Drag-Free Atomic Disturbance Reduction System for LISA-like Gravitational Wave Detection

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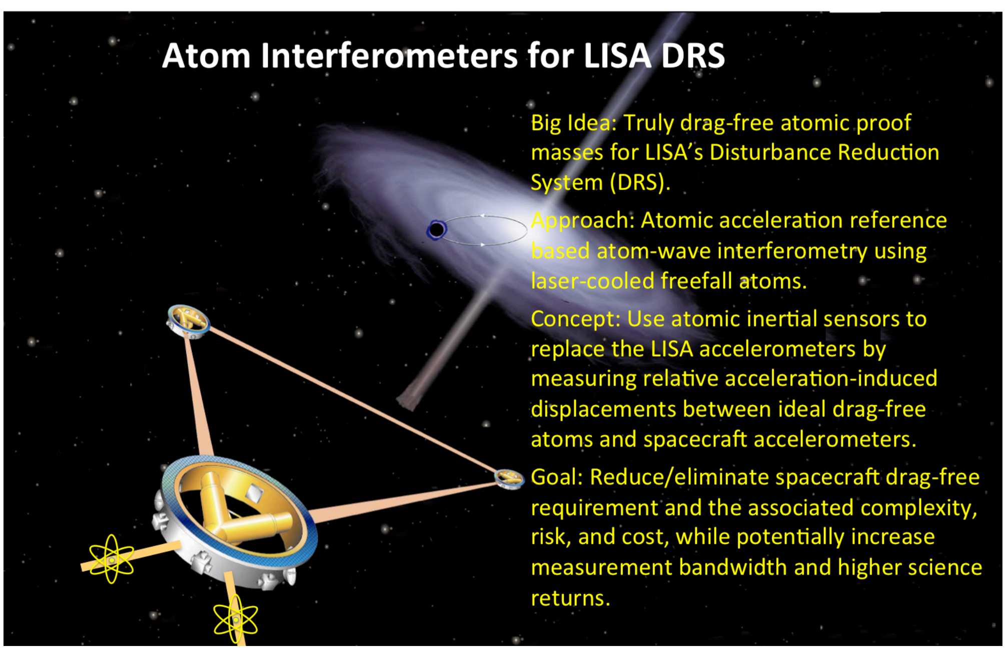
Category of response:
- Instrument concept – Atomic drag-free accelerometers using atom interferometer techniques for the disturbance reduction system (DRS) in LISA-like missions.
- Enabling technologies – Atom interferometers for precision inertial force measurements in space without cryogenics and drag-free satellites.

Answer to these questions:
- Yes, we are willing to participate and present your concept at the workshop if invited.
- Yes, certain detailed technical information requires appropriate document clearance and may be subject to export control. We are willing to discuss this information with NASA if proper arrangements can be made to protect the information.



Introduction

The advent of laser cooling of atoms has led to an explosion of research activities over the last two decades that enable the ability to manipulate atoms and exploring their quantum nature. Of potential technological importance to a variety of research areas is the realization of atom-wave interferometers based on cold atoms and the potential for achieving sensitivity well beyond the current state-of-the-art for certain inertial force measurements, including gravitational wave detection.

Because cold atoms can be prepared in an essentially drag free state they can be used as nearly ideal proof-masses in atom interferometers to detect inertial and gravitational forces. The ability to precisely manipulate atoms with laser fields allows detection of exceedingly small motional changes in atomic sensors without the need for cryogenics or mechanical moving parts.

Already, there have been extensive discussions of using atom interferometers for gravitational wave detection [1] as well as proposed new mission concepts [2][3]. On the other hand, atomic drag-free proof masses can also be used to replace the accelerometers in the LISA-like mission architecture, addressing the most challenging aspect of the current LISA mission [4]. ***This approach basically substitutes the LISA DRS with atomic inertial sensors. The overall architecture, observing mode, and science performance of the mission remain the same.***

In this RFI, we will first describe the gravitational wave detection in general, putting contexts in perspective. We will then briefly describe light–pulse atom interferometers and their application as inertial sensors. Finally, we will discuss drag-free atomic acceleration reference [5]. Further information on both concepts is provided in Appendix.

Gravitational detection methods

The detection of gravitational radiation is one of the most challenging efforts in physics in this century. A successful observation will not only represent a great triumph in experimental physics, but will also provide a new observational tool for obtaining better and deeper understandings about its sources, as well as a unique test of the proposed relativistic theories of gravity [6].

Non-resonant detectors of gravitational radiation (with frequency content $0 < f < f_0$, where f_0 is some upper frequency cut-off) have one or more arms with coherent trains of electromagnetic waves (of nominal frequency $\nu_0 >> f_0$), or beams, and at points where these intersect, relative fluctuations of frequency or phase are measured (homodyne detection). Frequency fluctuations in a narrow Fourier band can alternatively be described as fluctuating sideband amplitudes. Interference of two or more beams, produced and monitored by a (nonlinear) device such as a photodetector, exhibits these sidebands as a low frequency signal again with frequency content $0 < f < f_0$. To observe these gravitational fields in this way, it is necessary to control all other sources of relative frequency fluctuations.

In present single-spacecraft microwave Doppler tracking observations, for instance, many of the noise sources can be either reduced or calibrated by implementing appropriate frequency links and by using specialized electronics, so the fundamental limitation is imposed by the frequency fluctuations inherent to the reference clock that controls the microwave system. By comparing phases of split beams propagated along equal but non-parallel arms, common frequency fluctuations from the source of the beams can be removed directly and gravitational wave signals at levels many orders of magnitude lower can be detected. Especially for interferometers that use light generated by presently available lasers, which have frequency stability of roughly a few parts in $10^{13}/\sqrt{Hz}$ to $10^{15}/\sqrt{Hz}$ (in the millihertz and kilohertz bands respectively), it is essential to be able to remove these fluctuations when searching for gravitational waves of dimensionless amplitude less than 10^{-20} in the millihertz band, or down to 10^{-21} – 10^{-23} desired in the kilohertz frequency band. Combined with the fact that plane gravitational waves have a spin-two polarization symmetry, this implies that the customary right-angled Michelson configuration is optimal. The response to gravitational waves is then maximized in Earth-based systems by having many bounces in each arm [7].

