TEAM X Summary for the Orbiting Medium Explorer for Gravitational Astronomy (OMEGA) Mission Concept

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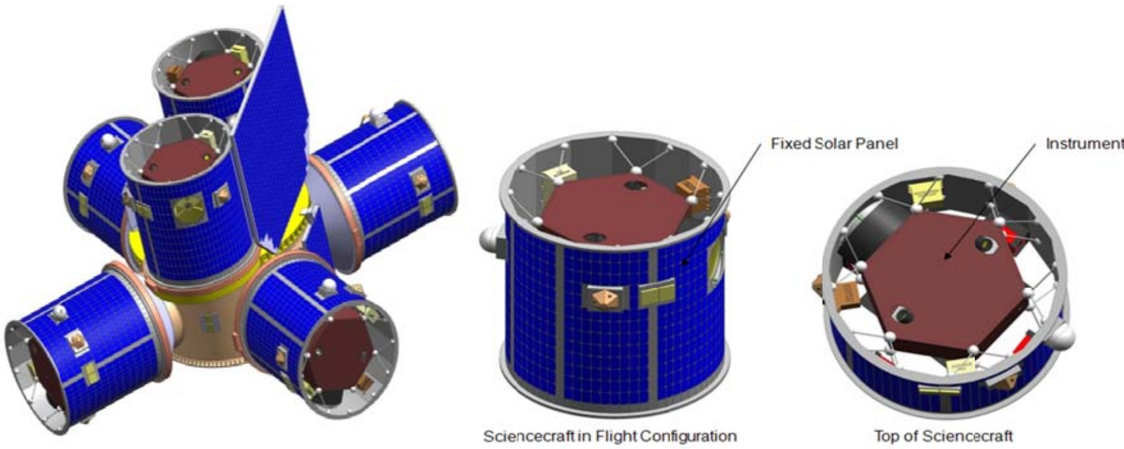

Title: Team X Study of the OMEGA Mission

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Overview

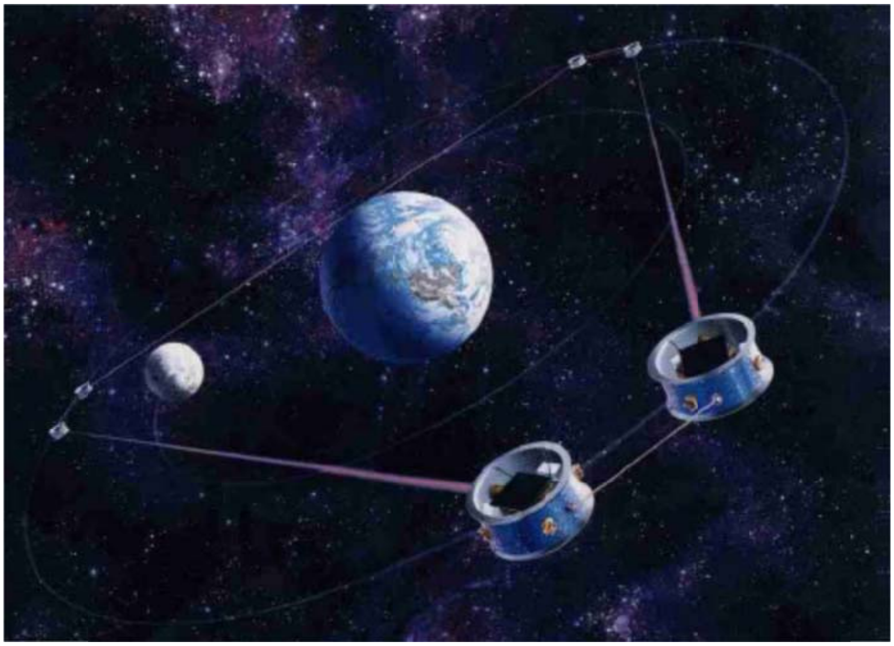
This study was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. In an effort to examine the current state of potential future gravity wave missions and assess the cost/risk/return tradespace that they represent, the NASA Gravity Wave Program Office commissioned a series of studies of candidate concepts that represent a variety of possible approaches toward advancing the current state of knowledge of gravitational astronomy and astrophysics, Of prime interest were concepts likely to be technologically ready for a start within the next decade. And of those mission concepts, the most important were missions considered likely to be implemented at a cost below one billion dollars. The OMEGA mission concept was of high interest because it represented a significant increase in gravitational science capability and had an advocate cost estimate of only $400M making it the lowest cost mission option of those submitted by the gravitational wave science community. Accordingly, it was submitted to JPL's concurrent engineering design team (Team X) for assessment under a standard set of study guidelines intended to provide a uniform comparison of the community's candidate missions. The goals of this study were to evaluate the OMEGA mission and payload design, complete the designs if needed or redo portions of the designs where not compliant with Program Office guidelines, estimate the cost and assess the risks. As work progressed on the initial evaluation, it quickly became apparent that differences between the Team X and advocate's views of the feasibility of the accelerometer design and a practical implementation schedule were having a significant impact on the overall result of the mission study. In the interest of quantifying this impact, the Program Office commissioned a second option of the OMEGA mission wherein Team X assumed the advocate's values for accelerometer mass and power, and the advocate's implementation schedule. Like the other gravity wave concepts studied by Team X, the OMEGA study focused on identifying the cost, risk and science return of the mission, and addressing what technologies needed development to enable the mission. The study was carried out as first and instrument team study evaluating both the accelerometer and the laser/telescope distance measurement system, then a full mission team study to assess the entire Earth orbiting constellation mission. The studies were carried out in late March and early April 2012.

