account for $12.2M (32%).
    - Could increase by millions (e.g., $4M) if tracker not available, alternate used.
  - Effort for design, analysis, and subsystem level system engineering accounts for $6.4M (17%).
    - Could increase by millions (e.g., $7M) if algorithm re-use is not realized.
- **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 SGO-Mid is $1.9B; 5% is $95M.
  - Team X mission cost for SGO-High is $2.1B; 5% is $105M.
  - ACS estimate of $38.1M is 2% of $1.9B and 1.8% of $2.1B.
- **Suggests that the ACS cost estimate is very low.**
  - Taking credit for ST7 development of algorithms/software.
  - Using relatively inexpensive Vendor star trackers.
- **Possible cost uppers noted above lead to $49M total; still very low.**

ACS
Risk (1 of 2)

- **Star tracker cost growth**
  - Few of the micro-Star tracker have been made or flown.
  - Their cost is low compared to commercial vendors, and the current accuracy is about half of what is needed.
  - may be able to improve performance before the tech cutoff date.
    - If so, the cost is likely to go up. If not, higher priced star trackers from a competitor may need to be procured.
  - Either way, there is a risk of cost growth in the ballpark of $6M to $7M.
    - Around $3M has already been priced into the ACS cost estimate.

- **Star tracker manufacturing process**
  - SGO will require 20 optical heads, 8 dual electronics boxes, plus engineering models.
  - The large number of items may overwhelm the vendor manufacturing process, possibly causing schedule delays and/or impacting product quality.

ACS

Risk (2 of 2)

- **Pointing algorithms/software cost growth**
  - The customer is assuming heritage algorithms and software from ST7, which has demonstrated a number of functions required for SGO.
  - There are questions as to who owns the algorithms and software from ST7 and whether they can be re-used as is.
  - In the time frame of the mission, with a launch date years away, also questions as to whether the same processor and compiler would be used.
  - Re-use may be significantly less than assumed, in which case, there would be a cost upper of $6M to $7M for pointing algorithms and software.

ACS
Option Comparison

- **Same sciencecraft design for both options. Similar prop modules.**

Element	CBE Mass (kg)	Cost ($M)	Architecture	Comments
Science-craft	6.3 CBE 6.93 with contingency	32.34	3-axis stabilized using colloidal thrusters. Instrument used as sensor during science ops.	Cost is the total for all sciencecraft, spares, and EMs.
Prop module	1.06 CBE 1.17 with contingency	5.77	3-axis stabilized using conventional thrusters. Hydrazine for Mid; Bi-prop/dual mode for High.	Cost is the total for all prop modules, spares, and EMs.

ACS
Additional Comments

- **ACS algorithms are assumed to be similar to those used for ST7, with minor modifications.**
  - Leads to $7M in cost savings on the sciencecraft.
    - Difference between “Similar with Minor Mods” and “Similar with Major Mods” selected in the ACS cost estimation tool.
- **Tendency among JPL engineers is to improve upon existing designs rather than re-use as is.**
  - Smart engineers who don’t accept a design without understanding it fully.
  - Detailed review tends to uncover things that need to be fixed or improved.
- **To fully realize the savings, must have the following:**
  - The rights to and a copy of the algorithms and software developed for ST7.
    - Raises the question of who owns these and where they are currently.
  - Re-use the software without making any changes.
  - Implement the software on the same processor, in the same environment.
- **In the time frame of this mission, may be a different processor.**
  - Code translation could increase costs.

CDS Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Dwight Geer

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CDS

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- Design Requirements
- Design Assumptions
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- Design Rationale
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- Cost
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CDS
Design Requirements

- **Mission:**
    - The Space-based Gravitational-Wave Observatory (SGO) measures gravity waves using a three-spacecraft “non-formation” flying constellation
    - The SGO constellation flies in a heliocentric earth-trailing orbit
    - This is a Class B Flagship mission – the C&DH is redundant (cold sparing)
- **Data Volumes**
    - Each spacecraft produces 5 kbps of science plus engineering data continuously or, equivalently, 2.25 Mbytes per hour
    - One complete data downlink cycle is six days (i.e. every six days each S/C downlinks its science and engineering data) – the other two spacecraft wait two or four days to downlink their data (each with a six day wait to repeat)
    - Each spacecraft must therefore be able to store 324MBytes of data
    - To accommodate two downlink pass misses 1 GB storage is required
- **Interfaces**
    - Most interfaces in this architecture utilize the 1553 bus
    - There are RS433 interfaces for the phase meter and telecom
    - There are analog interfaces for the ACS and thermal measurements
- **Radiation**
    - The mission TID requirement is 20.7 krad

CDS
Design Assumptions

- **The C&DH Interfaces**
  - The list on the right identifies the C&DH interface data rates. As shown, most interfacing devices use the 1553 bus.
- **MSAP type hardware is used**
  - As a Flagship fully redundant subsystem the MSAP hardware has the lowest risk profile for this mission
- **Differences from the customer MEL**
  - Although not directly evident from the provided MEL the customer block diagram implied functionality in the C&DH which, in the MSAP architecture, is in the Power chassis
    - The analog I/O board (MREU) is costed in the CDS workbook but will reside in the Power chassis
    - Power issues thruster commands to Propulsion (commanded by the C&DH via the MREU)

Source	Destination	Rate BPS
FEEP-PCU1	OBC	33936
FEEP-PCU2	OBC	33936
FEEP-PCU3	OBC	33936
GRS-Front End Electronics 1	OBC	25680
GRS-Front End Electronics 2	OBC	25680
Phase Meter Subsystem	OBC	11214
Ultraviolet Light Unit	OBC	1440
CCU	OBC	1104
Laser Subsystem 1	OBC	576
Laser Subsystem 2	OBC	576
Laser Subsystem 3	OBC	576
Laser Subsystem 4	OBC	576
OAME	OBC	384
OAE	OBC	72
DDE	OBC	7958
PCDU	OBC	9456
STR1	OBC	1910
STR2	OBC	1910
GYP1	OBC	22416
GYP2	OBC	22416
SCTH	OBC	720
HGAE	OBC	192
DSS1	OBC	1440
DSS2	OBC	1440
DSS3	OBC	1440
RFDU	OBC	24
TRAN1	OBC	288
TRAN2	OBC	288
AMP1	OBC	84
AMP2	OBC	84
Total 1553 Buss Traffic		241752
PMS Data 1 (Dedicated RS-422)	OBC	283800
PMS Data 2 (Dedicated RS-422)	OBC	283800
UL/DL 1(Dedicated RS-422)	OBC	90000
UL/DL 2(Dedicated RS-422)	OBC	90000

Cleared for public release. For discussion purposes only.

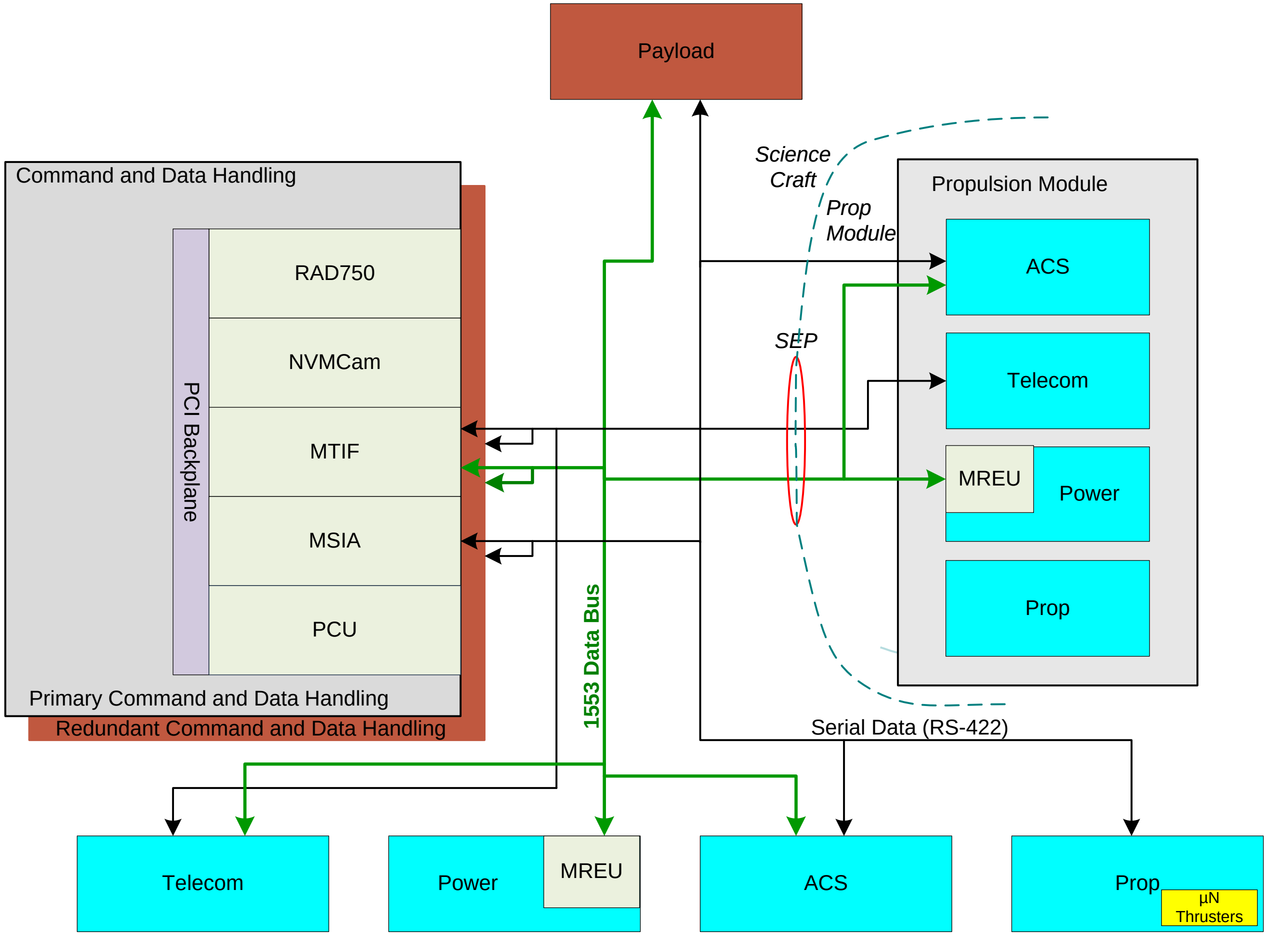
CDS

Design – Options

- **Hardware**
  - The C&DH for both options (SGO)-Mid and -High) are identical
    - The Sciencecraft includes most of the C&DH hardware including the computer
    - The Prop Module has an MREU the resides in the Power Chassis
    - The HIGH SGO-High Sciencecraft and Prop Module are, again, identical
    - The Prop Modules (both options) are single string
  - See the next two pages for the developed MEL
- **Functionality**
  - Data Storage
    - To ensure adequate storage the 4 GB NVMCam board was selected
    - This provides memory storage for missed downlink passes and margin for growth (margin usually required when in an early development phase)
  - The RAD750 computer has more than enough performance capability to provide the required functionality for this mission

CDS
Block Diagram

- **C&DH Block Diagram**



CDS
Design Rationale

- MSAP type hardware was selected to take advantage of both hardware and software heritage
- The NVMCam memory board was selected for the nonvolatile memory size (4 GB). This provides enough of this type memory to accommodate 2 missed downlink passes (needs about 1 GB) plus the memory design margin of 4 for a pre-PDR mission phase
- Hardware configuration (such as putting the MREU analog interface board in the Power Subsystem chassis) was used per the MSAP architecture

CDS
Cost Assumptions

- **Flight spares**
  - Although there are three science spacecraft in the constellation one spare set of hardware is reasonable so the Spares input parameter was set to 1/3
    - Note that this result in 1 spare board for 6 in the spacecraft constellation
- **Testbeds**
  - Two sets of GSE per science spacecraft is selected
    - This will result in 6 sets of GSE for the 3 spacecraft
    - This quantity may be appropriate for the mission development
      - Subsystem Testing and Troubleshooting: 2 sets
      - Mission System Testing and S/W Development: 2 sets
      - ATLO Testing: 2 sets

CDS

Cost – Options 1 & 2

- **MID: SGO-Mid**
  - 1ST Unit Cost : $32.2M (Science S/C) + $0.7M (Cruise S/C) = $32.9M
  - Nth Unit Cost: $11.5M (Science S/C) + $0.7M (Cruise S/C) = $12.2M
    - MID NRE: $20.7M
  - For all three elements of the constellation:
    1ST Unit Cost : $55.2M (Science S/C) + $2.0M (Cruise S/C) = $57.2M
- **HIGH: SGO-High**
  - 1ST Unit Cost : $32.2M (Science S/C) + $0.7M (Cruise S/C) = $32.9M
  - Nth Unit Cost: $11.5M (Science S/C) + $0.7M (Cruise S/C) = $12.2M
    - MID NRE: $20.7M
  - For all three elements of the constellation:
    1ST Unit Cost : $55.2M (Science S/C) + $2.0M (Cruise S/C) = $57.2M

- **Note:**
  - For the Cruise S/C only recurring costs are used
  - There are no costs in Phase E and F

CDS
Cost and Risk

- **Potential Cost Savings**
  - The NVMCam memory board could be down-sized from 4 GB to 1 GB
    - There is probably limited savings potential here but, with a technology cutoff date of 2015, a less expensive board is possible.
  - During the subsequent LaGrange study, an alternative memory card was found that would reduce the CDS cost for the SGO-Mid study by ~$1M.

- **List of Risks**
  - No risks were identified – design, fab, and test phase durations are good

Power Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Paul Stella/Keith Chin

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Power

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- Additional Comments

Power
Design Requirements – Option Mid & High

- **Mission:**
  - 1 AU, heliocentric, Earth trailing
  - No eclipses
  - 2020/10 launch
- **Stabilization: 3-Axis**
- **60 degrees sun off pointing during primary science mode**
  - Cruise is nominally at normal sun incidence
  - Cruise may revert to 60 degrees off pointing for array temperature control/string series length commonality
- **High gain antenna can shadow the array during portions of the annual orbit due to off-sun pointing**
  - May require use of cell keep-out areas, extra cells added to string length for shadow compensation of affected strings, or flight rules to rotate S/C to move shadow off the panel (if power limited)
  - Potential shadow area does not appear to need cell coverage at present power level

Power

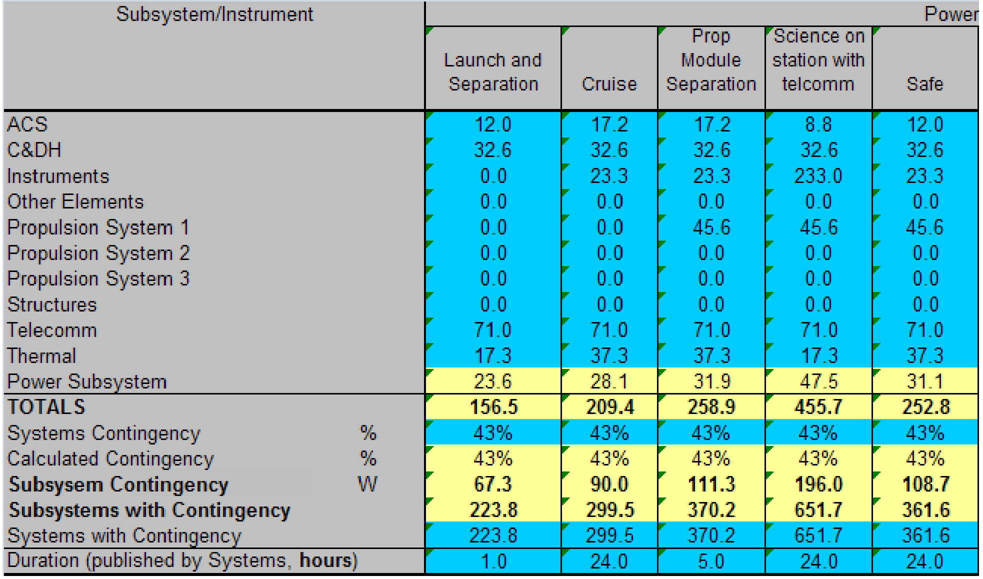
Design Assumptions – Option Mid & High

- **Fixed body solar array panel mounted to spacecraft bus**
  - Body mounted will run hot due to lack of rear side view factor to space.
  - Solar orbit with sizing driven by science + telecom power mode.
- **Assume 1 hour for launch and separation**
  - Drives battery size
- **Options**
  - Mid Option – Least expensive variant with 6 laser links, comprising 3 interferometer arms.
    - Shortened mission life, selective redundancy
  - High Option - LISA with optimized cost savings, full science performance & redundancy.

Power

Summary – Spacecraft - Mid

Power Mode Summary Chart

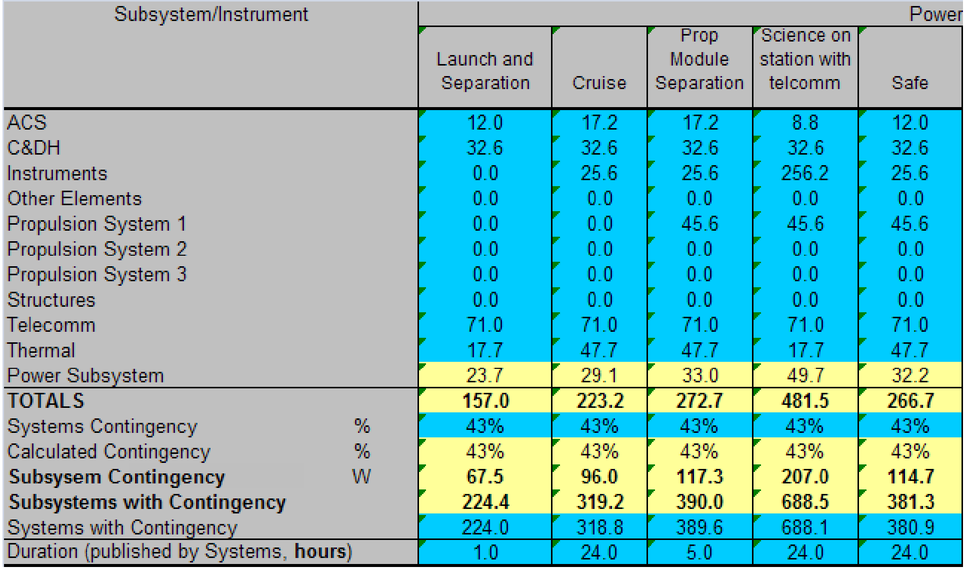


Subsystem/Instrument		Power				
		Launch and Separation	Cruise	Prop Module Separation	Science on station with telecomm	Safe
ACS		12.0	17.2	17.2	8.8	12.0
C&DH		32.6	32.6	32.6	32.6	32.6
Instruments		0.0	23.3	23.3	233.0	23.3
Other Elements		0.0	0.0	0.0	0.0	0.0
Propulsion System 1		0.0	0.0	45.6	45.6	45.6
Propulsion System 2		0.0	0.0	0.0	0.0	0.0
Propulsion System 3		0.0	0.0	0.0	0.0	0.0
Structures		0.0	0.0	0.0	0.0	0.0
Telecomm		71.0	71.0	71.0	71.0	71.0
Thermal		17.3	37.3	37.3	17.3	37.3
Power Subsystem		23.6	28.1	31.9	47.5	31.1
TOTALS		**156.5**	**209.4**	**258.9**	**455.7**	**252.8**
Systems Contingency	%	43%	43%	43%	43%	43%
Calculated Contingency	%	43%	43%	43%	43%	43%
Subsysem Contingency	W	**67.3**	**90.0**	**111.3**	**196.0**	**108.7**
Subsystems with Contingency		**223.8**	**299.5**	**370.2**	**651.7**	**361.6**
Systems with Contingency		223.8	299.5	370.2	651.7	361.6
Duration (published by Systems, **hours**)		1.0	24.0	5.0	24.0	24.0

Power

Summary – Spacecraft - High

Power Mode Summary Chart



Subsystem/Instrument		Power				
		Launch and Separation	Cruise	Prop Module Separation	Science on station with telecomm	Safe
ACS		12.0	17.2	17.2	8.8	12.0
C&DH		32.6	32.6	32.6	32.6	32.6
Instruments		0.0	25.6	25.6	256.2	25.6
Other Elements		0.0	0.0	0.0	0.0	0.0
Propulsion System 1		0.0	0.0	45.6	45.6	45.6
Propulsion System 2		0.0	0.0	0.0	0.0	0.0
Propulsion System 3		0.0	0.0	0.0	0.0	0.0
Structures		0.0	0.0	0.0	0.0	0.0
Telecomm		71.0	71.0	71.0	71.0	71.0
Thermal		17.7	47.7	47.7	17.7	47.7
Power Subsystem		23.7	29.1	33.0	49.7	32.2
TOTALS		**157.0**	**223.2**	**272.7**	**481.5**	**266.7**
Systems Contingency	%	43%	43%	43%	43%	43%
Calculated Contingency	%	43%	43%	43%	43%	43%
Subsysem Contingency	W	**67.5**	**96.0**	**117.3**	**207.0**	**114.7**
Subsystems with Contingency		**224.4**	**319.2**	**390.0**	**688.5**	**381.3**
Systems with Contingency		224.0	318.8	389.6	688.1	380.9
Duration (published by Systems, **hours**)		1.0	24.0	5.0	24.0	24.0

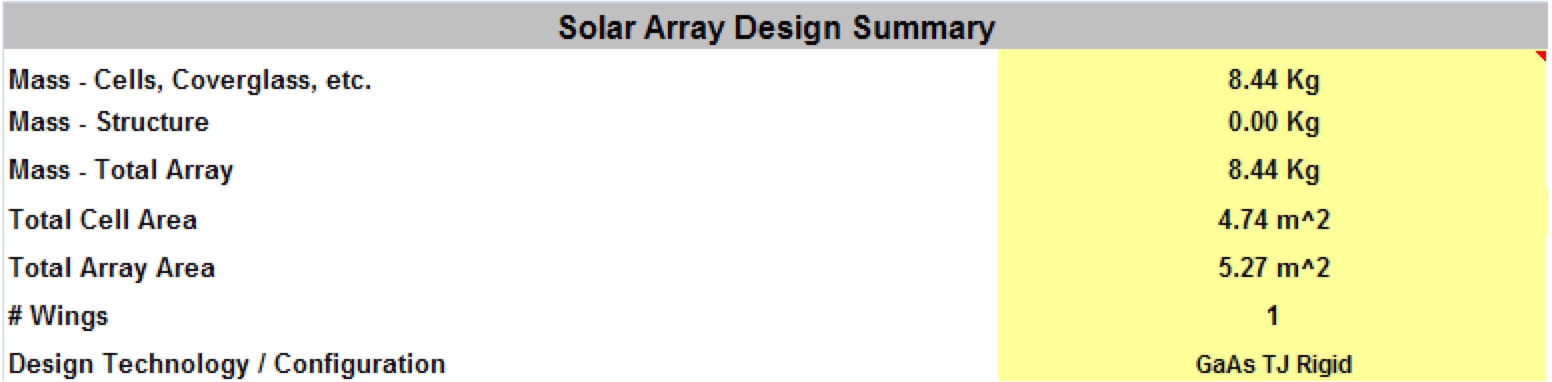
Power – Propulsion Stage

- **No power required for propulsion stage, only power related hardware as list here:**

Boards	2 Each	Boards	1.60
Board Size	6U Boards	Chassis	0.59
Converters	COTS	Shielding	0.17
Switching:	Dumb Solid State	Total Mass	2.36

Power
Design – Option Mid – Array

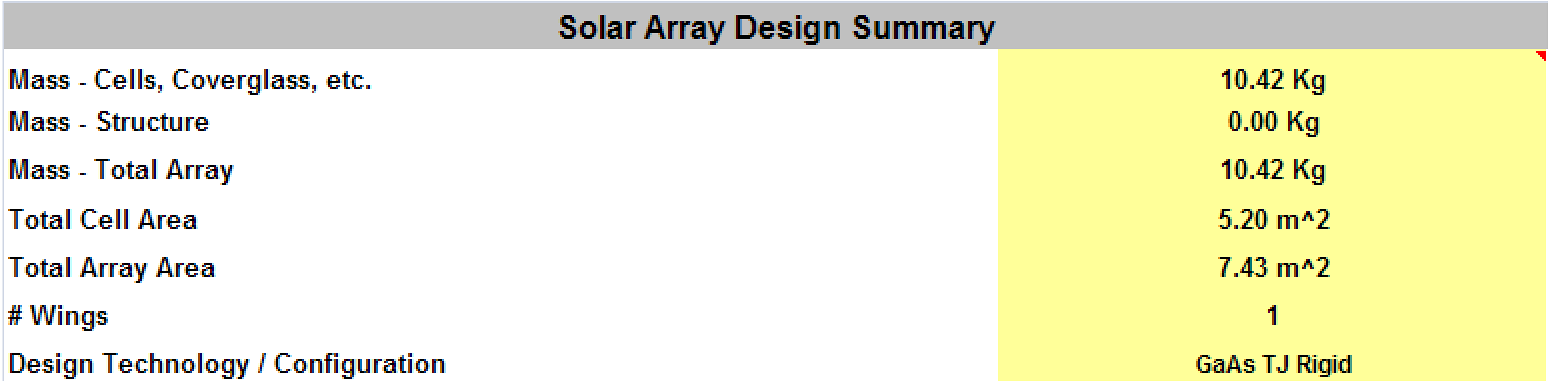
- **Fixed panel mounted to spacecraft bus**
  - Assume 29.5% efficiency three Junction solar cells
  - Circular shape substrate, 5.27 m^2 area
  - Array cell active area is 4.74 m^2
    - Packing factor = 0.90 (allows for shadowing from high gain antenna and circular panel inefficiency)
  - Body mounted will run hot due to lack of rear side view factor to space
    - Estimate 100C
  - Assume moderate flare particulate radiation degradation (2 years) - 8%
  - 60 degrees off sun pointing



Solar Array Design Summary	
Mass - Cells, Coverglass, etc.	8.44 Kg
Mass - Structure	0.00 Kg
Mass - Total Array	8.44 Kg
Total Cell Area	4.74 m^2
Total Array Area	5.27 m^2
# Wings	1
Design Technology / Configuration	GaAs TJ Rigid

Power
Design – Option High – Array

- **Fixed panel mounted to spacecraft bus**
  - Assume 29.5% efficiency three Junction solar cells
  - Circular shape substrate, 7.43 m^2 area
  - Array cell active area is 5.2 m^2
    - Packing factor = 0.90 (allows for shadowing from high gain antenna and circular panel inefficiency)
  - Body mounted will run hot due to lack of rear side view factor to space
    - Estimate 100C
  - Assume moderate flare particulate radiation degradation (5 years)- 10%
  - 60 degrees off sun pointing

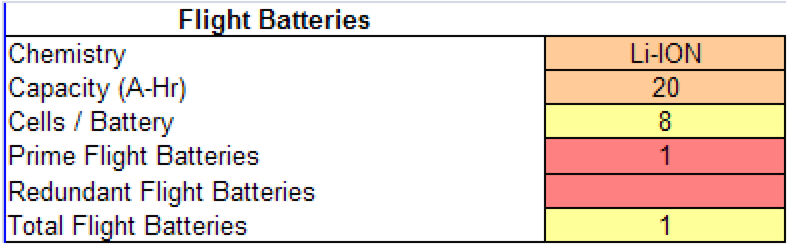


Solar Array Design Summary	
Mass - Cells, Coverglass, etc.	10.42 Kg
Mass - Structure	0.00 Kg
Mass - Total Array	10.42 Kg
Total Cell Area	5.20 m^2
Total Array Area	7.43 m^2
# Wings	1
Design Technology / Configuration	GaAs TJ Rigid

Power

Design – Option Mid/High- Batteries

- **20 A-hr Li-Ion ABSL Secondary Battery.**
  - 40% DoD design size based on launch/separation power mode.
- **Cost Includes one spare battery**



Flight Batteries	
Chemistry	Li-ION
Capacity (A-Hr)	20
Cells / Battery	8
Prime Flight Batteries	1
Redundant Flight Batteries	
Total Flight Batteries	1

Power

Design Rationale – Option Mid/High

- **Array**
  - Driving power mode - Science on station with telecommunications
  - Off sun pointing decreases effective array efficiency
  - Cell packing factor requires additional reduction due to potential high gain antenna shadowing (considered modest)
- **Batteries**
  - Driving power mode – Launch and separation
  - Redundancy best met with use of ABSL design with its inherent series/parallel design allowing for additional strings
    - Avoids need for complete additional redundant battery
- **Electronics**
  - Design Drivers – Science on station with telecomm
  - Redundant boards
  - Spares are based on three S/C total design, e.g., 1 spare for all three S/C.

