<u>In</u>terferometer in <u>Sp</u>ace for Detecting Gravity Wave <u>R</u>adiation using <u>L</u>asers (*InSpRL*)

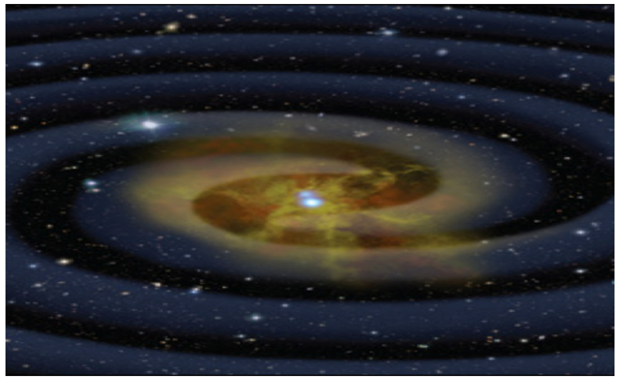

Figure 1: Measuring the signature of Inspiralling Black Holes using Atom Interferometry in Space (LISA Handbook)

Gravitational-Wave Mission RFI

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1.0 Executive Summary

Our *InSpRL* space-based gravity wave detector, equipped with Atom Interferometers (AI), has the potential to enable exciting science spanning the gamut from white dwarf binaries to inspiralling black holes, and cosmologically significant phenomena like inflation. This measurement approach, interferometer and mission concept would open a whole new window on the origin of our universe, heralding a deeper understanding of the fundamental laws of physics. Unlike light, Gravitational Waves (GW) permit observations beyond the so-called surface of last scattering; that is, before the white hot fog of hydrogen plasma cooled to give way to the formation of atoms. Goddard has teamed with Stanford and Princeton Universities, and we have assembled a team of top astrophysicists, engineers and technologists to explore this innovative detector concept. We are proposing to analyze and better understand the realm of applicability of this new, “disruptive” technology for exploring GW physics. The technological readiness of this approach for space flight will be critically examined in light of significant DARPA and DoD investments over the past decade or more. Cold atom-based inertial sensors have recently made it out of the laboratory and are in the process of being engineered and ruggedized for a variety of real-world applications in the fields of navigation and remote sensing, including some very demanding mission applications. Gravity wave detection is arguably the most compelling scientific application for atomic quantum sensors of this sort in space. Thus, we feel that this technology is ripe for focused investment by NASA space mission developers.

Our team began almost 2 years ago, undertaking a critical assessment of the technological maturity of atom based sensors, and subsequently conducting a mission design concept study in Goddard’s Mission Design Lab (MDL) of a single space platform equipped with AI and deployable boom antennas. Stanford and Goddard have since collaborated on a number of laboratory experiments supported by extensive calculations and model analyses. Our analyses have suggested two variants of the GW detector discussed above, flying in high Earth orbit; the single small spacecraft with two 500 m deployable booms and, additionally, a pair of small spacecraft flying in formation, separated by 500km in the same orbit.

The single platform configuration can be used to test strong field gravity and the near horizon geometry of black holes. It will also allow the study of the astrophysics of these compact objects and their mergers, and the study of structure formation from the cosmological mergers of massive Black Holes (BHs). The separated spacecraft configuration is even more scientifically powerful. It's longer baseline, still modest by comparison with previous light-based interferometric approaches, and strong sensitivity allows for observations of most sources observable with the LISA design, as well as essentially any binary observable with Advanced LIGO. In addition, stochastic GWs can be measured to verify most inflationary models. Importantly, known sources such as HM Cancri are within range of this detector sensitivity!

Why submit two designs for further study? The spacecraft with boom antenna is an aggressive approach, but the science return per dollar would be very compelling. Our MDL study estimated the cost of this configuration at $444 M, in constant FY'10 dollars, and including ample reserves. This mission concept would fall in cost bin #1 in the RFI. The estimate for the cost for the separated spacecraft mission is $678 M, and was derived based on engineering estimates – essentially a delta off the 2010 MDL boom flyer estimate - and would thus put this mission in the second RFI cost bin. This estimate would be refined in a subsequent MDL run after selection. The orbital dynamics constraints on the AI free flyers are substantially less that the legacy light-based interferometer concept (LISA), and as such the essentials of formation flying of this AI concept have been demonstrated in the space environment by the European PRISMA mission in 2010 (*http://www.prismasatellites.se/?id=16291*).

Our core *InSpRL* Team stands ready to support the PCOS Workshop on December 21-22nd. We have invited several distinguished GW astrophysicists from the external community to provide us with (non-advocate) advice as we think about using this breakthrough technology for GW detection from space. Finally, we look forward to the opportunity to continue our study of this exciting new approach to this important new region of the observing spectrum.

