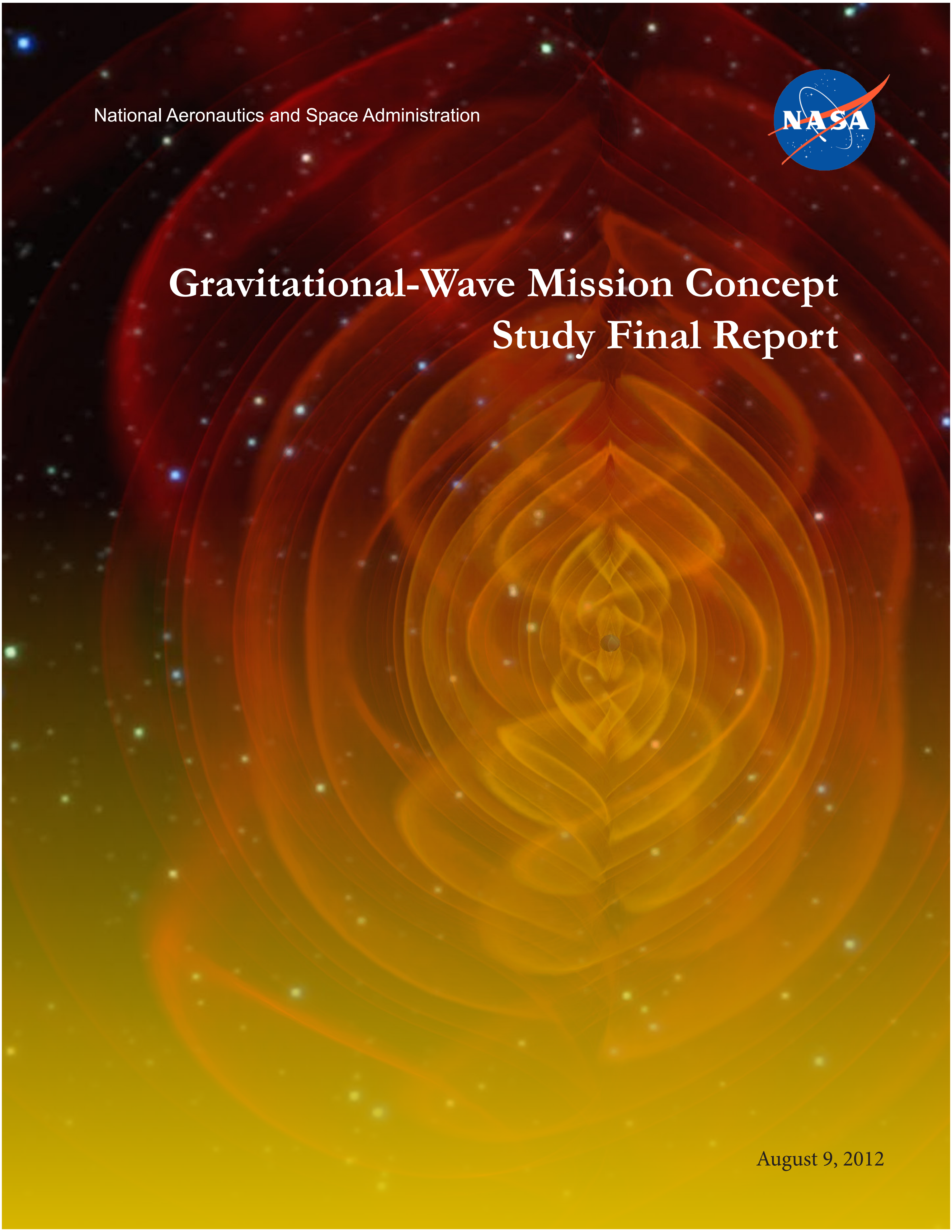

National Aeronautics and Space Administration

Gravitational-Wave Mission Concept Study Final Report

August 9, 2012

On the Cover...

A supercomputer simulation of gravitational waves emanating from two merging black holes.
Credit: NASA/Chris Henze

National Aeronautics and Space Administration

Gravitational-Wave Mission Concept Study
Final Report

Submitted to

Astrophysics Division
Science Mission Directorate
NASA Headquarters

and

Physics of the Cosmos Program Office
Astrophysics Projects Division
NASA Goddard Space Flight Center

Written by

Gravitational-Wave Community Science Team,
Gravitational-Wave Core Team, and
Gravitational-Wave Science Task Force

August 9, 2012

National Aeronautics and Space Administration

Gravitational-Wave Mission Concept Study Final Report

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Executive Summary

The exploration of the universe with gravitational waves is about to begin. The Laser Interferometer Gravitational-wave Observatory (LIGO) will make the first ground-based observations at high frequencies before the end of this decade. NASA has the opportunity to explore the most fertile frequency band, one that is only accessible from space. Between 0.1 mHz and 1 Hz lie sources that speak to the formation of galaxies, the formation and evolution of black holes, stellar evolution, and the behavior of extreme gravity. In the low frequency band, astrophysics tells us we will observe gravitational radiation from (1) mergers of massive black holes anywhere from the current epoch back to the earliest era of proto-galaxies, (2) the extremely relativistic inspiral of stellar compact objects into the massive black holes at galactic centers, and (3) thousands of compact binaries in the Milky Way. As Astro2010 noted, what astrophysics and physics has not told us about gravitational-wave observations—the discovery potential—may be more rewarding. But the expected observations will deliver astrophysical information such as masses, spins, luminosity distances, and orbital parameters with accuracy and reliability obtainable no other way. The ability to extract sky position, distances and merger times prior to cataclysmic events enables coordinated electromagnetic observations for the fullest astrophysical benefit.

The Laser Interferometer Space Antenna (LISA) mission concept has been extensively studied, and ranked highly for science, technical readiness and low risk by several National Research Council (NRC) reviews. NASA, the European Space Agency (ESA) and ESA member states have invested heavily in LISA technology. LISA Pathfinder (LPF), an ESA-led LISA technology demonstration mission with a NASA payload, is nearly ready for launch. Much of the flight hardware on board has been designed and developed for LISA. ESA considered, but did not select, the New Gravitational-wave Observatory (NGO), a LISA-like concept for the L1 opportunity in the Cosmic Visions Programme. A strong European research community is preparing to propose for the next ESA opportunity. This history and these investments will strongly affect the future program of gravitational-wave observations.

To search for lower-cost concepts, NASA's Astrophysics Division and its Physics of the Cosmos (PCOS) Program Office initiated a study to develop mission concepts that would accomplish some or all of the LISA science objectives at lower cost points. The science performance of these mission concepts was evaluated against the LISA science endorsed by the Astro2010 astronomy and astrophysics decadal survey. The study explored how architecture choices in gravitational-wave mission concepts impact the science return, the risk and the cost.

The study solicited community input through a Request for Information, a public workshop and an inclusive study process. The study was conducted by a Study Team, consisting of a Core Team of scientists and engineers, a Community Science Team representing the gravitational-wave, astrophysics, and fundamental physics communities, and a Science Task Force—approximately 40 people in all. Three mission concepts and two options were selected for analysis and costing by Team X, the Jet Propulsion Laboratory's (JPL) concurrent design facility.

The concepts studied by Team X were selected to explore the greatest diversity of mission concepts rather than as the 'best' concepts. They included SGO High, identical in design to LISA but with a single-agency cost model; SGO Mid, a LISA-like concept with shorter arms and shorter mission life; LAGRANGE/McKenzie, designed to avoid the drag-free test mass of the LISA design; and OMEGA, a design utilizing six spacecraft in a geocentric orbit that included an option adopting an aggressive schedule and payload design to reduce costs (OMEGA Option 2).

The community input, the Study Team's analyses, and the Team X results are summarized in this document; extensive supporting information is available at the PCOS Web site (cf. http://pcos.gsfc.nasa.gov/). Table 1 summarizes the results of the science performance, risk, and cost analyses for the mission concepts studied by Team X. Further explanation of these results can be found in Section 8 of this report. Section 8 also lists both the General Findings of the study as well as a summary of the Specific Findings related to the science performance, risk, and cost of individual architecture choices.

Science Performance	**SGO-High**	**SGO-Mid**	**LAGRANGE/ McKenzie**	**OMEGA Option 1**	**OMEGA Option 2**
Massive Black Hole Binaries					
Total detected	108–220	41–52	37–45	21–32	21–32
Detected at $z \geq 10$	3–57	1–4	1–5	1–6	1–6
Both mass errors ≤ 1%	67–171	18–42	8–25	11–26	11–26
One spin error ≤ 1%	49–130	11–27	3–11	7–18	7–18
Both spin errors ≤ 1%	1–17	<1	0	<1	<1
Distance error ≤ 3%	81–108	12–22	2–6	10–17	10–17
Sky location ≤ 1 deg^2	71–112	14–21	2–4	15–18	15–18
Sky location ≤ 0.1 deg^2	22–51	4–8	≤1	5–8	5–8
Total EMRIs detected[†]	800	35	20	15	15
WD binaries detected (resolved)	4×10^4	7×10^3	5×10^3	5×10^3	5×10^3
WD binaries with 3-D location	8×10^3	8×10^2	5×10^2	1.5×10^2	1.5×10^2
Stochastic Background Sensititvity (rel. to LISA)	1.0	0.2	0.15*	0.25	0.25
Top Team X Risk	Moderate[‡]	Low	Moderate	Moderate	High
Top Team X + Core Team Risk	Moderate[‡]	Low	High	High	High
Team X Cost Estimate (FY12$)	2.1B	1.9B	1.6B	1.4B	1.2B

[†] Based on median rate; estimates for EMRI rates vary by as much as an order of magnitude in each direction.

* Two-arm instruments such as LAGRANGE/McKenzie lack the "GW null" channel that can be used to distinguish between stochastic backgrounds and instrumental noise, making such measurements more challenging.

[‡] The moderate risk for SGO High comes about from the thruster development necessary to demonstrate the required lifetime for 5 years of science operations.

Table 1. Summary of science return, risk, and cost for the mission concepts considered by Team X. SGO High science performance is the same as LISA. This table is repreated as Table 20 in Section 8 with additional explanation.

The General Findings are listed below with brief explanations:

- Scientifically compelling mission concepts can be carried out for less than the full LISA cost. No concepts were found near or below $1B.

  Team X cost estimates ranged from $1.2 to 2.1B. The mission risk level at the low end of the cost range was "high;" the risk level at the high end of the cost range was "moderate" or "low." The high-cost, moderate-risk mission was LISA, included as a reference point.

- Scaling the LISA architecture with 3 arms down to the SGO Mid concept preserves compelling science, reduces cost, and does not increase risk.

  Shortening the measurement baseline, keeping the constellation closer to Earth, reducing the telescope diameter, reducing the laser size, and shortening the science observations all save cost while not increasing the risk found for LISA by Astro2010 and Team X.

- Eliminating a measurement arm reduces costs modestly, reduces science, and increases mission risk.

  Cost savings, in concepts like SGO Low and LAGRANGE/McKenzie, accrue because the payload equipment is reduced by about one third, saving recurring engineering costs. The costs of the flight system, propulsion module, and launch vehicle can also potentially be reduced. These savings are offset to some degree by the additional non-recurring engineering for the differences in the end and center payloads, spacecraft, and propulsion modules.

  Science is reduced by the loss of the capability to continuously monitor the instrumental noise and search for unmodeled signals, and the loss of simultaneous acquisition of the second polarization, which improves parameter estimation during late inspiral and merger.

  Simply descoping an instrument from three to two arms—without a compensating increase in the reliability of the critical payload subsystems—increases the risk because a three-arm design degrades gracefully to a two-arm instrument with failure of up to two links, while a two-arm instrument fails with the loss of a single link.

- More drastic changes, such as eliminating drag-free operation or adopting a geocentric orbit, significantly increase risk, and the associated cost savings are uncertain.

  Eliminating drag-free operation obviates the need for a Gravitational Reference Sensor (GRS), complex spacecraft stationkeeping. and associated testing in final integration. However, using the spacecraft as an inertial reference requires monitoring instruments that are substantially more expensive than the GRS, requires advances in the performance of those instruments, and depends on risky modeling of disturbances, some of which may not be verifiable on ground.

  High geocentric orbits do not use significantly less propulsion than heliocentric orbits. They confer additional technical demands on the spacecraft and payload because of the changing thermal environment, possible eclipses, and protection of the payload from direct sunlight.

- Scientific performance decreases far more rapidly than cost.

  Scaling SGO High down to SGO Mid produces a modest cost reduction (10%) and a substantial reduction in science (3–20×, depending on the metric).

- We have found no technology that can make a dramatic reduction in cost.

  The science payload constitutes a small fraction of the mission cost. Major changes in the technology underlying the science instrument only have modest impacts on cost.
  Atom interferometry has been under consideration for gravitational-wave detection for some time. In neither the literature nor this study have we seen a viable proposal. Atom interferometry does not appear promising for reducing or simplifying the scientific payload.

- There is an urgent need for NASA to prepare for the imminent exploration of the universe with gravitational waves, leading to revolutionary science. The U.S. needs a sustained and significant program supporting technology development and science studies to participate in the first space-based gravitational-wave mission.

Astrophysics with an entirely new spectrum will begin in this decade when ground-based gravitational-wave instruments make their first observations, intensifying the motivation for a space-based mission with broad astrophysical science potential.

A vigorous program of technology development and risk reduction for a future gravitational-wave mission is essential for reducing future mission costs, sustaining a knowledgeable and engaged community, and preserving programmatic flexibility in the future. A vigorous research program in gravitational-wave astrophysics, waveform modeling, instrument response and data analysis is also essential for preserving U.S. leadership in these areas and sustaining progress in extracting science from gravitational-wave observations.

Specific Findings

The Specific Findings below have been gathered from subsections of the document where they were arrived at.

Orbits and Trajectories Findings

- Choices of orbits and trajectories have an immediate impact on propulsion requirements, but they also have consequences for the payload, flight system and launch vehicle.
- Contrary to expectations, high geocentric orbits have no significant propulsion savings over heliocentric orbits.
- Heliocentric missions are favored with respect to spacecraft thermal stability related to solar flux.
- Stable orbits, possibly with stationkeeping, allow extended missions.

Inertial Reference Findings

- The estimated cost of the inertial reference instrumentation for the missions studied by Team X does not vary significantly and is not a major contributor to the overall mission cost.
- The LPF GRS is the most highly developed inertial reference, and therefore the least risky.
- The non-drag-free approach is potentially interesting in the unlikely event that a serious flaw with the drag-free design is uncovered by LPF. However, the non-drag-free approach brings a different set of risks, some of which are potentially severe, that would require further study if this approach is to be pursued.
- Refinement or enhancement of GRS technologies has the potential to reduce risk, reduce cost, or improve measurement performance but will not enable a probe-class mission.

Time-of-Flight Findings

- The LISA-derived Interferometric Measurement System (IMS) employed by SGO High and SGO Mid is a well-developed, low-risk concept capable of meeting the measurement requirements.
- The non-drag-free approach brings an additional risk associated with relative motion between the spacecraft center of mass and the fiducial optic. Mitigating this effect may place severe requirements on the thermal, mechanical, and gravitational stability of the spacecraft. Further study would be required to assess this.

- Refinement or enhancement of core interferometry technologies have the potential to reduce risk, reduce cost, or improve measurement performance but will not enable a probe-class mission.

Flight System Findings

- All mission concepts considered require a spacecraft bus with unusual requirements on mechanical stability, thermal stability, and gravitational stability. Meeting these requirements leads to a payload and bus that are tightly integrated during design, development, test and operations.
- The design of the flight system influences the potential for extended operation of the mission.
- Of the missions studied by Team X, the flight systems of SGO High and SGO Mid are most mature, and appear to have the lowest risk.
- The requirements placed on the spacecraft bus for a non-drag-free design are different than those for a drag-free design and are less well understood. Further work would be necessary to determine the exact nature of these requirements and the resulting implications for the flight system.

Science Findings

- Several mission concepts, including those studied by Team X, were found to be capable of delivering a significant fraction of the LISA science related to massive black hole mergers and galactic binaries.
- The science of compact object captures (EMRI systems) may be at risk due to significantly reduced detection numbers relative to the LISA mission.
- Concepts with three arms significantly improve parameter estimation over two-arm designs for black holes and enhance the ability to detect unanticipated signals.
- Additional years of science observations produce more science return for very modest expense.
- Gravitational-wave astrophysics and data analysis research has had a major impact on the anticipated science return from gravitational-wave missions and has the potential to continue doing so.

Risk Findings

- A three-arm design has lower risk than a similar two-arm design, allowing for graceful degradation.
- Three dual-string spacecraft appear to be more robust than six single-string spacecraft for most mission failures.
- A non-drag-free architecture introduces significant additional risk.
- Overlapping construction of multiple units adds significant schedule risk.

Cost Findings

- In all cases, the Team X estimated costs were found to be well over $1B, thus putting the mission in the flagship class.
- The choice of heliocentric versus geocentric mission designs does not seem to be a significant cost driver.
- Reducing a three-arm design to two arms will not necessarily reduce the cost significantly.

- Eliminating the drag-free inertial reference achieves at most modest savings.
- Optimizing the build plan could be a source of modest savings.

Technology Findings

- No new or unproven technology is needed to enable a LISA-like mission such as SGO High or SGO Mid.
- Refinement and enhancement of core LISA technologies could provide cost, risk, or performance benefits that integrate to a moderate effect on the mission as a whole, but will not enable a probe-class mission.
- Coordinated U.S. investment in core LISA technologies will preserve the U.S. research capability and support mission opportunities on a variety of time scales for a variety of partnering arrangements.
- System test beds for drag-free control and interferometric measurement are a good investment, providing an arena in which to develop technologies and an opportunity to gain deep insight into the measurement process.

1 Introduction

With the end of the decade-long NASA/ESA partnership to develop the Laser Interferometer Space Antenna (LISA) mission concept [LISA Concept 2009], the Astrophysics Division at NASA Headquarters initiated the Gravitational-Wave Mission Concept Study to look for mission concepts and new technologies that might achieve some of the LISA science in the cost range from ~ $300M to $2B in FY12 dollars. The LISA science endorsed by Astro2010, the National Research Council's decadal survey of astronomy and astrophysics for the decade 2010–2020, was the reference point [NWNH 2010]. This document is the summary report of the Gravitational-Wave Mission Concept Study.

The Gravitational-Wave Mission Concept Study consisted of the following activities: (1) a public solicitation for alternate mission concepts and "game-changing" technologies, (2) a quantitative analysis of the science performance for the suggested concepts, (3) a critical technical assessment of those concepts, (4) studies by the Jet Propulsion Laboratory's Team X design lab of three concepts that explored a wide range of architecture choices, and (5) a synthesis of the findings from all these activities. This volume only summarizes the final synthesis; extensive intermediate results from the other activities can be found in the related volumes listed in Appendix B.

Research on a space-based gravitational-wave mission had been going on since before the NASA/ESA partnership started, and by now NASA, ESA, and ESA member states have made very substantial investments in the LISA conceptual design and LISA technology. Conceptual designs similar to LISA benefit from that maturity and from the advanced state of development of related technology. This study recognizes that alternative concepts are less well studied and may rely on technology that is less developed. The study endeavors to compensate for these differences so that cost estimates of future missions can be fairly compared. In only 9 months, this study has not resolved all technical issues encountered in the less studied designs, but we have endeavored to identify and describe those issues, and account for them when assessing the science, risk, and potential cost consequences.

The LISA concept received very strong endorsement from two decadal reviews and two other NRC reviews as well. The relatively low risk of the LISA concept has been a critical, recurring element in these endorsements. In flight projects, accepting more risk can often reduce estimated cost, but that risk can lead to increased actual costs. Although it was not explicitly requested in the charge, this study has tracked risk, as well as cost, in order to capture a sense of the relative potential for unrecognized costs or for mission failure.

The remainder of this Introduction is organized as follows: Subsection 1.1 gives a brief overview of gravitational-wave science and the place of LISA science in the discipline. Subsection 1.2 describes the LISA partnership, the LISA Pathfinder technology demonstration mission, and the current international situation—all of which profoundly affect consideration of other mission concepts. LISA Pathfinder (LPF) is an ESA-led LISA technology demonstration mission, scheduled to launch in 2014 and carrying a NASA contribution. Subsection 1.3 is an overview of this study's goals and activities. And finally, Subsection 1.4 gives a primer on gravitational-wave detection for the interested reader.

The remainder of the document is organized as follows: Section 2 summarizes the response to the Request for Information, which is the main community input, and explains how three concepts were chosen for closer study. Section 3 reviews the architecture choices considered by the Study Team, and the science, risk, and cost consequences of those choices are reported in Sections 4, 5 and 6, respectively. Section 7 addresses the associated technology issues and strategies for investment. Each of these latter 5 sections has subsections where specific findings are stated with brief explanations. These are the Specific Findings of the study that are collected together in the Summary (Section 8). Many of the Specific Findings are related to each other. So, the Summary also gives General Findings that express those relationships, along with brief explanations. The General Findings and the Specific Findings are repeated in the Executive Summary.

1.1 Gravitational-Wave Science

It is rare in astronomy that an entirely new window on the universe opens up for observation. However, this is exactly what will happen this decade, when gravitational waves will be observed for the first time. Initially, detections will be made using ground-based interferometers at high frequencies (>10 Hz) or with pulsar timing arrays at very low frequencies (<1 μHz). However, the full potential of gravitational-wave astronomy will only be realized by high-sensitivity space-based observations in the frequency range from 0.1 mHz to 1 Hz, where a very rich set of gravitational-wave sources can be found. Realizing this revolutionary potential of gravitational-wave observations from space, the 2010 decadal review of astronomy and astrophysics [NWNH 2010] recommended LISA as one of only two missions (in addition to Explorers) for a possible NASA new start during the current decade.

The science rationale for a space-based gravitational-wave mission is succinctly summarized by the decadal review's description of LISA:

> "LISA is a gravity wave observatory that would open an entirely new window in the universe. Using ripples in the fabric of space-time caused by the motion of the densest objects in the universe, LISA will detect the mergers of black holes with masses ranging from 10,000 to 10 million solar masses at cosmological distances, and will make a census of compact binary systems throughout the Milky Way. LISA's measurements of black hole mass and spin will be important for understanding the significance of mergers in the building of galaxies. LISA also is expected to detect signals from stellar-mass compact stellar remnants as they orbit and fall into massive black holes. Detection of such objects would provide exquisitely precise tests of Einstein's theory of gravity. There may also be waves from unanticipated or exotic sources, such as backgrounds produced during the earliest moments of the universe or cusps associated with cosmic strings." The review later states: "It would be unprecedented in the history of astronomy if the gravitational radiation window being opened up by LISA does not reveal new, enigmatic sources."

The earlier 2007 NRC Beyond Einstein report (BEPAC 2007) was even more emphatic in its assessment of the potential of space-based gravitational wave astronomy:

> "LISA is an extraordinarily original and technically bold mission concept. The first direct detection of low-frequency gravitational waves will be a momentous discovery, of the kind that wins Nobel Prizes. The mission will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of both physics and astronomy in unforeseen ways."

The current study adopted the LISA science performance as its baseline for comparison, and several of the missions studied were able to realize a significant fraction of the LISA science scope. Indeed, it is imperative that any contemplated space-based gravitational-wave mission delivers a reasonable fraction of the gravitational-wave science that underpins the *New Worlds New Horizons* (NWNH) recommendation for development of a space-based gravitational wave mission to be started in the current decade.

1.2 Context

Any consideration of future mission concepts is dramatically influenced by the extensive mission formulation work done for LISA, the major investments in technology development, and current international circumstances. This subsection summarizes that context for considering future mission concepts.

Work on a space-based gravitational-wave detector was triggered by a dinner conversation at a meeting of the Management and Operations Working Group for Shuttle Astronomy in the fall of 1974. Four of the five key ideas underlying the LISA concept were articulated in a 1985 publication [Faller et al 1985] about a concept referred to as LAGOS. From 1993 to 2000, ESA conducted a study that included a six-spacecraft version of LISA and, initially, a concept called SAGITTARIUS, a precursor to the OMEGA concept considered in this study. The present, three-spacecraft configuration of LISA emerged from a Team X study at JPL in 1997. That concept was highly recommended by the NRC's 2000 decadal review of astronomy and astrophysics [AANM 2001].

The NASA/ESA LISA partnership was established in 2001, and recognized as a Phase A project by both agencies in 2004. The combined Project teams and a European prime contractor extensively studied the mission concept, producing many detailed analyses and extensive documentation. Considerable ground-based technology development work was carried out in Europe and the U.S.

The technology flight demonstrations that have become LISA Pathfinder (LPF) and ST7 started about 2001. Since sufficiently low-noise levitation of a test mass in six degrees of freedom is unobtainable in a terrestrial laboratory, the principal goals of LPF are to demonstrate drag-free flight and supporting technologies at a level of performance approaching that required for LISA and to validate the attendant error budget to support an extrapolation to LISA performance.

LPF is now in late Phase D, with launch scheduled in 2014. The flight units of the U.S. technology have been qualified and integrated onto the LPF spacecraft for over a year. The European technologies have been qualified, and flight units for all but the test mass launch lock and the microthrusters are ready for final integration. The knowledge of the LISA design and technology and the existence of flight units strongly favor mission concepts that take advantage of these very substantial investments. An extraordinary amount of development risk has been retired.

The LISA architecture and technology has been critically examined and found to be mature and robust by several reviews: NASA Headquarters requested the Technical Readiness and Implementation Plan (TRIP) Review in 2003 that compared LISA against the Constellation-X mission concept. The NRC carried out the very thorough Beyond Einstein Program Assessment Review in 2007 [BEPAC 2007]. Most recently, the NRC conducted the Astro2010 decadal review (NWNH 2010) of LISA's science, mission concept, technical readiness, and project plan.

Following the termination of the NASA/ESA partnership on LISA in March 2011, a European consortium proposed the New Gravitational-wave Observatory (NGO) for ESA's Cosmic Visions L1 opportunity. As proposed for L1, NGO was an exclusively European mission, with the flight system, telescopes, and lasers provided by ESA and the remainder of the scientific payload provided by the member states. This partnering arrangement reduced the costs incurred by ESA and enabled the proposed mission to meet the L1 cost cap (initially 850 M€, exclusive of member state contributions). NGO was not selected for L1 in the spring of 2012, despite receiving high marks for science. The consortium of member states, continuing as the eLISA Consortium (www.elisa-ngo.org), is currently preparing to propose a gravitational-wave (GW) mission for ESA's next large mission opportunity (L2), with a call possibly in the 2013/2014 timeframe and launch expected in the mid- to late 2020s. The eLISA Consortium has expressed an interest in a NASA as a minor partner.

1.3 Goals and Structure of the Study

With the end of the NASA/ESA LISA partnership, NASA's Physics of the Cosmos (PCOS) Program is developing alternative plans to address the high priority, gravitational-wave science objectives described in the Astro2010 decadal survey [NWNH 2010]. The constrained budgets anticipated for the remainder of the decade militate for lower-cost mission concepts. Through this study, the PCOS Program Office engaged the research community to develop new GW astronomy mission concepts satisfying some or all of the LISA science objectives endorsed by Astro2010 decadal survey. Astro2010 anticipated that GW measurements might address the science questions listed in Table 2.

This subsection describes the study goals, the science objectives, and the elements of the study.

1.3.1 Study Goals

The goals of this Gravitational-Wave Mission Concept Study are:

- Determine the range of primary science objectives of LISA (Table 2) that can be achieved at lower cost points.
- Explore alternative mission architectures and technical solutions, if these are viewed as scientifically desirable.
- Identify key enabling technologies for each mission architecture concept and assess the gaps between the current state-of-the-art and the performance required for the mission concept.
- Fully engage the GW astrophysics community and ensure that all perspectives are considered through the study.
- Produce a report that describes options for science return at multiple cost points for GW astrophysics.

1.3.2 Primary Gravitational-Wave Science Objectives

Gravitational-wave observations address two of NWNH's top three science themes: searching for the first stars, galaxies, and black holes; and advancing understanding of the fundamental physics of the universe.

In its prioritized recommendation for LISA, New Worlds, New Horizons (2010) lists the most important science that LISA could achieve as the following:

1. Measurements of black-hole mass and spin will be important for understanding the significance of mergers in the building of galaxies;
2. Detection of signals from stellar-mass compact stellar remnants as they orbit and fall into massive black holes would provide exquisitely precise tests of Einstein's theory of gravity; and
3. Potential for discovery of waves from unanticipated or exotic sources, such as backgrounds produced during the earliest moments of the universe or cusps associated with cosmic strings.

The Panel on Particle Astrophysics and Gravitation, the cognizant implementation panel of the 2010 Astrophysics Decadal Survey, gives a more detailed list of the science from gravitational waves in the form of science questions and the gravitational-wave measurements expected to address those questions, reproduced in Table 2.

