A LOW-COST, HIGH-PERFORMANCE SPACE GRAVITATIONAL ASTRONOMY MISSION

A Mission-Concept White Paper

ROM COST: SMALL

SUBMITTERS:

Ronald Hellings (LEAD): Physics Department, Montana State University, Bozeman MT 59717, (406) 994-1693, hellings@physics.montana.edu

Shane L. Larson: Physics Department, Utah State University, Logan UT 84322, (435) 797-8838, s.larson@usu.edu

Scott Jensen: Space Dynamics Laboratory, Utah State University, North Logan UT 84341, (435) 713-2341, scott.jensen@sdl.usu.edu

Chad Fish: Space Dynamics Laboratory, Utah State University, North Logan UT 84341, (435) 713-3355, chad.fish@sdl.usu.edu

Matt Benacquista: Department of Physics and Astronomy, University of Texas – Brownsville, Brownsville TX 78520, (956) 882-6617, benacquista@phys.utb.edu

Neil Cornish: Physics Department, Montana State University, Bozeman MT 59717, (406) 994-7985, cornish@physics.montana.edu

Ryan Lang: Department of Physics, Washington University, St. Louis MO 63130, ryan.n.lang@nasa.gov

Questions:

- We will be willing to participate and present our concept at a workshop if invited.
- Some of our partners have sensitive information that might be useful for this exercise. If proper arrangements are made to protect this information, we would be willing to discuss this information with NASA.

A LOW-COST, HIGH-PERFORMANCE SPACE GRAVITATIONAL ASTRONOMY MISSION

1. The OMEGA Concept

In 1998, the Orbiting Medium Explorer for Gravitational Astronomy (OMEGA) was proposed by an international team of scientists and engineers as a candidate MIDEX mission. The science goals and the gravitational-wave detection techniques of the OMEGA mission were essentially the same as those of the LISA mission. The estimated total cost for the OMEGA mission, including launch vehicle, was 153M$ in FY98 dollars (211M$ in $FY12, estimated using the on-line NASA inflation calculator). The TMCO panel that reviewed the 1998 OMEGA proposal concluded that

> "Exclusive of the launch vehicle cost problem, and assuming that the drag-free technology is proven by some other means such as ODIE [a University-Explorer-class mission planned to provide an in-flight test of the OMEGA drag-free system], the OMEGA costs seem reasonable."

There are a few design decisions that were made for the 1998 MIDEX opportunity that we would like to revisit. The changes we envision would typically increase the cost above the projected 211 $M total cost. Nevertheless, we are convinced that a mission along the lines of the OMEGA mission can be flown for an overall cost near 300 M$ in FY-12 dollars, that the hardware will be robust and reliable, and that the mission will be able to accomplish all of the basic science goals of the LISA mission.

The OMEGA mission consists of six identical microprobes in a 600,000-km-high earth orbit, two probes at each vertex of an equilateral triangle. These orbits are stable, allowing for 3 years of planned science operations, as well as the possibility of an extended mission if desired. Each probe is protected from external disturbances by a drag-free system. The two microprobes at each vertex exchange laser phase signals to monitor their relative position, and each microprobe tracks its counterpart at a far vertex with a laser phase tracking system. All six microprobes are launched together on a propulsion module called the carrier, taking 384 days to deploy the probes in their on-orbit locations. During cruise, control of, and communication with, the carrier is redundantly accomplished using the hardware available in any one of the microprobes. Once operational, the tiny changes in the geometry of the million-km arms of the triangle, produced by passing gravitational waves will be detected and their astronomical sources may be analyzed and catalogued.

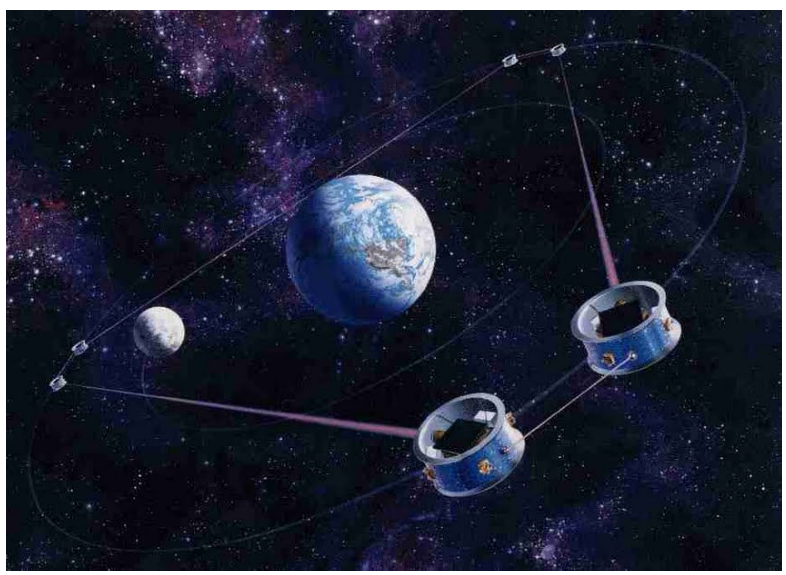

Figure 1. Artist's conception of the OMEGA mission geometry.

The advantages of the OMEGA mission concept as a low-cost gravitational astronomy mission are the following:

Well-Understood Detector Techniques. An OMEGA-type mission would not depend on untested or on new poorly-developed detection techniques. Its basic instrumentation is the same as that proposed for the LISA mission, an approach that has been investigated by hundreds of researchers over a period of thirty years. Because of LISA, there has been significant laboratory development of the type of hardware that OMEGA will require. The heart of the OMEGA spacecraft is an accelerometer similar to LISA's gravitational reference sensor, but smaller and lighter. The position and attitude control system will employ microthrusters like LISA's, though smaller and requiring less power. The laser interferometer tracking system that provides the measurement of the gravitational waves is a simplified version of the LISA system. As is the case for LISA, the measurement and systematic errors for the OMEGA instrument have been extensively studied. Confidence is high that the mature design chosen for OMEGA will produce the sensitivity required to yield the desired scientific results.