Power

Cost and Risk– Option Mid & High

Cost Drivers

- Major cost is in the redundant Electronics.
- Electronics includes spares (3X spares not needed for 3X spacecraft)

Potential Cost Savings

- Single spare for all three S/C lowers recurring cost.

Potential Cost Uppers

- Long duration safe mode may require larger battery than assumed for launch/separation mode.

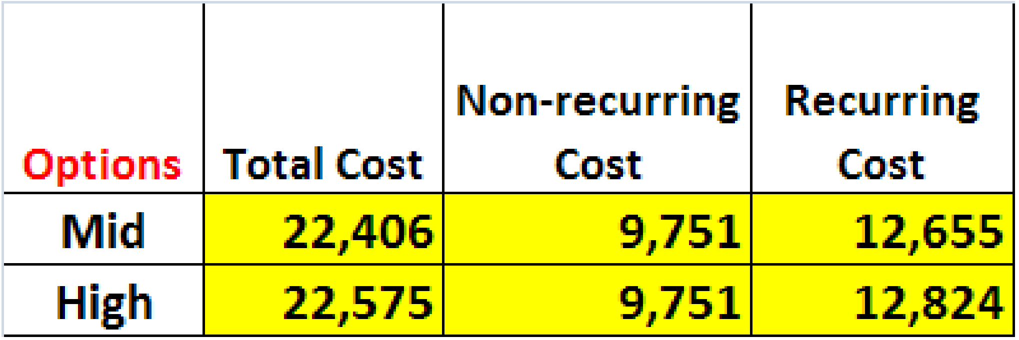
Risks: List of Risks

- Design is based on high heritage technology – low risk
- Mass and size savings feasible with electronic board re-designs
  - Reduced TRL

Power

Option Comparison

- **No appreciable differences in power subsystem design for options Mid vs High.**
  - Only difference is solar array sizing, with battery and electronics identical.
  - Cost comparison are as follows:



Options	Total Cost	Non-recurring Cost	Recurring Cost
Mid	22,406	9,751	12,655
High	22,575	9,751	12,824

Power

Additional Comments

- **Induced magnetic field during battery charge/discharge may impact proof mass position.**
  - Low risk since sun synchronous orbit with no battery loading.
  - Possible fixes include no battery operations during science mode, additional insulation, and battery location.

Propulsion Report

(1279) SGO-MID 2012-03

Date March 5-8, 2012

Author: Frank Picha

Email: frank.q.picha@jpl.nasa.gov

Propulsion

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Propulsion
Design Requirements – Option 1 and 2

- **Mission:**
  - Three spacecraft in earth trailing formation

- **Mission Design**
  - Require delta-v for TCMs during cruise to final orbit with a much higher delta-v requirement for Option 2
  - Science spacecraft micro positioning

- **ACS**
  - Micro delta-v for station keeping during science orbit
  - Minimum ACS propellant during cruise

- **Configuration**
  - Science orbit requires extremely low spacecraft jitter, so a typical hydrazine system with propellant slosh is not an option

Propulsion

Design Assumptions – Options 1 and 2

- **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 a Colloidal propulsion system for the Science spacecraft to reduce vibration and jitter**

Propulsion
Design – Options 1 and 2

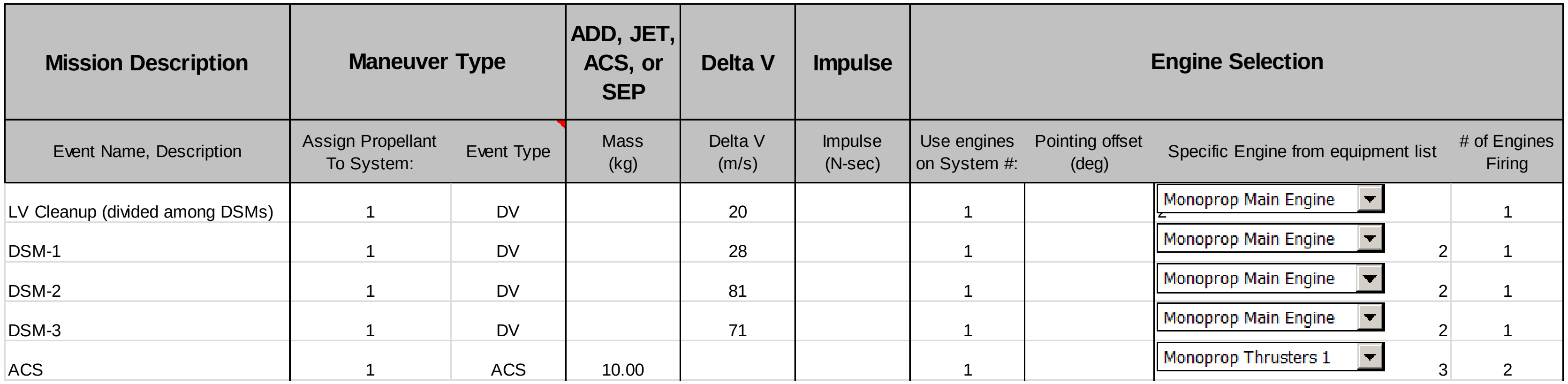
- **Hardware**
  - Science Spacecraft Options 1 and 2 is a colloidal propulsion system based on ST7 design and heritage, 49.9 kg CBE including 50% contingency
  - Propulsion Stage Option 1, blowdown Hydrazine monopropellant system, 38.7 kg CBE including 7% contingency
    - Two heritage Titanium diaphragm tanks
    - One main engine
    - Four TVC engines
    - Eight 0.9N RCS engines
  - Propulsion Stage Option 2, regulated Hydrazine/NTO bi-propellant system, 82.9 kg CBE including 9% contingency
    - Two heritage Titanium diaphragm oxidizer tanks, and two heritage PSI 80469 Titanium diaphragm fuel tanks
    - Two heritage COPV pressurant tanks for fuel and oxidizer
    - One 445N main engine
    - Four TVC engines
    - Eight RCS engines
- **Functionality**
  - Science Craft colloidal propulsion system provides low jitter station keeping for mission duration
  - Propulsion Stage Options 1 and 2 provide delta-v required to get to science orbits

Propulsion
Design – Option 1 Propulsion Stage

Propellant

- 139 kg Hydrazine monopropellant
- 200 m/s delta-v sized for 1495 kg total spacecraft initial mass

DV table for Option 1



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
LV Cleanup (divided among DSMs)	1	DV		20		1		Monoprop Main Engine	1
DSM-1	1	DV		28		1		Monoprop Main Engine 2	1
DSM-2	1	DV		81		1		Monoprop Main Engine 2	1
DSM-3	1	DV		71		1		Monoprop Main Engine 2	1
ACS	1	ACS	10.00			1		Monoprop Thrusters 1 3	2

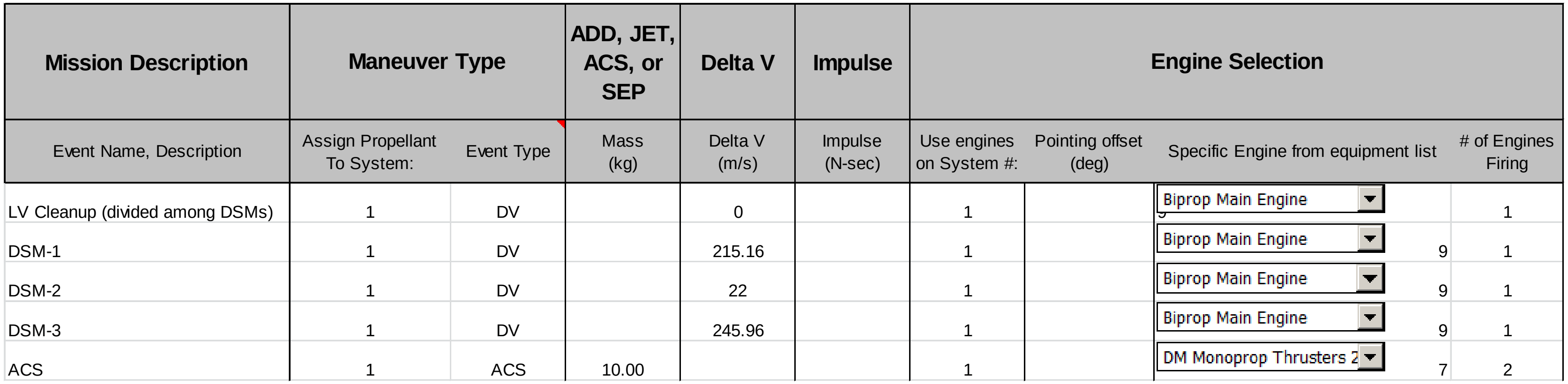
Propulsion

Design – Option 2 Propulsion Stage

Propellant

- 167 kg Hydrazine and 133 kg NTO
- 1098 m/s delta-v scaled down to 44% of original value in order to fit on launch vehicle capability of 2025 per spacecraft

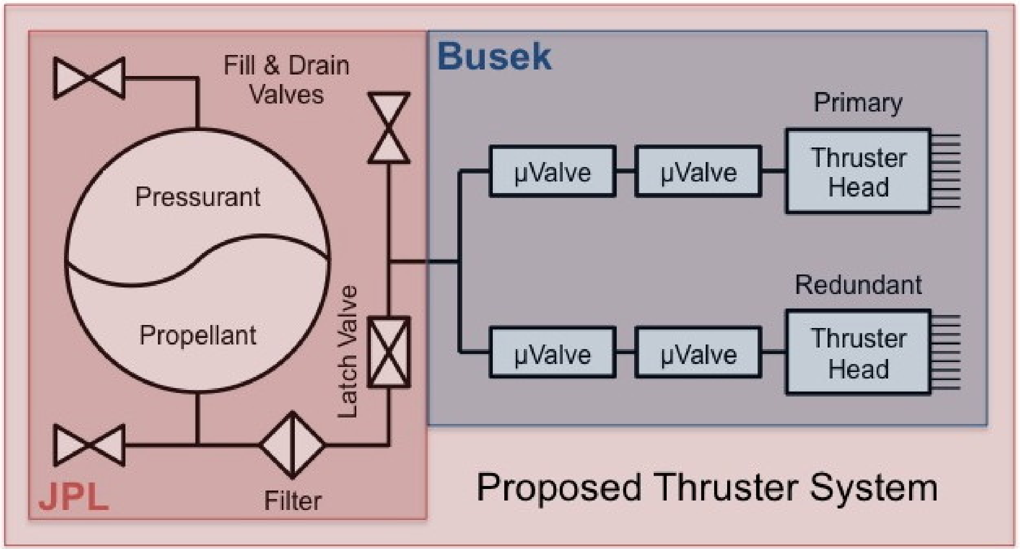
DV table for Option 2, note 1098 m/s downgraded to fit on launch vehicle



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
LV Cleanup (divided among DSMs)	1	DV		0		1		Biprop Main Engine ▾		1
DSM-1	1	DV		215.16		1		Biprop Main Engine ▾	9	1
DSM-2	1	DV		22		1		Biprop Main Engine ▾	9	1
DSM-3	1	DV		245.96		1		Biprop Main Engine ▾	9	1
ACS	1	ACS	10.00			1		DM Monoprop Thrusters 2 ▾	7	2

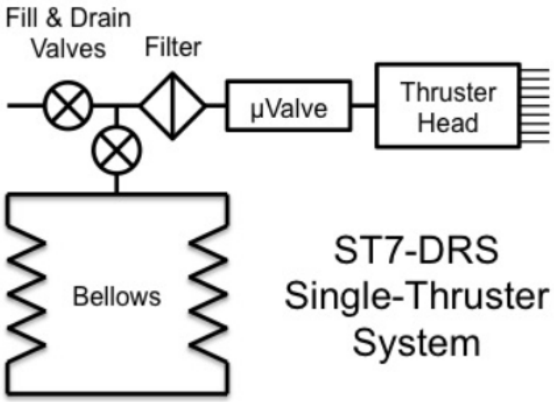
Propulsion
Block Diagram – Options 1 and 2 Science Spacecraft

- **Proposed system composed of three clusters of four engines:**



Proposed Thruster System

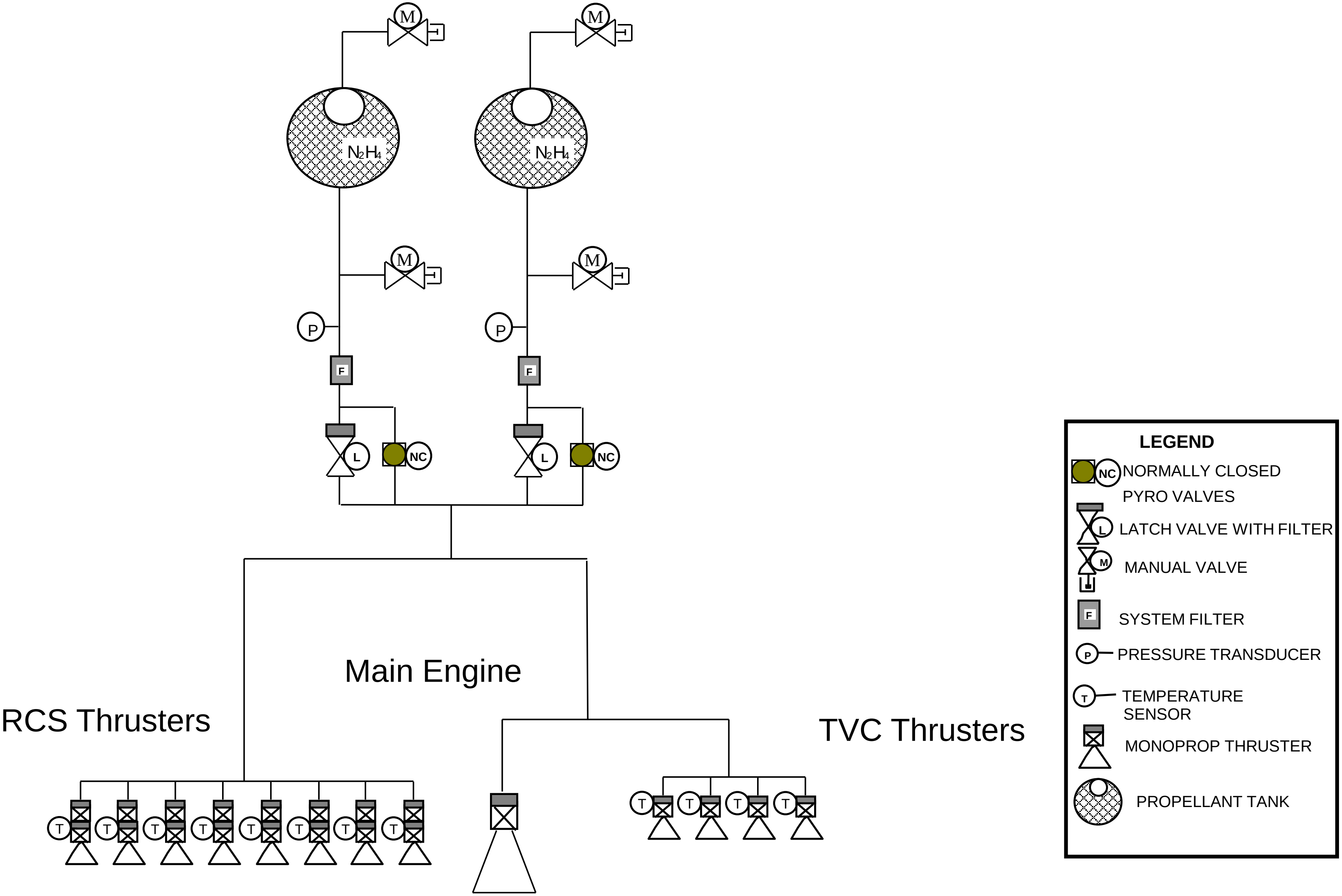
- **TRL=7 system ready to launch on ST7 in 2014**