2.0 Concept Description Single and Separated Spacecraft Platforms

We propose to search for gravitational waves using light-pulse atom interferometry in space. Our proposed measurement architecture is predicated on several requirements for making a precise differential acceleration measurement. First, the need for a space experiment is indicated, based on the frequency range and sensitivities required to do the science of mergers, inspiralling, known sources like HM Cancri and other fundamental cosmological effects. Seismological noise must be minimized to achieve the desired measurement signal regime. A high degree of isolation enables these instruments to detect minute changes in the baseline dimension to detect strains in regions of 10^{-20} $Hz^{1/2}$. Second, gravity wave measurements are baseline-dependent; as such, generally two isolated proof masses are separated by a baseline length, L, where in our proposed scheme, L is of order 500 kilometers in the case of a two-platform, separated spacecraft antenna implementation, and of order two 500 meter booms for a single platform, extensible boom configuration, both of which will be discussed in some detail below. The experiment particulars, like spacecraft orbit, altitude, attitude control, stability, etc., will be optimized in subsequent study, in an attempt to find a cost-effective mission configuration for this exciting scientific measurement which minimizes spurious noise sources associated with the platform.

The advanced instrumentation element is a differential gravity gradiometer effectively based on 3 pulse-atom interferometers. The main feature of the gradiometer is dual opposing atom-based accelerometers that are separated by the baseline length L, and interact via a common laser beam. This configuration is extremely useful for rejection of common mode, rigid body motions between the two accelerometers. Space-based AI detectors are compelling for both technological and scientific applications due to the exceptional projected performance enabled by long interferometer interrogation times in a zero-gravity environment. Gradient acceleration is related to the relative motions of the 2 atom clouds, which in turn is related to the perturbation of the space-time metric caused by the gravity wave.

Concept 1: Separated Spacecraft Platforms

The first, more sensitive configuration is a pair of AI-equipped spacecraft, flying in formation with a separation (baseline) of 500 km, as shown schematically in **Figure 2**.

The concept is two AI-instrumented, two spacecraft, separated by 500 km (baseline length). Each vehicle has a small 20 meter deployable boom with a sunshield (or sock) to isolate the

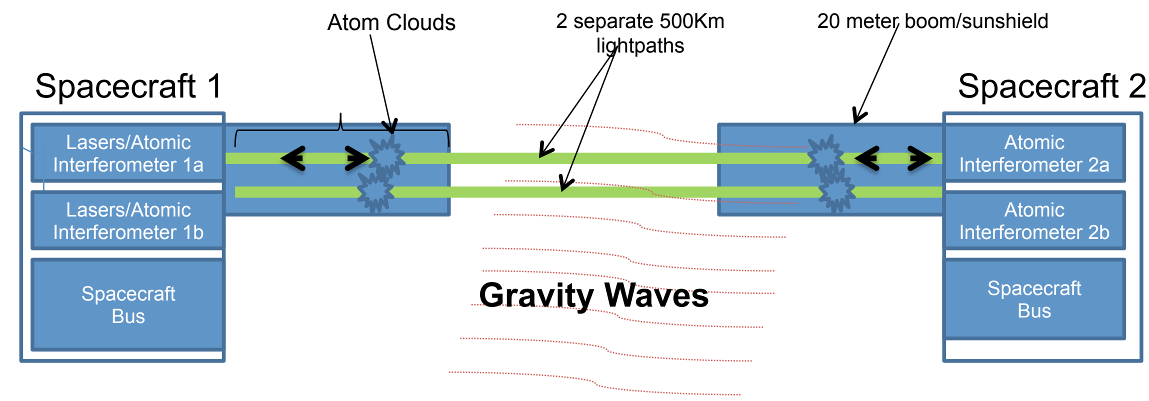

Figure 2: Separated Spacecraft Configuration.

atoms from sunlight. This configuration does not allow for repointing other than that provided by the orbital dynamics. The only formation requirements are orbital insertion and station keeping. The station keeping requirements are minimal. Detailed pointing between the spacecrafts is achieved with fast steering mirror mechanisms, the mirror of which is a superflat, similar to what LIGO is using. Quadrant arrays or CCD's can be used to provide sensing information for the fine steering mirror. The dynamic requirement can either be achieved with low disturbance thrusters (e.g., colloidal or FEEP) or via a combination of isolation and the fine steering mirror. In the latter case, the system can use cold gas thrusters and/or reaction wheels for insertion and station keeping. There are multiple orbit options though Super GEO (1200 km above GEO) is preferred to reduce cost, though Earth trailing and L2 are also options to investigate.

The incident gravity waves would pass through the system and the variability of the strain due to wave amplitude modifies the baseline length.

Simply put, laser beams will be emitted from the spacecraft in opposite directions along the boom and toward each cloud. Two counter propagating lasers will illuminate each cloud and effective three pulse interferometry is performed on each atom in the cloud. The gradient of the acceleration between clouds is measured, common rigid body motions are subtracted and relative motion of the clouds will be detected. This technique requires 10-20 watts of cw laser light at 780 nm wavelength, and we believe this level of performance can be achieved today using commercial-grade telecom equipment. (See **Figure 4** for a more complete description of the laser system proposed for development). The laser beams are modulated using electro-optic modulators. The wavefunction separation for interferometer is of order tens of meters. The atoms must be shielded from scattered or direct sunlight, so the boom has a deployed shield (sock) on it, as was mentioned earlier. Isolation from solar photons is required because they will decorrelate atoms (i.e., knock atoms out of the cloud), thereby reducing the overall signal and effecting the shot noise limit of the device in an unfavorable way.

