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

Customer: Kirk McKenzie
September 6, 2012
Final report v.1.95 (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.

1280 LaGrange 2012-03 Study, Team X Final Report, 9/6/12

TEAM X
Jet Propulsion Laboratory

Customer: Ken Anderson, Jeff Booth
Facilitator: Robert Kinsey
Sessions: March 20-22, 2012
Study ID: 1280

Data Use Policy

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

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

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Executive Report

(1280) LaGrange 2012-03
20, 21, 22 March 2012

Author: Bob Kinsey

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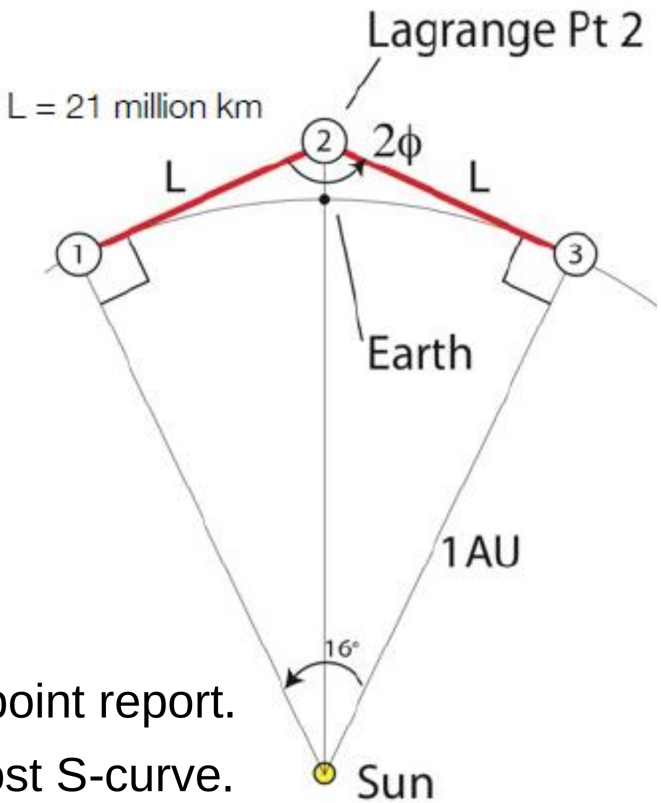
Study Purpose and Objectives

Study Purpose:

- Four session study to design and cost a gravity wave mission.
  - The customer also requested a risk report.
- Three spacecraft will fly as a constellation while closely measuring the distance between them.
  1. One spacecraft will be in an Earth leading heliocentric orbit 21M km from L2.
  2. One will be at Earth-Sun L2.
  3. One will be in an Earth trailing heliocentric orbit 21M km from L2.



Objectives:

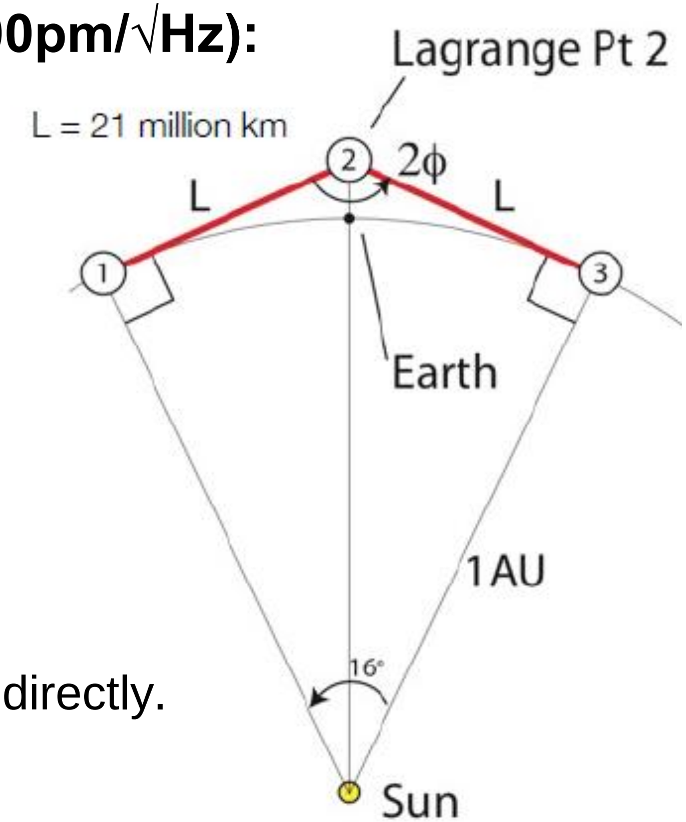
1. Estimate spacecraft mass and power.
2. Estimate the cost of the mission.
3. Create a risk report.
4. Capture design and assumptions in a power point report.
5. Team X may also be required to produce a cost S-curve.

Science Goal & Implementation

- **Goal: First detection of gravitational waves (GWs) from space.**
  - Sources include:
    - ~1e4 Galactic WD binaries.
    - ~1-100 Merging Massive Black Hole binaries, with ~half having SNR>100 (and hence allow good tests of general relativity predicts for the strong-field merger).
    - Of order ~100 inspirals of stellar-mass compact objects in Massive Black Holes, out z~0.2.
- **Implementation: Based to zeroth order on former "LISA" mission, but with significant changes with the aim of reducing cost.**
  - Not drag free: instead, reduced influence of external forces by factor of ~100 using orbital geometry, another factor ~100 by *measuring* solar wind and radiation pressure and taking them out in the data analysis.
  - Different geometry, with spacecraft 2 at the Earth-Sun L2.
  - There are only 4 arms, so
    - Measure only 1 polarization.
    - Significantly degrade ability to detect a stochastic gravitational-wave (GW) background, since it will be much harder to distinguish between a GW background and unmodeled instrumental noise.

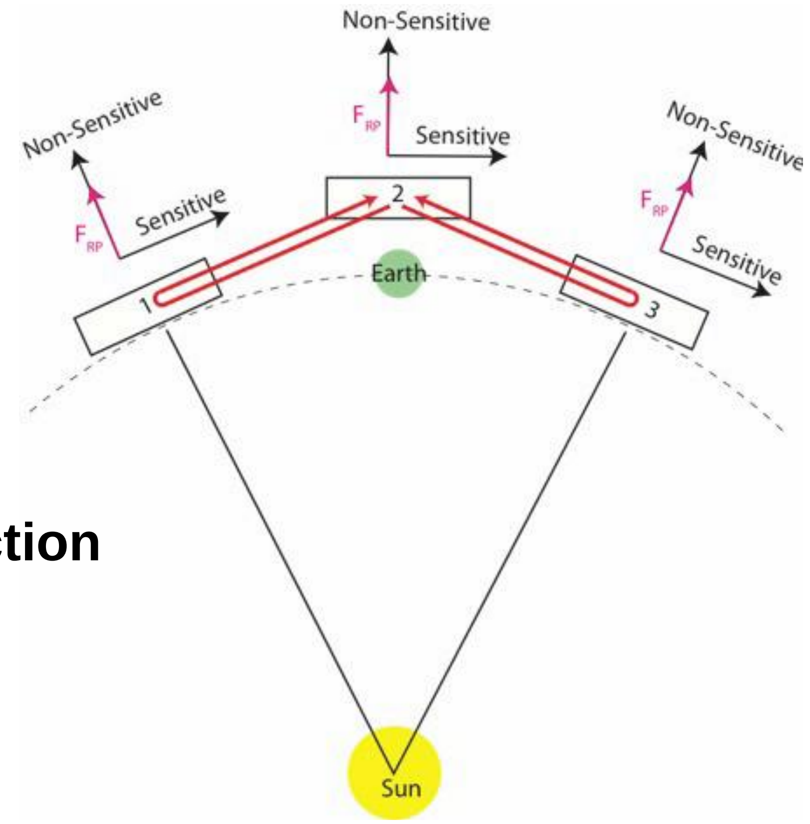
Mission Architecture (1 of 2)

- **The constellation is the instrument: spacecraft are "test masses".**
  - Orbits passively maintain formation (minimal station keeping).
  - Gravitational waves perturb the constellation.
  - Interferometry measures constellation.
- **Interferometer Measurement System (~100pm/√Hz):**
  - 4 one-way interferometer links combined in post-processing to form Michelson Interferometer.
  - Phasemeter records fringe signal.
  - Laser frequency noise correction by pre-stabilization and post processing.
- **Force Measurement System:**
  - The spacecraft are buffeted by solar wind, solar radiation etc.
  - Instruments will measure these disturbances directly.
  - Data sent to ground to remove noise from interferometer signal.



Executive Summary
Mission Architecture (2 of 2)

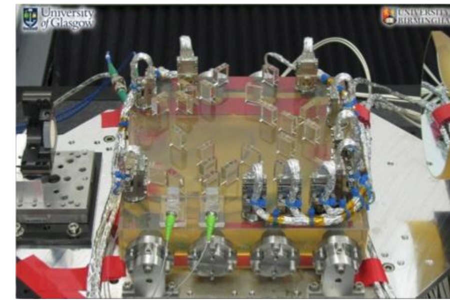
- **Geometric suppression:**
  - Constellation design reduces largest (solar derived) spacecraft disturbances.
- **End spacecraft:**
  - Interferometer links nominally orthogonal to solar forces (+/- 1 degree).
- **Center spacecraft:**
  - Solar forces common to both arms, differenced in Michelson combination.
- **“Relaxed” spacecraft stability requirements in two dimensions:**
  - Factor of 100 reduced sensitivity to difference in thermal radiation of spacecraft sides.
- **Measure force drivers in radial direction and subtract projection of them.**
  - Solar wind fluctuations.
  - Solar radiation fluctuations.



Executive Summary
Interferometer Measurement System

- **Baseline (simplified) LISA IMS - technology is relatively advanced.**
- **Laser: Master (NPRO-Nd:YAG) + power amplifier (2 Watt output).**
- **Telescope: in-line 40cm diameter.**
  - In-field guiding.
  - f/1.5 Cassegrain.

- **One optical bench per spacecraft.**
  - Hydroxy-bonded ULE bench; heritage from LISA pathfinder.



- **Phasemeter and phase measurement chain:**
  - TRL 6 most elements, to be tested GRACE-FO.
  - From 50 phasemeter channels (LISA) to 9 (LAGRANGE).
  - Relaxed sensitivity and fewer measurements.
  - No laser pre-stabilization.

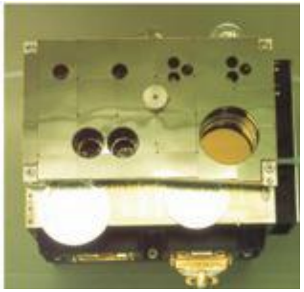
- **Science inter-spacecraft link also supports:**
  - Optical Communications (~20kbs).
  - Optical Raging on carrier (1m precision).
  - USO frequency transfer.

- **Payload Accommodation:**
  - Mass 87.1 kg CBE
    (customer supplied science complement less auxiliary sensors and dummy telescope).
  - Power 121 W CBE (customer supplied science complement less auxiliary sensors).
  - Data Rate 0.1 kbps (1/50 of SGO-High due to fewer channels and reduced sampling rate).
- **Also provides optical communication link between end and middle sciencecraft.**

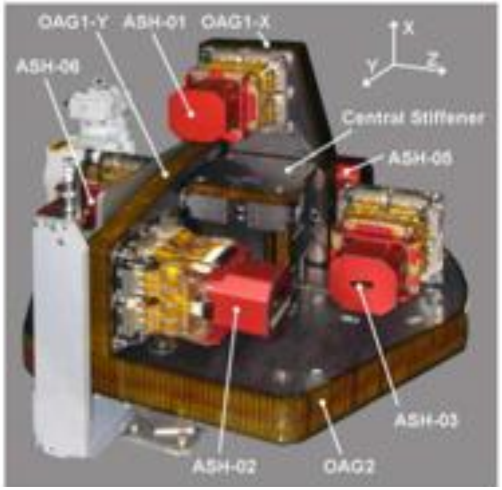
Executive Summary
Force Measurement System

- **Based on flown instruments.**
  - Small modifications required.
  - Technology exists and demonstrated.
  - Assume instruments shown will be used.

1. **Solar wind (particle) monitor (SWEPAM from ACE)**
   - Measure density, velocity of H, He ions in two dimensions.
   - Calculate force to 1%/rtHz.



2. **Radiometer (Solar Irradiance Monitor) (VIRGO from SOHO)**
   - Measure solar variations to 1 part in 10^5/rtHz; Calculate force to 1%/rtHz.

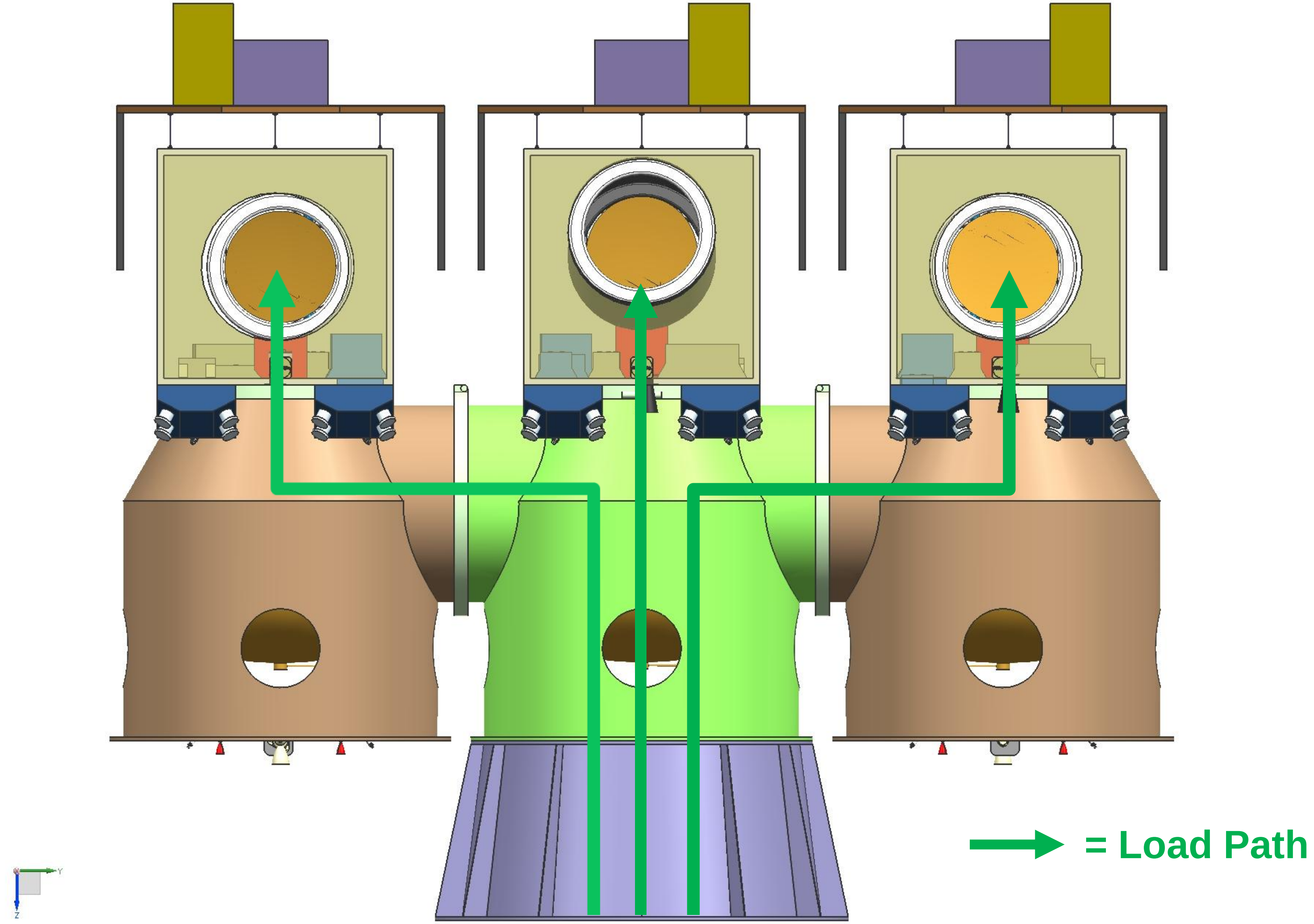


3. **Accelerometer (Electrostatic Gravity Gradiometer (EGG) for GOCE)**
   - For calibration, partial redundancy.
   - Only one axis.

Executive Summary
Instrument Strengths and Weaknesses

- **Strengths:**
  - Low data rates.
  - Smaller telescope than MOLA, HiRISE.
  - Smaller number of elements than some other concepts.
  - Simplified IMS.
- **Opportunities if truly “build to print” / “product line” / “catalog item” context sensors for solar wind/irradiance and/or acceleration are available:**
  - These instruments may be available for only recurring engineering costs.
- **Weaknesses:**
  - Baseline Solar Wind Monitor comes from “spinning” spacecraft; it may not give directional information required to post process the disturbance.
  - Loss of one instrument = loss of the mission.
- **Threats:**
  - JWST (lack of budget for a new $B mission).
  - Comparisons to SIM (Cost/Risk): 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).

Executive Summary
Selected Launch Stack Configuration



Executive Summary
Study Guidelines

- **Contingency added to CBE values:**
  - 53% on mass, to compare masses estimated by MDL at GSFC.
  - 43% on power.
- **30% reserves for development costs.**
- **30% margin on Phase E costs.**
  - As opposed to a nominal 15% that would be carried by Team X.
- **Three sciencecraft separated from three propulsion modules.**
  - Sciencecraft 1 and sciencecraft 3 are identical; each has one telescope.
  - Sciencecraft 2 is as similar to 1 and 3 as possible, but with two telescopes.
- **Propulsion modules 1 and 3 have identical structures.**
- **Propulsion module 2 will carry stack loads while on the launch vehicle and during cruise.**
- **Spacecraft will maintain a constant sun angle normal to the solar arrays.**
- **Selected spares.**

Mass Summary

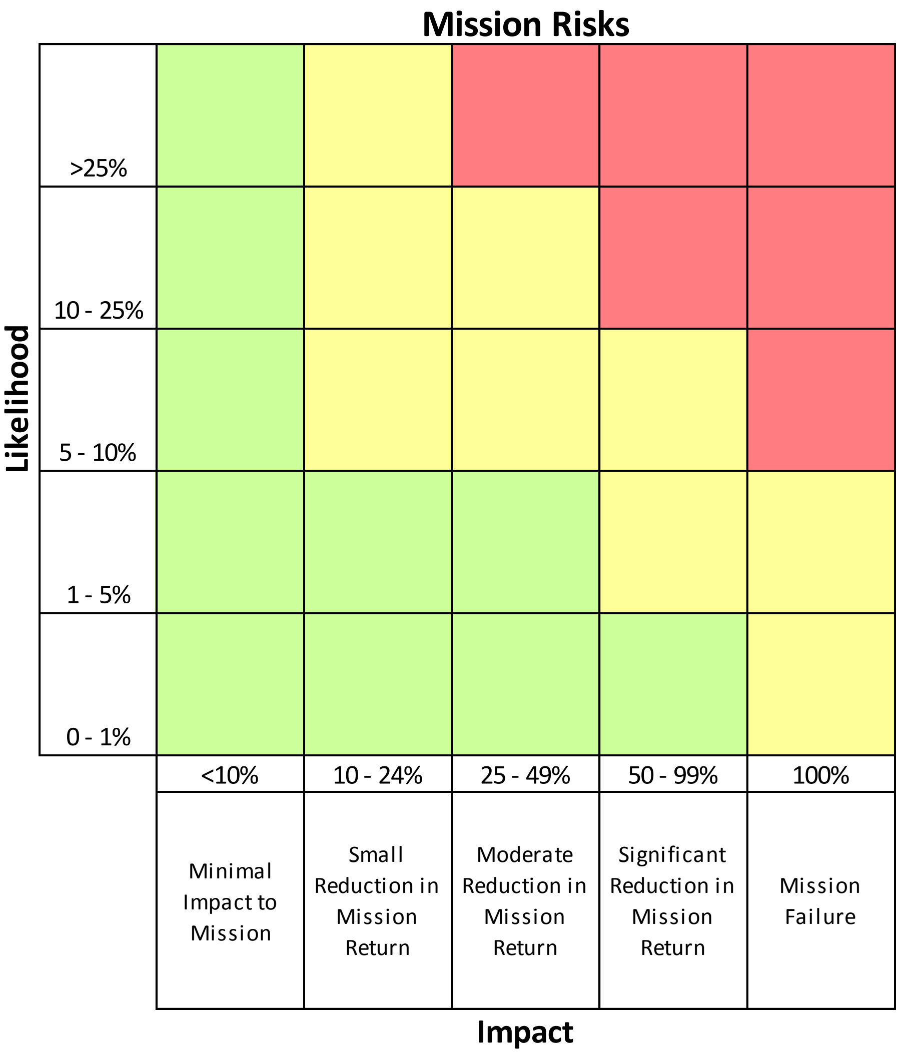
- Stack fits on a NLS-2 L/V.

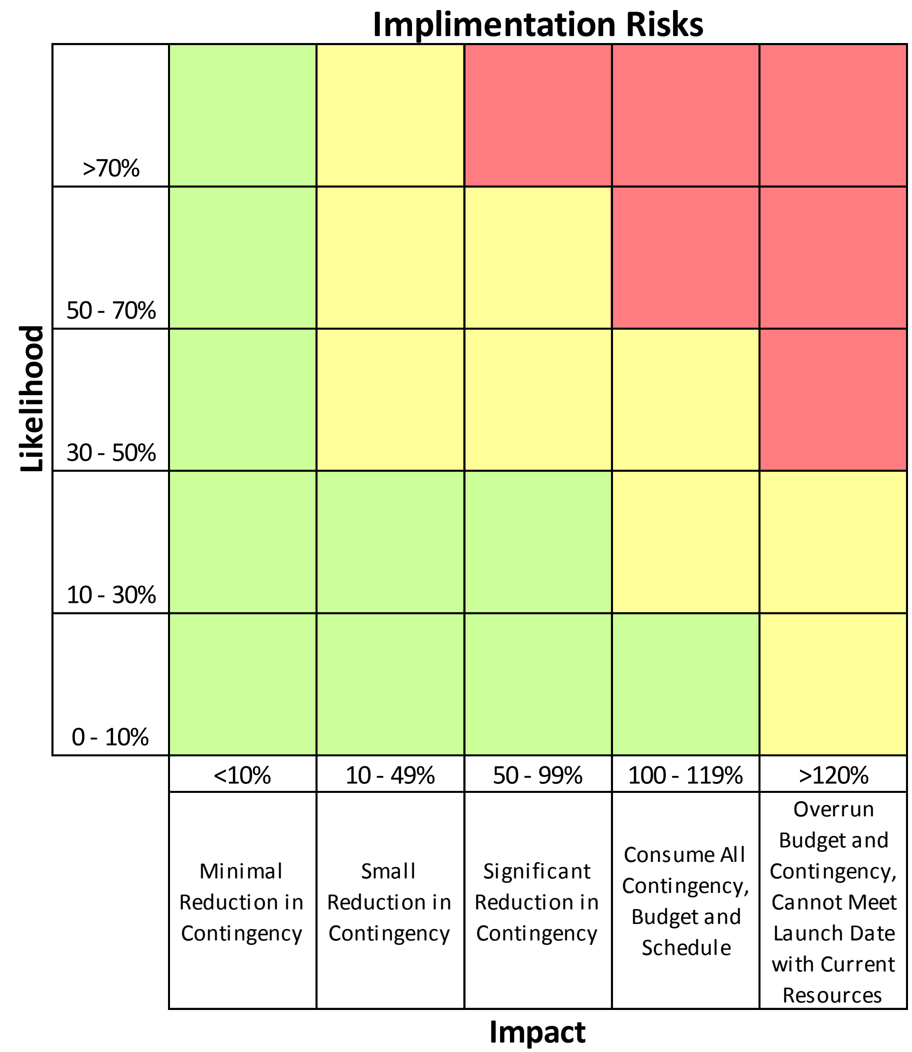
53% contingency already included.

	Mass (kg)	Subsys Contingency %	CBE+ Contingency (kg)
Prop Stage 2 carries the full stack to L2.			
Cruise Craft 1 = Sciencecraft 1 + Prop Stage 1	929.4	0%	929.4
Cruise Craft 3 = Sciencecraft 3 + Prop Stage 3	929.4	0%	929.4
Science Craft 2	586.4	0%	586.4
Carried Elements Total	2445.1	0%	2445.1
Prop Stage 2 Bus			
Attitude Control	0.1	10%	0.1
Propulsion	44.7	7%	47.6
Structures & Mechanisms	289.2	28%	369.6
S/C-Side Adapter	13.3	0%	13.3
Cabling	22.0	30%	28.6
Thermal	17.2	26%	21.6
Bus Total	386.4	24%	480.8
Spacecraft Total (Dry)	2831.5		2925.9
Spacecraft with Contingency	3036		
Propellant & Pressurant1	113.7		
Spacecraft Total (Wet)	3150		
L/V-Side Adapter	32.2		
Launch Mass	3182		
Launch Vehicle Capability	3285	Atlas V 511	
Launch Vehicle Margin	102.8	3%	

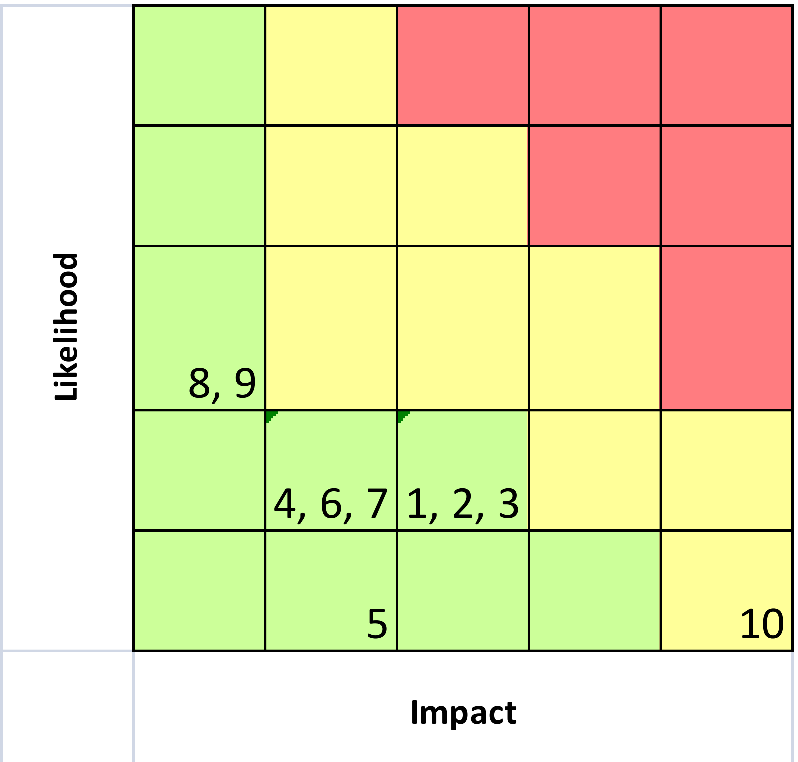
Risk Matrix Definitions

- NASA 5x5 Risk matrix.





System Level Risk Summary – All Options



- **As currently proposed LAGRANGE is relatively low risk for a mission of this scope**
- **There is one medium risk that may potentially affect the science return of the mission:**
  - Failure of a critical component will result in mission failure (10)
- **There are a number of minor risks including:**
  - Event rates for massive black hole binary mergers and extreme-mass-ratio-inspirals (1 & 2)
  - Low TRL photorecievers (4)
  - Star Tracker cost growth and manufacturing (8 & 9)
  - Heritage software algorithms (6)
  - Time critical maneuvers (3)
  - Difficulty measuring external forces (7)
  - Re-qualification of the Colloidal feed system (5)
- **There is also one proposal risks that require special attention when proposing the mission**
  - Inability to “test-as-we-fly” due to large spacecraft architecture

Executive Summary
Medium Risk Items

Risk #	Submitter	Risk Type	Title	Description of Risk	Likelihood	Impact
10	Programmatics/Risk	Mission	Failure of Critical Component	Mission requires all three spacecraft to be operational to make measurements. There is no graceful degredation in science if one of the instrument links are lost. Though the spacecraft and instruments are fully redundant, loss of a critical component aboard any spacecraft will result in mission failure.	1	5

Executive Summary

Minor Risk Items

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	Mission	Sciencecraft 1 and 3 Maneuver Separation	The post L2 insertion maneuvers for Sciencecraft 1 and 3 are only 2 days apart. Since this maneuver may be time critical, sufficient planning and testing for these maneuvers must occur prior to separation. If an anomaly occurs before or during either of the maneuvers, there may be significant additional time required for the Sciencecraft to achieve orbit. Since these orbits are only stable for roughly 2 years without significant orbit maintenance, this additional time may reduce the observing time in orbit.	2	3
4	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
5	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
6	Programmatics/Risk	Implementation	Algorithm / Software Cost Growth	The current cost estimate for the ACS pointing software algorithms assume small changes to extant ACS software, which seems reasonable. However, the Lagrange mission is novel and does not have the heritage of the LISA architecture. New extensions to ACS algorithms may be required as new details about the mission are learned.	2	2
7	Programmatics/Risk	Mission	Difficulty of measuring external forces	Mission success requires measurement of the force on S/C from the solar wind to ~1%. Currently this seems possible, but certainly requires more careful study. Fortunately, degradation in the science would be quite smooth. E.g., if solar-wind force errors are at ~2% level, then low-f noise increases by factor of 2, while high-f noise is practically unaffected. Similarly for noise from radiation pressure.	2	2
8	Programmatics/Risk	Implementation	Star tracker cost growth	Few of the proposed star tracker have been made or flown. The cost is low compared to other commercial vendors, and the current accuracy is about half of what is needed. The proposed manufacturer 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.	3	1
9	Programmatics/Risk	Implementation	Star Tracker Manufacturing Process	The proposed star tracker is a relatively new item for the manufacturer. Few have been made or flown. In addition, the manufacturer is not a typical commercial supplier. Lagrange will require 12 optical heads, 5 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.	3	1

Proposal Risk Items

Risk Type	Title	Description of Risk	Likelihood	Impact
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

Executive Summary –Quad Chart
1280 Lagrange 2012-03

Study Info

Customer Team:
Jeffrey Booth, Ken Anderson, Robin (Tuck) Stebbins, Jeffrey Livas

Study Type: Mission Study

Study Dates: 20, 21, 22 March 2012

Context: 4 sessions, PPT report

Purpose: Design and cost a gravity wave mission. Estimate spacecraft mass and power and the total cost of the mission. Create a risk report.