The frequency band in which a ground-based interferometer can be made most sensitive to gravitational waves [6] ranges from about a few tens of Hertz to a few kilohertz, with arm lengths ranging from a few tens of meters to a few kilometers. Space-based interferometers, such as the coherent microwave tracking of interplanetary spacecraft [8] and the proposed Laser Interferometer Space Antenna (LISA) mission are most sensitive to millihertz gravitational waves and have arm lengths ranging from 10^6 to 10^8 kilometers.

The specific measurement frequency band for LISA has been optimized for science returns [4]. This also makes LISA one of the most challenging mission concepts. As detailed in the LISA mission studies, *there are two critical but high-risk technologies that the LISA mission will have to rely on to achieve the science objectives: precision laser interferometer measurements of displacement and drag-free accelerometers as proof masses with minimum force disturbances.* The displacement measurements require a pm/Hz$^{1/2}$ noise floor. This by itself is not extremely challenging except that it is done at millions of kilometers distance and the laser phase noises have to be cancelled by a time-delayed interferometers (TDI) scheme [9] with equal arm-length interferometer configurations. At such large distances, the received laser power will be limited and the measurement noise is therefore limited by the photon shot noise. On the other hand, the noise reduction of accelerometer disturbances is considered a more challenging task. Not only does it require a drag-free controlled spacecraft, but any parasitic forces on the proof mass can result in acceleration errors. These parasitic forces include electric charges, magnetic fields, and static or varying local gravity gradients. The gravity gradient noise demands a stringent spacecraft mass distribution and thermal design. Even with the most careful compensation and stabilization designs, the drag-free control has to be at the nm/Hz$^{1/2}$ level in order to achieve the required accelerometer noise performance of $10^{-15}/f^2$ m/s^2/Hz$^{1/2}$. Such level of control has yet been demonstrated. Even the LISA pathfinder mission will only have a technology demonstration within ×10 of the LISA requirement [10].

The main point of this RFI is that free fall cold atoms offer an attractive alternative to the traditional drag-free proof masses. Atom wave interferometry allows precision measurements of the atom proof mass displacements and accelerations. The implementation of the drag-free atomic proof masses can drastically simplify the disturbance reduction system in a LISA-like gravitational detection mission architecture.

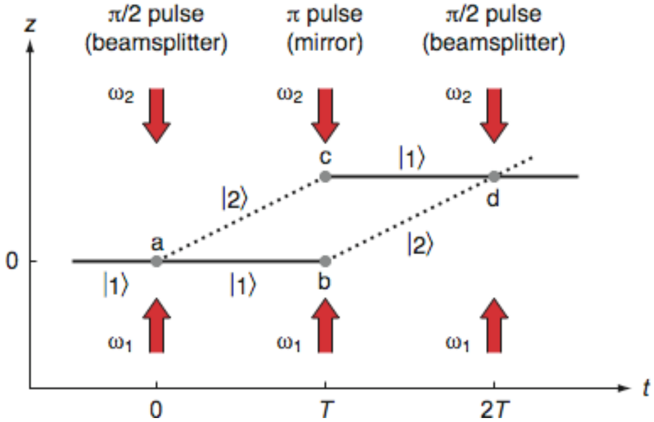
Atom interferometer technique

The concept of atom interferometer has been around for some time. In fact, J. Clauser proposed using an atom interferometer as space inertial sensors in 1988 [11]. This idea could not have been fully realized until subsequent advances in laser cooling and manipulation of atoms. Dr. S. Chu's group at Stanford first experimentally demonstrated the measurement of g using a light-pulse atom interferometer in 1992 [12]. The approach of the new inertial force measurement technique is drastically different from conventional mass-spring oscillator configurations. The fundamental concept behind atom interferometry is the quantum mechanical particle-wave duality. One can exploit the wave-like nature of atoms to construct an atom interferometer based on matter waves analogous to laser interferometers. Because of the finite mass of the atom, atom wave interferometers are extremely sensitive to the gravity influence. This great advantage can be appreciated by the fact that the atom interferometer has an inherent inertial-sensing sensitivity that is more than 10 orders of magnitude (the ratio of the atomic mass and photon energy) greater than an equivalent laser interferometer [11].

The basic principles of atom interferometry have been discussed extensively in literature [13]. We will only give a brief description here to facilitate the discussion in this paper.

Before discussing the light-pulse atom interferometer scheme, we should first point out that cold atoms are typically used in implementation. Atoms are first collected and cooled by lasers into a small cloud in a magneto-optic trap (MOT). The MOT, consisting of three pairs of counter-propagating laser beams along three orthogonal axes centered on a non-uniform magnetic field, collects a large assemble of cold atoms, typically 10^9 atoms in laboratory experiments. After these atoms are collected, further laser cooling brings the atoms' temperature down to 1–2 μK, corresponding to an rms velocity of a few cm/s, before being let free fall. In space of microgravity, one can take advantage of long free fall time. Therefore, atoms must be much colder than those typically used in the ground experiments. There are existing methods that produce ultra-cold atoms, i.e. Bose-Einstein condensate gas .