Concept 2: Single Platform Boom Configuration

A compact, single platform measurement architecture, located in Super GEO orbit, with 500 meter extended masts, is illustrated schematically in **Figure 3**. Preliminary analysis of the boom configuration and scalability was done by our mission partner, ATK, and this configuration appears feasible, based on experience with similar, 100m deployable booms of this nature in the space environment.

In this single platform configuration, two deployable booms, each 500m in length, will be deployed, one each from opposing sides of the spacecraft. A retroreflector is positioned at each boom endcap to reflect the laser light back towards the atom cloud. The apparatus for preparing the atoms and the manipulating and controlling laser systems are located in the body of the small spacecraft. Each cold atom cloud will be shuttled to the center of each boom using proven optical lattice techniques[1].

Instrument Booms

A pair of linear-deployed 500-m long booms, with each boom supporting a retro reflecting mirror assembly at its tip, is the principal structural component of the *InSpRL* instrument. The booms enclose the laser beam path and an external MLI "sock" around the booms protects against solar illumination of the beam path and direct solar heating of the boom structure. Boom

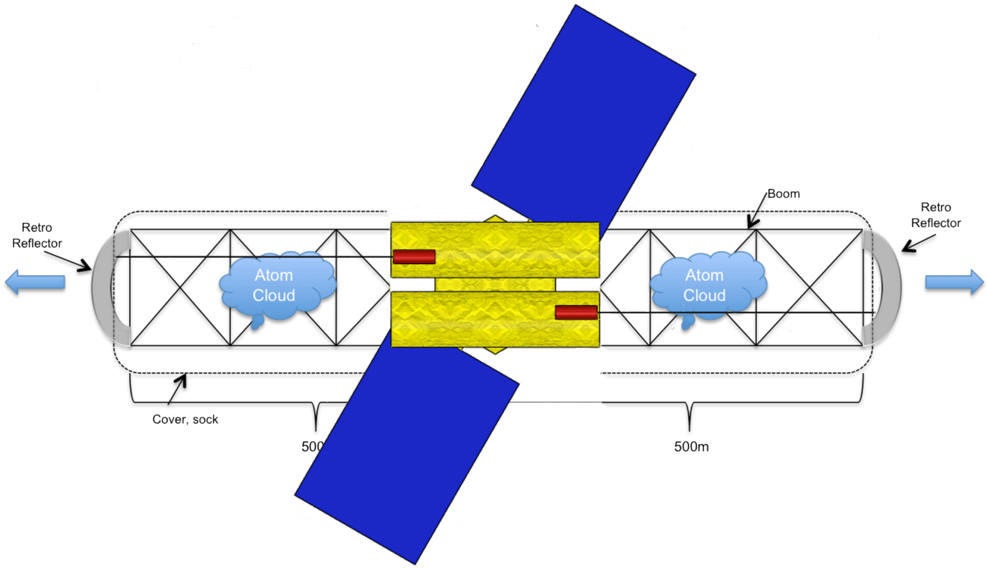

Figure 3: Schematic of a Single Boom Configuration. (Not to Scale)

straightness, to prevent the boom from violating the laser beam path, and boom-tip position stability, to minimize motion of the retro mirror, are of the key importance to instrument performance. To address issues associated with ground verification of boom performance, deployed boom straightness, and boom vibration control, a shape-controlled segmented boom concept will be developed (**Figure 3**). In addition to providing manufacturing and test advantages, boom segmentation could be combined with simple tip/tilt control between adjoining boom segments to provide in-orbit shape control.

We summarize our current understanding of the advantages and disadvantages of the two configurations from the technical perspective (**Table 1**).

Table 1: Comparison of the Two Mission Configurations.

	Boom	2 Spacecraft Formation
Advantages	Doesn't require Formation Flying	Can have very large baselines (more science)
	Single Spacecraft	Simpler Atomic Interferometry
	Can test configuration on ground	No boom dynamic issues
	Potentially lower cost	Scaleable to larger number or baseline
Disadvantages	Need active control for dynamics	Needs Formation Flying (Ranging, Orbit Insertion, etc.)
	Dynamic impacts on ACS system	2 spacecraft
	Limited Baseline Size	Hard to test
	More complicated Atomic Interferometer	

Laser Oscillator Fiber Amplifier Description

The laser source is a key component of the gravity wave detector apparatus. We require a high output power, narrow linewidth source of high stability. To address this requirement in the lowest cost way possible, we propose to take full advantage of telecom investments and existing Telcordia standards, and space qualify a narrow linewidth (<1KHz) fiber oscillator from NP Photonics (Tuscon, AZ) and an IPG Photonics (Boston, MA) fiber amplifier. The oscillator puts out 80 mW at 1560 nm, and the amplifier stage emits 30 W at 1560 nm, while avoiding line-broadening nonlinear effects (Stimulated Brilluoiun Scattering). The doubling efficiency using a resonant cavity configuration is in excess of 70%, and the amplified 780 nm radiation should have a linewidth less than 2 KHz.