Science Questions	Measurements Addressing the Questions
How do cosmic structures form and evolve?	Tracing galaxy-merger events by detecting and recording the gravitational-wave signatures
How do black holes grow, radiate, and influence their surroundings?	Using gravitational-wave inspiral waveforms to map the gravitational fields of black holes.
What were the first objects to light up the universe, and when did they do it?	Identifying the first generation of star formation through gravitational waves from core-collapse events.
What are the progenitors of Type Ia supernovae and how do they explode?	Detecting and recording the gravitational-wave signatures of massive-star supernovae, of the spindown of binary systems of compact objects, and of the spins of neutron stars.
How do the lives of massive stars end?	
What controls the mass, radius, and spin of compact stellar remnants?	
How did the universe begin?	Detecting and studying very-low-frequency gravitational waves that originated during the inflationary era.
Why is the universe accelerating?	Testing of general relativity—a deviation from general relativity could masquerade as an apparent acceleration—by studying strong-field gravity using gravitational waves in black hole systems, and by conducting space-based experiments that directly test general relativity.

Table 2. Science Questions and Gravitational-Wave Measurements. (Adapted from Astro2010 Panels 2011, box 8.2, p. 385).

1.3.3 Elements of the Study

The study approach consisted of issuing a Request for Information (RFI) to solicit community input for candidate mission designs; downselecting among these candidates to focus on three mission concepts that provide a representative sample of potential approaches over a range of cost, technologies, and mission architecture approaches; and performing more detailed design and cost assessments using the Team X mission design facility at JPL.

NASA HQ Astrophysics Division (APD) solicited potential new gravitational-wave mission concepts from the research community through an NSPIRES RFI. These concepts represent the starting point for the study in arriving at a set of gravitational-wave mission concepts representing varying science return, risk levels, cost points, and technologies. Seventeen RFI responses were received. Those responses are summarized in the next section.

A 10-member Community Science Team (CST) was selected to act as the science advisory body for the study effort. The CST was co-chaired by Dr. Rainer Weiss (Massachusetts Institute of Technology) and Dr. Edward Wright (University of California, Los Angeles). Members of the CST come from the LISA community and beyond, representing the broad range of relevant expertise for space-based gravitational-wave detection. There was also expertise in ground-based gravitational-wave detection, general astrophysics, spaceflight, and atom interferometry.

A Core Team consisting of science and engineering personnel from Goddard Space Flight Center (GSFC) and JPL performed much of the technical analyses of RFI responses and Team X studies for the study and the CST. Most of the Core Team have had a long association with the LISA Project and brought that experience base to the study.

A Science Task Force of volunteers was also organized to carry out the extensive science performance analyses that are essential for understanding what science a particular concept can produce. These volunteers were researchers with experience and software for performing similar analyses of LISA for NRC reviews and of NGO for the ESA L1 downselect.

The Study Team responsible for this report is the combination of the Community Science Team, the Core Team, and the Science Task Force. Names and institutional affiliations are listed in Appendix A.

Following receipt of the RFI responses and selection of the CST, a workshop was held December 21–22, 2011, at the Maritime Institute in Linthicum, MD. Representatives for each RFI response presented their concepts and responded to questions formulated by the Core Team. The Core Team presented assessments of each response. The workshop provided the astrophysics community an opportunity to comment on the responses and recommend missions to be further developed in the Team X design lab activity. It also provided a forum for discussion and exchanging information between the Study Team and the community.

The CST recommended three mission concepts for more intensive study by Team X, JPL's concurrent design lab. Concurrent design teams are collections of engineers (~20) from all of the specialties needed to design space missions. They use coordinated spreadsheet-based software tools to rapidly assemble a conceptual design that incorporates their institutional experience. The study reports (see links in Appendix B) contain a comprehensive description of the flight system, operations, launch vehicle, orbits, risks, schedule, and cost.

This report abstracts the conclusions drawn by the Study Team from the collected work of the community, the Study Team, and Team X.

1.4 A Primer on Gravitational-Wave Detection

This section provides a short primer on gravitational waves and their detection for readers unfamiliar with gravitational radiation. Others can skip this section.

A more extensive description of the science of space-based gravitational-wave observations can be found in The LISA Science Case [LISA Science 2009].

1.4.1 What Are Gravitational Waves?

Gravitational waves are “ripples in spacetime”—propagating strain waves in the geometry of spacetime. They are produced by accelerating masses; best if those masses are large and close—hence, dense—and moving rapidly.

In general, there are two polarizations. As a GW propagates through spacetime, it induces a tidal distortion in the plane transverse to the propagation direction. Figure 1 shows the effect of a GW propagating normal to the plane on an initially circular ring of inertial reference particles. In the first half-cycle of the wave, the particle separation is increased along one axis and decreased along the orthogonal axis. In the second half-cycle, the sign of the distortion is reversed. The simplest GW is quadrupolar, in general having two polarizations that differ by a $\pi/4$ rotation of the principal axes. The amplitude of the tidal distortion is characterized by the strain, $h=\Delta L/L$, where ΔL is the maximum change in separation and L is the original separation.

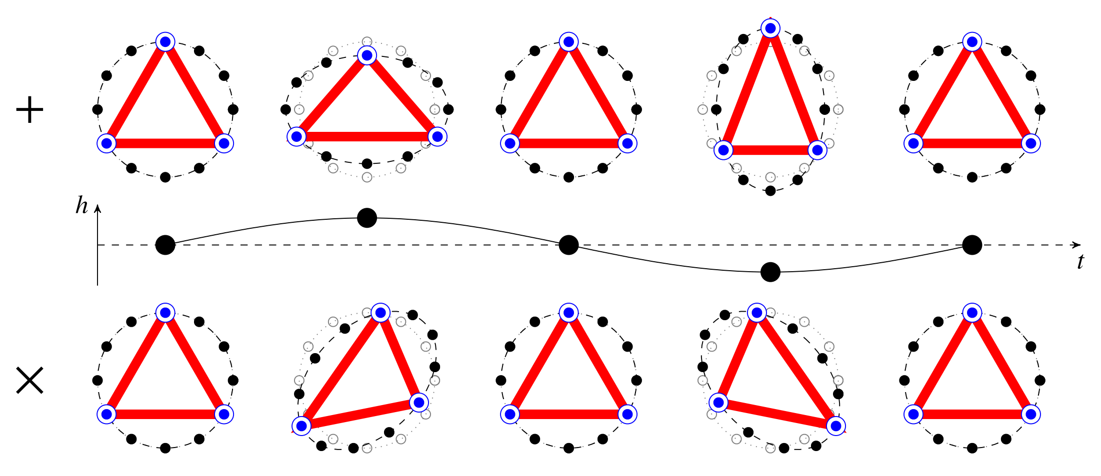

Figure 1. Effect of Gravitational-Wave Polarizations on a Ring of Masses.

1.4.2 How Are They Made?

Close binary systems of compact objects—white dwarfs, neutron stars, and black holes of any size—are the most common astrophysical sources. For example, the Hulse-Taylor binary pulsars indirectly proved the existence of gravitational waves by their slow loss of orbital energy. However, far more exotic and speculative sources have been predicted, like cosmic string oscillations and primordial stochastic backgrounds from the electroweak phase transition.

Astrophysical sources will produce time-varying strain amplitudes of $h \sim 10^{-21}/\sqrt{Hz}$. LISA science is performed at frequencies between 0.1 milliHz (mHz) and 0.1 Hz. For merging binary systems, the frequency scales inversely with the mass. Two massive black holes of a million solar masses each will merge at millihertz frequencies, while two neutron stars of a few solar masses merge at kilohertz frequencies, the upper end of the Laser Interferometer Gravitational-wave Observatory (LIGO) sensitivity band. LIGO is a pair of ground-based gravitational-wave interferometers (see http://www.

ligo.caltech.edu/ for further information) that will make the first gravitational-wave observations in the 2015–2017 timeframe, and those will be stellar-sized systems.

Frequencies below 1 Hz are accessible only from space because of Newtonian gravity noise on the Earth from seismic motions. The LISA band has the greatest variety and number of individually observable astrophysical sources, and it has the sources from which the most astrophysical information can be extracted. *This is the basis for NASA's unique opportunity to participate in this revolutionary science.*

Another important feature of most GW signals in this band is that they are generally observable for a long duration: galactic binaries persist far longer than any mission will; Extreme-Mass-Ratio-Inspirals (EMRIs are compact objects, typically stellar-mass black holes, spiraling into central regions) last about a year; massive black hole binaries are visible for weeks to years in advance of merger. In the millihertz band, that means that the phase evolution of these waveforms can be followed for up to hundreds of thousands of cycles, to a small fraction of a cycle. Much information about astrophysics and relativity is encoded in these waveforms.

Strong LISA sources are typically far more violent than the binary pulsars: black holes moving at an appreciable fraction of the speed of light and merging. LISA's premier sources are inspiraling binary massive black holes in the mass range of 10^2 to 10^7 $M_\odot$ (solar masses, the preferred unit of measure). These systems typically convert ~10% of their rest mass energy into gravitational radiation, half during the inspiral and half in the final few orbits and merger. At their peak, a single system of any size briefly releases more energy per unit time than all of the stars in all of the galaxies in the universe. Two merging, million-solar-mass black holes halfway across the universe would be brighter, in terms of energy per second per unit solid angle, than the full Moon.

Strong massive-black-hole binaries can be tracked for months in advance of merger. Sky positions and luminosity distances will be accurate enough to alert other observing assets to search for electromagnetic counterparts before the merger event.

The intrinsic weakness of gravity means that gravitational waves cross the universe without appreciable absorption. As a result, LISA can see merging massive black holes associated with proto-galaxy formation back to $z \sim 20$, if they exist.

1.4.3 How Are They Detected?

Pirani [1956] first outlined the most effective concept known for detecting gravitational waves. The basic idea is to measure variations in the time-of-flight between inertial reference points. A gravitational wave passing perpendicular to the monitored direction causes the time-of-flight to vary at the wave frequency. This idea necessitates two ingredients: suitably isolated reference masses, variously called 'test masses' or 'proof masses,' and a measurement system for monitoring time-varying changes in their apparent separation.

The weakness of gravitational-wave strain amplitudes establishes two driving requirements that define the detector: (1) the inertial references need to be isolated from disturbances that could produce real displacements comparable to the scale of the gravitational waves; and (2) the time-of-flight measurement system must have the sensitivity to detect the very small strains expected.

Inertial references have to be isolated from forces originating in the surrounding environment (spacecraft, solar wind, solar radiation, magnetic field, cosmic ray particles, residual gas) and originating from the test mass itself (thermal radiation, outgassing).

Laser metrology systems are easily capable of measuring displacements (ΔL) of a few picometers (10^{-12} m), or timing to a few microradians of phase (1 ppm of 1 μ wavelength), with modest amounts of light integrated for only fractions of a second. If the separation of the test masses is of order 10^6 km (1 Gm), then strain sensitivity $h \sim 10^{-21}/\sqrt{Hz}$ can be achieved. This is another compelling argument for a space-based gravitational-wave detector; ground-based detectors like LIGO have kilometer-long arms, and hence need measurement systems a million times more sensitive.

The test masses and the measurement system basically constitute a gravitational-wave 'antenna.' Several aspects of this antenna are important design choices: As with all antennas, the size roughly determines the useful measurement band. The arrangement of two, or usually more, masses in a "constellation" defines an antenna geometry. As with electromagnetic antennas, the geometry determines the sensitivity to polarization and direction of the radiation.

The measurement 'path' between two inertial references is commonly called an 'arm,' and the characteristic length is referred to as the 'armlength,' or the 'pathlength.' Because of the long distances involved, the time-of-flight is done with two one-way beams, rather than a reflected round-trip measurement. The one-way measurements and the associated equipment are referred to as 'links.' So, a path or arm is measured by two one-way links. This is important to reliability of the constellation, which is the scientific instrument. The individual spacecraft is part of the scientific instrument, rather than the instrument being part of the spacecraft, as in the usual mission. Depending on configuration choices, an instrument may or may not degrade gracefully with the loss of one, or more, links.

Most of the concepts considered in this report are quadrupole antennas. These primitive detectors are all-sky instruments that are sensitive to all sources all the time, albeit with varying sensitivity. In effect, the antenna has sensitivity lobes, commonly referred to as an antenna pattern, that confer a directional sensitivity that can be used for finding the direction to the source. For example, LISA detects tens of thousands of sources simultaneously, and through the orbital motion around the sun, a particular source is amplitude modulated by the antenna pattern rotating on the sky, frequency modulated by the changing Doppler effect, and phase modulated by the rotation of the constellation, all the while measuring a unique signal in two polarizations.

There is one other extraordinary aspect of gravitational-wave detectors that distinguishes them from electromagnetic observations: they are amplitude detectors, not power detectors. One measures the displacement of the "charges" in the antenna, not their energy. So, source strength falls off as $1/r$, rather than $1/r^2$. Consequently, while gravitational waves are difficult to detect initially, a detector with usable sensitivity has an extraordinary "horizon." This is also the reason that the GW community always quotes amplitude spectral densities, rather than power spectral densities, for source strengths, detector sensitivity, and noise levels; hence, the ubiquitous "per root Hertz."

1.4.4 The LISA Concept

The LISA mission concept is frequently referred to throughout this document. The LISA Mission Concept document [LISA Concept 2009] prepared for Astro2010 has a comprehensive description. For the purposes of this study, the concept referred to as SGO High is a reference design equivalent to LISA; it has all the same defining characteristics with minor modifications for cost reduction.

2 Responses to the Request for Information

The Gravitational-Wave Mission Concept Study was initiated by an RFI issued through NSPIRES, NASA's Web-based solicitation system. The solicitation (# NNH11ZDA019L) was released on September 27, 2011, and responses, in the form of 10-page white papers, were due November 10, 2011. The RFI states that "NASA is seeking information relevant to gravitational-wave mission concept(s) that will satisfy some or all the scientific objectives listed in Table 1. The RFI also requests standalone instrument concepts as well as relevant key enabling technologies for such missions or instruments. Mission concepts should range in cost from ~ $300M to $2B in FY12 dollars." Table 1 in the RFI is reproduced above as Table 2 in this document.

NASA Headquarters received 17 responses to the RFI; 12 self-identified as mission concepts, three as instrument concepts, and two as technologies. This study treated two of the instrument concepts as full mission concepts because sufficient description was given to do so. Several of the concept white papers describe multiple variants of a design. The variants typically differ in armlength, telescope aperture, or laser power. Team X also reported results for options on concepts. Those options are defined in the Team X Final Reports and Summary Reports (see Appendix B).

As a point of nomenclature, this report will refer to the RFI responses by the acronym, if any, or the first author's name, if none. Two concepts came up with the same acronym and will be referred to by the lead author or the acronym and lead author. Where variants are discussed, they are referred to by acronym or first author's last name, plus a distinguishing number (cf. Table 13).

The initial task of the Core Team was to comb through the RFI responses for promising ideas and concepts deserving further study, especially by Team X. To that end, the white papers were sorted into five groups with similar architectures. Section 2 describes those groups, and the rationale for the concepts selected for Team X studies.

To understand the grouping, it is useful to consider the essential elements of the LISA architecture, and their benefits:

- Drag-free control: The spacecraft are controlled to follow enclosed, free-falling test masses. These inertial references are protected from external disturbances, and the effects of varying forces arising in the spacecraft are reduced.
- Continuous laser ranging: Changes in the distance between widely separated test masses are measured with laser interferometry.
- Heliocentric orbits: The constellation of three spacecraft defines a stable equilateral triangle without orbital maintenance. The environmental disturbances can be made very low.
- Million kilometer long arms: Very long arms make the very precise strain measurement easier. The armlengths set the scale of the antenna and, hence, the useful frequency band.
- Laser frequency noise subtraction: Time Delay Interferometry makes it possible to subtract laser frequency noise by an emulation of Michelson's white-light fringe condition in post processing.

The various RFI responses are grouped into five groups according to how they deviate from the five elements of a LISA-like architecture:

- Group 1—LISA-like: Five concepts are LISA-like, but are either descoped or implemented differently.
- Group 2—Non-drag-free: Two concepts eliminated test masses and drag-free control in favor of measuring and removing disturbances.
- Group 3—Geocentric: Four concepts are based on orbits around the Earth.
- Group 4—Other: Three concepts differ from LISA-like in several ways.
- Group 5—Instruments and Technology: The remaining three responses were instrument or technology ideas that could be applied to many of the mission concepts.

The RFI responses in each of these groups are summarized below. The key characteristics in the tables, notably the cost estimates, are taken from the white papers and have not been validated by the Core Team or CST. The RFI white papers themselves can be downloaded from the Mission Concept Study Page at the PCOS Web site (http://pcos.gsfc.nasa.gov/).

2.1 Group 1 - LISA-like Concepts

The key characteristics of the five mission concepts with all of the LISA elements are listed in Table 3. Members of the LISA community, including many members of the Core Team, the CST and the Science Task Force, submitted four of these, known collectively as the Space-based Gravitational-wave Observatory (SGO). These concepts bring the many years of LISA formulation and analysis to the study.

The four SGO concepts are meant to capture the range of LISA-like designs. SGO High is the LISA concept as presented to Astro2010, modified to include all known cost savings, but with the same science performance. In SGO Mid, the scalable parameters—the armlength, distance from the Earth, telescope diameter, laser power, and duration of science operations—are all reduced for near maximum cost savings. SGO Low eliminates one of the measurement arms, giving it similar performance as ESA's NGO concept. However, in contrast with NGO, SGO Low has four identical spacecraft, rather than two end and one corner spacecraft, and it has a single launch direct to escape, rather than two launches to low-Earth orbit and then apogee raising maneuvers to escape. Finally, SGO Lowest collapses the triangular constellation onto a single line in an attempt to probe the bottom of the cost range for LISA-like designs, possibly at the expense of a viable science return.

The RFI response by Shao et al. is the fifth mission concept in this group. It proposes two variations on the LISA architecture. The first is a "disturbance-free payload" that is achieved through a separate payload craft that is flown in close-proximity formation after release from the main spacecraft. The goal is to reduce disturbances from the spacecraft and thereby relieve system requirements. The second variation is to use a torsion pendulum in place of a test mass to achieve a suspension with one extremely soft degree of freedom. The test mass consists of a 1 kg mass cantilevered off of a fused-silica torsion fiber.

Acronym	**SGO High**	**SGO Mid**	**SGO Low**	**SGO Lowest**	
Lead Author	**Stebbins**	**Livas**	**Thorpe**	**Baker**	**Shao**
Novel Idea	LISA with all known cost savings	Smallest LISA-like design with 6 links	Smallest LISA-like design with 4 links	Smallest in-line LISA-like design with 4 links	Formation-flying payload, torsion suspension for test mass
Cost Estimate (FY12 $M)	$1,660	$1,440	$1,410	$1,190	$990
Variants	1	1	1	1	1
Arm length (km)	5.0 x 10^6	1.0 x 10^6	1.0 x 10^6	2.0 x 10^6	5.0 x 10^6
Spacecraft/ Constellation	3/equilateral triangle	3/equilateral triangle	4/60° Vee	3/In-line	3+3/triangle
Orbit	22° heliocentric, earth-trailing	9° heliocentric, earth drift-away	9° heliocentric, earth drift-away	≤9° heliocentric, earth drift-away	LISA-like
Trajectory: direct injection to escape plus	recirculalization and out-of-plane boost, 14 months	out-of-plane boosts, 21 months	out-of-plane boosts, 21 months	small delta-v for S/C separation, 18 months	LISA-like
Inertial Reference	Two, rectangular	Two, rectangular	Single, rectangular	Single, rectangular	Single, torsion pendulum
Displacement Measurement	3 arms, 6 links	3 arms, 6 links	2 arms, 4 links	2 unequal arms, 4 links	LISA-like
Launch vehicle	Shared Falcon Heavy	Falcon 9 Block 3	Shared Falcon 9 Heavy	Falcon 9 Block 2	Falcon 9
Science Ops (yrs) Base/extension	5/3.5	2/2	2/2	2/0	5
Telescope Diameter (cm)	40	25	25	25	LISA-like
Telescope Output Power, EOL (W)	1.2	0.7	0.7	0.7	LISA-like

Table 3. Key Characteristics of Group 1 RFI Responses—LISA-like Mission Concepts. Green shaded concepts were studied by Team X. SGO High, essentially LISA, was considered as a variant of SGO Mid.

2.2 Group 2—Non-drag-free Concepts

The key characteristics of the two mission concepts that do not have test masses or use drag-free control are listed in Table 4. Both of these concepts eliminate the test mass and associated drag-free control. The fiducial point for the time-of-flight measurement then becomes the spacecraft center of mass, rather than a test-mass face. The elimination of the test mass offers potential reduction of the payload, simplification of the spacecraft, and reduction in integration testing.

The spacecraft, in effect, becomes the inertial reference point for the measurement, and its deviations from a geodesic must be understood at a suitable level to achieve the desired strain sensitivity. The spacecraft is subject to environmental disturbances like variability in solar radiance, solar wind, and thermal radiation, which the test mass had been sheltered from. Effects such as these require careful modeling and measurement.

Acronym		**LAGRANGE**
Lead Author	**Folkner**	**McKenzie**
Novel Idea	Long baseline, no drag-free	No drag-free, geometric reduction
Cost Estimate (FY12 $M)	$924	$1,120
Number of Variants	2	2
Armlength (km)	2.6×10^8	2.09×10^7
Spacecraft/Constellation	3/equilateral triangle or 4/square	3/isosceles triangle with 164° central angle
Orbit	Heliocentric	Heliocentric/Earth-Sun L2
Trajectory	Not specified beyond HEO parking, double lunar assist, solar electric propulsion mentioned	Direct escape to L2, "drift" of SC1/3 to 8° leading/trailing
Inertial Reference	None	GOCE accelerometer
Displacement Measurement	3 arms, 6 links	2 arms, 4 links
Launch Vehicle		Falcon 9 Block 3
Science Ops (yrs) Base/Extension	3	2
Telescope Diameter (cm)	30	20/40
Telescope Output Power, EOL (W)	1	1.2

Table 4. Key Characteristics of Group 2 RFI Responses—Non-Drag-Free Concepts. The green-shaded concept was studied by Team X.

The Folkner concept achieves the requisite strain sensitivity by very long arms (50× LISA) and by measuring and modeling spacecraft acceleration from solar luminosity, solar wind momentum transfer, and temperature fluctuations. By arranging the constellation so that the radius from the sun is perpendicular to the measurement direction, the LAGRANGE/McKenzie concept achieves the requisite strain sensitivity through geometry and longer arms (4× LISA). This concept carries a solar radiometer, solar wind instruments, and a high-sensitivity accelerometer to aid in the measurement, modeling, and diagnosis of disturbances on the spacecraft.

2.3 Group 3—Geocentric Concepts

The key characteristics of the four mission concepts that orbit the Earth are listed in Table 5. These concepts inhabit a variety of orbits ranging from geostationary to a retrograde orbit one and a half times the lunar distance. The two geostationary designs, GEOGRAWI/Tinto and GADFLI/McWilliams, have measurement arms ~100× shorter than LISA. As noted in Section 4.4, the short orbital periods of these geosynchronous concepts provide surprisingly good parameter estimation performance for massive black-hole binaries. However, there are other drawbacks in science, such as the inability to detect EMRIs and reduced detection numbers of galactic binaries and massive black holes.

Acronym	**GEOGRAWI**	**GADFLI**	**OMEGA**	**LAGRANGE**
Lead Author	**Tinto**	**McWilliams**	**Hellings**	**Conklin**
Novel Idea	Geostationary orbits, single spherical TM	Geostationary orbits, smaller telescope and laser	Novel trajectories, Explorer cost approach	Earth-Moon Lagrange points, spherical test mass, grating
Cost Estimate (FY12 $M)	$1,122	$1,200	$300	$950
Variants	3	3	1	1
Armlength (km)	7.3×10^4	7.3×10^4	1.04×10^6	6.7×10^5
Spacecraft/Constellation	3/equilateral triangle	3/equilateral triangle	6/equilateral triangle	3/equilateral triangle
Orbit	Geostationary	Geostationary	600,000 km geocentric, Earth-Moon plane (retrograde)	Earth-Moon L3, L4, L5
Trajectory	Not specified	Direct launch together to geostationary, rephase 2 S/C	Butterfly trajectories to Weak Stability Boundary (WSB), 384 days total	Direct to WSB, return and lunar flyby; or direct to Trans-Lunar Injection, return and lunar flyby
Intertial Reference	Single, spherical	Two, rectangular	Single, rectangular	Single, spherical
Displacement Measurement	3 arms, 6 links	3 arms, 6 links	3 arms, 6 links	3 arms, 6 links
Launch Vehicle		Falcon 9 Block 2	Small Delta or Falcon 9	Falcon 9
Science Ops (yrs) Base/ Extension		2	Submitted as 3, revised to 1	5
Telescope Diameter (cm)	Same as LISA	15	30	20
Telescope Output Power, EOL (W)	Same as LISA	0.7	0.7	1

Table 5. Key Characteristics of Group 3 RFI Responses—Geocentric Concepts. The green-shaded concept was studied by Team X.

GEOGRAWI/Tinto reduces the payload by having a single, spherical test mass in each spacecraft. The LAGRANGE/Conklin concept also employs spherical test masses, as well as a grating-based interferometer. LAGRANGE/Conklin orbits at the L3, L4 and L5 points of the Earth-Moon system, after sophisticated trajectories involving the weak stability boundary (WSB) and lunar fly-bys.

The OMEGA/Hellings concept takes a novel approach to spacecraft design and costing. This relatively well-developed concept, proposed as a MidEx in 1996 (cf. §1.2), proposes six, small, Class-C satellites with lightweight inertial subsystems (known as Gravitational Reference Sensors in the LISA context) and lightweight interferometry subsystems. The concept locates two spacecraft—each with a single telescope, test mass, and aft optical system for exchanging reference laser beams—at each vertex of the constellation triangle.

2.4 Other Concepts

The key characteristics of the three mission concepts that differ dramatically from a LISA-like architecture are listed in Table 5. Two rely on atom interferometry as inertial references, one of those two uses atom interferometry for the time-of-flight measurement, and one is predicated on currents in a superconductor.

Acronym	**InSpRL**		
Lead Author	**Saif**	**Yu**	**Gulian**
Novel Idea	Atom interferometry	Atom interferometer for inertial sensor	Electrons in superconductor
Cost Estimate (FY12 $M)	$444/$678		
Number of Variants	2		
Armlength (km)	0.5/500	LISA-like	N/A
Spacecraft/Constellation	1, 2, or 3 spacecraft/ in-line or triangle	3/equilateral triangle	Not specified
Orbit	1200 km above geostationary	LISA-like	Not specified
Trajectory	Not specified	LISA-like	Not specified
Inertial Reference	Atom interferometers	Atom interferometers	
Displacement Measurement			
Launch Vehicle	Falcon		
Baseline/Extended Mission Duration (years)			
Telescope Diameter (cm)			
Telescope Output Power, EOL (W)	10–20		

Table 6. Key Characteristics of Group 4 RFI Responses—Other.

The InSpRL/Saif mission concept with a 500 km baseline claimed the most ambitious scientific performance. It employs two spacecraft with atom interferometers at either end of the baseline used as both inertial references and phasemeters. The Core Team and CST studied several variants of the InSpRL concept and concluded that it was insufficiently defined for a comprehensive analysis. Further discussion of atom interferometry can be found in Appendix C.

The Yu concept employed atom interferometers only as inertial references for an otherwise LISA-like design. This was, strictly speaking, only an instrument concept.

The Gulian white paper described a new concept for a gravitational-wave detector, one that does not require a space mission. The CST believed the concept to be fundamentally flawed.

2.5 Instrument Concepts and Technologies

Three responses to the RFI addressed technologies that could be employed in a gravitational-wave mission. Two of those, Fritz and MacIntyre, were for computer interface hardware and laser comm systems, broadly applicable products from aerospace companies. Neither of those white papers included the content required by the RFI, and they were not considered further.

The response from de Vine described an interferometric technique for making not only the science measurement, but also monitoring pathlength noise elsewhere within the instrument.

2.6 Rationale for Team X Study Selections

A critical engineering review and independent cost estimate by JPL's Team X are important elements of this mission concept study. However, there are many architecture choices among the RFI responses, and only a few studies could be done within the scope of this study. Three concepts, two of which included a second option, were chosen for a Team X study so as to explore the design space as extensively as possible, not necessarily as the most compelling concepts. The selections were made to maximize the insight into the effects of architecture and programmatic choices on science, risk ,and cost. The Science Task Force calculated the effects of architecture choices on science for all viable RFI submissions.

After the submissions in response to the NASA RFI had been reviewed, a Workshop on Gravitational Wave Mission Concepts was held December 20–21, 2011. The groups submitting most of the responses were invited to present summaries and updates of them at the Workshop (the Workshop agenda and presentations can be downloaded from http://pcos.gsfc.nasa.gov/), and discussions were held between the respondents, the CST, the Core Study Team, and other participants. In these discussions and later ones, it was decided that Team X would perform mission studies for the following concepts:

1. SGO Mid/Livas, a heritage design based on the LISA concept. SGO High, which is essentially LISA, was costed as a delta study to provide a comparison to the 10-year history of LISA cost estimates, including Astro2010. SGO Mid is intended to be the lowest cost LISA-like design still having six links.
2. LAGRANGE/McKenzie, a design that eliminated the drag-free subsystem and relied on orbit geometry and measurement and modeling of disturbances to correct for disturbances. LAGRANGE is a four-link design with concomitant payload reductions, but compensating instrumentation and multiple spacecraft and propulsion module designs. Four-link designs also have different reliability characteristics.
3. OMEGA/Hellings, claimed a lower cost approach using simplified satellites in a 600,000 km geocentric orbit. Geocentric orbits have unique challenges in the constantly changing Sun direction, possible eclipse, and sunlight directly entering the telescope on occasion. In a unique deployment, OMEGA positions six spacecraft with a single propulsion craft. A shortened Phase C schedule and lightweighted payload were costed as Option 2 of the OMEGA mission study to further explore the impact of schedule on mission cost. Team X also performed an Instrument Study of OMEGA/Hellings.