ST7-DRS Single-Thruster System

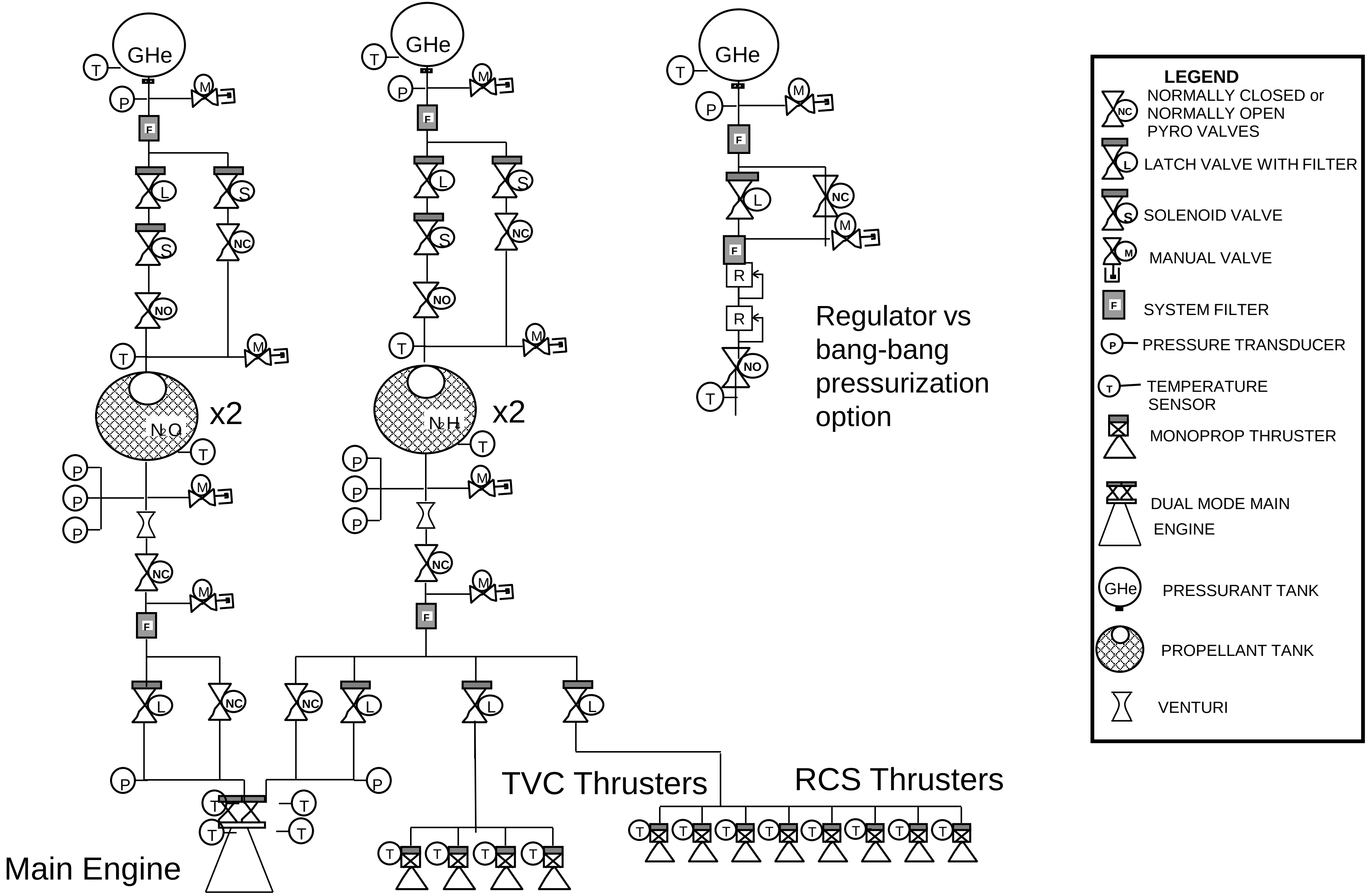
Propulsion

Block Diagram – Option 1 Propulsion Stage



Propulsion

Block Diagram – Option 2 Propulsion Stage



Regulator vs bang-bang pressurization option

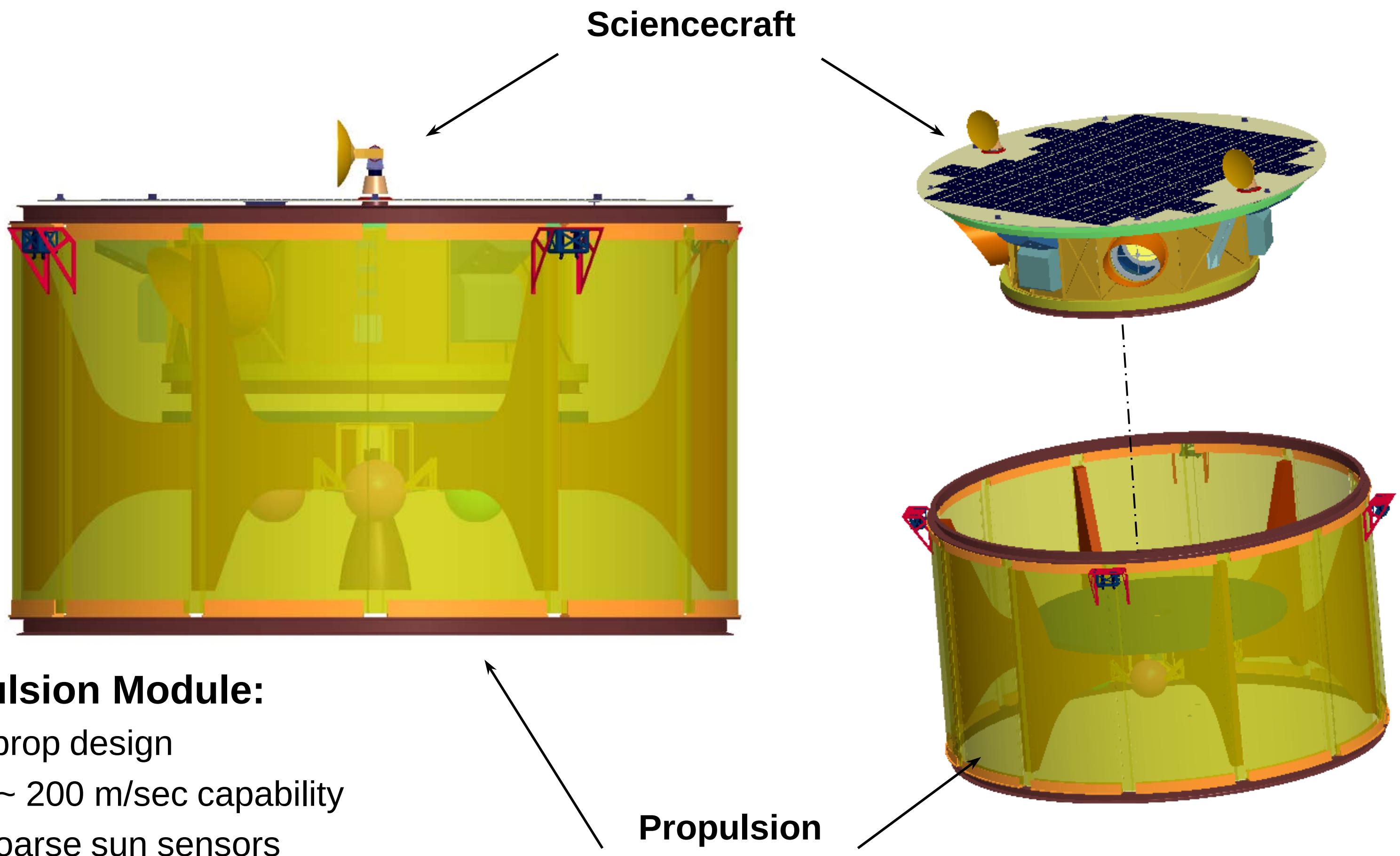
TVC Thrusters

RCS Thrusters

Main Engine

Propulsion

Prop Module/Cruise Configuration



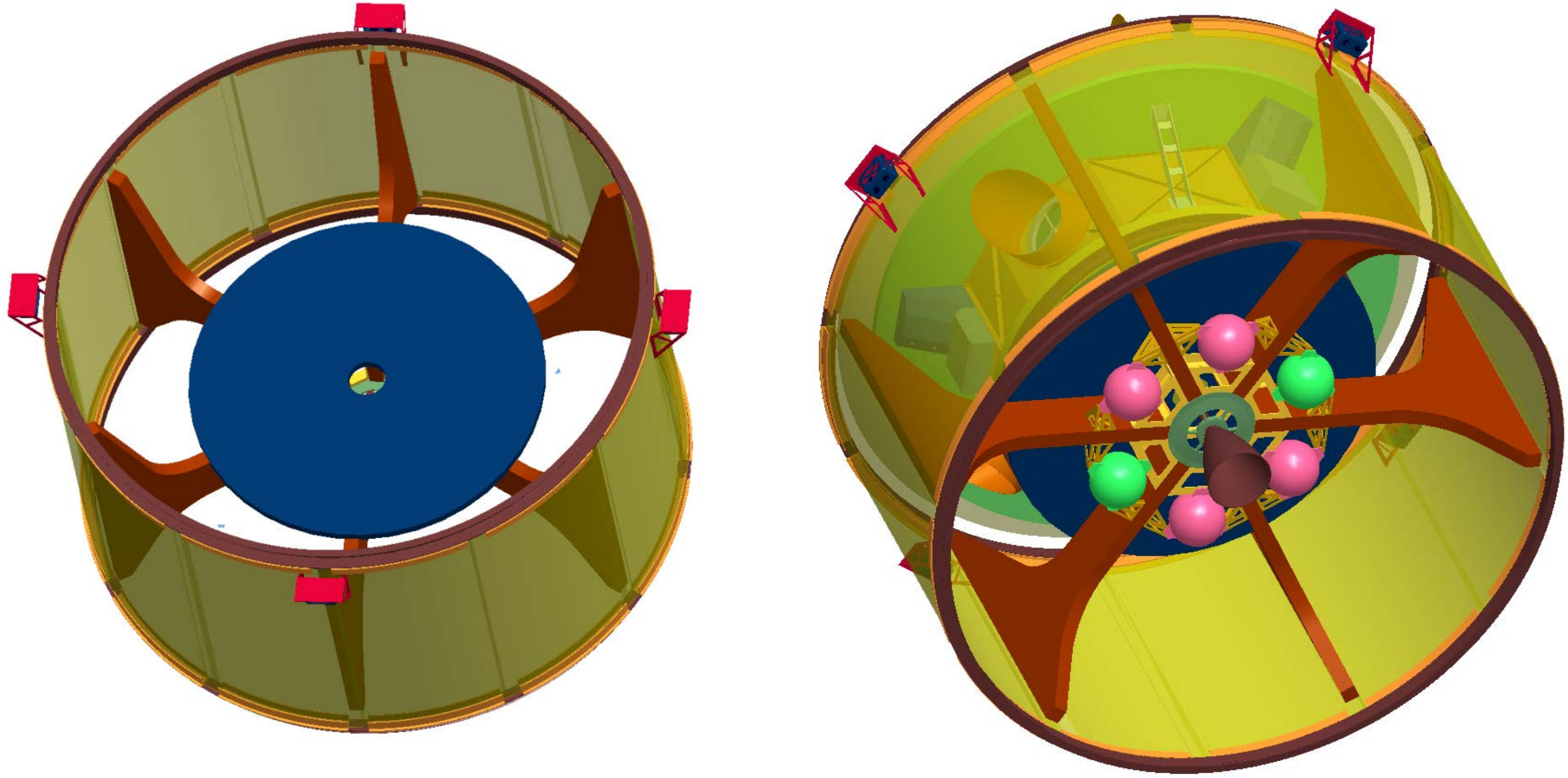
Propulsion Module:

- Bi-prop design
- Δv ~ 200 m/sec capability
- 6 coarse sun sensors
- 2 star tracker heads
- 2 omni antennas

Structural design shown has been scaled from SGO-High/LISA but not yet optimized.

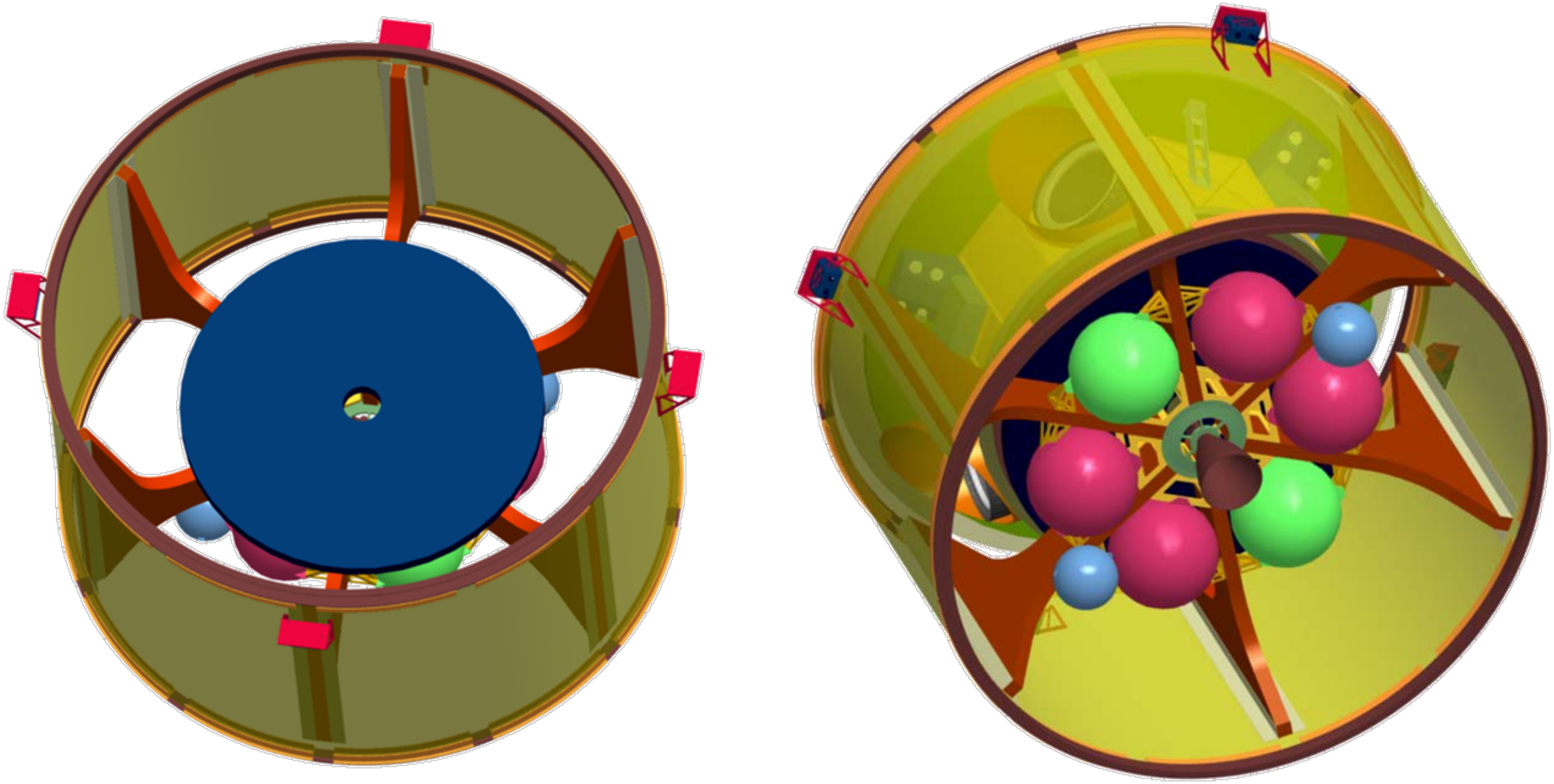
Propulsion

Propulsion Module (PM): SGO-High



Propulsion

Propulsion Module (PM): SGO-High



Propulsion
Design Rationale – Options 1 and 2

- **Option 1 design optimization as determined by the lower delta-v requirements led to a monopropellant system which saved cost**
- **Option 2 required higher delta-v which led to a higher cost bi-propellant system to take advantage of fuel mass savings due to the higher Isp**

- **Trades**
  - For Option 1 Propulsion Stage, a monopropellant system was traded against the baseline bi-prop stage from the customer MEL, and the monopropellant saves 39 kg in prop system dry mass, and $20.5M in system cost for three flight systems combined
  - For Option 2, a bi-propellant system was the only choice due to increased delta-v capability and higher Isp

Propulsion

Cost Assumptions – Options 1 and 2

- Colloidal four engine cluster cost based on customer supplied estimate from 2007
- Cost reduction is a design driver
- Spares for each component per standard practice
- Workforce adjusted for prolonged phase C/D duration

Propulsion

Cost – Options 1 and 2

- **Cost Drivers**
  - Extended phase duration C/D drive cost higher
- **Potential Cost Savings**
  - Reduction of phase C/D duration would save workforce cost
  - Utilization of off-the-shelf propellant tanks save cost
- **Potential Cost Uppers**
  - Delta-qualification of the colloidal thruster for increased mission life and propellant through-put will add cost
  - Custom design propellant tanks save mass but add cost

Propulsion

Risk

- **Delta-qualification of the colloidal thruster for increased mission life and propellant through-put will add minimal risk**
- **For the propulsion stage risk is low when using flight proven components**

Propulsion
Option Comparison

- Mass, cost, and count is per spacecraft

Option	Mass (kg)	Cost ($M)	Thrusters	Tank Size (m)	Propellant mass (kg)	Comments
1	38.7 CBE incl. 7% contingency	$12.2M	1 – 250N main 4 – 22N TVC 8 – 0.9N RCS	0.58 dia x 0.65 long	139 kg N2H4	
2	82.9 CBE incl. 9% contingency	$20.6M	1 – 445N main 4 – 22N TVC 8 – 0.9N RCS	Ox: .56 sph F: .58 x .65 Pres: .34x.74	167 kg N2H4 133 kg NTO	
Colloidal system	49.9 CBE incl. 50% contingency	$27.2M	4 colloidal thrusters per cluster	1.3 liter		

Propulsion
Additional Comments

- **Did not properly close design to fit launch vehicle capability for Option 2 Propulsion Stage**

- **Continued micro-thruster development is required both for the thruster and system to account for longer lifetime requirements and fuel capacity required over existing NM ST-7 hardware. This includes incorporation of a larger diaphragm tank, rather than a bellows assembly, increased system redundancies, thruster life, and other system optimizations (thruster cluster design and analysis).**

Mechanical Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Matt Spaulding

Email: Matthew.D.Spaulding@jpl.nasa.gov

Mechanical

Table of Contents

- Design Requirements
- Design Assumptions
- Design
- Design Rationale
- Cost Assumptions
- Cost
- Risk
- Option Comparison
- Additional Comments

Mechanical
Design Requirements

- **Mission:**
  - The mission is traveling in an equilateral triangular formation in 22 degree earth trailing orbit canted at 60 degrees from Earth's planar orbit.
- **Launch Vehicle: Atlas V 551**
- **Stabilization: 3-Axis**
- **Sciencecraft Payloads:**
  - MID (Mid) – Two 25cm Aperture Telescope Assemblies
  - HIGH (High) – Two 40 cm Aperture Telescope Assemblies

Mechanical

Design Assumptions - Sciencecraft

- The materials utilized to construct the Primary Structure of the Sciencecraft for both the Mid and High options were a combination of machined aluminum and titanium with flat panels constructed of metallic honeycomb composite.
- It was additionally noted that due to the presence of the Gravitational Reference Sensors (GRS) and their dependence on self-gravity and magnetic interference from the Sciencecraft itself, additional effort beyond that found in more common spacecraft builds needs to be incorporated by the Mass Properties Engineer and the Materials and Processes Engineer. Specifically, a more detailed understanding of mass locations needs to be recorded and understood by the Mass Properties Engineer, and the Material and Processes Engineer needs to limit or eliminate the usage of material which are magnetic or could cause other interference to the GRS.
- A single Sciencecraft configuration will be built three times in order to minimize costs.

Mechanical

Design Assumptions – Propulsion Stage

- **The materials utilized to construct the Primary Structure of the Propulsion Stage for both the Mid and High options were a combination of machined aluminum with flat panels constructed of metallic honeycomb composite.**
- **Due to the stacked launch configuration, in order to support the additional Sciencecraft/Propulsion Stage assemblies additional support needs to be added to the Propulsion Stage’s Primary Structure beyond that which is necessary to support an individual Sciencecraft.**
- **A single Propulsion Stage configuration will be built three times in order to minimize costs.**

Mechanical
Design – Sciencecraft

- **Design**
  - The general configuration of the Sciencecraft did not vary significantly from the design contributed to Team X. The necessary solar array area changed slightly from what was presented. However, since the array support structure is also providing a sun shade for the telescope baffles and bus, its size remained the same rather than taking advantage of the decreased area.
  - The two low gain antennas were relocated from the top of the solar array support panel to two opposing sides of the cylindrical bus in order to provide adequate coverage.
  - The interface to the Propulsion Stage takes place through a lightband separation mechanism located on the opposite side of the cylindrical bus as the solar array support structure.
- **Mechanisms and Deployments**
  - Due to the nature of the mission, attention was paid to minimize the quantity of mechanisms and deployments necessary. With this in mind, the only mechanism present on the Sciencecraft is the 2-axis gimbal for the HGA.

Mechanical
Design – Propulsion Stage

- **Design**
  - The cylindrical shape of the Propulsion Stage is the most logical configuration and allows for a clean stacking geometry within the launch vehicle payload fairing. Because the Sciencecraft geometry changed very little, the Propulsion Stage remained similar to that proposed to Team X.
  - One variation to the geometry presented was the addition of windows in the cylindrical walls of the Propulsion Stage in order to provide fields of view to space for the Sciencecraft radiators during cruise.
  - As previously mentioned in the report, a single design for the Propulsion Stage will be constructed three times in order to conserve cost. This aspect results in the necessity of the lowest Propulsion Stage being designed in order to incorporate the ability to support a total quantity of three Sciencecraft and two Propulsion Stages at launch. This increased the mass of the Mid Propulsion Stage by 209 kg and the High Propulsion Stage by 242 kg.
- **Mechanisms and Deployments**
  - The Propulsion Stages for the Mid and High options each have two lightband separations. One separation occurs between the Propulsion System and the carried Sciencecraft and a second between the neighboring Propulsion Module or Launch Vehicle Adapter in the launch stack.

Mechanical
Design – Sciencecraft Mid

- **Detailed Mass List**
  - The highest mass contributions of the mechanical subsystem are the Primary Structure and the Sciencecraft Harness.
  - The Primary Structure mass is influenced by the subsystem elements being supported. The largest influencing factor was the mass of the two Telescope Assemblies followed by the Propulsion System.
  - The Sciencecraft Harness mass was determined by the number of separate electronics boxes counted within the provided CAD model as well as the necessity to carry some high voltage harness for power supplied to the two lasers.

Item	Type	Quantity	CBE	Contingency	CBE + Cont.
Primary Structure	Structure	1	68.7 kg	30%	89.3 kg
Secondary Structure	Structure	1	9.3 kg	30%	12.2 kg
Tertiary Structure	Structure	1	2.4 kg	30%	3.2 kg
Power Support Structure	Structure	1	3.5 kg	30%	4.5 kg
Telecom Support Structure	Structure	1	0.2 kg	30%	0.3 kg
Telecom Mechanisms	Mechanism	1	3.0 kg	30%	3.9 kg
Balance/Ballast	Structure	1	4.6 kg	30%	5.9 kg
Solar Array Thermal Isolators	Structure	1	2.0 kg	30%	2.6 kg
Prop. Stage to Sciencecraft Separation Upper	Mechanism	1	13.5 kg	30%	17.6 kg
Harness	Cabling-Mfg	1	21.2 kg	30%	27.6 kg

Mechanical
Design – Propulsion Stage Mid

Detailed Mass List

- The highest mass contribution to the Propulsion Stage is the Primary Structure.
- The breakdown of the Primary Structure mass is comprised of approximately 77kg of structure necessary for supporting the miscellaneous subsystems and the carried Sciencecraft. In addition to the 77kg,the two separation mechanisms add an additional 35.3kg. The largest portion of the remaining mass (~209kg) stems from the necessity of the base Propulsion Stage needing to carry the additional mass of the stacked Propulsion Stages and Sciencecraft within the payload fairing during launch.

Item	Type	Quantity	CBE	Contingency	CBE + Cont.
Primary Structure	Structure	1	286.1 kg	30%	371.9 kg
Secondary Structure	Structure	1	4.8 kg	30%	6.2 kg
Tertiary Structure	Structure	1	2.9 kg	30%	3.7 kg
Telecom Support Structure	Structure	1	0.1 kg	30%	0.1 kg
Balance/Ballast	Structure	1	8.8 kg	30%	11.5 kg
Integration Hardware	Mechanism	1	20.6 kg	30%	26.7 kg
Inter-Propulsion Module Separation Mechanism	Mechanism	1	21.8 kg	30%	28.3 kg
Prop. Stage to Sciencecraft Separation Lower	Mechanism	1	13.5 kg	30%	17.6 kg
Harness	Cabling-Mfg	1	9.7 kg	30%	12.6 kg

Mechanical
Design – Sciencecraft High

Detailed Mass List

- The highest mass contributions of the mechanical subsystem are the Primary Structure and the Sciencecraft Harness.
- The Primary Structure mass is influenced by the subsystem elements being supported. The largest influencing factor was the mass of the two Telescope Assemblies followed by the Propulsion System.
- The Sciencecraft Harness mass was determined by the number of separate electronics boxes counted within the provided CAD model as well as the necessity to carry some high voltage harness for power supplied to the two lasers.

Item	Type	Quantity	CBE	Contingency	CBE + Cont.
Primary Structure	Structure	1	76.3 kg	30%	99.2 kg
Secondary Structure	Structure	1	10.7 kg	30%	13.8 kg
Tertiary Structure	Structure	1	2.7 kg	30%	3.5 kg
Power Support Structure	Structure	1	8.0 kg	30%	10.3 kg
Telecom Support Structure	Structure	1	0.2 kg	30%	0.3 kg
Telecom Mechanisms	Mechanism	1	3.0 kg	30%	3.9 kg
Balance/Ballast	Structure	1	5.1 kg	30%	6.7 kg
Solar Array Thermal Isolators	Structure	1	2.0 kg	30%	2.6 kg
Prop. Stage to Sciencecraft Separation Upper	Mechanism	1	13.5 kg	30%	17.6 kg
Harness	Cabling-Mfg	1	22.4 kg	30%	29.1 kg

Mechanical
Design – Propulsion Stage High

Detailed Mass List

- The highest mass contribution to the Propulsion Stage is the Primary Structure.
- The breakdown of the Primary Structure mass is comprised of approximately 105.5kg of structure necessary for supporting the miscellaneous subsystems and the carried Sciencecraft. In addition to the 105.5kg,the two separation mechanisms add an additional 35.3kg. The largest portion of the remaining mass (~242kg) stems from the necessity of the base Propulsion Stage needing to carry the additional mass of the stacked Propulsion Stages and Sciencecraft within the payload fairing during launch.

Item	Type	Quantity	CBE	Contingency	CBE + Cont.
Primary Structure	Structure	1	347.5 kg	30%	451.7 kg
Secondary Structure	Structure	1	6.4 kg	30%	8.3 kg
Tertiary Structure	Structure	1	3.7 kg	30%	4.8 kg
Telecom Support Structure	Structure	1	0.1 kg	30%	0.1 kg
Balance/Ballast	Structure	1	10.6 kg	30%	13.8 kg
Integration Hardware	Mechanism	1	25.0 kg	30%	32.5 kg
Inter-Propulsion Module Separation Mechanism	Mechanism	1	21.8 kg	30%	28.3 kg
Prop. Stage to Sciencecraft Separation Lower	Mechanism	1	13.5 kg	30%	17.6 kg
Harness	Cabling-Mfg	1	12.9 kg	30%	16.8 kg

Mechanical
Design Rationale – Sciencecraft

- The general configuration of the Sciencecraft varied little from the supplied configuration proposed by the customer. The top deck which provides a surface capable of supporting the required solar array area and a surface for mounting the HGA antenna and actuator is thermally isolated from the bus as well as provides shade for the Telescope Baffles and bus throughout the orbit. Because of the solar shielding aspect, the diameter cannot be further decreased.
- In order to minimize the presence of vibrations and outside sources of error to the two Gravity Reference Sensors, nearly everything is rigidly fastened to the primary structure. The two exceptions are the HGA antenna gimbal and the Solar Array Deck which is thermally isolated using thermal standoffs.

Mechanical
Design Rationale – Propulsion Stage

- The geometry of the Propulsion Stage varied only slightly from the configuration proposed by the customer. The only variation occurs in the addition of radiator ports through which the internal Sciencecraft radiators can get a view to space during cruise to their final orbit locations.
- During the study, in an effort to decrease the launch mass, the feasibility of flying three similar but individually designed Propulsion Stages tailored to their placement within the launch stack was quickly researched. If the internal subsystems of the three Propulsion Stages remained the same, the top most Propulsion Stage in the launch stack would have a structural mass of 183kg (not including the masses of the carried subsystems). The middle Propulsion Stage would have a structural mass of 340kg. Each Propulsion Stage would require individual attention resulting in increased cost compared to designing a single Propulsion Stage for the worst case launch load case and simply building multiple copies. Repercussions of three separate designs also have design and behavior ripples through the other subsystems which while similar may behave slightly differently based on the differences between the Propulsion Stage designs.

Mechanical
Cost Assumptions

- Management and mission wide costs were book kept in the Sciencecraft's costs.
- Both the Sciencecraft and Propulsion Stages were designed as In-House builds and costed based on models derived from actual data.
- Both the Sciencecraft and Propulsion Stages were considered contamination sensitive and a contamination analysis and analytical chemistry services were added to the cost of the mission.

Mechanical

Cost – Sciencecraft Mid

- Mechanical (Including I & T): $33.87M
- Cabling: $4.64M
- Contamination Control: $1.47M
- Materials & Processes: $0.71M

Mechanical
Cost – Sciencecraft Mid

- **Cost Drivers**
  - The largest cost items for the Sciencecraft are the Primary Structure and the Telecom 2-Axis Gimbal combined resulting in $12.25M.
  - An additional ~$16M is comprised of the non-physical deliveries and management costs.
- **Potential Cost Savings**
  - The Telecom Gimbals were costed as individual items on the three separate spacecraft. It may be possible to purchase a set of three or four identical units at a lower cost.
- **Potential Cost Uppers**
  - Due to the increased knowledge necessary to understand the Sciencecraft’s self gravitation on the Gravity Reference Sensor it may be worth increasing the level of effort/involvement of the Mass Properties Engineer and the Materials and Processes Engineer(s).
  - The launch locks necessary for protecting the Gravity Reference Sensor are still in development, and further development may require additional cost.

Mechanical

Cost – Propulsion Stage Mid

- **Mechanical (Including I & T): $27.18M**
- **Cabling: $2.96M**
- **Contamination Control: Book kept with Sciencecraft**
- **Materials & Processes: $0.55M**

Mechanical
Cost – Propulsion Stage Mid

Cost Drivers

- The primary cost driver of the Propulsion Stage is the Primary Structure. This is caused by the number of interfaces as well as the required structure necessary for launch.

Potential Cost Uppers

- Development of a larger diameter Lightband Separation System may result in cost increases.
- Depending on if additional launch vehicle isolation is required for protection of the Gravity Reference Sensors, an additional dynamics isolation system may be necessary.

Mechanical

Cost – Sciencecraft High

- Mechanical (Including I & T): $34.12M
- Cabling: $4.64M
- Contamination Control: $1.47M
- Materials & Processes: $0.71M

Mechanical

Cost – Sciencecraft High

Cost Drivers

- The largest cost items for the Sciencecraft are the Primary Structure and the Telecom 2-Axis Gimbal combined resulting in $12.36M.
- An additional ~$18M is comprised of the non-physical deliveries and management costs.

Potential Cost Savings

- The Telecom Gimbals were costed as individual items on the three separate spacecraft. It may be possible to purchase a set of three or four identical units at a lower cost.

Potential Cost Uppers

- Due to the increased knowledge necessary to understand the Sciencecraft's self gravitation on the Gravity Reference Sensor it may be worth increasing the level of effort/involvement of the Mass Properties Engineer and the Materials and Processes Engineer(s).
- The launch locks necessary for protecting the Gravity Reference Sensor are still in development, and further development may require additional cost.

Mechanical

Cost – Propulsion Stage High

- Mechanical (Including I & T): $31.09M
- Cabling: $2.96M
- Contamination Control: Book kept with Sciencecraft
- Materials & Processes: $0.55M

Mechanical
Cost – Propulsion Stage High

- **Cost Drivers**
  - The primary cost driver of the Propulsion Stage is the Primary Structure. This is caused by the number of interfaces as well as the required structure necessary for launch.

- **Potential Cost Uppers**
  - Development of a larger diameter Lightband Separation System may result in cost increases.
  - Depending on if additional launch vehicle isolation is required for protection of the Gravity Reference Sensors, an additional dynamics isolation system may be necessary.

Mechanical

Risk

- Launch loads imparted into the Gravity Reference Sensor may damage the reference mass. Fully understanding the dynamics of the launch will help clarify the requirements for the launch restraint system. Analysis of the dynamics will also determine which of the stacked Sciencecraft will see the most detrimental loads.
- Due to the sensitivity of the instrument, additional level of effort will need to be implemented early in the spacecraft design in order to make certain that all engineers involved pay attention to what materials are utilized as well as proximity to the two reference masses. This information along with masses and locations needs to be clearly vetted through both the Materials and Processes group as well as documented with the Mass Properties Engineer. Early involvement and careful attention can mitigate possible sources of error.
- A solid understanding of the thermal environments within the spacecraft will be necessary to determine locations where rigid mounts may be difficult due to thermal expansion issues. Thermal isolation through the implementation of low thermally conductive materials may be necessary to limit thermal loads to the two telescopes and other thermally sensitive areas.

