TEAM X SUMMARY for Space-Based Gravitational-Wave Detector
with Geometric Suppression of Sciencecraft Noise (LAGRANGE)
FOR UNLIMITED RELEASE

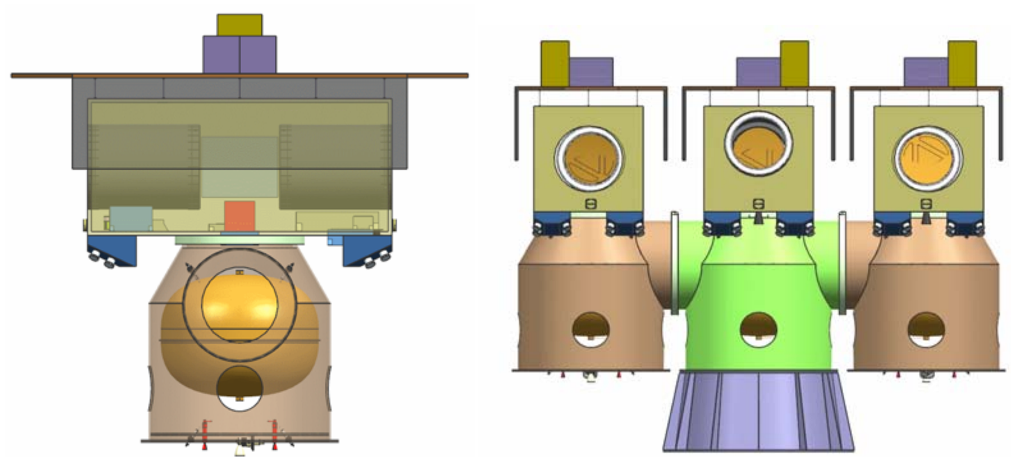

Figure 1: Sciencecraft with prop module (left); launch configuration (right)

Title: Team X Study of the LAGRANGE Mission

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Overview

This study was carried out by the Advanced Projects Design Team (Team X) at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The goal was to provide a cost estimate and risk assessment for the proposed LAGRANGE mission. The LAGRANGE mission concept is derived from a mature concept for the Laser Interferometer Space Antenna (LISA) mission that was conceived in 1974 and has been studied in collaboration with the European Space Agency since 1993. Compared to LISA, LAGRANGE would provide reduced science return at a lower cost. The customer characterized the LAGRANGE concept as immature and gave Team X the charge to develop the concept further. Team X performed architectural trades related to constellation deployment, considering the configuration of the stack on the launch vehicle and trajectories that could be used to place each of three sciencecraft at its station. Starting from the customer baseline, Team X proposed concepts for sciencecraft designs and for nominal operations. Cost, schedule, and technical risks were captured for the Team X mission concept, and a project cost estimate was generated.

Baseline and Key System Parameters

LAGRANGE high-level scientific objectives are essentially the same as for LISA:

1. Understand the formation of massive black holes.
2. Trace the growth and merger history of massive black holes and their host galaxies.
3. Explore stellar populations and dynamics in galactic nuclei.
4. Survey compact stellar-mass binaries and study the structure of the Galaxy.
5. Confront General Relativity with gravitational wave observations.
6. Probe new physics and cosmology with gravitational waves.
7. Search for unforeseen sources of gravitational waves.