3 Architecture Choices

The RFI process generated a large number of mission concepts and technologies as described in the preceding chapter. To better understand these concepts and relate them to one another, it is useful to place them in a common context. Each mission concept can be thought of as a set of choices made within the same architectural framework. The Team X studies provided detailed information, such as mass and cost estimates, for five individual points within this framework; their conclusions, and those from the analyses by the Study Team, can be extrapolated to the RFI submissions that were not studied and also to mission concepts that may be considered in the future.

All of the viable mission concepts[1] submitted in response to the RFI followed the basic detection scheme outlined in Section 1.4.3: a time-of-flight measurement between two or more inertial references separated by a long baseline. As described there, the experimental challenges associated with building a GW instrument can roughly be divided into two categories: producing a set of inertial references with residual non-gravitational accelerations that are sufficiently small, and measuring the time of flight of photons exchanged between these references.

Building an inertial reference requires the removal, or knowledge of, a wide variety of forces that can cause unwanted accelerations. These include classical electromagnetic forces, particle impacts, thermal effects, and time-varying Newtonian gravitational fields from nearby planets or objects (e.g., spacecraft). In practice, the amplitude of non-inertial forces tends to increase over longer averaging times. As a result, acceleration noise is typically the limiting noise source at the low-frequency end of a given GW detector's measurement band. The LISA requirement for residual non-inertial acceleration of the reference mass is 3 $\mathrm{fm/s^2/\sqrt{Hz}}$. With a baseline of $L = 5\ Gm$, this gives an acceleration-noise-limited strain sensitivity of $1.5 \times 10^{-20}\ \sqrt{\mathrm{Hz}}$ at 1 mHz.

The most well-studied approach to making the time-of-flight measurement is laser interferometry, in which a set of lasers serve as the time references, and optical phase comparison is used to make the timing measurement. The LISA project expressed the requirement on the measurement accuracy of this phase as an equivalent distance of 18 $\mathrm{pm/\sqrt{Hz}}$ at 1 mHz over a 5 Gm baseline, yielding a strain sensitivity of $3.6 \times 10^{-21}/\sqrt{\mathrm{Hz}}$ at 1 mHz. The primary limitations for this measurement are photon shot noise, which limits the accuracy of the phase measurement, and laser frequency noise, which is effectively a corruption of the time reference. To address the latter problem, GW interferometers use multiple-arm designs that exploit the tidal nature of the GW signal to allow laser frequency noise to be cancelled while retaining the GW signal.

A consequence of the long baselines and multiple arms is that a constellation of separate spacecraft is required. As a result, a practical problem for a space-based GW detector is designing a set of orbits that will provide a stable constellation over an extended period of observation. While it is not required that the baselines remain constant to a part in 10^{21}, it is advantageous to have baselines that are smoothly varying and relatively constant. It is also desirable to keep the spacecraft in as benign a thermal environment as possible so as not to disturb the reference mass or interferometric measurement.

In summary, when designing a space-based GW instrument, the following major architectural decisions must be made:

- What are the nominal orbital trajectories of the gravitational reference masses?
- What physical objects define the inertial reference and how are non-gravitational forces addressed?
- How are time-of-flight measurements realized?

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[1] *The superconducting antenna concept proposed by Gulian, et al. is the one exception but it was not considered a viable concept as discussed in Section 2.4.*

- What are the spacecraft requirements necessary to support the selections made above?

The following subsections address each of these major questions including the available choices, the solutions presented in the RFI submissions, the results of the considerations by Team X and the Core Team, and specific findings from these results.

3.1 Orbits and Trajectories

Orbits and trajectories are important because they can have a significant impact on the design and cost of a mission. Just as the proper choice of a site for a ground-based telescope can affect the performance, the proper choice of an orbit can simplify the design of the measurement system and bound the lifetime of the mission, and careful design of the trajectory can minimize the fuel consumption, risk (by minimizing maneuvers) and time to start of science operations, both of which influence cost.

From a mission-design perspective, each mission has two distinct phases: (a) the cruise phase from launch through science constellation creation, during which the spacecraft follows a trajectory designed to efficiently deliver each to the proper orbital insertion point, and (b) the science operations phase including initial commissioning and periodic maintenance phases when the spacecraft are following their orbits.

For completeness there is also a disposal or shutdown phase that occurs when science operations are completed. The disposal phase is particularly important for constellations in crowded places such as geosynchronous orbits or a Lagrange point. In general, this disposal phase will require additional propellant and a spacecraft design capable of larger thrust than the micronewton levels needed for drag-free control (and increase the cost). For a drift-away orbit, no formal disposal is required. In this study we focused on the trajectory and orbit design and did not consider disposal in any detail. Mission design analysis for each phase provides an indication of whether there are serious orbit-related challenges that will need to be addressed (and costed).

Since the measurement system in this case consists of a constellation of multiple spacecraft, the stability of the constellation is important and will impact the cost. Ideally the orbits will be independent and Keplerian—that is, no periodic maneuvering (and, therefore, propellant) should be required to maintain the constellation. In addition to requiring propellant, the maneuvers may disrupt science operations. Table 7 summarizes some of the parameters of the constellation that should remain stable or have limited variability, and the impact of each on the system design.

Constellation Parameter	Impact
Armlength changes ($\Delta L/L$)	Dynamic range of TDI, ranging, may also require stationkeeping
Doppler shits (Δv)	Front-end electronics bandwidth
Line-of-sight pointing angles ($\Delta\alpha$)	Telescope field of view (FOV) and/or articulation
Point ahead angles ($\Delta\gamma_{\|\|}$, $\Delta\gamma_{+}$):	Telescope FOV and/or point ahead compensator
Eclipses/Solar flux variation	Thermal design
Line of sight to the Earth	Communications system antenna fixed or gimballed

Table 7. Stability of constellation parameters and the impact on subsystems or measurement system design.

3.1.1 Orbital Choices

For space-based gravitational-wave detectors, two basic types of orbits have been considered: geocentric and heliocentric. Within these two basic types, the various RFI responses submitted for this study span a wide range of possibilities with different characteristics. Table 8 summarizes the range of choices considered.

Orbit Type	Characteristics	RFI Response/Mission(s)
Geocentric	Low-Earth Orbit	InSpRL (Saif, et al.)
	Geosynchronous	GADFLI (McWilliams), GEOGRAWI (Tinto, et al.)
	Geo-orbit at lunar distances	LAGRANGE-Concklin
	Geo-orbit at > lunar distance, retrograde orbit, in the plane of the ecliptic	OMEGA (Hellings, et al.)
Heliocentric	Drift-away, 60° constellation plane with respect to ecliptic	SGO-Mid
	Fixed range, 60° constellation plane with respect to ecliptic	SGO-High
	Straddling Sun/Earth L2	LAGRANGE-McKenzie, et al.
	Earth-orbit spanning, very long arms	Folkner, et al.

Table 8. Summary of the range of orbital choices considered by various RFI responses.

Although one might expect that "geocentric" orbits would be less expensive than "heliocentric" orbits, this is not necessarily true when the total impact on mission cost is considered. Geocentric orbits are troubled by: the thermal instability and power complexity caused by the direction to the sun moving about the spacecraft, the thermal shock of eclipses, and the occasional pointing of the telescope at the sun. These effects place additional demands on spacecraft and payload design over what is required for heliocentric orbits. The communications distances are much shorter, but the costs are about the same for heliocentric and high geocentric orbits. Some geocentric orbits require stationkeeping to maintain the constellation, but so do heliocentric orbits using Lagrange points. Natural changes in the constellation geometry impact telescope pointing, point-ahead (the small, time-varying angle between the incoming beam and the outgoing beam set by the distant spacecraft's apparent angular velocity), or the phasemeter bandwidth requirements through the Doppler frequencies.

Table 9 shows a comparison of various mission design features for the three missions studied by Team X, plus a summary of the significance and/or impact of each factor considered on the design.

Feature	SGO Mid	LAGRANGE	OMEGA
1. Trajectory Phase ΔV	~3 x 200 m/s	Stack (all 3 SC) ~ 120 m/s to L2, then [SC1,SC3]: [460,300]	[200, 330, 450] + 4 m/s
Significance:	Prop module (PM) size(s), propellant mass, complexity and risk		
2. Trajectory Phase D_T (mo)	~ 17	~ 27	~ 12
Significance:	Cost/complexity of trajectory phase operations		
3. Lunar Flyby required?	No	Yes	No
Significance:	Ops complexity with lunar flyby		
4. Constellation Stability Doppler (MHz)	Low (±1.5 MHz)	high (±94 MHz)	high (±60 MHz)
Relative length change $\Delta L/L$	<1%	10%	2.5%
Telescope articulation?	No: In-field guiding	None	Yes – aft telescope
Point ahead required?	No	No	No
Significance:	Possible cost of additional mechanisms and electronics		
5. Station keeping?	No	Yes (SC2, ~10 m/s/yr)	Minor
Significance:	Cost/sophistication of μN-/mN-thruster system		
6. Distance to Earth ($\times 10^6$ km) Comm hardware	24 to 55 Gimbaled HGA	[21, 1.5, 21] ISC and LGA	0.6 LGA
Significance:	Cost/complexity of communications; ISC = inter-spacecraft laser comm		
7. Earth eclipses	No	No	Possible
Significance:	(a) Sun direction variation (thermal stability) (b) Sun in telescope aperture (thermal, optical interference) (c) Earth eclipses (thermal, science interruptions)		
8. Orbit Ops Cost ($M)	$18	$27	$23
Cost Drivers:	Trajectory and science phase durations and complexity (staffing cost)		

Table 9. Comparison of orbit and trajectory characteristics for concepts studied by Team X.

3.1.2 Trajectory Choices

Trajectory-phase mission-design analysis includes the following products:

- Propulsion-system-induced velocity change (ΔV) required to achieve mission science phase constellation geometry, including timing of individual ΔV events
- Duration (D_T) of trajectory phase
- Possible inclusion of special orbit dynamic events, e.g., lunar flybys

These various features effectively translate into mission costs. Large ΔV implies a larger, more massive propulsion system, perhaps leading to a need for a larger launch vehicle. Long D_T implies more trajectory phase operations support. Inclusion of flyby events implies a cost for special operations support by orbit dynamics experts, as well as some extra risk due to the critical timing of thruster firing during the flybys.

3.1.3 Orbits and Trajectories Science Impact

The choice of orbits impacts flight system design and, secondarily, science performance through environmental disturbances, Doppler rates between spacecraft, usable duration of the constellation, interruptions for stationkeeping, and antenna sensitivity. The environment in the operational orbit directly affects the type and magnitude of disturbances that the payload and spacecraft design needs to mitigate, and ultimately the residual acceleration budget. The heliocentric orbits naturally maintain the spacecraft in a relatively static orientation toward the sun; body-mounted solar arrays readily become the first stage in a conventional passive thermal design that shields the inertial reference. Satellites in geocentric orbits must contend with the thermal disturbances from changing sun direction, and possibly eclipses. The changing solar heat flux can pose both direct thermal disturbances (differential thermal radiation pressure, differential outgassing, radiometer effects) and secondary effects like changing gravity field from thermoelastic distortion and acoustic noise from thermal stress release. Satellites in geocentric orbits generally have to cope with occasional telescope pointing close to the sun. The OMEGA proposal requires a critical, full-aperture, narrow passband filter to reject all solar radiation from the near UV to the mid IR, except in the narrow spectral band of the laser at 1 μm.

The constellation stability impacts the science performance through the Doppler frequencies and the demands on telescope pointing and point-ahead angle (cf. Table 9). High Doppler rates can be a driving requirement on photoreceiver and phasemeter bandwidth. OMEGA has an additional analog mixing stage in the front end of the phasemeter to cope with the high bandwidth. Both of these effects will add noise to the displacement budget not present in the heliocentric designs.

Long-term changes in the constellation geometry are generally life limiting. SGO High can extend science observations to 8.5 years with its more stable constellation, whereas the LAGRANGE constellation becomes unusable after 2 years. The number of massive black-hole mergers and EMRIs detected is directly proportional to the duration of observations.

Finally, the orbit choices impact the need for stationkeeping, which requires interruption of science observations. LAGRANGE needs regular stationkeeping at the center spacecraft because of the intrinsic instability of an L2 lissajous orbit. This can be accommodated, but complicates operations and data analysis. OMEGA has a unique need to reposition one of the spacecraft at each vertex from time to time to keep the two within the pointing dynamic range of the aft optical link.

Choice of orbit also impacts the instrumental sensitivity through the motion of the antenna pattern on the sky and the phase effects of the gravitational wave washing across the constellation. See the discussion of GADFLI, GeoGRAWI, and Folkner at the end of Section 4.4.

3.1.4 Orbits and Trajectories Risk Impact

The single largest risk factor for a mission is usually the probability of a successful launch. For example, an Atlas 5 launch vehicle has a realized success rate of 0.96 since 2002 (http://www.spacelaunchreport.com/log2011.html). The probability of success for a mission that requires multiple launches is the product of the success rate for each launch, so a mission requiring three Atlas 5 launches would have a probability of success of $(0.96)^3 = 0.885$. Therefore, it is best to avoid multiple launches. A single launch also avoids the complication and risk associated with timing the launches and the risk associated with weather, as well as the additional cost of keeping the launch crew in place between launches.

Trajectories can be designed to use another body, usually the Moon, for a gravitational boost, and therefore lower the cost of propellant, but this tradeoff requires accepting increased risk for making orbital corrections and timing the encounter properly.

3.1.5 Orbits and Trajectories Cost Impact

The choices associated with orbits tend to affect the design of the measurement system, and are therefore somewhat indirect in terms of impact. Choices associated with the trajectory tend to have a more direct impact on the cost because they often involve determining things such as propellant mass and total launch mass, which can affect selection of launch vehicle. Another cost driver is the time to achieve science operations. While the sciencecraft are in transit to their orbital stations, it is necessary to maintain staff on the ground for navigation and control. The choice of orbit also affects the design of the communications system for data transmission to the ground, but is not a large cost driver. Communications system designs are very mature, and the requirements for space-based gravitational-wave detection do not stress the capabilities of these systems, so the cost is a small fraction of the total mission cost.

The net cost impact of the chosen orbit and trajectory on the total mission cost is relatively small. The mission design choice was not found to be a significant cost driver for any of the missions studied.

3.1.6 Orbits and Trajectories Findings

- Choices of orbits and trajectories have an immediate impact on propulsion requirements, but they also have consequences for the payload, flight system, and launch vehicle.

  The variability of the constellation, as measured by quantities such as armlength variation, inter-spacecraft Doppler shifts, and constellation angle variations, places demands on payload systems such as the phase measurement system and optical tracking mechanisms. Requirements for stationkeeping place demands on the propulsion system.

- Contrary to expectations, high geocentric orbits have no significant propulsion savings over heliocentric orbits.

  SGO Mid, LAGRANGE/McKenzie, and OMEGA make significant propulsion savings over SGO High but have similar delta-V requirements (see Table 8). SGO Mid's low delta-V numbers are enabled by the use of a 'drift-away' orbits that save fuel costs at the expense of overall constellation lifetime.

- Heliocentric missions are favored with respect to spacecraft thermal stability related to solar flux.

  The angle at which the sun hits the solar array in a heliocentric orbit is relatively constant, walking around the normal to the surface at an angle of 30 degrees with the orbital period for the SGO High and SGO Mid concepts. Geocentric orbits can have eclipses of the sun by the Earth, and it is also possible to have the telescope line of sight point close to the sun, both of which require additional thermal management beyond that required for heliocentric orbits.

- Stable orbits, possibly with stationkeeping, allow extended missions.

  SGO High and SGO Mid are in stable orbits that don't require stationkeeping. LAGRANGE requires stationkeeping during the baseline mission and cannot be extended. OMEGA orbits are stable, but it requires minor stationkeeping to hold the two spacecraft at each vertex of the constellation in a working relationship.

3.2 Inertial Reference

The basic principle of the GW detector outlined by Pirani [1956] is a time-of-flight measurement between two or more inertial references separated by a long baseline. This is a direct measurement of the geodesic deviation, and hence the curvature, of the local spacetime around the detector.

3.2.1 Importance of the Inertial Reference

The inertial reference plays a key role in the detector. Conceptually, the idea is that the references are shielded from all extraneous forces over the measurement bandwidth and the separations between them are monitored by the time-of-flight measurement system. If the separation changes in a systematic way, it must therefore be due to the influence of gravitational forces (which cannot be shielded), and gravitational waves have a distinctive pattern that can be used to discriminate against noise.

One of the key technological challenges in building a practical GW detector is developing the system that shields the reference (a "proof" or "test" mass). Real references are subject to various non-gravitational forces that cause them to stray from true geodesics, sources of noise that can obscure the GW signal. In practice, the amplitude of non-inertial forces tends to increase over longer averaging times. As a result, acceleration noise is typically the limiting noise source at the low-frequency end of a given GW detector's band. The LISA requirement for residual non-inertial acceleration of the reference mass is 3 $\mathrm{fm/s^2/\sqrt{Hz}}$. With a baseline of $L = 5\ Gm$, this gives an acceleration-noise-limited displacement sensitivity of 75 $\mathrm{pm/\sqrt{Hz}}$ at 1 mHz.

3.2.2 Inertial Reference Choices

Three different approaches to achieving LISA-like acceleration noise were present amongst the 12 mission concepts submitted in response to the RFI. The majority of submissions specified some variant of the drag-free test mass that has been the baseline for the LISA concept since its inception. Two submissions proposed the alternative of utilizing the spacecraft as the test masses, along with a suite of instruments to measure the known non-inertial forces and a plan to remove them from the data in post-processing. The remaining two submissions proposed cold-atom clouds as inertial references. Of the five mission variants considered by Team X, four of them (SGO High, SGO Mid, and both OMEGA options) used some variant of the drag-free control approach, while the remaining one (LAGRANGE McKenzie) took the spacecraft-as-test-mass approach.

3.2.2.1 Drag-free Test Mass

The drag-free test mass is the most well-studied of the three proposed approaches to disturbance reduction. The test mass, which also serves as an optic for the time-of-flight measurement, is contained inside a hollow housing inside the spacecraft. After launch, the test mass is released so that it floats freely. External forces act on the outer spacecraft, causing the housing to drift towards the test mass. A sensing system (typically capacitive) measures this motion and a control system commands thrusters on the main spacecraft to counteract the drag, keeping the spacecraft centered on the proof mass. This illustrates an important difference between a drag-free system and an accelerometer. In the former, the corrective force is applied to the spacecraft, while in the latter it is applied to the test mass. This distinction is important when pushing the performance limits, as forces applied to the test mass generally bring associated noise.

Drag-free control was developed by the U.S. Navy and at Stanford and has flown on TRIAD I/II, TIP II/III, NOVA I/II/III, GP-B, and GOCE. All of these have operated in the "high-drag" regime of low Earth orbit. For GW detection, the drag-free approach is applied in an environment that is already intrinsically "low-drag," such as a high geocentric or heliocentric orbit. As a point of reference, the performance of the GOCE drag-free system is about a factor of 10^3 worse than the LISA requirement.

The LISA test-mass and housing/sensor design, referred to as the Gravitational Reference Sensor (GRS), has undergone significant technology development in Europe. Its validation is the primary goal of ESA's LPF mission. Current on-ground laboratory tests of the GRS using torsion pendulums place an upper limit on acceleration noise of 30 $\mathrm{fm/s^2/\sqrt{Hz}}$ at 1 mHz. While this already meets the deliberately relaxed goal of the LPF mission, it is expected, based on modeling validated by laboratory measurements, that the on-orbit performance of the LPF GRS will meet the LISA requirements.

Of the RFI responses that adopted drag-free control, all but two of them baselined the LISA/LPF GRS, perhaps with some minor modifications such as optimized electronics or UV LEDs replacing Hg vapor lamps in the discharging system. While such technologies could have a beneficial impact on performance, cost, or risk, they will not enable a probe-class mission. RFI responses not employing the LPF drag-free test mass included LAGRANGE (Conklin, et al.) and GEOGRAWI, which assumed a Stanford-developed spherical GRS with heritage from GP-B and the pre-descope ST-7, and OMEGA, which assumed a new lightweight GRS design from ONERA, with some heritage from GOCE. The Team X studies of SGO Mid/High and OMEGA Option 1 assumed the LISA GRS. For OMEGA Option 2, Team X adopted the lower mass and power numbers supplied by the OMEGA team for the ONERA design but added additional technology-development risk due to the current immaturity of the design.

3.2.2.2 Force Correction

A novel approach proposed in the LAGRANGE/McKenzie and Folkner, et al. RFI submissions is to forgo the GRS altogether in favor of using the spacecraft as the test masses. This approach had traditionally been avoided because it was known that forces such as the pressure from the solar irradiance have sufficiently large fluctuations in the measurement band that they would lead to unacceptably high acceleration noise. The Folkner and LAGRANGE/McKenzie concepts address this by including a suite of instruments with which to measure the forces (or some proxy for the forces) and then use the data from these instruments to remove the non-inertial accelerations from the time-of-flight measurements in post-processing on the ground. Both concepts include a solar-irradiance monitor and a solar wind instrument. LAGRANGE/McKenzie also includes an accelerometer to aid in the calibration of the force-measurement instruments. When compared with LISA, both concepts benefit from larger armlengths (4×/52× for LAGRANGE/Folkner), which give the same peak strain sensitivity for a higher acceleration noise, albeit at a lower Fourier frequency. Section 4 contains more information on the impact of armlength on the GW science. The LAGRANGE concept has an additional benefit from the geometry of its orbits, which are configured so that forces in the radial direction from the sun are suppressed by about 100× in the interferometer channel. The LAGRANGE/McKenzie design was included in the Team X studies.

3.2.2.3 Atom Interferometry

The final approach for an inertial reference proposed in the RFI submissions is cold-atom clouds measured using atom interferometry, which has been successfully applied to gravity gradient measurements on the Earth. The response from Yu, et al., proposed using a local atom interferometer (AI) to measure the non-inertial motion of each spacecraft while retaining the traditional laser-interferometry architecture for the long-baseline measurement. In the response from Saif, et al., the AI was applied to measure the long-baseline displacement directly. In both approaches, a cloud of Rb atoms is cooled in a magneto-optical trap (MOT) to a temperature of 100 pK. The cloud is then moved from the trap and is targeted at a location some distance from the spacecraft. In principle this can have a beneficial effect by reducing noise sources associated with the spacecraft, such as gravity-gradient noise. A series of laser pulses of precise duration and frequency is then applied to the cloud, causing the atom wavefunctions to split, recombine, and interfere with one another. The phase of the atom wavefunctions is read out by measuring the population state at the AI output using a fluorescence technique. The measured atom phase includes a contribution from the motion of the light source and associated optics. The Yu proposal utilizes this effect to measure the acceleration of the spacecraft relative to the atoms by reflecting the light off of a mirror fixed to the spacecraft. In the Saif proposal, the signal contains the spacecraft acceleration as well as the GW signal and laser frequency noise [Baker & Thorpe, 2012]. While these approaches can work in principle, both require performance of the individual components (number of atoms per cloud, cloud repetition rate, cloud temperature, beamsplitter order, etc.) that exceed current laboratory capabilities by significant margins, several orders of magnitude in some cases. There are also other known sources of potential noise that have not been analyzed and may severely limit the performance of the AI. The AI mission concepts submitted in response to the RFI and presented at the December workshop (Saif, et al.) were not sufficiently well-defined to perform a Team X study. Further discussion of AI for GW detection can be found in Appendix C.

3.2.2.4 Micropropulsion

Many of the concepts considered require some form of micropropulsion to provide precision attitude or position control of the spacecraft. In the case of drag-free inertial references, this micropropulsion is used to force the spacecraft to follow the geodesic trajectory of the test mass. For the non-drag-free and AI systems, micropropulsion can be used for attitude control required to maintain pointing for the laser links without introducing disturbances such as those generated by reaction wheels. A number of microthruster designs have been developed for LISA and LPF. The NASA developed colloidal micro-Newton Thruster (CMNTs) and a European-developed Field-Emission Electric Propulsion (FEEP) thruster will fly on LPF.

Both SGO Mid and LAGRANGE baselined CMNTs for micropropulsion. For SGO Mid, the thruster design for LPF meets all requirements while for SGO High, additional qualification is needed to meet lifetime requirements. For LAGRANGE, the LPF thruster will have to be scaled up in thrust capability to allow the microthrusters to perform the station-keeping maneuvers required for the central sciencecraft. OMEGA assumes an Indium needle FEEP thruster, a version of which had been under development for LPF but was rejected in favor of a Cesium slit FEEP. Indium needle FEEPs have operated in flight as charge-control devices but have yet to be qualified as thrusters.

3.2.3 Risk and Cost Results from Team X Studies

The five mission concepts studied by Team X included a total of three options for inertial references. The estimated mass, power, and cost are included in Table 10. Note that the values are for the first link (where a link is a one-way measurement) and the cost values are for the first unit. For LAGRANGE/McKenzie, a factor of ¾ was applied to the numbers for the first unit because a total of three force-measurement systems are needed to complete four links. In general, the mass and power numbers are without contingency and were provided by the Core Team, or, in the case of OMEGA, the proposal team. Team X provided the costs using the NASA Instrument Cost Model (NICM).

Option	**Mass**	**Power**	**Cost**	**Risks**
	(kg)	(W)		
LPF/LISA GRS	28 (32)	35 (41)	$14M	Unexplained failure of LPF
ONERA GRS	7	5–10	$7M	Performance or cost/power growth
LAGRANGE	42	35	$35M	Inability to measure/model accelerations

Table 10. Mass, Power, Cost and Risks of Options Studied by Team X.

There are several caveats worth noting in the Team X numbers. When costing the LISA/LPF GRS, Team X appears to have left off control electronics weighing 4 kg and consuming 6 W. The numbers in parentheses include these contributions but were not used in the NICM costing. Without access to NICM, it is not possible to know precisely how this would affect the cost. The LAGRANGE concept is also somewhat penalized in cost by the fact that each of the three instruments were costed separately, which is known to lead to higher costs in the NICM for the same total mass and power. Finally, these costs assume technology at TRL-6 and do not include any development costs. Despite these deficiencies, it is still possible to make some general findings. Team X also identified some risks associated with each approach, which are summarized in the table.

3.2.4 Inertial Reference Findings

- The estimated cost of the inertial reference instrumentation for the missions studied by Team X does not vary significantly and is not a major contributor to the overall mission cost.

  The non-drag-free concepts, represented to Team X by LAGRANGE/McKenzie, remove the GRS, one of the most complex payload components of the basic LISA architecture, and replace it with a suite of instruments designed to measure forces acting on the spacecraft. This trade does not appear to result in a significant difference in mass or power, and the costs as estimated by Team X are similar. The ONERA GRS design specified by the OMEGA team does have a lower cost estimate as a result of its lower mass and power estimates, but the overall cost is not significant in terms of total mission cost.

- The LPF GRS is the most highly developed inertial reference, and therefore the least risky.

  Validation and understanding of the GRS is the primary goal of the upcoming LPF mission. Preparations for LPF, including ground-testing in torsion-pendulum facilities, have retired a number of GRS risks and demonstrated a performance within an order of magnitude of LISA requirements. A successful demonstration of the GRS on LPF will cement its position as the world standard for future GW missions.

- The non-drag-free approach is potentially interesting in the unlikely event that a serious flaw with the drag-free design is uncovered by LPF. However, the non-drag-free approach brings a different set of risks, some of which are potentially severe, that would require further study if this approach is to be pursued.

The non-drag-free concepts are unique in that they do not rely on a technology (drag-free control) that is assumed by all other viable mission concepts. As such, they represent an important region of design space that would deserve further exploration should LPF produce negative results.

- Refinement or enhancement of GRS technologies have the potential to reduce risk, reduce cost, or improve measurement performance but will not enable a probe-class mission.

  Economies in mass and power or improvements in performance could be had at the component and subsystem level. Examples include modernizing the GRS electronics leading to mass savings, performing discharging with UV LEDs leading to power savings, and an improved caging mechanism leading to higher reliability. While the direct effects of these improvements will be small, they could have moderate effects at the system level.

3.3 Time-of-Flight Measurement

Nearly all of the proposed mission concepts utilize continuous-wave heterodyne interferometry to measure the optical phase accumulated during the travel between inertial references. The one exception is the proposal by Saif, et al., which uses Atom Interferometers (AIs) to measure the optical phase. In both cases, the measurement is sensitive to two classes of noise sources: fluctuations in optical phase from non-gravitational effects and phase measurement noise. The former category is dominated by intrinsic variations in the laser phase, which typically exceed the GW signal by several (4–6) orders of magnitude after near state-of-the-art laser stabilization techniques have been applied. Most GW detector concepts address this by using multiple-arm interferometers that can separate the intrinsic laser phase noise, which is common to all arms, from the GW signal, which depends on the orientation of the arm relative to the GW polarization vector. The classic example of such an arrangement is the Michelson-like topology of ground-based GW detectors such as LIGO. A variant of this approach developed for LISA, and known as Time Delay Interferometry (TDI), allows the laser phase noise cancellation to occur for interferometers with unequal length arms.