The schematic diagram (Li et al., Opt Comm 201) of the complete laser system, including the electro-optical (EO) modulator and magnesium oxide-doped (MgO), Periodically-Poled Lithium Niobate (PPLN) resonant doubling crystal/cavity configuration, is shown in **Figure 4**. A commercial version of this system has been purchased on Goddard IR&D FY'12 funds during this RFI evaluation and selection period, and the output beam power spectral density (PSD) will be characterized to obtain the laser phase noise over the frequency range of interest, informing subsequent study efforts.

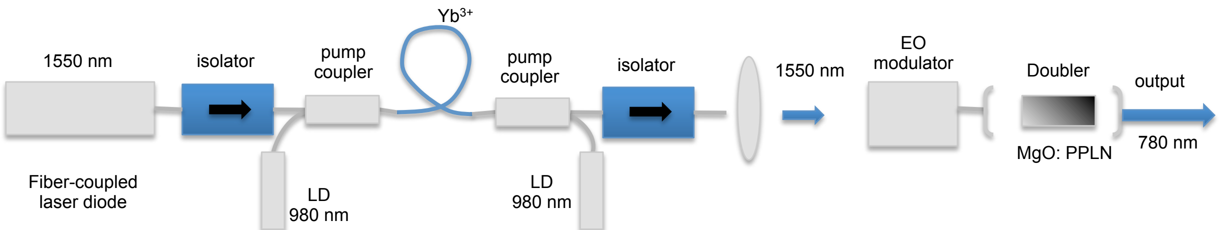

Figure 4: Master Oscillator Fiber Laser for Atom Interferometry. (We envision using fiber EOM before the amplifier with serrodyen shifting.)

3.0 Gravity Wave Science Payoff

The 500 m single flyer configuration can detect many exciting astrophysical and cosmological sources. Likely sources include mergers of white dwarfs (WD), neutron star (NS), and black hole (BH) binaries:

- Mergers of massive black holes binaries (MBHB) of 10^5 solar mass holes (curve c in **Figure 5**) can be observed out to z = 17. With expected rates between 12 - 80 mergers/yr[5], the observed mergers will reveal the assembly history and the physics of black holes. MBHB's with two 10^6 M_s BH's (curve b in **Figure 5**) can be seen to z = 8 with rates between 8-40 mergers/yr. MBHB's with two 10^7 M_s BH's (curve a in **Figure 5**) can be seen to z = 1.2 with rates of 0.5- 2.5 mergers/yr.
- Extreme mass ratio inspirals provide an important testing ground for GR[6]. For example an EMRI with 10^6 M_s and 10 Ms BH components can be seen to a distance of 0.65 Gpc (curve d in **Figure 5**) with an estimated rate of approximately 1 per 3 years[7].
- WD-WD (and other compact object) binaries in our galaxy down to a frequency of 10^{-2} Hz. There should be approximately 60 such expected continuous gravitational wave sources[8]. Such binaries can be seen outside the galaxy to a distance of 100 kpc (curve f in **Figure 5**) with frequencies above $3x10^{-2}$ Hz, though there is only about a 10% chance of such an extragalactic binary.
- Intermediate mass ratio inspirals (IMRI's) where one component is an intermediate mass black hole (IMBH) are also visible but the rates are more uncertain. IMRIs have been inferred from X-ray observations; however, there are large uncertainties in their abundance. This configuration could detect, for example, an IMRI with a 10^4 M_s BH and a 1 M_s compact object to a distance of 40 Mpc (curve e in **Figure 5**).

There are a number of potentially revolutionary sources that could be detected including network of cosmic strings with Gμ ~ 10^{-13}, three orders of magnitude below the current limits from pulsars (**Figure 6**). Other stochastic sources such as first order phase transitions in the early universe and reheating may be observable if they are strong and in the frequency band between approximately 10^{-3} and 1 Hz which translates into phase transitions in the early universe at scales of ~100 GeV - 100 TeV.

Such merger observations will allow the single flyer configuration to test strong field gravity and the near horizon geometry of black holes including the "no hair" theorem. It will also allow the study of the astrophysics of these compact objects and their mergers and the study of structure formation from the cosmological mergers of massive BH's. Binary mergers may also give a precise, gravitationally calibrated measure of luminosity distance, useful in precision cosmology tests. Further, it can detect cosmological sources giving a direct probe of the early universe before last scattering.