The most maturely demonstrated cold atom interferometers use laser-induced stimulated Raman transitions [12,13] to split and recombine atom waves; they are equivalent of atom optics without physical splitters and mirrors. As illustrated in Fig. 2, the atom interferometers are realized by using a $\pi/2$–π–$\pi/2$ laser pulse sequence to drive velocity-sensitive stimulated Raman transitions between the two ground hyperfine states in alkaline atoms. The first $\pi/2$ pulse at time t_1 creates an equal superposition of atoms in the two hyperfine ground states. Only the excited state receives a photon recoil kick and therefore travels at a slightly different velocity, realizing a beam splitting analogous to that in a traditional Mach-Zehnder interferometer. Subsequent π and $\pi/2$ pulses at times $t_2 = t_1 + T$ and $t_3 = t_1 + 2T$, respectively, similarly redirect and recombine the atom waves to complete an interferometer loop, as illustrated in Fig. 2. The transition probability resulting from this interferometer sequence is given by $P = ½[1 - \cos(\Delta\phi)]$, where $\Delta\phi$ is the net phase difference between the two interferometer paths. This phase difference can be calculated from the Raman laser phases at the time and location of each interaction, *i.e.* $\Delta\phi = \phi(t_1, z_1) - 2\phi(t_2, z_2) + \phi(t_3, z_3)$. The phase shift $\Delta\phi$ is related to the acceleration $\mathbf{a}$ according to $\Delta\phi = \mathbf{k_{eff}} \cdot \mathbf{a}T^2$, where T is the time between pulses and $\mathbf{k_{eff}} \equiv \mathbf{k_1} - \mathbf{k_2} \approx 2\mathbf{k_1}$ is the effective Raman laser wave number. The atom interferometer phase shift can be measured by detecting the relative populations of the two hyperfine ground states via laser-induced fluorescence.



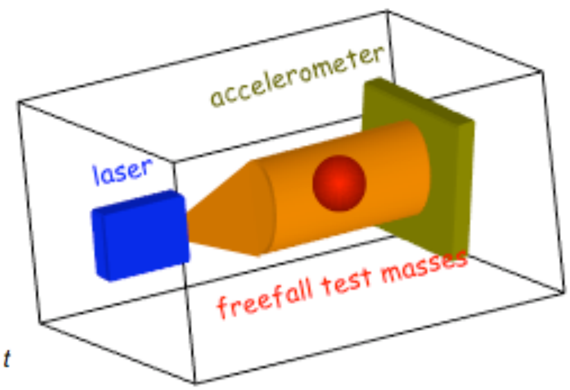


Fig. 2. Light-pulse atom interferometer diagram (left) and configuration illustration of atom interferometer acceleration measurements relative to a retro-reflecting mechanical accelerometer (right).

It should be emphasized that the acceleration measured in this way is that of atoms relative to the instrument reference platform. In this case of the stimulated Raman method discussed here, it is the retro-reflecting mirror that produces the counter-propagating Raman laser beam, as shown in Fig. 2.

In general, one can show that the acceleration-induced atom interferometer phase shift is given by $\Phi_{AI}=NkaT^2$, where N is the number of photon momentum transfer in the atom interferometer. In the above described atom interferometer with a pair of stimulated Raman photons, $N = 2$. A large momentum transfer (LMT) interferometer of $N = 24$ has been demonstrated [14], while $N = 100$ has been also demonstrated in a different experiment [15]. N=1 allows an interesting one-arm interferometry detection scheme [3].

For a constant acceleration, $1/2aT^2$ is the acceleration-induced displacement x_a. Therefore, we can rewrite $\Delta x_a = (\lambda/4\pi N)\,\Phi_{AI}$. With typical optical wavelength of 1 μm, $N = 2$, and an achievable phase resolution of 100 μrad, the equivalent displacement resolution reaches pm, well within the required LISA displacement measurement sensitivity. On the other hand, for cold atoms in free space, the interaction time is not unlimited. Nevertheless, a free evolution time of tens of seconds is possible [16, 17].

On the ground, however, the interaction time is much more limited. For a typical laboratory apparatus, T would be a fraction of a second. Nevertheless, impressive acceleration and gravity measurement sensitivities have been demonstrated. A laboratory measurement demonstrated a resolution of $3 \times 10^{-9}g$ after 60 s and $1 \times 10^{-10}g$ after two days integration time [18]. More recent demonstration shows sensitivity at $4 \times 10^{-9}g/\mathrm{Hz}^{1/2}$ [19]. Efforts are being made to bring this technology to space for Earth gravity field measurements [17] and tests of fundamental physics [20].

Recently, atom-wave interferometers have been proposed as potentially new gravitational waves detectors, as their technology has reached a high-level of maturity in providing extremely sensitive inertial sensors. The discussions on how to use atom interferometers as gravitational wave detectors have mainly focused on two fundamental types of proposed approaches. The first relies on exploiting the atom wave and the interferometers directly [1]. In this scheme, atoms in an atom-wave interferometer correspond to photons in a Michelson laser interferometer, and the effects of a gravitational wave signal are measured by monitoring the phase (momentum) changes of the atoms due to the GW. Although this design has been shown of not providing any sensitivity improvements over optical interferometers, it stimulated more thoughts on the subject. The result was an alternative design in which atom interferometers are used as local inertial sensors and laser beams imprint on the atoms the phase fluctuations generated by a gravitational wave signal propagating across the detector [1-3]. This approach is fundamentally the same as using atom interferometers for gravity gradient measurements, which has been pursued both on the ground and in space.

Here we propose an approach to replace the LISA accelerometers with atomic acceleration references. This concept takes full advantage of the well-developed LISA mission concept, yet addresses the risk of DRS, the most technically challenging part of the LISA mission. By using atomic drag-free proof masses, the original LISA DRS can be significantly simplified, which leads to low risk and cost savings.

Drag-free atomic disturbance reduction system

In 2006, we proposed and demonstrated a way to combine an atom interferometer and a mechanical accelerometer in an integrated system through simultaneous measurements [5]. This technique employs a compensation feed-forward control for error readout, see Fig. 3. A mechanical accelerometer will be used for short-term, high bandwidth measurement while the atom interferometer accelerometer provides calibration reference and error correction to the mechanical accelerometer. The arrangement is inspired by precision atomic clocks where a flywheel local oscillator is compared with an atomic transition at a narrower bandwidth and locked to the atomic transition frequency for highly long-term stability.