The TDI approach was adopted by all of the optical interferometer RFI concepts. The as-submitted concept from Saif, et al., did not explicitly address laser phase noise mitigation. In subsequent conversations, the AI proposal team advocated using a high-performance phase reference based on atomic clock technology to directly read out, and correct for, the laser phase noise. Such a phase reference would require several decades of improvement over current capabilities and would be equally applicable in a LISA-like optical interferometer if it were available. It is also important to note that a single-arm instrument enabled by this technology would suffer serious science penalties such as the loss of the ability to localize GW sources or measure polarization.

Other non-gravitational sources of optical phase noise include pathlength variations in the optics used to transmit, receive, and interfere the beams. The traditional approach is to construct dimensionally stable telescopes and optical benches that meet these pathlength requirements passively. An alternative approach, advocated in the technology RFI submission by De Vine, et al., is to relax dimensional requirements on the structures in favor of a multi-target interferometric measurement system capable of simultaneously measuring all varying optical paths. While the basic measurement principle has been demonstrated, it remains to be seen whether this approach is practical or cost effective.

For optical interferometers, the fundamental source of phase measurement noise is photon shot noise. Other noise sources, such as clock jitter, photoreceiver noise, and phase readout noise, are given allocations such that shot noise dominates. The AI concepts need to be better defined to understand their performance.

3.3.1 Team X Studies

Each of the five mission concepts considered by Team X employs the heterodyne interferometry architecture described above. The SGO High concept utilizes the LISA Interferometric Measurement System (IMS) with no modifications. SGO Mid employs reduced armlength, laser power and telescope diameter, but otherwise is identical to LISA. Interferometry for the LAGRANGE/McKenzie concept differs in two important ways: It is a four-link (two-arm) instrument with large, nearly parallel arms; and the distance measurement is made to a fiducial reference optic that is fixed to the spacecraft, rather than a freely floating test mass. The OMEGA interferometer is a six-link instrument, but with an individual spacecraft for each link. In place of the optical fiber used to connect the two interferometers aboard each SGO High/Mid spacecraft, OMEGA uses two spacecraft at each vertex of the constellation, connected by a free-space laser link with a ~10 km baseline. The OMEGA orbits also lead to large Doppler shifts on the heterodyne signals that are not compatible with the current LISA phasemeter designs. The IMS parameters for the five mission variants considered by Team X can be found in Table 3, Table 4, Table 5, and Table 10.

The Team X analysis of the IMS payloads for each of the missions was limited to a cost assessment, which was performed using the NICM model with mass, power, and instrument type being the model inputs. With the exception of the LAGRANGE concept, the entire scientific payload (IMS plus disturbance reduction system) was costed as a single instrument. Because of this, and the coarseness of parametric models such as NICM, it is not possible to make a reliable cost comparison between the IMS payloads of the five concepts. Team X also identified a technology development risk for low-noise photoreceivers that was common to all concepts. While it is true that the lower-noise photoreceivers specified are below TRL 6, there are existing designs with higher TRL and higher noise that still meet the requirements. Should the development of the low-noise photoreceivers be successful, they will be used to add margin or redistribute error allocations.

3.3.2 Core Team Assessment

In addition to the analysis by Team X, several members of the Core Team and Community Science Team with experience in interferometry evaluated the concepts. The SGO High and SGO Mid concepts benefit significantly from the investments made in the LISA concept over the past decades. While careful system design is still required, the interferometry design is low-risk. The LAGRANGE and OMEGA designs are less well studied and bring additional risks. Determining the likelihood and severity of these risks or developing mitigation strategies would require more time than was available during this study. Here we simply identify and explain these risks.

For LAGRANGE, the chief risk results from the fact that the displacement measurement is made to a fiducial optic fixed to the spacecraft rather than a drag-free test mass. The desired measurement for GW detection is between the centers of gravity of two inertial objects. Fluctuations in the projected line-of-site distance between the LAGRANGE fiducial optic and the spacecraft center of mass will be a source of noise. The likely mitigation strategy for this is to minimize in-band temperature fluctuations and their resulting mechanical distortions. Evaluating this noise source would require a detailed thermal model and could be highly dependent on the specific spacecraft design. On the positive side, not requiring a measurement to a freely floating optic inside the spacecraft results in some simplifications of the LAGRANGE IMS, such as a smaller optical bench and reduced phasemeter channel count.

OMEGA has a number of additional risks associated with the IMS that are not present in the other concepts. Several of these are consequences of the OMEGA orbits. The first effect is that the

OMEGA telescopes regularly point near the sun, potentially allowing sunlight into the temperature-sensitive inner payload. The proposed solution to this problem is to place a narrowband non-dissipative filter in the telescope aperture that passes the laser light but rejects the majority of the sunlight. As this filter is in the measurement path, its optical pathlength must remain stable at the picometer level. While significant progress has been made developing prototype filters, some risk remains. The second consequence of the OMEGA orbit is that the sun angle varies with a period of 53.2 days, resulting in a time-varying thermal load. +While the fundamental frequency of this thermal disturbance is well below the mHz GW measurement band, there is some risk that some non-linear process upconverts an unacceptably large portion of it into the measurement band.

A second set of complexities with OMEGA arise in the free-space back link. To maintain pointing this will require an active, two-axis angle adjustment on each spacecraft. When the dynamic range of this angle adjustment is exceeded, science measurements will need to be interrupted and a stationkeeping maneuver will need to be executed with one of the spacecraft. Finally, OMEGA baselines a compact, lightweight interferometry system based on optical fibers. This requires picometer optical pathlength stability within the fibers. While this may be achievable with careful mounting and environmental control, it will require a technology development effort.

3.3.3 Time-of-Flight Findings

- The LISA-derived IMS employed by SGO High, SGO Mid, and LAGRANGE/McKenzie is a well-developed, low-risk concept capable of meeting the measurement requirements.

  The LISA IMS has been extensively developed in both the U.S. and Europe. Highlights include a phase measurement system developed at NASA/JPL and validated in a hardware testbed, the optical bench constructed for LPF, laser development in the U.S. and Europe, and laser frequency stabilization efforts that have demonstrated multiple viable approaches to addressing laser frequency noise.

- The non-drag-free approach brings an additional risk associated with relative motion between the spacecraft center of mass and the fiducial optic. Mitigating this effect may place severe requirements on the thermal, mechanical, and gravitational stability of the spacecraft. Further study would be required to assess this.

  In the non-drag-free approach, the GW signal is manifest in changes in the distance between the spacecraft centers of mass. The interferometry will measure between fiducial optics on each spacecraft and must rely on the relative position of these optics to the spacecraft mass centers remaining stable in the measurement band. A similar effect is present in the drag-free approach, except that the mass center of interest is that of the test mass and is expected to be more stable. Neither the Core Team nor Team X were able to quantify this effect during this study; should a non-drag-free approach be pursued, further work would be needed to determine the impact of stability requirements on the spacecraft design.

- Refinement or enhancement of core interferometry technologies has the potential to reduce risk, reduce cost, or improve measurement performance but will not enable a probe-class mission.

  Economies in mass and power or improvements in performance could be had at the component and subsystem level. Examples include lower-noise photoreceivers, which could enable reductions in laser power or telescope size, a higher-reliability laser system, or replacement of some bulk optical components with optical fibers through the use of digital interferometry. While the direct effects of these improvements will be small, they could have moderate effects at the system level.

3.4 Flight System

The measurement of gravitational waves makes unusual demands on the spacecraft hardware. The spacecraft bus functions as the laboratory in which a precision measurement apparatus (the scientific payload) operates. Just as in terrestrial laboratories, extreme care must be taken to ensure that the spacecraft provides a quiet environment. Deployable structures such as solar arrays, moving parts such as reaction wheels, and reservoirs of fluid such as fuel tanks are generally prohibited due to the disturbances they induce. The spacecraft bus must also be magnetically clean, thermally stable, and dimensionally stable to prevent fluctuations in the spacecraft's local gravity field.

All of these considerations lead to a highly integrated spacecraft for science operations, which the community calls a 'sciencecraft,' and a separable propulsion module that can deliver the sciencecraft to its initial orbital state. The number of sciencecraft and propulsion modules and the number of unique designs among them drives the total cost of the flight system. A secondary (but potentially large) impact of configuration on cost is the ability to meet the volume and mass requirements of a given launch vehicle.

Mitigating the technical challenges of the flight systems is the simplicity of operations, comparable to WMAP or Kepler. Each sciencecraft performs constant pointing (toward another sciencecraft or two) and data collection with regular downlink of modest quantities of data. All systems studied made use of the Deep Space Network (DSN) 34 m antennas for commands and telemetry. The power systems are limited by not allowing articulated arrays, but for those mission concepts with heliocentric orbits (e.g., SGOs, LAGRANGE), it is simplified by the lack of eclipses and constant or near-constant sun angle.

3.4.1 Team X Assessment

The Flight System is perhaps the mission element that is best suited to concurrent engineering studies such as those performed by Team X. Unfortunately, the detail-oriented nature of the process makes it expensive, and the resources were not available to perform engineering studies of all of the RFI concepts. The five configurations studied (SGO High, SGO Mid, LAGRANGE/McKenzie, and both OMEGA options) had many similarities, but also had enough differences that the results from Team X may be applicable to some broader interpretation. It is also worth noting that the maturities of the design inputs to Team X varied significantly among the concepts. In the case of SGO, the Team X study provided a check on the current design, an opportunity for some new ideas, and an assessment of cost and risk for easy comparison with the LAGRANGE and OMEGA concepts. While the OMEGA concept has existed in some form for almost as long as the LISA concept, very little work had been done on it in recent years prior to the announcement of the RFI. The LAGRANGE/ McKenzie concept was an entirely new idea conceived in response to the RFI.

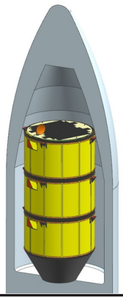
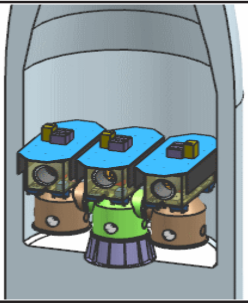
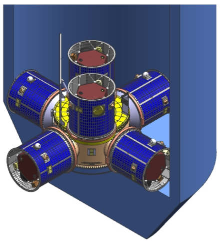
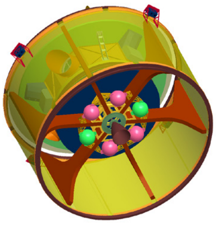
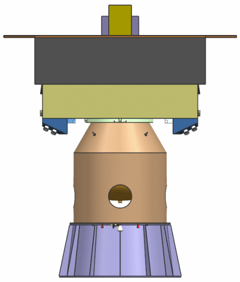
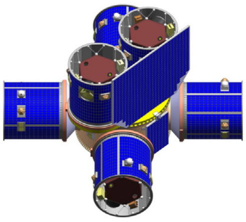
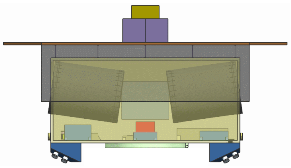
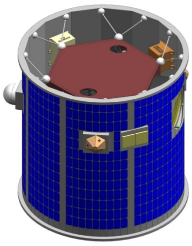
	SGO Mid/-High	**LAGRANGE/McKenzie**	**OMEGA**
Launch Stack			
Cruise Configuration			
Sciencecraft			

Table 11. Sciencecraft Configurations for Mission Studied by Team X. The bottom row shows the configuration of the sciencecraft, the middle row shows the cruise vehicle (sciencecraft and propulsion module), and the top row shows all vehicles housed in the launch vehicle fairing. Note that these configurations reflect the designs proposed by Team X, and in some cases differ from the configurations proposed by the RFI submitters.

Table 11 provides renderings of the spacecraft configuration for each of the Team X studied concept during three mission phases: launch, cruise, and science operations. Table 12 highlights some of the relevant Flight System parameters determined by Team X.

	SGO-Mid (-High)	LAGRANGE	OMEGA Option 1 (2)
S/C Configuration	3 identical	1 center and 2 outer	3 left-hand + 3 right-hand
Payload Mass (kg)	216 (260)	140 (center) 130 (outer)	75 (55)
Payload Power (W)	233 (256)	180 (center) 156 (outer)	85 (54)
S/C Mass (kg)	717 (979)	586 (center) 531 (outer)	218 (196)
S/C Power (W)	652 (689)	544 (center) 450 (outer)	258 (220)
S/C Propulsion	μN for drag-free and attitude control	Center: mN thrusters for 10 m/s/yr ACS + attitude control Outer: mN thrusters for attitude control	μN for drag-free and attitude control
Sun Angle	60° to top deck normal, azimuthal rotation with 1-year period	constant normal to top deck	Nearly edge-on, rotation with 56-day period
Earth Distance (Gm)	23.4 to 57.5 (~50 constant)	1.6 (center) 20.8 (outer)	0.6
Data Rate (kbps)	90 (90)	28 (center) 0.05 (outer)	75 (75)
P/M Configuration	3 identical*	1 center and 2 outer	1 "smart" carrier
P/M Mass (kg)	661 (844)	591 (center) 224 (outer)	572 (553)
P/M Prop. Mass (kg)	139 (300)	114 (center) 174 (outer)	466 (466)
Total Launch Mass Wet (kg)	4553 (5938)	3182	2347 (2223)
L/V, Margin	Atlas 551, 25% (2%)	Atlas 511, (3%)	Falcon 9, 5% (11%)

* as proposed by customer team. Team X raised the possibility of increasing the structure on the bottom P/M in the launch stack.

Table 12. Sciencecraft Parameters as determined by Team X.

SGO Mid achieves a smaller sciencecraft mass and power relative to SGO High by a smaller inter-spacecraft distance (1 Gm vs. 5 Gm), allowing a smaller telescope and lower-power laser, and sacrificing some performance. LAGRANGE has smaller solar arrays that are normal to the sun, the same size telescope as SGO High, no GRS, but a number of other sensors. OMEGA has a much lighter instrument that is the same in function as SGO Mid, with roughly the same distance between sciencecraft.

In all concepts, the entire constellation is launched in a single vehicle and propulsion modules are used to deliver the sciencecraft to their individual operational orbits. In the case of SGO High and

Mid, each sciencecraft is mated with a dedicated propulsion module that also serves as a telescope shroud during launch, separation, and cruise. The three 'cruisecraft' (sciencecraft mated to propulsion module) separate shortly after launch and perform their trajectory burns individually. The orbits and trajectory design of OMEGA allow a different strategy: a single carrier spacecraft delivering all six sciencecraft to their respective orbits. LAGRANGE, as studied by Team X, utilizes a hybrid strategy: the three cruisecraft remain mated after launch and the central propulsion module is used to deliver the entire stack to the Earth-Sun L2 point. After the transfer burn to L2 is complete, the two outer cruisecraft can separate and, at the appropriate time, use their propulsion systems to inject the outer sciencecraft into their respective orbits.

SGO Mid/High and OMEGA require a single propulsion module design. For LAGRANGE, the center propulsion module has the same engine and tanks but is mechanically stronger and capable of supporting the mass at launch and during the transfer to L2. The central propulsion module also requires two additional separation rings to accommodate the outer cruisecraft. The total propellant mass is similar for four of the five mission concepts, the exception being SGO High which requires roughly five times the others, allowing it to "park" at a fixed distance from the Earth and enable mission lifetimes on the decade timescale.

In each case, the sciencecraft support only their own weight during launch, and all other loads are carried by the propulsion module structures. In the case of SGO, Team X was concerned that either the proposed propulsion module structure was inadequate or that the structure mass had been underestimated. This concern could be remedied by increasing the structure in the propulsion module at the bottom of the stack, but this would result in slightly different propulsion module designs and, hence, increased engineering costs.

When Team X applied more conservative estimates for propulsion module mass, the SGO High mission was determined to 'not close' due to the total mass exceeding the launch capability of the Atlas 551 for the required delta-V. Revisiting the propulsion module mechanical design may solve this problem. Alternatively, a more capable launch vehicle, such as the Space-X Falcon Heavy, would provide substantial mass margin even with conservative mass estimates. While Space-X vehicles were explicitly prohibited from consideration during these studies, it is worth noting that Space-X has signed a contract with a commercial customer (INTELSAT) for a Falcon Heavy, and its first flight is scheduled in 2013, with the price likely under $125M.

The SGO High sciencecraft is the largest of the four options, with a mass just under one metric ton. This is primarily driven by the payload, which has the most elements of any of the designs considered. SGO Mid achieves a smaller sciencecraft mass and power relative to SGO High by reducing laser power and telescope size. Most of the mass savings is due to the reduction in sciencecraft height allowed by the smaller telescope. The resulting drop in GW sensitivity is mitigated by reducing the baseline of SGO Mid to 1 Gm as opposed to SGO High's 5 Gm.

It is worth noting that the mass estimates for SGO High, and to a lesser extent SGO Mid, were derived from a detailed master equipment list and have some traceability through more than a decade of project development on LISA. As a result, they are likely to be more accurate than the first-cut estimates made for new mission concepts such as LAGRANGE or even OMEGA.

The smaller solar array of LAGRANGE and its simpler interferometry system further reduce the estimated mass compared to SGO Mid. Interestingly, the replacement of the GRS with a force measurements system appears to be mass and power neutral (see section 3.2). The OMEGA sciencecraft mass estimate is reduced because the number of payload elements per sciencecraft is cut in half relative to SGO Mid (twice as many spacecraft) and OMEGA's design philosophy is predicated on aggressively light-weighting all components, including instrumentation. For example, the OMEGA team's estimate for the payload at a single vertex (two OMEGA sciencecraft) is 128 kg, compared to 217 kg for SGO Mid. The measurement performance and baseline between the two missions are approximately the same. Clearly, if the mass and power reductions assumed in the OMEGA design can be achieved, they could equally well be applied to SGO Mid.

3.4.2 Development Schedule and Model Philosophy

Out of the five systems, the two SGO systems both have three identical sciencecraft and three identical propulsion modules. LAGRANGE has two outer sciencecraft and two outer propulsion modules, and one middle sciencecraft and one middle propulsion module that are modestly different from the outer two. By contrast, the two OMEGA options have a single propulsion module, with six identical sciencecraft.

For the SGO concepts and LAGRANGE, the first flight unit is treated as a protoflight, receiving additional testing to qualify the design. Of the other two, one (or both, if they are identical) is tested at acceptance test levels and the other, differently designed unit is tested as protoflight.

In contrast, the two OMEGA options each have a single propulsion unit that is tested as protoflight, then six identical flight sciencecraft, of which the first is tested as a protoflight unit and the other five as flight units with acceptance tests.

Multiple units may increase the complexity of the integration process by potentially requiring multiple sets of test equipment, multiple teams, etc. depending on the build approach chosen. The decision to build in parallel, series, or some combination can have large impacts on cost and schedule. If a design flaw is discovered during the protoflight testing, it may need to be repaired on all flight hardware that has already been built, and that hardware may require 'regression testing' or a repeat of flight testing already completed, to verify that the repaired hardware still meets requirements. The more flight units being developed in parallel, the larger the potential impact of finding problems that require substantial rework and regression testing. This risk can be avoided by completing all testing on the first flight model before building the rest, but at the expense of an overall longer nominal schedule. Alternately, when a large number of flight units are being built, a qualification model can be built and tested first, then any needed changes can be implemented on all the flight units, which are then tested to acceptance test levels. The six flight units for OMEGA are at the edge, where either a protoflight or qualification unit approach would be considered.

3.4.3 Impact of Payload Requirements

As mentioned earlier, GW payloads can place unfamiliar and strict requirements on aspects of the flight system such as dimensional stability, thermal stability, and magnetic cleanliness. For a drag-free concept (SGOs, OMEGA), the strictest requirements are generally defined at the test mass. For example, the local gravitational field induced by the spacecraft at the test mass must be stable to prevent unintended accelerations. This requires a 'self-gravity' model of the spacecraft to be developed and maintained during integration. It is worth noting that innovative procedures for accomplishing this have been developed for LPF.

For LAGRANGE, the test mass has effectively been replaced by the sciencecraft and, as a result, the challenging thermal and mechanical requirements are distributed throughout the sciencecraft rather than being concentrated at the proof mass. For example, one concern is maintaining a constant position offset between the sciencecraft center of mass and the reference optic used in the time-of-flight measurement. This will place strict requirements on the dimensional stability of the entire sciencecraft. Also, the sciencecraft structures normal to the sensitive direction must maintain a constant temperature in order to suppress fluctuating forces resulting from emission of thermal radiation.

For LAGRANGE, the test mass has effectively been replaced by the sciencecraft and, as a result, the challenging thermal and mechanical requirements are distributed throughout the sciencecraft rather than being concentrated at the proof mass. For example, the surface temperature of the sciencecraft structures normal to the sensitive direction must maintain a constant temperature in order to suppress fluctuating forces resulting from emission of thermal radiation. Another concern is maintaining a constant position offset between the sciencecraft center of mass and the reference optic used in the time-of-flight measurement. This will place strict requirements on the dimensional stability of the entire sciencecraft.

3.4.4 Flight System Findings

- All mission concepts considered require a spacecraft bus with unusual requirements on mechanical stability, thermal stability, and gravitational stability. Meeting these requirements leads to a payload and bus that are tightly integrated during design, development, test, and operations.

  All of the measurement architectures presented to this study required a flight system that functions as a laboratory for precision measurement and consequently must meet some strict stability requirements. The experience with LPF has demonstrated that early and vigorous engagement of systems engineers is critical to the success of GW missions, more than most space science missions. There is also a need to develop and maintain an engineering workforce that is familiar with the unique requirements presented by GW missions.

- The design of the flight system influences the potential for extended operation of the mission.

  Extending science operations beyond the primary mission can make a significant impact on science return. While some savings in the flight system can be had at the expense of reliability, this limits the possibilities for extended operations.

- Of the missions studied by Team X, the flight systems of SGO High and SGO Mid are most mature, and appear to have the lowest risk.

  The SGO concepts benefit from the significant effort expended in developing the LISA flight system both at NASA and through ESA's industrial study. Many flight system risks have been retired through these efforts.

- The requirements placed on the spacecraft bus for a non-drag-free design are different than those for a drag-free design and are less well understood. Further work would be necessary to determine the exact nature of these requirements and the resulting implications for the flight system.

  While both drag-free and non-drag-free measurement architectures place requirements on the flight system, the requirements for the non-drag-free systems are not well understood. The Core Team identified a number of distinct effects, some of which have the potential to place severe requirements on the flight system. Neither the Core Team nor Team X were able to perform a comprehensive evaluation of these effects during the course of the study. At present, these effects could be considered as risks that could potentially be retired through further study should a non-drag-free approach be of interest.

4 Science Consequences

The goal of this section is to provide a quantitative assessment of the scientific capabilities of the mission concepts that were submitted in response to the RFI for Concepts for a NASA Gravitational-Wave Mission, and a qualitative assessment of the fraction of the LISA science these concepts can deliver.

The diversity and richness of the LISA science objectives make it impossible to compare the capabilities of alternative mission concept with a single metric. Instead, we define a collection of metrics that, taken together, provide a general sense of the scientific capabilities of the instrument. Obvious candidates include the number of sources that can be detected, the distance to which a fiducial system can be detected, and how well the physical parameters of a source can be inferred from the observations. These metrics can be computed for each of the standard LISA source populations: galactic binaries, massive black-hole binaries, and compact object captures (EMRIs). What is less clear is how to weight the various metrics in an overall science assessment, or to quantify concepts like "discovery potential" for exotic or unknown sources. For example, are a small number of detections with very precise parameter estimates more valuable than a large number of detections with poor parameter estimates? The answer will depend on the scientific objective. If the goal is to constrain astrophysical population models, then a 10% measurement of the binary masses may suffice. If the goal is to test general relativity, then the higher the precision the better.

4.1 Sensitivity Curves

The starting point for any science performance study is an instrument sensitivity curve that combines the effects of the detector response function and the instrument noise levels. The sensitivity curve sets the "horizon distances," the distances to which a source can be detected, for fiducial sources, and when combined with a population model and an observation time, it determines the number of sources that can be detected. The sensitivity curve also impacts the parameter recovery accuracy, in part through the overall signal-to-noise of the detection, but also through the relative weighting of the signal as a function of frequency. Changes in the sensitivity curve affect different populations in different ways. The LISA design carried significant margin for detecting massive black holes and galactic binaries, but less for EMRIs. The LISA sensitivity curve promised massive black hole detections out beyond redshift $z = 10$ for systems with total mass between 10^3 to $5 \times 10^7\ M_\odot$, and the ability to detect white dwarf binaries with orbital frequencies above 1 mHz anywhere in the galaxy. For EMRI systems, the horizon distance peaked at $z = 2$ for central black-hole masses of $5 \times 10^5\ M_\odot$, and fell away for higher or lower masses. A factor of two change in the sensitivity in the frequency range 2–10 mHz results in roughly an order of magnitude change in the number of EMRI systems that can be detected, making them the "canary in the coal mine" in the performance trade space. It is also worth noting that the LISA sensitivity curve was close to optimal: improvements in sensitivity would be limited by additional sources of astrophysical confusion noise, such as those from extra-galactic white-dwarf binaries or unresolved EMRI systems.

The majority of the mission concepts provided either sensitivity curves or instrument noise levels, with some of the submissions listing multiple options. A science task force reviewed the noise budgets and instrument response calculations, and in most instances the submitted performance levels were accepted without change for the purposes of the science assessment study. However, we caution that the review was at a very high level—for example, checking whether the specified telescope diameter and laser power were compatible with the assumed shot noise levels—and a far more detailed study would be needed to verify the performance models. In particular, the task force was concerned about thermal issues for the geocentric concepts and the subtraction of spurious accelerations for the non-drag-free concepts. Following discussions between the science task force and the RFI respondents, the sensitivity curves for the Folkner, McWilliams, and Saif proposals were amended prior to the final science assessment study. For the Folkner proposal, the noise contribution from the solar wind was revised upward, and for the McWilliams proposals optical path noise was added to the noise budget. The instrument parameters used in the science performance study are listed in Table 13. As proposed in the RFI response, the Saif atom-interferometry sensitivity curve was found to be un-realizable, and no science assessment was performed. See Appendix C for details.

Concept	Armlength (*m*)	Duration (years)	# of links	S_p (m^2 Hz^{-1})	S_a (m^2 s^{-4} Hz^{-1})
SGO-Lowest	$\sim 1.6 \times 10^9$	2	4	1.0×10^{-22}	2.1×10^{-29}
SGO-Low	1×10^9	2	4	1.0×10^{-22}	$9 \times 10^{-30} (1 + (10^{-4}\ \mathrm{Hz}/f))$
SGO-Mid	1×10^9	2	6	1.0×10^{-22}	$9 \times 10^{-30} (1+ (10^{-4}\ \mathrm{Hz}/f))$
SGO-High	5×10^9	5	6	3.2×10^{-22}	$9 \times 10^{-30} (1+ (10^{-4}\ \mathrm{Hz}/f))$
Folkner	2.6×10^{11}	3	6	1.0×10^{-18}	$1 \times 10^{-24} (f/10^{-4}\ \mathrm{Hz})^{-3/2}$
McKenzie20	2.1×10^{10}	2	4	6.4×10^{-21}	$1.6 \times 10^{-26} (f/10^{-4}\ \mathrm{Hz})^{-3/2}$
McKenzie40	2.1×10^{10}	2	4	6.4×10^{-21}	$1.6 \times 10^{-26} (f/10^{-4}\ \mathrm{Hz})^{-3/2}$
Omega	1×10^9	1	6	2.5×10^{-23}	9.0×10^{-30}
Conklin	6.7×10^8	5	6	6.4×10^{-23}	$1.0 \times 10^{-30} (1 + (10^{-3}\ \mathrm{hz}/f))$
GADFLI 0.1	7.3×10^7	2	6	4.0×10^{-24}	$9.0 \times 10^{-32} (1 + (10^{-3}\ \mathrm{Hz}/f))$
GADFLI 1	7.3×10^7	2	6	4.0×10^{-24}	$9.0 \times 10^{-30} (1 + (10^{-3}\ \mathrm{Hz}/f))$
GADFLI 10	7.3×10^7	2	6	4.0×10^{-24}	$9.0 \times 10^{-28} (1 + (10^{-3}\ \mathrm{Hz}/f))$
Tinto 1	7.3×10^7	2	6	8.0×10^{-26}	9.0×10^{-28}
Tinto 2	7.3×10^7	2	6	1×10^{-22}	9.0×10^{-28}
Tinto LISA	7.3×10^7	2	6	8×10^{-26}	9.0×10^{-30}

Table 13. Mission Parameters. The parameters used in analyzing the concepts are the measurement armlength, the duration of the science observations, the number of links, and the power spectral densities of displacement sensitivity (S_p) and residual acceleration noise (S_a).