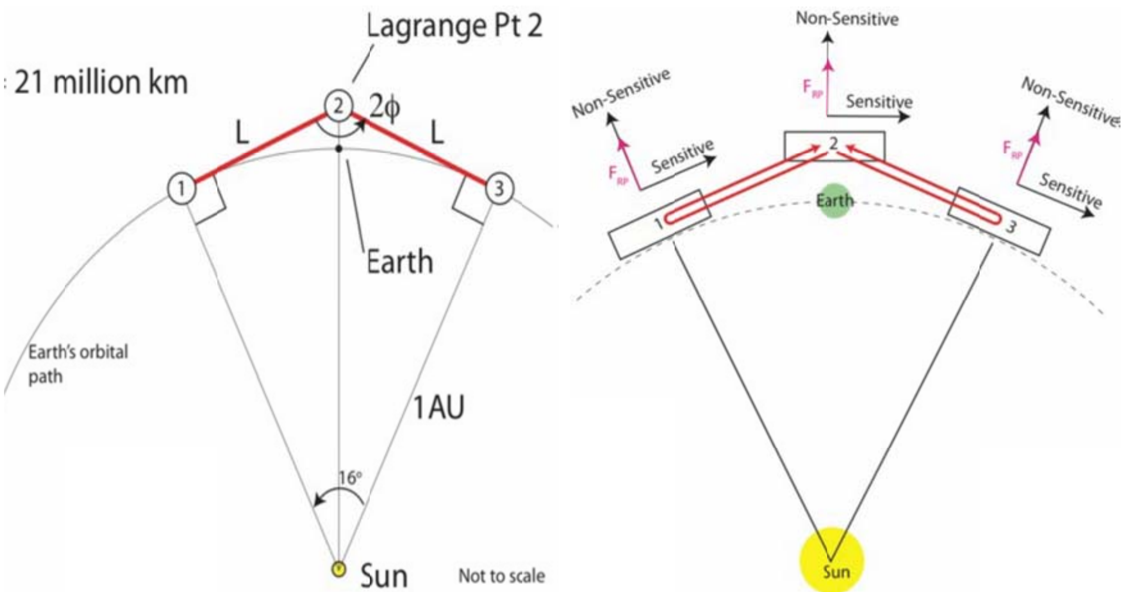

Figure 2: LAGRANGE constellation with geometric suppression

LAGRANGE will be a triangular constellation of three sciencecraft (SC). See Figure 2. SC-1 will be in an Earth-leading heliocentric orbit. SC-3 will be in an Earth-trailing orbit. SC-2 will be at Earth-Sun Lagrange point L2. The distance between adjacent pairs will be 21 million km. The constellation is the science instrument. Sciencecraft will be "proof masses". Gravitational waves will perturb sciencecraft relative positions by small but measureable distances.

Accurate measurements (~100pm/√Hz) will be obtained using an Interferometer Measurement System (IMS) consisting of four one-way interferometer links that are combined in post-processing to form a Michelson Interferometer. The phasemeter records the fringe signal with laser frequency noise correction by post processing. The LISA IMS has 50 channels; LAGRANGE has 9 channels. LAGRANGE will have relaxed sensitivity and fewer measurements.

The LAGRANGE baseline includes a simplified LISA IMS laser. The master is an NPRO-Nd:YAG with a 2 Watt power amplifier. The telescope is an in-line 40cm diameter f/1.5 Cassegrain with in-field guiding. There will be one LISA pathfinder heritage hydroxyl-bonded ULE optical bench per sciencecraft.

The inter-sciencecraft link also supports optical communications at up to 20 kbps, optical ranging on the carrier at 1 meter precision, and USO frequency transfer. Optical communications will be used to relay data from SC-1 and SC-3 to the SC-2, which will downlink data to Earth.

Each sciencecraft will be buffeted by solar wind and solar radiation fluctuations. A Force Measurement System (FMS) will measure these disturbances directly, and ground processing will remove these effects from the interferometer signal. Geometric suppression is a key feature in that regard. SC-1 and SC-3 have interferometer links nominally orthogonal to solar forces (within ±1 degree). SC-2 reacts to solar forces common to both arms, and is differenced in Michelson combination. There are “relaxed” stability requirements in two dimensions with a factor of 100 reduced sensitivity to the difference in the thermal radiation on the sciencecraft sides.

The FMS will be based on flown instruments with small modifications:

- Solar wind (particle) monitor (SWEPAM from ACE) to measure density, velocity of H, and He ions in two dimensions, to calculate force to 1%/rtHz.
- Radiometer (solar irradiance monitor) (VIRGO from SOHO) to measure solar variations to 1 part in 10^5/rtHz and calculate force to 1%/rtHz.
- Accelerometer (Electrostatic Gravity Gradiometer (EGG) for GOCE). This is for calibration with partial redundancy. Only one axis will be measured.

Key design features and mission parameters are summarized in Table 1.