Key Results

Launch Mass: 3182 kg versus 3285 kg capability.

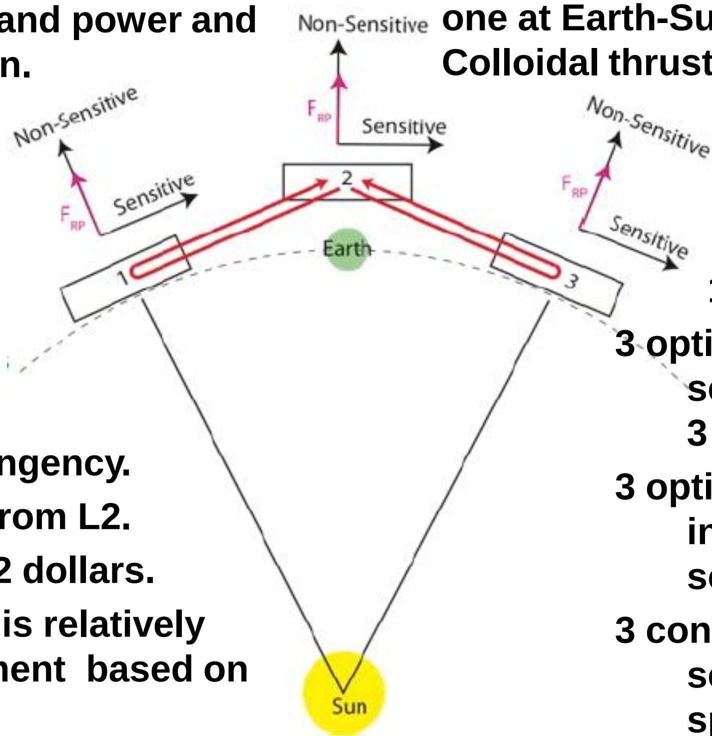
JPL DP Margin: ~35% margin.

Required Sciencecraft Power: 544 W including 43% contingency.

Downlink Data Rate: 28 kbps from L2.

Project Cost: $1.64B in FY2012 dollars.

Technology Needed: IMS tech is relatively advanced; force measurement based on flown instruments.



Mission Summary

Launch Date: 2023 **Launch Vehicle:** NLS-2 contract

Science: First detection of gravity waves from space.

Sciencecraft Instruments: 1-axis accelerometer, solar wind monitor, radiometer, inteferometer measurement system (IMS).

Architecture: One sciencecraft in an Earth leading heliocentric orbit, one in Earth trailing orbit, and one at Earth-Sun L2. Prop stage for each. Colloidal thrusters for attitude control during science ops. Active orbit maintenance only at L2.

Trades

1 System Architecture studied.

3 options to build up the constellation: selected option involves taking 3 spacecraft to L2 first.

3 options to get to L2: selected option involves sciencecraft 2 carrying sciencecrafts 1 and 3.

3 configurations for the launch stack: selected option has the three spacecraft in a horizontal line.

Systems Report

(1280) LaGrange 2012-03
March 20-22, 2012

Author: George Sprague

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Phone: 818-393-1988

Systems
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Customer Overview

- **LAGRANGE borrows heavily from the Laser Interferometer Space Antenna (LISA) aka SGO,**
  - Mature joint NASA/ESA mission (1993-2011).
  - LISA ranked highly for science and technology readiness.
  - Est cost 1.8 Billion USD (FY 2010) for LISA
- **- Many technologies have been demonstrated. Significant documentation**
- **- Differences between LAGRANGE and LISA are to significantly reduce cost and complexity:**
  - - Reduction in science return
  - - Reduced redundancy
  - - Immature concept at this stage

Systems
Customer Overview

- **Advance the LAGRANGE concept into a mission**

  A bare bones mission plan has been developed: Many details lacking. Desire a more complete mission architecture: Launch vehicle and launch strategy; Trajectories; Spacecraft design; Operations; Attitude control.

- **Cost estimate and cost reductions**
  - Grass-roots cost estimate
  - What are the parameters that result in cost savings?

- **• Technology development areas and risk assessment.**

Operational Scenario

- **Mission:**
  - Three science craft
    - One in Earth-Sun L2 lissajous orbit (Sciencecraft 2)
    - One each in a 1 AU heliocentric orbit, 8 deg ahead and behind the Earth (Sciencecraft 1 & 3)
  - Each science craft has a propulsion module to perform maneuvers en route to their positions. The propulsion module will then be disgarded.
  - Launch after October 2022
- **Mission Design**
  - 3 month commissioning phase after the constellation has been established with all spacecraft in position
  - Two year science phase

Assumptions on LAGRANGE

- Assumptions
  - 53% contingency on mass (in order to compare masses assumed by MDL at GSFC)
  - 43% contingency on power and 30% reserves on cost
  - 30% margin on Phase E costs as opposed to a nominal 15%.
  - Three Sciencecraft designed to be separated from three propulsion modules.
  - 2 sciencecraft are identical (1&3). The third sciencecraft is similar as possible but with two telescopes.
  - Propulsion Modules with identical structures on Sciencecraft 1&3
    - Cruisecraft 2 (sciencecraft 2 and propulsion module 2) will carry the loads for cruisecraft 1 & 3)
  - Besides the telescopes and associated measurement system there is a Solar wind (particle) monitor, radiometer (Solar Irradiance Monitor) and an one axis accelerometer.
  - Spacecraft will maintain constant sun angle normal to the solar panel.
  - A policy of selected spares was assumed.

Systems

Design Assumptions – Sciencecraft 1 & 3

Team X Study Guidelines

LaGrange Gravitational Wave Detector Study

Science Craft 1&3

Project - Study

Customer	Ken Anderson
Study Lead	Robert Kinsey
Study Type	Space Physics Study
Report Type	PPT Presentation

Project - Mission

Mission	LaGrange Gravitational Wave Detector Study
Target Body	Sun-Earth system for Science Craft
Science	Gravity Wave Detection
Launch Date	1-Jun-23
Mission Duration	24 months
Mission Risk Class	B
Technology Cutoff	2018
Minimum TRL at End of Phase B	6
Planetary Protection	Outbound: II, Inbound: N/A
Flight System Development Mode	Hybrid

Project - Architecture

Science Craft	on	Propulsion Module
Propulsion Module	on	Launch Vehicle

Trajectory	Trajectory to L2 then earth leading and trailing orbits
L/V Capability, kg	3285 kg to a C3 of -2 with 0% contingency taken out
Tracking Network	DSN
Contingency Method	Apply Total System-Level

Systems

Design Assumptions – Sciencecraft 1 & 3

Spacecraft

Science Craft	Science Craft 1&3
Instruments	IMS,Accelerometers,Solar Wind Monitor,Solar Radiance Monitor,,,,,,,,, etc
Potential Inst-S/C Commonality	None
Redundancy	Dual (Cold)
Stabilization	3-Axis
Heritage	LISA
Radiation Total Dose	21.6 krad behind 100 mil. of Aluminum, with an RDM of 2 added.
Type of Propulsion Systems	Monoprop
Post-Launch Delta-V, m/s	24 m/s
P/L Mass CBE, kg	99.7 kg Payload CBE
P/L Power CBE, W	99.3
P/L Data Rate CBE, kb/s	1000
P/L Pointing, arcsec	1 arcsecs knowledge, 2 arcsecs control
RSDO bus?	NO
Hardware Models	Protoflight S/C, EM Telescope with interferometer

Project - Cost and Schedule

Cost Target	$1116 M
Mission Cost Category	Large - e.g. New Frontiers
FY$ (year)	2012
Include Phase A cost estimate?	Yes
Phase A Start	October 2014
Phase A Duration (months)	15
Phase B Duration (months)	15
Phase C/D Duration (months)	75
Review Dates	PDR - April 2017, CDR - April 2019, ARR - April 2021
Phase E Duration (months)	53
Phase F Duration (months)	24
New Development Tests	On the main instrument
Project Pays Tech Costs from TRL	6
Spares Approach	Selected
Parts Class	Commercial + Military 883B
Launch Site	Eastern Test Range

Systems
Design Summary – Sciencecraft 1 & 3

SYSTEMS WORKSHEET: ***LaGrange Gravitational Wave Detector Study***
Science Craft 1&3

Analyst: George Sprague | Start Date: 3/20/12 | Study Level: 1st point design with placeholders in MEL

Stabilization - cruise	3-Axis		Pointing Direction - cruise	L2	Mission Duration	4.5	years
Stabilization - science	3-Axis		Pointing Direction - science	L2	Max probe sun distance	0	AU
					Instrument Data Rate	1000	kbps (0)
Pointing Control	2	arcsec	Radiation Total Dose, krad	22	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:	Instrument		Technology Cutoff	2018	Return Data Rate	0	kbps

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch	Mode 2 Power (W) Cruise (telecom on)	Mode 3 Power (W) Separation	Mode 4 Power (W) Telecom with Instr	Mode 5 Power (W) Science with Telecom off	Mode 6 Power (W) Safe Load Dumping	Mode 7 Power (W) TBD
Power Mode Duration (hours)					*1*	*24*	*1*	*24*	*24*	*24*	
Payload on this Element											
Instruments	28%	99.8	18%	117.7	0	0	0	99	99	10	0
Payload Total	28%	**99.8**	18%	**117.7**	**0**	**0**	**0**	**99**	**99**	**10**	**0**
Spacecraft Bus			do not edit formulas below this line, use the calcualtions and override tables instead -->								
Attitude Control	1%	4.3	10%	4.8	12	17	17	5	5	12	0
Command & Data	6%	19.5	15%	22.3	39	39	39	39	39	39	0
Power	10%	36.1	30%	46.9	30	28	32	39	36	32	0
Propulsion1	13%	45.6	30%	59.3	0	0	76	76	76	76	0
Structures & Mechanisms	26%	92.5	29%	119.3	0	0	0	0	0	0	0
Cabling	6%	22.8	30%	29.6							
Telecom	1%	4.4	11%	4.9	40	40	40	40	5	40	0
Thermal	8%	28.8	20%	34.4	16	16	16	16	16	16	0
Bus Total		253.9	27%	321.5	138	141	221	215	177	215	0
Thermally Controlled Mass				321.5							
Spacecraft Total (Dry)		353.7	24%	439.2	138	141	221	315	276	225	0
Subsystem Heritage Contingency		85.5	24%	24%							
System Contingency		92.0	26%	26%	59	60	95	135	119	97	0
Spacecraft with Contingency		**531**	of total	w/o addl pld	**197**	**201**	**315**	**450**	**395**	**322**	**0**
Spacecraft Total (Wet)		**531**									
Launch Mass		**531**	Dry Mass for Prop Sizing		531						

Systems
Design Summary – Cruisecraft 1 & 3

SYSTEMS WORKSHEET: *LaGrange Gravitational Wave Detector Study*
Propulsion Module 1&3

Analyst: George Sprague   Start Date: 3/21/12   Study Level:

Stabilization - cruise	3-Axis		Pointing Direction - cruise	Earth
Stabilization - science	3-Axis		Pointing Direction - science	N/A
Pointing Control	1800	arcsec	Radiation Total Dose, krad	11
Pointing Knowledge	900	arcsec	Redundancy	Single
Pointing Stability	10	arcsec/sec		
Determined by:	Science Craft		Technology Cutoff	2018

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch	Mode 2 Power (W) Cruise
Power Mode Duration (hours)					*1*	*24*
Additional Elements Carried by this Element						
Carried Elements Total	78%	531	0	531	0	0
Propulsion Module			do not edit formulas below this line, use the calcualtio			
Attitude Control	0%	0.1	10%	0.1	0	0
Power	0%	0.0	0%	0.0	3	1
Propulsion1	7%	44.7	7%	47.6	36	1
Structures & Mechanisms	12%	82.2	27%	104.8	0	0
Cabling	1%	7.2	30%	9.4		
Thermal	2%	12.3	21%	14.9	29	29
Bus Total		146.5	21%	176.7	68	31
Thermally Controlled Mass				176.7		
Cruise Craft Total (Dry)		677.7	4%	707.9	68	31
Subsystem Heritage Contingency		30.2	4%	21%		
System Contingency		47.5	7%	32%	29	13
Spacecraft with Contingency		**755**	of total	w/o addl pld	**98**	**44**
Propellant & Pressurant1	19%	174.0		For S/C mass =	755.3	
Cruise Craft Total (Wet)		**929**				
Launch Mass		**929**		Dry Mass for Prop Sizing	755	

Systems
Design Summary – Sciencecraft 2

SYSTEMS WORKSHEET: ***LaGrange Gravitational Wave Detector Study***
Science Craft 2 at L2

Analyst: George Sprague | Start Date: 3/21/12 | Study Level: 1st point design with placeholders in MEL

Stabilization - cruise	3-Axis		Pointing Direction - cruise	L2	Mission Duration	4.5	years
Stabilization - science	3-Axis		Pointing Direction - science	L2	Max probe sun distance	0	AU
					Instrument Data Rate	1000	kbps (0)
Pointing Control	2	arcsec	Radiation Total Dose, krad	22	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	2018	Return Data Rate	0	kbps

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch	Mode 2 Power (W) Cruise	Mode 3 Power (W) Separation	Mode 4 Power (W) Telecom with Instrs'	Mode 5 Power (W) Science with Telecom off	Mode 6 Power (W) Safe Load Dumping	Mode 7 Power (W) TBD
Power Mode Duration (hours)					*1*	*24*	*1*	*24*	*24*	*24*	
Payload on this Element											
Instruments	37%	143.3	22%	174.3	0	0	0	160	160	16	0
Payload Total	37%	**143.3**	22%	**174.3**	**0**	**0**	**0**	**160**	**160**	**16**	**0**
Spacecraft Bus		do not edit formulas below this line, use the calcualtions and override tables instead –>									
Attitude Control	1%	4.3	10%	4.8	12	17	17	5	5	12	0
Command & Data	5%	19.5	15%	22.3	39	39	39	39	39	39	0
Power	9%	36.8	30%	47.8	27	25	32	44	41	32	0
Propulsion1	12%	45.9	30%	59.7	0	0	76	76	76	76	0
Structures & Mechanisms	23%	89.3	29%	115.2	0	0	0	0	0	0	0
Cabling	5%	20.6	30%	26.7							
Telecom	1%	4.3	10%	4.7	0	0	40	40	5	40	0
Thermal	7%	28.7	20%	34.3	16	16	16	16	16	16	16
Bus Total		249.3	27%	315.5	94	97	220	221	182	216	16
Thermally Controlled Mass				315.5							
Spacecraft Total (Dry)		392.6	25%	489.8	94	97	220	380	342	232	16
Subsystem Heritage Contingency		97.1	25%	25%							
System Contingency		96.6	25%	25%	40	42	95	163	147	100	7
Spacecraft with Contingency		**586.4**	of total	w/o addl pld	**134**	**138**	**315**	**544**	**489**	**331**	**23**
Launch Mass		**586.4**	Dry Mass for Prop Sizing		586						

Systems

Design Summary – Cruisecraft 2 + Total

SYSTEMS WORKSHEET: *LaGrange Gravitational Wave Detector Study*
Propulsion Module 2

Analyst: George Sprague Start Date: 3/21/12 Study Level:

Stabilization - cruise	3-Axis	Pointing Direction - cruise	L2
Stabilization - science	3-Axis	Pointing Direction - science	N/A
Pointing Control	1800 arcsec	Radiation Total Dose, krad	3
Pointing Knowledge	900 arcsec	Redundancy	Single
Pointing Stability	0 arcsec/sec		
Determined by:	Science Craft	Technology Cutoff	2018

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Launch	Mode 2 Power (W) Cruise
Power Mode Duration (hours)					*1*	*24*
Additional Elements Carried by this Element						
Cruise Craft 1	33%	929.4	0%	929.4		
Cruise Craft 3	33%	929.4	0%	929.4		
Science Craft 2	21%	586.4	0%	586.4		
Carried Elements Total	86%	**2445.1**	0%	**2445.1**	**0**	**0**
Spacecraft Bus			do not edit formulas below this line, use the calcualtic			
Attitude Control	0%	0.1	10%	0.1	0	0
Power	0%	0.0	0%	0.0	3	1
Propulsion1	2%	44.7	7%	47.6	36	1
Structures & Mechanisms	10%	289.2	28%	369.5	0	0
S/C-Side Adapter	0%	13.3	0%	13.3		
Cabling	1%	22.0	30%	28.5		
Thermal	1%	17.2	26%	21.6	29	29
Bus Total		386.3	24%	480.7	68	31
Thermally Controlled Mass				480.7		
Spacecraft Total (Dry)		2831.4	3%	2925.8	68	31
Subsystem Heritage Contingency		94.4	3%	24%		
System Contingency		110.4	4%	29%	29	13
Spacecraft with Contingency		**3036**	of total	w/o addl pld	**98**	**44**
Propellant & Pressurant1	4%	113.7		For S/C mass =	3285.0	De
Spacecraft Total (Wet)		**3150**				
L/V-Side Adapter		32.2		Wet Mass for Prop Sizing	3285	
Launch Mass		**3182**		Dry Mass for Prop Sizing	3036	
Launch Vehicle Capability		**3285**	NLS-2 Contract			Missior
Launch Vehicle Margin		**103.0**	3%			

Systems
Power Modes – LaGrange

Power Mode	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Name	Launch	Cruise	Separation	Telecom with Instrs.	Science with Telecom off	Safe Load Dumping
Duration (hrs)	1	24	1	24	24	24

- **The power modes are coordinated between the propulsion modules and sciencecrafts because all power comes from the sciencecrafts.**
- **Launch until light is on the array is nominally to last 1 hour. During that time, telecom is transmitting from science craft 1 or 3 on battery.**
- **Cruise is 24 hours with Science craft 1 or 3 always transmitting.**
- **Separation is nominally an hour with telecomm transmitting**
- **Telecommunications with instruments calibrating has a multiple of 24 hour periods.**
- **Science with telecomm off is the nominal mode 24 hrs/day**
- **Several levels of safe mode are forecasted with load dumping as the last line of defense because of thermal considerations in cycling the instruments.**

Systems
Additional Comments – Mass Margins

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

	LV capability (kg)	Propellant mass (kg)	Science-craft dry mass CBE (kg)	Propulsion module mass CBE (Kg)	Wet Mass with Conting. (Kg)	JPL Design Principles margin (%)	LV Margin (kg)	LV Margin (%)
LaGrange	3285	174 174 113.7	373.7 373.7 392.6	146.5 146.5 386.4	929 929 3182 (all up)	35% before L/V margin	102.8	2%

Conclusions

- **From the aspect of the mission, the Lagrange design closes.**
  - The three cruisecrafts (3 sciencecraft + 3 propulsion modules) fit comfortably on an smaller Launch Vehicle in a side by side configuration.
  - Propulsion Module 2 takes all three cruisecraft to L2.
- **Strengths**
  - Low data rates with a smaller telescopes than MOLA, HiRISE
  - Smaller number of elements than some other concepts and simplified inertial measurement system (IMS.)
  - Simple mission operations.
  - Simple mission with a very efficient mechanical configuration.
  - Needs less capable Launch Vehicle.
  - Shorter mission
- **Weaknesses**
  - Loss of one instrument puts the entire mission at risk.

Conclusions

- **Instrument layout based on two main components IMS and FMS**
  - IMS (Inertial measurement system)
    - Baseline (simplified) LISA IMS - technology is relatively advanced
    - Laser: Master (NPRO-Nd:YAG) + power amplifier (2 Watt output)
    - Telescope: in-line 40cm diameter with one optical bench per spacecraft
    - Phasemeter and phase measurement chain
      - From 50 phasemeter channels (LISA) to 9 (LAGRANGE)
    - Science inter-spacecraft link also supports :
      - Optical Communications (~20kbs), Optical Raging on carrier (1m precision) and USO frequency transfer
- **Force Measurement System (FMS) based on flown instruments**
  - 1) Solar wind (particle) monitor (SWEPAM from ACE)
  - 2) Radiometer (Solar Irradiance Monitor) (VIRGO from SOHO)
  - 3) Accelerometer (Electrostatic Gravity Gradiometer (EGG) for GOCE)
- **Main Difference between LISA concept and LAGRANGE**
  - Spacecraft does not fly drag free around proof masses. LAGANGE measures **distance between spacecraft** as opposed to distance between the proof masses.
- **Spacecraft noise is reduced through:**
  - 1) Geometry (factor of 100), 2) Calibration (factor of 100)
  - The interferometry precision is relaxed compared with LISA (by 4-16 times)

Conclusions

- **Mission: The entire stack to L2 (6 mos), then use lunar flybys and maneuvers to move SC-1 and SC-3 to their stations.**
  - 27 months for both SC-1 and SC-3.
  - 460 and 300 m/s after departure from L2 for SC-1 and SC-3, respectively
- **ACS:** Nearly equivalent ACS requirements and components for Lagrange as for SGO.
- **C&DH: the C&DH for all three spacecraft are identical**
  - The science crafts have an identical dual string C&DH (cold sparing)
- **Propulsion**
  - Science spacecraft colloidal propulsion system provides low jitter station keeping for mission duration for all sciencecraft, and sciencecraft 2 colloid system also provides 10 m/s/year delta-v for Lissajous maintenance
  - The Propulsion Stage optimized design for low cost permitted a simple blowdown monopropellant system for all three spacecraft for insertion into target locations.
- **Telecom system description**
  - Telecom is a single string S-band system on both types of sciencecraft and each vehicle will have two S-Band patch LGAs.

Conclusions

- **Of primary interest in saving mass, propulsion modules 1 and 3 are the primary load paths for their carried sciencecraft. The load path is through propulsion module 2 down to the launch vehicle including sciencecraft 2.**
  - Upon arrival at L2, the Propulsion Modules attached to Sciencecraft 1 and 3 will be deployed from Propulsion Module 2 along with their carried Sciencecraft
  - A softride system is recommended for the entire stack to minimized any risk to the telescope optics.
- **Power: Single array design, battery and electronics for all three science craft.**
- **Thermal: All sciencecraft will maintain constant sun angle normal to the solar panel.**
  - There will nonetheless be thermal variations due to the sun, even over relatively short times scales (e.g., 20 minutes).
  - Requires active and passive balancing of time varying temperatures and temperature gradients.

Systems
Risks for LAGRANGE

- **As currently proposed LAGRANGE is a relatively low risk mission for a mission of this scope**
- **There is one medium risk that may potentially affect the science return of the mission:**
  - Failure of a critical component will result in mission failure (10)
- **There are a number of minor risks including:**
  - Event rates for massive black hole binary mergers and extreme-mass-ratio-inspirals (1 & 2)
  - Low TRL photoreceivers (4)
  - Star Tracker cost growth and manufacturing (8 & 9)
  - Heritage software algorithms (6)
  - Time critical maneuvers (3)
  - Difficulty measuring external forces (7)
  - Re-qualification of the Colloidal feed system (5)
- **There is also one proposal risks that require special attention when proposing the mission**
  - Inability to “test-as-we-fly” due to large spacecraft architecture

Instruments Report

(1280) LaGrange 2012-03
March 20-22, 2012

Author: Alfred E Nash
Email: Alfred.E.Nash@JPL.NASA.Gov
Phone: X 3-2639

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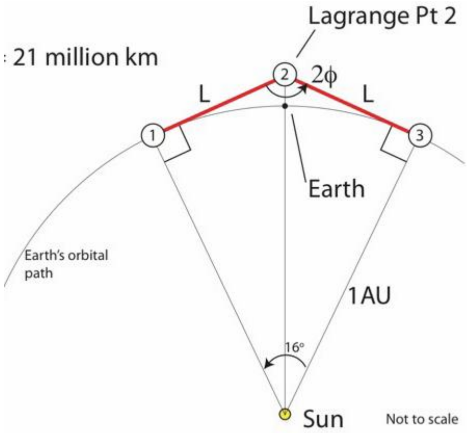
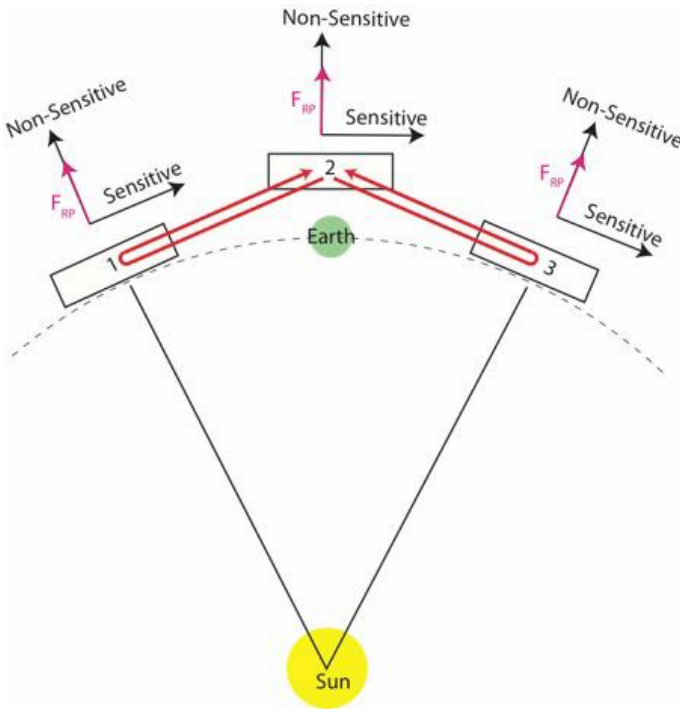
Instruments
Design Requirements



- **Mission:**
  - 3 S/C: 1 @ L2, 1 Earth Trailing, 1 Earth Leading
- **Constraints**
  - Continuous observations
- **Measurement**
  - Interferometric Interspacecraft Distance
- **Spacecraft in "middle" (Sciencecraft2) has two telescopes and associated instrumentation, spacecraft at ends (Sciencecraft1) has one "active" telescope and associated instrumentation, and one "dummy" telescope.**

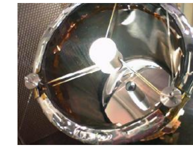
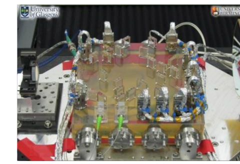
Design Assumptions

- **List Assumptions made for the Design**
  - Design from Customer MEL



- Rough Mission Timeline
- • 18-24 months to reach formation:
- - Luna flyby after launch
- - 6 months for S/C 2 to reach L2
- - Another 12-18 months for S/C 1 & S/C 3 to reach initial positions
- • Optical link acquisition and commissioning (2 months)
- • 2 years science operation
- - Formation decays over 2 years,
- - Doppler shifts increase:
- - Geometric suppression degrades

Instruments
Design – Interferometer Measurement System

- **Baseline (simplified) LISA IMS - technology is relatively advanced**
- **Laser: Master (NPRO-Nd:YAG) + power amplifier (2 Watt output)**
- **Telescope: in-line 40cm diameter**
  - In-field guiding
  - f/1.5 Cassegrain
- **One optical bench per spacecraft**
  - Hydroxy-bonded ULE bench:heritage from
  - LISA pathfinder
- **Phasemeter and phase measurement chain**
  - TRL 6 most elements, to be tested GRACE-FO
  - From 50 phasemeter channels (LISA) to 9 (LAGRANGE)
  - Relaxed sensitivity and fewer measurements
  - No laser prestabilization
- **Science inter-spacecraft link also supports :**
  - Optical Communications (~20kbs)
  - Optical Raging on carrier (1m precision)
  - USO frequency transfer
- **Payload Accommodation**
  - Mass 87.1 kg CBE (Customer supplied Science Complement less Auxillary sensors & dummy telescope)
  - Power 121 W CBE (Customer supplied Science Complement less Auxillary sensors)
  - Data Rate 0.1 kbps (1/50 of SGO-High due to fewer channels and reduced sampling rate)
- **Also provides optical communication link between sciencecraft1s (ends) and sciencecraft2 (middle)**

Design – Force Measurement System

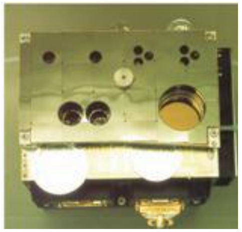
Based on flown instruments

- Small modifications required:
- Technology exists and demonstrated
- Assume instruments shown will be used

1) Solar wind (particle) monitor (SWEPAM from ACE)

- Measure density, velocity of H, He ions in two dimensions
- Calculate force to 1%/rtHz
- Mass 3 kg CBE Customer Supplied Number – NSSDC reports 6.6 kg
- Power 3 W CBE Customer Supplied Number – NSSDC reports 5.5 W
- Data Rate 1 bps (NSSDC)

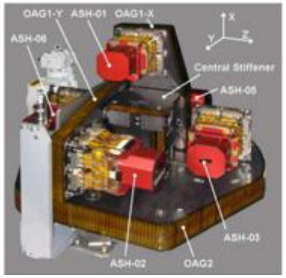
2) Radiometer (Solar Irradiance Monitor) (VIRGO from SOHO)



- Measure solar variations to 1 part in 10^5/rtHz
- Calculate force to 1%/rtHz
- Mass 20 kg CBE Customer Supplied Number (13 kg according to VIRGO: Experiment for helioseismology and solar irradiance ... www.springerlink.com/index/r25x828l7354m042.pdf by C Fröhlich - 1995)
- Power 20 W CBE Customer Supplied Number (Power supplied It is designed for a maximum output power of 9.3 W and has an efficiency of 69% (13.5W) according to VIRGO: Experiment for helioseismology and solar irradiance ... www.springerlink.com/index/r25x828l7354m042.pdf by C Fröhlich - 1995)
- Data Rate 0.1 kbps (source)

3) Accelerometer (Electrostatic Gravity Gradiometer (EGG) for GOCE)

- for calibration, partial redundancy
- Only one axis
- Mass 30 kg CBE Customer Supplied Number
- Power 20 W CBE Customer Supplied Number
- Data Rate 0.3 kbps (1 kps from GOCE Requirements document / one axis vs 3)
- Mark R. Drinkwater, R. Haagmans, D. Muzi, A. Popescu, R. Floberghagen, M. Kern and M. Fehringer, The GOCE Gravity Mission: ESA's First Core Earth Explorer, Proceedings of 3rd International GOCE User Workshop, 6-8 November, 2006, Frascati, Italy, ESA SP-627, ISBN 92-9092-938-3, pp.1-8, 2007, states, "The EGG assembly has a mass of 180 kg and requires up to 100 W of electric power.)