There are various ways that can be used to incorporate the two types of accelerometers together. The central idea for this implementation is the following. A mechanical accelerometer is mounted on a platform whose acceleration is to be measured. At the same time, the inertial reference point (a retro-reflecting mirror in the atom interferometer accelerometer) is rigidly mounted to the same platform or to the test mass of the mechanical accelerometer. Simultaneous measurements are made and various schemes can be used to compare and extract acceleration measurement data.

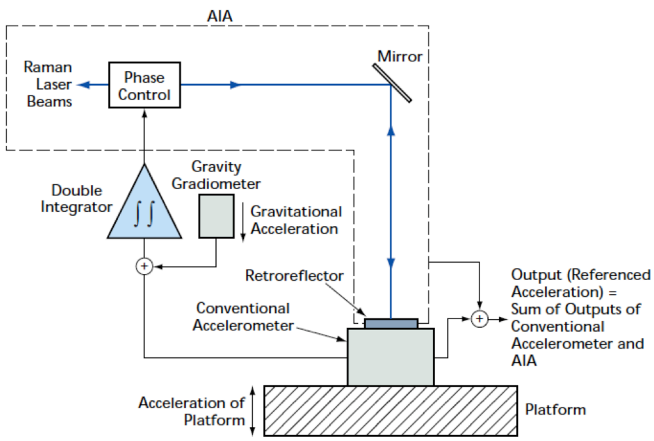


Figure 3. Illustration of atom interferometer accelerometer as atomic acceleration reference.

In one particular implementation, a phase compensation scheme will be used (Fig. 3). In this scheme, a mechanical accelerometer is mounted on the platform under measurement. The inertial reference mirror of AI is rigidly attached to the platform (or the accelerometer) such that it has the same acceleration as the platform. In operation, the acceleration measurement by the mechanical accelerometer is converted to the equivalent atom interferometer phase shift through a double integrator. (A seismometer can also be used here and a simple integration will be sufficient in that case.) The equivalent phase shift is then fed back electronically to the atom interferometer phase control to cancel out the measured acceleration-induced phase shift in the atom interferometer. Clearly, if both mechanical accelerometer and the feedback were perfect, the atom interferometer would have a null phase shift. In practice, any residual acceleration seen by the atom interferometer accelerometer will then be the correction signal to the mechanical accelerometer measurement.

In the special case of space application, a truly drag-free mass is required. The necessary drag-free measurement (accelerometer) and control have back actions on the proof mass, which amount to an equivalent accelerometer error. The atom interferometer accelerometer can then be used to detect the small non-drag-free motion. In such cases, the atom interferometer inertial reference point will be on the spacecraft accelerometer. The residual acceleration measured by the atom interferometer is then the disturbance deviations from an ideal drag-free accelerometer. *In this implementation, the sensitivity and control of the spacecraft accelerometers only need to be in the dynamic range of the atomic sensors, which is a factor of 1000*. An implementation concept for LISA is illustrated in Fig. 4. More detailed descriptions are given in the presentation slides in the Appendix.

The equivalent strain sensitivity for LISA is given by

$$S_h(f) = \frac{\sqrt{2}}{(2\pi)^3 N} \cdot \frac{\lambda}{L} \cdot \left(\frac{\sqrt{T}}{f^2 T^2} \right) SNR$$

where $\Delta\Phi_{AI}$ is the AI phase measurement, λ AI laser wavelength, N is the number of photon momentum transfer in AI, and T the AI interrogation time (about half of the measurement time).

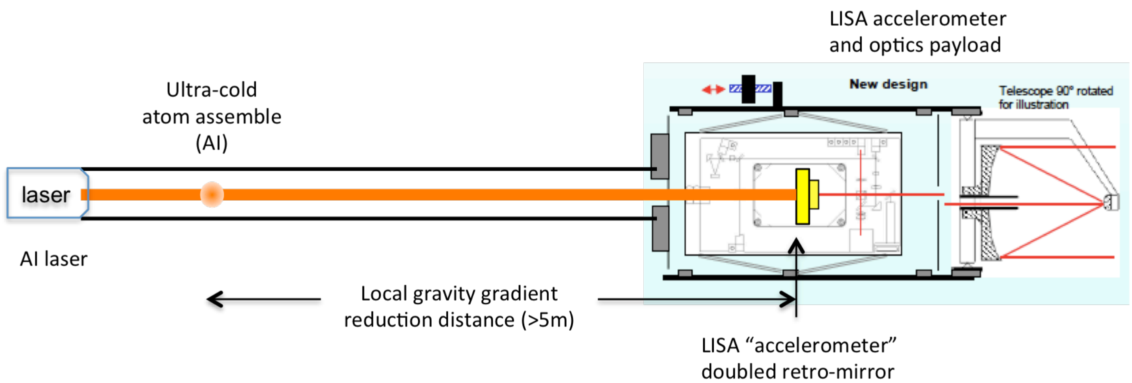


Figure 4. Atomic acceleration reference for LISA spacecraft accelerometer using atom interferometer (AI).

For an estimate of the atom interferometer displacement readout sensitivity, we can assume an interferometer phase noise of $140(T)^{1/2}$μrad/Hz$^{1/2}$ (limited by the atom shot noise of 10^8 atoms), N = 20 (as already demonstrated in laboratory), and the interrogation time T = 10 s. This will give us the strain readout spectrum of $S_h(f)=2 \times 10^{-25}/f^2$, which meets the LISA accelerometer performance requirement.

Note that the atom interferometer time T can be varied in operation to optimize a given measurement frequency range.