Mechanical

Option Comparison

- **The general configurations of the two Sciencecraft are fairly identical with the exception of a change in the aperture diameters of the two Telescopes. The increase in the Telescope mass between Options Mid and High resulted in an increase in the support structure for the High Sciencecraft.**

Configuration Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Derik Townsend

Email: Derik.J.Townsend@jpl.nasa.gov

Configuration

Table of Contents

- Design Requirements and Assumptions
- Design
- Design Rationale
- Option Comparison
- Additional Comments

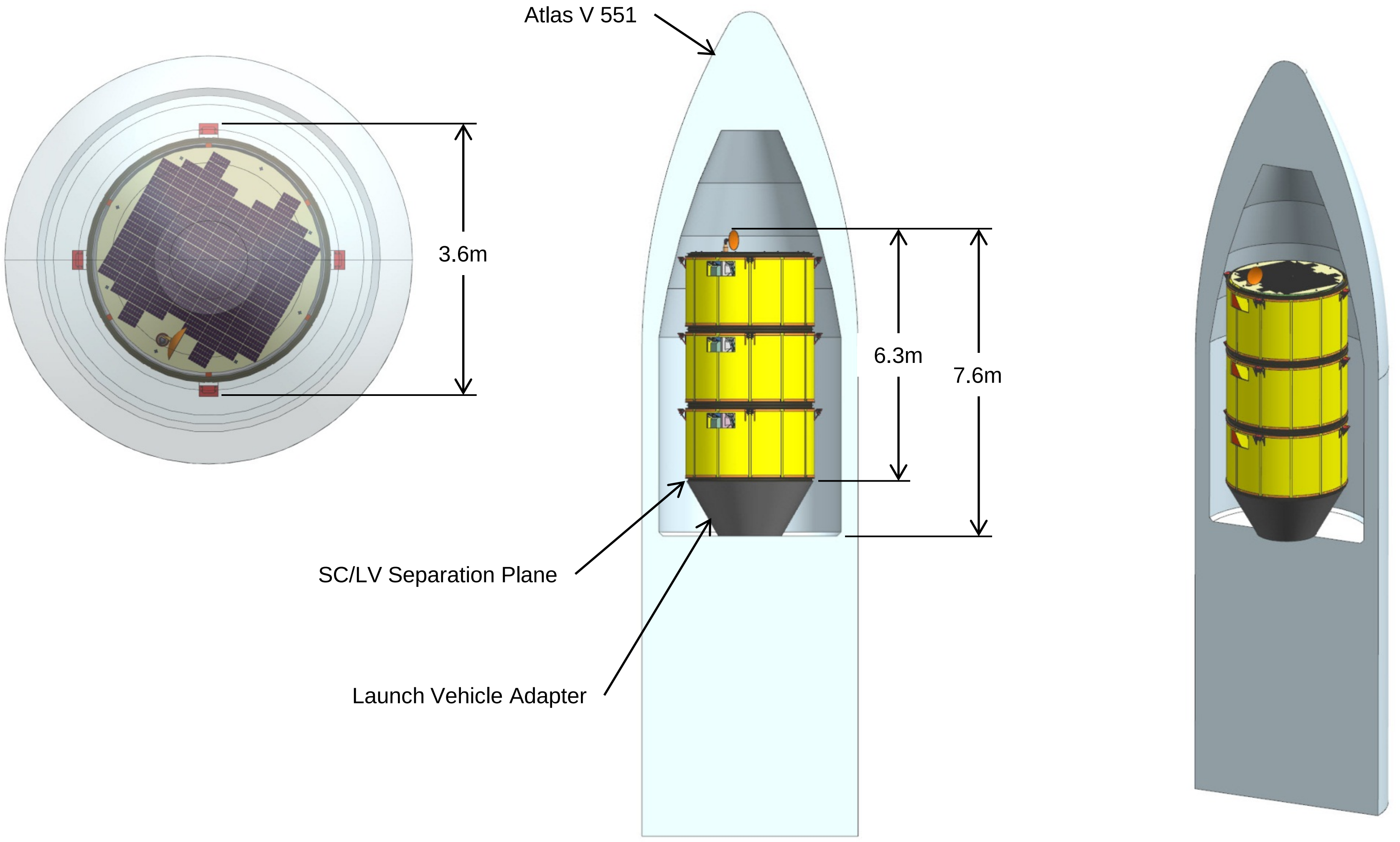
Configuration
Design Requirements and Assumptions

- **Requirements**
  - One 0.35m X-Band HGA
  - Two X-Band low gain horn antennas
  - 4 radiator holes on the exterior of the propulsion module.
  - Monoprop system (MID SGO Mid)
  - Bi-prop system (HIGH SGO High)
  - Launch Vehicle: Atlas V 551
  - Payload:
    - Space-based Gravitational-wave Observatory (SGO)

- **Assumptions**
  - Customers configuration CAD files are up to date and accurate.

Configuration

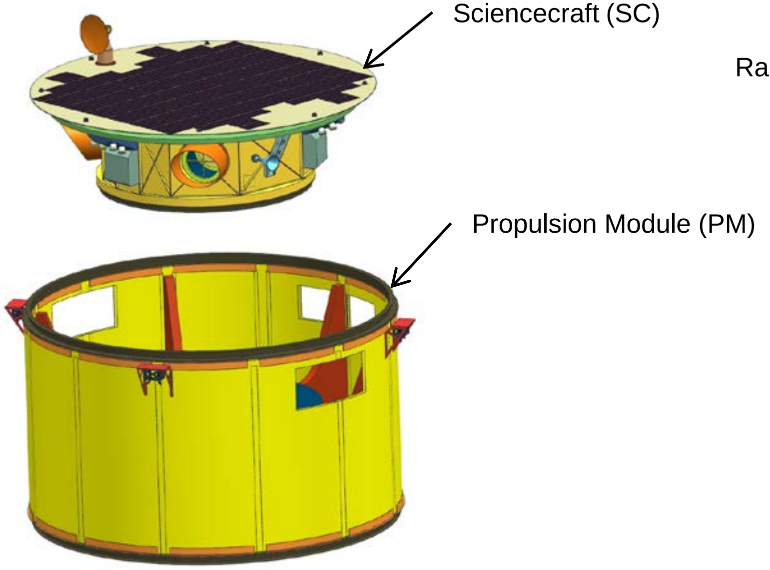
Design Configuration – MID SGO Mid



Cleared for public release. For discussion purposes only.

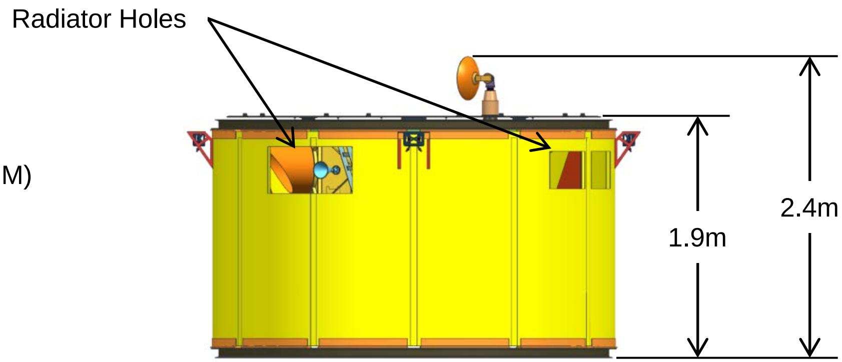
Configuration

Design Configuration – MID SGO Mid



Sciencecraft (SC)

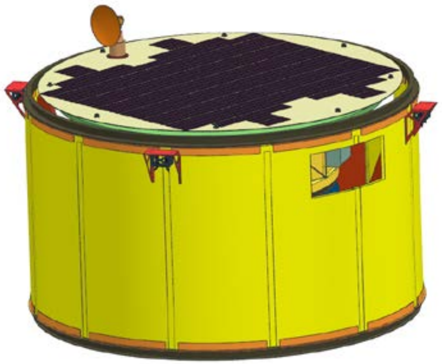
Propulsion Module (PM)

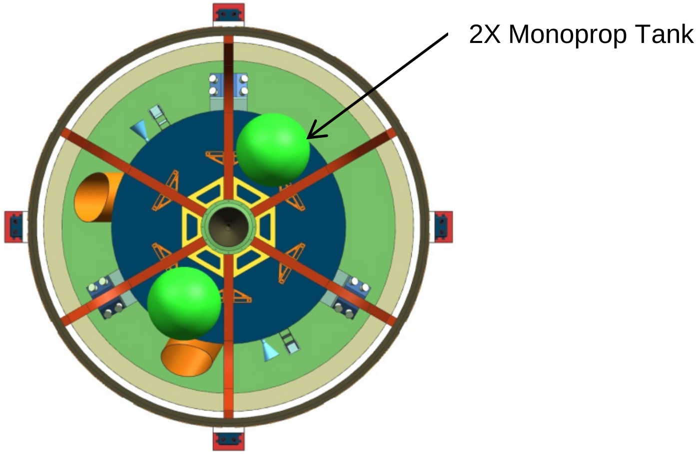


Radiator Holes

1.9m

2.4m

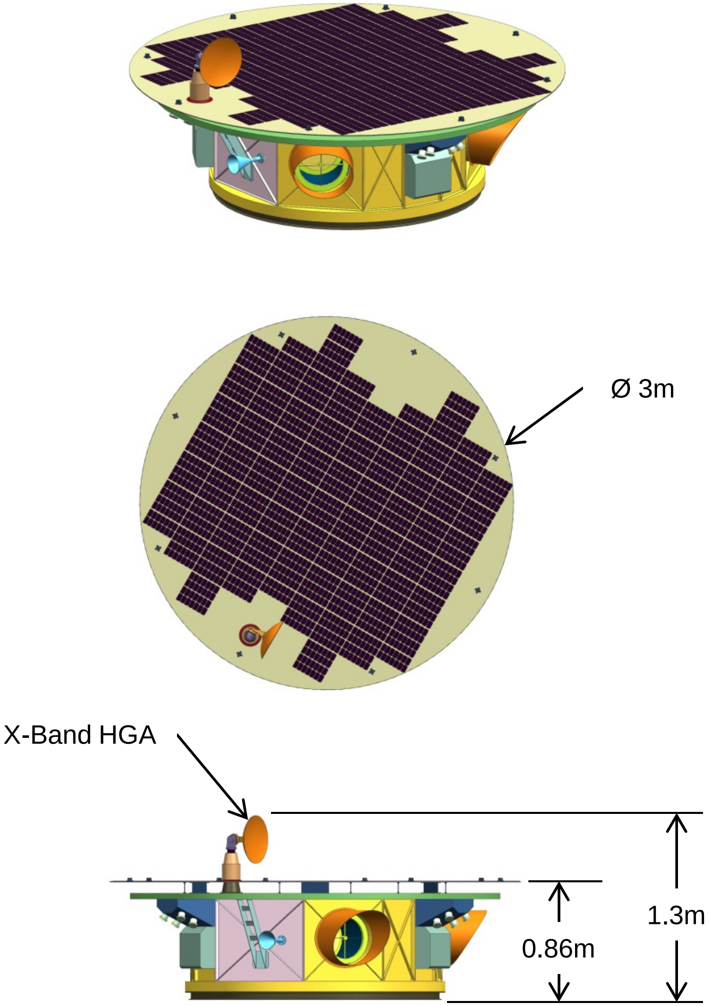


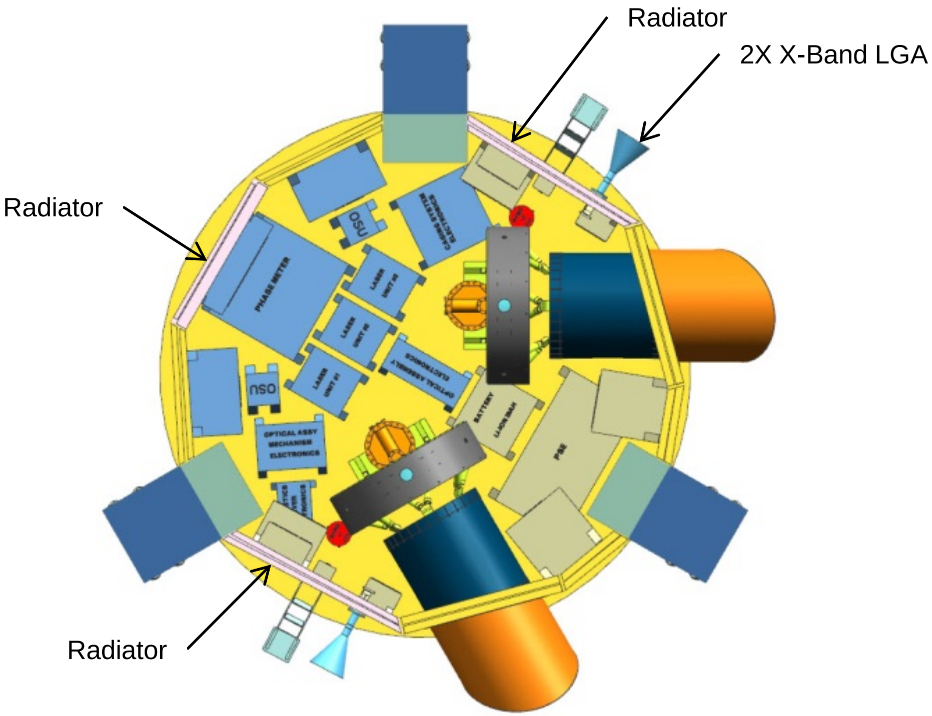


2X Monoprop Tank

Configuration

Design Configuration – MID SGO Mid





Configuration
Design Rationale – MID SGO Mid

- **Removed and replaced the two HGA's on top of the SC with a single .35m X-Band HGA per Telecom requirements.**

- **Explored reducing the size of the SGO Mid Propulsion Module, but the size of the solar array and the sun's FOV cast shadow prevented any reductions.**

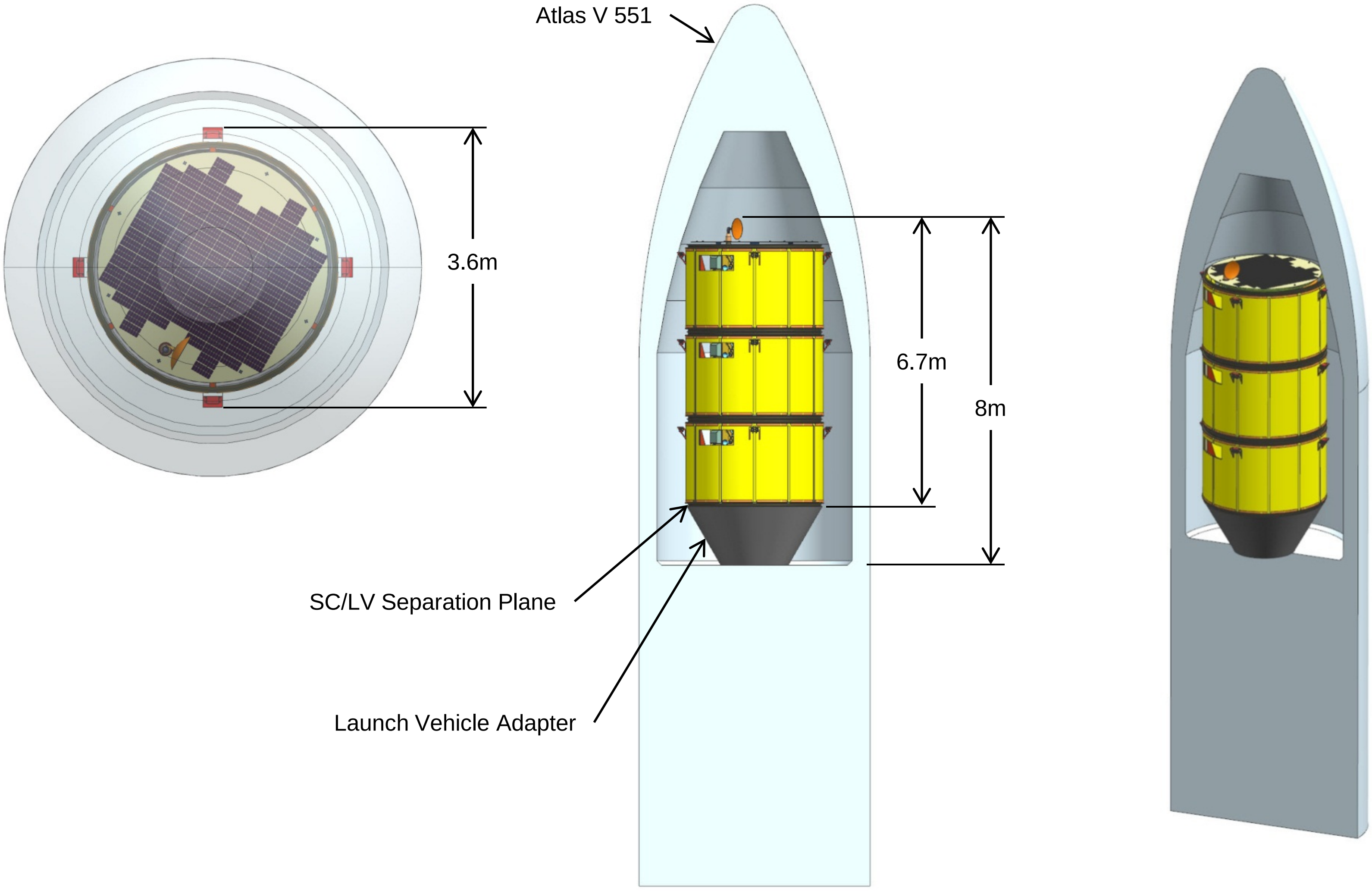
- **Propulsion Module radiator holes are approximately 75% of the total SC radiator area per Thermal subsystem requirements.**

- **Two additional LGA antennas were added to the sides of the SC per Telecom requirements.**

- **Changed the propulsion system to a Monoprop system per propulsion requirements.**

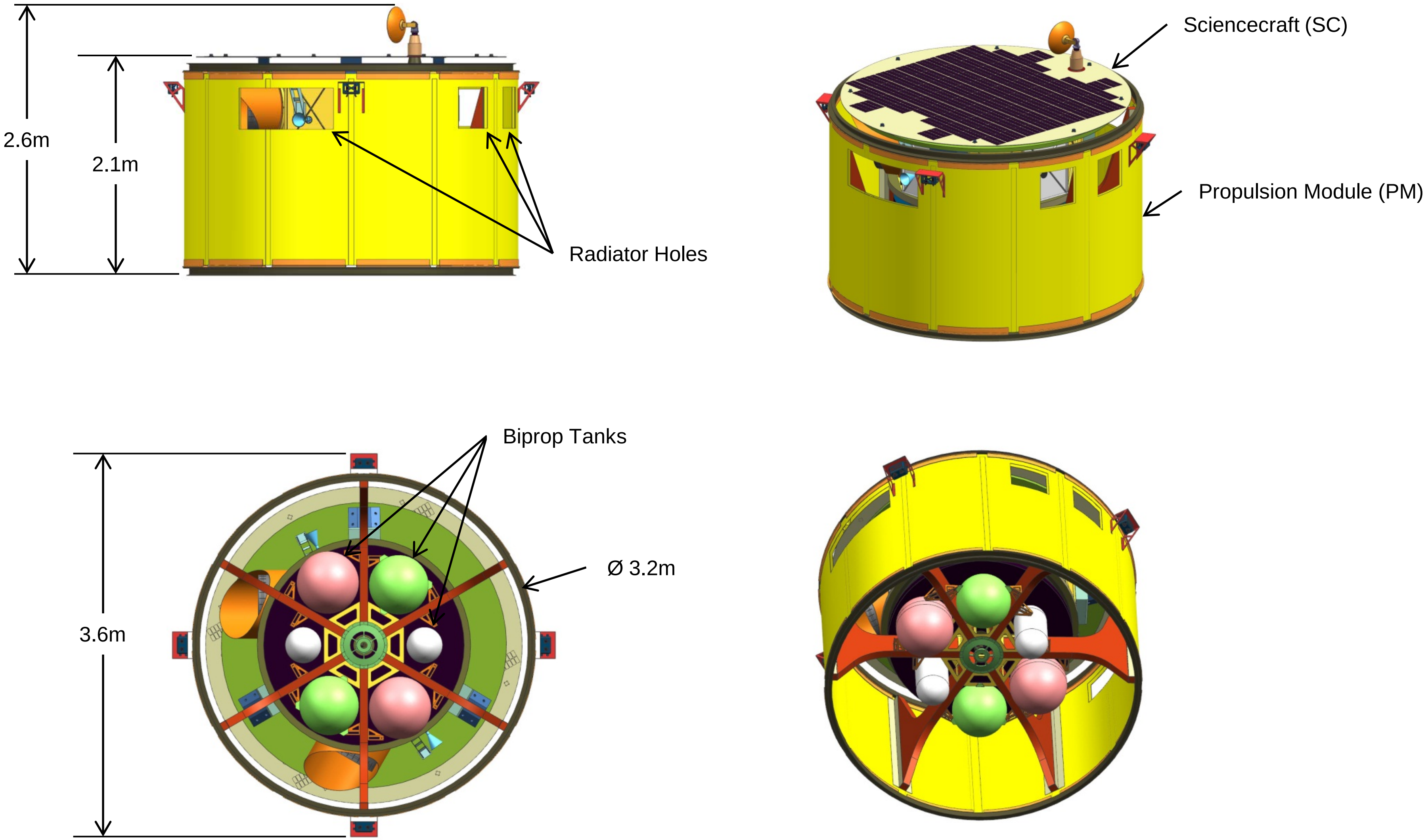
Configuration

Design Configuration – MID SGO High



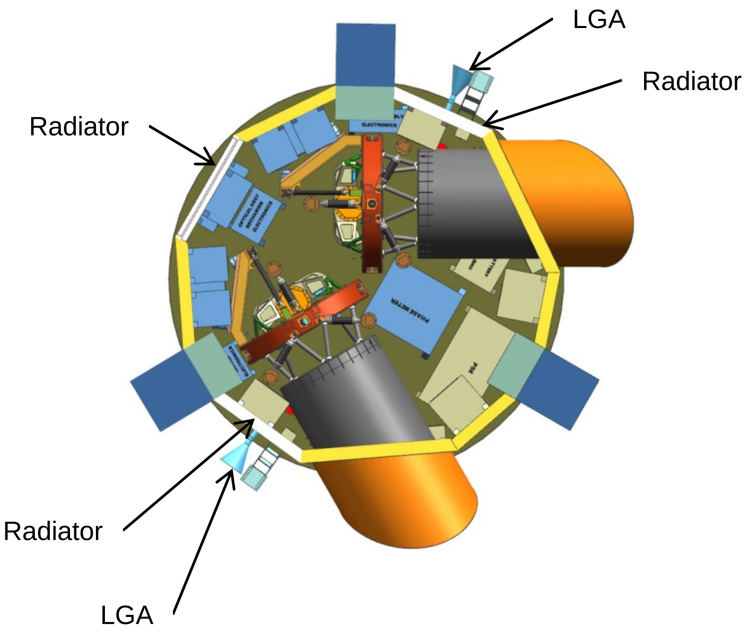
Configuration

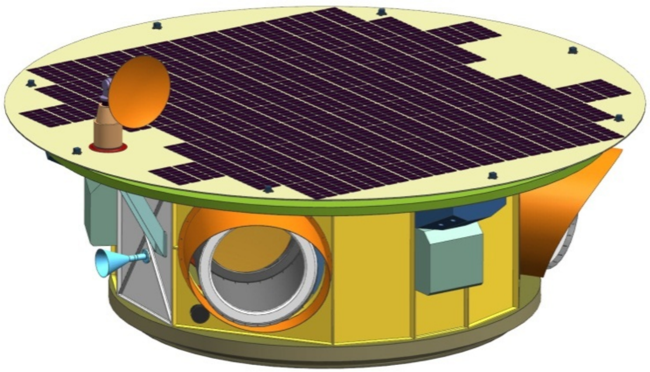
Design Configuration – HIGH SGO High

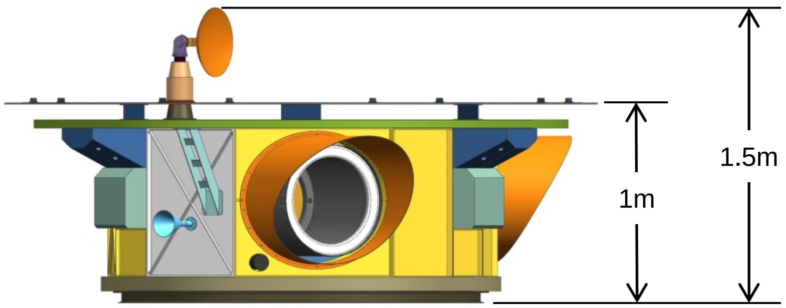


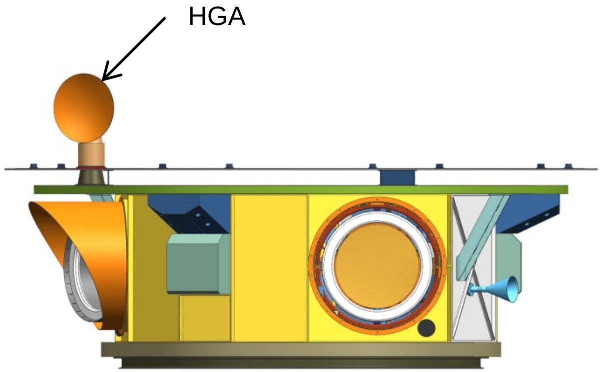
Configuration

Design Configuration – HIGH SGO High









Configuration
Design Rationale – HIGH SGO High

- **Removed and replaced the two HGA's on top of the SC with a single .35m X-Band HGA per Telecom requirements.**

- **Propulsion Module radiator holes are approximately 75% of the total SC radiator area per Thermal subsystem requirements.**

- **Two additional LGA antennas were added to the sides of the SC per Telecom requirements.**