Design – subsystems being carried by other chairs

- **The dummy telescope mass and cost for sciencecraft1 is carried by the mechanical chair for purposes of more accurate costing**

Instruments
Cost

- **Cost Assumptions**
  - No contributions assumed.
  - Second unit savings assumed across all three spacecraft

- **Cost Method**
  - NASA Instrument Cost Model (NICM) – System Mode
    Recurring costs for all three spacecraft summed correctly on cost sheets – NRE not "triple counted")

Cost Drivers

- Some “model” penalty for breaking one instrument (Science Compliment=IMS+GRS) into “self contained” instruments (Payload = IMS + Accelerometer + Solar Wind Monitors + Solar Radiance Monitors), but IMS simplified from SGO concepts (and is cheaper).

Potential Cost Savings

- None noted.

Potential Cost Uppers

- “build to print” assumption for Accelerometers and Solar Radiance Monitor may break down
  - In particular, assumption that only a one axis “module” of the EGG on GOCE can be used as is should be confirmed.

Design Analysis and Risk

- **Strengths**
  - Low data rates
  - Smaller telescope than MOLA, HiRISE
  - Smaller number of elements than some other concepts
  - Simplified IMS
- **Opportunities**
  - If truly “build to print” / “product line” / “catalog item” context sensors for solar wind/irradiance and/or acceleration, are truly available, then these instruments may be available for only recurring engineering costs (i.e., the Non-Recurring Engineering costs have already been incurred by a prior project and the supplier can pass the savings of only repeating the build and test of the design on to the customer).
- **Weaknesses**
  - Baselined Solar Wind Monitor comes from “spinning” spacecraft – may not give directional information required to post process disturbance.
  - Loss of one instrument = loss of mission.
- **Threats**
  - JWST (lack of budget for a $B mission)
  - Comparisons to SIM (Co$t/Risk)
    - 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)

Science Report

(1280) LaGrange 2012-03
March 20-22, 2012

Author: Curt Cutler

Email: cjcutler@jpl.nasa.gov

Phone:818-393-3251

STATUS: Ready

Science
Cost Summary

Total Science cost is $45.6M, including $18M for Guest Observer Program. Science Cost for Lagrange is almost identical to that for SGO-Mid, since the work involved is almost the same.

Table of Contents

Science Goals & Implementation

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

Sources include: ~1e4 Galactic WD binaries; ~1-100 Merging Massive Black Hole binaries, with ~half of them having SNR>100 (and hence allow good tests of general relativity predicts for the strong-field merger); and of order ~100 inspirals of stellar-mass compact objects in Massive Black Holes, out z~0.2.

- **Implementation – based to zeroth order on former "LISA" mission, but with significant changes with aim of reducing cost:**

a) Not drag free; instead reduced influence of external forces by factor ~100 by orbital geometry, another factor ~100 by *measuring* solar wind and radiation pressure and taking them out in the data analysis

b) Different geometry, with S/C 2 at Lagrange pt.

c) Only 4 arms, so i) measure only 1 polarization, and ii) significantly degrade ability to detect a stochastic gravitational-wave (GW) background, since it will be much harder to distinguish between a GW backgrd and unmodelled instrumental noise).

Science
Design Assumptions

Instrument

- Complex
- The "instrument" is the entire constellation, including gravitational reference sensors and laser metrology.
- The main science data is a time-series of a synthesized Michelson signal (with "TDI" delays added in software), which effectively cancel laser phase noise.

Operations

- Operations are extremely simple. There is no pointing, since the observatory has all-sky sensitivity. Data is taken continuously. All communication with the ground is via the middle (vertex) S/C. The constellation generates 3.3 kb/s (of which 3.0 kb/s are housekeeping), and downloads the data to the DSN in 5-hour intervals every 2 days. Therefore the download bit rate has to be (48/5) x the data collection rate, or ~32 kb/s.
- 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

- Lagrange 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 output data streams. Thus the searches for the different source types have to be closely coordinated. A "Guest Observer" program is highly useful for coordinating extracting the science; e.g., for looking for optical counterparts to GW events or using results to test alternative theories of gravity.

Science
Cost Assumptions

- 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 Science team receives level-0 data and produces 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 data set is ~ 25 GByte (~90% of which is housekeeping data).
- 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.

Cost

- **Cost Drivers—only ways to significantly decrease/increase science cost is to decrease/increase mission data-taking lifetime, or eliminate Guest Observer Program.**
- **Potential Cost Uppers**
  - Unexpected systematics that must be “fitted out” (ala GP-B) could significantly complicate and stretch out the data analysis. E.g., one can imagine that measuring and subtracting out the acceleration from the solar wind reveals unexpected complications.

Risk

- **List of Risks**

  1) Event rates and/or number densities in Nature are significantly lower than estimated, for one or two of the source types.

  2) The GW measurement relies on being able to accurately measure the force on the S/C's from radiation and solar wind (so that one can subtract it out). This is a relatively new idea, and it could end up being significantly more difficult than early estimates suggest to attain the required accuracy.

Mission Design Report

(1280) LaGrange 2012-03
March 20-22, 2012

Mark S Wallace

mark.s.wallace@jpl.nasa.gov

x4-4236

Significant Trajectory work by Min-Kun Chung and Ted Sweetser

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Design Requirements

- **Mission:**
  - Three science craft
    - One in Earth-Sun L2 lissajous orbit
    - One each in a 1 AU heliocentric orbit, 8 deg ahead and behind the Earth
  - Each science craft has a sacrificial propulsion module to perform maneuvers en route to their positions
  - Launch after October 2022
- **Mission Design**
  - 3 month commissioning phase after the constellation has been established with all spacecraft in position
  - Two year science phase in the constellation
- **Launch Vehicle**
  - Desire cheapest consistent with requirements

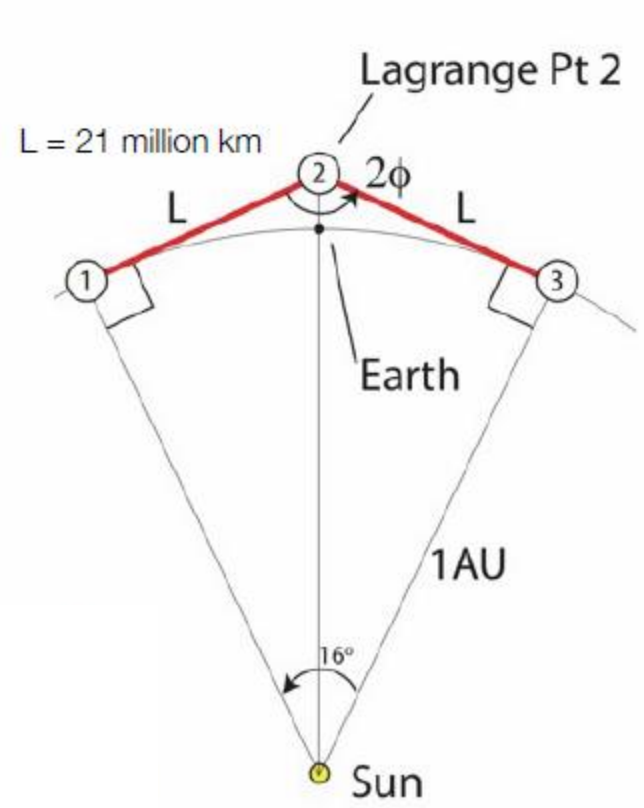


Image from customer

Design Assumptions

- **This design is a piece-wise design by analogy and it is assumed that we can put together an end-to-end trajectory without greatly changing the timelines and delta-v requirements**
- **Delta-V assumptions**
  - 120 m/s is a good assumption for a the DV required to achieve an L2 lissajous orbit with a lunar flyby. This requires phasing loops to build a launch period, which was unacceptable to the customer team. It is potentially possible to use a low-energy trajectory to set up that lunar flyby a la GRAIL. GRAIL allocated 40 m/s for its trans-lunar cruise (TLC). We assume:
    - That we can indeed do this
    - 60 m/s for the TLC and lissajous orbit insertion is adequate and conservative
  - 10 m/s/yr to maintain a lissajous orbit is a standard assumption
- **The SC-1 and SC-3 arrivals at the 8 deg point can be biased such that they spend 27 months near the designated point, after which they depart under the influence of Earth's gravity. This is assumed to be acceptable and can thus eliminate 30 m/s/yr of maintenance at this point.**
- **The SC-1 and SC-3 trajectories were developed for a Jan 2012 departure from the lissajous. I assumed that they were the same for a Jan 2023 departure.**

Mission Design

Design: Timeline and Delta V Budget

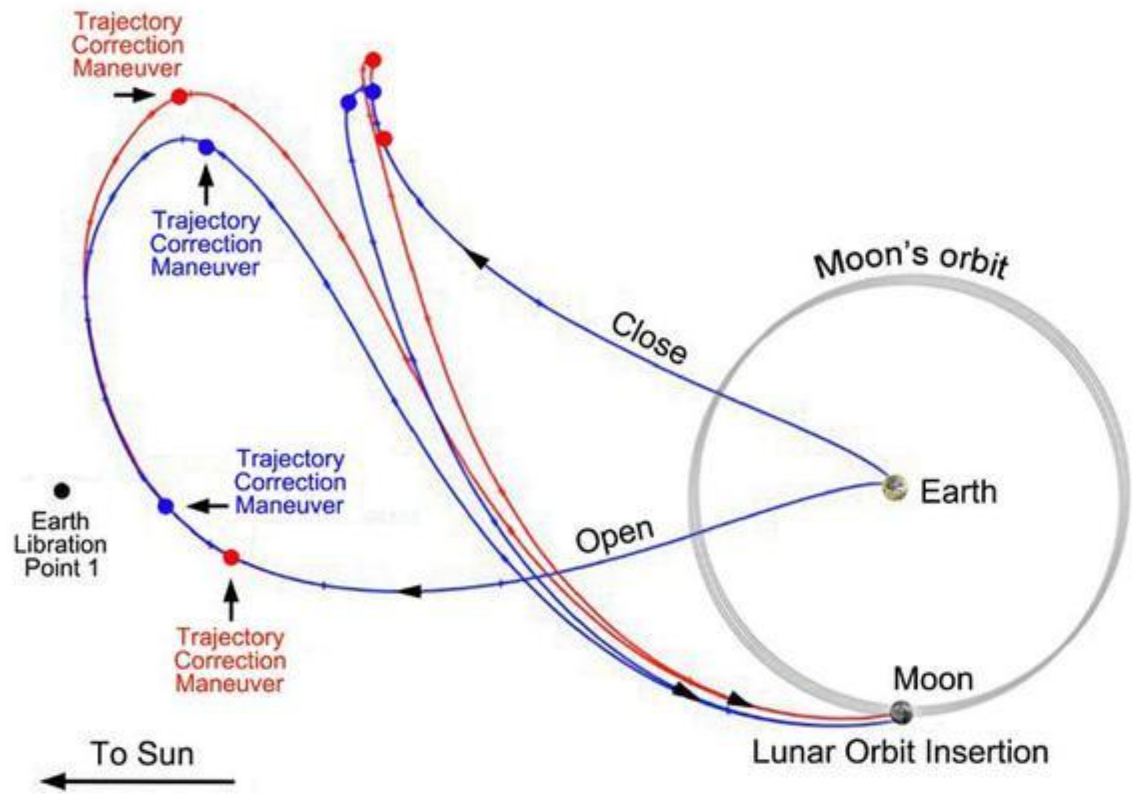
Event / Phase	Duration/Time	Delta V	# Maneuvers
GRAIL-like low energy trajectory to set up a lunar flyby en route to establishing a small L2 lissajous	Launch to L+6 mo.	60 m/s, including TCMs	3-5 on Prop-2
L2 staging orbit, with all three spacecraft attached	L+6 mo to L+8 mo	2 m/s	~2 on Prop-2
SC-1 and SC-3 separate from SC-2	L+8 mo		
SC-1 and SC-3 depart L2 on the 1st and 3rd of January, 2024	L+9 mo	0.5 m/s	1 on Prop-1 and -3
SC-1 inbound Lunar flyby: 9 Jul 2024	L+15 mo	20 m/s are allocated for cruise TCMs on SC-1 and SC-3.	
SC-3 outbound Lunar flyby: 24 Aug 2024	L+16 mo		
SC-1 heliocentric shaping burn: 18 Sep 2024	L+17 mo	181 m/s	1 on Prop-1
SC-3 heliocentric shaping burn: 6 Mar 2025	L+ 22 mo	103 m/s	1 on Prop-3
SC-1 parking burn: 27 Jun 2025	L + 27 mo	239 m/s	1 on Prop-3
SC-3 parking burn: 4 Aug 2025	L + 27 mo	176 m/s	1 on Prop-3
SC-2 maintenance of L2 lissajous during SC-1/3 cruise	L+8 mo to L+27 mo	18 m/s	~18 on Prop-2
Propulsion Modules separate from Science Craft	L+27 mo.		
Constellation Commissioning	L+27 mo to L+29 mo.		
Science	L+29 mo to L+53 mo		
SC-2 maintenance of L2 lissajous during Commissioning & Science	L+27 mo to L+53 mo	23 m/s	Many on colloidal thrusters

- **Propulsion Module-1**
  - Science Craft 1 only: 460.5 m/s
- **Propulsion Module-2**
  - Entire stack: 62 m/s
  - Science Craft 2 only: 18 m/s
- **Propulsion Module-3**
  - Science Craft 3 only: 299.5 m/s
- **Science Craft 2:**
  - 23 m/s on colloidal thrusters
- **No DV on Science Craft 1 or 3**

Mission Design

Design: Stack and SC-2

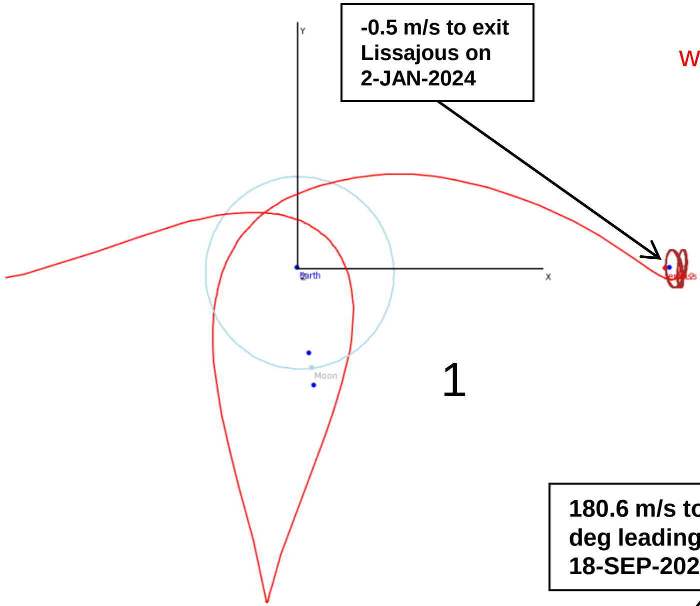
- **After launch, the entire stack flies under SC-2's control to the L2 Lissajous Orbit**
- **Uses a low energy trajectory to lunar flyby similar to GRAIL's trajectory to lunar orbit insertion**
  - 60 m/s allocated
- **L2 lissajous:**
  - 25000 km out-of-plane amplitude
  - 75000 km cross-track amplitude

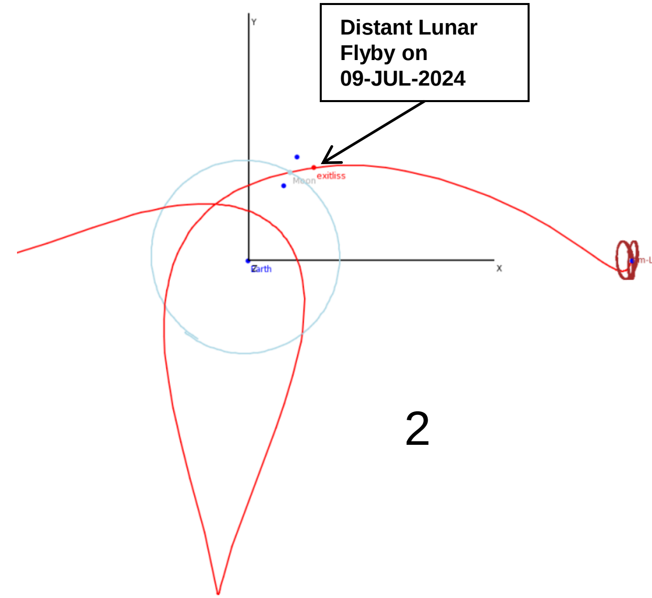


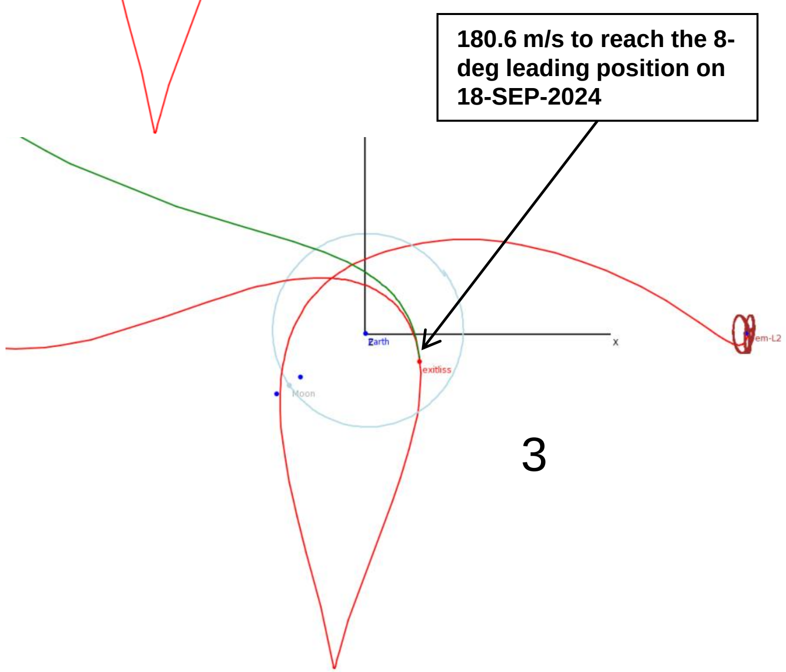
GRAIL Trans-Lunar Cruise Trajectory:
Earth and Moon sizes not to scale

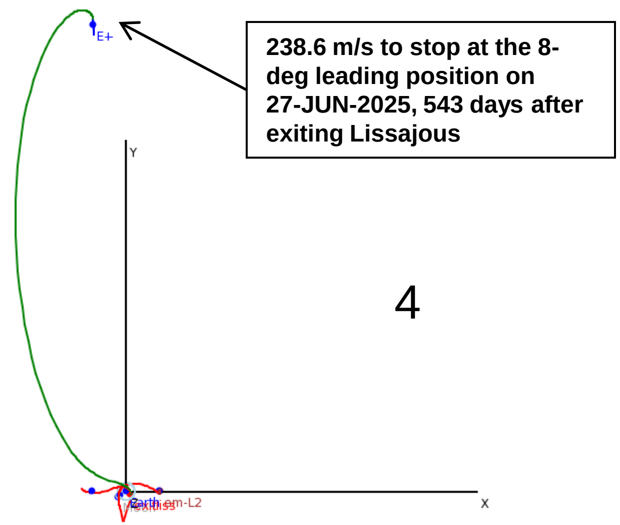
Mission Design
Design: SC-1

by Min-Kun Chung
with different years by Mark Wallace





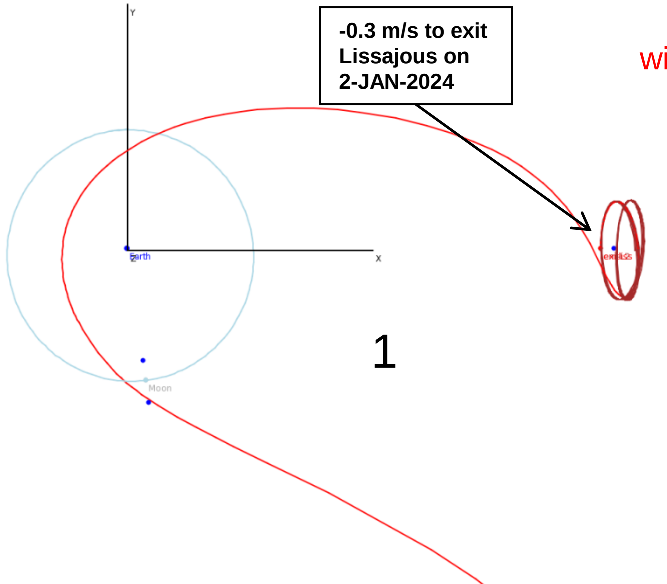


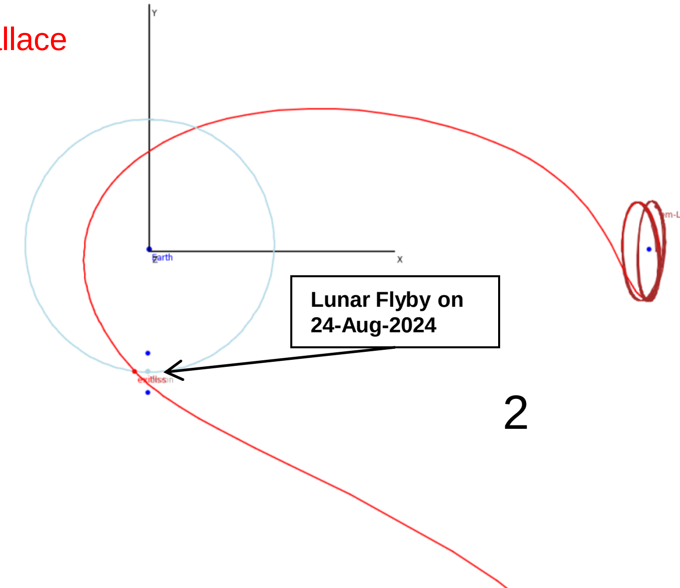


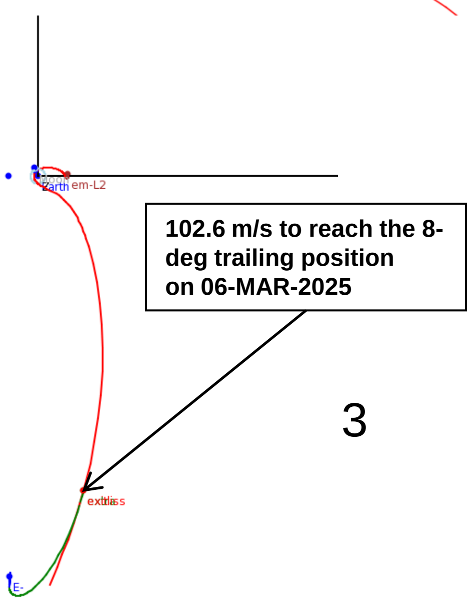
Mission Design

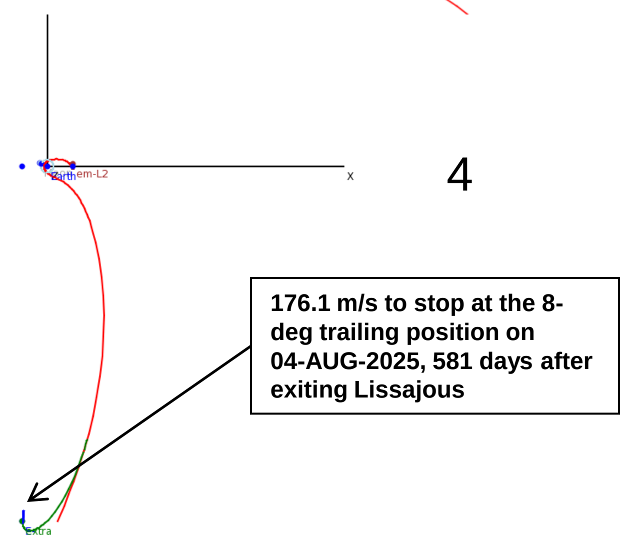
Design: SC-3

by Min-Kun Chung
with different years by Mark Wallace









Design: LV

- **GRAIL required a -0.3 km2/s2 launch C3. We assumed that LAGRANGE requires the same C3.**
- **The launch vehicle selected was the smallest vehicle that met the fairing size requirements and throw capability.**

Parameter	Value	Unit
Launch Vehicle	NLS – 2 Contract	
Fairing Diameter	4.57	m
C3	-0.3	km^2/s^2
Fairing Length	5.10	m
Performance Mass	3285	kg

Cost

- **Cost Assumptions**
  - All costs are FY2011
  - Costs include MDN/SAS service center
- **The model, which is generally very good, was not built to cost spacecraft multiple spacecraft doing different things.**
  - It can, however, cost mulitple spacecraft doing the same thing, e.g MER, GRACE, and GRAIL.
  - I modeled the mission as three spacecraft doing an SC-1 trajectory with an over-ride to force the design of the science lissajous and its maintenance during operations

Mission Design
Cost

- **Cost Drivers**
  - The long cruise time before the science phase begins is a major driver
  - The different spacecraft doing different things is a driver.

- **Potential Cost Savings/Uppers**
  - The modeling issues described in the previous slide potentially:
    - Over-estimates the ops costs of the transfer to L2 (we don't have three separate spacecraft to navigate)
    - Under-estimates:
      - The design effort of coordinating the timing of all three trajectories with the very different transfers.
      - The ops costs of navigating in two different dynamical environments (lissajous vs. heliocentric orbit)
    - This may be a wash
  - As the cost model author, I attempted a re-write of the model to attempt to model the mission more accurately, but I was getting a large spread of costs depending on how I tried to apply the multiple-spacecraft modifiers in ways they weren't intended for and I decided to use the original estimate
    - Low end: 14% reduction in ops + 6% increase in development, leading to 2% total increase (+$0.54M)
    - High end: 21% increase in ops + 29% increase in development, leading to 28% total increase (+$7.54M)

Risk

- **Approximate nature of the Team X design.**
  - The various pieces of the design (transfer to lissajous, departure from lissajous, etc) are not continuous and involve several approximations and expert opinions that it should be do-able. An end-to-end trajectory needs to be generated to validate this design.
- **Time criticality of the lissajous departure maneuver**
  - The Min-Kun Chung design had SC-1 and SC-3 departing the lissajous on the same day, and I assumed (with Ted Sweetser) that we could advance and delay those maneuvers by a day without greatly affecting the design.
  - Delaying SC-3 by two weeks added 5 months of flight time, and it wasn't obvious what kinds of delays in the maneuver lead to what delays in the flight time or delta-v increases
  - Development risk.
    - The departure maneuver is not time-critical like an orbit insertion, but there is some sensitivity.
    - What duration of delays in a planned maneuver can be acceptable without overly decreasing the science phase or increasing the DV budget needs to be investigated
  - Operational risk:
    - A spacecraft anomaly may cause a delay in the departure maneuver beyond the acceptable duration limit.