The most notable advantage from using atomic proof masses is the possibility of simple disturbance reduction implementation. When shielded within an ultra-high vacuum enclosure, atoms are free from collisions. Any residual collision would lead to an atom number loss rather than acceleration noise. Atoms have some sensitivity to local electric and magnetic fields, but with proper choice of atomic species and transition levels, the effects can be reduced to negligible levels (as is routinely demonstrated in modern atomic clocks [21]). The local gravity gradient force will be potentially the dominant contributor. With atomic sensors, however, one has the option of placing the atom proof masses away from the main mass of the spacecraft, as illustrated in Fig. 4. We estimate that, when located 5 meters away from spacecraft and even without any clever mass compensation design, the LISA disturbance noise requirement can be met with a spacecraft position jitter of μm/Hz$^{1/2}$, which is a ×1000 less stringent level than the LISA drag-free precision of nm/Hz$^{1/2}$. This approach can significantly reduce, if not completely eliminate, the need for drag-free satellite operation.

Technology readiness of atom interferometer

Laboratory atom interferometers have achieved a sensitivity of ~ 10^{-8} m/s^2/Hz$^{1/2}$ [18,19] as accelerometers, already surpassing the state of the art in traditional room temperature sensors on the ground. Significant advances have been made more recently in the sensor performances and the technology maturity. Various transportable systems are being developed around the world including gravimeters [23] and gravity gradiometers [16,22].

Major advances are still being made today in laboratories. For example, a large momentum-transfer (an $N = 24$) for atom-wave splitting has been demonstrated with a high fringe contrast (Müller *et al*., 2008) [14]. $N = 200$ has also be shown experimentally possible [15]. A larger momentum transfer results in a larger effective interferometer area and, therefore, higher sensitivity for inertial force measurements. In addition, the use of coherent quantum matter waves offers the potential of further improvement to overcome standard atom projection noise by exploiting quantum entanglement and non-classical states.

The concept of atomic accelerometer references for DRS has a very similar implementation approach to those already demonstrated in the laboratory. The key challenges lie in producing sufficient number of ultra-cold atoms and demonstrating the necessary long interrogation time T in the microgravity environment of space. A technology demonstration in microgravity would help significantly reduce the risk associated with the use of atom interferometers in space.

We have not performed a detailed cost analysis for the entire atomic disturbance reduction system. The replacement of the LISA DRS will involve redesign of spacecraft, propulsion, accelerometers, and modifications in the optical system. However, most of the changes are expected towards architecture simplification and cost reduction. The atom interferometer instrument itself would be the range of $100M, based on a similar but more complicated cold atom experiment mission designed for ISS.

Acknowledgment

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Drag-free Atomic Acceleration Reference for LISA Disturbance Reduction System

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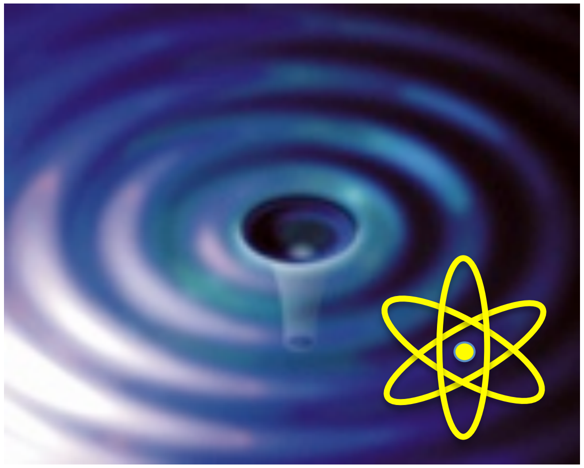
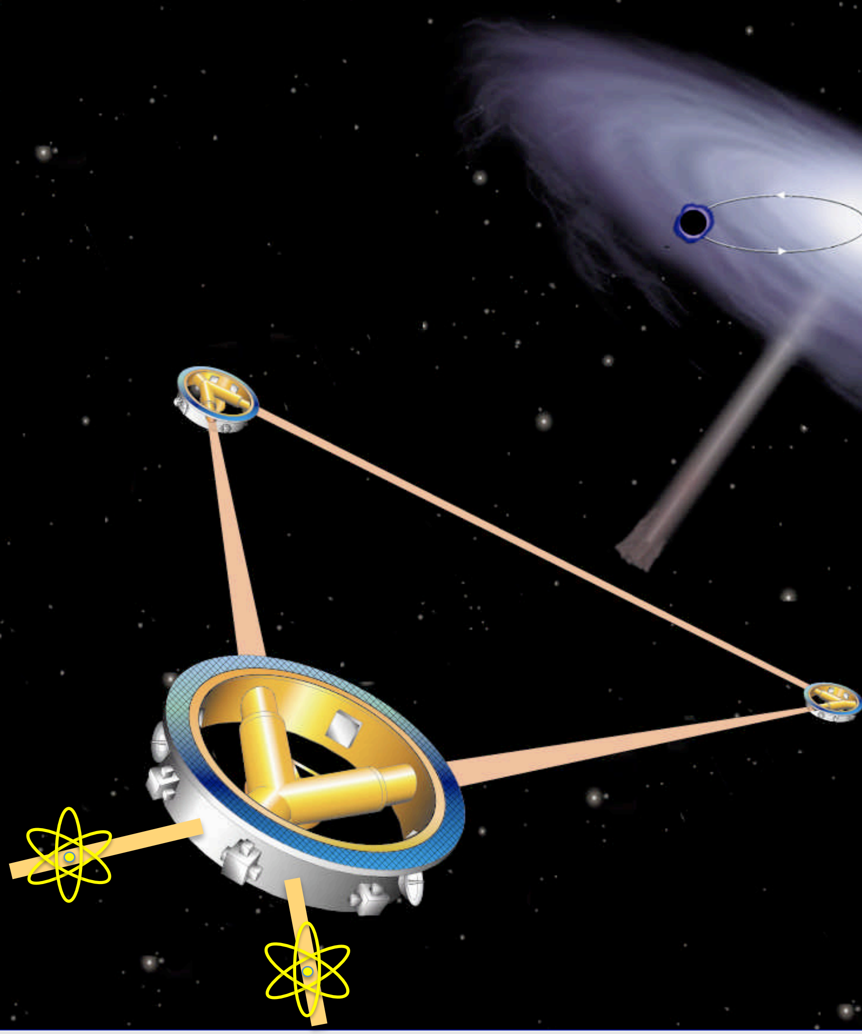