Well-Studied Mission Design. In preparation for the 1998 MIDEX competition, an unusually complete pre-Phase-A design was produced. For the science instrumentation, circuit boards were designed, components were identified, and mass, power, and cost were based on these designs. For spacecraft avionics, high heritage space-qualified components were chosen, again allowing robust mass, power, and cost estimates to be made. This level of detail in the instrument and spacecraft design allowed for reliable data estimates, setting the requirements on the telecommunications system, and for reliable mass estimates, setting the requirements for the choice of launch vehicle.

Low-Cost Design Choices. The choice of a geocentric orbit for the OMEGA mission simplifies and reduces costs for launch, operations, and communication, *but the choice of orbit alone is not enough to explain the difference between the OMEGA and LISA cost estimates*. Other characteristics of the OMEGA design are required to accomplish this. First, as the OMEGA instrumentation and probes were being developed, trades were consistently made in favor of light weight and low power. The result was a set of six 70 kg microprobes, each consuming 80 W of total power. In fact, all six microprobes plus their propulsion-module carrier weigh less and consume less power than a single LISA on-orbit spacecraft. Second, the 1998 OMEGA spacecraft contractor proposed a build-and-test approach to new hardware that allowed mil-spec commercial parts to be utilized and space-qualified. Third, a policy in favor of simplified interfaces characterized the entire OMEGA design. Fourth, the fact that OMEGA has two spacecraft at each of the three vertices of the constellation means that the mission can absorb the loss of one entire spacecraft, or a second spacecraft not at the same vertex, without a mission failure. This built-in mission-level redundancy allows OMEGA to implement a selected hardware redundancy policy with an eye to cost savings.

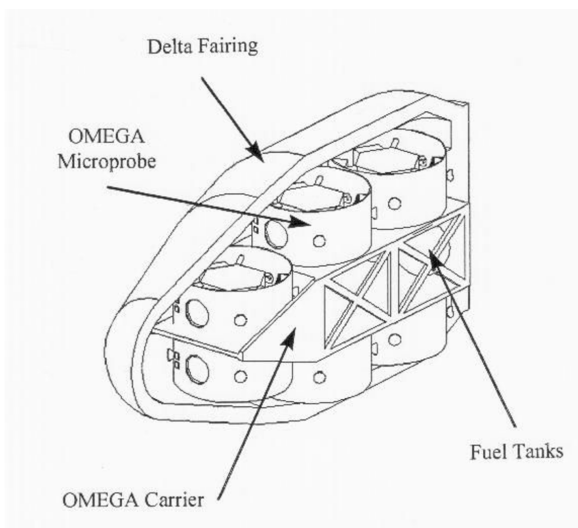

Figure 2. The six microprobes and carrier inside the Delta II fairing.

In the following sections, we will discuss the science goals that OMEGA will be able to accomplish (§ 2), address some technical misconceptions about OMEGA (§ 3), explain in more detail how it is that OMEGA accomplishes its cost savings relative to LISA (§ 4), estimate the current TRL levels for the main OMEGA instrumentation (§ 5), and draw a couple of brief conclusions (§ 6).

2. OMEGA Science

OMEGA Sensitivity Curves. The sky-averaged sensitivity curve for OMEGA is displayed in Figure 3. This curve was generated using the Online Sensitivity Curve Generator[1]. The armlength used was the OMEGA baseline of L = 1 x 10^9 meters, which is 1/5 the LISA baseline. The noise-level inputs to the Generator were set at $(S_a)^{1/2}$ = 3 x 10^{-15} m/($s^2 Hz^{1/2}$) for acceleration noise, identical to LISA acceleration noise levels, and at $(S_x)^{1/2}$ = 5 x 10^{-12} m/($Hz^{1/2}$) for position noise, which is one-fourth the LISA position noise, reflecting the advantages of the stronger signals due to the shorter armlengths. The figure is overlaid with representative tracks of the major source classes in this band. As may be seen, OMEGA will be sensitive to all the source classes in the LISA science portfolio: massive black hole binaries, extreme mass ratio inspirals, ultra-compact galactic binaries, as well as known verification binaries.