ACS Report

(1280) LaGrange 2012-03
March 20-22, 2012

Author: Robert Haw

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

Phone: (626) 354-2567

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Introduction

- **Similar to the SGO-mid study of March 6, 2012**
  - Nearly equivalent ACS requirements and components for Lagrange
- **Lagrange is a constellation of 3 sciencecraft**
- **ACS design is identical for all 3 sciencecraft**

ACS
Design Requirements

- **Acquisition phase drives the choice of ACS star tracker**
  - Satisfactory knowledge of sciencecraft orientation needed in order to support the search strategy for locating and locking onto other spacecraft
- **Requirements during acquisition (assumed)**
  - Knowledge: 1 arcsec (3σ) per axis
  - Control: 2 arcsec (3σ) per axis to allow for thruster deadband
  - Stability: 0.1 arcsec (3σ) per axis
- **Relative position knowledge requirement**
  - Knowledge: ~5-10 km cross-track
- **Science instrument (not ACS) does the following tasks**
  - Points outgoing beam(s) at other sciencecraft
  - Senses direction of incoming beam(s) relative to host sciencecraft
  - Provides position and orientation commands to host sciencecraft for maintaining lock on remote sciencecraft

Sciencecraft Architecture

- **Architecture based on SGO-mid (see LISA)**
- **During Cruise**
  - Propulsion module attached to sciencecraft
    - No ACS requirements on prop module
- **During Acquisition**
  - 3-axis stabilized using colloidal thrusters
    - No reaction wheels onboard
  - All-stellar attitude determination:
    - Star tracker with multiple heads
    - Sun sensors for safe mode
- **During Science Operations**
  - Science instrument provides relative-sciencecraft pointing
    - i.e. responsibility for beam pointing falls to the payload
  - Attitude control during science operations
    - Colloidal thrusters

Attitude determination hardware

- Star Tracker
  - 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
  - Single axis analog with 120 deg FOV; 5 deg accuracy (3σ)
- IMU
  - Used primarily for initial check-out and cruise phase
  - Redundant units; each contains 3 gyros, 3 accelerometers
  - Performance: 3 deg/hr bias (3σ) per axis
- Propulsion module also carries 6 coarse Sun sensors for safe-mode recovery

Attitude control actuators

- Colloidal thrusters with a thrust range of 4 to 150 μN.
- See the Propulsion section for details on thrusters.

ACS
Trades

- **Team X ACS did not perform any trades, but did discuss the choice of star tracker with the customer team**
- **Star Tracker is not adequate to meet the customer's cross-track knowledge requirement during acquisition**
  - Assumed requirement is 0.707 arcsec (3σ) in pitch and yaw
  - Tracker performance is 1.45 arcsec (3σ) in pitch and yaw
  - For this report, it is assumed that an improved version of the star tracker will be available, or another star tracker with the required performance will be substituted
- **Position knowledge (~ 5 km, from navigation) should be sufficient to allow a straightforward search for remote sciencecraft with a stepping algorithm across a 3x3 pixel mosaic**

ACS
Cost Assumptions

- **Level of heritage used in costing:**
  - **"Similar with Minor Modifications"**
    - **40% new; 60% heritage**
- **Level of pointing performance:**
  - **<0.01 deg; < 0.2 arcsec/sec**

<- Heritage spacecraft pointing functionality (e.g., attitude determination, inertial pointing).

- **Optional ACS control functions:** None
- **Non-standard costs manually added:** None
- **Star tracker cost assumptions**
  - Vendor's star trackers prices are very low compared to comparable products
    - Resource shortages (eg Peak Oil) and general state of world economy suggests that the cost of this component, just like everything else, could go higher
  - The following costs are assumed, taken from SGO-mid report:
    - Flight unit: $300K per head; $500K for processing electronics/power supply
    - Flight spares same; engineering models at 80% of flight unit costs

ACS
Cost Assumptions

- **Spares for each 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.

- **EMs for each sciencecraft**

Item	EMs	Comments
Sun sensor	3	2 plus 1 spare EM
Star tracker	1	Full unit
IMU	3	2 units plus 1 spare EM

ACS
Sciencecraft Cost

- **Cost Estimate in FY 2012 $M**
  - Non-Recurring (NRE): 12.3   Recurring (RE): 5.9
  - Total = 1 x NRE + 3 x RE = $30 M

Propulsion Module Cost

- **Cost Estimate in FY 2012 $**
  - Non-Recurring (NRE): 18k   Recurring (RE): 45k
  - Total = 1 x NRE + 3 x RE = $0.153 M

ACS
Cost Summary

- **Total ACS cost is estimated at $31M in FY 2012**
- **Cost Drivers**
  - Star tracker procurement equals $11M
    - Could double if tracker is not available / exceeds specs & alternate used
- **Rule-of-thumb: ACS cost is usually at least 5% of total mission cost**
  - Team X mission cost for Lagrange is $1.6B; 5% is $80M
  - Team X ACS estimate of $31M is 2% of $1.6B
    - Suggests that the ACS cost estimate is very low
      - i.e. Lagrange is using anomalously inexpensive star trackers
      - But then again, ACS has off-loaded a lot of knowledge and control functionality to the science instrument & propulsion subsystem, so ACS is relatively simple for Lagrange
- **Note well: actual ACS cost might be higher (as determined via analogy)**

Risk

- **Star tracker cost growth**
  - Few vendor 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
  - The vendor may be able to improve performance before the tech cutoff date
    - If not, higher priced star trackers from a competitor may need to be procured
  - So there is a risk of cost growth due to star trackers of potentially up to $12M
- **Star tracker manufacturing process**
  - Lagrange requires 9 optical heads, 3 dual electronics boxes, plus engineering models
  - The vendor is not a typical commercial supplier
    - So conventional manufacturing processes and procedures may not apply
      - This carries the risk of non-conventionality
- **Pointing algorithms/software cost growth**
  - Re-use of current s/w may be significantly less than assumed, in which case, there could be a cost upper of $6M to $7M for pointing algorithms and software

ACS
Module Comparison

- Same design for all three sciencecraft. Same prop modules.

Element	CBE Mass (kg)	Cost ($M)	Architecture	Comments
Science-craft	4.3 CBE 4.8 with contingency	30.8	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	0.06 CBE 0.07 with contingency	0.15	Sun sensors only	Cost is the total for all prop modules, spares, and EMs.

CDS Report

(1280) Lagrange 2012-03
March 20-22, 2012

Dwight Geer
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818-354-0511

CDS
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CDS
Design Requirements

- **Mission:**
  - LAGRANGE is the second of three space-based gravity-wave observatories
    - Measures gravity waves using a three-spacecraft constellation
    - LAGRANGE borrows heavily from the Laser Interferometer Space Antenna (LISA) aka SGO
    - The constellation spacecraft's are the instrument "test masses"
    - Where SGO spacecraft are separated by 5 million km, Lagrange separation is 21 million km
    - Spacecraft #1 and #3 are in a leading and trailing Earth Orbit – Spacecraft #2 is at L2
- **Data Volumes**
  - The data volume over the two day downlink period is about 570 Mbits – mostly housekeeping data
  - To insure storage for at least 3 missed downlink periods 1.7 Gb storage is required
- **Interfaces**
  - Most interfaces in this architecture utilize the 1553 bus
  - There are discrete and serial RS422 interfaces
  - There are analog interfaces (via 1553 to the Power Remote Engineering Units)
- **Radiation**
  - The mission TID requirement is 21.7 krad

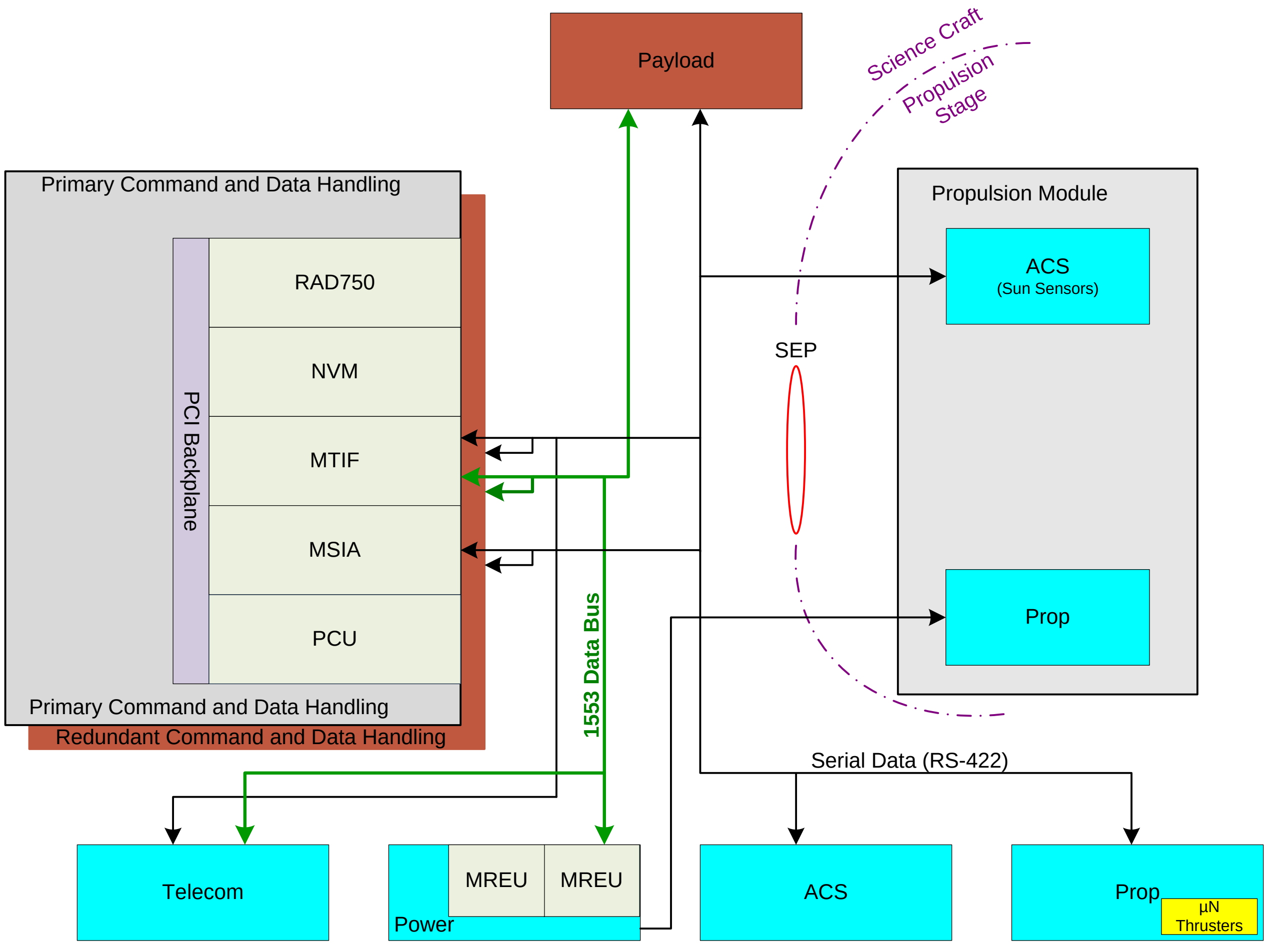
CDS
Design Assumptions

- **C&DH Functions (as identified in the Customer Block Diagram)**
  - Constellation Software
  - Time Keeping
  - Charge Management
  - Caging Control
  - ACS Control Laws
  - DRS Control Laws (includes DRS)
  - Science Operational Mode
  - Downlink Data Formatting
  - Command Processing
  - Whitening and discrete Differencing
  - Time Delay Interferometry Processing
  - Laser Locking Control
  - Science signal Processing
- **Data rates for three spacecraft**
  - S/Cs #1 & #3 send data to the center S/C, each about 20 kbps
  - The middle (#2) S/C collects the end S/Cs data for downlink at about 28 kbps (downlink rate and period is adequate to deliver all stored data)
- **Communications**
  - All data is downlinked via central spacecraft (once operational)
  - Downlink every 4 hours every 4 days

CDS
Design

- **Hardware**
  - The C&DH for all three spacecraft are identical
    - The Science crafts have an identical Dual String C&DH (cold sparing)
    - The are no C&DH elements in the Propulsion Stage (unlike SGO)
    - The MREU (remote engineering boards) reside in the Power Subsystem
    - To ensure adequate memory a 6U NVM with large capability is used
      - The required memory storage is 1.7 Gb (214 MBytes)
      - The 2 Gb board would be ideal except it is not in production now
        (it could be resurrected with substantial NRE to port FPGA code to a current device)
      - The 96 GB board (that's Bytes, not bits) is a commodity board (it costs less)
      - By the TRL 2017 date options should be available to more closely meet needs
- **Functionality**
  - As in the SGO spacecraft design, much of the interfacing between subsystems is over the 1553 bus
  - And as in SGO, there are serial interfaces (RS422) to subsystems
  - Analog data is collected via the MREU in the Power Subsystem
- **Thermal Stability due to variances in power dissipation**
  - To insure thermal stability certain subsystem power usage is monitored and backup heaters are used to maintain constant power dissipation

CDS
Block Diagram



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 results 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: 1 set
      - Mission System Testing and S/W Development: 2 sets
      - ATLO Testing: 3 sets

CDS
Cost

- 1^{ST} Unit Cost : $34.1M
- Nth Unit Cost: $12.5M

For Constellation: $59.1M

(Three S/C – identical CDS)

Cost, Risk and Additional Comments

Potential Cost Savings

- There may be potential cost saving in getting a better memory fit by the TRL date

List of Risks

- No risks were identified – design, fab, and test phase durations are good

Additional Comments

- None

Power Report

(1280) LaGrange 2012-03
March 20-22, 2012

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Power
Design Requirements

- **Mission:**
  - Three spacecraft in formation flying to perform a gravity science mission
  - Three spacecraft
    - One S/C earth trailing, one S/C at Lagrange point, one S/C earth leading.
  - No Eclipse – continuous sun pointing
- **Stabilization: 3-Axis**

Design Assumptions

- **Customer trajectory Option 2 is the only viable option**
- **Propulsion stage spacecraft are "dead on departure"**
  - The stage has no function after separation
  - The stage has no power subsystem components – powered equipment supplied by power electronics on the science spacecraft
- **All electric propulsion electronics is provided by the propulsion subsystem**
- **Solar Panel fixed and sun-facing all the time**
  - 3mm thick aluminum solar panel backing
  - 3.4 m^2 gross panel area available
  - 3.2 m^2 net panel area available for solar cells
  - Available active area
    - 2.6 m^2 ceiling assuming 80% packing factor
    - 2.4 m^2 ceiling assuming 75% packing factor

Power
Summary

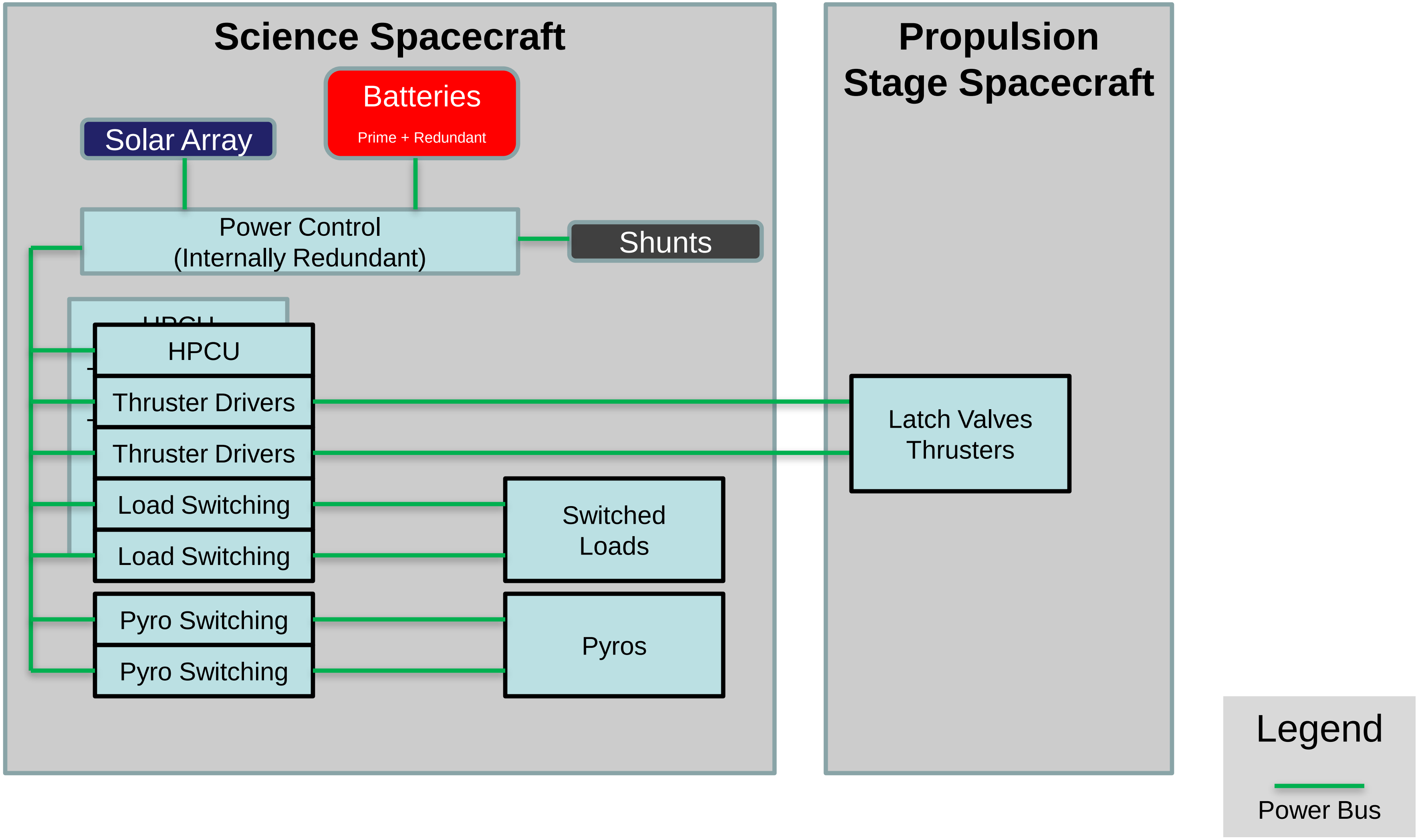
Power Summary Chart Science Spacecraft 1

Subsystem/Instrument		Power [W]					
		Launch	Cruise (telecom on)	Separation	Telecom with Instr	Science with Telecom off	Safe Load Dumping
ACS		12.0	17.2	17.2	5.2	5.2	12.0
C&DH		38.9	38.9	38.9	38.9	38.9	38.9
Instruments		0.0	0.0	0.0	99.3	99.3	9.9
Other Elements		0.0	0.0	0.0	0.0	0.0	0.0
Propulsion System 1		0.0	0.0	76.0	76.0	76.0	76.0
Prop Stage 1		68.5	31.0	0.0	0.0	0.0	0.0
Propulsion System 3		0.0	0.0	0.0	0.0	0.0	0.0
Structures		0.0	0.0	0.0	0.0	0.0	0.0
Telecomm		40.4	40.4	40.4	40.4	5.4	40.4
Thermal		16.1	16.1	16.1	16.1	16.1	16.1
Power Subsystem		30.2	27.9	31.7	38.5	35.3	31.7
TOTALS		**206.1**	**171.5**	**220.3**	**314.3**	**276.2**	**225.0**
Systems Contingency	%	43%	43%	43%	43%	43%	43%
Calculated Contingency	%	43%	43%	43%	43%	43%	43%
Subsysem Contingency	W	**88.6**	**73.7**	**94.7**	**135.2**	**118.8**	**96.8**
Subsystems with Contingency		**294.7**	**245.2**	**315.0**	**449.5**	**395.0**	**321.8**

Power Summary Chart Science Spacecraft 2

Subsystem/Instrument		Power [W]					
		Launch	Cruise	Separation	Telecom with Instrs'	Science with Telecom off	Safe Load Dumping
ACS		12.0	17.2	17.2	5.2	5.2	12.0
C&DH		38.9	38.9	38.9	38.9	38.9	38.9
Instruments		0.0	0.0	0.0	159.6	159.6	16.0
Other Elements		0.0	0.0	0.0	0.0	0.0	0.0
Propulsion System 1		0.0	0.0	76.0	76.0	76.0	76.0
Prop Stage 2		68.5	31.0	0.0	0.0	0.0	0.0
Propulsion System 3		0.0	0.0	0.0	0.0	0.0	0.0
Structures		0.0	0.0	0.0	0.0	0.0	0.0
Telecomm		0.0	0.0	40.4	40.4	5.4	40.4
Thermal		15.8	15.8	15.8	15.8	15.8	15.8
Power Subsystem		26.8	24.5	31.7	43.9	40.7	32.2
TOTALS		**161.9**	**127.4**	**220.0**	**379.8**	**341.6**	**231.2**
Systems Contingency	%	43%	43%	43%	43%	43%	43%
Calculated Contingency	%	43%	43%	43%	43%	43%	43%
Subsysem Contingency	W	**69.6**	**54.8**	**94.6**	**163.3**	**146.9**	**99.4**
Subsystems with Contingency		**231.5**	**182.1**	**314.5**	**543.1**	**488.5**	**330.7**

Power Block Diagram – Common to all Science Spacecraft



Power

Design – Array (1)

- **Single array design for all three science spacecraft**
  - Solar distance ~1AU for all spacecraft
  - The same operating environment for all spacecraft
  - Same solar array area constraint for all spacecraft
  - Essentially the same power requirements for all spacecraft:
    - Power mode: "Telecom with Instr(uments)"
- **Solar array efficiency: 29.5% BOL – based on 3-junction GaAs cells**
- **Body mounted rigid array voltage operating at 34V**
- **100ºC operating temperature**
- **Pointed directly at the sun**
- **Prototypical thermal coefficients**
  - Cell Absorptance: 0.90 (5 mil cover-glass)
  - Cell Emmitance: 0.85

Power
Design – Array (2)

- **This table provides the operating environment and other detailed parameters used to size the solar array for all spacecraft**

Mission:	LaGrange Gravitational Wave Detector Study			3/22/2012 10:55
	Default (DON'T MODIFY)	User Input	Calc'd/Linked Value	
Main Selection Panel				
		User Input	Lookup Index	Legend
Articulation		Fixed	1	Default
Configuration		Non Deployable	2	Calculated or Linked
Technology		GaAs TJ Rigid	1	Direct Entry
	Default	User Input/Override	Used in Design Calcs	Pulldown
Nominal Array Voltage	36 volts	34 volts	34 volts	Nominal Power Bus V
Solar W/m^2 @ 1 AU	1353 w/m^2		1353 w/m^2	Baseline Incident W
EOM Nuclear Power (W)			0 watts	Addl Nuclear W
Manufacturing Loss Factors (0 = total loss, 1 = no loss)				
Mismatch & fabrication	0.98		0.98	Factor
Wiring loss	0.96		0.96	Factor
User Spec'd Mfg Factor 1	1.00		1.00	Factor
User Spec'd Mfg Factor 2	1.00		1.00	Factor
EoL / Sizing Power Mode Environmental Losses / Loss Factors (0 = total loss, 1 = no loss, >1 = gain)				
Nominal operating distance from sun	1.00		1353 w/m^2	Incident Power
Sun offset angle (from array surface normal)	0°		1.00	Factor
Nominal cell operating temp. for Sizing Mode	55° C	100° Celsius	100° C	Cell Operating Temp.
Shadowing factor	1.00		1.00	Factor
BoL Power Mode Environmental Losses / Loss Factors (0 = total loss, 1 = no loss, >1 = gain)				
Nominal operating distance from sun	1.00		1353 w/m^2	Incident Power
Sun offset angle (from array surface normal)	0°		1.00	Factor
Nominal cell operating temp., BoL	50° C	100° Celsius	100° C	Cell Operating Temp.
Shadowing factor	1.00		1.00	Factor
End of Life (EoL) Degradation Loss Factors (0=total loss, 1 = no loss)				
Ultraviolet degradation	0.98		0.98	Factor
Radiation degradation	0.96		0.96	Factor
Fatigue (thermal cycling)	0.98		0.98	Factor
Micrometeoroid loss	0.98		0.98	Factor

Design – Array (3)

- **This table summarizes the resulting solar array design for the Science spacecraft**
  - Science spacecraft 2 has a slightly larger array because the instrument power requirement is slightly higher than for Science 1/3

Solar Array Design Summary Science 1 / 3		
Mass - Cells, Coverglass, etc.	3.26 Kg	
Mass - Structure	0.00 Kg	
Mass - Total Array	3.26 Kg	
Total Cell Area	1.69 m^2	Packing Factor
Total Array Area	2.11 m^2	80%
# Wings	1	
Design Technology / Configuration	GaAs TJ Rigid	

Solar Array Design Summary Sceince 2		
Mass - Cells, Coverglass, etc.	3.94 Kg	
Mass - Structure	0.00 Kg	Carried in the Structures subsystem
Mass - Total Array	3.94 Kg	
Total Cell Area	2.04 m^2	Packing Factor
Total Array Area	2.55 m^2	80%
# Wings	1	
Design Technology / Configuration	GaAs TJ Rigid	

Power
Design – Batteries

- **All batteries are on the science spacecraft**
- **All batteries are rechargeable Li-Ion chemistry**
- **The spacecraft has prime and redundant batteries**
- **The prime 32 ah battery is sized to support two hour launch operations prior to orientating the solar arrays toward the sun**
  - Allowable DOD 70% because it happens only once during the mission
  - Off-sun safe modes were not analyzed
- **The following tables summaries battery sizing and depth of discharge for launch and for the worst case TCM**
  - 2 hour Launch is the sizing case
  - ~64% DOD for Science Craft 1 & 3, ~50% DOD Science Craft 2

Flight Battery Capabilities

	Cell	Single Battery	Flight Batteries: Prime	Flight Batteries: Redundant	Flight Batteries: Total
		1	1	1	2
Voltage (V)	3.60	28.80			
Rated Energy (W-Hr)		921.60	921.60	921.60	1,843.20
Mass (Kg)		8.36	8.36	8.36	16.73
Volume (Liters)		5.76	5.76	5.76	11.52
Depth of Discharge -User Def Launch			64%	0%	0%
Depth of Discharge - Array Sizing			0%	0%	0%
Depth of Discharge - Max Custom Case			0%	0%	0%

Flight Batteries	
Chemistry	Li-ION
Capacity (A-Hr)	32
Cells / Battery	8
Prime Flight Batteries	1
Redundant Flight Batteries	1
Total Flight Batteries	2

Incremental TCM Power & Energy	Warmup	TCM worst case	Total
Incremental Req (w)	36.0	80.0	
Cruise with Telecom S/C Req (w)	202.6	202.6	
Total Req (w)	238.6	282.6	
SA (w)	454.1	-	
Req battery (w)	-	282.6	282.6
duration (hr)	1.5	0.5	
Req. battery whr	-	40.0	
Req battery ah (@ 30v)	-	1.3	1.3

Power
Design – Electronics (1)

- **Power Bus Control**
  - Internally redundant power bus control card incorporating array interface, battery interface and shunt interface functionality
- **Dual string Power Distribution Assembly each string having**
  - 1 Housekeeping Power Converter (HPCU) to support power electronics command and control interfaces
  - 2 thruster drivers cards to support 2 latch valves and 12 thrusters on each propulsion stage spacecraft
  - 1 switch card capable of switching up to ~500W of switched loads
- **Dual string Pyro Firing Assembly, each string having one pyro switch card**
  - The card command and control logic is powered directly from the primary power bus

Design – Electronics (2)

- **Development costs are carried on science spacecraft 1**
- **Flight Models, Engineering Models, Prototypes, and spares are shared appropriately across the science spacecraft according to the following tables**
  - One full-up EM system
  - One prototype of each card
  - One full-up "system's worth" of spares

Development and Sparing for Costing			Science 1 Card / Slices	
EM Systems	Prototypes	Spares	# Flight	Parts cost factors (relative to FM parts)
0	0	0	0	Array Segment Switches* [for 1 Distinct Array Panels]
1	1	1	1	Power Control* (Bus Mgmt, ABSL Battery I/F, Shunt I/F)
2	1	2	2	Pyro Switches*
4	1	4	4	Thruster Drivers* (2 Latch Valves, 8 Thrusters)
2	0	2	2	Houskeeping DC-DC Converters*
2	1	2	2	Load Switches (500W per switch card)
0	0	0	0	Battery Control
0	0	0	0	High Voltage Down Converter*
0	0	0	0	ARPS (Stirling) Controller*
1	1	1	1	Diodes