Baseline Option and Key System Parameters

The high-level scientific objectives of OMEGA are:

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

The OMEGA mission consists of 6 identical spacecraft flying in pairs at approximately 600,000km altitude Earth orbit within 5º of the ecliptic plane. The three pairs are equally spaced to form an equilateral triangular constellation when in operational configuration (See **Error! Reference source not found.**). The distance between vertices of the triangle will be 1 million km. The constellation is the science instrument. The 6 "sciencecraft" are controlled to hold position with respect to an internal "proof mass" within the sciencecrafts' payload accelerometer. Because the sciencecraft shields the proof mass from external disturbances the proof mass orbits Earth "drag free" and by extension each sciencecraft is behaving as a drag free object in Earth orbit. The small sciencecraft positional adjustments are achieved through the use of micro-Newton Field Effect Electric Propulsion (FEEP) thrusters. Conventional chemical propulsion systems do not have the required fine control capability and present propellant slosh issues which would be difficult or impossible to address on the sciencecraft so all operational control is achieved with the FEEP system. The FEEP system lacks the thrust needed to move the sciencecraft to their operational orbits so all are carried to operational stations on a single ESPA-based carriercraft utilizing its own monoprop propulsion system.



Gravitational waves moving through the constellation will perturb the sciencecraft relative positions by small but measureable distances. Changes in distance along the 1M km arms of the constellation are made using laser interferometric phase measurements. Laser phase information is exchanged between vertex pairs of sciencecraft to determine relative positions. Long arm laser link is achieved using a 1064nm 300mW CW laser coupled with a 25cm Cassegrain transmit/receive telescope. The vertex pair link uses a 15mW laser signal and 12mm optics.

The sciencecraft are cylindrical in shape, with an outside cylindrical solar panel that also functions as a thermal shield, and the interior payload containing the accelerometer, interferometer, laser and telescope. The payload is suspended from the solar array on 12 pairs of thermally isolating bipods. Supporting avionics subsystems are attached to the cylinder's interior surface to provide additional thermal isolation of the payload. Because the constellation is functionally redundant (i.e, the loss of a single sciencecraft will not prevent OMEGA from achieving its minimum science goals) the sciencecraft were permitted to be single string architectures.

Key design features and mission parameters are summarized in **Error! Reference source not found.** and 2.

Table 1: Key Baseline Design Features for OMEGA (Option 1).