The multiple flyer configuration has a strong sensitivity with a baseline of just 500 km, allowing observation of almost any source observable with the original LISA design, as well as essentially any binary observable with Advanced LIGO (even before it appears in Advanced LIGO), plus a large number of other sources with frequencies in the intermediate band between 10^{-2} Hz and 10 Hz. Importantly, known "verification" binaries such as HM Cancri (point "g" in **Figure 5**) are visible to this detector. It will detect IMRI's with almost any masses. For example an IMRI with 10^3 M_s and 1 M_s components can be seen to 4 Gpc giving a rate estimate of roughly 80/yr. Frequencies above 10^{-1} Hz are the lowest that avoid white dwarf confusion noise, making this an ideal band for searching for stochastic cosmological sources. This configuration could even begin to probe or constrain gravitational waves from inflation if it occurs around the grand unification scale 10^{16} GeV (the maximum allowable), a long-sought goal for gravitational wave detectors (**Figure 6**). If the sensitivity can be increased

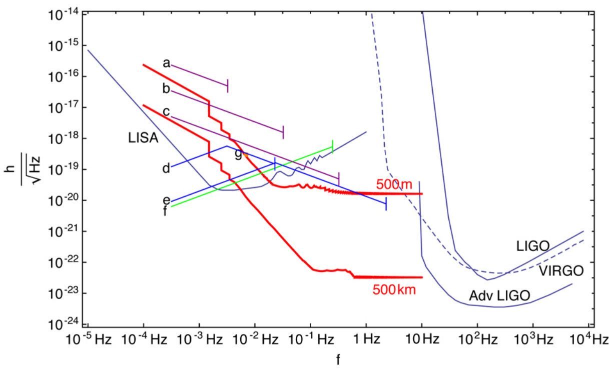

Figure 5: Sensitivity of single flyer ("500 m") and long-baseline ("500 km"). "a", "b", and "c" are massive BH binaries with pairs of objects with 10^7, 10^6, and 10^5 solar masses respectively at redshift z = 0.5. "d" is a BH binary with 10^6 and 10 solar mass components at 0.65 Gpc. "e" is a binary with 10^4 and 1 solar mass components at 40 Mpc. "f" is an extragalactic white dwarf binary at 100 kpc. "g" is HM Cancri.

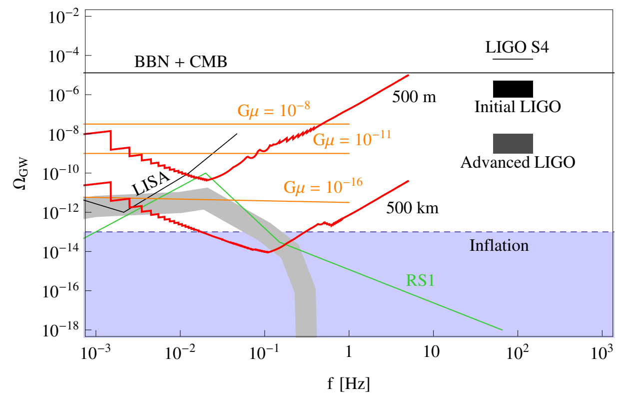

Figure 6: An example GW spectrum from a TeV scale phase transition in an extra-dimensional model is shown ("RS1"). Curves "Gμ" are spectra from networks of cosmic strings with given tension. The top of the "inflation" area is the maximal strength of the GWs produced during inflation.

past the level of the 500 km baseline configuration, even lower scales of inflation can be probed. Further, many models of reheating after inflation produce gravitational waves observable with this configuration. Networks of cosmic strings are visible with string tensions as small as $G\mu \sim 10^{-18}$ and possibly smaller. This would also be an excellent probe of TeV scale first-order phase transitions in the early universe. Such a gravitational wave detector would thus not only provide valuable information on astrophysics and gravitation, it would also directly probe early universe cosmology and, through this, the high energy frontier of physics, far above what any collider can achieve.

4.0 Enabling Technology Description And Instrument Overview

In the *InSpRL* instrument, gravitational radiation is sensed through the gravity wave-induced phase shifts on the propagation of laser beams between two spatially separated, inertially isolated, laser-cooled atomic ensembles. Momentum recoil associated with the coherent interactions between the laser and atomic ensembles results in the concomitant interference of atomic wavepackets. Functionally, the atomic ensembles serve as precision wavefront sensors for the optical fields. Given the quantum nature of the interaction between the atom and the light field, the proposed configuration naturally evades quantum measurement noise and amplifies/multiplies the single pass gravitational wave-induced optical phase shift.

Laser cooling methods are employed to periodically prepare the ensembles of atoms which serve as inertially isolated proof-masses. In this method, atoms are manipulated through controlled momentum exchange between a laser light field and the atomic ensemble. The interaction results in production of ensembles of $\sim 10^{10}$ atoms nearly at rest, at low density ($<10^8$ atoms/cm^3), and mechanically decoupled from the apparatus housing. The envisioned ensemble kinetic temperatures are associated with rms velocity spreads at or below 100 micrometers/sec. Spurious forces on the atomic ensembles, due to magnetic field gradients, electric field gradients or gravitational gradients are readily controlled at levels below those required to achieve the envisioned instrument sensitivities. The methods for achieving such sources are largely understood and continuing to improve. They have been the subject of engineering refinements for numerous defense and national security applications, including ground-based atom interferometric gyroscopes, accelerometers, and clocks, and they have been integrated into truck-based mobile accelerometers and also airborne accelerometers.