Development and Sparing for Costing			Science 2 Card / Slices	
EM Systems	Prototypes	Spares	# Flight	Parts cost factors (relative to FM parts)
0	0	0	0	Array Segment Switches* [for 1 Distinct Array Panels]
0	0	0	1	Power Control* (Bus Mgmt, ABSL Battery I/F, Shunt I/F)
0	0	0	2	Pyro Switches*
0	0	0	4	Thruster Drivers* (2 Latch Valves, 8 Thrusters)
0	0	0	2	Houskeeping DC-DC Converters*
0	0	0	2	Load Switches (500W per switch card)
0	0	0	0	Battery Control
0	0	0	0	High Voltage Down Converter*
0	0	0	0	ARPS (Stirling) Controller*
0	0	0	1	Diodes

Power
Cost

All costs in fiscal year 2012 $k	Science 1 / 3 Cost							
	A Concept Study 15 months	B Prelim Design 15 months	C1 Ph C Design 24 months	C2 Ph C Fab 12 months	C3 Ph C S/S I&T 12 months	Total Cost	Non-recurring Cost	Recurring Cost
Power Subsystem	477	1,829	10,708	9,649	3,155	25,818	14,153	11,665

All costs in fiscal year 2012 $k	Science 2 Cost							
	A Concept Study 15 months	B Prelim Design 15 months	C1 Ph C Design 24 months	C2 Ph C Fab 12 months	C3 Ph C S/S I&T 12 months	Total Cost	Non-recurring Cost	Recurring Cost
Power Subsystem	95	366	2,194	5,448	937	9,040	2,707	6,333

Cost

- **Cost Drivers**
  - Dual string electronics drives up parts costing and testing complexity
- **Potential Cost Savings**
  - Remove the Pyro drivers – potential savings: ~$1M on each spacecraft
  - Remove the redundant battery – potential savings: ~$0.6M on each spacecraft
- **Potential Cost Uppers**
  - Costs could increase if power requirements grow beyond CBE + 43%

Risk

- **Power requirement growth exceeding 43% contingency**
  - If growth is to great the array may grow beyond the 3.6 m^2 maximum array area constraint
- **An off-sun safe mode has not been analyzed**
  - Battery may be undersized for extended off-sun operations

Propulsion Report

(1280) LaGrange 2012-03
March 20-22, 2012

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Design Requirements

Mission:

- Three spacecraft, one in Earth leading, one in Earth L2, and one in Earth trailing orbits

Mission Design

- Require delta-v for TCMs during cruise to final science orbit
- Science spacecraft requires micro positioning

ACS

- Micro delta-v for station keeping and pointing 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 for the science spacecraft

Propulsion
Design Assumptions

- Assume any style propulsion system for the propulsion 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

- **Hardware**
  - Science Spacecraft 1, 2, & 3 is a colloidal propulsion system based on ST7 design and heritage, 59.7 kg CBE including 30% contingency
  - Propulsion Stage 1, 2, & 3 is a simple blowdown Hydrazine monopropellant system, 47.6 kg CBE including 7% contingency
    - One heritage titanium diaphragm tank
    - One 220N main engine
    - Four 22N TVC engines
    - Eight 0.9N RCS engines
- **Functionality**
  - Science spacecraft colloidal propulsion system provides low jitter station keeping for mission duration, and Science spacecraft 2 colloid system provides 10 m/s/year delta-v for Lissajous maintenance
  - Propulsion Stages 1, 2, & 3 provide delta-v required to get to science orbits

Design – Propulsion Stages 1, 2, & 3

Propellant

- Hydrazine: 174 kg for Prop Stages 1 & 3, 114 kg for Prop Stage 2
- 461 m/s delta-v for 849 kg final mass for Prop Stages 1 & 3
- 78 m/s delta-v for 3285 kg launch vehicle capability for Prop Stage 2

Propulsion Stage 1 & 3 Delta-V

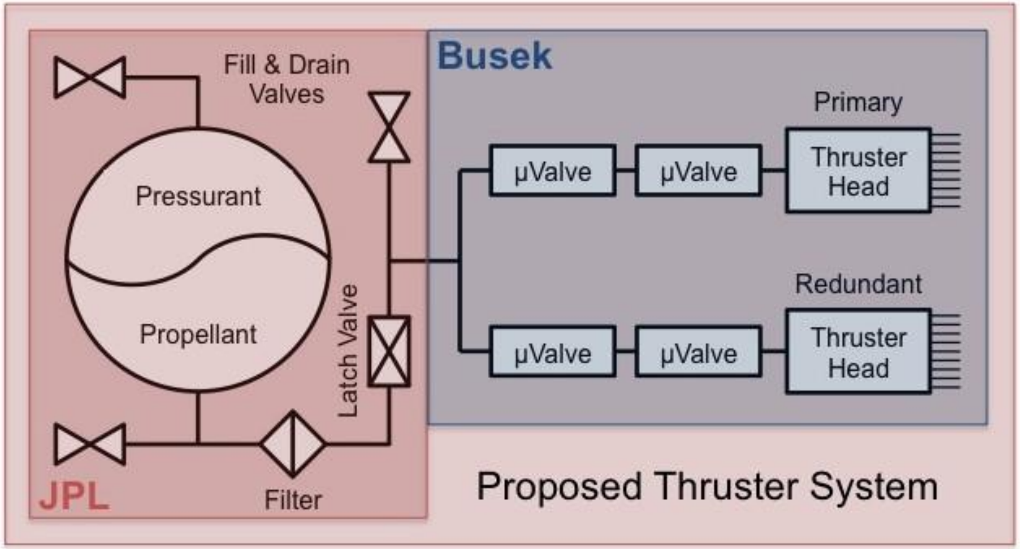
Mission Description	Maneuver Type		ADD, JET, ACS, or SEP	Delta V	Impulse	Engine Selection			
Event Name, Description	Assign Propellant To System:	Event Type	Mass (kg)	Delta V (m/s)	Impulse (N-sec)	Use engines on System #:	Pointing offset (deg)	Specific Engine from equipment list	# of Engines Firing
Lissajous Departure	1	DV		0.5		1		Monoprop Main Engine	1
Maneuver 1	1	DV		181		1		Monoprop Main Engine	1
TCMs	1	DV		20		1		Monoprop Main Engine	1
8 Degree Parking Maneuver	1	DV		259		1		Monoprop Main Engine	1

Propulsion Stage 2 Delta-V

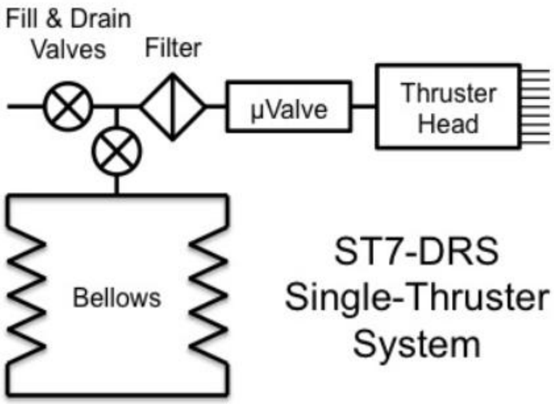
Mission Description	Maneuver Type		ADD, JET, ACS, or SEP	Delta V	Impulse	Engine Selection			
Event Name, Description	Assign Propellant To System:	Event Type	Mass (kg)	Delta V (m/s)	Impulse (N-sec)	Use engines on System #:	Pointing offset (deg)	Specific Engine from equipment list	# of Engines Firing
Transfer to Lissajous	1	DV		60		1		Monoprop Main Engine	1
Lissajous Maint. With All 3 S/C	1	DV		2		1		Monoprop Main Engine	1
Separate S/C #1 and #3	1	DV		0		1		Monoprop Main Engine	1
Lissajous Maint. with 1 S/C before	1	DV		16		1		Monoprop Main Engine	1

Block Diagram – Science Spacecraft 1, 2, & 3

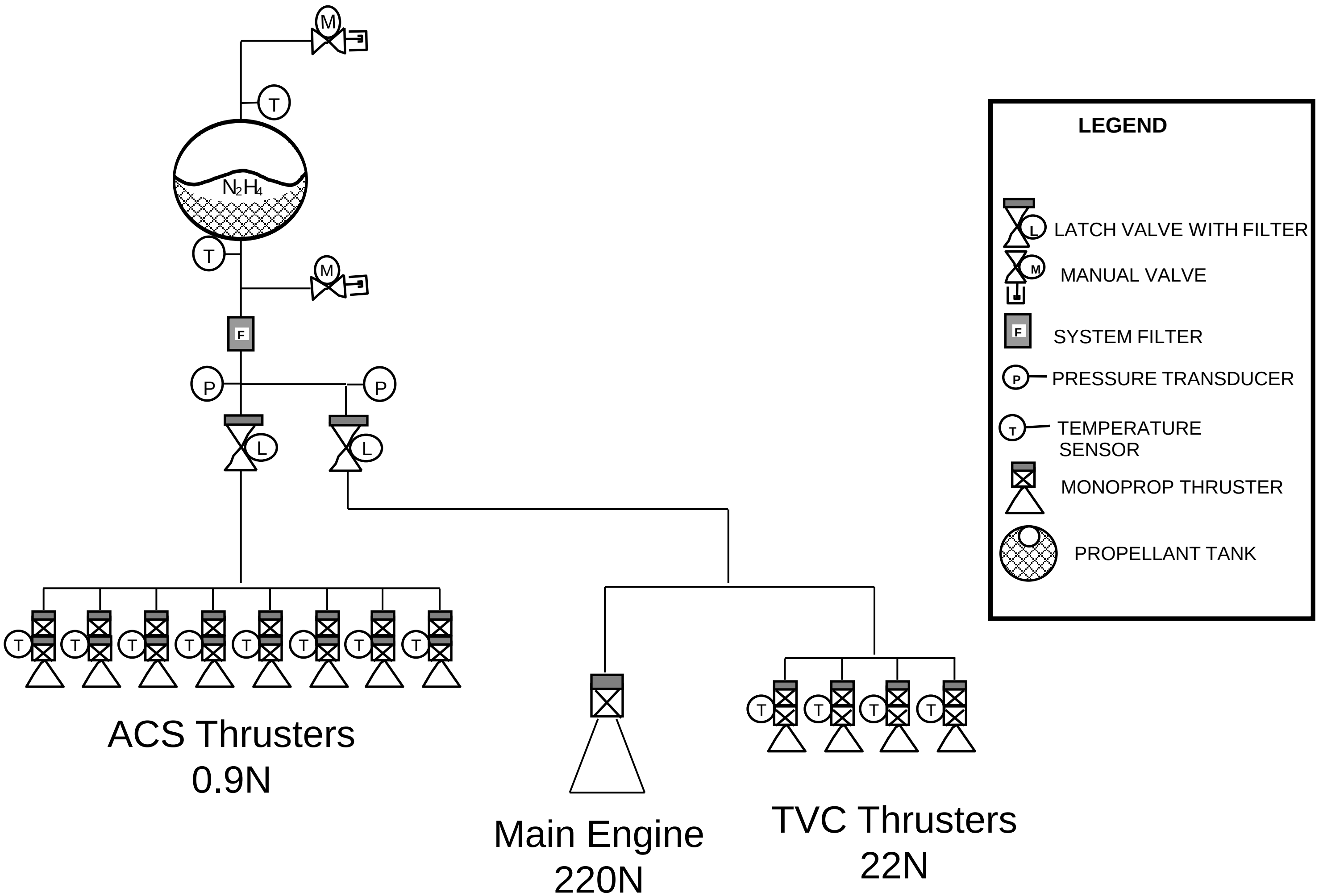
- **Proposed system composed of three clusters of four engines:**



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



Block Diagram – Propulsion Stage 1, 2, & 3



Propulsion
Cost Assumptions – Options 1 and 2

- Colloidal four engine cluster for the Science spacecraft propulsion system
- Cost reduction is a design driver
- Spares for each component per standard practice
- Workforce adjusted for prolonged phase C/D duration

Propulsion
Cost

- **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 tank PMDs save mass but add cost

Risk

- Delta-qualification of the colloidal thruster for increased mission life and propellant through-put on Science spacecraft 2 will add minimal risk
- For the propulsion stage risk is low when using flight proven components

Propulsion Element Comparison

- Mass, cost, and count is per spacecraft

Element	Mass (kg)	Cost ($M)	Thrusters	Tank Size (m)	Propellant mass (kg)	Comments
Prop Stage	47.6 CBE incl. 7% contingency	$12.4M	1 – 220N main 4 – 22N TVC 8 – 0.9N RCS	1.02 dia x 0.81 long	N2H4: 1&3) 195 kg 2) 146 kg	
Colloid system	59.7 CBE incl. 30% contingency	$27.2M	4 colloidal thrusters per 3 clusters			

Propulsion
Additional Comments

- **The additional 10 m/s Lissajous orbit maintenance requirement is for <u>one</u> of the three science spacecraft only. Added delta-v clusters for one, but not the other two science spacecraft results in two different S/C designs, resulting in higher non-recurring S/C costs through system ripple effects (thermal, mechanical, C&DH etc subsystem level impacts). These costs might far outweigh the cost & risk of increased lifetime testing.**
- **Based on this information, the following approach is recommended:**
  - maintain three colloid clusters per <u>each</u> science craft
  - Utilize these thrusters to double as delta-v thrusters on <u>one</u> of the three science spacecraft
  - Assume <u>only</u> the 10 m/s/year delta v role in science mode ops, <u>not</u> the 18 m/s Lissajous orbit maintenance prior to science mode ops
  - Assume a 2 yr mission life only – the propellant savings over LISA may thus partially offset the added 10 kg propellant requirement for the 10 m/s Lissajous orbit maintenance maneuvers
  - There is still an increased throughput requirements for the thrusters on one of the science craft, possibly as high as 10* 2/3 + 1.5 (half of LISA throughput) = 8.1 kg, or 8.1 – 3 = 5.1 kg above LISA requirements per cluster for the clusters of one of the science spacecraft. The above statement includes the assumptions that: 1)10 m/s are required per year for 2 yrs mission life, 2) Each of the three clusters of the science spacecraft in question will provide an equal portion of the delta- v required (unknown), and 3) Propellant requirements for disturbance control are reduced by half over LISA requirements due to reduced mission life.
- **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 due to Lissajous orbit maintenance. This includes incorporation of a larger diaphragm tank, rather than a bellows assembly, increased system redundancies, thruster life, and system optimizations (thruster cluster design and analysis).**

Mechanical Report

(1280) Lagrange 2012-03

March 20th-22nd, 2012

Author: Matt Spaulding

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Table of Contents

Design Requirements

- **Mission:**
  - Trajectory to L2, then Earth Leading and Trailing Orbits
- **Launch Vehicle: NLS-2 Contract**
- **Stabilization: 3-Axis**
- **Payload:**
  - Sciencecraft 1 and 3 – Two 40 cm Telescopes
  - Sciencecraft 2 – One 40 cm Telescope and a Telescope Dummy Mass

Mechanical
Design Assumptions - Sciencecraft

- The Primary Bus Structure of the Sciencecraft will be thermally isolated from the radiator attached to the back of the rigid solar array.
- Hardware located internal to the Sciencecraft will be rigidly mounted in order to have solid understanding of locations of all subcomponents throughout any thermal loading of the Sciencecraft.
- Components internal to the Sciencecraft will be located in as close to a symmetric layout as possible in order to simplify the knowledge of the location of the CG of the Sciencecraft.
- CG variation from the preferred location will be tuned using balance mass.
- The Telescope Dummy located on Sciencecraft 1 and 3 will need to have one surface exposed to space and polished to match the thermal behavior of the optic located on the telescope.

Design Assumptions – Propulsion Module

- **The Propulsion Modules will be the primary load path to the Launch Vehicle.**
  - Propulsion Module 2 will attach to the Launch Vehicle Adapter, Sciencecraft 2, and Propulsion Modules 1 and 3.
  - Propulsion Modules 1 and 3 will only be carried to their respective Sciencecraft.
- **The Propulsion Modules will be simple in that they will be slaved to the sciencecraft. They will not be carrying any electronics or additional solar arrays.**

Design

- The general layout of each of the Sciencecraft is rectangular with a thermally isolated Solar Array and Solar Array Radiator. The decision to thermally isolate the Solar Array was made in order to simplify the management of thermal gradients on the Sciencecraft Bus.
- The internal layout between the three Sciencecraft is similar with the exception of the cant angle of the Telescopes in Sciencecraft 2.
- Masses and thermal generation sources will be placed in a configuration as close to symmetric about the central plane (normal to the sensitive axis of the Sciencecraft) as possible.
- All three Sciencecraft share the same Solar Array Substrate Panel which doubles as a Solar Shade for the Bus and Telescopes.
- The launch configuration is comprised of the three Sciencecraft resting in line with their Solar Arrays facing along the axis of the launch vehicle. The opposite face of the Sciencecraft Buses is the location where the Sciencecraft interface with their Propulsion Stages. This allows for a more symmetric mass configuration for the Sciencecraft as well as allow for all three Sciencecraft to utilize their Solar Arrays during cruise to L2.

Mechanisms and Deployments

- In order to minimize jitter and simplify the thermal analysis of the Sciencecraft, the overall mission has very few mechanisms and deployments.
- Five 31.6” Lightbands will be utilized for separations between the various Sciencecraft and Propulsion Stages.
  - Propulsion Stages 1 and 3 and their respective Sciencecraft. (2)
  - Propulsion Stage 2, Propulsion Stages 1 and 3, and Sciencecraft 2. (3)
- Telescope covers will be locate and ejected from the Sciencecraft for the four telescopes and the two dummy telescopes in order to protect them from debris during launch.
- A Marmon Clamp will be used to separate Propulsion Stage 2 from the Launch Vehicle Adapter.

Design – Science Craft 1 and 3

Detailed Mass List

- The two largest mass contributions are the Primary Structure and the cabling Harness.
- The Primary Structure mass is determined by applying historical percentages to the masses of the various subsystems being supported within the spacecraft.
- The harness mass is developed by estimating the number of internal electronics boxes as well as taking into account the masses various subsystems and instruments. Additional Mass was also added by adding a small percentage of high voltage harness to be used for powering the lasers.

Design – Science Craft 2

Detailed Mass List

- The two largest mass contributions are the Primary Structure and the cabling Harness.
- The Primary Structure mass is determined by applying historical percentages to the masses of the various subsystems being supported within the spacecraft.
- The harness mass is developed by estimating the number of internal electronics boxes as well as taking into account the masses various subsystems and instruments. Additional Mass was also added by adding a small percentage of high voltage harness to be used for powering the lasers.
- The additional mass increase for Sciencecraft 2 is primarily attributed to the additional instrument and electronics being carried within Sciencecraft 2.

Detailed Mass List

- Propulsion Modules 1 and 3 are designed such that they are slaves to their respective Sciencecraft and their only supported element beyond their internal propulsion subsystem is the attached Sciencecraft.

Design – Propulsion Module 2

Detailed Mass List

- The Primary Structure mass is the largest fraction of the overall structural mass largely due to the launch configuration. Propulsion Module 2 is the primary the interface for all of the Sciencecraft and Propulsion Modules to the Launch Vehicle.

Cost Assumptions

- Sciencecraft 1 was selected as the roll-up element for cost for the Lagrange Study. This results in the mission wide costs such as Management, Contamination Control, and Loads & Dynamic Environments to be attributed to this element.
- Separation mechanism costs were bookkept on the element which contained the larger portion of the separation mechanism. This resulted in an individual Lightband release system located on each of the Propulsion Modules 1 and 3, and three Lightband release systems located on Propulsion Module 2.

Mechanical
Cost – Sciencecraft 1 and 3

- **Mechanical (Including I & T): $33.87M**
- **Cabling: $3.09M**
- **Contamination Control: $1.60M**
- **Materials & Processes: $0.54M**

Mechanical

Cost – Sciencecraft 2

- **Mechanical (Including I & T): $10.85M**
- **Cabling: $3.1M**
- **Contamination Control: $0.00M**
- **Materials & Processes: $0.54M**

Mechanical
Cost – Propulsion Modules 1 and 3

- **Mechanical (Including I & T): $11.48M**
- **Cabling: $2.83M**
- **Contamination Control: $0.00M**
- **Materials & Processes: $0.45M**

Mechanical
Cost – Propulsion Module 2

- **Mechanical (Including I & T): $14.40M**
- **Cabling: $2.83M**
- **Contamination Control: $0.00M**
- **Materials & Processes: $0.45M**

Mechanical
Cost

- **Cost Drivers**
  - The largest cost element for each of the various mission elements was always the Primary Structure. This cost is acquired through a mass vs cost approximation based on historical data with variation attributed to mission specifics. In this mission, the sensitivity to thermal gradients was implemented as an increase in the payload stability requirements resulting in an increase to complexity which increases slightly the cost for a specific mass.
- **Potential Cost Savings**
  - If a large portion of the three Sciencecraft development can be shared, the non-recurring costs between Sciencecraft 1/3 and 2 may decrease. The costing tool assumes that Sciencecraft1/3 and 2 are completely new designs. The configurations for the Sciencecraft are different, but those differences are primarily in the internal differences in the telescope orientations and the inclusion of the dummy telescopes.
- **Potential Cost Uppers**
  - Implementation of a Softride system to the Launch Vehicle if deemed necessary for the safety of the Telescope Optics could add to the cost of the launch stack.
  - Mitigation of thermal expansion within the Sciencecraft through the implementation of more exotic tailored composite materials could increase the cost of fabrication and development of the Sciencecraft.

Mechanical

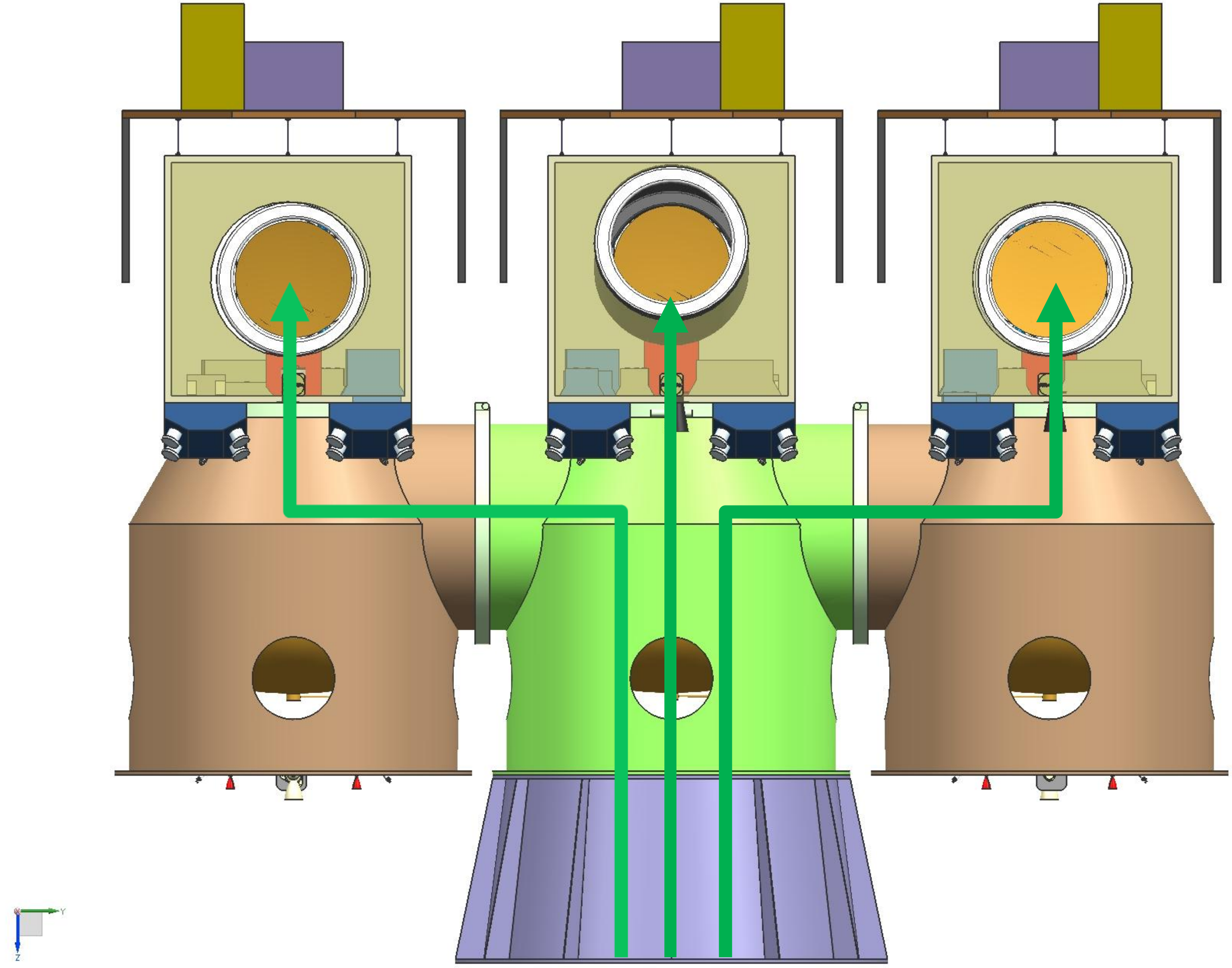
Risk

- Depending on the temperature deltas within the Sciencecraft, rigid mounting of internal items may result in high shear loads on mounting fasteners. Structures capable of releasing thermal stresses may result in minor shifting of the CG location of the Sciencecraft. Detailed knowledge of any present thermal gradients as well as proper selection of materials can mitigate this issue.
- Launch loads being transmitted through the launch stack may result in high loads on the telescope optics. Implementation of a Softride system below the Launch Vehicle Adapter can minimize the launch loads seen by the launch payload.
- A separation guide may be necessary between the three Sciencecraft in order to prevent possible contact during the separation of Sciencecraft 1 and 3 at L2. This is dependent on how clean and uniformly linear the Lightband separation occurs.