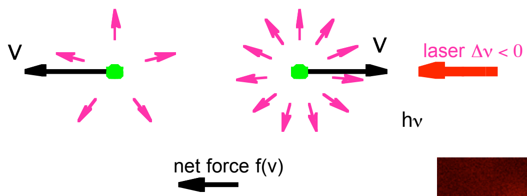
Atom Interferometers for LISA DRS

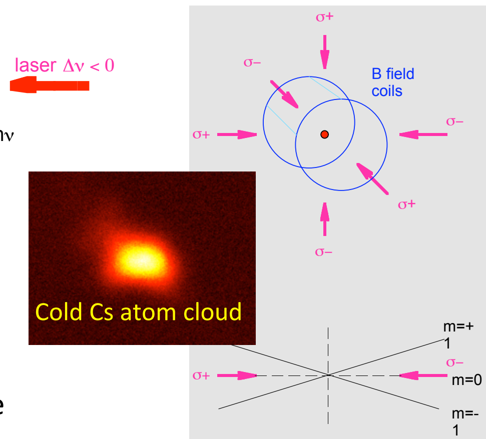


- Big Idea: Truly drag-free atomic proof masses for LISA's Disturbance Reduction System (DRS).
- Approach: Atomic acceleration reference based atom-wave interferometry using laser-cooled freefall atoms.
- Concept: Use atomic inertial sensors to replace the LISA accelerometers by measuring relative acceleration-induced displacements between ideal drag-free atoms and spacecraft accelerometers.
- Goal: Reduce/eliminate spacecraft drag-free requirement and the associated complexity, risk, and cost, while potentially increase measurement bandwidth and higher science returns.

Atom Interferometer (AI) – Introduction

Light forces are used for cooling and trapping atoms

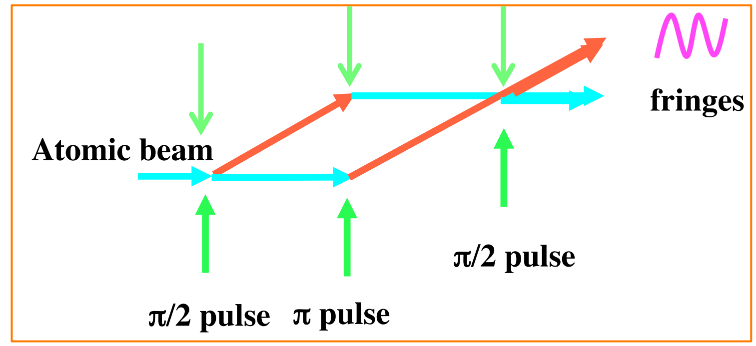




Cooling by Doppler (velocity)-dependent viscous force (top) and trapping by magnetic (spatial)-dependent light force (left).

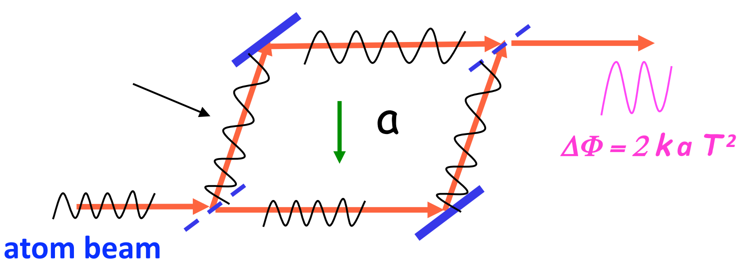
Magneto-optical trap (MOT)

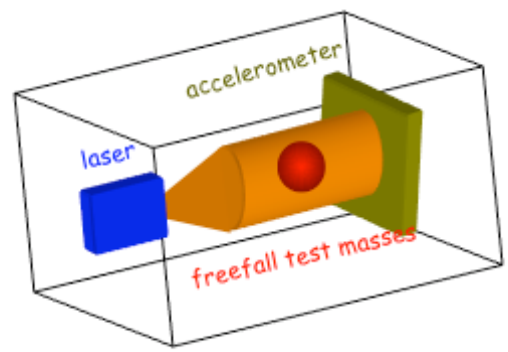
Light-atom interaction creates atom-wave optics



Acceleration/gravity sensing [Kasevich, 1991]

Phase shift due to acceleration $\Delta\Phi = 2\,k\,a\,T^2$

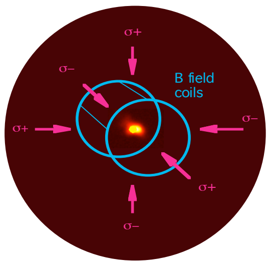




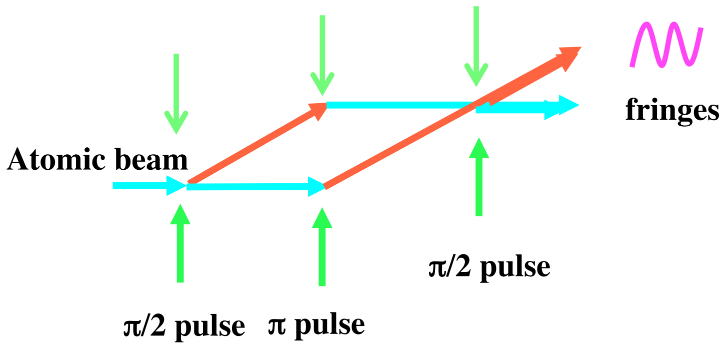
AI referenced accelerometer [Yu 2006]
(laser + atoms + retro-reflector)