Because the physical properties of the atoms (e.g,. polarizability, magnetic moment) are calculable and regular, it is straightforward to specify the environmental requirements necessary to achieve the specified degree of inertial isolation. Furthermore, interactions with spurious high energy particles do not lead to a collective modification of the properties of the ensemble. Rather, in contrast to macroscopic proof-masses, they are responsible for deletion of individual atoms from the ensemble, but do not effect the aggregate properties of the ensemble. This obviates the need, for example, to consider effects such as proof-mass charging. We expect that it will be possible to verify that the required levels of inertial isolation are achievable using a ground-based apparatus. Currently, ground-based limits are at the 10^{-11} g level. In the coming year, Stanford experiments expect to push this to 10^{-15} g. In the envisioned detector configuration, gravitational gradient perturbations are controllable, as the atom ensembles are positioned at significant offsets from massive nearby objects (e.g., the spacecraft bus), and since the relative motion between the bus and the atom clouds is expected to be stable.

A sequence of light pulses driving stimulated transitions between atomic ground-state levels is responsible for the division, redirection and finally recombination of atomic wavepackets. During this process, the phases of the optical fields gets read into the atomic coherences in such a way that they essential record the change in the phase of the optical field between successive pulses in the sequence. It is these changes which are the ultimate origin of the gravitational wave sensitivity of the instrument. By using the same laser beams to drive these transitions between two spatially separated ensembles, global fluctuations in the phase offsets of the optical fields enter as a common mode phase shifts between the two ensembles. Higher order phase asymmetries, resulting diffraction of the optical fields as the propagate, set limits on the phase front homogeneity of the laser beams.

A crucial aspect of the optical interaction is that the momentum exchange between the atom and the light field is regularized by the quantum nature of the interaction. In particular, only a fixed number of photons is scattered by an individual atom over the course of the interferometer interrogation sequence. This is in contrast with the scattering of light from an optical element in a conventional optical interferometer; in the case of a classical interferometer, there is an intrinsic uncertainty in the momentum exchanged with the optical element which ultimately translates into an uncertainty in the momentum of the proof-mass (back-action noise), and which manifests as a noise source.

During each pulse interaction, simple application of the Schroedinger equation governing the atom/field interaction indicates that the phase of the optical field at the (mean) position of the atomic wavepacket is read into the atomic coherence. This phase manifests itself in the probability of finding the atom in a particular state following the atom optics sequence, and observation of this (transition probability) with a detector constitutes measurement of this phase. An important feature of the proposed atom optics sequences is that they are composed of suitably configured trains of pulses which read this phase into the coherence multiple times, thus providing a mechanism for phase amplification/multiplication. Properly implemented, this dramatically improves that performance of the interferometer over that which can be achieved with the simplest (previously demonstrated) sequences. Very recently, we have demonstrated 102 photon recoil momenta large momentum beamsplitter using a multiple two photon Bragg process. This amplification of momentum corresponds to a phase amplification of a factor of 100. For the envisioned detectors, this amplification factor can be 1000 or more.

It is important to emphasize that the ideas discussed above can all be studied and verified in a ground-based apparatus.

5.0 Environmental Effects for Space Demonstration

There are two classes of environmental effects: effects that reduce the instrument sensitivity and effects that introduce spurious interferometer phase shifts. In the first case, mechanisms that result in atom loss leading to a lower interferometer Signal to Noise Ratio (SNR) and a degradation in instrument sensitivity. While atom loss should be minimized, these effects do not result in confounding background signals. In contrast, any effect that induces spurious phase shifts must be tightly controlled at a level exceeding the weakest target science signal. In particular, the atoms must be protected from time-dependent, environmentally-induced phase shifts that have oscillation periods in the measurement band, since these can mimic a gravitational wave.

Collisions with particles in the background gas due to imperfect space vacuum cause atom loss, reducing instrument sensitivity. At an altitude of 700 km the average time between collisions of an atom with the residual background gas of Earth's atmosphere is 100 s[1]. Therefore the quality of space vacuum does not present a limit for a mission in super GEO, since the collision rate is even smaller at higher altitudes. Outgassing from the satellite itself must be engineered within the atom interferometry region so as to maintain an ultra-high vacuum environment.

The atoms must be protected from sunlight. The scattering rate of sunlight for Rb at 1 AU is 10 s^{-1}, which is sufficient to cause complete loss of the ensemble[2]. A lightweight sunshield (sock) covering the booms can eliminate this loss mechanism. Additionally, protons and electrons from the solar wind can cause atom loss. However the mean collision time between an atom and a solar wind particle is greater than 1000 s[2], so the solar wind is not a concern.

The magnetic field in space and its gradient can cause spurious phase shifts by inducing a second order Zeeman shift of the atom's energy level. A calculation using the "World Magnetic Model 2010" for a 500 km baseline instrument in LEO shows that this effect is negligible[1]. The effect scales with the spatial variation of the field across the instrument, and so it is smaller for shorter baselines. In super GEO the effect is even more suppressed since the magnetic field and its gradient are reduced by 200 and 1000 times, respectively[3]. In either case, temporal variations of these phase shifts occur at orbital frequencies which are well outside the target band.