Domain	Category (unit)	Values with Comments
System	Launch Mass (kg)	2347
	Spacecraft Power (W)	258 (Each sciencecraft on station with telecom)
	Total Cost ($B FY12)	1.4
Science	Science Goals	Measuring gravitational waves
	Key Measurements	Laser ranging among 3 pairs of sciencecraft 1M km apart
	Total Data Volume (Gbits)	153
Mission Design	Launch Date	September 1, 2021
	Launch Mass Allocation (kg)	2490
	Trajectory/Orbit Type	High earth orbit , 600,000 km
	Mission Duration (months)	12
	Key Mission Phases	Launch, 12 mos cruise, 3 mos checkout (inc'g establish laser links), 12 mos science ops,18 mos Phase F (data analysis)
Payload	Telescope: Type	Cassegrain
	Telescope: Size	25 cm
	Instrument Types	1 integrated instrument with a telescope, a laser, and interferometer mounted on an optical bench with electronics
	Payload Mass (kg)	64.3
	Payload Power (W)	80
ACS	Stability (arcsec/sec)	0.3 (sciencecraft) 10 (carrier)
	Stabilization Type	3-axis
	Pointing Technologies	Star trackers, sun sensors, and FEEPs for the sciencecraft. Star trackers, sun sensors, IMUs and hydrazine thrusters for the carrier.
CDS	Redundancy	Single string (sciececraft) Dual cold (carrier)
	Data Storage (Mbytes)	256
Telecom	Bands	S
	Antenna Types	4 patch LGAs (sciencecraft and carrier each)
	Uplink Rate (kbps)	2
	Downlink Rate (kbps)	2
Power	Solar Array Area (m^2)	1.04 (sciencecraft) 2.16 (carrier)
	Solar Array Type	GaAs Triple junction, fixed panel, no articulation
	Battery Size (A-hrs)	30/ Li-Ion both sciencecraft and carrier
Propulsion	Type(s) of System(s)	Blowdown hydrazine monoprop for Delta V and control for carriers, FEEPs for microprobe.
	Propellant Mass (kg)	465.5 (hydrazine)
Structures	Primary Structural Material	Machined aluminum and titanium with metallic honeycomb composite panels
Thermal	Thermal Stability	1µK/100s
	Technologies	MLI, heaters, white paint
Ground System	Ground Antenna(s)	BWG ground station, 34m antenna
	Average Pass Duration (hrs)	2= 1 link per week per microprobe

Table 2: Key Design Features for OMEGA (Option 2).

Domain	Category (unit)		Values with Comments
System	Launch Mass (kg)		2223
	Spacecraft Power (W)		220 (Each sciencecraft on station with telecom)
	Total Cost ($B FY12)		1.22
Science	Science Goals		Measuring gravitational waves
	Key Measurements		Laser ranging among 3 pairs of sciencecraft 1M km apart
	(Gbits)		153
Mission Design	Launch Date		September 1, 2021
	Allocation (kg)		2490
	Trajectory/Orbit Type		High earth orbit , 600,000 km
	(months)		12
	Key Mission Phases		links), 12 mos science ops,18 mos Phase F (data analysis)
Payload	Telescope	Type	Cassegrain
		Size	25 cm
	Instrument Types		interferometer mounted on an optical bench with electronics
	Payload Mass (kg)		55 CBE
	Payload Power (W)		54 CBE
ACS	Stability (arcsec/sec)		0.3 (sciencecraft) 10 (carrier)
	Stabilization Type		3-axis
	Pointing Technologies		trackers, sun sensors, IMUs and hydrazine thrusters for the carrier.
CDS	Redundancy		Single string (sciececraft) Dual cold (carrier)
	Data Storage (Mbytes)		256
Telecom	Bands		S
	Antenna Types		4 patch LGAs (sciencecraft and carrier each)
	Uplink Rate (kbps)		2
	Downlink Rate (kbps)		2
Power	Solar Array Area (m^2)		1.04 (sciencecraft) 2.16 (carrier)
	Solar Array Type		GaAs Triple junction, fixed panel, no articulation
	Battery Size (A-hrs)		30/ Li-Ion both sciencecraft and carrier
Propulsion	Type(s) of System(s)		FEEPs for microprobe.
	Propellant Mass (kg)		465.5 (hydrazine)
Structures	Material		composite panels
Thermal	Thermal Stability		1µK/100s
	Technologies		MLI, heaters, white paint
Ground System	Ground Antenna(s)		BWG ground station, 34m antenna
	Duration (hrs)		2= 1 link per week per microprobe

Technical Findings

The primary finding from the Team X study was that the cost of the mission was in the neighborhood of $1.4B FY12 when using assumptions consistent with the Program Office guidelines and the other two gravitational wave studies. This far exceeded the initial white paper estimate. Without documentation, Team X did not accept the assertion of a low mass, low power accelerometer in development in Europe and instead, defaulted to a LISA Pathfinder based accelerometer for the payload design. Team X did not accept the spacecraft vendor’s cost estimate for the sciencecraft; there was nothing like it in the vendor’s standard products and it appeared to be a completely new design using heritage parts (as do most new spacecraft designs). The Team X sciencecraft estimate compared reasonable well with the costs of the recent Grail mission (adjusted for the 4 additional OMEGA sciencecraft) and the payload estimate was near the average cost per kilogram for historic Earth orbiting instruments in the larger competed and flagship mission classes. In the end, we saw no reason to lower the Team X estimate for the OMEGA mission. It should be noted that $1.4B is the lowest cost of the gravitational wave missions studied by Team X and OMEGA may present some good ideas for cost containment for future mission concepts.