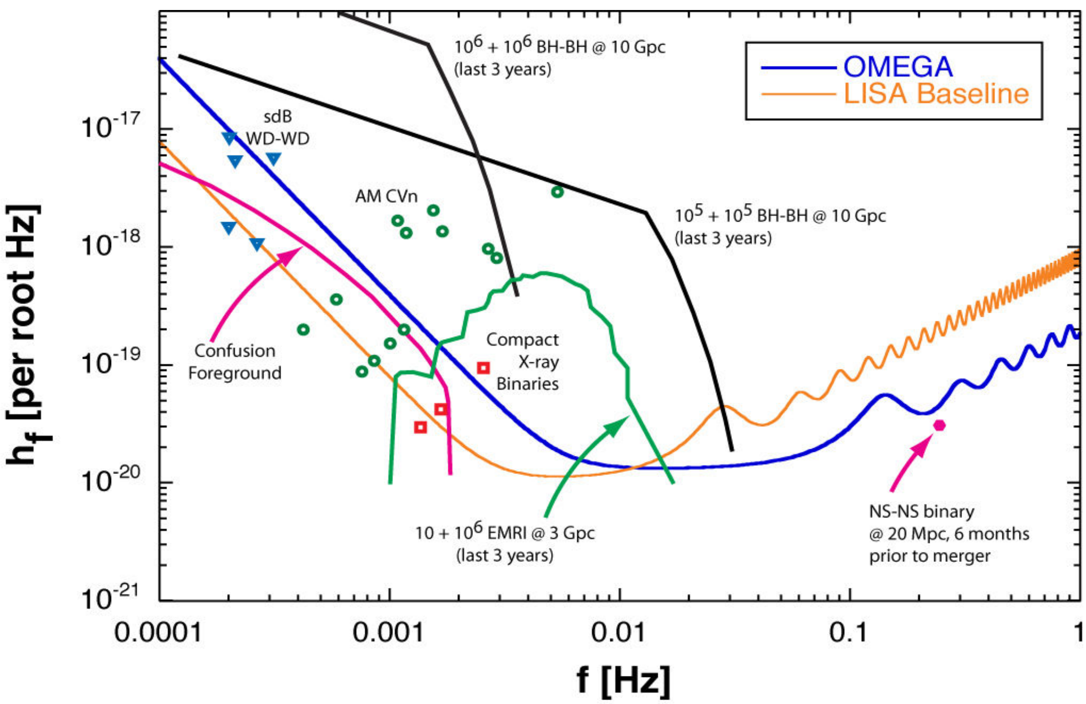

Figure 3. OMEGA's root spectral amplitude sensitivity (in units of $Hz^{-1/2}$) is plotted against the baseline LISA sensitivity. Overlaid on the figure are expected signal strengths for the low-frequency gravitational wave source classes. The height above the curve is roughly the signal-to-noise ratio to be expected for matched filtering in a one-year observation. For the EMRI and MBH binaries, the sources evolve dramatically during the observations, and the indicated curves represent the SNR contributed in each logarithmic frequency interval. [1,2,3]

As can be seen in Figure 3, the OMEGA sensitivity window covers roughly the same band as LISA, but shifted to higher frequencies. The OMEGA instrumental noise performance at low-frequencies stands above the expected level of the foreground confusion noise from the unresolved galactic binaries which ultimately limit the performance of any low-frequency detector in this band. Thus, OMEGA does not demand instrument performance in a band where the performance is unnecessary. The decline in low frequency performance will affect the mass of massive black hole binaries that will merge in-band, though, as Figure 3 depicts, many systems will still evolve into the primary OMEGA discovery space to be tracked for the final inspiral, merger, and ringdown. At the lowest frequencies covered by OMEGA, there will still be significant massive black hole science, as the merger and ringdown waveforms themselves contribute significantly to the overall SNR [4].

Source Science. The appeal of the low-frequency band is that it is replete with gravitational wave sources that are expected to be strong and, in many cases, plentiful. The diversity of astrophysical sources that can be seen by a mission like OMEGA makes the science portfolio interesting and accessible to a wide cross section of the scientific community. Low-frequency gravitational wave astronomy, as traditionally defined by the LISA Science Requirements [2], has the following goals: 1) Understand the formation of massive black holes, 2) Trace the growth and merger history of MBHs and their host galaxies, 3) Explore stellar populations and their dynamics in galactic nuclei, 4) Survey compact stellar-mass binaries and study the morphology of the Galaxy, 5) Confront General Relativity with observations, 6) Probe new physics and cosmology with gravitational waves, and 7) Search for unforeseen sources of gravitational waves. Based on sensitivity and source studies, we have estimated OMEGA's ability to satisfy these goals and summarize our projections as follows [5]:

- *Galactic ultra-compact binaries and verification binaries*. OMEGA will detect gravitational waves from at least 8 of the population of known compact binaries [6], and will discover more than 17,500 new systems. Of these, more than 5000 are expected to be localized to better than 2 square degrees on the sky, making electromagnetic follow-up possible. Of these, the inspiral will be measured well enough to determine the distance to the binaries in the galaxy for more than 2500 systems, making it possible to map out the three-dimensional structure of the galaxy (goals 3, 4). Long term observations of these binaries are also expected to provide excellent platforms for testing general relativity (goal 5).

- *Massive Black Hole (MBH) Binaries*. Massive black hole binaries with masses less than ~10^7 $M_\odot$ will track into and merge in the OMEGA discovery space. Many tens of these sources are expected to be visible with OMEGA. The detected waveforms from these events will determine the individual masses of the black holes in the binary to better than 1%, their spins to better than 1%, and their luminosity distance to better than 10%. The eventual OMEGA catalog of MBH systems out to redshifts of 10 to 15 will provide the ability to discriminate between competing MBH population models [7,8] and answer the question of the origin and evolution of these objects and their role in galaxy formation and evolution (goals 1, 2). The sky positions of these sources will be determined to better than 10 square degrees at z = 10 and better than 0.01 square degrees at z = 3.

- *Extreme Mass-Ratio Inspirals (EMRIs)*. The capture of compact stellar-mass objects by massive black holes will produce gravitational waves in which the smaller body probes the potential of the black hole during its long inspiral [9,10,11,12]. The detectability of these sources is fixed by the noise floor of the detector. OMEGA's sensitivity is therefore similar to LISA's, but with the lowest frequencies during the earliest parts of the inspiral suppressed. OMEGA observations will detect about 100 of these events per year, though the event rate is still highly uncertain, and will provide precise measurements of the central black hole mass and spin at low redshifts ($z \sim 1$) for black holes of mass up to $M \sim 2 \times 10^6$ solar masses (goals 3, 5). High mass counterparts featuring the capture of intermediate mass black holes (EMRIs) will also be detectable by OMEGA out to large redshift [13].