- **Changed the propulsion system to a Bi-prop system per propulsion requirements.**

Configuration

Option Comparison

Option	LV	Configuration	Comments
1	Atlas V 551	SGO Mid : 25mm Telescope, Monoprop system	Radiator area 1m^2
2	Atlas V 551	SGO High: 40mm Telescope, Bi-Prop system	Radiator area 1.1m^2

Thermal Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Dan Klein

Email: daniel.b.klein@jpl.nasa.gov

Thermal

Table of Contents

- Design Requirements
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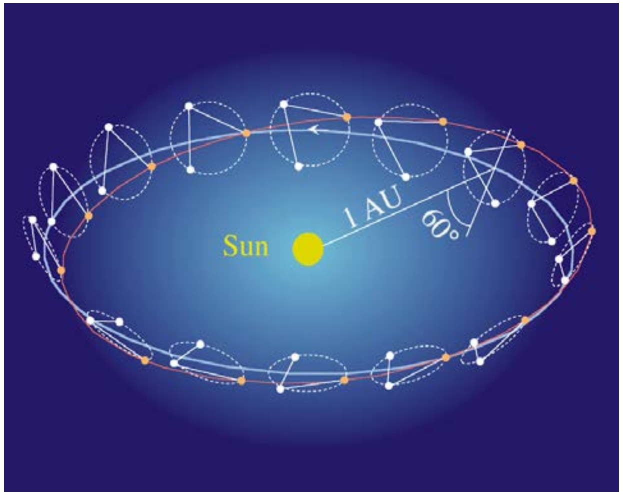
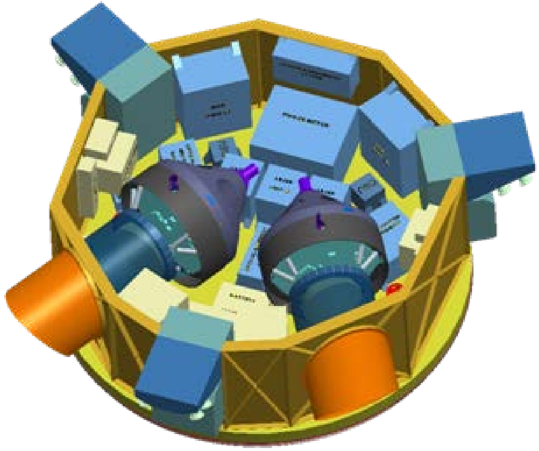
Thermal
Design Requirements – MID

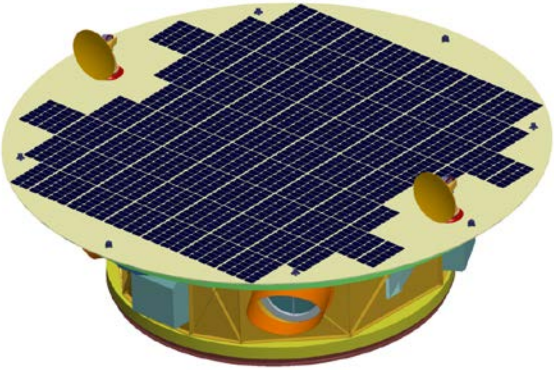
- **Mission:**
  - Heliocentric orbit, Earth trailing by 9° to 22°
  - Similar to LISA mission
  - Three spacecraft 1,000,000 km apart in equilateral triangle
    - Inclined at 60° to sun
  - 18 month cruise with a 2 year science mission
- **Stabilization: 3-Axis with micro thrusters**
  - Orbits are independent: No formation flying. No station-keeping.
- **Payload: Telescope with laser tracking**
  - 25 cm aperture



Thermal
Design Assumptions – MID

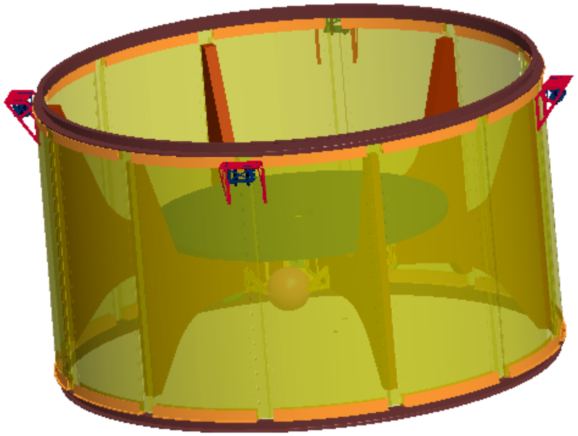
- **Steady environment**
  - Very stable/ultra low disturbance, with constant sun angles and no eclipses.
  - No orbital maintenance, no pointing maneuvers
  - High duty cycle science operations
- **Science Requirements**
  - Structural and optical stability require the thermal control system to be passive with no active heaters cycling on and off. The system makes use of tailored MLI and radiators, with steady payload electronics dissipation.
    - Thermal dissipation during science periods must be constant; no heaters cycling
    - Heater power is available to provide 'make-up' power if needed, to keep total thermal dissipation constant if electronics has varying power dissipation profiles in different phases of the science data collection mode.
  - The propulsion module, which has active thermal control, gets jettisoned at the end of cruise.





Thermal
Summary – Propulsion module

Thermal Summary Chart

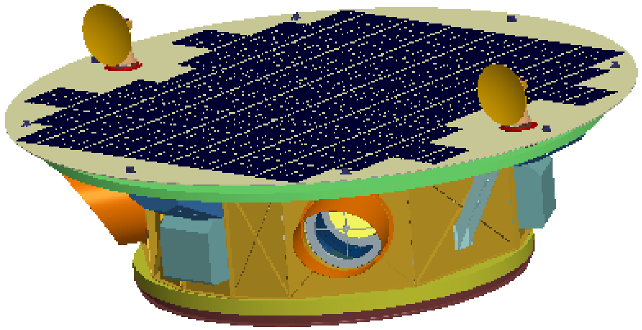


	Suggested	Used
Thermal Design Inputs		
Thermally Controlled Mass	548.7 kg	548.7 kg
Spacecraft Dry Mass Density	200.0 kg/m3	200.0 kg/m3
Spacecraft Wet Mass Density	200.0 kg/m3	200.0 kg/m3
Thermal Power/Controlled Mass	0.05 W/kg	0.05 W/kg
Conduction Ctrl Mass/Ctrlled Mass	0.001 kg/kg	0.001 kg/kg
Bus Geometry 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	1.0 W
Line Heaters	0.5 W	0.5 W
Thermal Design Calculations		
Thermally Controlled Surface Area	11.8 m2	11.8 m2
Total Propulsion Tank Surface Area	4.6 m2	4.6 m2

Subsystems	Mass			Power Modes									
	CBE	Cont.	PBE	Launch 1.0 hr.	Cruise 24.0 hr.	Traj change 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)	1247.7 kg	18%	1470.3 kg	36.5 W	38.0 W	38.0 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W
Carried Elements	696.6 kg	0%	696.6 kg										
Wet Element (w/o Thermal)	551.1 kg	40%	773.7 kg	36.5 W	38.0 W	38.0 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W
Pressurant & Propellant	139.9 kg	0%	139.9 kg										
Dry Element (w/o Thermal)	411.2 kg	54%	633.8 kg	36.5 W	38.0 W	38.0 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 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)	411.2 kg	54%	633.8 kg	36.5 W	38.0 W	38.0 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W
ADC	1.1 kg	10%	1.2 kg	0.0 W	1.4 W	1.4 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
CDH	0.8 kg	6%	0.9 kg	3.8 W	3.8 W	3.8 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Power	2.4 kg	30%	3.1 kg	6.1 W	6.2 W	6.2 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W	4.3 W
Propulsion	36.2 kg	7%	38.7 kg	26.7 W	26.7 W	26.7 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Mechanical	368.1 kg	30%	478.5 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	2.7 kg	20%	3.3 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
Systems Contingency			108.2 kg										
Thermal	18.3 kg	27%	23.3 kg	50.4 W	48.4 W	48.4 W	48.4 W	48.4 W	48.4 W	48.4 W	48.4 W	48.4 W	48.4 W

Thermal
Summary – Sciencecraft

Thermal Summary Chart



	Suggested	Used
Thermal Design Inputs		
Thermally Controlled Mass	321.4 kg	321.4 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	0.50 m2/blanket
Propulsion Heater Power		
Tank Heaters	2.5 W	0.0 W
Line Heaters	0.5 W	0.0 W
Thermal Design Calculations		
Thermally Controlled Surface Area	8.2 m2	8.2 m2
Total Propulsion Tank Surface Area	0.0 m2	0.0 m2

Subsystems	**Mass**			**Power Modes**									
	CBE	**Cont.**	**PBE**	Launch and Separation 1.0 hr.	Cruise 24.0 hr.	Prop Module Separation 5.0 hr.	Science on station with telecomm 24.0 hr.	Safe 24.0 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)	450.6 kg	49%	672.8 kg	139.1 W	159.4 W	208.9 W	311.3 W	202.8 W	10.9 W	10.9 W	10.9 W	10.9 W	10.9 W
Carried Elements	0.0 kg	0%	0.0 kg										
Wet Element (w/o Thermal)	450.6 kg	49%	672.8 kg	139.1 W	159.4 W	208.9 W	311.3 W	202.8 W	10.9 W	10.9 W	10.9 W	10.9 W	10.9 W
Pressurant & Propellant	0.0 kg	0%	0.0 kg										
Dry Element (w/o Thermal)	450.6 kg	49%	672.8 kg	139.1 W	159.4 W	208.9 W	311.3 W	202.8 W	10.9 W	10.9 W	10.9 W	10.9 W	10.9 W
Instruments	216.6 kg	30%	281.5 kg	0.0 W	11.6 W	11.6 W	116.5 W	11.6 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)	234.1 kg	67%	391.3 kg	139.1 W	147.8 W	197.2 W	194.8 W	191.2 W	10.9 W	10.9 W	10.9 W	10.9 W	10.9 W
ADC	6.3 kg	10%	6.9 kg	12.0 W	17.2 W	17.2 W	8.8 W	12.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
CDH	16.2 kg	16%	18.9 kg	32.6 W	32.6 W	32.6 W	32.6 W	32.6 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Power	25.1 kg	30%	32.7 kg	23.5 W	27.0 W	30.8 W	36.8 W	30.0 W	10.9 W	10.9 W	10.9 W	10.9 W	10.9 W
Propulsion	38.4 kg	30%	49.9 kg	0.0 W	0.0 W	45.6 W	45.6 W	45.6 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Mechanical	128.1 kg	30%	166.5 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	20.0 kg	14%	22.7 kg	71.0 W	71.0 W	71.0 W	71.0 W	71.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Systems Contingency			93.7 kg										
Thermal	18.8 kg	27%	23.8 kg	16.1 W	36.1 W	36.1 W	16.1 W	36.1 W	16.1 W	16.1 W	16.1 W	16.1 W	16.1 W

Thermal

Design – MID

- **Active**
  - Propulsion module has heaters and thermostats on tanks and prop lines
- **Passive**
  - Sciencecraft's passive design includes MLI and radiators
  - 1 m^2 radiator area is designed in to handle 310 watts payload dissipation
  - The Sciencecraft radiator must have a view out through the propulsion module when it is attached. A window is assumed, whose size is tailored for power that must be dissipated in cruise (160 watts)

Thermal
Design Rationale – MID

- **Passive design is necessary due to strict stability requirements**
- **Active heaters cycling on and off would disturb the system.**
  - Maximum allowable temperature difference fluctuation across the GRS reference housing = 60 μK/√Hz at 0.1 mHz.
  - Maximum allowable temperature fluctuation of the laser stabilization cavity = 10 μK/√Hz at 1 mHz
- **Environment is steady, 60 degree inclination results in one revolution per year for the Sciencecraft.**
  - Solar panel overhang shades Sciencecraft sides to maintain constant environment, and steady temperatures

Thermal
Cost – MID

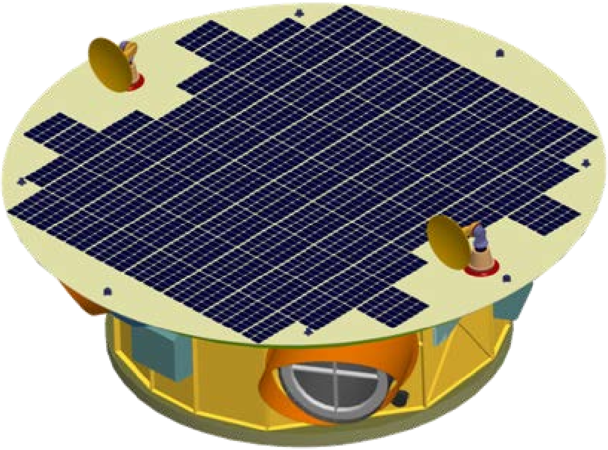
- **Cost Tables**

  Sciencecraft: $ 10,766K
  Propulsion module: $ 5,631.2K

- **Cost Drivers**
  - Passive designs are low cost in nature. No complicated thermal hardware.
- **Potential Cost Savings**
  - Passive design with MLI and radiators leave little room for optimization. MLI and radiator sizes are tailored for specific temperatures needed and power dissipation levels expected.
- **Potential Cost Uppers**
  - If passive design is not adequate for stability requirements, a more complicated active thermal control system with computer controlled heaters may be needed.

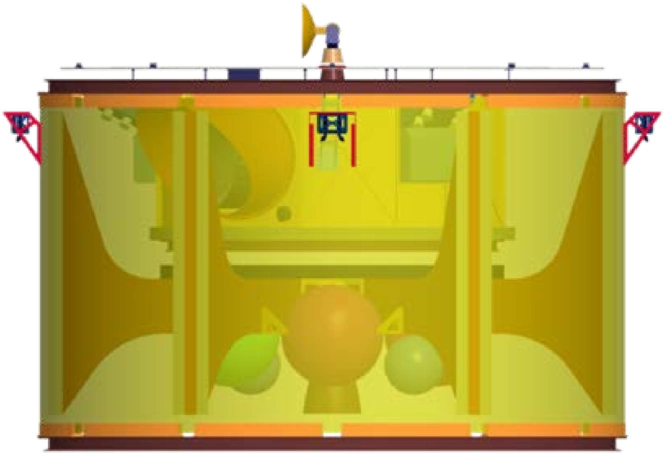
Thermal
Design Assumptions – HIGH

- **SGO High**
  - Starts at 22 degree earth trailing orbit.
  - Otherwise same environment as MID
  - Longer path length between spacecraft; 5,000,000 km.
  - 5 year mission versus 2 year mission for MID
- **Differences that affect Thermal**
  - Larger aperture on telescope, 40cm versus 25cm
  - Slightly more power consumption during science mode
  - Slightly larger MLI and radiator area required
  - Slightly more heater power required



Thermal
Summary – Propulsion module 2

Thermal Summary Chart

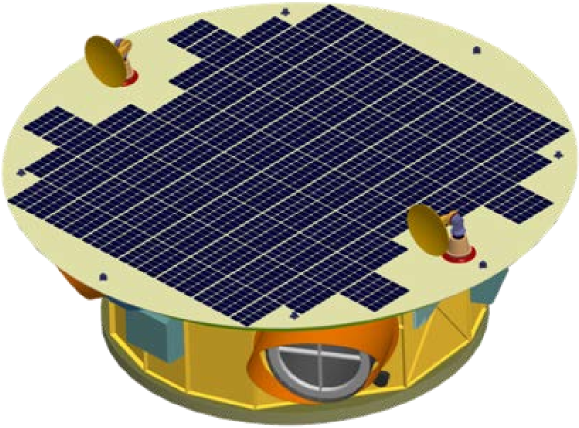


	Suggested	Used
Thermal Design Inputs		
Thermally Controlled Mass	634.9 kg	634.9 kg
Spacecraft Dry Mass Density	200.0 kg/m3	200.0 kg/m3
Spacecraft Wet Mass Density	200.0 kg/m3	200.0 kg/m3
Thermal Power/Controlled Mass	0.05 W/kg	0.05 W/kg
Conduction Ctrl Mass/Ctrlled Mass	0.001 kg/kg	0.001 kg/kg
Bus Geometry 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	1.0 W
Line Heaters	0.5 W	0.5 W
Thermal Design Calculations		
Thermally Controlled Surface Area	13.0 m2	13.0 m2
Total Propulsion Tank Surface Area	12.3 m2	12.3 m2

Subsystems	**Mass**			**Power Modes**									
	CBE	**Cont.**	**PBE**	Launch 1.0 hr.	Cruise 24.0 hr.	Traj change 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)	1927.5 kg	13%	2184.6 kg	39.5 W	41.0 W	41.0 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W
Carried Elements	784.2 kg	0%	784.2 kg										
Wet Element (w/o Thermal)	1143.3 kg	22%	1400.4 kg	39.5 W	41.0 W	41.0 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W
Pressurant & Propellant	670.8 kg	0%	670.8 kg										
Dry Element (w/o Thermal)	472.5 kg	54%	729.7 kg	39.5 W	41.0 W	41.0 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 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)	472.5 kg	54%	729.7 kg	39.5 W	41.0 W	41.0 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W
ADC	1.1 kg	10%	1.2 kg	0.0 W	1.4 W	1.4 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
CDH	0.8 kg	6%	0.9 kg	3.8 W	3.8 W	3.8 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Power	2.4 kg	30%	3.1 kg	6.4 W	6.5 W	6.5 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W	4.6 W
Propulsion	62.0 kg	9%	67.8 kg	29.3 W	29.3 W	29.3 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Mechanical	403.6 kg	30%	524.6 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	2.7 kg	20%	3.3 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
Systems Contingency			128.9 kg										
Thermal	26.5 kg	28%	34.0 kg	64.7 W	61.7 W	61.7 W	61.7 W	61.7 W	61.7 W	61.7 W	61.7 W	61.7 W	61.7 W

Thermal
Summary – Sciencecraft 2

Thermal Summary Chart



	Suggested	Used
Thermal Design Inputs		
Thermally Controlled Mass	342.9 kg	342.9 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	0.0 W
Line Heaters	0.5 W	0.0 W
Thermal Design Calculations		
Thermally Controlled Surface Area	8.6 m2	8.6 m2
Total Propulsion Tank Surface Area	0.0 m2	0.0 m2

Subsystems	Mass			Power Modes									
	CBE	Cont.	PBE	Launch and Separation 1.0 hr.	Cruise 24.0 hr.	Prop Module Separation 5.0 hr.	Science on station with telecomm 24.0 hr.	Safe 24.0 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)	510.0 kg	49%	759.4 kg	139.2 W	161.6 W	211.1 W	324.0 W	205.0 W	11.0 W	11.0 W	11.0 W	11.0 W	11.0 W
Carried Elements	0.0 kg	0%	0.0 kg										
Wet Element (w/o Thermal)	510.0 kg	49%	759.4 kg	139.2 W	161.6 W	211.1 W	324.0 W	205.0 W	11.0 W	11.0 W	11.0 W	11.0 W	11.0 W
Pressurant & Propellant	0.0 kg	0%	0.0 kg										
Dry Element (w/o Thermal)	510.0 kg	49%	759.4 kg	139.2 W	161.6 W	211.1 W	324.0 W	205.0 W	11.0 W	11.0 W	11.0 W	11.0 W	11.0 W
Instruments	260.1 kg	30%	338.1 kg	0.0 W	12.8 W	12.8 W	128.1 W	12.8 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)	249.9 kg	69%	421.3 kg	139.2 W	148.8 W	198.3 W	195.9 W	192.2 W	11.0 W	11.0 W	11.0 W	11.0 W	11.0 W
ADC	6.3 kg	10%	6.9 kg	12.0 W	17.2 W	17.2 W	8.8 W	12.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
CDH	16.2 kg	16%	18.9 kg	32.6 W	32.6 W	32.6 W	32.6 W	32.6 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Power	25.6 kg	30%	33.3 kg	23.6 W	28.0 W	31.9 W	37.9 W	31.0 W	11.0 W	11.0 W	11.0 W	11.0 W	11.0 W
Propulsion	38.4 kg	30%	49.9 kg	0.0 W	0.0 W	45.6 W	45.6 W	45.6 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Mechanical	143.4 kg	30%	186.4 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	20.0 kg	14%	22.7 kg	71.0 W	71.0 W	71.0 W	71.0 W	71.0 W	0.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Systems Contingency			103.2 kg										
Thermal	19.6 kg	27%	24.8 kg	17.1 W	47.1 W	47.1 W	17.1 W	47.1 W	17.1 W	17.1 W	17.1 W	17.1 W	17.1 W

Cleared for public release. For discussion purposes only.

Thermal
Cost – HIGH

- **Cost Tables**

Sciencecraft: $10,819.6K	Propulsion module: $6,031.2K

- **Cost Drivers**
  - Cost concerns are the same as those for MID

Thermal

Risk

- **List of Risks**
  - A passive thermal design with MLI and radiators as the primary source of control, linked with the steady power dissipation levels from the payload electronics, provides a robust thermal system with very low risk.

Thermal
Option Comparison

Option	Mass (kg)	Cost ($)	Radiator size (m^2)	Comments
1	111.3	34,053K	1.0	SGO Mid: 25 cm telescope
2	138.3	35,410K	1.1	SGO High: 40 cm telescope, larger propulsion system

Telecom Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: D. Hansen/M. Pugh

Email: david.m.hansen@jpl.nasa.gov

Telecom
Design Requirements – SGO-Mid

- **General Telecom Requirements**
  - The Telecom subsystem on the sciencecraft will support two-way communications with Earth through all mission phases for launch, cruise, science phase and safe mode
    - Support uplink CMD, downlink TLM, science data return and two-way Navigation – Doppler, Ranging and DOR
- **Downlink/Return Requirements**
  - Support a downlink rate of 90 kbps to a DSN 34m BWG ground station to a maximum range of 55 million kms
  - Support a cruise downlink rate of 100 bps
  - Minimum safe mode data rate of 10 bps
  - Each sciencecraft will return science data once/6 days during the science phase
  - During cruise will nominally communicate with each spacecraft once/week
- **Uplink/Forward Requirements**
  - Support a nominal uplink rate of 2 kbps through the HGA
  - Support a nominal uplink rate of 125 bps through the LGAs
  - Minimum safe mode CMD rate of 7.8125 bps
- **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

Telecom
Design Assumptions – SGO-Mid/High

- **Operational Assumptions**
  - Sciencecraft is 3-axis stabilized
  - Sciencecraft is in an Earth-trailing orbit, carried there by the propulsion stage
  - Propulsion stage carries two low gain antennas and waveguide to support communications during cruise
    - It uses the RF electronics on the sciencecraft
    - Propulsion stage is released at an Earth range of 28 million kms or less for SGO-Mid
    - Propulsion stage is released at an Earth range of 55 million kms for SGO-High
    - The RF connection between the sciencecraft and the propulsion stage is via waveguide that pulls apart when the vehicles separate – could also be done via coaxial cable
- **Antenna Assumptions**
  - HGA is gimbaled and will be pointed with an accuracy of 2 degrees
  - Two LGAs will be positioned on opposite sides of the S/C to provide near 4 pi steradian coverage
    - LGAs will be on the top deck
  - There are two sets of LGA patches (receive and transmit) on the propulsion stage for cruise
- **Ground Station Assumptions**
  - 34m BWG DSN ground stations with 20 kW transmitters
- **Coding Assumptions**
  - Will use turbo codes for the downlink telemetry
    - Rate 1/6, 8920 code for science data
    - Rate ½ 1784 code for low rate engineering and safe mode downlink

Telecom

Design – SGO-Mid/High

- **Overall system description**
- **SGO Mid and High designs are the same**
  - Telecom has a fully redundant design for the DTE X-Band subsystem
- **Sciencecraft:**
  - One 0.35m X-Band HGA – two DOF gimbal
  - Two X-Band body-fixed low gain antennas
    - Cassini LGA horns
  - Two X/X SDST transponders
  - Two X-Band 25W X-Band TWTAs
  - Waveguide switches, a coaxial transfer switch, hybrid, 2 X-Band isolators, 2 X-Band diplexers, coax cabling and waveguide
- **Estimated total mass of 20.0 kg**
  - The propulsion stage has two sets of X-Band patch antennas on opposite sides of the vehicle
  - It also has waveguide and a Magic Tee to combine the two X-Band LGAs into one antenna
  - Estimated mass for telecom equipment on the prop stage is 2.7 kg

Telecom
Design – SGO-Mid/High

- Science downlink sized at maximum range – 55 million kms
- X-Band link to 34m BWG ground station supports 90 kbps with a margin of 3.1 dB
- Will support 100 bps via the LGAs out to maximum range with a margin of 4.0 dB
- The Prop Stage X-Band LGA will support 100 bps with a margin of 5.3 dB
- All of the Command links have ample margin
- Note: The LGA links were sized at a boresight angle of 60 degrees. There are two LGAs on both the Prop stage and the sciencecraft. At a 90 degree boresight angle, where the LGA patterns cross, the gain is down 10 dB from the 60 degree point. The CMD links will always close. The TLM links at maximum range will not using a 34m ground station. Safe mode communications with a 10 bps downlink rate will close into a 70m ground station for both the prop stage and sciencecraft at their respective maximum ranges and at 90 degrees off boresight.