Atom Interferometers – Salient Features and Benefits

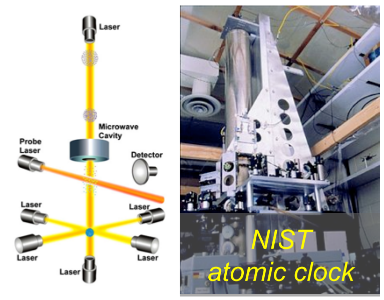
Freefall test mass **+** ***Displacement Detection*** **+** ***Atomic system stability***



Laser-cooled Cs atom cloud at μK [Berman 1996]



atom-wave interferometer [Kasevich 1991]



Atoms are stable clocks [Jefferts, 2011]

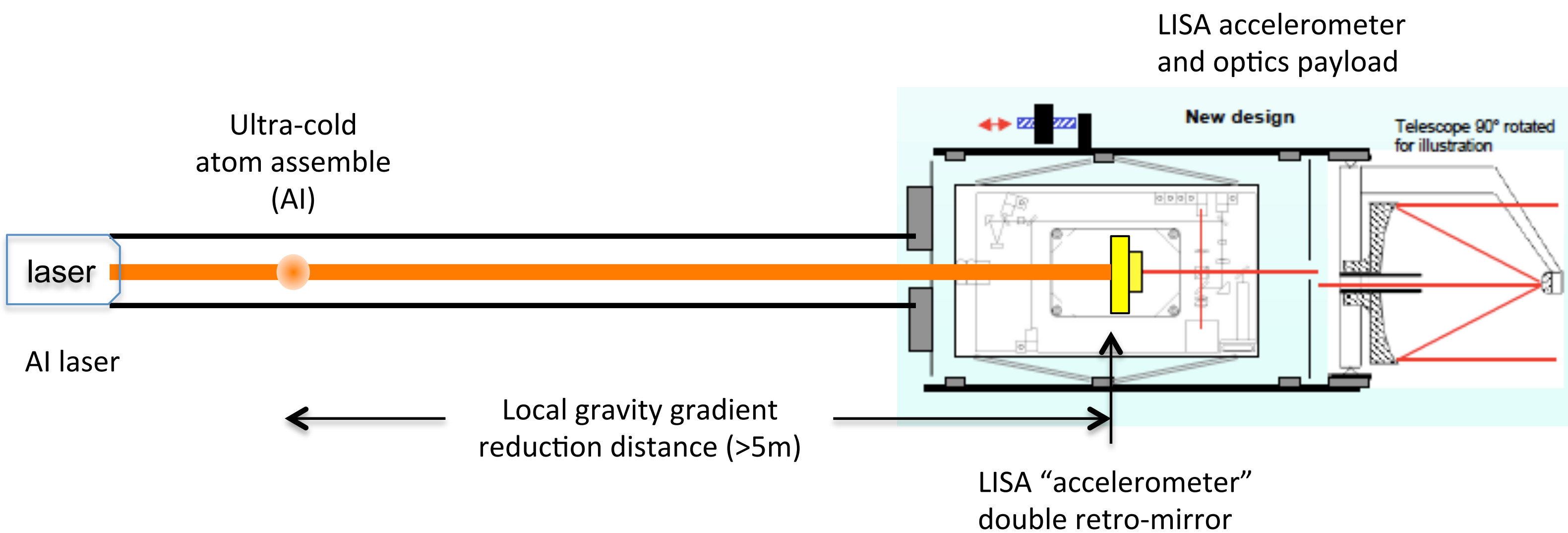
- Use totally freefall atomic particles as ideal test masses

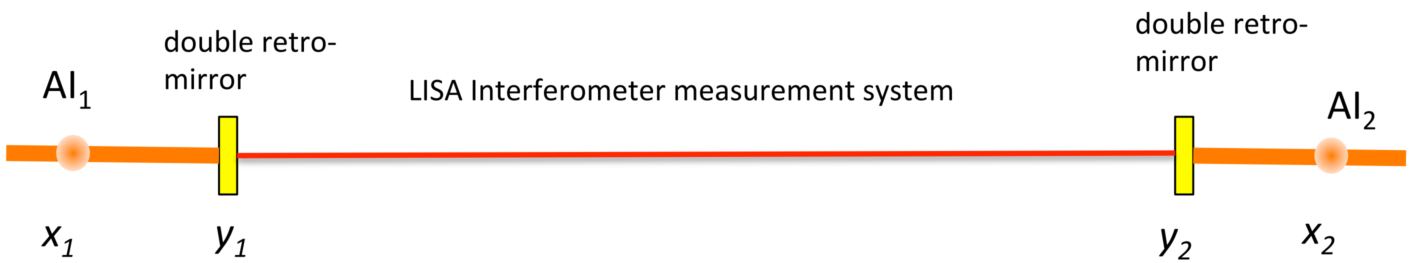
  , *identical atomic particles are collected, cooled, and set in free fall in vacuum with no external perturbation other than gravity/inertial forces; laser-cooling and trapping are used to produce the atomic test masses at μK and nK; no cryogenics and no mechanical moving parts.*
- Matter-wave interference for displacement measurements

  displacement measurements through interaction of lasers and atoms, pm/Hz$^{1/2}$ when in space; laser control and manipulation of atoms with opto-atomic optics.
- Intrinsic high stability of atomic system

  use the very same atoms and measurement schemes as those for the most precise atomic clocks, allowing high measurement stabilities.
- Enable orders of magnitude sensitivity gain when in space

  microgravity environment in space offers long interrogation times with atoms, resulting orders of magnitude higher sensitivity compared terrestrial operations [Yu 2002].





$$\Delta X = x_2(t) - x_1(t) = \underbrace{\left[x_2(t) - y_2(t)\right]}_{\text{Measured by AI}_1} + \underbrace{\left[y_2(t) - y_1(t)\right]}_{\text{Measured by IMS}} + \underbrace{\left[y_1(t) - x_1(t)\right]}_{\text{Measured by AI}_2}$$

Note: ideally, the displacement jitters of the mirrors are completely cancelled out, therefore, reducing the spacecraft "accelerometer" drag-free requirements.