- *Cosmology and Stochastic Backgrounds*. While the expected strength of gravitational waves from standard slow-roll inflation is expected to be undetectable by any first generation gravitational wave detectors, many proposed models have predicted stronger backgrounds than would be detectable by OMEGA (goals 6,7). These include exotic cosmological phenomena such as phase transitions [14] or networks of cosmic strings [15] at frequencies within the OMEGA band. OMEGA will be able to detect such cosmic phenomena producing gravitational waves in the center of its sensitivity window at strengths corresponding to energy densities below $\Omega \sim 10^{-8}$. Also, OMEGA measurements of the distance to MBH events, particularly when coupled with electromagnetic observations, will independently determine cosmological model parameters (goal 6) [16,17,18].

- *Unknown Sources*. OMEGA's strong Doppler modulation of incoming gravitational-wave signals allows pointing algorithms to target small patches of the sky, where intermediate data products may be generated and used to search for bright sources of unknown origin (goal 7).

OMEGA Position Sensitivity

The geocentric OMEGA orbits lie within 5° of the ecliptic plane and have periods of 53.2 days. The short orbital period provides a strong Doppler frequency modulation and many cycles of modulation, leading to excellent position determination for most of the sources in the band, particularly for those with frequencies above 1 mHz. However, because of its constant detector-plane orientation, OMEGA does not produce phase and amplitude modulations of incoming gravitational-wave signals like the modulations produced by LISA with its precessing detector plane. In 1998, when OMEGA was proposed as a MIDEX mission, it was thought that OMEGA's lack of a precessing detector plane would severely limit its ability to determine the position of sources at the low end of the window, the region where the MBH binary coalescences would appear. In 1998, this was identified as a major weakness of the OMEGA proposal. Since that time, however, the situation has completely changed.

Beginning in 2001, it was discovered that the higher gravitational-wave harmonics, which had been ignored in previous work, provided a significant improvement to position determinations of MBH binaries, particularly in OMEGA's fixed-plane orbit [19,20]. Then, starting in 2004, it was discovered that LISA's position sensitivity to BHB coalescences in which the black holes in the binary system are spinning (and most black holes are expected to spin) was much more accurate than what would be expected from the modulation produced by LISA's precessing plane alone [21,22]. The key to this improvement appeared to be a spin-induced precession in the source orbit plane that produced a detectable position-dependent modulation of the signal [23]. Suspecting that this same mechanism would be able to provide improved position sensitivity, even in the case of a fixed-plane detector like OMEGA, we have simulated OMEGA parameter estimation sky-position accuracies for binary MBH coalescences. We have also included ringdown waveforms which give position information in the high-frequency regime where OMEGA is particularly sensitive. We conclude (see Figure 4) that OMEGA will indeed provide exceptional accuracy in determining the sky position of MBH binary coalescences, equal, in fact, to the accuracy that is expected with LISA [6]. In short, despite its fixed detector plane, OMEGA is capable of determining the sky location of sources all across its sensitivity window.

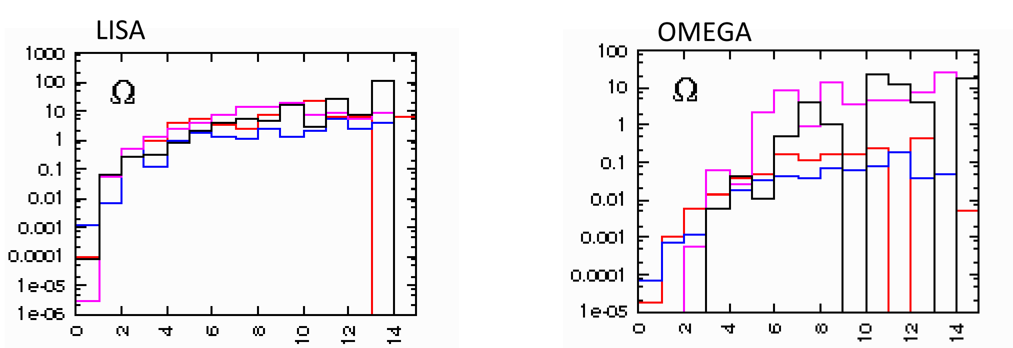

Figure 4. The angular sensitivity (in deg^2) vs. redshift for the MBM binary coalescences arising in four different BMBH population models (the different colored lines) for both LISA and for OMEGA.

3. Technical Issues

In the 1998 MIDEX review, several weaknesses were found in the OMEGA mission proposal, leading to the mission not being selected. The first of these was a scientific weakness – the issue of poor position sensitivity for black hole binary inspiral sources. This was addressed in the last section. The remaining issues were technical ones. These will be addressed in this section.

Sun Filter. Because the plane of the OMEGA constellation is near the ecliptic plane, there will be times when sunlight is coming in along the line-of-sight of the laser link. Unaddressed, direct sunlight in the optics would destroy the photodetectors, while even indirect light would produce variable heating of the interior of the instrument and would generate unacceptable thermal fluctuations in the position of matter near the accelerometer, engendering large self-gravity perturbations of the proof mass that forms the position reference for the drag-free system. The solution chosen for the OMEGA mission was to develop a band-pass sun filter that would reflect 98% of the incoming sunlight and pass only a narrow band near the 1064 nm laser wavelength. This filter would allow an OMEGA microprobe to track its far companion right across the face of the sun. The 1998 MIDEX reviewers were concerned that such a filter did not exist. But the filter had, in fact, been designed and constructed in time for the proposal, and its performance had been verified. Based on a design by JPL's Nasrat Raouf, Barr & Associates produced several test filters for us. The front surface filter was a low-pass filter, employing dielectrics that were transparent across the entire solar spectrum. This filter reflected the visible and ultraviolet light across the solar spectrum with wavelength $\lambda < 1064$ nm. The substrate was a Corning D-glass with a low thermal coefficient of optical path length expansion and high transparency to IR. The back surface was an infrared hi-pass filter that reflected light of wavelength $\lambda >$ 1064 nm. The measured reflectivity performance of the filter is shown in Figure 5.