The sensitivity curves generated using the parameters in Table 13 are shown in Figure 2. These include estimates for the galactic confusion noise computed using the technique described in Arun et al. (2009).

4.2 Horizons and Detection Counts

A basic performance metric is the distance to which a fiducial source may be detected above a designated signal-to-noise ratio (SNR) threshold. Figure 3 shows the horizon distances for comparable mass black hole mergers and compact object captures (EMRIs) as a function of the total mass of the binary system.

For the massive black-hole binaries, the fiducial system was taken to have a 3:1 mass ratio with aligned spins and dimensionless spin parameters $\chi = 0.5$ for both bodies. The sky and orientation averaged signal-to-noise ratios were computed using a hybrid phenomenological waveform model that blends a post-Newtonian inspiral with a parameterized merger and ringdown waveform that has been calibrated against waveforms from numerical relativity [Santamaria et al. 2010], with a detection threshold set at $SNR = 10$. For the EMRI systems, the fiducial system was taken to be the capture of a 10 $M_\odot$ stellar remnant black hole by a central black hole with dimensionless spin parameters $\chi = 0.5$. The orbit was taken to have an eccentricity of 0.5 two years before capture, and the signal-to-noise detection threshold set at $SNR = 15$. The Barack-Cutler "kludge" waveforms [Barack & Cutler 2004] were used to compute the sky and orientation averaged signal-to-noise ratios. A closely related performance metric is the number of systems that may be detected assuming a specific mission lifetime and a population model for the sources. For massive black-hole mergers, the so-called large and small seed population models described in Arun et al. [2009] were used in conjunction with the same waveform model and signal-to-noise threshold used to compute the horizon distances. Results for the "chaotic" and "efficient"

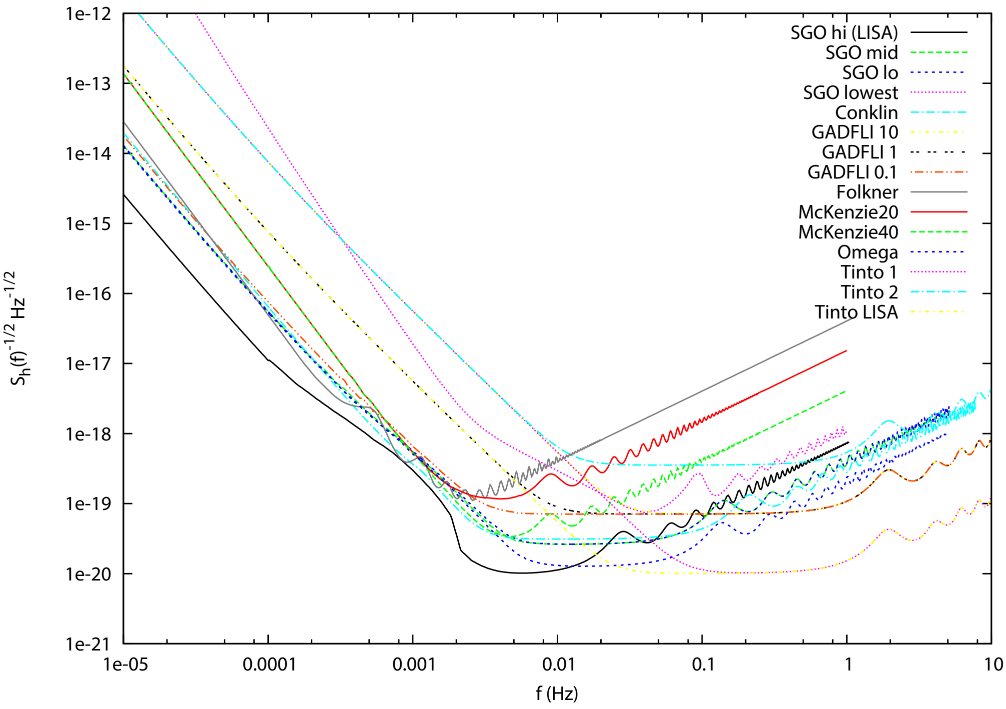


Figure 2. Single Channel Sensitivity Curves. The curves are amplitude spectral density of gravitational wave strain (S_h) versus frequency. Since gravitational wave antennas are amplitude detectors, source strength falls off inversely with distance, not inverse squared. The SGO High sensitivity matches LISA's, and is used as a proxy for the LISA mission in this study.

accretion scenarios were averaged to produce the detection estimates shown in Figure 4. The reduction in detections from the LISA design (here represented by "SGO High") is a combination of the reduced sensitivity and the reduced mission lifetimes. The impact is greatest for the small seed models which, like the EMRIs, are very sensitive to a loss of sensitivity in the 2–10 mHz band.

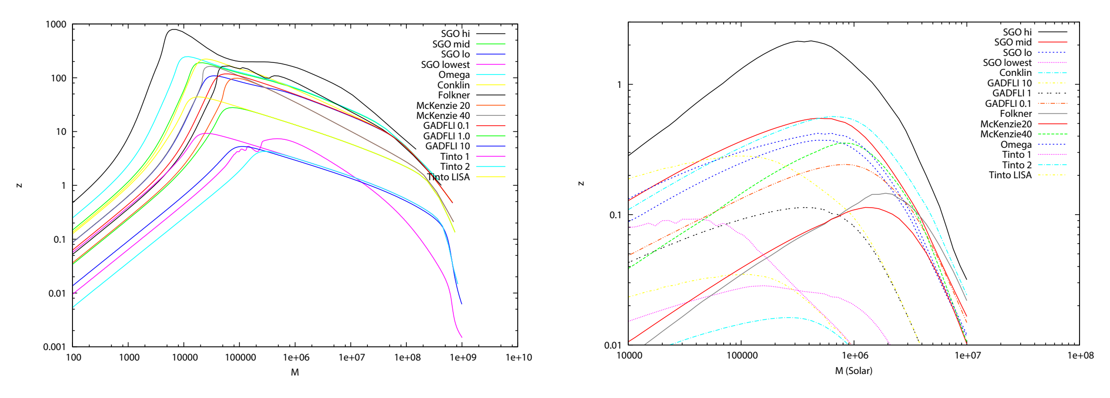


Figure 3. Horizon distances (expressed in redshift) as a function of rest-frame total mass (M) in solar masses for massive black-hole binaries (left) and EMRIs (right).

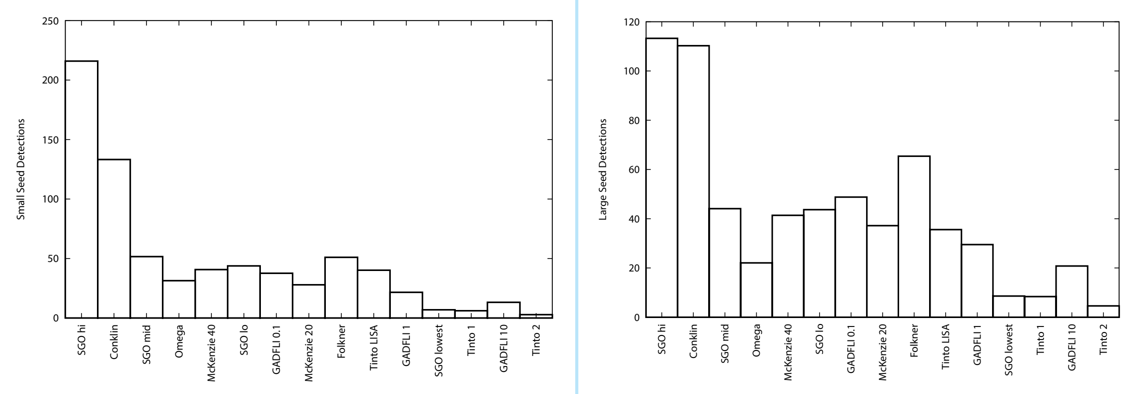


Figure 4. Detection number estimates for the small (left) and large (right) seed models for massive black-hole mergers. Note that not all missions have the same duration of science observations.

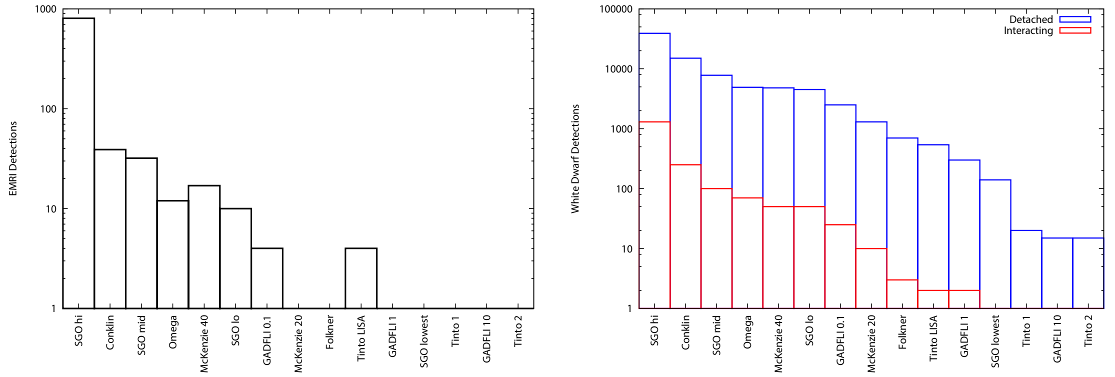


Figure 5. Detection number estimates for the EMRIs (left) and white dwarf binaries (right). The white dwarf systems estimates are broken out into detached (blue) and interacting AM CVn type systems (red). Both of these plots use a logarithmic scale. Note that not all missions have the same duration of science observations.

For the EMRI detection estimates shown in Figure 5, the population model described in Gair et al. [2004] was used with the same waveform model and signal-to-noise threshold used to compute the horizon distances. Also shown in Figure 5 are the detection estimates for white dwarf binaries based on the Nelemans et al. population model used in the 4th round of the Mock LISA Data Challenge [Babak et al. 2010]. The detection criteria for galactic binaries and the associated confusion noise estimate were computed using the techniques described in Arun et al. [2009]. The theoretical EMRI merger rate predictions are uncertain by roughly an order of magnitude, so the reduction in detection rates relative to the LISA design seen in Figure 5 represent a science risk for concepts with shorter lifetimes and reduced sensitivity in the 2–10 mHz range. And while the detection numbers for galactic binaries are more secure, some of the less sensitive concepts run the risk of detecting few interacting white dwarf binaries, which are expected to play a crucial role in unraveling the life cycle of binary star systems.

4.3 Discovery Space

The New Worlds New Horizons report [NWNH 2010] called out LISA's "potential for discovery of waves from unanticipated or exotic sources", which might ultimately prove to be the biggest scientific impact of the mission. But how can this be quantified? One of several possible measures might be the amplitude signal-to-noise ratio for detecting a gravitational wave background with energy density per logarithmic frequency interval Ωgw(f):

$$SNR^4 \sim \frac{T}{H_0^4} \int \frac{\Omega^2(f)}{S_n^2(f) f^6} df$$

Many of the potential sources for a gravitational wave background have been found to produce spectra $\Omega_{gw}(f) \propto f^{a}$ that are with mildly red or blue ($|a| < 1$), so it is reasonable to compare the amplitude sensitivity for a scale invariant spectrum $a = 0$. This comparison is shown in Figure 6, with the sensitivity scaled relative to the "SGO High" or LISA mission. If the spectra happened to be bluer, or if the spectra had a peak above ~10 mHz, then the shorter baseline missions would fare better than they do for the scale-invariant spectrum used to produce Figure 6.

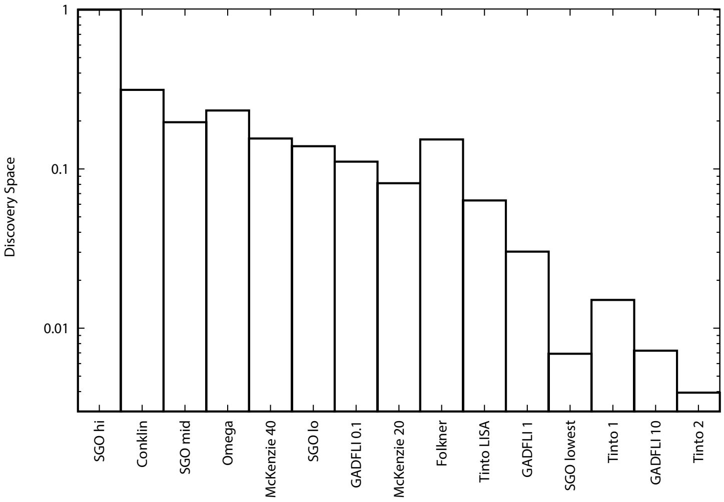


Figure 6. The relative amplitude sensitivity of the various mission concepts to a scale-invariant stochastic background.

The amplitude sensitivity tells only part of the story, as it assumes that there is some way to distinguish between instrumental noise and a stochastic background. While this may be possible with a four-link concept [Adams and Cornish 2010], the analysis is made far more robust when six links are available. This allows gravitational-wave null channels to be constructed, which can be used to measure the low-frequency instrument noise on orbit [Hogan and Bender 2001].

4.4 Parameter Estimation

Mission concepts that have higher detection numbers will also have a larger number of high signal-to-noise detections, and this generally translates into superior parameter estimation capabilities. However, several other factors play a role in how the information about a source is encoded in the data. These include the number of interferometry channels, the shape of the sensitivity curve, the size of the detector, and the sweep of the antenna pattern. Parameter estimation for massive black-hole binary mergers are particularly sensitive to these factors because the majority of the signal-to-noise is accumulated in the final days to hours before merger, during which time the signals sweep through several decades in frequency. Designs with six laser links are able to make instantaneous measurements of both gravitational-wave polarization states, which proves to be a key factor in breaking degeneracies between orbital inclination, distance, and sky location for these burst-like signals. In contrast, the signal-to-noise from galactic binaries and EMRIs accumulates steadily over several years, allowing polarization information to be extracted from the evolving projection onto the antenna pattern, thus lessening the impact of having four rather than six laser links.

Parameter estimation studies were performed for galactic binaries and massive black-hole mergers, but not for EMRIs. For EMRIs the expectation is that if they are detected, then the parameter estimates will be excellent because the templates used to make the detection must match the signals for hundreds of thousands of cycles. For galactic binaries the results of the parameter estimation studies have been summarized in Figure 7, which shows the number of systems that can be localized to better than one square degree, and the number that can also be localized to better than 10% in distance. The latter systems also yield chirp masses that are measured to better than ~10%.

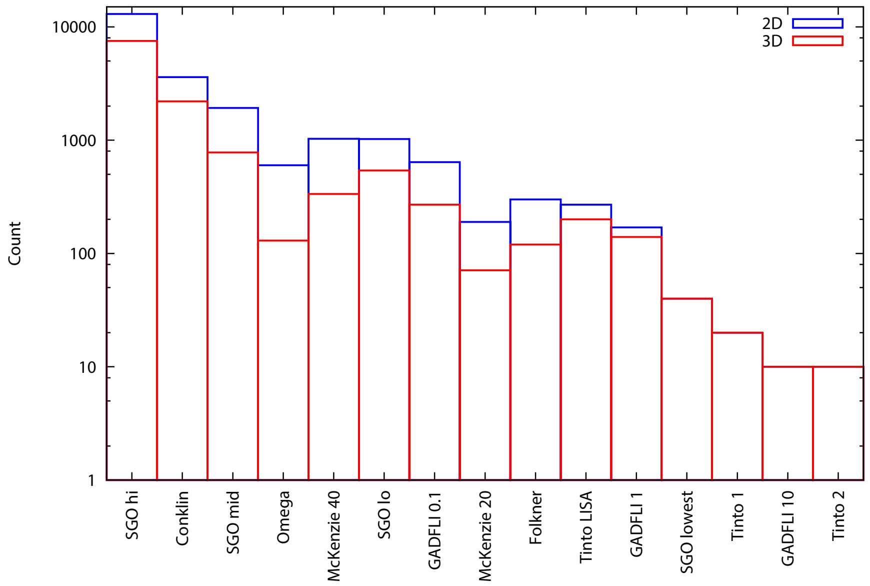


Figure 7. The number of white dwarf binaries that can be localized within one square degree (2-D blue) and the number that can additionally be localized within 10% in distance (3-Dred).

Parameter estimation for massive black=hole mergers shows the most sensitivity to design changes, and this can critically impact the ability to carry out many of the key LISA science goals. Previous studies have shown that using more complete waveform models can improve the parameter estimates and lessen the impact of design changes, such as having four rather than six links. In addition, many of the new concepts are less sensitive at low frequencies than the LISA design, which enhances the importance of the merger and ringdown portion of the signal relative to the inspiral. To account for these considerations, the most complete waveform models available were used. At present there is no single analytic waveform model capable of describing the inspiral, merger and ringdown phases of a binary merger in full detail, so it was necessary to combine information from the best approximations available. For the inspiral portion of the signal, a post-Newtonian waveform model that includes the effects of spin precession and multipole moments beyond the quadrupole was used [Lang et al. 2011]. The merger and ringdown signal was modeled using the same phenomenological waveform [Santamaria et al. 2010] used to compute the signal-to-noise ratios. The merger-ringdown waveform is incomplete in that it only models the dominant quadrupole emission, and it requires that the spins are aligned with the orbital angular momentum vector (hence, precession effects are absent). However, the spin expansion for binary mergers [Boyle & Kesden 2008] indicates that it is the projection of the spins onto the angular momentum direction that largely determines the properties of the merged black hole; moreover, there is little time for spin precession effects to act during the merger. Based on these considerations, the information from the inspiral and merger/ringdown were combined by adding together their Fisher Information Matrices, with the spin parameters for the merger taken to equal the projection of the spins along the orbital angular momentum direction at the end of the inspiral. The simulations included a complete instrument response model computed directly from the orbital ephemeris of the spacecraft in the constellation.

The signal from a generic binary merger depends on seventeen parameters, but in the studies performed here the orbits were taken to be quasi-circular, which reduces the number of parameters to fifteen. Some of the more important parameters are the sky location and distance to the system, and the masses and spins of the individual black holes. The accuracy with which these parameters can be inferred from the measured signals is a strong function of the system parameters, and it is impossible to summarize the performance with a single number. A more complete picture can be gleaned from histograms of the parameter errors derived from representative population models. An example is shown in Figure 8, where histograms of the parameter estimation errors for the large seed, efficient accretion model [Arun et al. 2009] are compared for the four SGO mission concepts. Similar results were found for the three other population models. The first thing to note is the wide spread in the measurement accuracies for each concept, with the range spanning four orders of magnitude in each parameter (A factor of 8 in the sky area Ω from the product of the errors in azimuth and altitude. Ω is shown in units of square degrees). The second thing to note is that going down the sequence from "SGO High" to "SGO Lowest" results in a factor of ~3 loss in measurement accuracy at each step. While the mid and low concepts have the same sensitivity curves, the reduction from 6 to 4 links increases the covariance between parameters, resulting in a loss of measurement accuracy that exceeds the factor of √2 we would expect from the reduction in signal-to-noise alone . On the other hand, based on the detection numbers shown in Figure 4 and the parameter estimation errors shown in Figure 8, SGO High, Mid and Low could deliver on a significant fraction of the LISA science goals for massive black-hole binaries.

Figure 9 displays histograms of the parameter estimation errors for the three concepts studied by Team X. The relative performance was similar for all four population models considered (two models are shown in Figure 9). The OMEGA and SGO Mid concepts were found to have almost identical performance, while the McKenzie (LAGRANGE) concept was a factor of ~3 less capable. Based on the detection numbers and the parameter estimation capabilities, all three concepts were assessed as being capable of exploring the black hole merger history and discriminating between competing population models [Sesana et al. 2011].

Black hole parameter estimation studies were performed for several additional mission concepts, including the Folkner and GADFLI 1 concepts, that spanned the extremes of detector armlength. The result was that the Folkner concept delivered angular resolution comparable to the LISA design, while the angular resolution for GADFLI 1 was somewhat better than for LISA. Neither of these results would have been easy to predict because the position information gets encoded very differently in these three missions. For the Folkner concept, the position information comes from the timing of when the gravitational wavefronts encounter each spacecraft, while for the GADFLI concept the position information comes from the rapidly rotating antenna patterns for each polarization state. Less extreme versions of these effects are seen in the McKenzie concept (long baseline, similar to Folkner) and the OMEGA concept (antenna rotation, similar to GADFLI). These studies showed that good angular resolution could be achieved with configurations that are very different than the familiar LISA precessing plane geometry. Figure 10 shows the relative performance of the SGO High and GADFLI 1 concepts for two of the black=hole population models. GADFLI 1 outperforms SGO High for all parameters save the luminosity distance. Despite the excellent parameter estimation for massive black-hole binaries, GADFLI science suffers from fewer massive black-hole binaries, fewer detections of galactic binaries, and no EMRI detections.

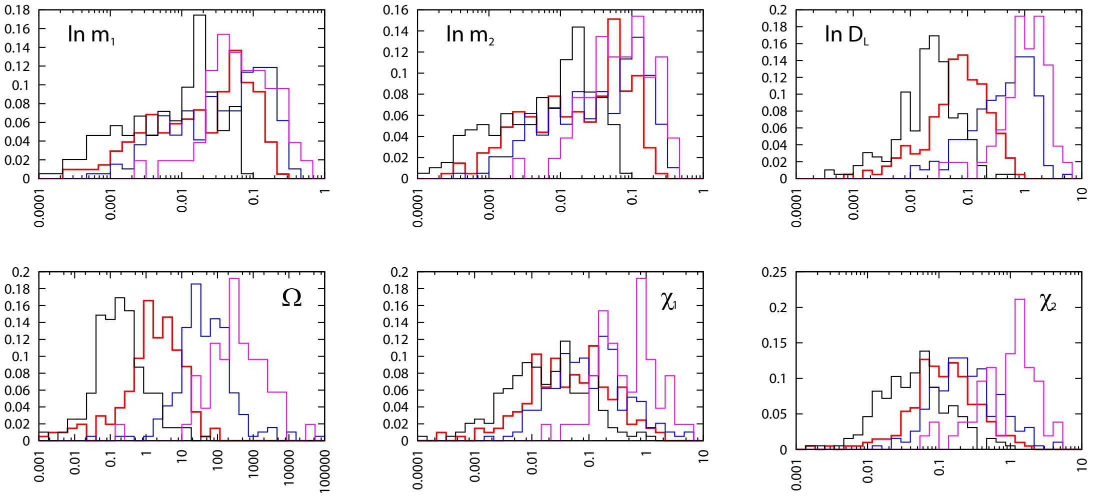


Figure 8. Histograms of the black-hole parameter estimation accuracies for the four SGO mission concepts based on a population of sources drawn from a large seed, efficient accretion model (SGO High-black, SGO Mid-red, SGO Low-blue, SGO Lowest-magenta). All accuracies are expressed as fractional values, except solid angle which is in square degrees. Top row (left to right): mass of the primary (m_1), mass of the secondary (m_2), luminosity distance (D_L); bottom row (left to right): solid angle of the error box on the sky (Ω), spin of the primary (χ_1), spin of the secondary (χ_2).

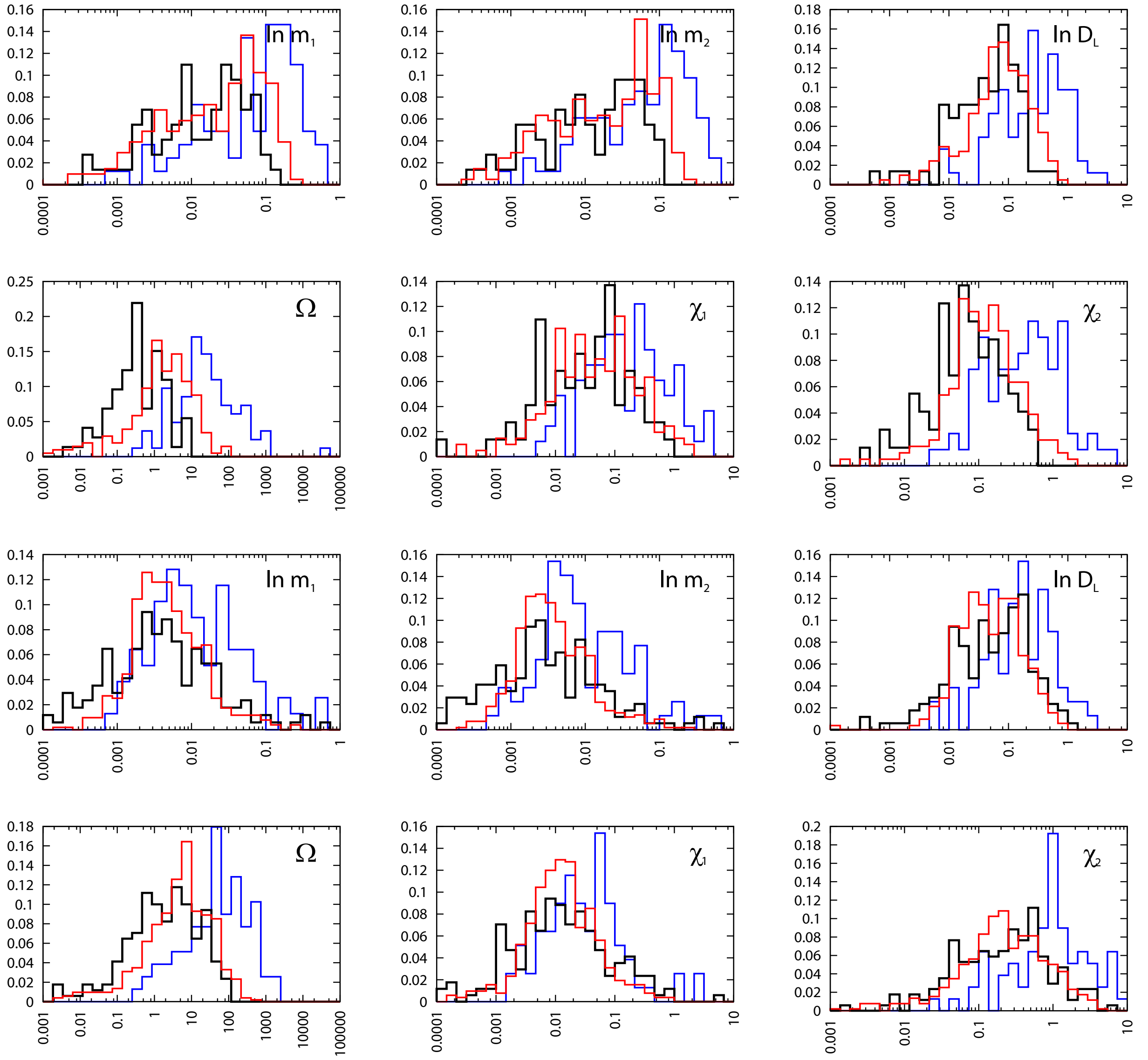


Figure 9. Histograms of the black-hole parameter estimation accuracies for the three missions that were studied by Team X (OMEGA-black, SGO Mid-red, McKenzie 40-blue) for the large seed, efficient accretion model (upper panel), and the small seed, chaotic accretion model (lower panel). The plots in each panel are the same variables in the same arrangement and format as the plots in Figure 8.

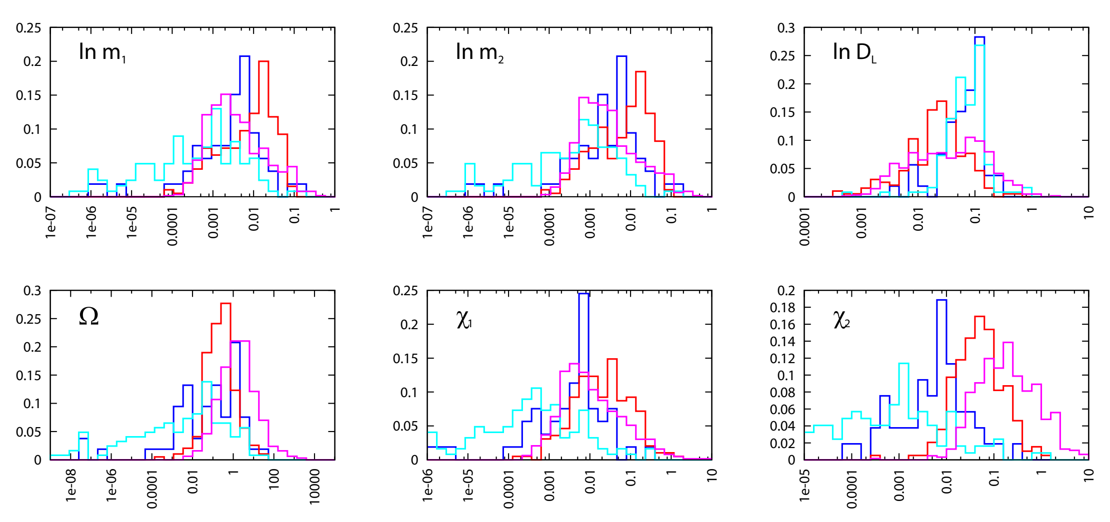


Figure 10. Histograms of the black-hole parameter estimation accuracies showing the relative performance of SGO High (red and magenta) and GADFLI 1 (blue and cyan) for the large seed, efficient accretion model (red, blue) and the small seed, chaotic accretion model (magenta, cyan). The plots are the same variables in the same arrangement and format as the plots in Figure 8.