Mechanical
Additional Comments

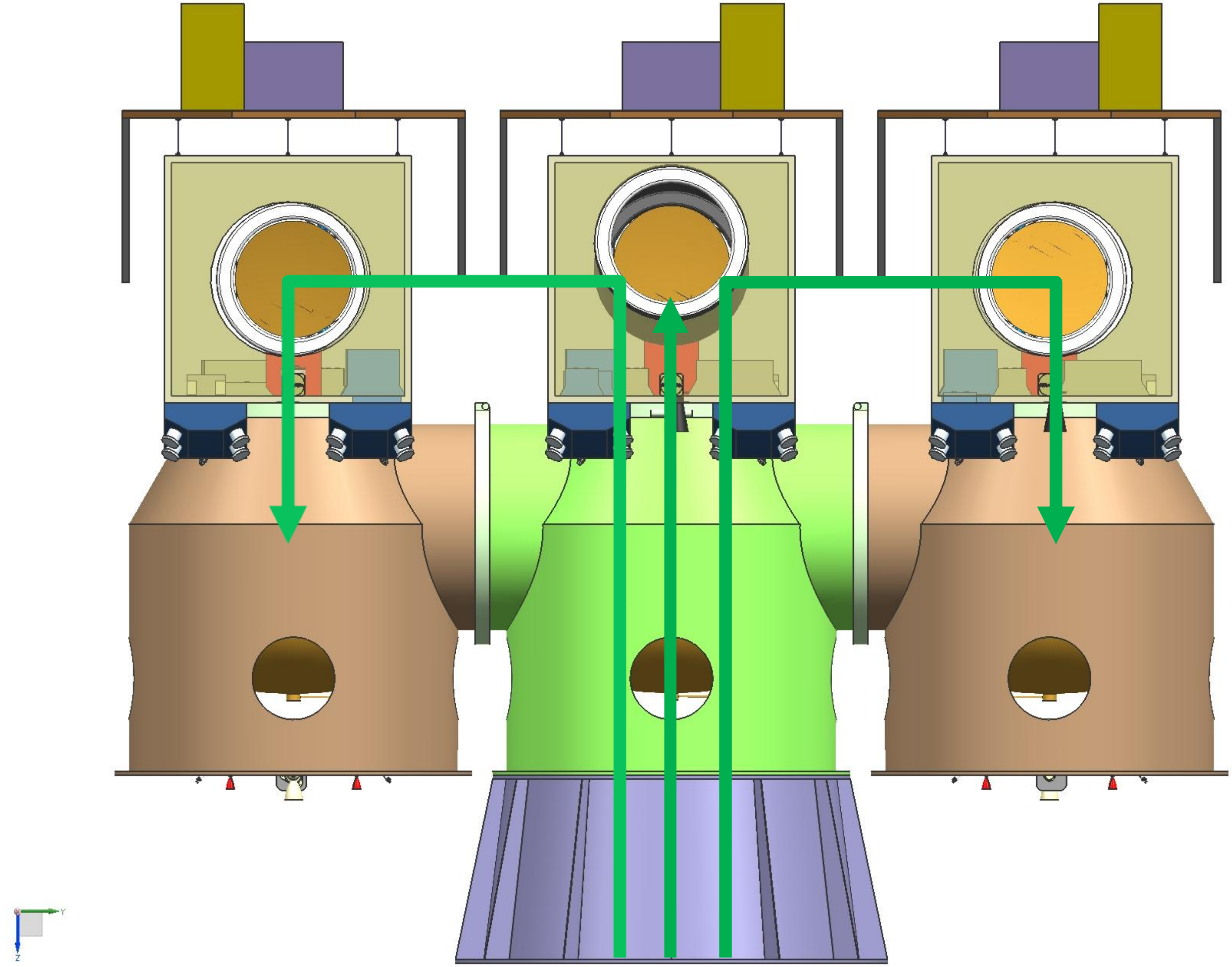
- **Following the design session, an additional configuration was discussed where rather than passing the primary launch load path through Propulsion Modules 1 and 3 the primary load path could pass through Propulsion Module 2 and the three Sciencecraft. This would result in more mass being attributed to the three Sciencecraft while light weighting Propulsion Modules 1 and 3. It was suggested that additional mass on the Sciencecraft would benefit the thermal stability of the Sciencecraft as well as minimize the impact of solar wind, however manipulation of the Sciencecraft with the ACS system may also become more difficult and inadequate time was available to detail the second configuration.**

Additional Comments – In Session Load Path



Mechanical

Additional Comments – Post Session Load Path



Configuration Report

(1280) Lagrange 2012-03
March 20-22, 2012

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Phone: (818) 354-0993

Configuration
Table of Contents

Design Requirements and Assumptions

Requirements

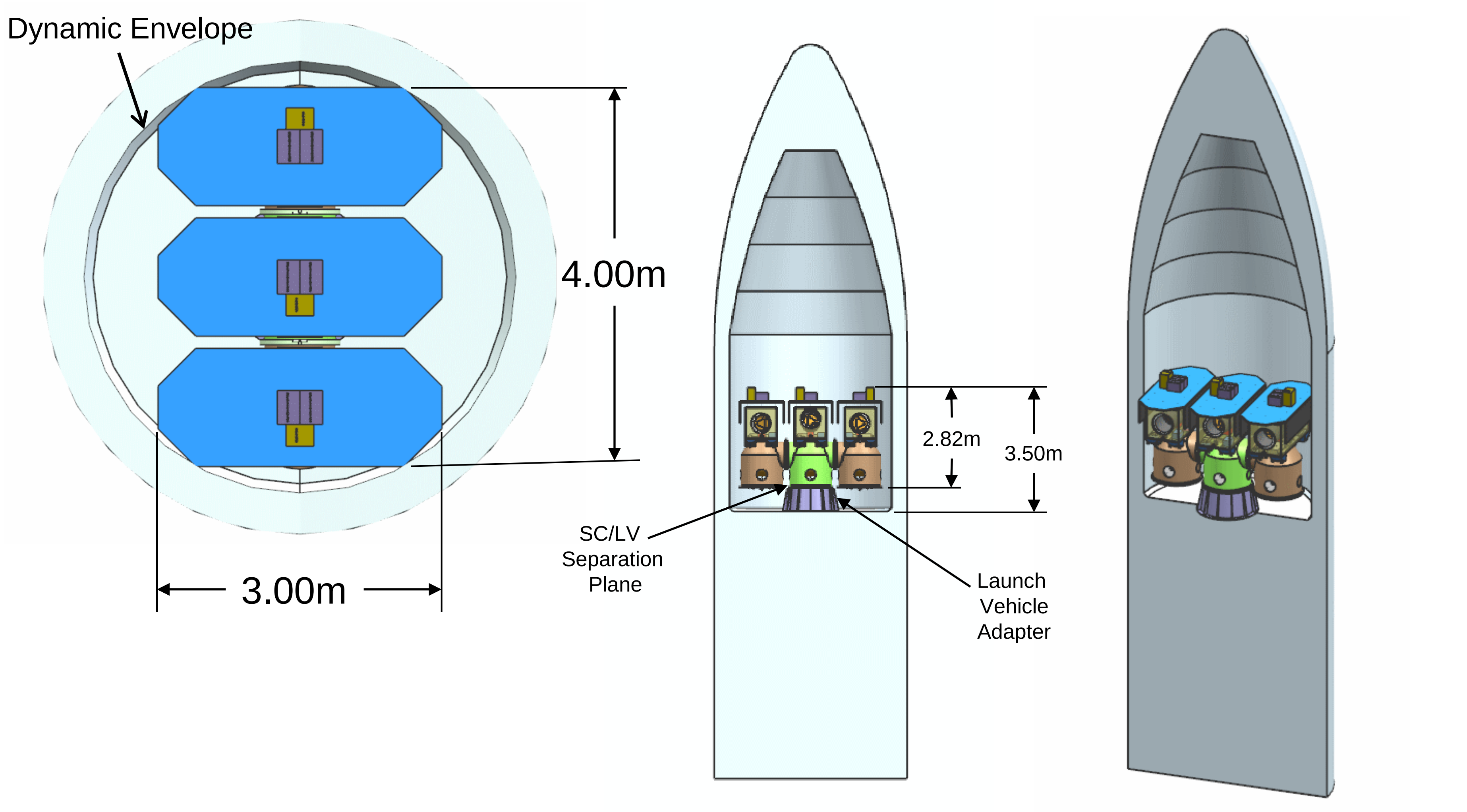
- The mission requires three spacecrafts to take the science measurement. All three spacecrafts will be as similar as possible and the C.Gs. will be known at all the time and the thermal expansion will affect the C.G. locations as little as possible.
- Launch Vehicle: NLS-2 Contract
- Payload:
  - Science craft 1 and 3 – each carries one 40 cm telescope, one equal mass dummy.
  - Science craft 2 carries two 40 cm telescopes end to end with 8 degree off the centerline.

Assumptions

- When starts science measurement, all three crafts fly in a triangular formation and Science craft 2 at the center.

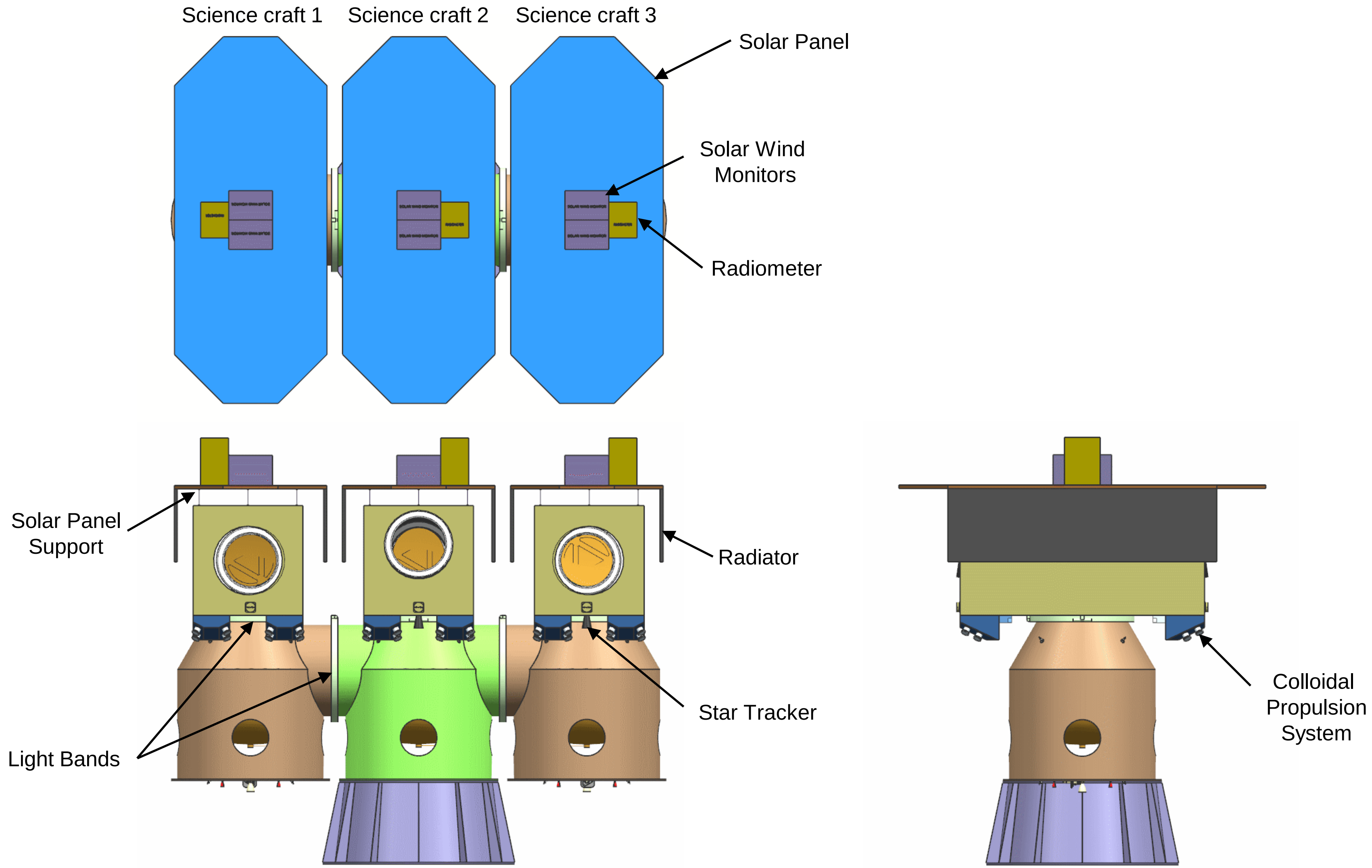
Design Configuration

Configuration Drawings – In Payload Fairing



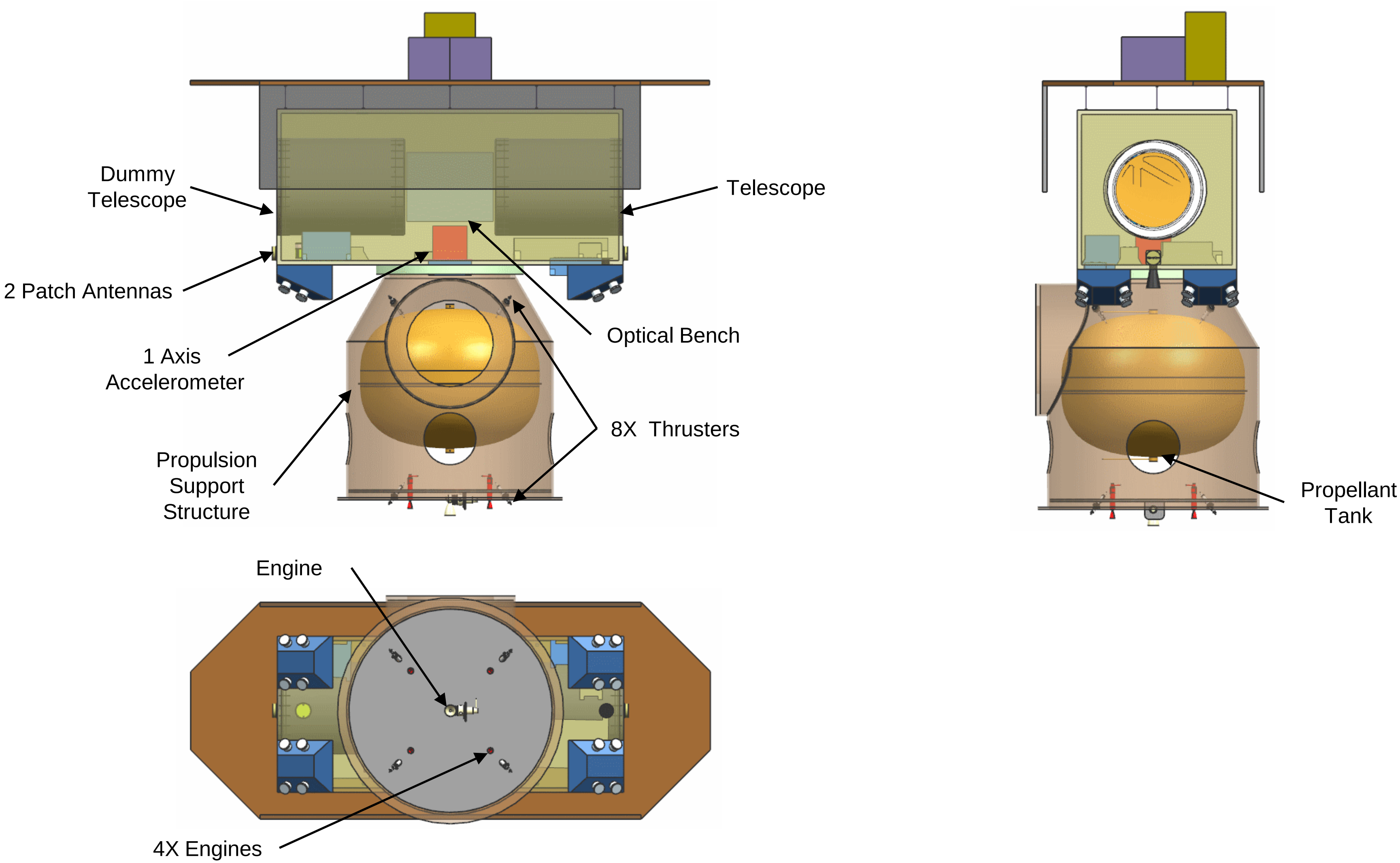
Design Configuration

- **Configuration Drawings – 3 Science crafts together**

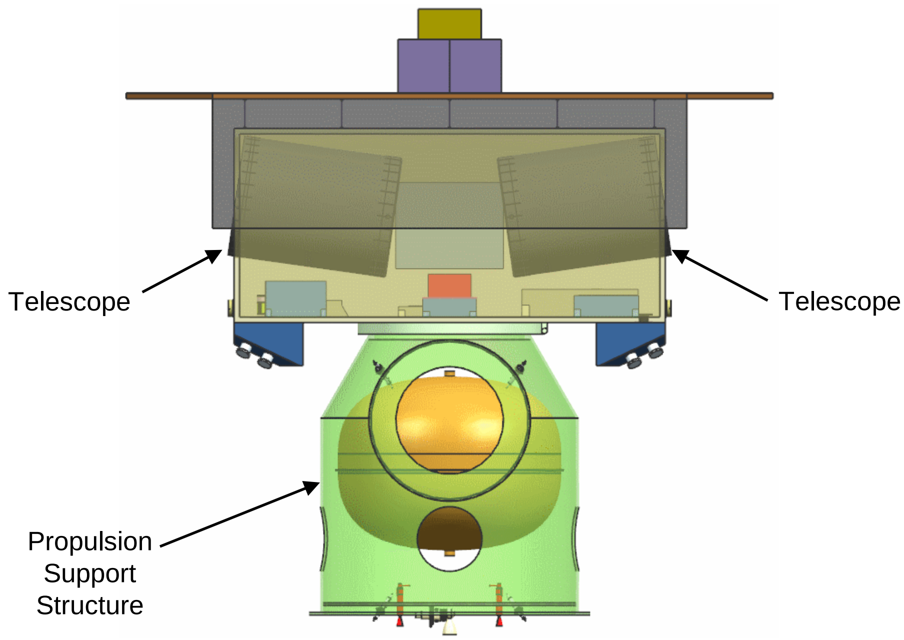


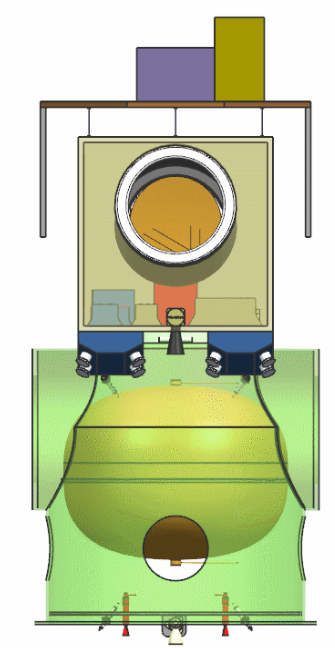
Design Configuration

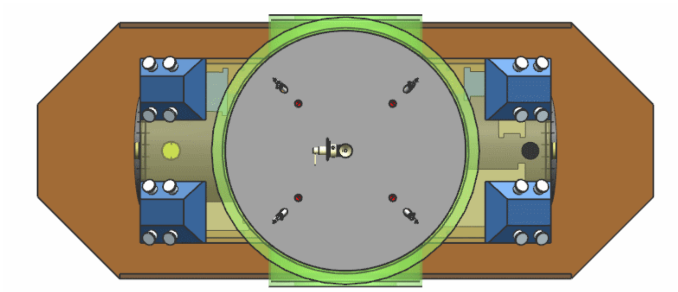
Configuration Drawings – Science craft 1 & 3



Configuration Drawings – Science craft 2







Thermal Report

Space Based Gravitational Wave Detector
(1280) LaGrange 2012-03
March 20-22, 2012

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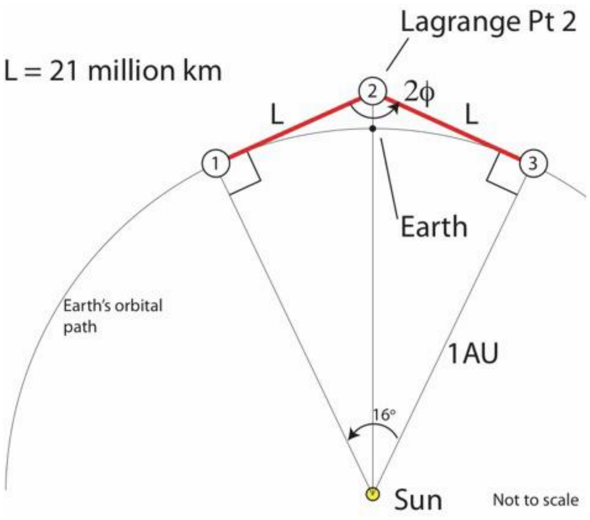
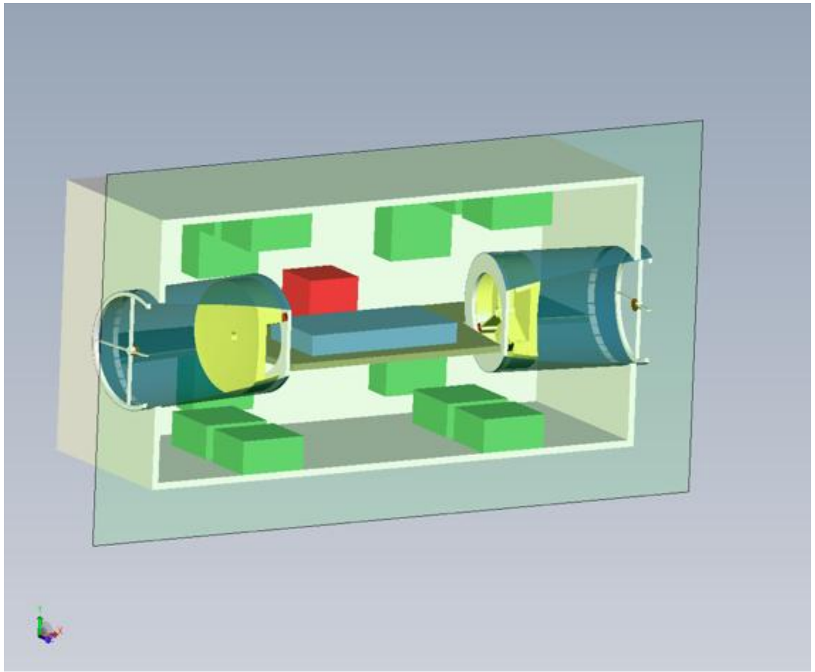
Thermal
Design Requirements

- **Mission:**
  - Heliocentric orbit, Lagrange points
  - Three spacecraft system
  - No eclipses
- **Stabilization: three axis stabilization**
- **Payload: telescope 40 cm diameter, laser communication**
  - Requires very stable temperatures and balanced heat rejection from external spacecraft surfaces.
    - Tailor external S/C surfaces to radiate equal amounts from opposite sides of spacecraft.
  - We are measuring the distance between S/C
  - Measures external forces with
    - Radiometer
    - Solar wind monitor
    - accelerometer



Thermal
Design Assumptions

- **Spacecraft will maintain constant sun angle normal to the solar panel**
- **If we can eliminate time varying heat loads, we can eliminate time varying temperatures and temperature gradients**



Thermal
Summary – Science Craft

- **Power Thermal Summary Chart for Science Craft**

	Suggested	Ov	Used
Thermal Design Inputs			
Thermally Controlled Mass	395.9 kg		395.9 kg
Spacecraft Dry Mass Density	200.0 kg/m3		200.0 kg/m3
Spacecraft Wet Mass Density	200.0 kg/m3		200.0 kg/m3
Thermal Power/Controlled Mass	0.05 W/kg		0.05 W/kg
Conduction Ctrl Mass/Ctrlled Mass	0.001 kg/kg		0.001 kg/kg
Bus Geometry Approximation	Cube		Cube
Multi-Layer Insulation			
MLI Type	Interlayered		Interlayered
Number of Layers	20		20
Specific Mass	0.75 kg/m2		0.75 kg/m2
Specific Area	0.50 m2/blanket		0.50 m2/blanket
Propulsion Heater Power			
Tank Heaters	2.5 W		2.5 W
Line Heaters	0.5 W		0.5 W
Thermal Design Calculations			
Thermally Controlled Surface Area	9.5 m2		9.5 m2
Total Propulsion Tank Surface Area	0.0 m2		0.0 m2

Subsystems	Mass			Power Modes									
	CBE	Cont.	PBE	Launch 1.0 hr.	Cruise 24.0 hr.	Separatio 1.0 hr.	Telecom 24.0 hr.	Science 24.0 hr.	Safe Load 24.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.
Total Wet Stack (w/o Thermal)	518.5 kg	51%	783.3 kg	74.3 W	78.3 W	196.9 W	183.4 W	148.4 W	191.1 W	13.9 W	13.9 W	13.9 W	13.9 W
Carried Elements	0.0 kg	0%	0.0 kg										
Wet Element (w/o Thermal)	518.5 kg	51%	783.3 kg	74.3 W	78.3 W	196.9 W	183.4 W	148.4 W	191.1 W	13.9 W	13.9 W	13.9 W	13.9 W
Pressurant & Propellant	0.0 kg	0%	0.0 kg										
Dry Element (w/o Thermal)	518.5 kg	51%	783.3 kg	74.3 W	78.3 W	196.9 W	183.4 W	148.4 W	191.1 W	13.9 W	13.9 W	13.9 W	13.9 W
Instruments	230.3 kg	30%	299.4 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
Other Payload	0.0 kg	0%	0.0 kg										
Dry Bus (w/o Thermal)	288.2 kg	68%	483.9 kg	74.3 W	78.3 W	196.9 W	183.4 W	148.4 W	191.1 W	13.9 W	13.9 W	13.9 W	13.9 W
ADC	4.3 kg	10%	4.8 kg	12.0 W	17.2 W	17.2 W	5.2 W	5.2 W	12.0 W	0.0 W	0.0 W	0.0 W	0.0 W
CDH	19.5 kg	15%	22.3 kg	38.9 W	38.9 W	38.9 W	38.9 W	38.9 W	38.9 W	0.0 W	0.0 W	0.0 W	0.0 W
Power	18.6 kg	30%	24.2 kg	23.4 W	22.2 W	24.4 W	22.9 W	22.9 W	23.8 W	13.9 W	13.9 W	13.9 W	13.9 W
Propulsion	64.0 kg	30%	83.2 kg	0.0 W	0.0 W	76.0 W	76.0 W	76.0 W	76.0 W	0.0 W	0.0 W	0.0 W	0.0 W
Mechanical	177.6 kg	30%	230.3 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
Telecom	4.3 kg	10%	4.7 kg	0.0 W	0.0 W	40.4 W	40.4 W	5.4 W	40.4 W	0.0 W	0.0 W	0.0 W	0.0 W
Systems Contingency			114.5 kg										
Thermal	52.6 kg	20%	63.0 kg	19.8 W	19.8 W	19.8 W	19.8 W	19.8 W	19.8 W	19.8 W	19.8 W	19.8 W	19.8 W

Thermal
Summary – Propulsion Module

- **Power Thermal Summary Chart for Propulsion modules**

	Suggested	Ov	Used
Thermal Design Inputs			
Thermally Controlled Mass	114.1 kg		114.1 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	#	0.00 W/kg
Conduction Ctrl Mass/Ctrlled Mass	0.001 kg/kg		0.001 kg/kg
Bus Geometry Approximation	Cube		Cube
Multi-Layer Insulation			
MLI Type	Interlayered		Interlayered
Number of Layers	20		20
Specific Mass	0.75 kg/m2		0.75 kg/m2
Specific Area	0.50 m2/blanket		0.50 m2/blanket
Propulsion Heater Power			
Tank Heaters	2.5 W		2.5 W
Line Heaters	0.5 W		0.5 W
Thermal Design Calculations			
Thermally Controlled Surface Area	4.1 m2		4.1 m2
Total Propulsion Tank Surface Area	4.3 m2		4.3 m2

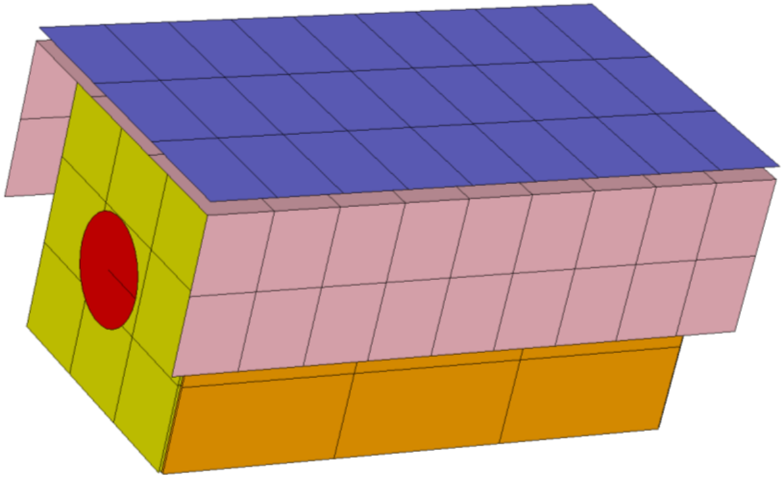
Subsystems	Mass			Power Modes									
	CBE	Cont.	PBE	Launch 1.0 hr.	Cruise 24.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.	TBD 0.0 hr.
Total Wet Stack (w/o Thermal)	282.7 kg	13%	319.8 kg	5.2 W	5.2 W	5.2 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W
Carried Elements	0.0 kg	0%	0.0 kg										
Wet Element (w/o Thermal)	282.7 kg	13%	319.8 kg	5.2 W	5.2 W	5.2 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W
Pressurant & Propellant	207.7 kg	0%	207.7 kg										
Dry Element (w/o Thermal)	75.0 kg	49%	112.1 kg	5.2 W	5.2 W	5.2 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 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)	75.0 kg	49%	112.1 kg	5.2 W	5.2 W	5.2 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W
ADC	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
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	0.0 kg	0%	0.0 kg	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W	1.4 W
Propulsion	34.0 kg	27%	43.0 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
Mechanical	40.2 kg	30%	52.3 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
Telecom	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
Systems Contingency			15.9 kg										
Thermal	9.4 kg	26%	11.9 kg	29.0 W	29.0 W	29.0 W	29.0 W	29.0 W	29.0 W	29.0 W	29.0 W	29.0 W	29.0 W

Thermal Design

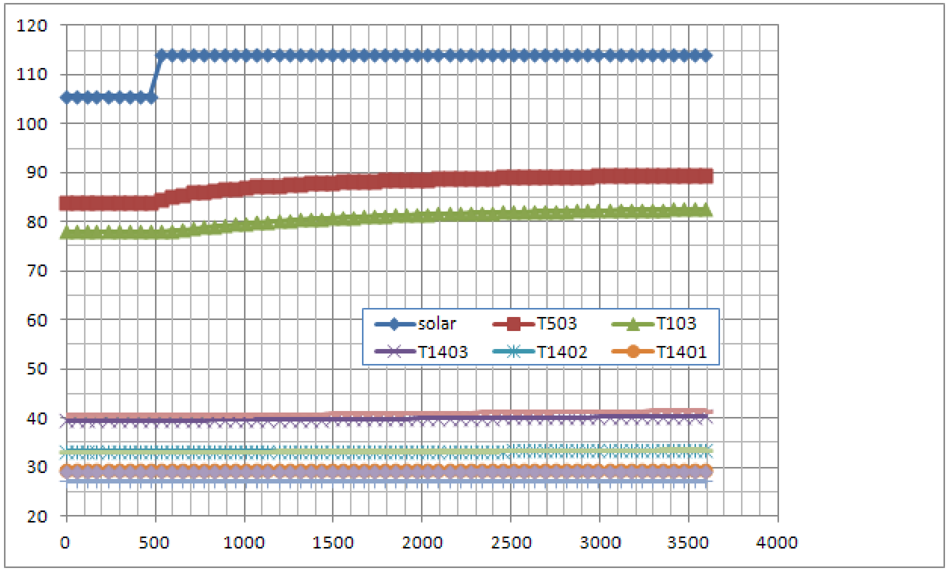
- **Thermal Design strives to maintain constant temperatures and balance the heat rejected from external surfaces to space**
- **During Science mode, payload configuration is unchanging**
- **Any variation in thermal dissipation within the electronics should be made up with heater power at the same location**
  - This maintains a constant power level in the S/C
- **Active**
  - Flight software will be used to monitor payload processing activity and apply make-up power to heaters as necessary
  - Propulsion system will make use of thermostats to keep tanks and prop lines within desired temperature ranges.
- **Passive**
  - Solar Panel has “radiator wings” on non-sensitive sides of the S/C
    - Designed to keep unwanted heat out of the payload cavity
  - Payload radiator will can be opposite the solar panel and tailored to balance heat rejection forces

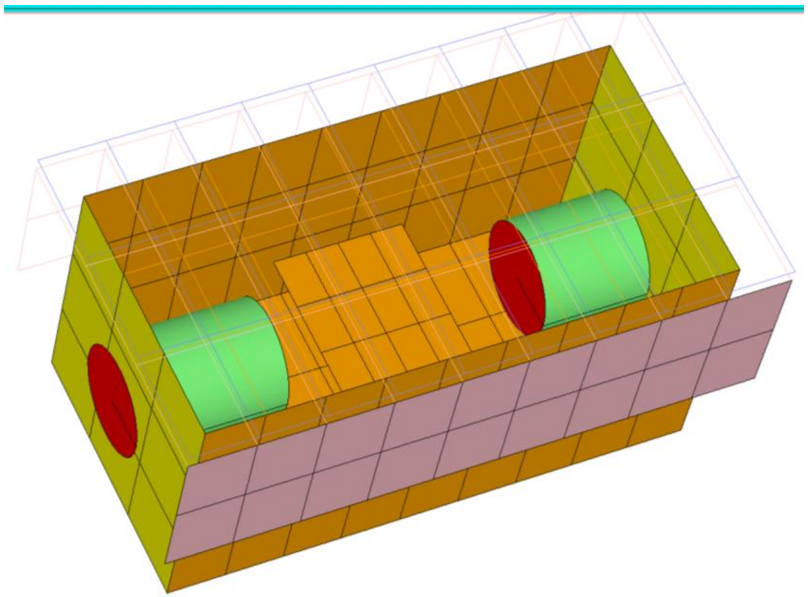
Thermal Design

- **Analysis model**
  - A simple thermal model was created



- **Analysis results**
  - Transient response was predicted to a step input change (8%) in the solar load on the solar panel





Thermal PEM is carried in Sciencecraft 2

- Each subsystem (spacecraft and propulsion) has a thermal lead.
  - Thermal lead cost is carried in Sciencecraft 2 and Prop module 2.
- Sciencecraft 2 cost includes much of the thermal design engineering for all three sciencecraft.
  - Sciencecraft 1 cost includes additional thermal design engineering to handle the differences between sciencecraft 2 and the two outer sciencecraft.
- Propulsion module 2 cost includes much of the engineering for all three.
  - Propulsion module 1 cost includes additional engineering to handle differences.