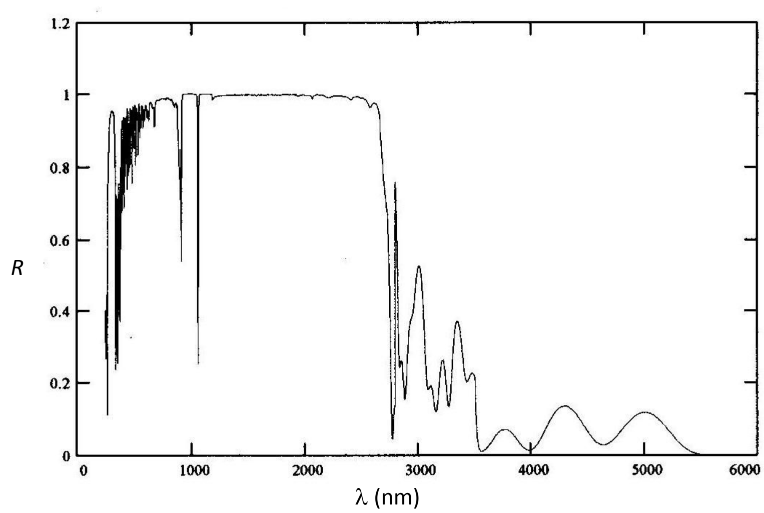

Figure 5. The reflectivity *R* of the OMEGA sun filter.

Solar Thermal Problems. There has been a concern among some in the LISA community for the temperature variation produced across the OMEGA spacecraft due to the variation of the sun's orientation relative to an OMEGA probe. Because of OMEGA's ecliptic-plane orbits, the sun will indeed travel around each probe's outer cylinder once per orbit. This is often contrasted with the constant angle the sun makes to the cylinder axis of the LISA spacecraft. In preparation for the 1998 MIDEX proposal, JPL's thermal engineering group generated a thermal model of the OMEGA spacecraft in this environment and found that the temperature on the outer cylinder, the sun shield on which the solar cells are mounted and to which some elements of the avionics are attached, will vary between 310K on the sun side to 205K on the space side. Passive thermal isolation between the sun shield and the instrument bay produces a temperature variation across the instrument bay of less than 1K. Currently, Utah State University's Space Dynamics Laboratory (SDL) is building a new spacecraft thermal model for OMEGA to enable us to capture the thermal impact of whatever design changes may arise.

It should be remembered, however, that the question is not the size of the temperature variation *per se*, but what its effect will be on the performance of the detector. The sunshield, which suffers the greatest temperature variation, is a 50-cm-radius cylinder, constructed of carbon-polycyanate honeycomb. The total mass of the structure, including its solar cell covering and the avionics packages that are mounted to it, is about 40 Kg. Our thermal-mechanical model of the OMEGA probes predicts a thermally-driven gravitational acceleration of the proof mass of order 3×10^{-14} m/s^2. While this is an order of magnitude greater than the acceleration noise requirement for OMEGA, the acceleration varies at the OMEGA orbital period of 5×10^6 s, well outside the OMEGA sensitivity window. Even if some non-linear stick-slip mechanism were to up-convert the signal into the OMEGA band, the amount of accumulated variation in 10^3 seconds would be less than 10^{-17} m/s^2. In short, this is not a problem for an OMEGA-like mission.

4. Designing for a Reliable Low Cost Solution

An important contribution to the low-cost design in the 1998 MIDEX proposal was the partnership with Spectrum Astro, Inc. In generating this white paper, Spectrum Astro's place has been taken by a partnership of Utah State University's Space Dynamics Laboratory (SDL) and Surrey Satellite Technology – US (SST-US). SDL has expertise in mission management, mission systems engineering, mission operations, and sensor development and calibration. SST-US has expertise in reliable small spacecraft solutions, launch integration, and in on-orbit checkout and support. Both SDL and SST-US are small aerospace companies that have records of delivering missions on time and in budget. In this section, we will address some of the design characteristics that produce a low-cost mission.

Figure 6. Assembly of the WISE payload at SDL.

Earth Orbit. The mission design for the geocentric orbit begins with a launch phase whose -1.57km^2/s^2 C3 requirement may be satisfied, given the total launched mass of 550 Kg, by a medium launch vehicle such as a small Delta or the Falcon 9. After 15 days in elliptical earth orbit, a 185-day weak-stability-boundary orbit will bring the carrier back to a retrograde 600,000-km-radius geocentric orbit, where two probes are deployed. Two successive phases of 90-day elliptical orbits followed by re-circularization provide a constellation of six spacecraft in 53.2-day circular earth orbits, two spacecraft at each of the vertices of a one-million-kilometer equilateral triangle. The time required for complete deployment is 384 days and the total Δv required of the carrier is 502 m/s. In their 600,000 km orbits, the data requirements may be satisfied by once-per-week tracking by a DSN station or by a dedicated network of small (3m) antennas with near-continuous coverage. The earth orbits also allow for continuous short-time-lag probe communication during times of possible spacecraft emergency. In summary, the choice of a geocentric orbit permits modest costs for the launch vehicle procurement and low costs for telecommunications, tracking, and operations.