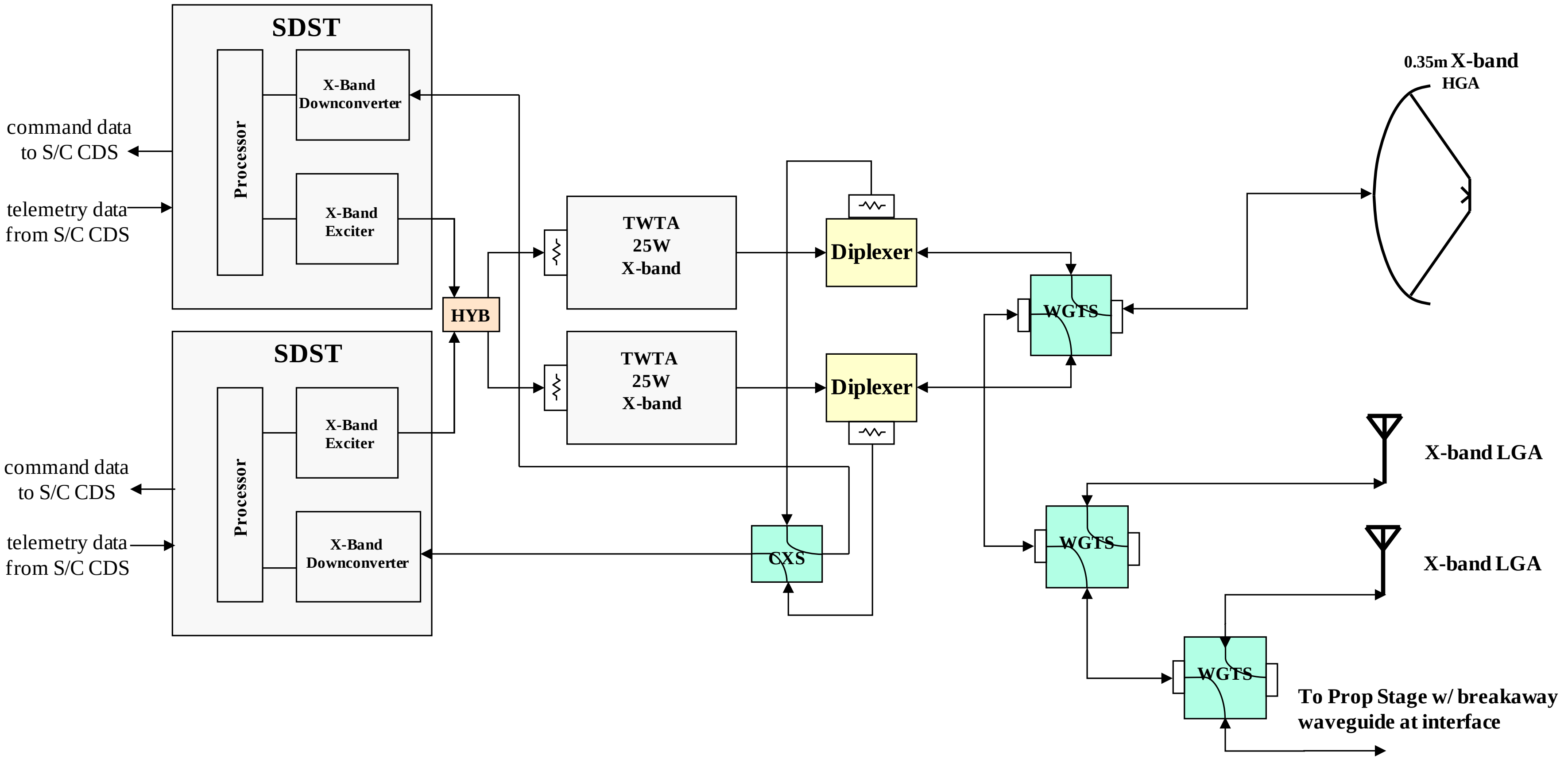
Telecom
Design Rationale – SGO-Mid

Rationale for Design

- The nominal design from the customer was to have a Ka-Band downlink for the science data and X-Band communications via LGAs for cruise and low rate engineering data
- The science data rate is only 90 kbps – Ka-Band is not needed
- The sciencecraft can save money, mass and volume by using an X-Band only telecom design
- The design was changed to remove the Ka-Band equipment as well as the second HGA

Telecom

Block Diagram – SGO-Mid Sciencecraft



Telecom

Cost – Sciencecraft

- **Costing Assumptions**
  - Single Spares
    - A single spare can be shared between the three vehicles
  - Costs and mass for antenna gimbal carried by mechanical chair
  - Costs for telecom support to ATLO carried by systems chair
  - No telecom hardware or support is included for testbeds
- **Option SGO Mid – Sciencecraft**
  - Total: $30.04M

Telecom

Cost – Propulsion Stage

- **Costing Assumptions**
  - Single Spares
    - A single spare can be shared between the three vehicles
- **Option SGO Mid – Propulsion Stage**
  - Total: $0.41M

Telecom

Risk

- **Low risk telecom mission**
  - Standard X-Band dual string design
  - All components have flight heritage
  - All links have robust margins

Telecom

Option Comparison

- No differences for Telecom between the Mid and High designs
- High design operates at maximum range for Mid design where the telecom links were sized

Telecom
Additional Comments

- **Design Trades**
  - May be able to remove the antennas and waveguide from the propulsion stage if the sciencecraft antennas have visibility to Earth during cruise
    - Would also remove a switch and waveguide from the sciencecraft design
- **Concerns**
  - Want to guarantee that the 2 X-Band LGAs on the sciencecraft will be mounted to give good coverage of the Earth. They are presently on the side of the top deck. During science ops want to look at the antenna angles back to Earth. The HGA should be fine with its 2 DOF gimbal.

Ground Systems Report

1279 SGO-Mid 2012-03 Study
March 5 – March 8, 2012

Author: Greg Welz

Email: gwelz@jpl.nasa.gov

Ground Systems

Table of Contents

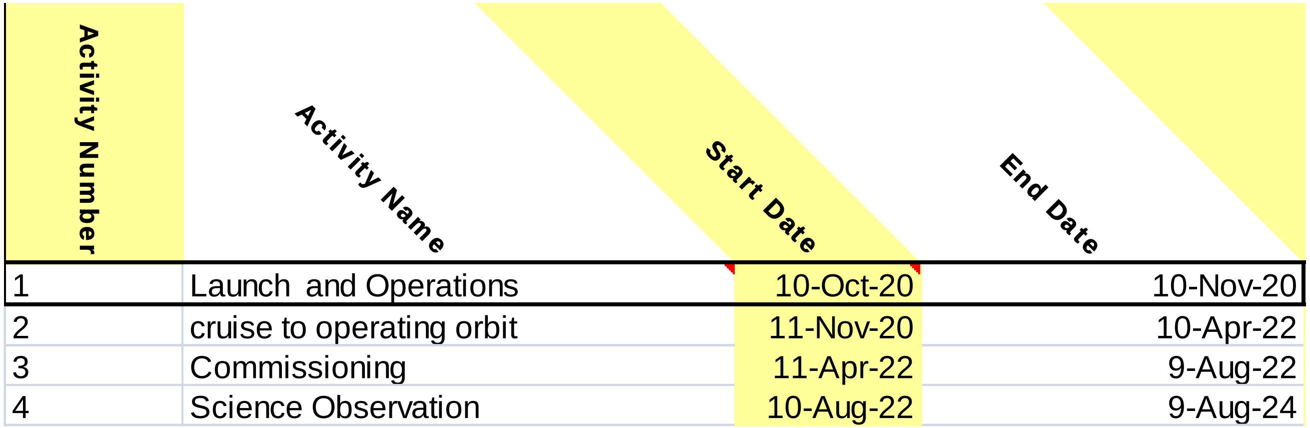
- Design Requirements
- Design Assumptions
- Design
- Design Rationale
- Cost Assumptions
- Cost
- Risk
- Additional Comments

Ground Systems
Design Requirements

- **Mission:**
  - Gravity Wave observatory, with 3 spacecraft in similar orbits effectively flying in formation around a center point
    - Very quiet operations once on station, mission requires very quiet stable spacecraft to perform observations. Automated systems handle fine tuning and maintaining s/c relationships.
    - 3 spacecraft maintaining
  - Earth Trailing orbit, roughly 22° at maximum range (~.37 AU)
- **Data Volumes**
  - 190 Gb of science data over 2 years of science, 473 Gb over 5 years
  - Production per S/C: ~ 1 Kb/s of science data, 4 Kb/s of housekeeping
- **EEIS**
  - No stressing requirements for QQC
  - Short periods where low latency is required for working with science partners is establishing concurrent observations of merging objects
- **Commanding Requirements**
  - Planned for once a week for nominal commanding
  - Recalibration of positioning done every few weeks

Ground Systems
Design Assumptions

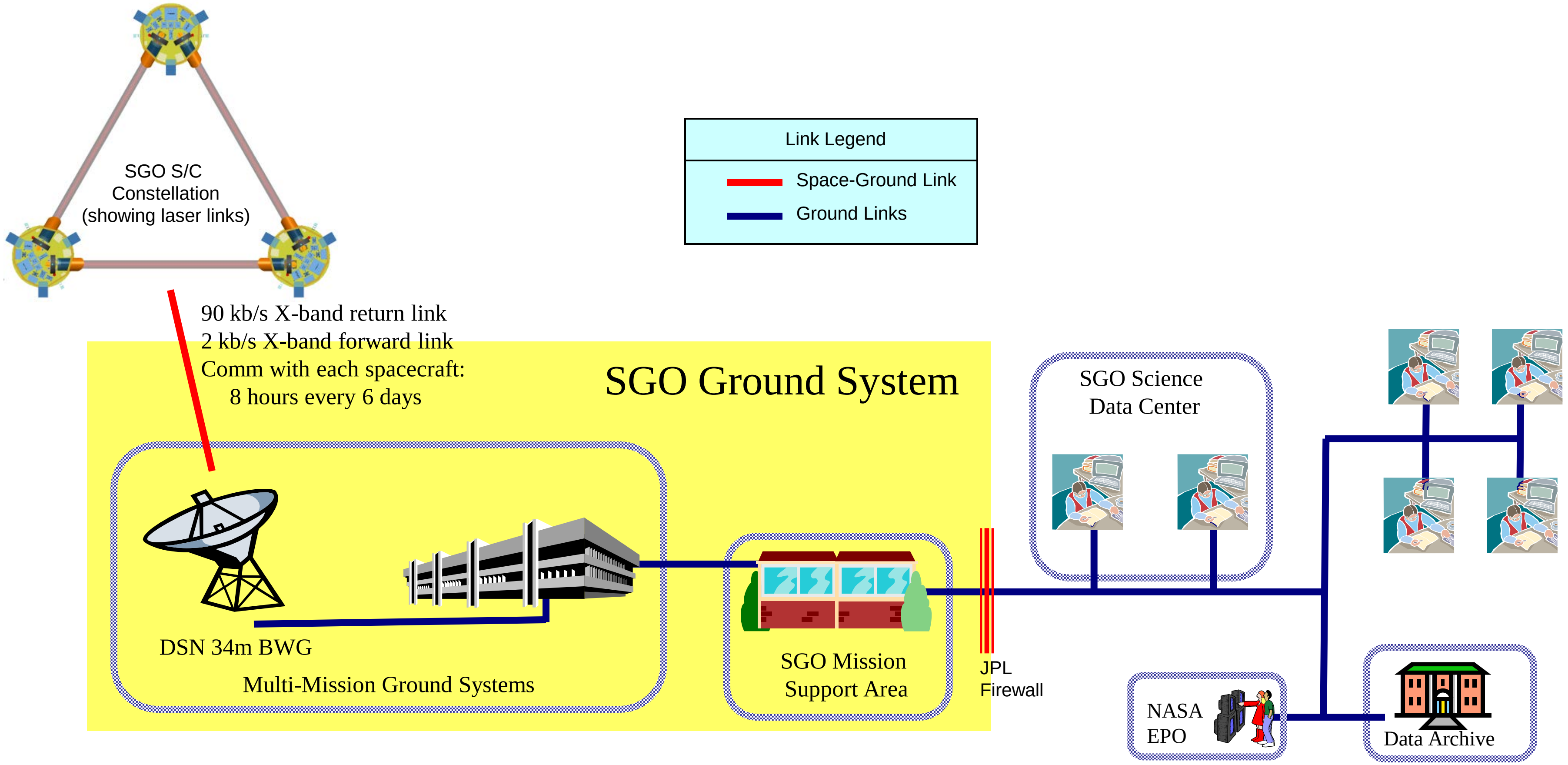
- **List Assumptions made for the Design**
  - JPL built and operated spacecraft
  - Quiet operations during science period
- **Ground system is based on a mission specific implementation of the standard JPL mission operations and ground data systems**
- **Phase E Activity Description**
  - Time up through commissioning the same for both options
  - Mid 2 years of Science, High is 5 years of Science



Activity Number	Activity Name	Start Date	End Date
1	Launch and Operations	10-Oct-20	10-Nov-20
2	cruise to operating orbit	11-Nov-20	10-Apr-22
3	Commissioning	11-Apr-22	9-Aug-22
4	Science Observation	10-Aug-22	9-Aug-24

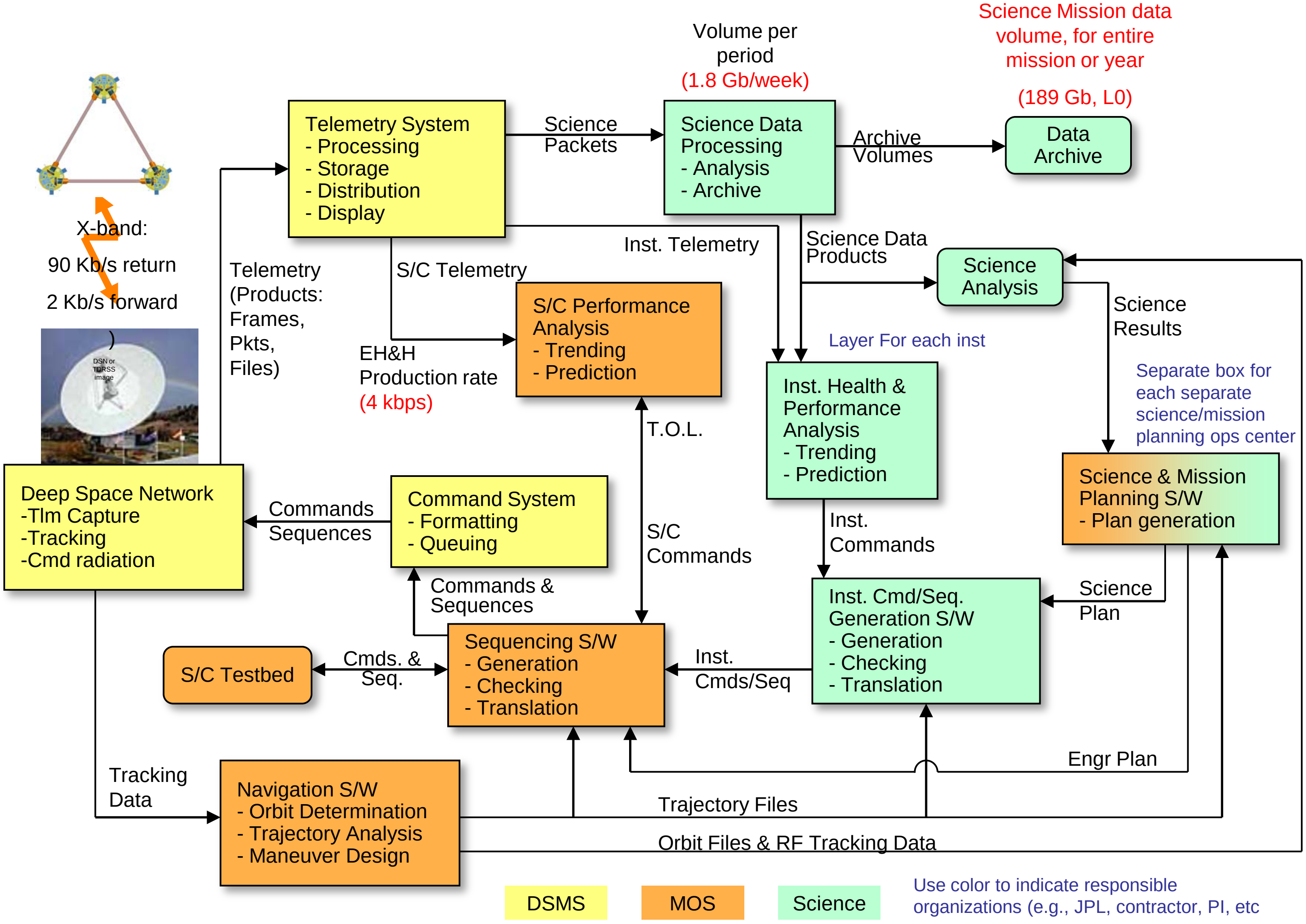
Ground Systems
Design

- **Operational View**



Ground Systems Design

Functional View



X-band:

90 Kb/s return

2 Kb/s forward

Deep Space Network
-Tlm Capture
-Tracking
-Cmd radiation

Telemetry (Products: Frames, Pkts, Files)

Telemetry System
- Processing
- Storage
- Distribution
- Display

Science Packets

Volume per period
(1.8 Gb/week)

Science Data Processing
- Analysis
- Archive

Archive Volumes

Science Mission data volume, for entire mission or year

(189 Gb, L0)

Data Archive

Inst. Telemetry

Science Data Products

Science Analysis

Science Results

S/C Telemetry

EH&H Production rate (4 kbps)

S/C Performance Analysis
- Trending
- Prediction

T.O.L.

Layer For each inst

Inst. Health & Performance Analysis
- Trending
- Prediction

Separate box for each separate science/mission planning ops center

Science & Mission Planning S/W
- Plan generation

Commands Sequences

Command System
- Formatting
- Queuing

S/C Commands

Inst. Commands

Commands & Sequences

Science Plan

S/C Testbed

Cmds. & Seq.

Sequencing S/W
- Generation
- Checking
- Translation

Inst. Cmds/Seq

Inst. Cmd/Seq. Generation S/W
- Generation
- Checking
- Translation

Engr Plan

Tracking Data

Navigation S/W
- Orbit Determination
- Trajectory Analysis
- Maneuver Design

Trajectory Files

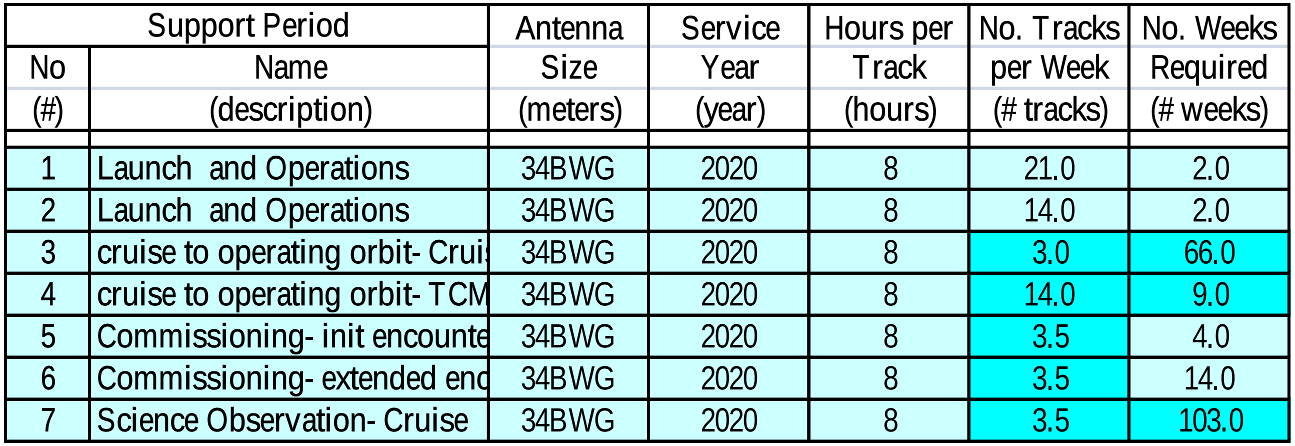
Orbit Files & RF Tracking Data

DSMS	MOS	Science

Use color to indicate responsible organizations (e.g., JPL, contractor, PI, etc

Ground Systems
Design

- **Ground Network**
  - DSN 34m BWG located at all 3 DSCCs (Goldstone, Canberra, Madrid)
- **Discuss Details of the Design**
  - Assumed 1 pass per week per spacecraft during cruise
  - Assumed 14 passes around TCMs (3 per S/C) during cruise to adjust for final orbit for each spacecraft, (spread over cruise period but lumped together here for simplification)
  - Applied provided plan of 1 pass every 6 days per spacecraft (works out to 3.5 passes per week)
  - Spacecraft too far apart to enable multi-spacecraft per antenna reception
  - Mid option: 2 years Science (figure uses Mid example), High option: 5 years science



Support Period		Antenna Size (meters)	Service Year (year)	Hours per Track (hours)	No. Tracks per Week (# tracks)	No. Weeks Required (# weeks)
No (#)	Name (description)					
1	Launch and Operations	34BWG	2020	8	21.0	2.0
2	Launch and Operations	34BWG	2020	8	14.0	2.0
3	cruise to operating orbit- Crui	34BWG	2020	8	3.0	66.0
4	cruise to operating orbit- TCM	34BWG	2020	8	14.0	9.0
5	Commissioning- init encounte	34BWG	2020	8	3.5	4.0
6	Commissioning- extended end	34BWG	2020	8	3.5	14.0
7	Science Observation- Cruise	34BWG	2020	8	3.5	103.0

Ground Systems
Design Rationale

- **Key design drivers**
  - Flying 3 identical spacecraft, enable shared operations team
  - Operations from launch through commissioning has heaviest operator support for the mission, once on station performing science observations team reduces to less than half of the cruise/commissioning team size.
    - Arrival at commissioning is staggered to enable each spacecraft to be checked out with common team.
    - 3 large maneuvers during cruise for each spacecraft to get into the correct final orbit.
    - There is room for some reduction in operations team during cruise, but we need to keep staffed to support maneuvers, and planning and training for commissioning.
  - Very quiet science operations, minimal operator interaction are required since there is very little activity occurring on the spacecraft
  - Relationship between spacecraft is monitored as part of the science mission, automated control on the spacecraft to maintain spacecraft relationship.
- **Mission operations and ground data system processes and procedures are based on mission specific implementations of the standard JPL ground system processes and procedures**

Ground Systems
Cost Assumptions

- **Staffing for Phase E by activity**
  - During the cruise, standard practices have us spending 6 to 12 months characterizing the spacecraft before we should reduce staffing, and we need to ramp up 3 to 6 months before we start the commissioning. For the baseline estimate staffing was kept at the full level because there was insufficient time to justify a staffing reduction.
  - The Spacecraft team has a lead SE for each S/C and shared subsystem analysts across the 3 spacecraft. There is a shared team for handling planning, sequence development, testing, and the rest of the mission operation activities. Once on station everything has been characterized, the processes have become regular and very repetitious and staffing can be reduced and planning activities reduced.
  - GDS is staffed to handle flight rule changes, and typical flight software changes that occur during the cruise stage, and in preparation for commissioning. Once on station and performing routine science the staffing drops to maintenance and minimal support levels.

Duration (months)	17.0	3.9	24.0
Activity	cruise to operating orbit	Commissioning	Science Observation
07 MOS	33.1	33.8	12.7
09 GDS	7.4	7.4	2.8
Total FTE	40.5	41.2	15.5

Ground Systems

Cost

Option	MOS Dev ($M)	MOS Ops ($M)	GDS Dev ($M)	GDS Ops ($M)	Tracking Dev ($M)	Tracking Ops ($M)	EEIS ($M)	Total ($M)
Mid	25.4	24.1	28.7	6.4	1.9	10.3	1.6	98.4
High	25.4	35.0	28.7	9.4	1.9	16.8	1.6	118.9

Ground Systems
Cost

- **Cost Drivers**
  - Development schedule for project is long and so the level of ground system engineering and support expended is increased in the cost model to reflect the ongoing SE support during development
- **Potential Cost Savings**
  - Offsetting the ground system development from the project schedule will reduce cost. The key is ensuring that sufficient MOS engineering is kept on to ensure a easily operable spacecraft is built so that when the ground system development does start it does not need to develop significant tools to compensate for poor spacecraft implementation. In addition the GDS needs to be available for S/C testing in ATLO, and possible as early as S/S I&T.
  - Staffing during the cruise can be reduced about 3 to 6 months after launch and kept low until about 3 months before arrival into the science orbit. There would need to be special effort made to retain the talent, either via documentation and training, or by retaining the engineers but at a low level. This could reduce phase E cruise cost by around $5M but increase risk of operator/command error and less resiliency to problems.
- **Potential Cost Uppers**
  - If the spacecraft requires significant management during the science phase the operations team will easily need to double or more.

Ground Systems

Risk

- **List of Risks**
  - No risks of note for the ground system. The challenges in this mission are in the instrument design and autonomy, if these don't work there is no mission.

Software Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Ashton Vaughs & Karen Lum

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Software

Table of Contents

- Design Requirements
- Design Assumptions
- Design
- Design Rationale
- Cost Assumptions
- Cost
- Risk
- Option Comparison
- Additional Comments

Software
Design Requirements – (All Options)

- **Mission:**
  - The Mission is a constellation of Earth Trailing Orbiters

- **Data**
  - No data compression in FSW
  - Some Data Analysis required to generate delta-v inputs to ACS
  - Ground provides each orbiter with the location of the other orbiters

- **Instrument**
  - An instrument interface is required for passing through commands/data and receiving/storing telemetry
  - The constellation of Spacecrafts is the instrument
  - Each node has multiple sensors – combination of sensors create the instrument

- **The Flight Software Development will be a fully co-located in-house development**

Software

Design Assumptions – All Options

- **Moderately complex orbiter with medium bandwidth communications and full ACS**
  - Each Sciencecraft is in an Earth Trailing orbit
  - Flight software does not perform formation flying, the instrument does
- **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
- **The Flight Software Subsystem also includes the science data analysis that will be performed by the RAD750 space flight computer**

Software

Design – All Options

- **ACS Features**
  - 3-axis control and Precision Pointing requirements. Challenging attitude control requirements with interactions between basebody and other pointable systems (lasers), and driven by precision pointing and knowledge requirements.
  - High Gain Antenna with 2 degrees of freedom
  - Propulsion Stage places Science/Spacecraft into position with a high degree of accuracy
  - Deployables: 1 simple release mechanism for Propulsion stage separation
- **CDS Features**
  - Sends Commands, Science Data and EHA over either Telecom or LASER. May need to be Rated as "Very High".
  - Low Earth orbit; low radiation environment
  - FSW Primary and Spare images on Flash Memory
  - Two flight computers Dual String, Cold Sparing
  - Single CPU (RAD750) per flight computer
- **Engineering Subsystems**
  - Moderate thermal control requirements for control of heaters on Prop Module and Sciencecrafts
  - Simple power control requirements. Advance Array Controller chips are used for solar array power. FSW just acquires and reports power data.
  - Complex telecom control requirements. Relay data is sent from a Node's NVM to/from other sciencecraft. Store-and-forward capability.
- **Payload Accommodation**
  - The instrument interface is complex. In addition to passing through commands/data and receiving/storing telemetry, the instrument interface requires real-time control (each node has to monitor the Proof Mass and keep the sciencecraft centered around it).
  - Data processing will be performed by the spacecraft RAD750 processor
    - There will be a large amount of data processing by the flight computer. It has to control the gimballing of the mirror and telescopes associated with the laser systems. This is highly critical to the achievement of the mission requirements. The data is time critical to maintain the sciencecraft's pointing.