Inertial forces experienced in orbit are the origin of a number of susceptibilities to noise and spurious signals. Gravitational gradients and rotational effects such as the Coriolis force result in phase shifts that depend on the atomic trajectories, enforcing tight constraints on the stability of the initial atom kinematics. These effects can be mitigated in LEO by appropriate choice of the interferometer geometry (e.g., five pulse sequences)[1]. In super GEO, inertial forces are less important since the Earth's gravity gradients are smaller by a factor of 10^3 and the rotational frequency is 14 times smaller. This is even less of an issue for earth trailing or L2.

The gravity gradients from the satellite bus and boom can cause spurious signals due to motion of the structures with respect to the atoms. Gradients from the bus are mitigated by keeping the atom trajectories away from the bus, or by ensuring that it is inertially quiet[1]. Gravity gradient effects from the booms have not been thoroughly evaluated, although longitudinal gradients are naturally suppressed because of the boom aspect ratio. This analysis will be informed by better modeling of boom dynamics.

Aberrations of the interferometer laser wavefront must be tightly controlled. Intrinsic wavefront imperfections of the laser can be mitigated using a mode cleaning cavity[4]. Mechanical vibrations of the primary telescope mirror as well as thermal fluctuations of the mirror substrate induce dynamic wavefront aberrations that add to the instrument noise. Preliminary considerations for 200 photon recoil Large Momentum (LMT) atom optics suggests that dynamic aberration noise can be suppressed to the required level with a 300 K SiC mirror[1]. Static wavefront aberrations are another source of instrument noise when coupled to satellite vibration. Static wavefront requirements depend on the satellite and boom stability but are estimated to be around lambda/100[1]. For a fixed strain sensitivity, wavefront requirements are more demanding for an instrument with a shorter baseline since it requires higher LMT atom optics to compensate.

6.0 Technology Development Roadmap

The technology development process for space based atomic interferometry builds upon the successful development of ground based atomic interferometry hardware. This ground hardware has already demonstrated most of the basic technologies of atom trapping and interferometry. The basic plan for technology development is shown below in **Figure 7**. As seen in this figure, we anticipate architecture studies will go in parallel with continued technology development in an iterative fashion.

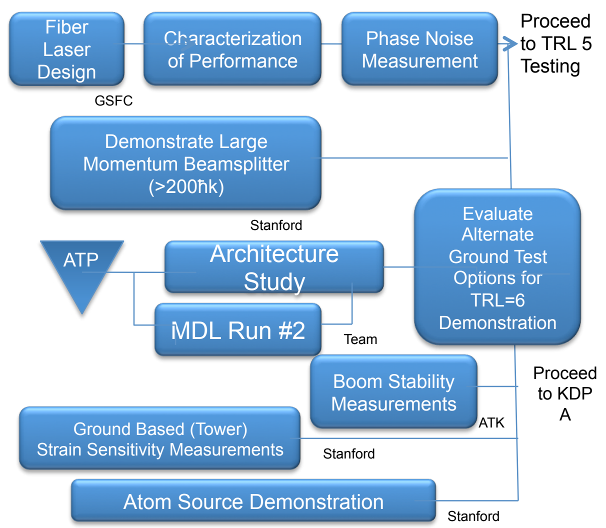

Figure 7: Technology Maturation Plan.

Our assessment of TRL (**Table 2**) is driving our technology development program (**Figure 7**). That is, we are emphasizing the rapid maturation of low TRL items to level 6.

Table 2: Technology maturity (TRL) of *InSpRL* Elements.

Technology Element	TRL
Laser System	5
Atom Source	3
LMT	3
Wave Packets Separation	3
Boom System (500m)	4
100m Boom	7
Formation Flyer	7

7.0 Study and Mission Budget

Earlier this year, the Stanford/GSFC/AOSense team conducted a Mission Design Laboratory (MDL) study of a 300 meter boom antenna approach. The study assumed the emerging SpaceX Falcon launch vehicle, and the cost of this mission was determined to be $444M, including the ELV estimated cost, and 30% reserve on hardware elements. The Estimate was based on PRICE-H and SEER-H except the boom and ELV that are vendor estimates. However, there were several assumptions made during this initial assessment, and we have a significantly better understanding of several of the architecture considerations. Therefore, we would propose to perform a follow-up study after the next iteration of the concept in the MDL, or equivalent. The team has not performed a rigorous mission study of a multiple spacecraft approach, which our simulations herein show is more scientifically powerful than a boom approach, though likely at higher cost. Therefore, we would propose two separate MDL studies, a primary one for the separated spacecraft architecture, and a second to compare and contrast this approach with that of the single boom configuration:

- **Study 1:** Assessment of a 2 spacecraft solution with a baseline optimized for the HM Cancri source. A key goal of this study will be to assess the relative cost of this approach relative to a boom-based architecture, and to determine which cost bin applies
- **Study 2:** Assessment of the boom concept using the fiber laser system as now understood, and including pre-work on error budgets, dynamics of the boom, and pointing options.

In constant year 2012 dollars, for the single spacecraft boom configuration, based on our previous Mission Design Lab study in the winter of 2010 using PRICE-H and SEER-H and 30% reserve on all hardware elements. We had estimated $444M through launch and one year of operations. Although premature, the costing for the separated spacecraft mission would be similar in terms of profile and relative funding per year requirements; however, the mission cost ROM is $678M, and would be refined in the next Design Center iteration. The upper end of the range is twice the cost of one spacecraft and the lower number assumes one ELV and similar satellites with simpler instruments.