Low Mass and Power. As OMEGA hardware was being designed, trades were consistently made in favor of low-mass, low-power hardware that could be implemented without sacrificing capability or reliability. For example, the OMEGA geocentric orbit enables a choice of a telecommunications subsystem based around a space-qualified 2-watt S-band transponder communicating through fixed-orientation patch antennas, meeting the tracking and data requirements with a total mass of 500 g and a total power of 10W. By way of contrast, the current LISA telecommunications system, with its requirement for an orientable high-gain antenna, weighs 40.5 kg and requires 150W of power in its science mode. Choices that favor low mass and low power for essential spacecraft components have a feedback effect that greatly affects the overall microprobe design. Our example of a low-mass, low-power spacecraft transponder (enabled by the Earth orbit) would reduce the power requirement that sizes the solar array and its supporting structure. It would also reduce the overall mass, which reduces the thrust authority required of the attitude control thrusters, which further reduces the power requirement and the size of the solar array. As a result of choices like these, each OMEGA microprobe has ended up weighing 70 kg. This may be compared to the 634 kg for the current mass of a single LISA on-orbit spacecraft.

Design and Manufacture Policy. One of the design approaches that led to low cost for OMEGA hardware was the choice of small-sat space-qualified parts when they were available and the use of a build-and-test policy for new hardware developments. Commercially-available, MIL-spec, space-qualifiable parts were chosen wherever possible and planned to be used in early manufacture of flight prototypes. The result is that mass, power, and cost estimates would be founded on actual hardware. As an example, a power control unit for the FEEP thrusters, providing and regulating the power to a single cluster, was designed using commercially-available high voltage DC converters. The result was a radiation-hardened electronics box with a total mass of 300 g per cluster, vacuum-potted for space qualification and built at a total cost of 640 $K for 24 boxes. The risks and limitations involved in the use of commercial parts can be mitigated by extensive space-qualification testing and by a "hot bench" type of integration in which prototypes, and eventually flight hardware elements, are tested in place with other hardware and with simulators where hardware is not yet available. *The obvious cost advantages of commercial parts allow a design policy to be implemented in which cost is an important element of trade studies*.

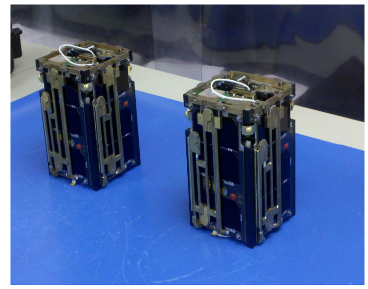

Figure 7. Two SDL-assembled DICE nano-satellites prior to launch vehicle integration

Simplified Interfaces. The gravitational wave detection system proposed for both the LISA and OMEGA missions necessarily involves complex interconnected control systems. The laser tracking system provides the error signal for the fine pointing by the position and attitude control system and the proof mass in the accelerometer is an element (in the original version of LISA and OMEGA) in the optical path of the laser tracking system. Links between multiple spacecraft are required in order to generate a single interferometer data channel. This level of complexity adds significantly to risk and cost. Choices should consistently be made in favor of decoupling complex interfaces and providing control loops that are simple and local. In the current version of LISA, for example, a choice was made to decouple the measurement of the proof-mass position relative to the spacecraft from the optical path measurement used for the interferometry. Though not a part of the 98 OMEGA proposal, this approach is certainly a step in the right direction and should be used in whatever space gravitational observatory is eventually flown. However, other LISA design decisions seem to have gone in the wrong direction. The original LISA design had a master laser in one spacecraft and required that all other lasers be locked to that one laser, creating a system where a single upset of the master laser would require re-initialization of the entire constellation. The current LISA design goes beyond this and employs a technique known as "arm-locking," in which the lasers are locked, not to a local cavity, but to the arms of the interferometer itself. Transmission and reception in all arms of the interferometer are tied together and the laser noise cancellation required for the LISA science is not available until the entire system is locked up. Restarting the system requires reacquisition and phase-locking over multi-spacecraft links with many-second latencies. For OMEGA, we chose to separate and simplify. Each laser transmitter locks only to its own local reference cavity and broadcasts a signal independently of any other links. Each laser receiver tracks whatever signal it is receiving from a far probe. If a single link is lost, other links continue to operate and provide science data while the faulty link is reinitialized and reacquired. Simplicity of interfaces characterizes the entire OMEGA design, allowing simplified hardware construction and testing and contributing to reduced cost.

Redundancy Policy. A fully-operational 6-microprobe constellation with its 6 independent links enables gravitational wave polarization to be measured, even for short-lived signals. This is a worthwhile science goal. However, a constellation with only 4 operational microprobes remains a viable gravitational-wave detector, as long as at least one probe is operating at each of the 3 vertices. Thus, the mission remains operational in the event of a complete loss of a single probe or even of a second probe, as long as it is not at the same vertex as the first. This mission-level redundancy allows a redundancy policy to be implemented in which the cost of any planned hardware backups can be taken into account. Hardware redundancy may be implemented if it can be done at little cost or if the piece of hardware has known reliability issues and requires a backup system, but single-string failures in individual probes may be permitted when they are unlikely and too expensive to mitigate. This is allowable because, once the probes are in their operational orbits, there are simply no single-string failure points at the mission level.

OMEGA in 2012. In response to the RFI, SDL has studied the OMEGA-98 design and identified places where the current state of the art provides lighter, more efficient, more capable, and less costly hardware choices. If OMEGA were to be redesigned in 2012, several improvements would be possible. Here are three examples.

- The C&DH system on OMEGA-98 employed a Honeywell HX1750 processor. This is a single-core 40 MHz, 16-bit, 3.3 WMIPS, 100 KRAD TID, SEL-immune processor, with a single 1553 bus. For OMEGA-12, we have identified a Glaiser Dual Core, 100 MHz, 32-bit, 300 DMIPS / 250 FLOPS, 300 KRAD TID (UT699), SEL-immune processor, with 1553, 4 SpW, 6 UART, eth, SPI, I2C, CCSDS, 26/38 GPI/O, and PCI connections. The mass is about half that of the HX1750, and the power consumption is about 5W, compared to the HX1750's 18.8W requirement.