Software
Design Rationale – All Options

- **The CDH flight software design is modeled as some MSAP inheritance with major hardware modifications to capture Goddard’s Common Flight Executive software product line heritage**
- **GNC software will have between 25% and 75% code reuse.**
  - There is Hammers algorithms heritage from ST-7 with minor modifications .
- **Engineering Applications software will have between 25% and 75% code reuse**
  - The heritage is from GSFC's Core Flight Executive.
- **Payload Accommodation software is assumed to have less than 25% code reuse**
  - Payload interfaces are usually unique and new to each spacecraft and will need to be written from scratch
- **System Services software will have between 25% and 75% code reuse.**
  - The heritage is from GSFC's Core Flight Executive.

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
  - 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)
- **The estimate does not include**
  - Testbed procurement
  - Phase E
  - Formal Software QA
  - System-Level Engineering functions
  - ATLO support
  - 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)

Software
Cost – All Options

- **Total (1st Unit): $24.2M**
- **Total (all 3 sciencecraft): $26.6M**

- **Cost Drivers**
  - Major Cost Driver is the Software (included in the FSW) to control Telescopes and Tracking system

- **Potential Cost Savings**
  - None

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

Software

Risk

- The design assumes reuse of flight software from another mission (ST-7). Most missions have specific software needs that may need to be developed for the mission. The GNC algorithms are assumed to be high heritage with minor modifications, but if major modifications occur, then this could increase cost by $1.3M. In addition, if the amount of reuse of the GSFC Core Flight Executive Software is optimistically estimated, costs can increase by another $4M.

Software
Option Comparison

- **There is no difference in Flight Software design and cost for the two options**
    - The duration of the mission does not affect the flight software design

Programmatics Report

1279 SGO-Mid 2012-03 Study

March 5 – March 8, 2012

Author: Jared Lang, Greg Dubos

Email: Jared.Lang@jpl.nasa.gov, Gregory.F.Dubos@jpl.nasa.gov

Programmatics

Table of Contents

- Schedule Requirements
- Schedule Assumptions
- Schedule
- Schedule Rationale

Programmatics

Schedule Requirements – All Option

- **Launch Date: Oct, 10, 2020**
- **Phase E Duration: 45 months (SGO-Mid); 81 months (SGO-High)**
- **Partners: GSFC**
- **Major Schedule Constraints**
  - No major long lead items
  - Technology Development Cutoff: 05/10/15

- **Schedule Reserves**
  - 1 month per year
  - ATLO has 2 month

Programmatics
Schedule Assumptions – All Option

- **Implementation Mode: In-House**
- **Mission Timeline**
  - Cruise: 18 months
  - Commissioning: 4 months
  - Science operations: 24 months (SGO-Mid); 60 months (SGO-High)
- **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 – All Options

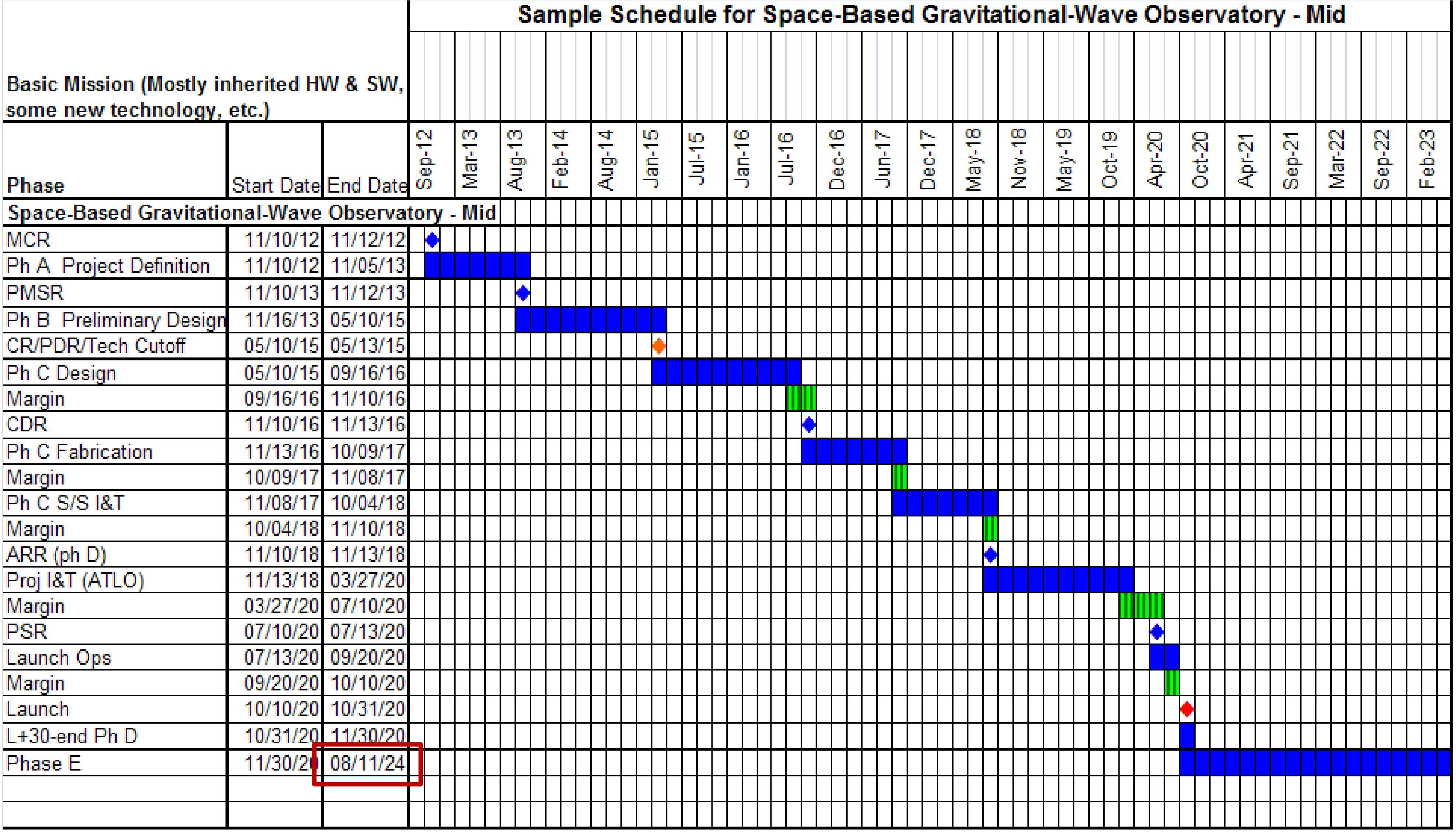
- **Key Dates:**
  - Phase A start: 11/10/2012
    - PMSR - 11/10/2013
  - Phase B start: 11/16/2013
    - PDR - 5/10/2015
  - Phase C start: 5/10/2015
    - CDR - 11/10/2016
  - Phase D start: 11/10/2018
    - PSR - 7/10/2020
  - Launch: 10/10/2020

Phase	***Duration (months)***
A	12
B	18
C/D	66
C Design	18
Fab	12
D I&T	12
D Launch	20
D: L + 30	4
E	45
A-D	96

Note: SGO-Mid (MID) Phase E is 45 months while SGO-High (HIGH) Phase E is 81 months

Programmatics

Schedule – All Option



Sample Schedule for Space-Based Gravitational-Wave Observatory - Mid

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

Phase	Start Date	End Date
Space-Based Gravitational-Wave Observatory - Mid		
MCR	11/10/12	11/12/12
Ph A Project Definition	11/10/12	11/05/13
PMSR	11/10/13	11/12/13
Ph B Preliminary Design	11/16/13	05/10/15
CR/PDR/Tech Cutoff	05/10/15	05/13/15
Ph C Design	05/10/15	09/16/16
Margin	09/16/16	11/10/16
CDR	11/10/16	11/13/16
Ph C Fabrication	11/13/16	10/09/17
Margin	10/09/17	11/08/17
Ph C S/S I&T	11/08/17	10/04/18
Margin	10/04/18	11/10/18
ARR (ph D)	11/10/18	11/13/18
Proj I&T (ATLO)	11/13/18	03/27/20
Margin	03/27/20	07/10/20
PSR	07/10/20	07/13/20
Launch Ops	07/13/20	09/20/20
Margin	09/20/20	10/10/20
Launch	10/10/20	10/31/20
L+30-end Ph D	10/31/20	11/30/20
Phase E	11/30/2	08/11/24

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

Note:
SGO-High (HIGH) schedule is identical except for End Date of Phase E: 07/27/2027

Programmatics
Schedule Rationale – All Options

- **Comparison with customer schedule**
  - **Phase A**: unchanged compared to initial estimate (12 months)
  - **Phase B**: duration estimate (18 months) was reduced by one year from initial customer schedule (30 months), due to large heritage from the previous LISA studies conducted since 1993.
  - **Phase C/D**: total duration (66 months) almost unchanged from customer schedule (67 months)
    - Phase C duration (42 months) reduced by 2 months compared to initial estimate:
      - Design duration (18 months) was reduced by 6 months from the initial customer schedule estimate (24 months), based on same design heritage reasons described for Phase B
      - Fabrication (24 months) assumed to take one year for the first spacecraft (based on historical data for medium-complexity missions), and six months for each of the next two identical ones (all three spacecraft are assumed to be identical). This represents a 4 month increase with respect to the initial customer schedule
    - Phase D duration (24 months) increased by 1 month compared to initial estimate:
      - Project I&T duration is 20 months (vs. 19 months in customer schedule)
  - **Phase E**: unchanged compared to initial estimate (45 months)

Risk Report

1279 SGO-Mid 2012-03 Study
March 5 – March 8, 2012

Author: Jared Lang, Greg Dubos

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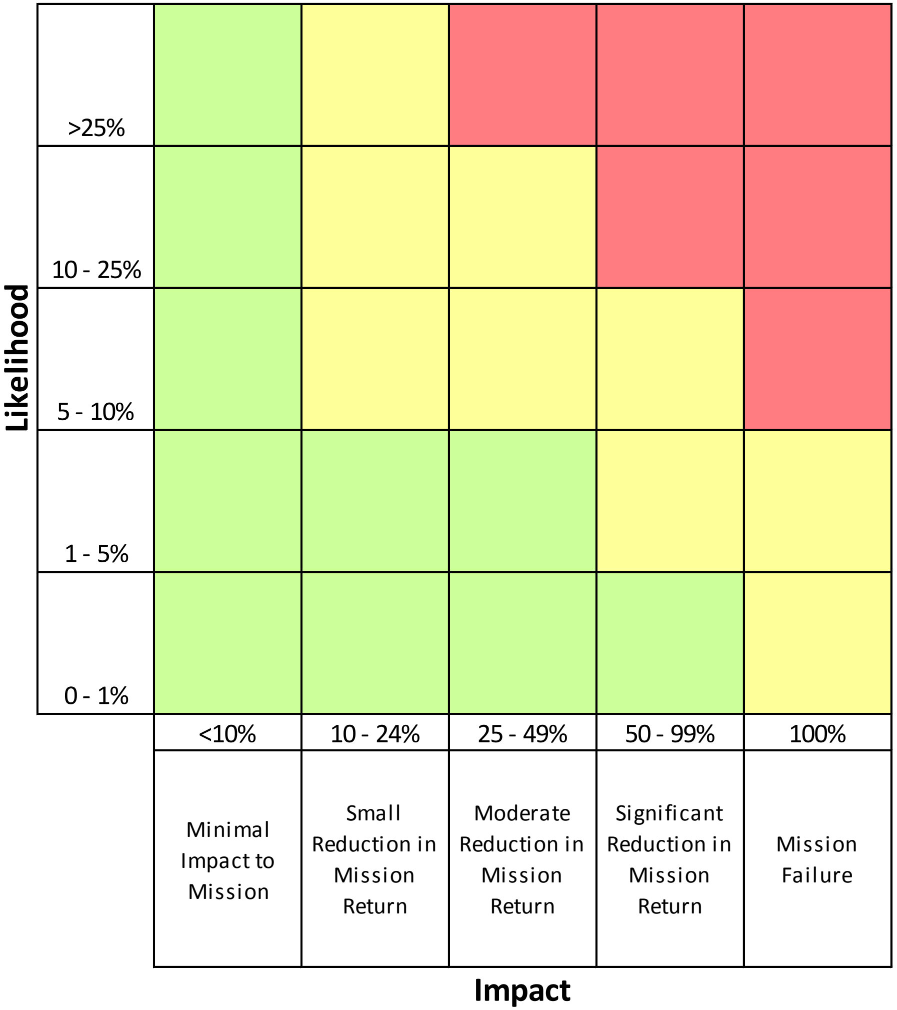
Methodology
Risk Guidance

- **Risk are scored on the NASA 5x5 Risk matrix**

Mission Risks

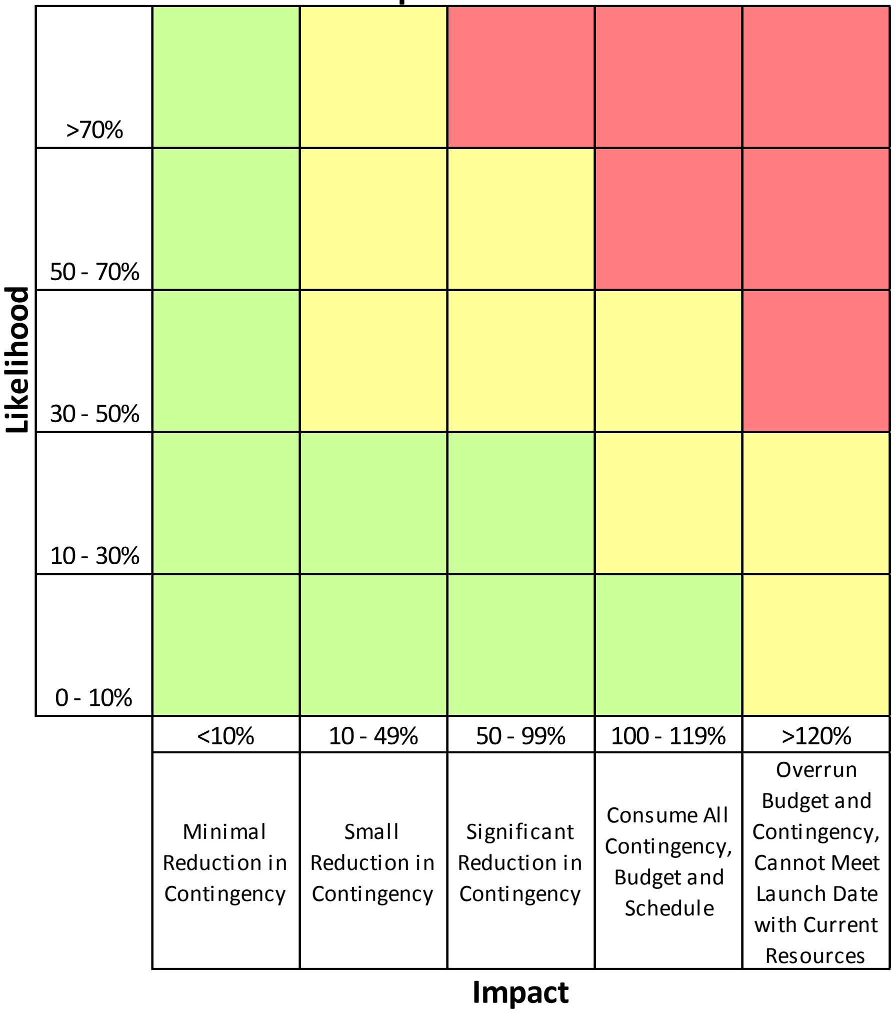


Likelihood

>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



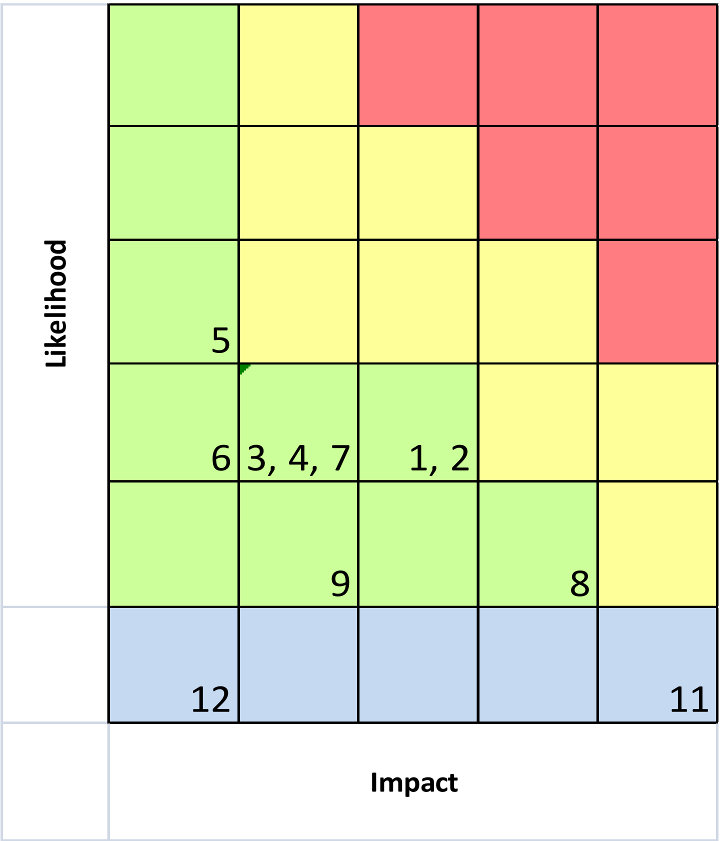
Likelihood

>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 – All Options



- **There are a number of minor risks that pose potential threats to the mission**
  - Event rates for massive black hole binary mergers and extreme-mass-ratio-inspirals
  - Low TRL photoreceivers
  - Technology inheritance from future mission
  - Star Tracker cost growth and manufacturing
  - Heritage software algorithms
  - Damage to proof mass in the event of a hard impact
  - Re-qualification of the Colloidal feed system
- **There are also two proposal risks that require special attention when proposing the mission**
  - Shock loads / cold welding of proof mass during launch
  - Inability to “test-as-we-fly” due to large spacecraft architecture

Risk

Minor Risk Items – All Options

Risk #	Submitter	Risk Type	Title	Description of Risk	Likelihood	Impact
1	Programmatics/Risk	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	Programmatics/Risk	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	Programmatics/Risk	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
4	Programmatics/Risk	Implementation	Technology / Data Inheritance from Future Missions	Maturation of the Disturbance Reduction System is highly dependant on the success of the LISA Pathfinder mission. Unexplained on-orbit failure will require the mission to completely redesign the Disturbance Reduction System.	2	2
5	Programmatics/Risk	Implementation	Star tracker cost growth	The selected star tracker is the micro-ASC. Few have been made or flown. The cost is low compared to commercial vendors, and the current accuracy is about half of what is needed. The vendor may be able to improve performance before the tech cutoff date. If so, the cost is likely to go up. If not, higher priced star trackers from a competitor may need to be procured. Either way, there is a risk of cost growth in the ballpark of $6M to $7M. Around $3M of that has already been priced into the ACS cost estimate.	3	1
6	Programmatics/Risk	Implementation	Star Tracker Manufacturing Process	The supplier for the baseline star tracker, the micro-ASC - This is a relatively new item. Few have been made or flown. The vendor is not a typical commercial supplier. SGO will require 20 optical heads, 8 dual electronics boxes, plus engineering models. The large number of items may overwhelm the manufacturing process, possibly causing schedule delays and/or impacting product quality.	2	1
7	Programmatics/Risk	Implementation	Pointing Algorithms/Software Cost Growth	The customer is assuming heritage algorithms and software from ST7, which has demonstrated a number of functions required for SGO. There are questions as to who owns the algorithms and software from ST7 and whether they can be re-used as is. In the time frame of the mission, with a launch date years away, there are also questions as to whether the same processor and compiler would be used. Re-use may be significantly less than assumed, in which case, there would be a cost upper of $6M to $7M for pointing algorithms and software.	2	2
8	Programmatics/Risk	Mission	Damage to a Proof Mass due to Hard Contact	The low level of thrust available on the sciencecraft makes it unlikely that the spacecraft could make hard contact with a proof mass in a failure scenario. But a micro-meteorite impact could knock the spacecraft into one or both proof masses. If so, there could be enough damage to render one or both proof masses unusable.	1	4
9	Programmatics/Risk	Implementation	Scaling up of colloidal feed system	The ST7 feed system must be scaled up to meet the 1.5 kg propellant requirement, which might require delta qualification of components.	1	2

Cleared for public release. For discussion purposes only.

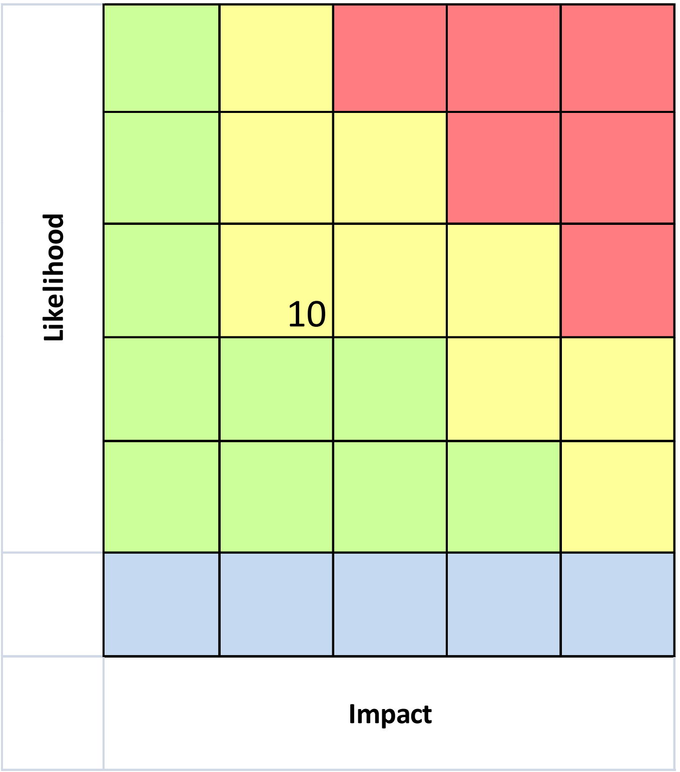
Risk

Proposal Risk Items – All Options

Risk #	Submitter	Risk Type	Title	Description of Risk	Likelihood	Impact
11	Programmatics/Risk	Proposal	Shock loads on sciencecraft during launch	Since sciencecraft is rigidly attached inside of the launch vehicle (lack of vibrations dampening), elements of the instrument could be deformed (thus jeopardizing science collection) or even damaged due to shock loads during launch. In particular the mechanical mounts holding the test mass within the GRS might fuse themselves together. This would significantly limit the capability of the mission to perform the attitude control algorithms required for precision pointing. Note: Significant design and prototype work have been performed to understand and mitigate this risk, however when proposing this mission special attention should be applied to describe the mitigation of this risk.	0	5
12	Programmatics/Risk	Proposal	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.	0	1

Risk

System Level Risk Summary – SGO High



Likelihood	🟩	🟨	🟥	🟥	🟥
	🟩	🟨	🟨	🟥	🟥
	🟩	🟨 10	🟨	🟨	🟥
	🟩	🟩	🟩	🟨	🟨
	🟩	🟩	🟩	🟩	🟨
	🟦	🟦	🟦	🟦	🟦

Impact

- **In addition to the common risks between the SGO-Mid and SGO-High architectures, there is one moderate risk specific to the SGO-High mission**
  - Colloidal thrusters lifetime limitations

Risk

Moderate Risk Items – SGO High

Risk #	Submitter	Risk Type	Title	Description of Risk	Likelihood	Impact
10	Programmatics/Risk	Mission	Colloidal Thruster Lifetime Limitations	The Colloidal thruster has a lifetime limitation that becomes a risk when going from SGO-Mid (2 year life) to SGO-High (4-5 year life). Test data exists documenting accelerated life test results supporting the ST7 thruster can last 4-5 years on continous opperation resulting in meeting 150% life over two years, but not meeting 150% life over five years.	3	2

Cost Report

1279 - SGO

March 5-8, 2012

Leigh Rosenberg

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Cost

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- Cost Requirements
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Cost

Cost Disclaimer

- The costs presented in this report are ROM estimates, they are not point estimates or cost commitments. The costs presented are based on Pre-Phase A design information, which is subject to change.