Cost S/C-1 (all values in $K)

Thermal Control System Cost		
Total	NRE	RE
105 mo	54 mo	51 mo
$ 3,249	$ 1,462	$ 1,786

Cost S/C-2

Thermal Control System Cost		
Total	NRE	RE
105 mo	54 mo	51 mo
$ 12,443	$ 5,998	$ 6,446

Cost Prop-1

Thermal Control System Cost		
Total	NRE	RE
105 mo	54 mo	51 mo
	$ -	$ 1,353

Cost Prop-2

Thermal Control System Cost		
Total	NRE	RE
105 mo	54 mo	51 mo
$ 5,597	$ 2,103	$ 3,494

Telecom Report

(1280) LaGrange 2012-03
March 20-22, 2012

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Telecom
Design Requirements

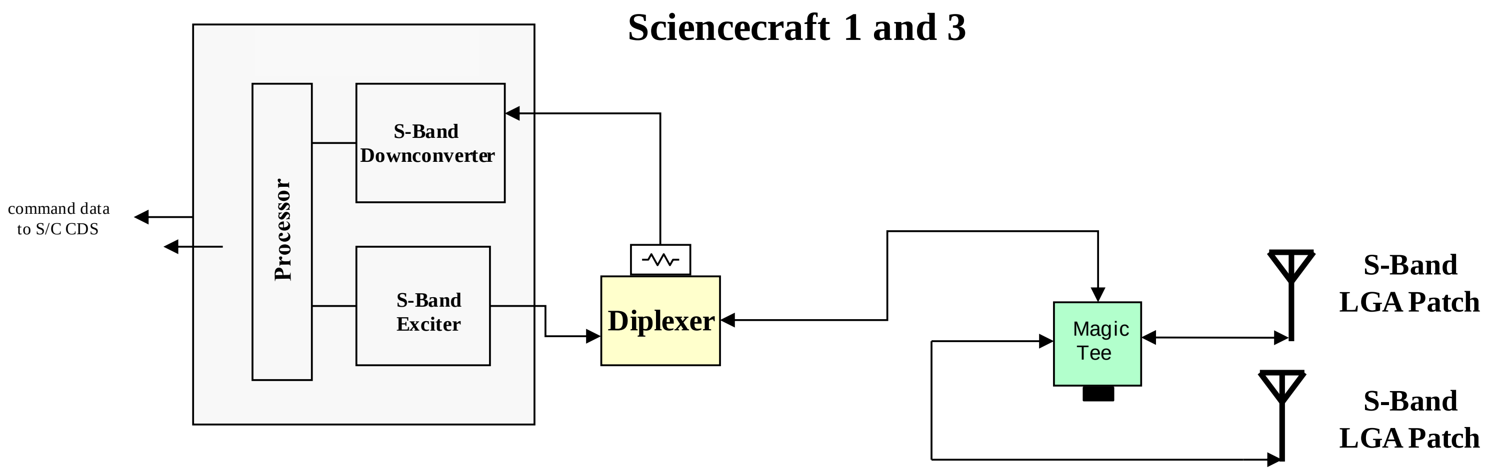
- **General Telecom Requirements**
  - Support two-way communications with Earth through all mission phases
    - Includes supporting uplink command, downlink telemetry and navigation – 2-way Doppler and ranging
- **Downlink/Return Requirements**
  - Support a downlink data rate of 28 kbps from Sciencecraft 1 to a 34m BWG ground station.
    - Note that the capability of the Team X baseline is 56 kbps or twice the requirement.
  - Support a downlink rate of 50 bps from Sciencecraft 1 and 3 to a 34m BWG ground station
  - One 5 hour pass every two days to return science data
    - Sciencecraft 1 and 3 transmit their data to Sciencecraft 2 via the science optical links.
    - Note that the Team X baseline includes one 4 hour pass every 4 days, taking advantage of the 56 kbps downlink capability to save on Ground Systems cost.
- **Uplink/Forward Requirements**
  - Support an uplink rate of 2 kbps to each Sciencecraft
- **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
- **Customer Inputs**
  - Desire LGAs on both sides of each S/C to provide near 4π steradian coverage
  - On Sciencecraft 1 and 3, the S-Band transmitter will be connected to the two antennas through a Magic Tee to balance the power going out of each end of the S/C
    - On Sciencecraft 2 the LGAs are on the front and back and will be connected through a switch

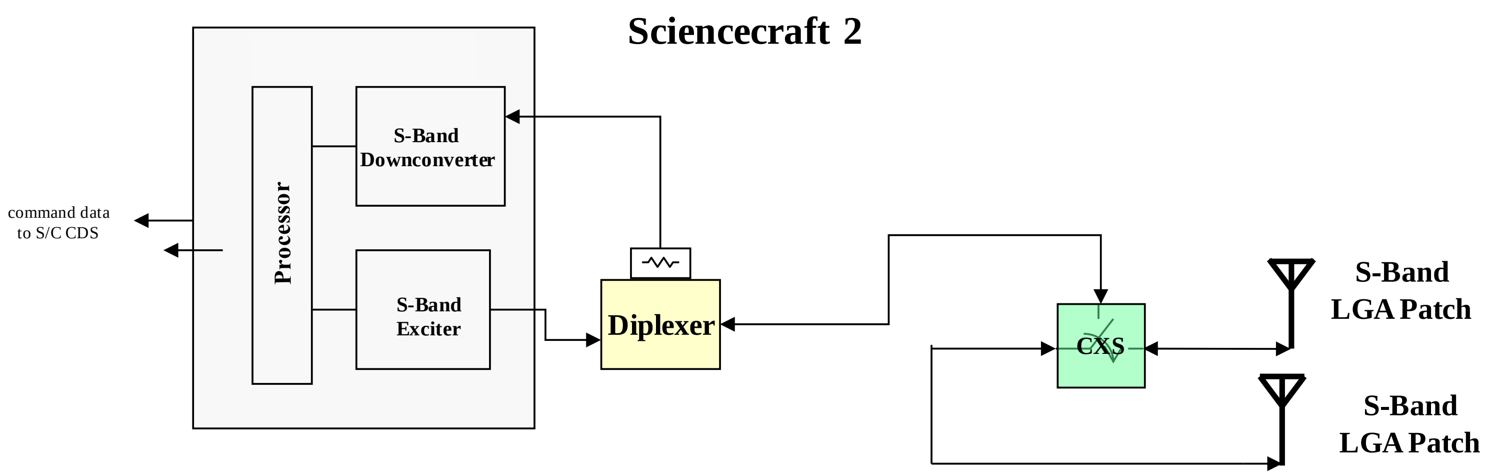
Telecom
Design Assumptions

- **Operational Assumptions**
  - Will use S-Band for communications
  - The subsystem is single string on each Sciencecraft
  - Each Sciencecraft will have two LGAs pointed opposite of each other
    - On Sciencecraft 1 and 3, the LGAs will be on the ends. On Sciencecraft 2, the LGAs will be on the front and back of the vehicle
- **Antenna Assumptions**
  - Two LGAs will be positioned on opposite sides of each S/C to provide 4π steradian coverage
- **Ground Station Assumptions**
  - 34m BWG DSN ground stations with 20 kW transmitters
- **Coding Assumptions**
  - Assume a rate ½, k=7 convolutional code concatenated with a Reed-Solomon outer code (255, 223)
  - If CDS can provide turbo coding, that will provide better performance with lower overhead
- **Launch and Cruise Phase**
  - During launch and cruise out to L2, the three vehicles are together on the propulsion stage
  - It is assumed that Sciencecraft 1 and 3 will be oriented toward the sun and Earth during launch and cruise
  - Can use the S-Band system on either one to communicate to Earth
  - If the prop stage design changes such that the Sciencecraft LGAs are covered up, it may be necessary to add one or two LGAs to the prop stage for communications
    - This could be done passively or through a switch from one of the Sciencecraft telecom subsystems

- **Overall system description**
  - Telecom is a single string S-band system on both types of sciencecraft
  - Each vehicle will have two S-Band patch LGAs
- **Hardware Includes:**
  - Two S-band low gain antennas
    - Surrey S-Band patch antenna or similar
  - One S-band transponder
    - With built in 5 W SSPA and diplexer
  - Filters, switch, and coax cabling
    - Will use a Magic Tee or splitter on Sciencecraft 1 and 3 to split the power equally between the LGAs
    - Sciencecraft 2 will use a switch to choose between the LGAs
- **Estimated total mass of 4.4 kg for Sciencecraft 1 and 3**
  - 4.3 kg for Sciencecraft 2

Block Diagram – Option X





Telecom
Cost

Costing Assumptions

- Single Spares for the 3 Sciencecraft
- Costs for telecom support to ATLO carried by systems chair
- No telecom hardware or support is included for testbeds

Option 1 – Sciencecraft 1

- Sciencecraft 1 And 3
- NRE: $9.7M   RE: $7.4M   Total: $17.1M
- Sciencecraft 2:
- NRE: $1.2M   RE: $1.6 K   Total: $2.8M
- Total for 3 Sciencecraft is $24.4M

Telecom
Risk, Option Comparison & Additional Comments

- **Low telecom risk mission**
  - Standard near-Earth S-band components
  - All components have flight heritage
  - Single-string design for relatively short mission duration
- **Option Comparison**
  - The designs for Sciencecraft 1 and 3 are identical
  - The design for Sciencecraft 2 is slightly different
    - The LGAs are on the front and back of the S/C and a switch is used instead of a splittler (Magic Tee)
- **Additional Comments**
  - The design is single string.
  - The cost to add redundancy would be around $4M.

Ground Systems Report

(1280) LaGrange 2012-03
March 20-22, 2012

Author: Douglas Equils

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Ground Systems
Design Requirements

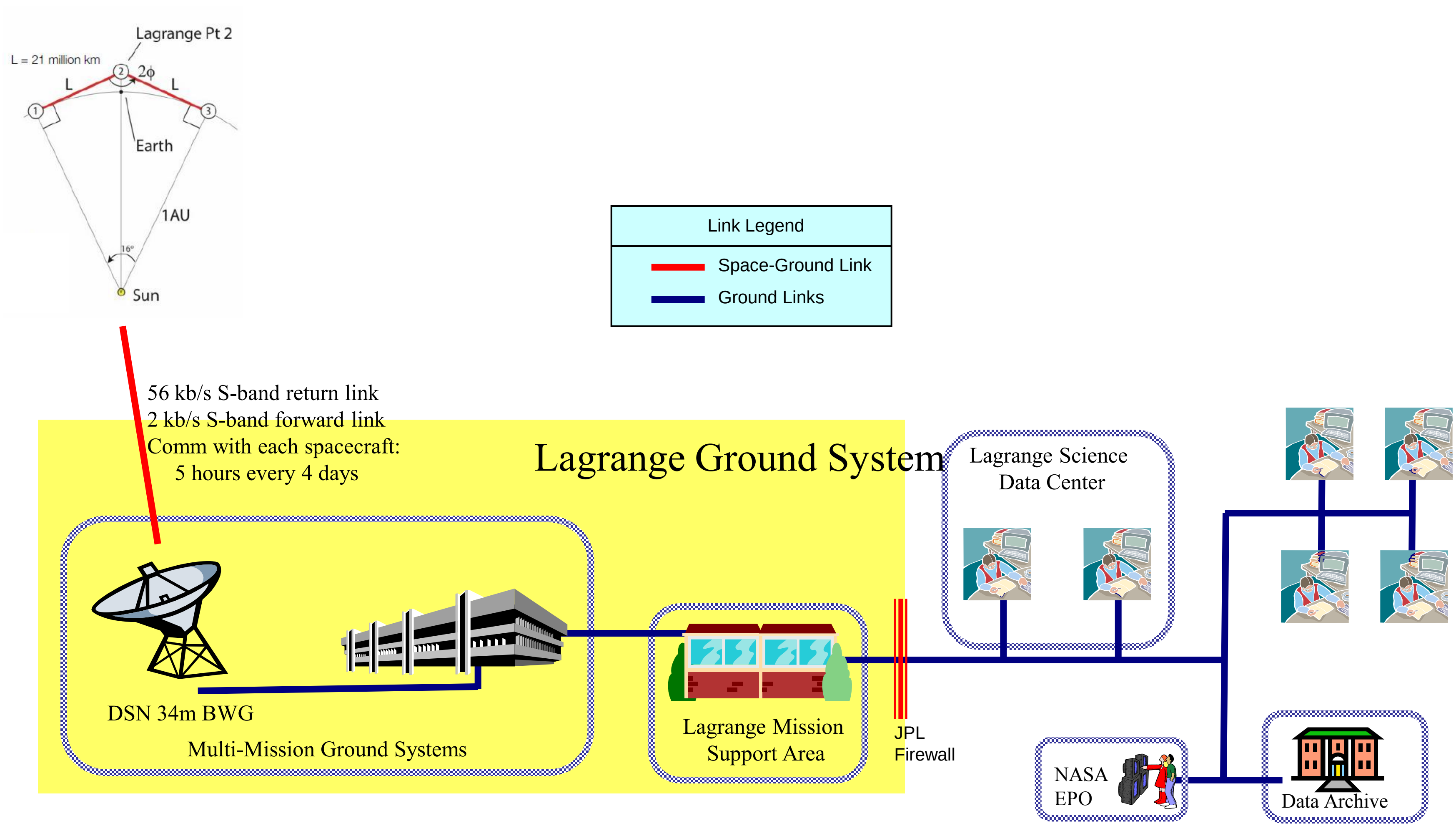
- **Mission:**
  - A Space-Based Gravitational-Wave Detector with Geometric Suppression of Spacecraft Noise
  - Three spacecraft flying in formation
  - Main S/C @ L2, one S/C Earth Trailing, one S/C Earth Leading
- **Data Volumes**
  - ~1 Gb every four days
    - Board capacity is 96GB (7670% margin).
  - Total Data Production: ~ 300 b/s of science data, 3 Kb/s of housekeeping
- **EEIS**
  - 95% return goal
  - No stressing timing requirements
- **Commanding Requirements**
  - Planned for once a week for nominal commanding

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**

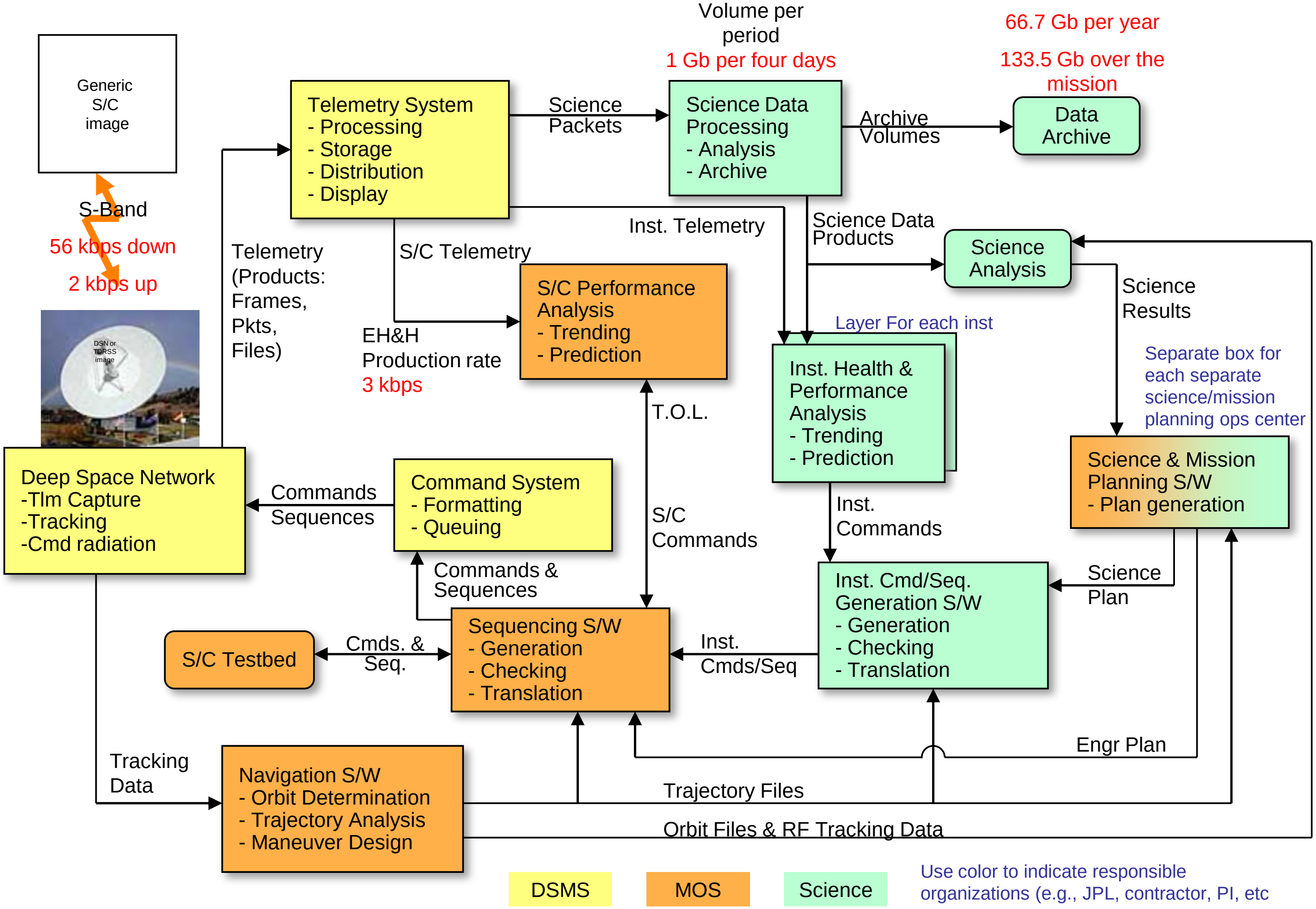
Activity Number	Activity Name	Start Date	End Date	Type	Numb
1	Launch and Operations	1-Jun-23	1-Jul-23	LEOP	
2	Cruise to operating orbit	2-Jul-23	28-Mar-25	Reg Cruise	
3	Commissioning	29-Mar-25	28-May-25	Encounter	
4	Science Observation	29-May-25	31-Oct-27	Routine Science	

Operational View



Ground Systems Design

Functional View



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
- Applied provided plan of 1 pass every 4 days per spacecraft (works out to ~1.75 passes per week)
- Spacecraft too far apart to enable multi-spacecraft per antenna reception

Support Period		Antenna	Service	Hours per	No. Tracks	No. Weeks
No	Name	Size	Year	Track	per Week	Required
(#)	(description)	(meters)	(year)	(hours)	(# tracks)	(# weeks)
1	Launch and Operations	34BWG	2023	8	21.0	2.0
2	Launch and Operations	34BWG	2023	8	14.0	2.0
3	Cruise to operating orbit- Crui	34BWG	2023	8	1.0	91.0
4	Cruise to operating orbit- TCM	34BWG	2023	8	7.0	1.0
5	Commissioning- init encounte	34BWG	2023	8	21.0	4.0
6	Commissioning- extended enc	34BWG	2023	8	7.0	5.0
7	Science Observation- DTE	34BWG	2023	5	1.8	127.0

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 this baseline estimate staffing was kept at the full level because the 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.

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)
1	$23.77	$29.25	$31.25	$8.32	$1.81	$8.78	$1.79	$103.18

Ground Systems
Cost

Cost Drivers

- Long development schedule drives ground system and engineering support during development.

Potential Cost Savings

- Offsetting the ground system development from the project schedule will reduce cost. You still need to 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.

Risk

List of Risks

- The post L2 insertion maneuvers for ScienceCraft 1 and 3 are only 2 days apart. Sufficient planning and testing for these maneuvers must occur prior to separation. If there is an anomaly during either of the maneuvers, this could be problematic.
- The challenges in this mission are in the instrument design and autonomy, if these don't work there is no mission.

Software Report

(1280) LaGrange 2012-03
March 20-22, 2012

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Software

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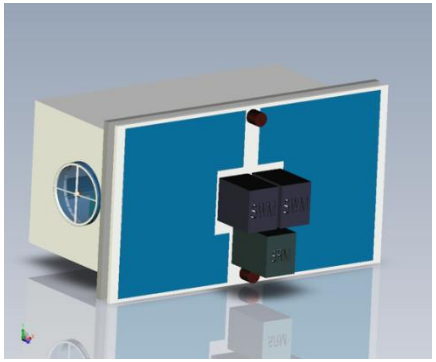
Software
Design Requirements – Option 1

- **Mission:**
  - Three Sciencecraft (S/C) constellation centered at Sun-Earth Lagrange point 2
    - S/C2 – located at Sun-Earth Lagrange Point 2
      - Dual Telescope System
      - Stores Science data
      - Downlinks Science data
    - S/C1 and S/C3 – located at +/-8 degrees, respectively, off the Sun-Earth axis
      - Single Telescope System
    - Ground provides each S/C with precision location of the other S/Cs
- **Data**
  - Optical Science Data is utilized to provide delta-v inputs to acs at each S/C
  - Science Data is accumulated on center S/C
- **Instrument**
  - Sciencecraft constellation IS the instrument
  - Suite of Sensors mounted on each S/C
    - Interferometer Measurement System (IMS)
    - Accelerometer
    - Solar Wind Monitor
    - Solar Radiance Monitor
- **Team Geographical Distribution: Fully co-located in-house flight software development team**



Design Assumptions – Option 1

- **Assumes Flight Software is identical for all 3 Sciencecraft**
  - Only difference is that the center S/C has 2 telescopes, while the other S/C only have one each
    - This does not affect FSW, as we count the number of different types of interfaces, not the count of all interfaces
- **Each sciencecraft is a medium complexity orbiter with S-band communications, several science instruments, and full ACS**
  - There are lunar flybys
    - One target (the Moon)
    - No science observation during flybys
    - S/C 2 has one flyby with S/C's 1 and 3 attached to S/C2
    - S/C 1 and S/C 3 each have a subsequent solo lunar flyby
  - Knowledge of the location of other S/C (provided by the Ground) is sufficient to locate and maintain lock on the optical signal provided by the other S/C

Software
Design – Option 1

ACS Features
- The ACS itself is probably medium complexity (3-axis control), but the instruments require the FSW to analyze and process data in real time in order to perform the challenging pointing requirements
- The commanding of the propulsion module is from the spacecraft computer, and it has moderate complexity thrust vector control
- 1 simple deployment: various optics covers
- 1 moderate complexity sequenced separation of the S/C from the propulsion modules

CDS Features
- Significant onboard storage and organization
  - S/C2 collects all the science data and sends it to the ground.
  - CDS is the same for all 3 S/C to save costs
- Moderate radiation environment: Sun-earth Lagrange
- flash memory on board
- Dual string, cold sparing
  - Single CPU per string

Engineering Subsystems (thermal, power, telecom)
- Difficult thermal and power control requirements
- Simple telecom requirements

Payload Accommodation
- Interface for Propulsion Module is costed as a Carrier Spacecraft Mission Configuration item
- Simple Interface for Force Measurement System
- Moderate complexity Interface for the Interferometer Measurement System (IMS)
  - Provide real time control and logic for processing S/C pointing data
- Moderately complex Science Data Analysis – determine delta-v inputs to acs needed to retain lock on the optical signal emitted by other nodes in the constellation

Software
Cost Assumptions – Option 1

- **Costing as 1 design versus 2 designs**
  - Single design based on the Center Sciencecraft with extra functionality disabled on End Sciencecrafts
  - If we model it as 2 different science crafts with heritage from one, can result in higher costs $15M
- **Treating FSW Development team as highly experienced**
  - Developer has past experience with Earth orbiting missions
- **MSAP heritage is assumed for this cost estimate**
  - Level: Major SW inheritance with minor HW modification
  - Note: MSAP Avionics is not used – using MSAP heritage for costing purposes only

Software

Cost – Option 1

- NRE: $18.9M
- RE: $1M
- Total: $19.9M
- Total (all 3 sciencecraft): $21.9M

Software
Cost – Option 1

Cost Drivers

- None

Potential Cost Savings

- As mentioned previously, costing as 1 design (with extra functionality disabled) instead 2 designs with high inheritance from the 1st design.

Potential Cost Uppers

- Level of inheritance from previous missions is typically over stated resulting in greater levels of new code. This would result in a change in the cost estimate.

Risk and Additional Comments

List of Risks

- Overly optimistic assumption of inheritance from heritage mission.
- Mitigation: reduce the level of assumed inheritance.

Additional Comments

- None

Programmatics Report

(1280) LaGrange 2012-03
March 20-22, 2012

Author: Jared Lang

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Schedule Requirements

- **Launch Date: June, 1, 2023**
- **Phase E Duration: 53 months (24 months prime science)**
- **Partners: GSFC**
- **Major Schedule Constraints**
  - Launch date is driven by lunar alignment required to achieve science orbit
  - Technology Development Cutoff: 04/01/17

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

Schedule Assumptions

- **Implementation Mode: In-House**
- **Mission Timeline**
  - Cruise: 26 months (for Sciencecraft 1 and 3)
  - Commissioning: 3 months
  - Science operations: 24 months
- **Location of assembly/testing**
  - S/C: In-House
  - Instruments: In-House
- **The assumption is that the mission will meet the TRL cutoff date with the elements that are part of technology development.**
- **A conservative low risk schedule was assumed for LAGRANGE**
  - With further analysis it is expected the Phase D schedule could be reduced from 3 to 6 months. But insufficient information is available to make the change at this time.
  - At a monthly burn rate of $10M-$15M in Phase D this could reduce cost by $30M to $90M.