4.5 Importance of Science Analysis

In producing the analysis described here, the Study Team has drawn on the results of a decade of development in LISA data analysis and GW astrophysics research. Through modest investments and with the enthusiastic support of a committed science community, this work has had a tremendous impact on preparations for a space-based GW mission. Research in these two areas over the past few years has resulted in important advances that allow more science to be extracted from a given instrument design. This has resulted in a reduced scientific risk and increased scientific payoff for GW missions in general. For example, SGO Mid's capability to address significant portions of the LISA science objectives can be attributed largely to advances in astrophysics, source physics, and data analysis. Conversely, SGO High's science potential is even greater than had been predicted in earlier studies of LISA. Some highlights from these activities are listed below.

- *Event-rate estimates:* Research in the astrophysics of compact objects has increased the community's confidence in the predicted event rates for target sources and improved understanding of their physical properties. This has reduced a class of science risks for all space-based GW missions.
- *Source physics:* The final merger phase of a binary black-hole merger was not theoretically understood a decade ago. Research in numerical relativity has opened this field to study, enabling better models of GW waveforms that effectively improve instrument performance by a factor of two. This research has also led to discoveries such as large "kicks" related to asymmetrical GW emission that are of interest to the broader astrophysics community.

- *Waveform Modeling:* A variety of techniques have been applied to produce more accurate predictions of GW waveforms that include additional physics such as the effects of higher harmonics and spin precession. These waveforms improve instrument performance.
- *Instrument Performance Estimates:* A decade ago, LISA's science case was built on estimates of the instrument performance made using crude (but available) models of the GW waveforms and the instrument response. Applying more sophisticated models of both have increased the expected performance of a given instrument. This provides a flexibility to achieve similar performance at a reduced cost or improved performance at the same cost. Further advances in this area can be expected to continue to guide details of the instrument design in order to maximize scientific return.
- *Data Analysis Strategies:* Efforts such as the Mock LISA Data Challenges have demonstrated techniques needed to distinguish the thousands of galactic binaries, many black-hole binaries, several EMRIs, and other sources simultaneously present in the data stream of a space-based GW instrument. As a result, a lower SNR detection threshold for EMRI systems may now be assumed, increasing the number of likely events and decreasing the risk that EMRI science will not be achieved due to lack of detections.

GW astrophysics and data analysis research has been a particular strength of the U.S. research community. This activity has been crucial in the guidance of space-based GW mission planning so far, and will continue to be important in the future. The unique nature of space-based GW science means many of the relevant research areas are directly dependent on NASA's commitment to a future space-based GW mission. A recognized commitment and continued investment is crucial to maintaining the vitality of this research community.

4.6 Science Findings

The science assessment was based on estimates of the horizon distances, detection numbers and parameter estimation capabilities for the anticipated LISA binary source populations. These are quantitatively summarized in Table 1 in the Executive Summary, which is repeated as Table 20 in Section 8.1. The key findings can be summarized as follows:

- Several mission concepts, including those studied by Team X, were found to be capable of delivering a significant fraction of the LISA science related to massive black-hole mergers and galactic binaries.

  Figures 4 and 6 demonstrate that detection numbers for massive black-hole binaries and galactic binaries are sufficiently high for most of the proposed mission concepts that it is highly likely that examples of both of these source classes would be detected. The science return from these sources will depend both on the number of sources detected as well as the quality of the astrophysical information that can be extracted from the measurements.

- The science of compact object captures (EMRI systems) may be at risk due to significantly reduced detection numbers relative to the LISA mission.

  Predicted EMRI event rates vary by roughly an order of magnitude in both directions from the values used here. If the true rate is closer to the low-rate estimates, several mission concepts have significant risk of detecting no EMRI systems, eliminating a significant fraction of LISA science.

- Concepts with three arms significantly improve parameter estimation over two-arm designs for black holes and enhance the ability to detect un-anticipated signals.

  Three arms enable simultaneous measurement of both polarization components of a GW, providing additional information that can be used to measure astrophysical parameters of detected systems. This is one of the primary reasons for the reduced parameter estimation performance of LAGRANGE/McKenzie compared to SGO Mid and OMEGA (Figure 9). Three arms also enable a 'GW null' channel to be constructed that is extremely helpful in distinguishing unmodeled signals or stochastic backgrounds from instrumental noise.

- Additional years of science observations produce more science return for very modest expense.

  The number of observed massive black-hole binaries increases linearly with observing time. Longer observation times are particularly important for increasing the probability of detecting rare systems, such as those at extremely high redshift or those that can be localized to fractions of a square degree. Parameter estimation for compact object captures (EMRIs) and galactic binaries improves as the square root of observation time.

- Gravitational-wave astrophysics and data analysis research has had a major impact on the anticipated science return from gravitational wave missions and has the potential to continue doing so.

  The ability of SGO Mid and other concepts to achieve significant fractions of the LISA science goals is in part due to improved understanding of GW waveforms and data analysis. Correspondingly, current estimates of the science capability of SGO High/LISA exceeds that of previous estimates.

5 Risk Consequences

Part of the goal of the Mission Concept Study was to understand the cost drivers for missions that can accomplish Decadal Survey-endorsed science for lower cost. Trading cost for risk was expected to be one of the ways to reduce cost, and the ability to identify risk and balance it against cost is key.

Risk is categorized by how the outcome affects a mission if the risk is realized. Although there seems to be no universally accepted classification, the main types of risks usually considered are safety, technical, cost, and schedule. Team X lumped these into two categories—implementation and mission—and they added a Proposal risk category that is not widely used elsewhere. Table 14 summarizes the classification. Note that Phases A–D are development through launch, and Phase E and F are active mission status and decommissioning and disposal.

Risk Type	Team X	Phase	Outcome
	Proposal	Pre-A	Difficulty getting acceptance of the mission concept
Safety	Not used	A–F	Personnel-related hazards. Not really applicable for un-manned missions.
Cost	Implementation	A–D	Cost increases
Schedule	Implementation	A–D	Schedule increases, which is usually the same as cost. Schedule risks often have a ripple effect, impacting more than one program element.
Technical	Mission	A–D	Compromised technical performance.
Mission	Mission	E–F	Reduced science return. Not usually mitigated by additional investment.

Table 14. Summary of risk types and the effects on mission outcomes.

5.1 Team X Assessment

5.1.1 Common Assumptions

To ensure uniformity between the Gravitational-Wave Mission Concept Study and the parallel X-Ray Mission Concept Study, Team X was given baseline assumptions for its studies that affect the risk posture:

- All missions were assumed to be Class B (consistent with NASA guidelines for high cost missions). Class B missions are single fault tolerant by design.
- For costing purposes only, all technologies were assumed to be at TRL 6.
- Only launch vehicles available in the present NASA Launch Services II (NLS) contract were to be considered.
- Mass margins of 53% and power margins of 43% were required.
- A 30% cost reserve (exclusive of launch vehicle) would be added to the Phase A–E costs.
- The missions were modeled as single-center, in-house builds for costing purposes.

5.1.2 Common Risks

Team X assessed four risks as common to all missions. Three are assessed as minor, and one as a proposal risk.

The first two, that the massive black-hole event rate is an order of magnitude lower than anticipated and the EMRI rate is two orders of magnitude lower, are an acknowledgement that there is astrophysical uncertainty about the gravitational wave sources. These risks are classified by Team X as Mission Risks, and the only thing that can be done to mitigate them is to increase the science operations lifetime.

The third risk is a development risk for an alternate photoreceiver under development, currently assessed as TRL3. This is likely a misunderstanding for two reasons. First, the baseline photoreceivers meet all performance requirements, and the missions would be fully capable of meeting their science goals with those photoreceivers. The TRL 3 version under development simply enhances performance. Second, the explicit assumption was that Team X was to assume that all technology was already at a level of TRL 6 or higher.

The proposal risk is that it is not possible to do a credible test of the mission under the conditions that would be encountered during flight because of the large distances involved and the fact that it is not possible to suspend the proof masses in all six degrees of freedom on the ground. This is a known risk, and it is good to flag it, but there should be some acknowledgement of the efforts that have been already made to reduce the risk, such as LISA Pathfinder and the torsion pendulum work for the GRS, and the interferometry test beds at JPL and the University of Florida. Due to the nature of the mission design, this risk would need to be accepted, and test plans should be developed to minimize it.

5.1.3 Risks Considered by Team X

Team X catalogued some Proposal, Cost, Schedule, and Mission risks. They also noted some Technical risks (e.g., the first two common risks discussed above), and some technology development risks (e.g., micronewton thruster lifetime for SGO High, OMEGA accelerometer).

They explored cost and schedule risks with different build strategies, and they explored different schedule approaches (LAGRANGE and OMEGA) to understand the sensitivity of the cost to different assumptions about schedule. Where they did not consider a particular schedule to be practical, they signaled this condition by tagging the risks with a likelihood rating of 5, essentially certain to happen.

5.1.4 Risks Not Considered by Team X

In accordance with the baseline assumptions, Team X did not adjust the risk posture across missions to reflect differing design maturities. Although they started with a set of baseline assumptions intended to treat the different concepts uniformly, in fact the concepts were at different stages of maturity. Team X assumed the same margins and contingencies for all missions, rather than varying them to reflect the design maturities.

In some cases, the relative risks of a mission concept may change under different assumptions. For example, lower mass and/or power margins for some subsystems may be appropriate for known spaceflight heritage. In general, Team X did not consider heritage and maturity of technical understanding as part of these studies.

The result of this risk approach is that the more mature missions were likely estimated to be larger in mass and power (and therefore cost) than would be the case if the margins were chosen in light of maturity. SGO Mid/High, the first concept to be evaluated, was treated very conservatively. In fact Team X assessed the mission as “very low risk.” No credit was given for the LISA Pathfinder heritage, which means that mass margins on some of the key scientific and spacecraft parts were kept high ,when in fact there are good estimates based on real hardware construction costs. Although Team X assessed SGO Mid as very low risk, the cost is higher than it would be if heritage were included.

In addition, Team X concluded that the SGO High Mission did not “close,” because the expected mass plus margins exceeded the capability of launch vehicles on the NLS contract for the required delta-V. This conclusion is the result of two conservative decisions: (1) the decision to exclude the Falcon Heavy launch vehicle from consideration, and (2) Team X’s assessment using a rule of thumb that the mass of the SGO High prop module from the MEL was too low to provide adequate stiffness.

The LAGRANGE mission included one additional moderate risk—that of critical component failure. This risk was given the lowest probability, but the highest impact. This risk appears to be primarily due to the lack of a graceful degradation in the event of failure of one link. Mitigating this risk is that fact that the mission is assumed to be Class B. As Class B, all of the missions are required to have some level of redundancy, and no single-point failures.

The OMEGA mission option 2 was classified as high risk based on schedule and schedule-driven staffing assumptions. Option 1 had a large number of moderate risks.

Team X did not comprehensively assess Mission risks (including Technical risks), particularly those stemming from science instrumentation (nor were they really expected to do so).

5.2 Core Team Assessment

The Core Team brings extensive experience from a decade of study of the LISA concept and the work on LISA Pathfinder. The Core Team risk assessment therefore concentrated primarily on technical risks, particularly those associated with the science instrumentation.

The LAGRANGE and OMEGA mission concepts have not been as thoroughly studied as the SGO Mid and High concepts, and there has not been adequate time to complete the necessary assessments. The Core Team gave LAGRANGE one additional moderate and one additional high risk that the known and unknown forces would be too large to allow the mission to meet the sensitivity budget. These risks have a cost consequence in that additional instrumentation is needed to measure components of the forces that are non-radial, but there is an additional technical risk that could result in the compromising the mission performance to an unacceptably low level, resulting in mission failure. Even if all of the expected forces are measured carefully, it may not be possible to use these measurements to calculate the disturbances on the interferometer and remove them.

For the OMEGA mission, the Core Team added two additional moderate risks and two high risks. One moderate risk is that the phasemeter must be modified to work with large Doppler shifts, which requires different front-end electronics than has been used in phasemeter development work to date. The second moderate risk arises because the direction to the sun moves around the spacecraft causing a time varying thermal environment. The risk is that a complex spacecraft thermal design may be necessary.

The first high risk is that the full-aperture narrowband optical filter, which is designed to exclude sunlight from entering the telescopes but allow the laser to pass, may not meet performance requirements. A design meeting the filtering requirements exists, but there is some concern that the additional requirements associated with making picometer-level optical pathlength measurements through the filter may not be met.

The second high risk is that the OMEGA interferometry design relies on picometer-level pathlength stability in optical fibers that has not been demonstrated. It is possible that this requirement can be met with careful design of the fiber mounts and environmental conditions, but it may lead to additional equipment or increased demands on the flight system. Another possibility is that this requirement cannot be met, in which case a LISA-like monolithic optical bench could be used at the expense of additional mass and volume.

5.3 Comparative Risk Assessment

A comparison of the risks between missions based on the Team X risk assessment is shown in Figure 11 in the NASA 5×5 risk table format [NASA Risk Management 2011]. In this scheme, each risk is given a quantitative assessment for the likelihood of the risky event occurring, and the size of the impact. The ratings are on a scale of 1–5, with 1 being the lowest likelihood or impact, and 5 being the highest. Regions on the risk table are colored according to whether the risks are low (green), moderate (yellow), or high (red). The formal implementation uses a somewhat different scale for mapping the assessment of likelihood and impact for the different classes of risk (Mission and Implementation) into the five levels, but the results of that mapping have been combined into a single 5×5 chart. Each individual risk is assigned a number which has been plotted on the 5×5 charts in Figure 11. A key to risks for each mission by risk number can be found in Appendix D. Risk associated with an option that was considered by Team X are shown in parentheses.

Figure 11 shows these tables based solely on the risk assessments from Team X. Note that SGO Mid was assessed only minor risks. Figure 12 shows the comparison between mission concepts with the Core Team risk assessment added to the Team X assessment. In general, the LAGRANGE and OMEGA missions become more risky, acquiring additional moderate and high risks.

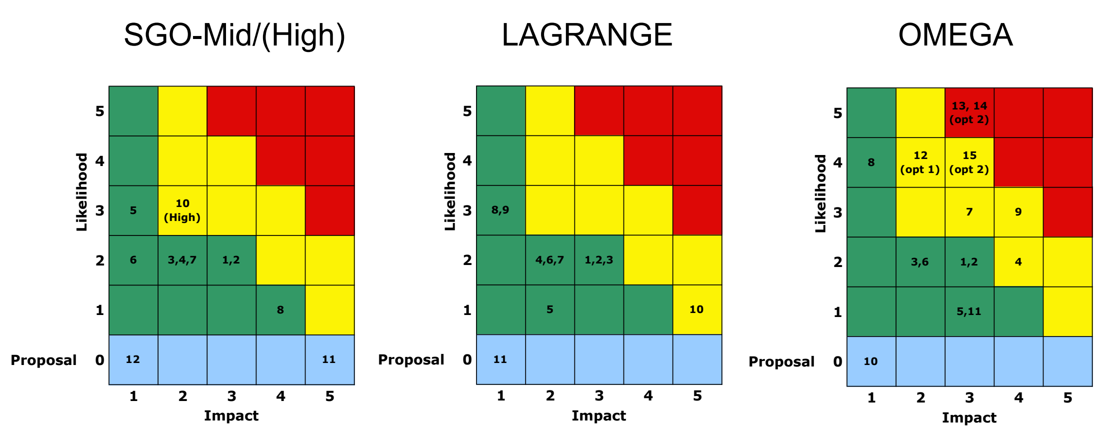


Figure 11. Comparison of Team X risk assessment of SGO Mid/(High), LAGRANGE, and OMEGA (Options 1 and 2). The risk associated with each identifying number can be found in Appendix D.

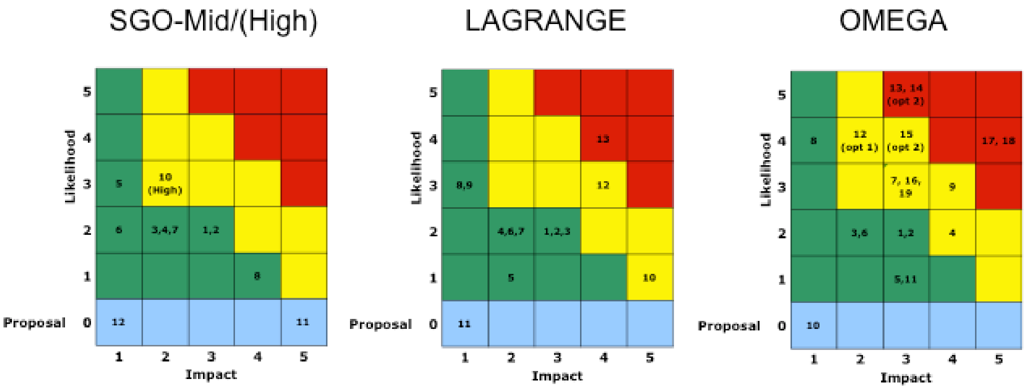


Figure 12. Comparison of Core Team plus Team X risk assessment of SGO Mid, LAGRANGE, and OMEGA. The risk associated with each identifying number can be found in Appendix D.

The LISA mission reviewed and recommended by the Decadal survey had 'medium' technical risk, assuming LISA Pathfinder was successful. It had a three-arm, equilateral triangle configuration with redundant interferometric detectors allowing data analysis strategies to measure two GW polarizations simultaneously and to give an independent overall check on the instrumental noise level, which is helpful in determining gravitational-wave background levels. The redundancy provided by the third arm also offers a graceful means of dealing with the loss of one or possibly two critical subsystems, while still allowing detections of signals with only moderate loss in the scientific results. It had the highest sensitivity for most of the known and posited sources due to the large baselines.

SGO High retains the capabilities of LISA, but with cost savings that do not affect the science or the risks. SGO Mid has a reduction in armlength, but no change in the mission architecture except for the reduction in propellant, and therefore represents a further cost reduction over High without significantly changing the risk but with a reduction in science. Newly developed data analysis algorithms based on numerical relativity derived templates may partially compensate for the change in instrument sensitivity due to the reduction in arm length, but of course those same developments could be used to improve the science obtained with SGO High as well.

LAGRANGE has higher technical and mission risk. With only two arms there is only one interferometer, so the ability to measure the gravitational-wave polarization and a cross-correlation measurement for a stochastic background are no longer possible. It is no longer possible to form a closed-loop Sagnac interferometer either, which is not sensitive to gravitational waves but allows monitoring of the system noise. The mission is intolerant to spacecraft or subsystem failure: loss of a single link is fatal. Possibly significant noise sources have been introduced by eliminating the drag-free control system. Demands are placed on the thermal stability and isotropy of thermal gradients needed to assure meaningful displacement measurements. The fluctuations in the solar wind and radiation are measurable with additional instrumentation, but it will be challenging to apply these measurements to solve for the spacecraft accelerations.

OMEGA has significantly higher scientific and technical risk and uncertainty. The science risk results from the one-year lifetime leading to the possibility that some rare, interesting events may not be observed. The major technical risk is a time-varying thermal and radiation environment. The geocentric orbit causes the solar heating to be variable, and in some types of orbits even to cause eclipses of the sun by the Earth and Moon, which means that maintaining the thermal stability of the interferometer paths is more difficult than for solar orbit. A related issue is the variation of the sun angle relative to the interferometer optical paths and the need to reject solar illumination from the telescopes. The risk comes from additional displacement noise associated with the time dependent and possibly uneven heating of the telescope sun filters and spacecraft.

Schedule risk: To examine the trade space, Team X used different schedule assumptions for each mission to examine the impact of schedule on cost and risk. The SGO and LAGRANGE schedules were estimated conservatively, assuming that the follow-on sciencecraft would not be started until the first sciencecraft had completed all testing. The OMEGA schedule, both Option 1 and (particularly) Option 2, was estimated aggressively by Team X, assuming overlapping builds and, in the case of OMEGA Option 2, highly parallel builds of the second through sixth spacecraft. The SGO and LAGRANGE schedules were low risk, but the OMEGA Option 2 schedule was considered high risk, and was ultimately not supported by Team X although they worked out the cost impact anyway.

Technology risk: SGO is considered to have the lowest technology development risk, with most technologies planned for demonstration on LPF launching in 2014. The major technology risk is considered to be demonstrating performance of the GRS). LAGRANGE has substantial reuse of LPF technologies, but would require development of significantly improved space environment sensors. The main advantage of the LAGRANGE approach is considered to be as an alternate approach in the event that the GRS performance demonstrated by LPF is significantly less than required. Major OMEGA development requirements include: demonstration of accelerometer performance that satisfies on-orbit requirements; demonstration of thruster performance (modification of existing charge control design for an alternative application); demonstration of optical pathlength stability in a complete telescope design including a sun filter and time-varying thermal loads; and demonstration of picometer-level optical pathlength stability in the optical fibers.

The LAGRANGE and OMEGA technologies would require further development and demonstration before, or at the start of, Phase A activities.

5.4 Risk Findings

- A three-arm design has lower risk than a similar two-arm design, allowing for graceful degradation.

  A three-arm design can continue to do useful science with the loss of up to two links, while a two-arm design fails with the loss of a single link. A link is defined as a measurement in one particular direction along an arm. Two links measuring in opposite directions constitute one arm.

- Three dual-string spacecraft appear to be more robust than six single-string spacecraft for most mission failures.

A single fault that causes a Class C spacecraft to fail will make for the loss of one arm of the interferometer, causing degradation of performance but not the loss of the mission. A single fault in a Class B spacecraft, being covered by its redundancy, will not cause any degradation of performance.

For a Class B spacecraft, spacecraft failure generally requires multiple failures of redundant elements. In a three-spacecraft constellation, loss of a spacecraft is a mission ending event. Spacecraft failure in a six-spacecraft Class C mission can be caused by a single event, but is not mission ending.

- A non-drag-free architecture introduces significant additional risk.

  The technical risks associated with the alternatives to a drag-free system require additional study beyond what was possible in this short study, and some may be show-stoppers.

  The non-drag-free architecture at this point is best preserved as a possible alternative if LPF encounters an unexpected noise source that cannot be remediated.

- Overlapping construction of multiple units adds significant schedule risk.

  Overlapping the build schedule of multiple identical units can shorten the implementation schedule and have cost impacts on the order of ~$100M. These savings are greater than most mission architecture changes.

  The savings come with increased risk that has both a high likelihood of occurring, and a high impact if it does occur: Any changes required must be applied to all copies that have been built rather than just the first one. The result is a potentially significant increase in both cost and schedule. Historical experience indicates that it is likely that some changes will be required.

6 Cost Consequences

As noted in the Gravitational-Wave Study Plan, one of the architecture considerations to be explored was the cost trade space. In selecting candidate missions for Team X studies, the estimated cost was included as one of the selection criteria.

6.1 Team X Costing Process and Common Assumptions

In order to ensure uniformity between the X-ray and Gravitational Wave Concept Studies, a set of common assumptions was created for the Team X Cost Studies. These included:

- All missions were assumed to be Class B (consistent with NASA guidelines for high-cost missions). Class B missions are single fault tolerant by design.
- For costing purposes only, all technologies were assumed to be at TRL 6.
- Only launch vehicles available in the present NASA Launch Services II (NLS) contract were to be considered.
- Mass margins of 53% and power margins of 43% were required.
- A 30% cost reserve (exclusive of launch vehicle) would be added to the Phase A–E costs.
- The missions were modeled as single-center, in-house builds for costing purposes.

The Team X pricing was performed in accordance with these assumptions.

Team X uses JPL-proprietary databases to determine estimated costs based on bottom up estimates from each discipline lead. Analogous and parametric models are used for cases where commercially available parts or subsystems are not available. The discipline leads also provide estimated labor-hours for pricing as well. Tools then estimate the other associated costs, such as management, systems engineering and mission assurance.

6.2 Initial Cost Estimates and Team X Estimates

The PI-estimated costs as included in the submitted RFI responses and the corresponding Team X estimates for each mission are shown in Table 15. Also shown is a metric of the cost per year of science operations. All costs are in FY12 dollars.

Mission	White Paper	Team X Estimate	$M/yr Science Ops
SGO High	$1.7B	$2.1B	$0.42B
SGO Mid	$1.4B	$1.9B	$0.95B
LAGRANGE	$1.1B	$1.6B	$0.82B
OMEGA Option 1		$1.4B	$1.4B
OMEGA Option 2	$0.3B	$1.2B	$1.2B

Table 15. White Paper and Team X Cost Estimates.

With the exception of OMEGA, the cost differences are roughly $0.5B between the PI and Team X estimates. The initial costs for SGO High and SGO Mid provided by the Core Team were based on previous LISA cost studies, and more grass-roots estimates for the payload based partly on reported European LISA Pathfinder cost estimates. The $0.5B difference between the Team X and Core Team cost estimates for SGO Mid can be found in four major contributions:

1) NLS-II vs Falcon Heavy launch vehicle difference is $164M
2) Learning curve for recurring engineering costs. For three identical units, Team X used a factor of 3.0 versus the Core Team factor of 2.6. Cost difference is $165M for the payload and $119M for the flight system (sciencecraft plus prop module), for a total of $285M.
3) Team X used 30% cost reserves versus the Core Team's 20%, which resulted in a difference is $105M.
4) Miscellaneous small cost estimate differences, including Project Management, Science data processing, Mission Ops preparation, etc. for a total savings of $52M (about 10% of the total difference).

The total difference ($164M + $285M + $105M - $52M) is $502M = $0.5B for SGO Mid. The difference for SGO High follows a similar pattern.

For OMEGA, the difference between the RFI response/white paper and the Team X estimate is:

1) Sciencecraft difference: $380M for six units.
2) Payload difference: $180M.
3) Launch vehicle cost estimate difference based on the NLS-II contract: $80M.
4) Assemble, test, and launch operations (ATLO) difference: $80M.
5) Contingency differences: ~ $200M

These difference estimates are approximate only, and total $920M. The remainder (~$180M) is distributed among various program elements (Project Management, Systems Engineering, etc.).

Cost Summary ($M)	SGO High	SGO Mid	LAGRANGE/ McKenzie	OMEGA/ Hellings
Launch Vehicle	247	247	179	125
Development (Phase A–D)	1260	1177	1017	897
Operations (Phase E–F)	165	99	111	64
Devel. and Ops. Reserves	422	379	335	286
Total	**$2095**	**$1903**	**$1643**	**$1372**

Table 16. Team X Mission Costs.

When we examine the overall cost variation among the missions considered by Team X, excluding OMEGA Option 2 (short schedule that Team X did not support), we find an overall cost variation of $720M from SGO High at the high end to OMEGA. Of that, $360M of the cost variation arises from flight system and instrument costs, the launch vehicle is about $125M, operations accounts for $100M, and $136M is the difference in reserves, which is a percentage.

Element Development Cost ($M)	SGO High	SGO-Mid	LAGRANGE/ McKenzie	OMEGA/ Hellings
PM + SE + MA	86	86	99	70
Science + Operations + Data	71	67	71	75
Payload	430	383	255	215
Flight System	578	546	491	436
Assembly, Testing, Launch Operations	81	81	81	85
Total	**$1246**	**$1163**	**$997**	**$881**

Table 17. Team X Mission Component Development Costs.

Within the development cost component, \$140M accrues from the flight system, which is 40% of the \$360M variation from flight and instrument system costs. The majority (60%) of the development cost variation (\$215M) is attributed to payload cost variation, though the payload comprises only one quarter to one third of the total development costs. Unfortunately, Team X payload costs were the least detailed part of the studies, derived from a parametric model based on mass and power estimates alone.

It should be noted that the lower cost estimates for LAGRANGE and OMEGA come at the expense of increased risk (and thus risk of actual cost growth) and reduced science potential. If we assume all missions have the same sensitivity for purposes of discussion, the science loss may be conservatively quantified by the time of science operations. In terms of cost per science-year, the ordering of the missions is nearly reversed: SGO high \$420M/year, SGO Mid \$950M/year, LAGRANGE \$820M/year, OMEGA \$1,370M/year. It is reasonable to suppose that these numbers could be improved by a proportional extension in mission lifetime for all missions other than LAGRANGE. Based on the difference in operational costs for SGO mid and SGO high, we may estimate mission extension to cost about \$30M per additional year.

There is no single big cost saving. Cost savings can be achieved only by numerous smaller economies, such as compressing schedule, shared launch, or lower cost launch vehicles.

6.3 Schedule

The Team X engineering tools inherently consider schedule as an input, and all 'marching army' costs associated with schedule duration (program management, systems engineering, mission assurance, etc.) are included. Hence, schedule strongly affects the cost estimate. In performing these studies, standard schedule assumptions were used; however, to fully examine the trade space, a conservative approach was taken on the LAGRANGE study, while a much more aggressive schedule was taken on the OMEGA Option 2. The LAGRANGE cost could be lowered by perhaps \$100M if less conservative schedule estimates were made. The schedule for the OMEGA Option 2 developed by Team X was considered outside the normal bounds for a mission of this size and complexity and was not supported by Team X, although they estimated the cost anyway to explore the trade space. To emphasize their non-support they assessed two high risks against the mission: one for the length of the schedule, and one for the risk of being able to staff up and de-staff quickly enough to meet the funding profile. (See Figure 11 and Appendix D.3 for more detail.) This very aggressive short schedule is the primary driver of the lower cost estimate in the OMEGA Option 2. The difference suggests a burn rate of \$100M per year in Phase C/D. This provides a measure of how schedule risk may convert to cost growth in development of a gravitational wave mission.