Cost

Cost Requirements

- **Costs reported as FY 2012 $M**
- **Cost Target: For background information the sponsor provided previous sponsor-derived costs for SGO-Mid ($1.4B) and SGO-High ($1.7B)**
- **Cost estimates down to WBS levels 2 and 3 lifecycle costs for Option 1 (SGO-Mid) and Option 2 (SGO-High).**
  - Option 1: 25 cm telescope (in field guiding), 0.7 W EOL Laser Power
  - Option 2: 40 cm telescope (articulates as unit), 1.2 W EOL Laser Power

Cost

Cost Assumptions – Options 1 & 2

- **Fiscal Year: 2012**
- **Mission Class: B**
- **Cost Category: Large**
- **Launch Vehicle: Atlas V 551**
- **For each option, there are 3 identical spacecraft**
- **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%
- **In addition to the baseline case, estimate total cost for each option based on:**
  - 1) 20% reserves (instead of 30%),
  - 2) 20% reserves and a $100M launch vehicle,

Cost

Cost Assumptions (cont) – Options 1 & 2

- Phase A start: February 2013
- Phase A duration: 12 mos
- Phase B duration: 15 mos
- Phase C/D duration: 66 mos
- Phase E duration: 45 mos for Option 1; 81 months for Option 2
- Phase F duration: 24 mos
- Instruments: Science compliment (2 instruments)
- Spares approach: Long lead and card level spares where appropriate
- HW models: Protoflight science craft
- Parts class: commercial and military 883B

Cost

Cost Assumptions

- **Management and Systems Engineering**
  - Project – Team X cost models used for estimating project-level Management (1.0), Systems Engineering (2.0), and Mission Assurance (3.0).
  - Payload – The payload management and systems engineering costs are assumed to be included in the individual instrument costs since there are only 2 instruments per Sciencecraft.
  - Flight System – Flight System Management and System Engineering costs are accounted for within the primary element (Sciencecraft) and were estimated using Team X models with an in-house build assumption.
- **ATLO: Team X ATLO cost model was run assuming the Sciencecraft as the primary element and the Prop Stage as the secondary unit.**

Generate ProPricer Input

Cost Results – Option 1, SGO Mid

	SGO-Mid
COST SUMMARY (FY2012 $M)	**Team X Estimate**
Project Cost	**$1903 M**
Launch Vehicle	**$247 M**
Project Cost (w/o LV)	**$1656 M**
Development Cost	**$1530 M**
Phase A	$15 M
Phase B	$103 M
Phase C/D	$1413M
Operations Cost	**$125 M**

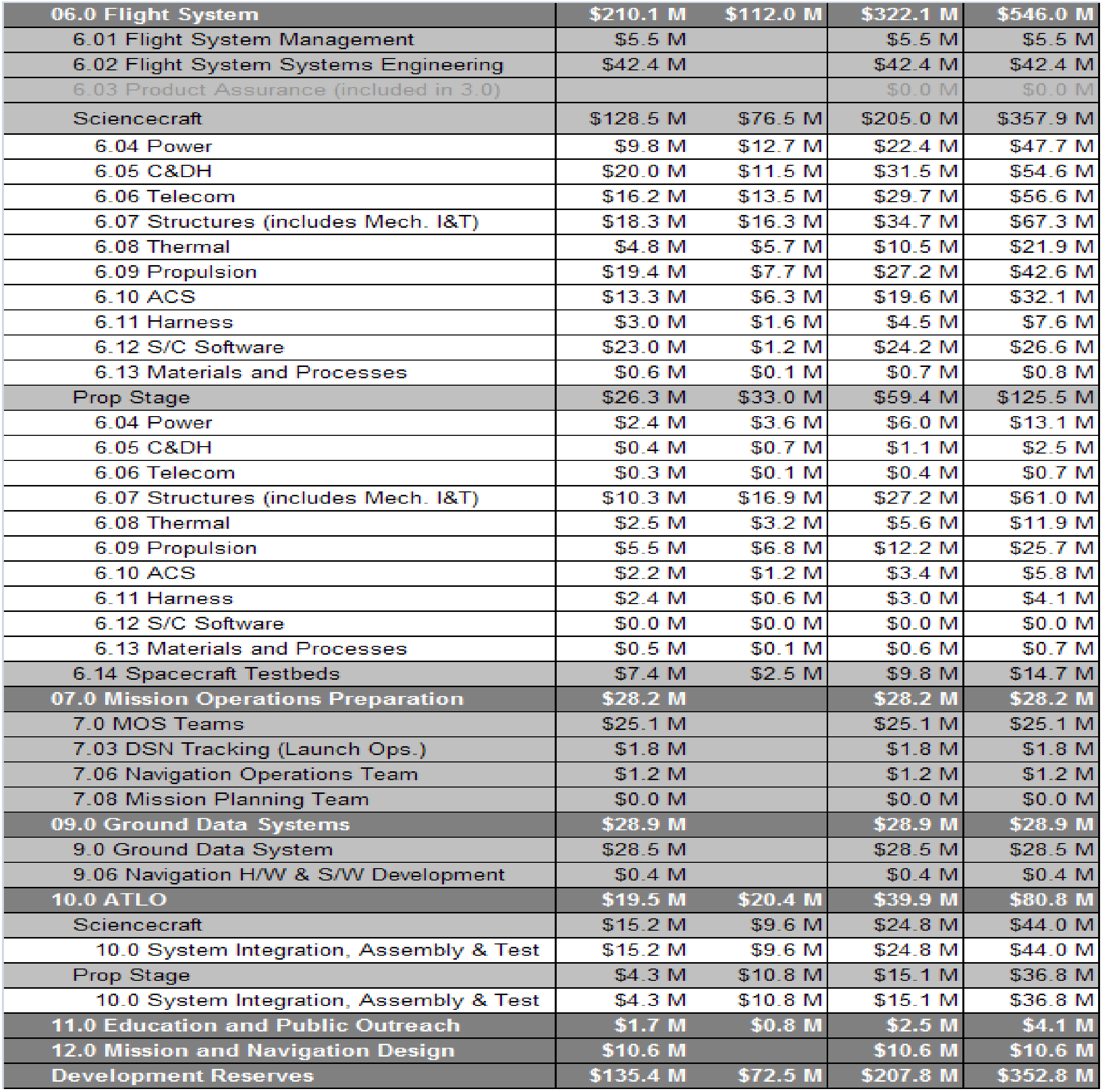
The total life cycle cost for Option 1 is $1.9B. The development cost including reserves is $1.5B. Total reserves are $379M. The launch vehicle (Atlas V 551) is $247M.

Cost

Cost Results (Phases A – D) – Option 1, SGO Mid

COST SUMMARY (FY2012 $M)	NRE	RE	1st Unit	All Units
Project Cost (including Launch Vehicle)	**$950.4**	**$317.5**	**$1,267.8**	**$1902.7 M**
Development Cost (Phases A - D)	**$588.6 M**	**$314.0 M**	**$902.5 M**	**$1530.4 M**
01.0 Project Management	**$22.8 M**		**$22.8 M**	**$22.8 M**
1.01 Project Management	$8.9 M		$8.9 M	$8.9 M
1.02 Business Management	$12.3 M		$12.3 M	$12.3 M
1.04 Project Reviews	$1.6 M		$1.6 M	$1.6 M
1.06 Launch Approval	$0.1 M		$0.1 M	$0.1 M
02.0 Project Systems Engineering	**$26.6 M**	**$0.3 M**	**$26.9 M**	**$27.5 M**
2.01 Project Systems Engineering	$10.5 M		$10.5 M	$10.5 M
2.02 Project SW Systems Engineering	$5.3 M		$5.3 M	$5.3 M
2.03 EEIS	$1.6 M		$1.6 M	$1.6 M
2.04 Information System Management	$1.9 M		$1.9 M	$1.9 M
2.05 Configuration Management	$1.9 M		$1.9 M	$1.9 M
2.06 Planetary Protection	$0.0 M	$0.0 M	$0.0 M	$0.0 M
2.07 Contamination Control	$1.2 M	$0.3 M	$1.5 M	$2.0 M
2.09 Launch System Engineering	$1.3 M		$1.3 M	$1.3 M
2.10 Project V&V	$2.6 M		$2.6 M	$2.6 M
2.11 Risk Management	$0.5 M		$0.5 M	$0.5 M
03.0 Mission Assurance	**$22.9 M**	**$4.4 M**	**$27.3 M**	**$36.2 M**
04.0 Science	**$10.2 M**		**$10.2 M**	**$10.2 M**
05.0 Payload System	**$71.6 M**	**$103.6 M**	**$175.2 M**	**$382.5 M**
5.01 Payload Management	$0.0 M		$0.0 M	$0.0 M
5.02 Payload Engineering	$0.0 M		$0.0 M	$0.0 M
Element 01	$71.6 M	$103.6 M	$175.2 M	$382.5 M
Science Compliment	$71.6 M	$103.6 M	$175.2 M	$382.5 M

Cost Results (Phases A – D) – Option 1, SGO Mid



06.0 Flight System	**$210.1 M**	**$112.0 M**	**$322.1 M**	**$546.0 M**
6.01 Flight System Management	$5.5 M		$5.5 M	$5.5 M
6.02 Flight System Systems Engineering	$42.4 M		$42.4 M	$42.4 M
6.03 Product Assurance (included in 3.0)			$0.0 M	$0.0 M
Sciencecraft	$128.5 M	$76.5 M	$205.0 M	$357.9 M
6.04 Power	$9.8 M	$12.7 M	$22.4 M	$47.7 M
6.05 C&DH	$20.0 M	$11.5 M	$31.5 M	$54.6 M
6.06 Telecom	$16.2 M	$13.5 M	$29.7 M	$56.6 M
6.07 Structures (includes Mech. I&T)	$18.3 M	$16.3 M	$34.7 M	$67.3 M
6.08 Thermal	$4.8 M	$5.7 M	$10.5 M	$21.9 M
6.09 Propulsion	$19.4 M	$7.7 M	$27.2 M	$42.6 M
6.10 ACS	$13.3 M	$6.3 M	$19.6 M	$32.1 M
6.11 Harness	$3.0 M	$1.6 M	$4.5 M	$7.6 M
6.12 S/C Software	$23.0 M	$1.2 M	$24.2 M	$26.6 M
6.13 Materials and Processes	$0.6 M	$0.1 M	$0.7 M	$0.8 M
Prop Stage	$26.3 M	$33.0 M	$59.4 M	$125.5 M
6.04 Power	$2.4 M	$3.6 M	$6.0 M	$13.1 M
6.05 C&DH	$0.4 M	$0.7 M	$1.1 M	$2.5 M
6.06 Telecom	$0.3 M	$0.1 M	$0.4 M	$0.7 M
6.07 Structures (includes Mech. I&T)	$10.3 M	$16.9 M	$27.2 M	$61.0 M
6.08 Thermal	$2.5 M	$3.2 M	$5.6 M	$11.9 M
6.09 Propulsion	$5.5 M	$6.8 M	$12.2 M	$25.7 M
6.10 ACS	$2.2 M	$1.2 M	$3.4 M	$5.8 M
6.11 Harness	$2.4 M	$0.6 M	$3.0 M	$4.1 M
6.12 S/C Software	$0.0 M	$0.0 M	$0.0 M	$0.0 M
6.13 Materials and Processes	$0.5 M	$0.1 M	$0.6 M	$0.7 M
6.14 Spacecraft Testbeds	$7.4 M	$2.5 M	$9.8 M	$14.7 M
07.0 Mission Operations Preparation	**$28.2 M**		**$28.2 M**	**$28.2 M**
7.0 MOS Teams	$25.1 M		$25.1 M	$25.1 M
7.03 DSN Tracking (Launch Ops.)	$1.8 M		$1.8 M	$1.8 M
7.06 Navigation Operations Team	$1.2 M		$1.2 M	$1.2 M
7.08 Mission Planning Team	$0.0 M		$0.0 M	$0.0 M
09.0 Ground Data Systems	**$28.9 M**		**$28.9 M**	**$28.9 M**
9.0 Ground Data System	$28.5 M		$28.5 M	$28.5 M
9.06 Navigation H/W & S/W Development	$0.4 M		$0.4 M	$0.4 M
10.0 ATLO	**$19.5 M**	**$20.4 M**	**$39.9 M**	**$80.8 M**
Sciencecraft	$15.2 M	$9.6 M	$24.8 M	$44.0 M
10.0 System Integration, Assembly & Test	$15.2 M	$9.6 M	$24.8 M	$44.0 M
Prop Stage	$4.3 M	$10.8 M	$15.1 M	$36.8 M
10.0 System Integration, Assembly & Test	$4.3 M	$10.8 M	$15.1 M	$36.8 M
11.0 Education and Public Outreach	**$1.7 M**	**$0.8 M**	**$2.5 M**	**$4.1 M**
12.0 Mission and Navigation Design	**$10.6 M**		**$10.6 M**	**$10.6 M**
Development Reserves	**$135.4 M**	**$72.5 M**	**$207.8 M**	**$352.8 M**

Cost

Cost Results (Phases E - F) – Option 1, SGO Mid

Operations Cost (Phases E - F)	**$114.9 M**	**$3.5 M**	**$118.4 M**	**$125.3 M**
01.0 Project Management	**$5.5 M**		**$5.5 M**	**$5.5 M**
1.01 Project Management	$3.2 M		$3.2 M	$3.2 M
1.02 Business Management	$2.1 M		$2.1 M	$2.1 M
1.04 Project Reviews	$0.1 M		$0.1 M	$0.1 M
1.06 Launch Approval	$0.0 M		$0.0 M	$0.0 M
02.0 Project Systems Engineering	**$0.0 M**	**$0.0 M**	**$0.0 M**	**$0.0 M**
03.0 Mission Assurance	**$0.4 M**	**$0.3 M**	**$0.7 M**	**$1.4 M**
04.0 Science	**$33.8 M**		**$33.8 M**	**$33.8 M**
07.0 Mission Operations	**$39.3 M**		**$39.3 M**	**$39.3 M**
7.0 MOS Teams	$24.1 M		$24.1 M	$24.1 M
7.03 DSN Tracking	$10.3 M		$10.3 M	$10.3 M
7.06 Navigation Operations Team	$4.9 M		$4.9 M	$4.9 M
7.08 Mission Planning Team	$0.1 M		$0.1 M	$0.1 M
09.0 Ground Data Systems	**$6.5 M**		**$6.5 M**	**$6.5 M**
9.0 GDS Teams	$6.4 M		$6.4 M	$6.4 M
9.06 Navigation HW and SW Dev	$0.1 M		$0.1 M	$0.1 M
11.0 Education and Public Outreach	**$5.2 M**	**$2.4 M**	**$7.6 M**	**$12.3 M**
12.0 Mission and Navigation Design	**$0.0 M**		**$0.0 M**	**$0.0 M**
Operations Reserves	**$24.1 M**	**$0.8 M**	**$24.9 M**	**$26.6 M**
8.0 Launch Vehicle	**$246.9 M**		**$246.9 M**	**$246.9 M**

Cost

Cost Rationale – Option 1

- **Cost Drivers**
  - The largest cost drivers for Option 1 are:
    - Payload ($383M) – driven by mass and power requirements
    - Sciencecraft ($358M).The most costly Sciencecraft subsystems and their drivers are:
      - Power ($48M) – redundant electronics
      - C&DH ($55M) – redundant dual cold spares, MSAP architecture
      - Telecomm ($57M) – redundant SDSTs and TWTAs
      - Structures/Mechanical ($67M) - primary and secondary power support structure, telecomm actuator
      - Propulsion ($43M) – colloidal thruster and di-electric propulsion
    - Prop Stage ($126M)
      - Structures/Mechanical ($61M) - primary and secondary power support structure, telecomm actuator
    - Reserves ($378M)
    - Launch vehicle ($247M)
  - These items account for 78% of total cost.

Cost

Cost Results – Option 2, SGO High

COST SUMMARY (FY2012 $M)	Team X Estimate		
	CBE	Res.	PBE
Project Cost	**$1672.8 M**	**25%**	**$2095.0 M**
Launch Vehicle	**$246.9 M**	**0%**	**$246.9 M**
Project Cost (w/o LV)	**$1425.9 M**	**30%**	**$1848.1 M**
Development Cost	**$1260.7 M**	**30%**	**$1638.4 M**
Phase A	$11.6 M	30%	$15.1 M
Phase B	$81.2 M	30%	$105.6 M
Phase C/D	$1167.9 M	30%	$1517.7 M
Operations Cost	**$165.2 M**	**27%**	**$209.7 M**

The total life cycle cost for Option 2 is $2.1B (10% higher than Option 1). The development cost including reserves is $1.6B. Total reserves are $422M. The launch vehicle (Atlas V 551) is $247M (same as Option 1). **Note that this design does not converge with respect the chosen launch vehicle.**

WBS Dictionary

Cost

Cost Results (Phases A – D) – Opt 2, SGO High

WBS Elements	NRE	RE	1st Unit	All Units
Project Cost (including Launch Vehicle)	**$1,057.2**	**$346.0**	**$1,403.1**	**$2095.0 M**
Development Cost (Phases A - D)	**$612.9 M**	**$341.8 M**	**$954.7 M**	**$1638.4 M**
01.0 Project Management	**$22.8 M**		**$22.8 M**	**$22.8 M**
1.01 Project Management	$8.9 M		$8.9 M	$8.9 M
1.02 Business Management	$12.3 M		$12.3 M	$12.3 M
1.04 Project Reviews	$1.6 M		$1.6 M	$1.6 M
1.06 Launch Approval	$0.1 M		$0.1 M	$0.1 M
02.0 Project Systems Engineering	**$26.6 M**	**$0.3 M**	**$26.9 M**	**$27.5 M**
2.01 Project Systems Engineering	$10.5 M		$10.5 M	$10.5 M
2.02 Project SW Systems Engineering	$5.3 M		$5.3 M	$5.3 M
2.03 EEIS	$1.6 M		$1.6 M	$1.6 M
2.04 Information System Management	$1.9 M		$1.9 M	$1.9 M
2.05 Configuration Management	$1.9 M		$1.9 M	$1.9 M
2.06 Planetary Protection	$0.0 M	$0.0 M	$0.0 M	$0.0 M
2.07 Contamination Control	$1.2 M	$0.3 M	$1.5 M	$2.0 M
2.09 Launch System Engineering	$1.3 M		$1.3 M	$1.3 M
2.10 Project V&V	$2.6 M		$2.6 M	$2.6 M
2.11 Risk Management	$0.5 M		$0.5 M	$0.5 M
03.0 Mission Assurance	**$22.9 M**	**$4.4 M**	**$27.3 M**	**$36.2 M**
04.0 Science	**$13.9 M**		**$13.9 M**	**$13.9 M**
05.0 Payload System	**$80.4 M**	**$116.4 M**	**$196.8 M**	**$429.6 M**
5.01 Payload Management	$0.0 M		$0.0 M	$0.0 M
5.02 Payload Engineering	$0.0 M		$0.0 M	$0.0 M
Element 01	$80.4 M	$116.4 M	$196.8 M	$429.6 M

Cost Results (Phases A – D) – Opt 2, SGO High

06.0 Flight System	**$216.0 M**	**$120.6 M**	**$336.6 M**	**$577.8 M**
6.01 Flight System Management	$5.5 M		$5.5 M	$5.5 M
6.02 Flight System Systems Engineering	$42.4 M		$42.4 M	$42.4 M
6.03 Product Assurance (included in 3.0)			$0.0 M	$0.0 M
Sciencecraft	$128.5 M	$76.6 M	$205.1 M	$358.4 M
6.04 Power	$9.8 M	$12.8 M	$22.6 M	$48.2 M
6.05 C&DH	$20.0 M	$11.5 M	$31.5 M	$54.6 M
6.06 Telecom	$16.2 M	$13.5 M	$29.7 M	$56.6 M
6.07 Structures (includes Mech. I&T)	$18.3 M	$16.3 M	$34.6 M	$67.1 M
6.08 Thermal	$4.8 M	$5.7 M	$10.5 M	$22.0 M
6.09 Propulsion	$19.5 M	$7.7 M	$27.2 M	$42.7 M
6.10 ACS	$13.3 M	$6.3 M	$19.6 M	$32.1 M
6.11 Harness	$3.0 M	$1.6 M	$4.5 M	$7.6 M
6.12 S/C Software	$23.0 M	$1.2 M	$24.2 M	$26.6 M
6.13 Materials and Processes	$0.6 M	$0.1 M	$0.7 M	$0.8 M
Prop Stage	$32.2 M	$41.5 M	$73.7 M	$156.8 M
6.04 Power	$2.4 M	$3.6 M	$6.0 M	$13.1 M
6.05 C&DH	$0.4 M	$0.7 M	$1.1 M	$2.5 M
6.06 Telecom	$0.3 M	$0.1 M	$0.4 M	$0.7 M
6.07 Structures (includes Mech. I&T)	$11.9 M	$19.7 M	$31.7 M	$71.1 M
6.08 Thermal	$2.5 M	$3.6 M	$6.0 M	$13.1 M
6.09 Propulsion	$9.6 M	$12.0 M	$21.6 M	$45.7 M
6.10 ACS	$2.2 M	$1.2 M	$3.4 M	$5.8 M
6.11 Harness	$2.4 M	$0.6 M	$3.0 M	$4.1 M
6.12 S/C Software	$0.0 M	$0.0 M	$0.0 M	$0.0 M
6.13 Materials and Processes	$0.5 M	$0.1 M	$0.6 M	$0.7 M
6.14 Spacecraft Testbeds	$7.4 M	$2.5 M	$9.8 M	$14.7 M
07.0 Mission Operations Preparation	**$28.2 M**		**$28.2 M**	**$28.2 M**
7.0 MOS Teams	$25.1 M		$25.1 M	$25.1 M
7.03 DSN Tracking (Launch Ops.)	$1.8 M		$1.8 M	$1.8 M
7.06 Navigation Operations Team	$1.2 M		$1.2 M	$1.2 M
7.08 Mission Planning Team	$0.0 M		$0.0 M	$0.0 M
09.0 Ground Data Systems	**$28.9 M**		**$28.9 M**	**$28.9 M**
9.0 Ground Data System	$28.5 M		$28.5 M	$28.5 M
9.06 Navigation H/W & S/W Development	$0.4 M		$0.4 M	$0.4 M
10.0 ATLO	**$19.5 M**	**$20.4 M**	**$39.9 M**	**$80.8 M**
Sciencecraft	$15.2 M	$9.6 M	$24.8 M	$44.0 M
10.0 System Integration, Assembly & Test	$15.2 M	$9.6 M	$24.8 M	$44.0 M
Prop Stage	$4.3 M	$10.8 M	$15.1 M	$36.8 M
10.0 System Integration, Assembly & Test	$4.3 M	$10.8 M	$15.1 M	$36.8 M
11.0 Education and Public Outreach	**$2.0 M**	**$0.9 M**	**$2.9 M**	**$4.6 M**
12.0 Mission and Navigation Design	**$10.6 M**		**$10.6 M**	**$10.6 M**
Development Reserves	**$141.0 M**	**$78.9 M**	**$219.9 M**	**$377.7 M**

Cost

Cost Results (Phases E - F) – Option 2, SGO High

Operations Cost (Phases E - F)	**$197.4 M**	**$4.1 M**	**$201.5 M**	**$209.7 M**
01.0 Project Management	**$8.5 M**		**$8.5 M**	**$8.5 M**
1.01 Project Management	$4.9 M		$4.9 M	$4.9 M
1.02 Business Management	$3.4 M		$3.4 M	$3.4 M
1.04 Project Reviews	$0.2 M		$0.2 M	$0.2 M
1.06 Launch Approval	$0.0 M		$0.0 M	$0.0 M
02.0 Project Systems Engineering	**$0.0 M**	**$0.0 M**	**$0.0 M**	**$0.0 M**
03.0 Mission Assurance	**$0.7 M**	**$0.6 M**	**$1.3 M**	**$2.5 M**
04.0 Science	**$70.2 M**		**$70.2 M**	**$70.2 M**
07.0 Mission Operations	**$60.6 M**		**$60.6 M**	**$60.6 M**
7.0 MOS Teams	$35.0 M		$35.0 M	$35.0 M
7.03 DSN Tracking	$16.8 M		$16.8 M	$16.8 M
7.06 Navigation Operations Team	$8.7 M		$8.7 M	$8.7 M
7.08 Mission Planning Team	$0.1 M		$0.1 M	$0.1 M
09.0 Ground Data Systems	**$9.7 M**		**$9.7 M**	**$9.7 M**
9.0 GDS Teams	$9.4 M		$9.4 M	$9.4 M
9.06 Navigation HW and SW Dev	$0.3 M		$0.3 M	$0.3 M
11.0 Education and Public Outreach	**$6.0 M**	**$2.6 M**	**$8.6 M**	**$13.7 M**
12.0 Mission and Navigation Design	**$0.0 M**		**$0.0 M**	**$0.0 M**
Operations Reserves	**$41.7 M**	**$0.9 M**	**$42.6 M**	**$44.5 M**
8.0 Launch Vehicle	**$246.9 M**		**$246.9 M**	**$246.9 M**

Cost

Cost Rationale – Option 2

Cost Drivers

- The largest cost drivers for Option 2 are:
  - Payload ($430M) – driven by mass and power requirements
  - Sciencecraft ($358M) The Sciencecraft is virtually the same as in Option 1
  - .The most costly Sciencecraft subsystems and the drivers within them are:
    - Power ($48M) – redundant electronics
    - C&DH ($55M) – redundant dual cold spares, MSAP architecture
    - Telecomm ($57M) – redundant SDSTs and TWTAs
    - Structures/Mechanical ($67M) - primary and secondary power support structure, telecomm actuator
    - Propulsion ($43M) – colloidal thruster and di-electric propulsion
  - Prop Stage ($157M)
    - Structures/Mechanical ($71M) - bigger primary structure than in Option 1
    - Propulsion ($46M) – Uses bi-propellant (Option 1 uses mono-propellant)
  - Reserves ($422M)
  - Launch vehicle ($247M)
- These items account for 77% of total cost.
- **Remember that this option does not converge with the launch vehicle capability.**

Cost

Cost Rationale – Option 1 vs Option 2

- **Cost Drivers**
  - Option 2 cost is 10% higher than Option 1 ($2.1B vs $1.9B).
    - The payload in Option 2 is 12% higher ($430M vs $383M) due to having to accommodate a larger telescope and higher power level in Option 2.
    - The Sciencecraft cost is virtually the same in both cases ($358M vs $358M).
    - The prop stage in Option 2 is 25% higher ($157M vs $126M) since the Option 2 structure is bigger and uses bi-prop instead of mono-prop.
    - Phase E/F in Option 2 is 67% higher ($210M vs $125M) due to Phase E having 81 months in Option 2 vs 45 months in Option 1.
    - The Launch Vehicle (Atlas V 551) cost the same in both cases ($247M).
    - Total reserves in Option 2 are 11% higher than in Option 1 ($422M vs $379M).

Cost

Risk

- **List of Risks**
  - Option 2 does not converge. It could be more cost effective to just plan on building Option 1. Otherwise, Option 2 would need to be redesigned which could also result in cost growth.
  - The coordination of the construction of three identical units is imperative in order to maintain cost control on this mission. The loss of such efficient builds by schedule increases, unavailable parts, or work force turnover would almost certainly result in cost growth.