Schedule

- **Key Dates:**
  - Phase A start: 10/1/2014
    - PMSR - 1/1/2016
  - Phase B start: 1/7/2016
    - PDR - 4/1/2017
  - Phase C start: 4/1/2017
    - CDR - 4/1/2019
  - Phase D start: 4/1/2021
    - PSR - 3/1/2023
  - Launch: 6/1/2023

Phase	***Duration (months)***
A	15
B	15
C/D	75
C Design	24
Fab	12
D I&T	12
D Launch	23
D: L + 30	4
E	53
A-D	105

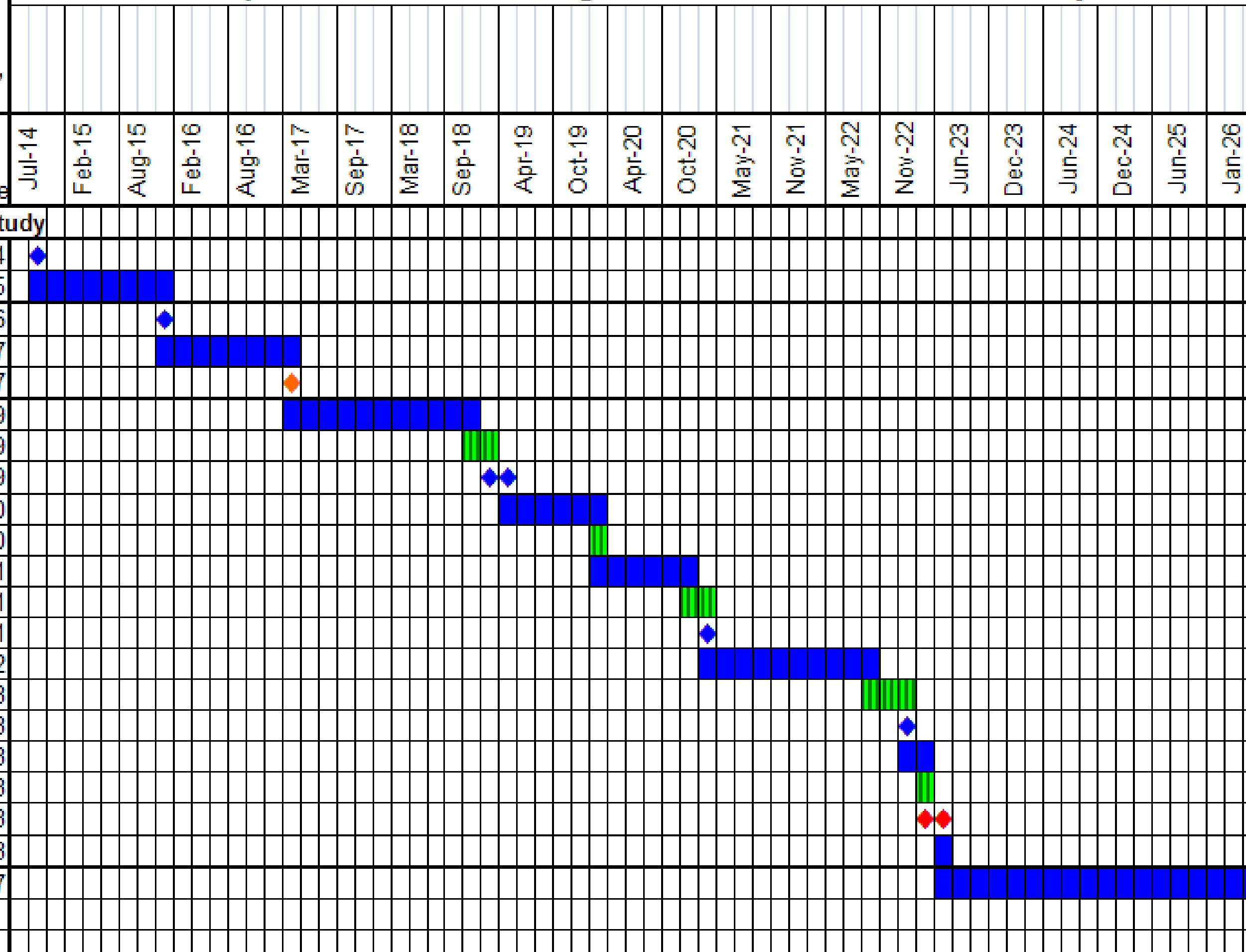
Programmatics

Schedule

Sample Schedule for LaGrange Gravitational Wave Detector Study

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

Phase	Start Date	End Date
LaGrange Gravitational Wave Detector Study		
MCR	10/01/14	10/03/14
Ph A Project Definition	10/01/14	12/25/15
PMSR	01/01/16	01/03/16
Ph B Preliminary Design	01/07/16	04/01/17
CR/PDR/Tech Cutoff	04/01/17	04/04/17
Ph C Design	04/01/17	01/21/19
Margin	01/21/19	04/01/19
CDR	04/01/19	04/04/19
Ph C Fabrication	04/04/19	02/28/20
Margin	02/28/20	03/29/20
Ph C S/S I&T	03/29/20	02/22/21
Margin	02/22/21	04/01/21
ARR (ph D)	04/01/21	04/04/21
Proj I&T (ATLO)	04/04/21	10/31/22
Margin	10/31/22	03/01/23
PSR	03/01/23	03/04/23
Launch Ops	03/04/23	05/12/23
Margin	05/12/23	06/01/23
Launch	06/01/23	06/22/23
L+30-end Ph D	06/22/23	07/22/23
Phase E	07/22/23	11/28/27



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

Risk Report

(1280) LaGrange 2012-03
March 20-22, 2012

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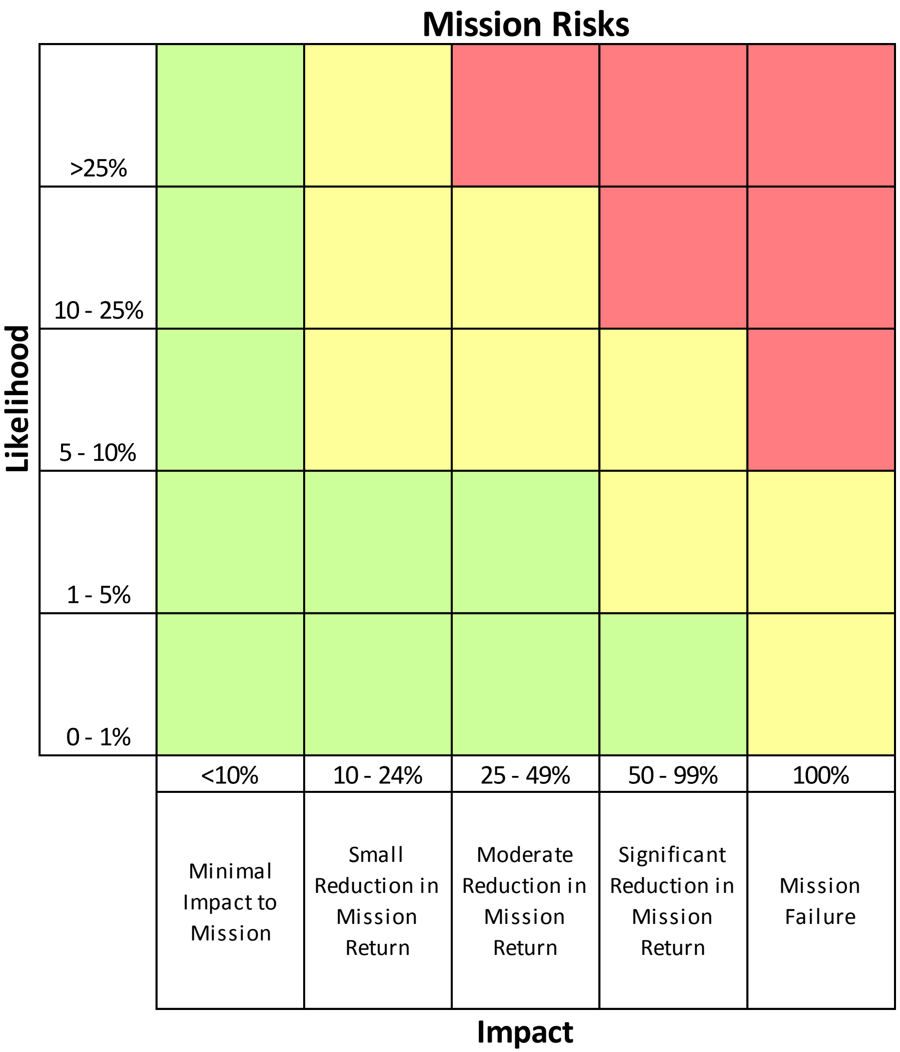
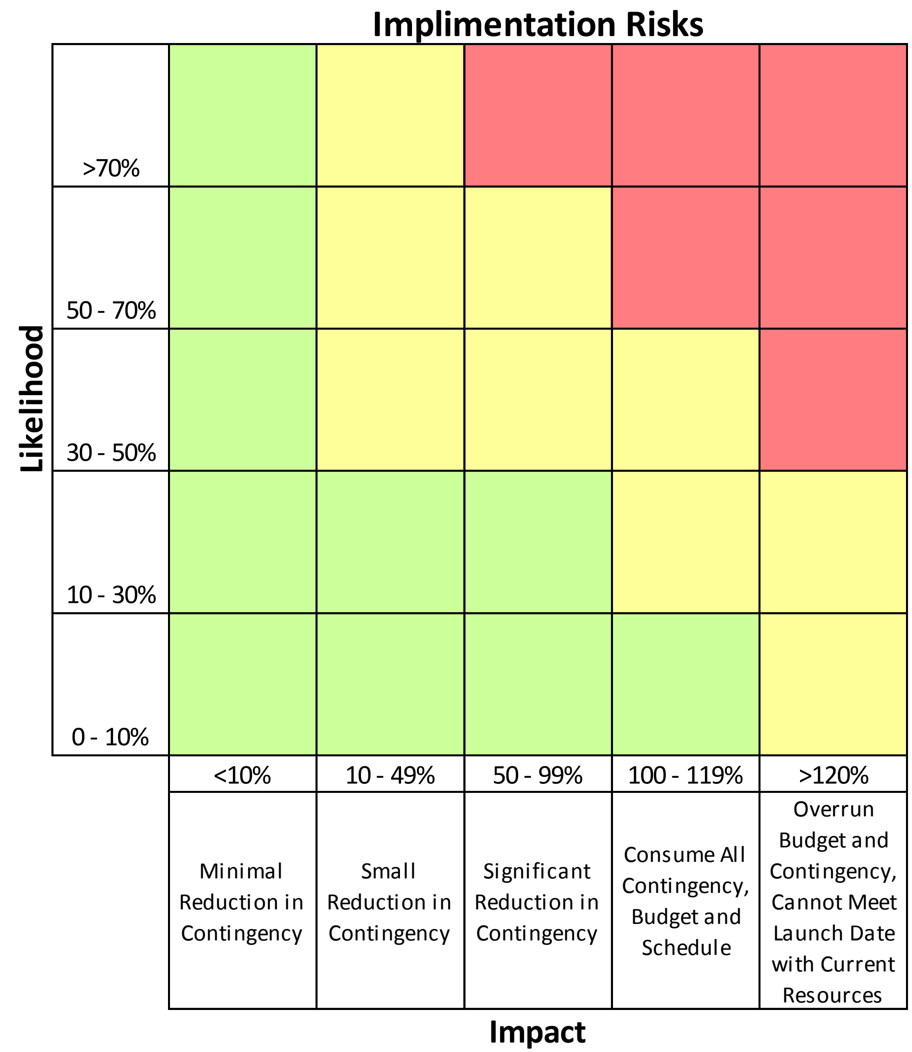
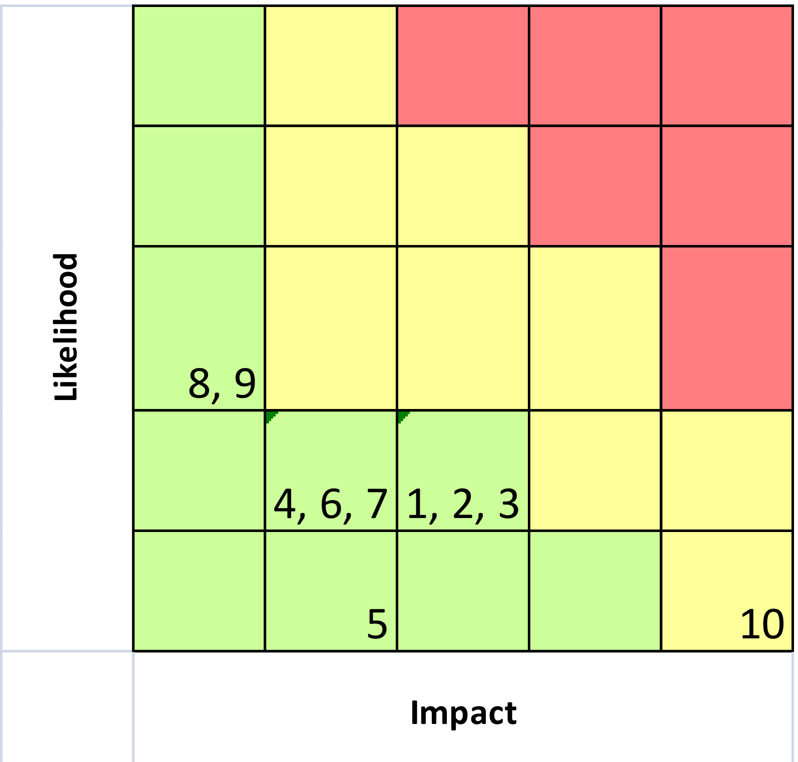
Methodology
Risk Guidance

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





Risk
System Level Risk Summary – All Options



- **As currently proposed LAGRANGE is relatively low risk for a mission of this scope**
- **There is one medium risk that may potentially affect the science return of the mission:**
  - Failure of a critical component will result in mission failure (10)
- **There are a number of minor risks including:**
  - Event rates for massive black hole binary mergers and extreme-mass-ratio-inspirals (1 & 2)
  - Low TRL photoreceivers (4)
  - Star Tracker cost growth and manufacturing (8 & 9)
  - Heritage software algorithms (6)
  - Time critical maneuvers (3)
  - Difficulty measuring external forces (7)
  - Re-qualification of the Colloidal feed system (5)
- **There is also one proposal risks that require special attention when proposing the mission**
  - Inability to “test-as-we-fly” due to large spacecraft architecture

Medium Risk Items

Risk #	Submitter	Risk Type	Title	Description of Risk	Likelihood	Impact
10	Programmatics/Risk	Mission	Failure of Critical Component	Mission requires all three spacecraft to be operational to make measurements. There is no graceful degredation in science if one of the instrument links are lost. Though the spacecraft and instruments are fully redundant, loss of a critical component aboard any spacecraft will result in mission failure.	1	5

Risk

Minor Risk Items

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	Mission	Sciencecraft 1 and 3 Maneuver Separation	The post L2 insertion maneuvers for Sciencecraft 1 and 3 are only 2 days apart. Since this maneuver may be time critical, sufficient planning and testing for these maneuvers must occur prior to separation. If an anomaly occurs before or during either of the maneuvers, there may be significant additional time required for the Sciencecraft to achieve orbit. Since these orbits are only stable for roughly 2 years without significant orbit maintenance, this additional time may reduce the observing time in orbit.	2	3
4	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
5	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
6	Programmatics/Risk	Implementation	Algorithm / Software Cost Growth	The current cost estimate for the ACS pointing software algorithms assume small changes to extant ACS software, which seems reasonable. However, the Lagrange mission is novel and does not have the heritage of the LISA architecture. New extensions to ACS algorithms may be required as new details about the mission are learned.	2	2
7	Programmatics/Risk	Mission	Difficulty of measuring external forces	Mission success requires measurement of the force on S/C from the solar wind to ~1%. Currently this seems possible, but certainly requires more careful study. Fortunately, degradation in the science would be quite smooth. E.g., if solar-wind force errors are at ~2% level, then low-f noise increases by factor of 2, while high-f noise is practically unaffected. Similarly for noise from radiation pressure.	2	2
8	Programmatics/Risk	Implementation	Star tracker cost growth	Few of the proposed star tracker have been made or flown. The cost is low compared to other commercial vendors, and the current accuracy is about half of what is needed. The proposed manufacturer 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.	3	1
9	Programmatics/Risk	Implementation	Star Tracker Manufacturing Process	The proposed star tracker is a relatively new item for the manufacturer. Few have been made or flown. In addition, the manufacturer is not a typical commercial supplier. Lagrange will require 12 optical heads, 5 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.	3	1

Proposal Risk Items

Risk Type	Title	Description of Risk	Likelihood	Impact
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

Cost Report

(1280) LaGrange 2012-03
March 20-22, 2012

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Cost

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Cost Disclaimer

- The costs presented in this report are ROM estimates, they are not point estimates or cost commitments. It is likely that each estimate could range from as much as 20% percent higher to 10% lower. The costs presented are based on Pre-Phase A design information, which is subject to change.

Cost Requirements

- Costs reported as FY 2012 $M
- Cost Target: For background information the sponsor provided previous sponsor-derived costs for Lagrange ($1.1B)
- Cost estimates down to WBS levels 2 and 3 lifecycle costs
- Includes comparison with SGO-Mid cost (Study 1279)

Cost Assumptions

- **Fiscal Year: 2012**
- **Mission Class: B**
- **Cost Category: Large**
- **Launch Vehicle: NLS-2 Contract**
- **Lagrange flight system is a constellation of three sciencecraft + prop stages, two of which are identical (end) and a third (center) that has many similar design features**
- **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, estimated total cost based on 20% reserves (instead of 30%)**

Cost Assumptions

- **Phase A duration: 15 mos**
- **Phase B duration: 15 mos**
- **Phase C/D duration: 75 mos**
- **Phase E duration: 52 mos**
- **Phase F duration: 24 mos**
- **Instruments:**
  - IMS (1 per end sciencecraft, 2 on center sciencecraft)
  - Accelerometers (1 per sciencecraft)
  - Solar Wind Monitors (1 per sciencecraft)
  - Solar Radiance Monitor (1 per sciencecraft)
- **Spares approach: Long lead and card level spares where appropriate**
- **Parts class: commercial and military 883**

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 itemized separately from the instrument costs
  - Flight System – Flight System Management and System Engineering costs are accounted for within the primary element (Sciencecraft 1) and were estimated using Team X models with an in-house build assumption
- **ATLO: Team X ATLO cost model was run assuming the Sciencecraft 1 as the primary element and the remaining Sciencecraft and Prop Stages as secondary units**
- **Costs for Subsystem Management and System Engineering, spares and GSE bookkept by subsystems typically within primary element (Sciencecraft 1) – see individual subsystem write-ups**

Generate ProPricer Input

Cost
Total Cost

COST SUMMARY (FY2012 $M)	Team X Estimate		
	CBE	Res.	PBE
Project Cost	**$1307.6 M**	**26%**	**$1643.1 M**
Launch Vehicle	**$178.7 M**	**0%**	**$178.7 M**
Project Cost (w/o LV)	**$1128.9 M**	**30%**	**$1464.4 M**
Development Cost	**$1017.6 M**	**30%**	**$1322.3 M**
Phase A	$14.9 M	30%	$19.3 M
Phase B	$73.1 M	30%	$95.1 M
Phase C/D	$929.6 M	30%	$1208.0 M
Operations Cost	**$111.3 M**	**28%**	**$142.0 M**

The total life cycle cost for Option 1 is $1.64B. The development cost including reserves is $1.3B. Total reserves are $335M. The launch vehicle is $179M.

TEAM X Jet Propulsion Laboratory

JPL

Cost

Cost – Development

WBS Elements	NRE	RE	1st Unit	All Units	
Project Cost (including Launch Vehicle)	$1,010.8	$414.3	$1,425.2	$1643.1 M	
Development Cost (Phases A - D)	$703.6 M	$409.8 M	$1113.4 M	$1322.3 M	
01.0 Project Management	$25.6 M		$25.6 M	$25.6 M	
02.0 Project Systems Engineering	$29.9 M	$0.3 M	$30.2 M	$30.8 M	
03.0 Mission Assurance	$25.8 M	$5.7 M	$31.5 M	$42.8 M	
04.0 Science	$11.4 M		$11.4 M	$11.4 M	
05.0 Payload System				$255.1 M	
End Spacecraft	$63.2 M	$49.9 M	$113.1 M	$163.1 M	
IMS	$38.4 M	$27.8 M	$66.2 M	$94.0 M	
Accelerometers	$7.7 M	$5.6 M	$13.3 M	$18.9 M	
Solar Wind Monitor	$5.8 M	$8.4 M	$14.1 M	$22.5 M	
Solar Radiance Monitor	$11.3 M	$8.2 M	$19.5 M	$27.7 M	
Center Spacecraft	$0.0 M	$77.8 M	$77.8 M	$77.8 M	
IMS	$0.0 M	$55.6 M	$55.6 M	$55.6 M	override for NRE
Accelerometers	$0.0 M	$5.6 M	$5.6 M	$5.6 M	override for NRE
Solar Wind Monitor	$0.0 M	$8.4 M	$8.4 M	$8.4 M	override for NRE
Solar Radiance Monitor	$0.0 M	$8.2 M	$8.2 M	$8.2 M	override for NRE

06.0 Flight System				$491.4 M	
6.01 Flight System Management	$6.2 M		$6.2 M	$6.2 M	
6.02 Flight System Systems Engineering	$47.6 M		$47.6 M	$47.6 M	
6.03 Product Assurance (included in 3.0)			$0.0 M	$0.0 M	
End Spacecraft	$162.4 M	$59.5 M	$221.9 M	$281.3 M	
6.04 Power	$14.2 M	$11.7 M	$25.8 M	$37.5 M	
6.05 C&DH	$21.6 M	$12.5 M	$34.1 M	$46.6 M	
6.06 Telecom	$9.7 M	$7.4 M	$17.1 M	$24.4 M	
6.07 Structures (includes Mech. I&T)	$23.1 M	$10.7 M	$33.9 M	$44.6 M	
6.08 Thermal	$1.5 M	$1.8 M	$3.2 M	$5.0 M	
6.09 Propulsion	$58.3 M	$7.7 M	$66.1 M	$73.8 M	override from prop
6.10 ACS	$12.3 M	$5.9 M	$18.2 M	$24.1 M	
6.11 Harness	$2.4 M	$0.7 M	$3.1 M	$3.8 M	
6.12 S/C Software	$18.9 M	$1.0 M	$19.9 M	$20.9 M	
6.13 Materials and Processes	$0.5 M	$0.1 M	$0.5 M	$0.6 M	
Center Spacecraft	$19.3 M	$46.6 M	$65.9 M	$65.9 M	
6.04 Power	$2.7 M	$6.3 M	$9.0 M	$9.0 M	
6.05 C&DH	$0.0 M	$12.5 M	$12.5 M	$12.5 M	override from CDH
6.06 Telecom	$1.2 M	$1.6 M	$2.8 M	$2.8 M	
6.07 Structures (includes Mech. I&T)	$6.5 M	$4.4 M	$10.8 M	$10.8 M	
6.08 Thermal	$6.0 M	$6.4 M	$12.4 M	$12.4 M	
6.09 Propulsion	$0.0 M	$7.7 M	$7.7 M	$7.7 M	override from prop
6.10 ACS	$0.0 M	$5.9 M	$5.9 M	$5.9 M	override from ACS
6.11 Harness	$2.4 M	$0.7 M	$3.1 M	$3.1 M	
6.12 S/C Software	$0.0 M	$1.0 M	$1.0 M	$1.0 M	override from SW
6.13 Materials and Processes	$0.5 M	$0.1 M	$0.5 M	$0.5 M	
Prop Stage End Spacecraft	$13.7 M	$15.0 M	$28.7 M	$43.8 M	
6.04 Power	$0.0 M	$0.0 M	$0.0 M	$0.0 M	
6.05 C&DH	$0.0 M	$0.0 M	$0.0 M	$0.0 M	
6.06 Telecom	$0.0 M	$0.0 M	$0.0 M	$0.0 M	
6.07 Structures (includes Mech. I&T)	$5.3 M	$6.2 M	$11.5 M	$17.7 M	
6.08 Thermal	$0.0 M	$1.4 M	$1.4 M	$2.7 M	
6.09 Propulsion	$5.6 M	$6.8 M	$12.4 M	$19.2 M	
6.10 ACS	$0.0 M	$0.0 M	$0.0 M	$0.1 M	
6.11 Harness	$2.4 M	$0.6 M	$3.0 M	$3.6 M	
6.12 S/C Software	$0.0 M	$0.0 M	$0.0 M	$0.0 M	
6.13 Materials and Processes	$0.4 M	$0.0 M	$0.5 M	$0.5 M	
Prop Stage Center Spacecraft	$13.6 M	$17.0 M	$30.6 M	$30.6 M	
6.04 Power	$0.0 M	$0.0 M	$0.0 M	$0.0 M	
6.05 C&DH	$0.0 M	$0.0 M	$0.0 M	$0.0 M	
6.06 Telecom	$0.0 M	$0.0 M	$0.0 M	$0.0 M	
6.07 Structures (includes Mech. I&T)	$8.6 M	$5.8 M	$14.4 M	$14.4 M	
6.08 Thermal	$2.1 M	$3.5 M	$5.6 M	$5.6 M	
6.09 Propulsion	$0.0 M	$6.8 M	$6.8 M	$6.8 M	override from prop
6.10 ACS	$0.3 M	$0.3 M	$0.6 M	$0.6 M	
6.11 Harness	$2.3 M	$0.6 M	$2.8 M	$2.8 M	
6.12 S/C Software	$0.0 M	$0.0 M	$0.0 M	$0.0 M	
6.13 Materials and Processes	$0.4 M	$0.0 M	$0.5 M	$0.5 M	
6.14 Spacecraft Testbeds	$8.0 M	$2.7 M	$10.6 M	$15.9 M	

Cost – Development (continued)

07.0 Mission Operations Preparation	$27.7 M	$27.7 M	$27.7 M
09.0 Ground Data Systems	$31.7 M	$31.7 M	$31.7 M
10.0 ATLO			$81.1 M
11.0 Education and Public Outreach			$3.6 M
12.0 Mission and Navigation Design	$16.3 M	$16.3 M	$16.3 M
Development Reserves			$304.7 M

Cost - Operations

Operations Cost (Phases E - F)	$128.5 M	$4.5 M	$133.0 M	$142.0 M
01.0 Project Management	$6.1 M		$6.1 M	$6.1 M
02.0 Project Systems Engineering	$0.0 M	$0.0 M	$0.0 M	$0.0 M
03.0 Mission Assurance	$0.5 M	$0.4 M	$0.9 M	$1.7 M
04.0 Science	$34.1 M		$34.1 M	$34.1 M
07.0 Mission Operations	$45.5 M		$45.5 M	$45.5 M
09.0 Ground Data Systems	$8.5 M		$8.5 M	$8.5 M
11.0 Education and Public Outreach	$6.2 M	$3.1 M	$9.3 M	$15.4 M
12.0 Mission and Navigation Design	$0.0 M		$0.0 M	$0.0 M
Operations Reserves	$27.6 M	$1.0 M	$28.7 M	$30.7 M
8.0 Launch Vehicle	$178.7 M		$178.7 M	$178.7 M
Launch Vehicle and Processing	$178.7 M		$178.7 M	$178.7 M
Nuclear Payload Support	$0.0 M		$0.0 M	$0.0 M

Cost Potentials

- **Potential Cost Savings**
  - Using 20% reserves brings the total project cost down about 7% to $1.5B but increases cost risk
  - Additional cost savings can be achieved if the development schedule is compressed so that it is consistent with the SGO-Mid schedule. 9 months of schedule reduction in Phases C/D could result in savings of as high as ~$100M.
  - Possible cost savings if the three prop stages were identical.

- **Potential Cost Uppers**
  - Cost efficiencies will be lost if there are changes to the design of the center sciencecraft that allow it to deviate further from the design of the end sciencecraft

List of Risks

- The cost includes significant savings due to the design similarities between the center sciencecraft and the two identical end sciencecraft. This allowed many of the subsystems to use recurring costs only for the center sciencecraft. Design changes that make the center sciencecraft deviate further from the end sciencecraft could result in significant cost growth.

Cost
Comparison Lagrange vs. SGO-Mid

- **Total project cost for Lagrange ($1.6B) is 14% lower than total project cost for SGO-mid ($1.9B)**
- **Major cost differences:**
  - Payload ($127M less than SGO-mid)
  - Launch vehicle ($68M less)
  - Structures subsystem ($73M less for sciencecraft)
  - A-E Reserves ($44M less)

	LaGrange	SGO-Mid
WBS Elements	All Units	All Units
Project Cost (including Launch Vehicle)	$1643.1 M	$1902.7 M
Development Cost (Phases A - D)	$1322.3 M	$1530.4 M
01.0 Project Management	$25.6 M	$22.8 M
02.0 Project Systems Engineering	$30.8 M	$27.5 M
03.0 Mission Assurance	$42.8 M	$36.2 M
04.0 Science	$11.4 M	$10.2 M
05.0 Payload System	$255.1 M	$382.5 M
06.0 Flight System	$491.4 M	$546.0 M
07.0 Mission Operations Preparation	$27.7 M	$28.2 M
09.0 Ground Data Systems	$31.7 M	$28.9 M
10.0 ATLO	$81.1 M	$80.8 M
11.0 Education and Public Outreach	$3.6 M	$4.1 M
12.0 Mission and Navigation Design	$16.3 M	$10.6 M
Development Reserves	$304.7 M	$352.8 M
Operations Cost (Phases E - F)	$142.0 M	$125.3 M
01.0 Project Management	$6.1 M	$5.5 M
02.0 Project Systems Engineering	$0.0 M	$0.0 M
03.0 Mission Assurance	$1.7 M	$1.4 M
04.0 Science	$34.1 M	$33.8 M
07.0 Mission Operations	$45.5 M	$39.3 M
09.0 Ground Data Systems	$8.5 M	$6.5 M
11.0 Education and Public Outreach	$15.4 M	$12.3 M
12.0 Mission and Navigation Design	$0.0 M	$0.0 M
Operations Reserves	$30.7 M	$26.6 M
8.0 Launch Vehicle	$178.7 M	$246.9 M