Concept Phase	SGO Mid (months)	SGO High (months)	LAGRANGE (months)	OMEGA-1 (months)	OMEGA-2 (months)
A	12	12	15	12	9
B	18	18	15	15	12
C/D	66	66	75	67	49
A–D Total	96	96	105	94	70
E: Science Ops	24	60	24	12	12
E: Total	45	81	53	24	24

Table 18. Summary of the Team X schedules for each mission concept studied.

6.4 Generic Gravitational-Wave Mission Costs

We have attempted to identify the lowest cost mission possible using the data obtained from the Team X studies. We assume that no Non-Recurring Engineering (NRE) costs are required, i.e., effectively assuming a mass-produced, off-the-shelf spacecraft and payload are available. We note that all approaches examined include the following similarities: multiple spacecraft (three or sox) widely separated using laser interferometry. Thermal stability is required in all cases for the interferometric measurements.

Using these assumptions, a crude estimate for the floor cost can be made as shown in Table 19.

WBS Element	Basis of Estimate/Comments	1st Unit	All Units
6.0 Flight System	SGO Mid RE sciencecraft cost (no NRE)	$70	$210
5.0 Payload	SGO Mid RE cost (no NRE)	$100	$300
7.0+9.0 Mission Ops and Ground Data	Team X estimates $100M; 50% used here for estimating purposes	$50	$50
4.0 Science	Consistent with Team X estimates	$50	$50
Subtotal			**$610**
1.0,2.0,3.0, PM, SE, MA	10% of subtotal (consistent with Team X estimates)		$61
Contingency (30%)			$201
8.0 Launch vehicle	Falcon 9		$150
Total			**$1022**

Table 19. Generic Gravitational Wave Mission Costs.

We again note that this assumes no NRE costs for the spacecraft or payload. We also note that this assumes a single launch, with no separate cruise vehicle or prop module. We believe, therefore, that this represents a best case scenario under optimistic assumptions, and thus conclude that it is very unlikely a sub-Flagship class mission can be developed.

6.5 Cost Findings

The cost results from the Team X studies provide some guidance in addressing the key questions highlighted in this report.

- In all cases, the Team X estimated costs were found to be well over $1B, thus putting the mission in the Flagship class.

  After consistent costing, none of the mission costs endorsed by Team X come in below $1.4B, well above the Probe-class range, and these cost reductions come at the expense of additional uncertainty and risk, even accounting for differences in the maturity of the concepts. While a variety of minor architectural changes were found to provide some cost flexibility, no major architectural or technological alternatives were revealed which change the basic cost class of the mission.

- The choice of heliocentric versus geocentric mission designs does not seem to be a significant cost driver.

  As discussed in the Mission Design section, the propulsion required to reach OMEGA's geocentric orbits provides little or no advantage over the heliocentric drift-away orbits of SGO-Mid. In general, the impact of propulsion on mission cost is small unless it is driving other costs such as launch vehicle or propulsion modules. The relative cost for telecommunications is also similar between SGO Mid and OMEGA, in part because the OMEGA concept requires double the number of spacecraft.

- Reducing a three-arm design to two arms will not necessarily reduce the cost significantly.

  A rough cost estimate for a two-arm version of SGO Mid can be made using the Team X estimates for the non-recurring expenses scaling down the recurring expense portion. This yields a payload estimate of $367M (including 30% reserves), a savings of $135M. Depending on details, a two-arm design may also be less massive, possibly reducing propulsion and launch costs. On the other hand, additional costs would arise from having two non-identical versions of the spacecraft. The Team X study of LAGRANGE provided an example of these costs, applying this to SGO Mid reduces the savings to about $90M out of a total cost of $1.9B, or about 5%.

- Eliminating the drag-free inertial reference achieves at most modest savings.

  The cost consequences of the non-drag-free architectural option have been discussed in Section 3.2. Direct savings from eliminating the GRS will be at least partially offset by the need for additional sensing apparatus, but there may be additional associated savings in the interferometric measurement system. The Team X LAGRANGE payload cost of $332M (including 30% reserves) is about 10% less than our rough estimate for a two-arm version of the SGO-mid payload.

- Optimizing the build plan could be a source of modest savings.

  Reducing schedule in Phase C and D by one year can save ~$100M. Overlapping construction of multiple units can significantly reduce estimated cost, but add significant risk of actual cost growth in the event of an anomaly during construction. See section 5.4 for a discussion of the risk associated with this approach.

7 Technology

The bulk of the effort in this study was devoted toward understanding and evaluating various architectures and mission concepts for future space-based gravitational wave detectors. However, the Study Plan did request "assessments of…the degrees of the proposed technology readiness" for the mission concepts of interest and comments on the "implications for technology development." This section attempts to briefly address these two requests.

A general finding of the study is that mission concepts utilizing the LISA architecture (heliocentric orbits, drag-free inertial test masses, continuous-wave heterodyne interferometry for time-of-flight measurement) present the lowest risk and highest science return for a given cost. Consequently, this section focuses on technologies supporting the LISA architecture.

Team-X assigned a "very low" risk rating to the SGO High and SGO Mid concepts once the constituent technologies have been developed to TRL 6. Investments in the core LISA technologies offer the potential for improvements in cost (e.g., via mass or power savings) and performance at the subsystem and component level. This could lead to moderate reductions in mission cost and a substantial reduction in cost risk.

7.1 Technology Status

Since the establishment of the NASA/ESA partnership on LISA in 2001, both agencies have invested in technologies following a workshare agreement. The goal of this agreement was to ensure that all critical technologies were addressed by at least one partner, but both partners were encouraged to pursue development activities in as many areas as possible. The level of investment in technology development in Europe has exceeded that in the U.S. by a large margin. This is due to (1) Europe's leadership role in LPF, (2) a separate program of ESA-sponsored technology development contracts to university research groups (~10M€/yr for >5 years) and (3) sustained support of national efforts by ESA Member States. By comparison, U.S. spending on technology development has been small ($1–3M/year) over the same period. Nonetheless, there are a few areas in which the U.S. retains technical leadership and others in which it could quickly become equally skilled with moderate investments.

During the LISA Project several comprehensive technology documents have been produced, including the Astro2010 LISA Technology Status Review, the 2008 BEPAC LISA Technology Status Document, the 2005 AETD Technology Assessment Review, and the 2005 LISA Project Technology Development plan (see http://lisa.gsfc.nasa.gov/). A brief summary of the status of key technologies follows, including information on additional activities that have occurred since the 2010 Decadal Review. [More extensive information is available on request.]

7.1.1 Technologies for Drag-free Inertial References

- *Gravitational Reference Sensor (GRS):* The European GRS design has advanced to flight model builds for LPF. Ground testing of the LPF GRS in torsion-pendulum facilities has demonstrated performance at the 30 $\mathrm{fm/s^2/\sqrt{Hz}}$ level at 1 mHz, within an order of magnitude of the LISA requirements. NASA investment in GRS technology ceased with the descope of ST-7 in 2005. While the European GRS design is likely to meet LISA performance requirements, there are opportunities for improvements at the subsystem and component level.
- *Micronewton thrusters:* The NASA-developed micronewton thrusters (CMNTs) have been demonstrated to meet thrust noise requirements in laboratory tests and the ST-7 colloidal thrusters have been integrated onto the LPF spacecraft. To meet LISA requirements, the CMNTs require additional lifetime testing. The European-developed FEEP thrusters are undergoing qualification for LPF, cold-gas thrusters are being studied in Europe as a third alternative.
- *Drag-Free Control Laws:* NASA has designed and implemented 18-DOF control laws for ST-7 on LPF. ESA has designed and implemented a separate 18-DOF design for the LTP payload on LPF. NASA and ESA have run simulations retiring the risks associated with the 57-DOF control laws required for LISA. Some modification of these control laws will be needed to maintain constellation pointing in LISA-like missions.

7.1.2 Technologies for Interferometric Distance Measurement

- *Phase Measurement System (PMS):* NASA has made significant investments in a PMS meeting LISA's requirements, including performance demonstration in an interferometer testbed at NASA/JPL. The current generation of the NASA PMS meets LISA performance requirements and implements auxiliary functions such as clock transfer, optical communication, and frequency control. Modifications to accommodate different mission parameters (e.g., Doppler shifts) and possible reductions in power and volume can be investigated at modest cost. ESA has recently accelerated development of a PMS and proposed to deliver flight units for the NGO mission.

- *Photoreceivers:* NASA has provided low-level funding for the development of high-speed, low-noise, quadrant photoreceivers for LISA. This includes developments at JPL and between GSFC and industry partners. ESA photoreceiver work has focused on LPF, which does not have the same bandwidth requirements; they have also developed prototypes meeting LISA's requirements. Some collaboration between European researchers and GSFC on LISA photoreceivers has also occurred.

- *Laser System:* Both the U.S. and Europe are pursuing a master-oscillator, power-amplifier design consisting of a seed laser, a phase modulator, and an amplifier. NASA has funded development of candidate seed lasers and amplifier technologies. LPF will fly a European laser that meets the requirements for the seed laser; NASA has flown a related laser on the Mars Orbiter Laser Altimeter (MOLA). Some laboratory work on modulators and amplifiers has been done in Europe. A coordinated system-level development program is needed to deliver a robust, space-qualified laser system. A laser system suitable for GW detection may have other applications of interest to NASA.

- *Optical Bench:* A method for building mechanically strong, dimensionally stable optical structures has been developed in Europe and applied to deliver flight optical benches for LPF. Initial studies have begun into extending these methods to the LISA optical bench. NASA has invested minimal (GSFC discretionary) funding to understand the technique. Stable optical structures may have other applications of interest to NASA.

- *Telescope:* GW missions require telescopes of a modest size (25–40 cm), but with strict requirements on dimensional stability and scattered light. NASA has made initial studies of an on-axis telescope and performed some preliminary laboratory tests of dimensional stability. ESA funded the study of an off-axis telescope as part of the LISA industrial study.

7.2 Investment Strategies

The nature of the partnership arrangement on a future GW mission will influence which flight components (if any) NASA is likely to provide. In the case of an ESA-led mission based on the NGO concept, the European partners have identified two technologies that best fit their programmatic and technical needs: a laser system and telescopes. In the case of a more balanced partnership, the opportunities for U.S. contributions would increase. For a NASA-led mission, some European technologies might need to be transferred to or re-developed in the U.S.

A sustained and coordinated technology development effort across the full spectrum of core LISA technologies would be the most prudent for the near term. This would allow the U.S. to retain its leadership in technology areas such as phase measurement and thrusters, while also developing expertise in technologies such as the GRS that are critical to a GW mission and yet are not well understood in the U.S. When the nature of the next opportunity becomes clearer, the technology development program can increase focus on those areas most likely to produce flight hardware. In parallel to technology development efforts in the laboratory, NASA would benefit from increased involvement with LPF, the primary focus of the European technology development effort. This could include maximizing science return from NASA's existing ST-7 program as well as active collaboration with the European LTP team on activities such as data analysis.

One strategy for developing a deep technology portfolio is to invest in general-purpose test facilities that can be used to evaluate a number of candidate technologies. In addition to producing technologies with a potential path to flight, such facilities provide a training ground for U.S. scientists and engineers and help preserve both the institutional knowledge and the research community needed to support a future mission. A deep understanding of the GW measurement and the relevant technologies will be essential for interpreting the data from a future GW mission, regardless of which agency provides the final flight hardware.

For GRS technologies, these facilities center around precision torsion balances that are capable of measuring the extremely small forces that can lead to disturbances of the test mass. Expertise in small-force torsion balances exists in the U.S. university research community and could potentially be tapped to develop such a facility. Torsion balances with different performance requirements are also used to study micro-thrusters.

Interferometry technologies are somewhat more separable than their drag-free counterparts and can in many cases be tested at the subsystem level. However, there are also system-level effects that are important to study and understand. This requires interferometry testbeds that are designed to mimic some properties of the LISA optical signals and exercise the relevant hardware. Examples include digital delay techniques used to mimic Gm propagation, and near-field electric field measurements that enable calculations of the far-field behavior. These could be part of a long-arm simulator as well as useful for telescope testing. Such testbeds have been, and should continue to be, developed both by university research groups and at NASA centers. In addition to validating core interferometry technologies, testbeds can also be used to study potential alternatives such as the digital interferometry proposed in the RFI response by deVine, et al.

An additional motivation for developing system-level testbeds is to develop techniques and technologies that may be applied to future Integration and Testing (I&T) or Verification and Validation (V&V) efforts. The fact that the GW instrument is distributed among a constellation of spacecraft will pose unique challenges for these activities. Experience on a system-level testbed will help prepare for these challenges.

7.3 Technology Findings

- No new or unproven technology is needed to enable a LISA-like mission such as SGO High or SGO Mid.

  Many of the core LISA technologies have been demonstrated in ground-based laboratory tests and software simulations. The LPF technology demonstrator mission is approaching launch and has already retired a number of technological risks during development.

- Refinement and enhancement of core LISA technologies could provide cost, risk, or performance benefits that integrate to a moderate effect on the mission as a whole, but will not enable a Probe-class mission.
  There are a number of subsystems and components where economies in mass, power, and complexity could be had. Examples include modernizing the capacitive sensing readout electronics for the GRS or applying an in-field guiding technique to accommodate changes in the constellation angles. While the direct effects of these improvements will be small, they could have moderate effects at the system level.

- Coordinated and sustained U.S. investment in core LISA technologies will preserve the U.S. research capability and support mission opportunities on a variety of time scales for a variety of partnering arrangements.

The options for U.S. technology contributions to a future GW mission will depend on the nature of the partnership and the state of technology readiness in the U.S. In the near term, a sustained research effort covering as many of the core LISA technologies as possible will provide the most flexibility. As the nature of the next opportunity becomes more clear, technology investments should be focused appropriately.

- System testbeds for drag-free control and interferometric measurement are a good investment, providing an arena in which to develop technologies, gain insight into the measurement process, and develop techniques that could eventually be applied to future integration and testing.

  The GW instrument is distributed over a constellation of multiple spacecraft. Many of the challenges arise not from the individual components but from their interaction at the system level. Testbeds that exercise components in a simulated system environment are important for evaluating technologies. They also provide deep insight into the measurement process, which will be essential for those who will eventually operate a full-scale mission. Testbeds also help develop techniques and technologies that can be applied for testing flight hardware in a simulated system environment, helping to address the 'proposal risk' identified by Team X of the difficulty to 'test-as-you-fly.'

8 Summary of Findings

Table 20 provides a summary of the science return (Section 4), risk levels (Section 5), and cost estimates (Section 6) for the mission concepts considered by Team X (SGO High, SGO Mid, LAGRANGE/McKenzie, OMEGA Option 1, and OMEGA Option 2). Science return is expressed in terms of number of detections of sources of a given class, mirroring the structure of Table 2 from the RFI and Table 8.1 from NWNH [2010], which identify "key astrophysics sources for LISA". For Massive Black Hole Binaries (MBHBs), the detection numbers are given as a range to allow for the uncertainty in current models of black hole formation. The total number of MBHBs detected is drawn from Figure 4. The following seven rows give the number of MBHB detections with certain qualities, such as precise determinations of mass, spin, distance, and sky location. These are measures of the "quality" of the MBHB detections and are derived from the parameter estimation studies described in Section 4.4. The ability to measure the astrophysical parameters of a MBHB enables far more science than a simple detection. Rates for Extreme Mass Ratio Inspirals (EMRIs) are taken from Figure 5, which was calculated assuming a "median" rate from the current literature. The range of predicted EMRI rates varies by more than an order of magnitude in each direction from this value. Unlike MBHBs, nearly all detected EMRIs will have comparable parameter measurement accuracy due to the complex waveform and long duration of EMRI events. Galactic binary science is represented by the total number of white dwarf binaries (Figure 5) detected, as well as the number of those localized within a 3-D error box of < 1 deg^2 in sky position and 10% in absolute distance (Figure 7). This latter population enables science investigations such as mapping galactic structure using compact objects. The mission concepts discovery potential is represented by their amplitude sensitivity to a scale-invariant stochastic background (Figure 6). For this metric, the values tabulated are fractions of LISA's sensitivity.

Two risk levels are listed in Table 20, one for risks identified by Team X (Figure 10) and one including both the Team X risks as well as risks identified by the Core Team (Figure 11). In each case, the risk level is the color level of the highest individual risk identified. Cost estimates are those provided by Team X in FY12 dollars. Further details can be found in Section 6.

In the remainder of this section, we list General Findings that are the cumulative product of the study activities and the collected experience of the Study Team, and we summarize the Specific Findings from our study of architecture choices, science consequences, risk consequences and cost consequences. The General Findings are followed by explanatory paragraphs to illuminate the rationale for them. They are repeated without the explanatory paragraphs in the Executive Summary. The rationale behind the Specific Findings was explained in their respective sections, and only the findings are repeated here to support the General Findings.

Science Performance	**SGO High**	**SGO Mid**	**LAGRANGE/ McKenzie**	**OMEGA Option 1**	**OMEGA Option 2**
Massive Black Hole Binaries					
Total detected	108–220	41–52	37–45	21–32	21–32
Detected at $z \geq 10$	3–57	1–4	1–5	1–6	1–6
Both mass errors ≤ 1%	67–171	18–42	8–25	11–26	11–26
One spin error ≤ 1%	49–130	11–27	3–11	7–18	7–18
Both spin errors ≤ 1%	1–17	<1	0	<1	<1
Distance error ≤ 3%	81–108	12–22	2–6	10–17	10–17
Sky location ≤ 1 deg^2	71–112	14–21	2–4	15–18	15–18
Sky location ≤ 0.1 deg^2	22–51	4–8	≤ 1	5–8	5–8
Total EMRIs detected[†]	800	~35	~20	~15	~15
WD binaries detected (resolved)	4×10^4	7×10^3	5×10^3	5×10^3	5×10^3
WD binaries with 3D location	8×10^3	8×10^2	3×10^2	1.5×10^2	1.5×10^2
Stochastic Background Sensititvity (rel. to LISA)	1.0	0.2	0.15[*]	0.25	0.25
Top Team X Risk	Moderate[‡]	Low	Moderate	Moderate	High
Top Team X + Core Team Risk	Moderate[‡]	Low	High	High	High
Team X Cost Estimate (FY 12$)	2.1B	1.9B	1.6B	1.4B	1.2B

[†] Based on median rate; estimates for EMRI rates vary by as much as an order of magnitude in each direction.
[*] Two-arm instruments such as LAGRANGE/McKenzie lack the “GW null” channel that can be used to distinguish between stochastic backgrounds & instrumental noise, making such measurements more challenging.
[‡] The moderate risk for SGO High comes about from the thruster development necessary to demonstrate the required lifetime for 5 years of science operations.

Table 20. Summary of science return, risk, and cost for the mission concepts considered by Team X. Science performance (see Section 4) is divided into source classes, mirroring the Table 2 in the RFI. For each class, the number of sources detected is listed for each mission concept. For Massive Black Hole Binaries, a range of detection numbers spanning different astrophysical mo dels is given. Team X Risk Level (see Section 5) for each concept is the level of the highest individual risk assigned by Team X. Team X + Core Team Risk Level is the same, except that technical risks identified by the Core Team have been included. SGO High science performance is the same as LISA. Costs (see Section 6) are cost estimates generated by Team X.

8.1 General Findings

These General Findings are compounded from the Specific Findings given in Section 8.2. Frequently an architecture choice will have consequences for more than one of science, cost and risk. Only the General Findings are reported in the Executive Summary.

- Scientifically compelling mission concepts can be carried out for less than the full LISA cost. No concepts were found near or below $1B.

  Team X cost estimates ranged from $1.2 to 2.1B. The mission risk level at the low end of the cost range was "high"; the risk level at the high end of the cost range was "low." The high-cost, low-risk mission was LISA, included as a reference point.

- Scaling the LISA architecture with three arms down to the SGO Mid concept preserves compelling science, reduces cost, and maintains low risk.

  Shortening the measurement baseline, keeping the constellation closer to the Earth, reducing the telescope diameter, reducing the laser size, and shortening the science observations all save cost while not increasing the risk found for LISA by Astro2010 and Team X.

- Eliminating a measurement arm reduces costs modestly, reduces science, and increases mission risk.

  Cost savings, in concepts like SGO Low and LAGRANGE/McKenzie, accrue because the payload equipment is reduced by about one third, saving recurring engineering costs. The costs of the flight system, propulsion module and launch vehicle can also potentially be reduced. These savings are offset to some degree by the additional non-recurring engineering for the differences in the end and center payloads, spacecraft and propulsion modules.

  Science is reduced by the loss of the capability to continuously monitor the instrumental noise and search for unmodeled signals, and the loss of simultaneous acquisition of the second polarization, which improves parameter estimation during late inspiral and merger.

  Simply descoping an instrument from three to two arms—without a compensating increase in the reliability of the critical payload subsystems—increases the risk because a three arm design degrades gracefully to a two arm instrument with failure of up to two links, while a two-arm instrument fails with the loss of a single link.

- More drastic changes, such as eliminating drag-free operation or adopting a geocentric orbit, significantly increase risk, and the associated cost savings are uncertain.

  Eliminating drag-free operation obviates the need for a GRS, complex spacecraft stationkeeping and associated testing in final integration. However, using the spacecraft as an inertial reference requires monitoring instruments that are substantially more expensive than the GRS, requires advances in the performance of those instruments and depends on risky modeling of disturbances, some of which may not be verifiable on ground.

  High geocentric orbits do not use significantly less propulsion than heliocentric. They confer additional technical demands on the spacecraft and payload because of the changing thermal environment, possible eclipses, and protection of the payload from direct sunlight.

- Scientific performance decreases far more rapidly than cost.

  Scaling SGO High down to SGO Mid produces a modest cost reduction (10%) and a substantial reduction in science (3–20X, depending on metric).

- We have found no technology that can make a dramatic reduction in cost.

  The science payload constitutes a small fraction of the mission cost. Major changes in the technology underlying the science instrument have only modest impacts on cost.

  Atom interferometry has been under consideration for gravitational-wave detection for some time. In neither the literature nor this study have we seen a viable proposal. Atom interferometry doesn't appear promising for reducing or simplifying the scientific payload.

- There is an urgent need for NASA to prepare for the imminent exploration of the universe with gravitational waves, leading to revolutionary science. The U.S. needs a sustained and significant program supporting technology development and science studies to participate in the first space-based gravitational-wave mission.

  Astrophysics with an entirely new spectrum will begin in this decade when ground-based gravitational-wave instruments make their first observations, intensifying the motivation for a space-based mission with broad astrophysical science potential.

  A vigorous program of technology development and risk reduction for a future gravitational wave mission is essential for reducing future mission costs, sustaining a knowledgeable and engaged community and preserving programmatic flexibility in the future. A vigorous research program in gravitational-wave astrophysics, waveform modeling, instrument response, and data analysis is also essential for preserving U.S. leadership in these areas and sustaining progress in extracting science from gravitational-wave observations.

8.2 Specific Findings

The Specific Findings below have been gathered from subsections of the document where they were arrived at. Brief explanations are given in italics after the respective Findings in the subsections. Note that architecture choices may have interacting science, risk, and cost consequences that are reflected in Specific Findings from more than one subsection.

8.2.1 Orbits and Trajectories Findings

- Choices of orbits and trajectories have an immediate impact on propulsion requirements, but they also have consequences for the payload, flight system and launch vehicle.
- Contrary to expectations, high geocentric orbits have no significant propulsion savings over heliocentric orbits.
- Heliocentric missions are favored with respect to spacecraft thermal stability related to solar flux.
- Stable orbits, possibly with stationkeeping, allow extended missions.

8.2.2 Inertial Reference Findings

- The estimated cost of the inertial reference instrumentation for the missions studied by Team X does not vary significantly and is not a major contributor to the overall mission cost.
- The LPF GRS is the most highly developed inertial reference, and therefore the least risky.

- The non-drag-free approach is potentially interesting in the unlikely event that a serious flaw with the drag-free design is uncovered by LPF. However, the non-drag-free approach brings a different set of risks, some of which are potentially severe, that would require further study if this approach is to be pursued.
- Refinement or enhancement of GRS technologies have the potential to reduce risk, reduce cost, or improve measurement performance but will not enable a Probe-class mission.

8.2.3 Time-of-Flight Findings

- The LISA-derived Interferometric Measurement System (IMS) employed by SGO High and SGO Mid is a well-developed, low-risk concept capable of meeting the measurement requirements.
- The non-drag-free approach brings an additional risk associated with relative motion between the spacecraft center of mass and the fiducial optic. Mitigating this effect may place severe requirements on the thermal, mechanical, and gravitational stability of the spacecraft. Further study would be required to assess this.
- Refinement or enhancement of core interferometry technologies have the potential to reduce risk, reduce cost, or improve measurement performance but will not enable a Probe-class mission.

8.2.4 Flight System Findings

- All mission concepts considered require a spacecraft bus with unusual requirements on mechanical stability, thermal stability and gravitational stability. Meeting these requirements leads to a payload and bus that are tightly integrated during design, development, test, and operations.
- The design of the flight system influences the potential for extended operation of the mission.
- Of the missions studied by Team X, the flight systems of SGO High and SGO Mid are most mature and appear lowest risk.
- The requirements placed on the spacecraft bus for a non-drag-free design are different than those for a drag-free design and are less well understood. Further work would be necessary to determine the exact nature of these requirements and the resulting implications for the flight system.

8.2.5 Science Findings

- Several mission concepts, including those studied by Team X, were found to be capable of delivering a significant fraction of the LISA science related to massive black hole mergers and galactic binaries.
- The science of compact object captures (EMRI systems) may be at risk due to significantly reduced detection numbers relative to the LISA mission.
- Concepts with three arms significantly improve parameter estimation over two-arm designs for black holes and enhance the ability to detect un-anticipated signals.

- Additional years of science observations produce more science return for very modest expense.
- Gravitational-wave astrophysics and data analysis research has had a major impact on the anticipated science return from gravitational wave missions and has the potential to continue doing so.

8.2.6 Risk Findings

- A three-arm design has lower risk than a similar two-arm design, allowing for graceful degradation.
- Three dual-string spacecraft appear to be more robust than six single-string spacecraft for most mission failures.
- A non-drag-free architecture introduces significant additional risk.
- Overlapping construction of multiple units adds significant schedule risk.

8.2.7 Cost Findings

- In all cases, the Team X estimated costs were found to be well over $1B, thus putting the mission in the flagship class.
- The choice of heliocentric versus geocentric mission designs does not seem to be a significant cost driver.
- Reducing a three-arm design to two arms will not necessarily reduce the cost significantly.
- Eliminating the drag-free inertial reference achieves at most modest savings while incurring additional risk.
- Optimizing the build plan could be a source of modest savings.

8.2.8 Technology Findings

- No new or unproven technology is needed to enable a LISA-like mission such as SGO High or SGO Mid.
- Refinement and enhancement of core LISA technologies could provide cost, risk, or performance benefits that integrate to a moderate effect on the mission as a whole, but will not enable a probe-class mission.
- Coordinated US investment in core LISA technologies will preserve the US research capability and support mission opportunities on a variety of time scales for a variety of partnering arrangements.
- System test beds for drag-free control and interferometric measurement are a good investment, providing an arena in which to develop technologies and an opportunity to gain deep insight into the measurement process.

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Appendix A — Team Membership

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Appendix B — Supporting Materials

The following materials,, among others, will be posted on the Gravitational Wave Mission Concept Study page of the Physics of the Cosmos Web site (http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php):

Responses to the Request for Information

Workshop Presentations

Team X Input

Team X Summary Reports

Team X Final Reports

CST Workshop Presentations

Appendix C — Atom Interferometry

C-1 Introduction

Atom interferometry (AI), a measurement technique that exploits the wave properties of matter, is a powerful tool that has found successful application in a number of fields. The application of AI to Gravitational Wave detection has been considered for some time and has been the subject of discussion in the scientific literature. Two submissions involving AI were among the responses received to the RFI: the response from Saif, et al. described a mission concept Interferometer in Space for Detecting Gravity-wave Radiation using Lasers (InSpRL) while the response from Yu, et al. described an AI-based inertial reference technology that would replace the drag-free test mass in an otherwise LISA-like mission architecture. These two responses have been discussed to some degree in the main body of this report, in particular in sections 3.2 and 3.3. This appendix expands the discussion of AI-based mission concepts such as InSpRL.

One reason the InSpRL concept was not selected for Team X analysis was that substantial changes in the mission architecture continued to be made after submission of the RFI response and after the workshop. Furthermore, no significant advantage in scientific performance or cost from this concept was evident. Both AI-based and light-interferometer GW instruments rely on the same basic measurement principle and share several of the most significant noise sources [Baker and Thorpe 2012]. As a result, many of the primary cost drivers are expected to be similar. For example, all of the optical interferometer concepts submitted to the RFI use two or more arms, requiring three or more spacecraft, to suppress the effect of laser frequency noise that would otherwise drown the GW signal. The original RFI submission describing InSpRL specified a single-arm AI that requires a high-precision atomic phase reference to measure and remove the effect of laser phase noise. This phase reference must maintain a stability of 1 part in 10^{21} over hundreds or thousands of seconds, many orders of magnitude beyond current capabilities. At the workshop, the InSpRL team also presented two- and three-arm AI instruments that would not require the phase reference but would require three spacecraft.