Technical Findings

The design concept converged, and its launch mass fits on an Atlas V 511. The launch stack just fits within the 5-meter fairing, but could be optimized further for greater clearance. Going to the 4-meter fairing does not appear to be an option.

There are several minor risks and one medium risk, namely, that the mission requires all three spacecraft to be operational in order to make measurements. There is no graceful degradation in science if one of the instrument links is lost. Since the spacecraft and instruments are fully redundant, the likelihood of losing an instrument link is low.

Table 1: Key Design Features for LAGRANGE

			LAGRANGE
System	Launch Mass (kg) each (total)		531 (1&3) 586 (2) (3150)
	Sciencecraft Power (W) each		450 (Science on station with telecomm)
	Total Mission Cost ($B FY12)		1.6
	Radiation TID (krad)		22 (behind 100 mil of Aluminum, with an RDM of 2)
Science	Science Goals		Measuring gravitational waves
	Key Measurements		Laser ranging among 3 sciencecraft 21 M km apart
	Total Data Volume (Gbits)		200
Mission Design	Launch Date		June 1, 2023
	Launch Vehicle		Atlas V 511
	Launch Mass Allocation (kg)		3285
	Trajectory/Orbit Type		L2, earth trailing and earth leading orbits
	Mission Duration (months)		24 for science, 53 mos including insertion.
	Key Mission Phases		Launch, 4 mos checkout (inc'g establish laser links), 53 mos overall, science ops 24 mos, phase F 24 mos.
Instruments	Telescope	Type	Cassegrain
		Size	40 cm
	No. of Instruments		4 total 1, 2 and 1
	Instrument Types		IMS Accelerometer Solar Wind Monitor Solar Radiance Monitor
	Payload Mass (kg)		99.8 (1&3), 143.3 (2)
	Payload Power (W) per sciencecraft		99 (1&3), 160 (2)
	Payload Data Rate (Kbps)		0.5
ACS	Pointing Control (arcsec)		2
	Pointing Knowledge (arcsec)		1
	Pointing Stability (arcsec/sec)		0.1
	Stabilization Type		3-axis
	Pointing Technologies		Star trackers, sun sensors, colloid thrusters
CDH	Processor Type		RAD 750
	Redundancy (hot, cold, single string)		Dual cold
	Data Storage (Gbytes)		96 (214 Mbytes required)
Telecom	Bands		X
	Antenna Types		LGA horns (2)
	Uplink Rate (kbps)		0.05 through LGA
	Downlink Rate (kbps)		28 through LGA,
Power	Solar Array Area (m^2)		2.11 (1 & 3) 2.55 (2)
	Solar Array Type		GaAs Triple junction, fixed panel, no articulation
	EOL Power (W)		460 (1&3) 544 (2)
	Battery Storage Size(s) (A-hrs/Ty)		32/ Li-Ion ABSL (1,2&3)
Propulsion	No. of Prop Systems		2 (each 1,2 &3)
	Type(s) of System(s)		Blowdown hydrazine monoprop for Delta V, colloidal microthrusters for Science
	Propellant Mass(es) (kg)		174 (1&3) 113.7 (2)
Structures	Primary Structural Material		Machined aluminum and titanium with metallic honeycomb composite panels
	No. of Mechanisms		1
Thermal	Active/Passive		Heaters/radiators
	Key Operating Temperature(s) (K)		293
	Thermal Control Technologies		MLI, heaters, radiators, white paint
Ground System	Ground Antenna(s)		BWG ground station, 34m antenna
	Average Pass Duration (hrs)		5 =1 link every 2 days at 28 kbps from SC-2

Design Assumptions

1. *Class B mission*
2. *Costs in FY2012$*
3. *Total mass margin of 53% of dry mass CBE*
4. *Cost reserves of 30% (excluding launch vehicle) on Phase A through E*
5. *JPL's Design Principle margins elsewhere*
6. *NLS II launch vehicles and L/V costs*
7. *Three sciencecraft separated from three propulsion modules.*
8. *SC-1 and SC-3 are identical; each has one telescope.*
9. *SC-2 is as similar to SC-1 and SC-3 as possible, but with two telescopes.*
10. *Propulsion modules 1 and 3 have identical structures.*