In addition to the undocumented accelerometer, Team X flagged the FEEPs as requiring technology development that was not included in the mission estimate. While the FEEPs have been used on another flight mission, they functioned as charge control devices – not propulsive thrusters – in that mission. As such, they have not be qualified for the proposed purpose and environment and will need additional development.

Team X found that OMEGA did continue to meet the launch mass requirements for the targeted launch vehicle, but with substantially less (though still adequate) margin.

Schedule was a point of considerable discussion during the study. The spacecraft vendor wanted to build a protoflight version of the sciencecraft followed a few months later by the start of the remaining 5 sciencecraft which would be built in parallel and largely overlapping with the integration and test of the protoflight unit. Furthermore, the vendor also planned on a short design and fabrication cycle due to assumed heritage which Team X did not accept. This compressed schedule was largely motivated by the presumption that a shorter schedule will equate to a lower cost. But the level of compression was inconsistent with historic schedules of missions of this size and presented a number of implementation risks. In the end Team X elected to use a less compressed schedule, more in line with historic experience.

Design Assumptions

1. *Class B mission with Class C microprobes*
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. *TRL 6 at technology for 3/1/2016*

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Technical Details for OMEGA

- **ACS** – Sciencecraft attitude control: 3-axis stabilized using FEEP thrusters. No reaction wheels. Propulsion stage: Stellar inertial attitude determination using star tracker and gyros and attitude control using hydrazine thrusters.

- **CDH** –. Integrated Avionics Unit (IAU). 1553, RS422, LVDS, discrete and analogue interfaces. Single string IAU for sciencecraft; redundant IAU for propulsion module.

- **Power** – Sciencecraft: 60 A-hr Li-Ion battery; 1 m^2 projected solar array area; GaAs Triple Junction cells. Propulsion Module: 30 A-hr Li-Ion battery; 2.2 m^2 projected solar array area; GaAs Triple Junction cells.

- **Propulsion** - The Propulsion Stage optimized design for low cost permitted a simple blowdown monopropellant system for the carrier The sciencecraft low thrust and stability requirements led to a FEEP thruster design.

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

- **Telecom** – Sciencecraft: Each vehicle has a single string S-band system with 4 body-fixed patch LGAs. Propulsion Module: The carrier has a redundant S-band system with 4 body-fixed LGAs

Key Trades or Options studies in Team X

To evaluate the impact of the Team X decisions to replace the proposed accelerometer with a known design and to increase the development schedule to levels more consistent with past experience, the Program Office elected to fund an additional option to look at what OMEGA would cost had Team X not made these decisions and simply used the design presented. This new option (Option2) resulted in a cost decrease of $150M FY12 to $1.22B for the mission. This number still exceeded the Program Office's $1B target and it added a yellow and a red risk, and raised a previously yellow risk to red. Mass did improve but since Option 1 was able to fit on the target launch vehicle with adequate margin the advantage from lower mass is small. Key parameters for Option 2 are summarized in Table 2.

Battery and solar array sizing were driven by eclipse period. In an effort to reduce the size (and assumedly the cost) of these components, the customer requested that the Team X Mission Design Chair look to see if an eclipse-free set of orbits could be found to support this mission. The Chair succeeded in finding the eclipse-free orbits but at a 30% increase in range variability and 21% increase in angular variability. The customer did not take a position on the acceptability of this trade. This work was done largely outside of the concurrent study and was not folded into the baseline design.

Cost Estimate Interpretation Policy

The cost estimates summarized in this document 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 3: Omega Cost Estimate ($M FY12)

Item	Option 1	Option 2
Management, Systems Engr., Mission Assurance	74	61
Payload System	215	197
-- Science Compliment	215	197
Flight System	436	374
-- Management, Systems Engr	36	26
-- Microprobes	281	241
-- Propulsion Module	93	84
-- Testbeds	27	23
Mission Ops Preparation/ Ground Data System	91	80
Launch Vehicle	125	125
Assembly, Test, Launch Operations	84	78
Science	33	30
Education and Public Outreach	15	13
Mission Design	14	11
Reserves	286	251
Total Project Cost	**1,372**	**1,221**

Table 4: Phase Cost profile ($M FY12)

	Phase A	Phase B	Phase C/D	Phase E/F	**Total**
OMEGA Opt 1	16.1	71.6	1203.4	81.0	**1372**
OMEGA Opt 2	13.3	64.8	1063.3	79.2	**1221**

Technology Costing

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