- The OMEGA-98 solar cells were costly GaAs/Ge cells, achieving 18% power conversion. At present, Emcore's inexpensive ZTJ InGaP/InGaAs/Ge solar cells, with a mass of 84 mg/cm^2, provide 135.3 mW/cm^2 of power, for 29.5% minimum average efficiency. This increased power collection allows a lower packing density on the probe's outer cylinder and provides the possibility of improved passive control of the surface temperature.

- DTU's Advanced Stellar Compass (ASC), the designated star tracker for OMEGA-98, was designed and developed to fly on the Danish satellite Ørsted. Since that time, the ASC has evolved into a more compact and sophisticated instrument that has flown on several missions including Astrid II, TeamSat, CHAMP, PROBA and GRACE.

Overall, we expect to now be able to save 15 to 20% in mass and about the same in overall power.

Cost Estimate. The 1998 MIDEX proposal involved both grass-roots costing and parametric cost-model analysis. Some details of this 1998 process are included in the Appendix. The OMEGA costing was twice reviewed by internal non-advocate cost teams at JPL before the proposal was allowed to go forward. During the MIDEX review the TMCO panel concluded that our total $FY98 cost estimate of 153.2 M$, including reserves, was "reasonable." Inflating this cost to $FY12, estimating the costs of the deltas we would like to make to the cost-capped MIDEX design, and allowing for forward-costing uncertainties, we arrive at a total cost estimate of 300 M$ for an OMEGA-like Space Gravitational Observatory mission.

5. Technology Readiness

Technology development for the LISA mission has advanced most gravitational-wave technologies to TRL level 6. For an OMEGA-like mission, we would be able to keep many of these elements, but we would also modify some of these to reduce mass and power. In Table 1, we list the major instrument subsystems, with TRL estimates from LISA's Astro2010 RFI#2, Table 2-8, for LISA-derived hardware and with our own estimates of the TRL for alternative hardware choices, with heritage sources or specific parts mentioned where appropriate.

Table 1. TRL levels for OMEGA instrument hardware. Shaded cells are for LISA instrumentation. Dual descriptions represent cases where LISA technology provides an acceptable solution, but where simpler solutions could provide equal performance at lower-cost.

Component	Hardware Description	TRL
Accelerometer	Modified from LPF, GRACE, Microscope designs	5
Attitude Control Law	6-DOF. Input from laser quadrant phase meter, accelerometer, star tracker.	6
Thrusters	Colloidal: ST-7/LPF thrusters, 30 μN max thrust, <0.1 μN/Hz$^{1/2}$ noise	6
	FEEP*: Microscope 2 μN max thrust, <0.05 μN/Hz$^{1/2}$ noise	5
Charge management	UV-LED lamps. High heritage from GP-B subsystem.	6
Laser subsystem	1.2 W 1064 nm master oscillator power amplifier (MOPA) design. Nd:YAG NPRO master with Yb-doped fiber amplifier.	6
Optical Bench	Graphite/cyanate composite optical bench, extensive use of fiber optics	4
Telescope	30 cm, f/1.5 on-axis Cassegrain with fiber-positioner refocus.	5
AFT assembly	2 cm flat optics. Two-axis stepper mount	3
Photoreceivers	Pyramid-prism to fast InGaAs cells, Spectrum Microwave 6160 low-noise amps	3
Phase Measurement	Digital heterodyne receiver based on GPS technology. ~60 channels per SC with ~1 µcycle/Hz$^{1/2}$ noise	5
Laser Frequency Stabilization	Heterodyne Mach-Zehnder (LPF) or Fabry-Perot cavity. 300 Hz/Hz$^{1/2}$ residual noise in MBW	5
Point-Ahead Mechanism	Piezo-actuated flex pivot mirror on optical bench. Angular range: 800µrad, angular jitter: 16nrad/Hz$^{1/2}$, piston jitter: 2pm/Hz$^{1/2}$(open loop)	4
* FEEP thrusters are less massive and require less power, but current designs have lifetime issues. We propose further study of the FEEP technology, but the present baseline should be the more massive and power-consuming colloidal thrusters.		

6. Conclusion

An OMEGA-style mission will be able to detect all the types of gravitational-wave sources that LISA is planning to detect, with an ultimate catalog size that is nearly the size of the projected LISA catalog. The overall cost of this mission should be near 300 $M in FY-12 dollars.

We want to be clear that the ability to accomplish this science at such a low cost is *not* the result of the choice of geocentric orbit alone, though this choice for the orbit helps. Rather, *lower costs could be achieved for any desired orbit by implementing an "explorer" approach to mission design*, meaning an approach in which mass, power, and cost are included as important elements of engineering trade studies and where management does not allow these elements to grow without limit. The point of this white paper is to urge the study of this approach to Space Gravitational Observatory mission design.

Appendix. The 1998 MIDEX Cost Estimate

In this section, we reproduce parts of the 1998 MIDEX mission cost analysis for OMEGA. The mission was to be managed at JPL, with spacecraft hardware provided by SAI and with instrument hardware provided by space laboratories associated with several US and European universities.

A. Grass Roots Estimate.

The grass roots estimate was based on the preliminary mission design, including flight and ground systems, the planned hardware and software development process, and the project schedule. The estimation process began with the development of a Work Breakdown Structure (WBS) that was taken to third and in some cases fourth level. The JPL Project Cost Analysis Tool (PCAT) was used to collect, burden, inflate, and display project cost data. Costs for special or unique components – the laser transmitter, OSCAR accelerometer, sun filter, and star tracker – are based on fixed-price quotes provided by the manufacturers. For generic hardware, costs were estimated based on a preliminary selection of components and subsystems and on recent cost data for this hardware. In all cases, management, system engineering, mission operations, workforce, supplies, travel, and service costs were estimated based on comparison with recent and ongoing projects and missions.