Technical Details for LAGRANGE Subsystems

- **Attitude Control** – All three sciencecraft are 3-axis stabilized using colloidal thrusters based on ST7 design and heritage. All three propulsion modules use conventional hydrazine thrusters. Sciencecraft attitude determination is based on measurements from star trackers prior to acquisition and on instrument measurements afterwards.
- **Structure/Configuration –** The general layout of each sciencecraft is rectangular with a thermally isolated solar array and solar array radiator. The three sciencecraft share the same solar array substrate panel, which shades the bus and telescopes. The launch configuration will be three sciencecraft resting in line with their solar arrays facing upward along the axis of the launch vehicle. See Figure 3. Array corners are trimmed so that the stack fits in the launch vehicle. Each sciencecraft will have a propulsion module interface on the face opposite its solar array. See Figure 1 on the cover page. The launch configuration provides symmetry for control during cruise and allows for pointing all three arrays to the sun.

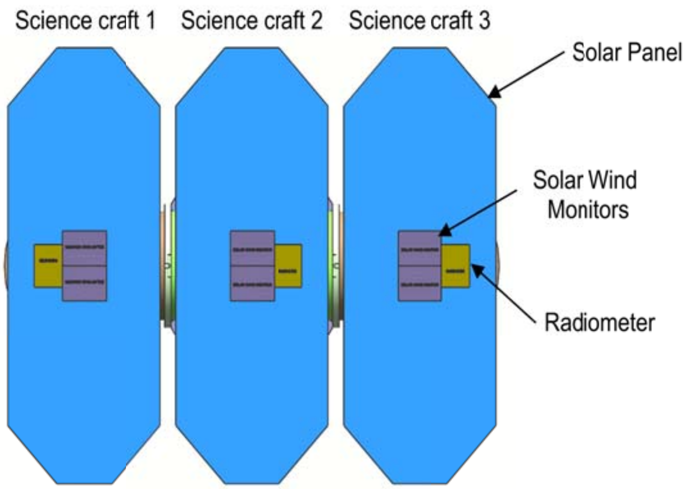

Figure 3: LAGRANGE Launch Configuration

- **Telecom –** The nominal telecom design is a single string S-band system on both types of sciencecraft. Each vehicle will have two S-Band patch LGAs.
- **Computer and Data Handling –** The three sciencecraft are identical. Each includes all C&DH hardware needed for the mission. There is no C&DH hardware on the propulsion modules.
- **Power –** There is a single solar array design for all three sciencecraft. All batteries are on the sciencecraft and are based on rechargeable Li-Ion chemistry. The prime battery is sized for 2-hour launch operations prior to orientating the solar arrays toward the sun. An internally redundant power bus control card incorporates array interface, battery interface and shunt interface functionality.
- **Propulsion –** The propulsion modules for all three sciencecraft will be simple, low cost, blowdown monopropellant systems. Low thrust and fine stability requirements for sciencecraft led to a colloid thruster design based on ST7 heritage.
- **Thermal –** The design strives to maintain constant temperatures and balance the heat rejected from external surfaces to space. Flight software will be used to monitor payload processing activity and apply make-up power to heaters as needed. The propulsion system will use thermostats to keep within specified temperature ranges. The solar panel will have "radiator wings" on non-sensitive sides of the sciencecraft, used to keep unwanted heat out of the payload cavity. A payload radiator will be opposite the solar panel and tailored to balance heat rejection forces.

A number of commercial bus manufacturers would be able to construct the needed sciencecraft, but for uniformity across studies (SGO, LAGRANGE, and OMEGA), Team X assumed a JPL built bus as the baseline.

Key Trades or Options studies in Team X

There were three options studied for trajectories to send each sciencecraft to its station. Two options would take the entire launch stack to L2 first, and the third option would send each SC directly to its station. Factors considered in the trade were ΔV, time to build up the constellation, and radiation exposure.

One of the options to take the stack to L2 first was ruled out because it required 850 m/s ΔV for SC-1 and 790 m/s for SC-3 after departure from L2. The second option uses lunar flybys to bring the ΔV down to 460 m/s for SC-1 and 300 m/s for SC-3. The 27 months required to do this was deemed acceptable, and this second option was selected for the baseline.