A second problem in evaluating the AI concepts was that not enough information was provided to independently verify the GW sensitivity for any specific concept, a key part of the Study Team's science analysis. Conversations between the Study Team and the InSpRL collaboration did not result in convergence to a complete description of the mission. Given this lack of definition, the Study Team took two approaches to understanding the AI concepts. The first was an attempt to choose reasonable parameters for the InSpRL concept as presented at the workshop and perform an analysis of the result. The second was to analyze recent concepts described in the literature by members of the InSpRL collaboration, most notably the Atomic Gravitational-wave Interferometer Sensor (AGIS) family of concepts. The results of these two activities are summarized below.

C-2 InSpRL 500 km Triangular Mission Concept

At the workshop, two versions were presented, one based on a central spacecraft with two 500 m long booms forming an 'L' and a second with three spacecraft forming an equilateral triangle 500 km on a side. The 500 km triangular concept is considered here.

The workshop presentation indicated that an optical lattice waveguide approach would be used to control the atom wavefunction splitting on each arm of the triangle, with sinusoidal modulation of the splitting at higher frequencies and trapezoidal modulation at low frequencies. The goal of this 'resonant' detection technique was to increase the instrument's GW sensitivity in one particular frequency band that could, in principle, be tuned to target different GW sources. The maximum acceleration and the observation time for each atom cloud were stated to be 10 m/s^2 and 1000 s. The maximum distance over which the wavefunction can be split is limited by the length of a boom/sunshield used to protect the atom clouds. The RFI submission specified this as 20 m in length. The measurement precision for the atom phase is assumed to be shot limited at 10^{-4} rad, corresponding to clouds containing 10^8 atoms.

With the above assumptions, the Core Team calculated a peak gravitational wave sensitivity for S/N = 1 of about 4×10^{-23}. This was achievable for Fourier frequencies above ~0.1 Hz, where the wavefunction splitting was limited by the assumed maximum acceleration. This is roughly consistent with the peak sensitivity for InSpRL included in the workshop presentation if the plotted curve is assumed to have units of strain amplitude rather than strain spectral density as was stated.

A closer examination suggests that some of the assumed parameters exceed current capabilities or are not consistent with one another. For example, the Study Team estimated the potential energy of the optical lattice as approximately five times the recoil energy for Rb-87 atoms for the 780 nm resonant transition and assumed that the lattice wavelength would be shifted strongly to the blue in order to reduce atom losses due to spontaneous emission. Under these assumptions, the blue shift of the optical lattice required to avoid serious spontaneous emission losses over 1000 s periods appears to be very high, likely exceeding the capabilities of the laser system. A more conservative assumption would be to reduce the observation time to 100 s, resulting in an order of magnitude loss in peak sensitivity.

Assuming blue detuning of the lattice wavelength to about 720 nm, the necessary one-way laser beam intensity at the atom clouds is roughly 6×10^6 W/m^2. Given the 20 W of optical power specified in the RFI submission and assuming a confocal Fabry-Perot cavity geometry between each pair of spacecraft, the required cavity finesse is about 75. The spontaneous emission probability for a 100 s observation is then limited to about 40%, a potentially acceptable level.

However, meeting even these requirements will be challenging. For example, at 0.1 Hz the optical lattice must be modulated with an amplitude of about 8 MHz, despite the cavity linewidth of roughly 4 Hz. A cavity mirror diameter of at least 1.4 m would be needed to preserve optical efficiency, and low degree wavefront aberrations in the cavity would be a serious limitation if they were not identical at both ends of the cavity. If an aggressive assumption of 100 pK is made for the temperatures for atom clouds, very small fractional differences in the initial sizes or temperatures of the different clouds plus the wavefront aberrations would cause phase difference fluctuations between the different clouds that are much larger than the shot noise fluctuations that were assumed when calculating the instrument sensitivity.

It is important to note that what was presented in the workshop is an 'envelope' curve comprised of the peak sensitivities for a number of detectors with different resonance frequencies. While in principle each of these sensitivities can be achieved with the same hardware, they cannot be achieved simultaneously.

This is in contrast to the curves for LISA, AdLIGO, and VIRGO, which are truly broad-band detectors. If 100 s measurements at 0.1 Hz modulation frequency were repeated many times, the results could in principle be used to determine the level of the expected extragalactic neutron star binary (XGNSB) gravitational wave foreground due to mergers of neutron star binaries out to large redshifts. The expected level of this foreground is roughly $1 \times 10^{-23}/\sqrt{\text{Hz}}$, or 1×10^{-24} in an 0.01 Hz bandwidth. With 4×10^{-22} sensitivity for individual 100 s observations, the S/N for observing the foreground with 1 year of observations would be about 1.4. If a non-standard source of a primordial gravitational wave background had a higher amplitude at 0.1 Hz frequency, the sum of the foreground and the primordial background would be observed.

Another source that the L = 500 km mission concept could see is the strong AM CVn galactic binary source HM Cancri, also known as RX J0806. It has an expected amplitude of about 2×10^{-22} at 6.3 mHz frequency. If one cycle of sinusoidal modulation at this frequency were used for each of many observations, a S/N of about 1 would be reached in 1 year. However, neither the possible XGNSB foreground observation with a limit on the non-standard primordial background level at that frequency nor observations of one or a few galactic binary signals would meet a substantial part of the high priority LISA gravitational wave scientific objectives described in the 2010 Astrophysics Decadal Survey report.

C-3 AGIS Concept

The InSpRL concept has some heritage in a series of earlier concepts referred to as Atomic Gravitational-wave Interferometer Sensor (AGIS) that have been discussed in the scientific literature. These concepts share a similar geometry but do not employ the resonant enhancement technique introduced by the InSpRL collaboration at the workshop. A recent version of this is the AGIS-LEO concept discussed by Hogan, et al. [2011]. The limitations of this concept have also been discussed in the literature [Bender 2012]

The AGIS-LEO concept suggests using a single arm between two spacecraft. It has recently been shown [Baker & Thorpe 2012] that this would lead to extremely tight requirements on the intrinsic stability of the laser phase or, alternatively, a high-precision absolute phase reference that can be used to measure and correct for variations in the optical phase. Here it is assumed that a two-arm version of the AGIS-LEO concept is employed to mitigate laser phase noise.

The AGIS-LEO spacecraft are in Earth orbit at about 1000 km altitude, with 30 km spacing between them. Light pulse interferometry with large momentum transfer (LMT) laser pulses would be used, with the transfer of 200 times the single photon momentum in a $\pi/2$ laser pulse. The use of a 5-pulse sequence of $\pi/2$ and π pulses separated by either 4 or 8 seconds is suggested. To be specific, it will be assumed here that single-photon Bragg pulses would be used as the subpulses making up each LMT laser pulse.

The rate at which atom clouds would be fed into the atom interferometer near each spacecraft is 20/s, with a total atom input rate of 10^8/s. The resulting sensitivity curve shown has a level of $2 \times 10^{-19}/\sqrt{\text{Hz}}$ at frequencies of 0.03–10 Hz, and increases as the inverse 4th power of the frequency at lower frequencies. This sensitivity curve appears to be more useful than the envelope sensitivity curve presented for the L = 500 km InSpRL mission concept, and the experimental requirements would be substantially less severe. However, the sensitivity curve still appears to permit observation of only a few of the gravitational wave sources expected for LISA, and to not permit achievement of any of the high priority LISA scientific objectives described in the 2010 Astrophysical Decadal Survey Report. Also, there still are considerably more severe experimental limitations to be considered than for the LISA, SGO Mid, or NGO mission concepts.

For the AGIS-LEO concept, as for the InSpRL concepts, one limitation is that even very small wavefront aberrations in the beams coming from the lasers could cause additional noise. In principle such laser wavefront aberration noise could be filtered out by a high finesse mode-cleaner cavity. However, one of the laser beams must be modulated quite rapidly to produce the sequences of stimulated Bragg pulses necessary for the atom interferometry, and thus passing it through a high finesse filter cavity appears difficult.

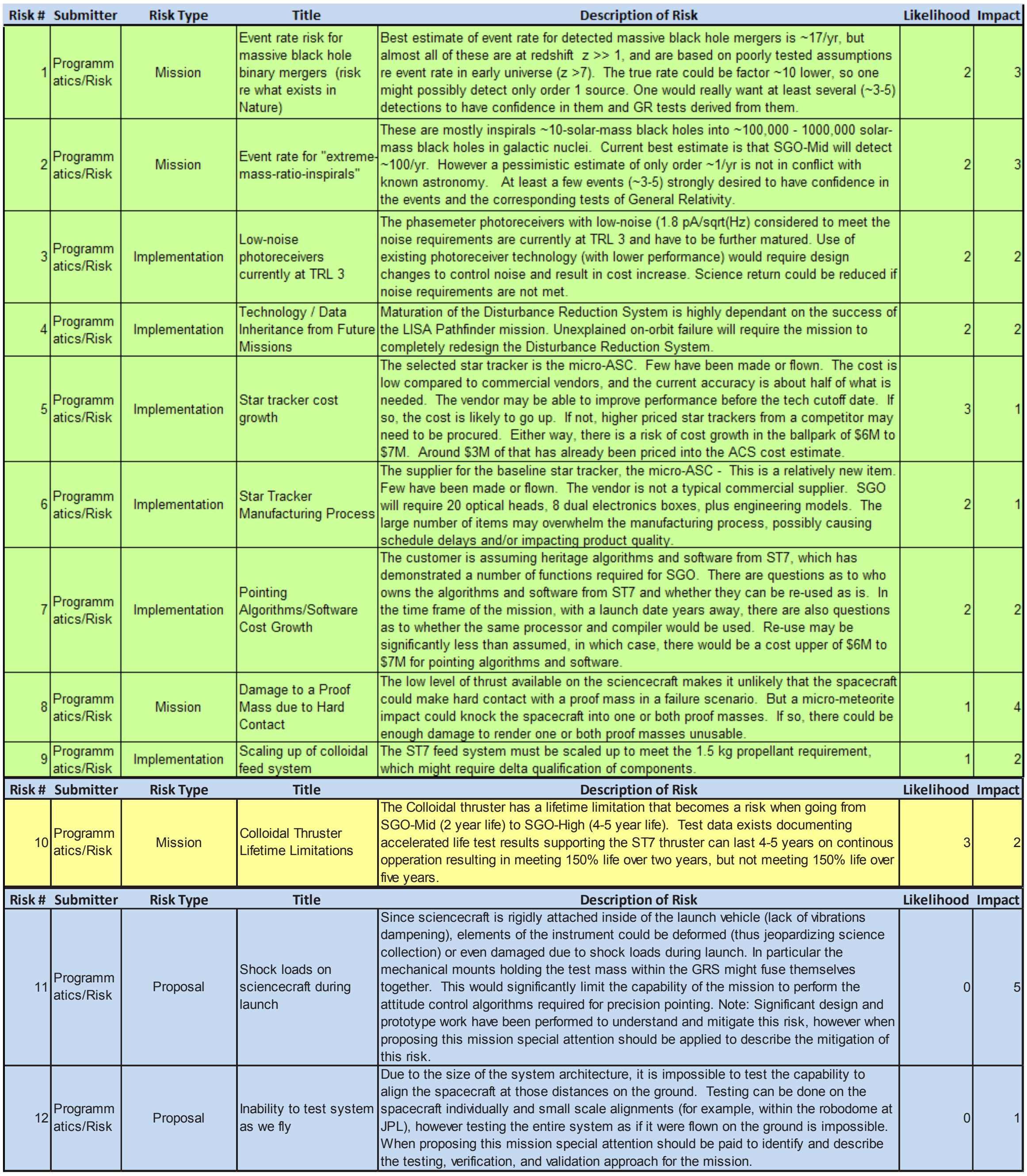
C-4 Summary

AI-based GW instruments like InSpRL operate on the same basic principle as LISA: the exchange of photons between pairs of inertial references separated by large baselines. The atom clouds serve two functions, they are both the inertial reference as well as the tool for measuring the optical phase of the light beams traversing the long baseline. Two of the chief noise sources for LISA-like detectors, the stability of the optical platform and the frequency stability of the light source, are also major contributors to noise in InSpRL-like detectors. Similar mitigation strategies must be applied to suppress these noise sources in both cases. The frequency stability requirement in particular drives the design to require at least two arms and three spacecraft, removing the most significant potential cost savings of the proposed AI-based GW concepts. Overall, the complexity of the AI apparatus seems to significantly exceed that of the technology required for a LISA-like optical interferometer and there are no significant advantages in scientific performance.

Appendix D — List of Risks

D–1 SGO-Mid and SGO-High Risks

Team X Risk List: SGO-Mid and SGO-High



Risk #	Submitter	Risk Type	Title	Description of Risk	Likelihood	Impact
1	Programmatics/Risk	Mission	Event rate risk for massive black hole binary mergers (risk re what exists in Nature)	Best estimate of event rate for detected massive black hole mergers is ~17/yr, but almost all of these are at redshift z >> 1, and are based on poorly tested assumptions re event rate in early universe (z >7). The true rate could be factor ~10 lower, so one might possibly detect only order 1 source. One would really want at least several (~3-5) detections to have confidence in them and GR tests derived from them.	2	3
2	Programmatics/Risk	Mission	Event rate for "extreme-mass-ratio-inspirals"	These are mostly inspirals ~10-solar-mass black holes into ~100,000 - 1000,000 solar-mass black holes in galactic nuclei. Current best estimate is that SGO-Mid will detect ~100/yr. However a pessimistic estimate of only order ~1/yr is not in conflict with known astronomy. At least a few events (~3-5) strongly desired to have confidence in the events and the corresponding tests of General Relativity.	2	3
3	Programmatics/Risk	Implementation	Low-noise photoreceivers currently at TRL 3	The phasemeter photoreceivers with low-noise (1.8 pA/sqrt(Hz) considered to meet the noise requirements are currently at TRL 3 and have to be further matured. Use of existing photoreceiver technology (with lower performance) would require design changes to control noise and result in cost increase. Science return could be reduced if noise requirements are not met.	2	2
4	Programmatics/Risk	Implementation	Technology / Data Inheritance from Future Missions	Maturation of the Disturbance Reduction System is highly dependant on the success of the LISA Pathfinder mission. Unexplained on-orbit failure will require the mission to completely redesign the Disturbance Reduction System.	2	2
5	Programmatics/Risk	Implementation	Star tracker cost growth	The selected star tracker is the micro-ASC. Few have been made or flown. The cost is low compared to commercial vendors, and the current accuracy is about half of what is needed. The vendor may be able to improve performance before the tech cutoff date. If so, the cost is likely to go up. If not, higher priced star trackers from a competitor may need to be procured. Either way, there is a risk of cost growth in the ballpark of $6M to $7M. Around $3M of that has already been priced into the ACS cost estimate.	3	1
6	Programmatics/Risk	Implementation	Star Tracker Manufacturing Process	The supplier for the baseline star tracker, the micro-ASC - This is a relatively new item. Few have been made or flown. The vendor is not a typical commercial supplier. SGO will require 20 optical heads, 8 dual electronics boxes, plus engineering models. The large number of items may overwhelm the manufacturing process, possibly causing schedule delays and/or impacting product quality.	2	1
7	Programmatics/Risk	Implementation	Pointing Algorithms/Software Cost Growth	The customer is assuming heritage algorithms and software from ST7, which has demonstrated a number of functions required for SGO. There are questions as to who owns the algorithms and software from ST7 and whether they can be re-used as is. In the time frame of the mission, with a launch date years away, there are also questions as to whether the same processor and compiler would be used. Re-use may be significantly less than assumed, in which case, there would be a cost upper of $6M to $7M for pointing algorithms and software.	2	2
8	Programmatics/Risk	Mission	Damage to a Proof Mass due to Hard Contact	The low level of thrust available on the sciencecraft makes it unlikely that the spacecraft could make hard contact with a proof mass in a failure scenario. But a micro-meteorite impact could knock the spacecraft into one or both proof masses. If so, there could be enough damage to render one or both proof masses unusable.	1	4
9	Programmatics/Risk	Implementation	Scaling up of colloidal feed system	The ST7 feed system must be scaled up to meet the 1.5 kg propellant requirement, which might require delta qualification of components.	1	2
10	Programmatics/Risk	Mission	Colloidal Thruster Lifetime Limitations	The Colloidal thruster has a lifetime limitation that becomes a risk when going from SGO-Mid (2 year life) to SGO-High (4-5 year life). Test data exists documenting accelerated life test results supporting the ST7 thruster can last 4-5 years on continous opperation resulting in meeting 150% life over two years, but not meeting 150% life over five years.	3	2
11	Programmatics/Risk	Proposal	Shock loads on sciencecraft during launch	Since sciencecraft is rigidly attached inside of the launch vehicle (lack of vibrations dampening), elements of the instrument could be deformed (thus jeopardizing science collection) or even damaged due to shock loads during launch. In particular the mechanical mounts holding the test mass within the GRS might fuse themselves together. This would significantly limit the capability of the mission to perform the attitude control algorithms required for precision pointing. Note: Significant design and prototype work have been performed to understand and mitigate this risk, however when proposing this mission special attention should be applied to describe the mitigation of this risk.	0	5
12	Programmatics/Risk	Proposal	Inability to test system as we fly	Due to the size of the system architecture, it is impossible to test the capability to align the spacecraft at those distances on the ground. Testing can be done on the spacecraft individually and small scale alignments (for example, within the robodome at JPL), however testing the entire system as if it were flown on the ground is impossible. When proposing this mission special attention should be paid to identify and describe the testing, verification, and validation approach for the mission.	0	1

D–2 LAGRANGE/McKenzie Risks

Team X Risk List: LAGRANGE McKenzie

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
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 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

Core Team Risk List: LAGRANGE

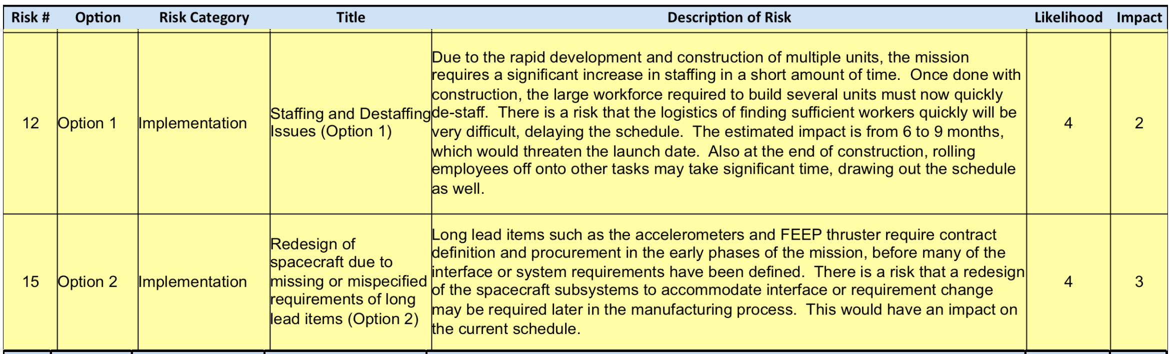
Risk #	Level	Risk Type	Title	Description	Likelihood	Impact
12	Moderate	Implementation	Unknown accelerations	unknown, unmeasured accelerations are too large	3	4
13	High	Implementation	Thermal-elastic effects	motion of fiducial optic with respect to S/C center of mass	4	4

D–3 OMEGA Risks

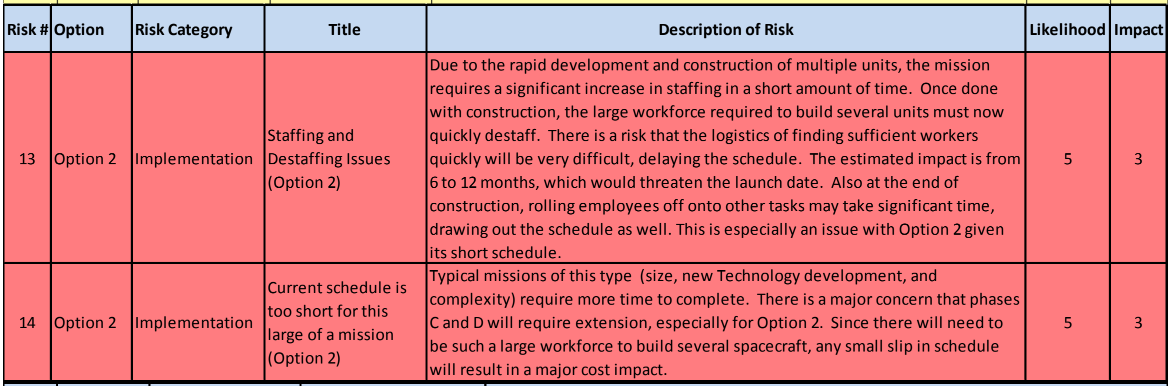
Team X Risk List: OMEGA

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

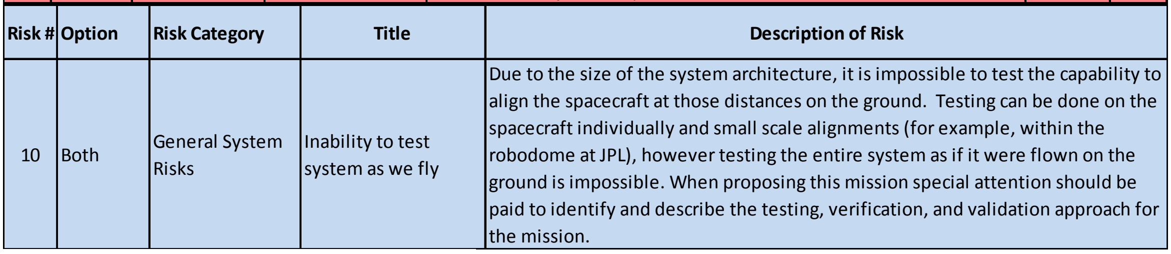
Risk #	Option	Risk Category	Title	Description of Risk	Likelihood	Impact
4	Both	Implementation	System Test Failure on Protoflight Spacecraft	The current design schedule assumes that the five additional spacecraft begin integration immediately following the integration of the proto-flight, prior to system testing. In the event of a system test failure or inability to meet the required capabilities as a system, integration of the five additional spacecraft will need to be postponed until the spacecraft team can resolve the failure. This would potentially cause a significant increase in phase D.	2	4
7	Both	Implementation	FEEP Development and Qualification	FEEP Development and Qualification: FEEP Thrusters require characterization and modification of original design. Thrusters have currently flown as charge controllers and will require significant thermal and structural engineering, PPU and DCIU characterization and modification, thruster characterization at different operating set point, and modeling to understand plume effects. A program to characterize and modify the thruster components is expected to take ~18 months. In addition to characterization, the thrusters will require a life test in it's operating mode of at least 1.5 years (50% more than the expected life). Due to schedule constraints, the characterization of the thrusters must start early in phase B (assuming that you can overlap some of the characterization with the life test). There is very little schedule margin for this development program and a risk that any anomalies occurring with the thrusters will cause a significant slip in schedule.	3	3
9	Both	Implementation	Unable to achieve sensitivity with Accelerometer	There is currently no paper evidence that the Vendor can provide an accelerometer capable of the sensitivities required for the mission. If they are unable to do so, the mission will have to fall back to the GRS based architecture used by LISA, resulting in a significant mass, power and cost increase.	3	4



Risk #	Option	Risk Category	Title	Description of Risk	Likelihood	Impact
12	Option 1	Implementation	Staffing and Destaffing Issues (Option 1)	Due to the rapid development and construction of multiple units, the mission requires a significant increase in staffing in a short amount of time. Once done with construction, the large workforce required to build several units must now quickly de-staff. There is a risk that the logistics of finding sufficient workers quickly will be very difficult, delaying the schedule. The estimated impact is from 6 to 9 months, which would threaten the launch date. Also at the end of construction, rolling employees off onto other tasks may take significant time, drawing out the schedule as well.	4	2
15	Option 2	Implementation	Redesign of spacecraft due to missing or mispecified requirements of long lead items (Option 2)	Long lead items such as the accelerometers and FEEP thruster require contract definition and procurement in the early phases of the mission, before many of the interface or system requirements have been defined. There is a risk that a redesign of the spacecraft subsystems to accommodate interface or requirement change may be required later in the manufacturing process. This would have an impact on the current schedule.	4	3

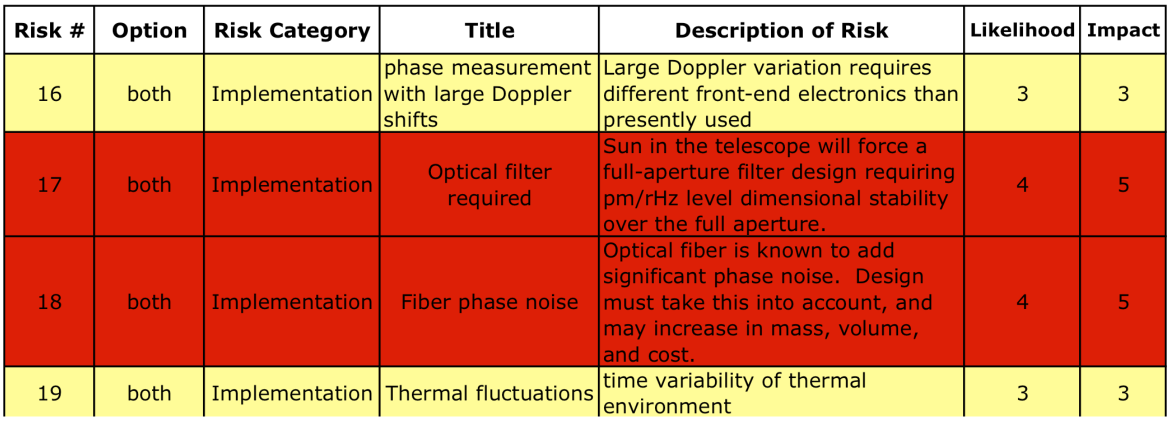


Risk #	Option	Risk Category	Title	Description of Risk	Likelihood	Impact
13	Option 2	Implementation	Staffing and Destaffing Issues (Option 2)	Due to the rapid development and construction of multiple units, the mission requires a significant increase in staffing in a short amount of time. Once done with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



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

Core Team Risk List: OMEGA



Risk #	Option	Risk Category	Title	Description of Risk	Likelihood	Impact
16	both	Implementation	phase measurement with large Doppler shifts	Large Doppler variation requires different front-end electronics than presently used	3	3
17	both	Implementation	Optical filter required	Sun in the telescope will force a full-aperture filter design requiring pm/rHz level dimensional stability over the full aperture.	4	5
18	both	Implementation	Fiber phase noise	Optical fiber is known to add significant phase noise. Design must take this into account, and may increase in mass, volume, and cost.	4	5
19	both	Implementation	Thermal fluctuations	time variability of thermal environment	3	3

Appendix E — Acronyms

AI	Atom Interferometer
ALMA	Atacama Large Millimeter/sub-millimeter Array
Am CVn	AM Canum Venaticorum star (cataclysmic variable)
AU	Astronomical Unit
BH	Black Hole
BW	Bandwidth
CMNT	Colliodal Micro-Newton Thruster
CW	Continuous-Wave
DOF	Degree of Freedom
DRS	Disturbance Reduction System
DSN	Deep Space Network
EELV	Evolved Expendable Launch Vehicle
eLISA	Enhanced LISA
EM	Electromagnetic
EMRI	Extreme Mass Ratio Inspiral
ESA	European Space Agency
Gm	Gigameter (1Gm = 1 × 10^9m)
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer (ESA mission)
GRS	Gravitational Reference Sensor
GW	Gravitational Wave
HEO	High Earth Orbit
HETO	Heliocentric Earth-Trailing Orbit
HGA	High-Gain Antenna
IMBH	Intermediate Mass Black Hole
IMS	Interferometric Measurement System
JWST	James Webb Space Telescope
LED	Light-Emitting Diode
LEOP	Launch and Early Operations
LISA	Laser Interferometer Space Antenna
LPF	LISA Pathfinder
MBH	Massive Black Hole
MBW	Measurement Bandwidth
MEL	Master Equipment List
MOC	Mission Operations Center
MOLA	Mars Orbiter Laser Altimeter
MOPA	Master Oscillator Power Amplifier

MOT	Magneto-optical Trap
NICM	NASA Instrument Cost Model
NGO	Next Generation Gravitational-wave Observatory
NPRO	Non-Planar Ring Oscillator
NRE	Non-Recurring Engineering
NS	Neutron Star
OATM	Optical Assembly Articulation Mechanism
P/M	Propulsion Module
PM	Proof Mass (same as a Test Mass)
RE	Recurring Engineering (costs)
S/C	Spacecraft (sciencecraft bus)
S/W	Software
SC	Sciencecraft
SGO	Space-Based Gravitational-wave Observatory
SNR	Signal-to-Noise Ratio
SODPC	Science Operations Data Processing Center
TDI	Time-Delay Interferometry
TM	Test Mass
TRL	Technology Readiness Level
UV	Ultra Violet