The major OMEGA procurement is the SAI-built carrier and probes. Hardware costs were estimated at the component level, with actual component costs being used where available for heritage and commonality. Labor estimates are based on the conservative assumption of little or no heritage connection to existing designs

The first year of mission operations is highly active, when the carrier is positioning the 6 probes in their operational orbit. The 2 years of operation thereafter are characterized by low activity with a small team monitoring the health of the probes and downlinking data once per week. Costs for AMOS and for use of the DSN are based on guidelines referenced in the MIDEX AO. Grassroots costs are rolled up in the first of the two cost columns in Table A1.

Table A1. Roll-up and Comparison of Parametric Cost Estimate and Grassroots Cost Estimate for OMEGA.

WBS #	Activity	FY98 $M	
		Grassroots Estimate	Parametric Model*
	Phase A	0.3	0.3
	Phase B	distributed	2.3
10000	Project management	5.9	5.1
20000	Science	9.8	8.6
30000	Project & Mission Eng.	5.5	8.7
40000	Instrument	25.0	25.0
50000	Spacecraft Bus	39.9	40.3
60000	ATLO	2.7	2.8
70000	Mission Operations	11.8	9.1
80000	Launch Vehicle	32.1	32.1
	Sub Total	133.0	133.8
90000	reserves	20.2	18.7
	TOTAL	153.2	152.6

*Aerospace parametric models: carrier - v.3, probe - v.2. Grassroots for instrument

B. Parametric Cost Estimate.

Costs were also estimated using parametric techniques. The input parameters for these models are given in Table A2. All parametric models are based on historical data and the accuracy with which they predict cost depends on the similarity of the spacecraft or instrument to those in the historical data base. In the case of OMEGA, special consideration must be given to: 1) the highly integrated sciencecraft microprobe design, 2) the simplicity of the microprobe bus requirements, 3) cost savings associated with building 6 identical probes, 4) the simplicity of the "dumb" carrier, and 5) the low level and simplicity of mission operations once the operational orbit is established.

Table A2. Mission Configuration Table (used for parametric cost estimates).

Mission Element	Probe (x6)	Carrier
Satellite dry mass (kg)	70.5	354[3]
Satellite wet mass (kg)	70.5	434.3[3]
Attitude control S/S mass (kg)	0.8[1]	N/A[2]
Stabilization type	3-axis	N/A[2]
Pointing accuracy (deg)	0.5	N/A[2]
Pointing knowledge (deg)	0.5	N/A[2]
Power subsystem mass (kg)	8.3	N/A[2]
Battery type	NiCd	N/A[2]
Battery capacity (A-h)	2	N/A[2]
Solar array type	GaAs	N/A[2]
Solar array area (m^2)	1.49	N/A[2]
Solar array mounting type	Body-mnt Cylinder	N/A[2]
Beginning of life power (W)	111	N/A[2]
End of life power (W)	97.3	N/A[2]
Propulsion S/S dry mass (kg)	N/A[1]	27.9
Propulsion system type	N/A[1]	Blow down
Propellant type	N/A[1]	Hydrazine
Propellant mass (kg)	N/A[1]	80.2
Number of thrusters	N/A[1]	12
Structure mass (kg)	8.1	39.8
Structure material	Composite	Al honey-comb
Thermal S/S mass (kg)	4.4	4.2
Telecom S/S mass (kg)	3.5	N/A[2]
Downlink data rate (kbps)	50	N/A[2]
Downlink band	S	N/A[2]
Transmitter power (W RF)	2	N/A[2]
Orbit inclination (deg)	5	
Apogee (km)	600,000	2,670,000
Design life (yrs)	2	1
Type of Mission?	science	deployment
Major spacecraft contractor	Spectrum Astro, Inc.	
Launch date	May 1, 2004	

Notes: **1**. FEEP thrusters (4 clusters of 3) are included as part of the instrument and are the only thrusters on the probe.
2. Carrier attitude control, electrical power, and telecom are provided by the probes.
3. Carrier mass includes probes as payload.

The OMEGA mission was evaluated using several different models and applying those models to elements of the OMEGA mission where their supporting data base was most similar. The functional requirements of the carrier vehicle are more typical of an interplanetary spacecraft, so the Aerospace Interplanetary Small Sat Model (v.3) was used. This model also recognizes the absence of typical spacecraft subsystems and therefore can best represent the "dumb" carrier vehicle costs. The functional requirements of the probes were judged to be more typical of Earth orbiters, so the aerospace Earth Orbiter Small Sat Model (v.2) was used. In applying this model, typical discount factors were applied to reflect the cost savings from the multiple build.

The Omega instrument is unique and nothing similar exists in the historical database. The JPL Instrument Cost Model (APDT) was run, based on mass and life parameters, and predicted a cost that was 44% higher than the grassroots estimate. Since the instrument cost model is so uncertain (including our instrument cost within the error bars) and since we are confident of our grassroots model, being based on quotes from experienced manufacturers, we have selected to use only the grassroots estimate for the instrument. The resulting cost model estimates for OMEGA are in the last column in Table A1.

C. Summary

Referring to the cost roll-ups in Table A1, reasonable agreement is indicated in most WBS categories, the largest difference being in project and mission engineering. The grassroots estimate reflects the new way of doing business, *i.e.*, a model-based "hot-bench" design/testbed development process and a highly-integrated management/contractor team to reduce project cost. The historical data base represents a more conventional development process.

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