The third option would send each sciencecraft directly to its station using phasing orbits and perigee maneuvers. This would require up to 6 months in the phasing orbit (~14 day orbit) and 355 m/s for SC-1 and SC-3, with 120 m/s for SC-2 (assuming a lunar flyby). This option was rejected early in the study due to multiple passes through the Van Allen belts, which raised concerns about the additional radiation dose. Later in the study, Team X estimated a relatively low additional dose due to flying through the Van Allen belts. So, this may be a viable option and further study may be warranted.

After the decision to take the stack to L2 first, there were three options studied for trajectories to get to L2. Factors considered were ΔV, launch window, and radiation exposure.

One option with a C3 of -2 km^2/sec^2 involved being prepared to launch a couple of days out of every month to target a lunar flyby en route to L2. The required ΔV would be somewhat less than 120 m/s. This option was rejected because of the presumed cost of tying up the launch pad (potentially for months).

A second option with a C3 of -2 km^2/sec^2 would use staging orbits to a lunar flyby. There would be a required ΔV of 120 m/s and up to three weeks in the staging orbit. This option was rejected because of concerns about additional radiation exposure. The customer had not budgeted any exposure for the instrument for this phase.

A third option with a C3 of -0.3 km^2/sec^2 was selected for the baseline. This option would use a low energy transfer to a lunar flyby. There would be a required ΔV of 60 m/s and an additional month beyond the second option timeline to reach L2. The relatively low ΔV led to the selection of this third option.

Given the choice to take the stack to L2, there were three options studied for the launch stack configuration. Factors considered were propulsion module tank size, load paths, controllability during cruise, and the ability to point all solar arrays to the sun during cruise.

One option would be to attach each propulsion module/sciencecraft to a dumb central launch vehicle (LV) adapter. The vehicles would all separate from the adapter right after launch and fly on their own. There would be 60 m/sec required for each vehicle to get to L2. The total ΔV would be 460+60 m/sec for vehicle 1 to reach its station, and this drives the tank size for (identical) vehicles 1 and 3. This option was rejected in favor of smaller tank size.

A second option would be for vehicles 1 and 3 to attach to vehicle 2, which would attach to the LV. The load path would be from the LV to the vehicle 2 propulsion module (PM), and then to the vehicle 1 and 3 PMs. See Figure 1. The vehicle 2 PM would provide 60 m/sec for all vehicles to get to L2. Vehicles 1 and 3 would separate after reaching L2. The total propulsion load for vehicle 2 would be comparable to the propulsion load for vehicles 1 and 3. The tank size for all three vehicles would be similar to but smaller than for the first option. This second option was selected for the baseline.

A third option would be similar to the second, but with a modified load path from the LV to the vehicle 2 sciencecraft (as opposed to the vehicle 2 PM) and then to vehicle 1 and 3 sciencecrafts. The result would be increased sciencecraft mass and decreased propulsion module mass. Larger sciencecraft mass may be an advantage for thermal stability. This option was discussed after the final study session and has yet to be explored fully.

Cost Estimate Interpretation Policy

The cost estimates summarized in Table 2 and Table 3 were generated as part of a pre-Phase-A preliminary concept study, are model-based, and do not constitute a cost commitment on the part of JPL or Caltech.

Table 2: LAGRANGE Cost Estimate

Item	Cost ($M 2012)
Management, Systems Engr., Mission Assurance	107
Payload System	255
-- Science Complement	255
Flight System	491
-- Management, Systems Engr	54
-- Sciencecraft	347
-- Prop Stages	74
-- Testbeds	16
Mission Ops Preparation/ Ground Data System	113
Launch vehicle	179
Assembly, Test, Launch Operations	81
Science	46
Education and Public Outreach	20
Mission Design	16
Reserves	335
Total Project Cost	**1,643**

Table 3: LAGRANGE *Phase Cost profile* – Costs are in $M FY2012

Phase A	Phase B	Phase C/D	Phase E/F	**Total**
19.3	95.1	1386.7	142.0	**1643**

Technology Costing

Team X does not provide technology development costing. Models are based on assuming TRL 6 by the end of Phase B.