8.0 Summary

Space-based gravity wave detectors based on today's advanced, mid-TRL atom optics technology potentially affords the astronomy and astrophysics communities a unique opportunity to conduct the observing campaigns that they desire at lower cost and risk. However, this value proposition must be critically examined by an interdisciplinary team of space scientists and engineers, and we hope to get the opportunity as a result of this RFI. Our early design center exploratory analyses indicate the promise of this new approach, but much needs to be done. Meanwhile, the laser system, a crucial part of the GW detector apparatus, must be assembled and tested in the laboratory before we apply funds necessary to space-qualify the components. Leveraging off a strong telecom-enabled US vendor base, we feel confident that our fiber laser approach, or some variant of it, will deliver the necessary narrowline output power.

The separated spacecraft configuration has a tremendous sensitivity, even with a baseline of just 500 km, allowing observation of almost any source observable with the original LISA design, as well as many of the sources observable with Advanced LIGO. Additionally, it promises a large number of other sources with frequencies in the intermediate band between 10^{-2} Hz and 10 Hz. Importantly, known "verification" binaries such as HM Cancri are available to this detector. Additionally, the technology of formation flying has been flown in 2010 (European PRISMA *http://www.prismasatellites.se/?id=16291*) and demonstrated formation flying to a level consistent with our requirements.

This configuration is capable of going beyond the legacy system and could even begin to probe or constrain gravitational waves from inflation if it occurs around the grand unification scale 10^{16} GeV (the maximum allowable), a long-sought goal for gravitational wave detectors. If the sensitivity can be increased past the level of the 500 km baseline configuration, even lower scales of inflation can be probed. Further, many models of reheating after inflation produce gravitational waves observable with this configuration. Networks of cosmic strings are visible with string tensions as small as $G\mu \sim 10^{-18}$ and possibly smaller. This would also be an excellent probe of TeV scale phase transitions in the early universe. Such a gravitational wave detector would thus not only provide valuable information on astrophysics and gravitation, but it would also directly probe early universe cosmology and, through this, the high energy frontier of physics, far beyond what any collider can achieve.

This technology is sufficiently powerful, and the uncertainties in the model predictions understandably large, that continued study of the single platform-deployable boom approach is warranted, and may in fact offer a low cost first step to the free flyer architecture. For example, the boom configuration can probably operate with the light in a high finesse cavity. This build-up cavity will spatially filter the laser wavefronts, ease the atomic physics constraints due to spontaneous emission, and permit faster lattice manipulations.

The AI detector seemingly scales gracefully to achieve the particular performance needed for the desired GW or cosmological science. This architecture lends itself to scaling in other ways besides performance, too; that is, in terms of cost and cost risk. The "go forward" approach needs to be optimized appropriately for all programmatic and technical dimensions. At this point in our understanding, both approaches appear viable. Thus, this enabling technology affords the community potential solutions in two of the three cost bins mentioned in the RFI, namely the lower bin ($444M) for the boom configuration, based on our earlier GSFC Mission Design Lab (MDL) study cost ROM using PRICE-H, and the high end of the middle bin ($678M) for the formation flyers, based on engineering judgment and scaling from the one spacecraft estimate. Both estimates are including a 40% reserve on instrument payload, 30% reserve on all other hardware elements except the ELV with 0% and the Two S\C hardware reserve of 35% see **Table 3** Clearly, the cost realism for both configurations would be improved with this next MDL (or equivalent) run. In each case an estimated $45M is necessary to elevate the TRLs in advance of the mission ATP.

The *InSpRL* Science Team stands ready to support the Physics of the Cosmos (PCOS) Program with further mission and systems studies, along with the results of our current laser brassboard efforts, both at GSFC and at Stanford University.

9.0 References

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Table 3: Mission Budget for One and Two Spacecraft Configuration (preliminary for planning purposes only).

WBS Element	Total Phase A-F	Contingency (%)	Total w/ Contingency Boom	Total Two S/C	Contingency (%)	Total w/ Contingency Two S/C
1. Project Management	13.9	30	18.1	23.8	30	30.9
2. Systems Engineering	13.9	30	18.1	23.8	30	30.9
3 Safety and Mission Assurance	8.7	30	11.3	14.8	30	19.2
4. Science and Technology	11.3	15	13.0	19.2	15	22.1
5. Payload	50.0	40	70.0	50.0	40	70.0
6. Flight System	124.0	30	161.2	248.0	35	334.8
7. Mission Operations	12.3	30	16.0	20.7	30	26.9
8. Launch Vehicle	125.0	0	125.0	125.0	0	125.0
9. Ground System	3.2	30	4.2	5.6	30	7.3
10. Systems Integration and Testing	4.1	30	5.4	7.1	30	7.0
11. Education and Public Outreach	1.7	15	2.0	3.0	15	3.5
		Total:	**444.3**		**Total:**	**677.6**