Atom interferometer phase shift due to an acceleration *a*:

$$\Delta\Phi_{AI} = NkaT^2$$

Where $\Delta\Phi_{AI}$ is the AI phase measurement, λ AI laser wavelength, *N* is the number of photon momentum transfer in AI, and *T* the AI interrogation time (about half of the measurement time).

- N=2 is most common.
- AI with *N*=24 has been demonstrated [Mueller 2008].
- *N*=1 allows one-legged bandit interferometer concept [Yu 2010].
- T can be long in microgravity for LISA mission, to be determined by the LISA measurement bandwidth.

"Acceleration-integrating" displacement measurement concept

$$\Delta x_a = \frac{1}{2} aT^2 \longrightarrow \Delta x_a = \frac{\lambda}{4\pi N}\Delta\Phi_{AI}$$

where Δx_a is the "integrated" atomic proof mass displacement due to an acceleration a. With λ=1 μm and a phase resolution of 100 μrad, *pm* displacement resolution can be reached.

Atomic Referenced GW Strain Sensitivity Estimate

- Assuming a quantum projection noise limited detection of realistic SNR=1x10^{8} atoms, we have $S_{\Phi}\left(f\right)=SNR\cdot\sqrt{2T}=1.4x10^{-4}\sqrt{2T}$ if the small measurement deadtime neglected.

- Recall: $a=\Delta\ddot{x}=\omega^{2}\Delta x$

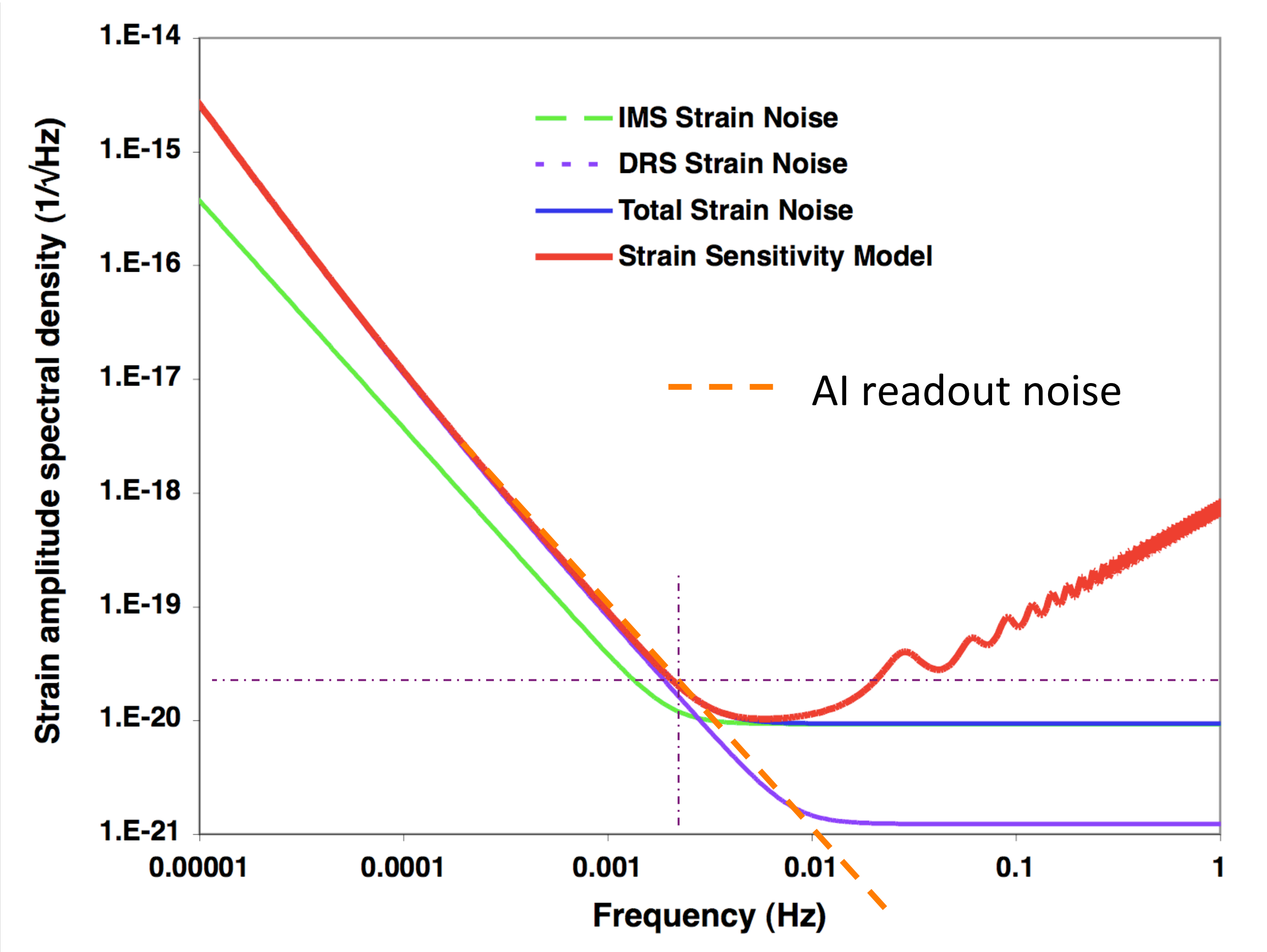
- Putting all together, we have: $S_{h}(f)=\left(\frac{1}{L}\right)\cdot S_{\Delta x}(f)=\frac{1}{L}\cdot\frac{\lambda}{\left(2\pi\right)^{3}N}\left(\frac{1}{f^{2}T^{2}}\right)S_{\Delta\Phi}$

$$\boxed{S_{h}(f)=\frac{\sqrt{2}}{\left(2\pi\right)^{3}N}\cdot\frac{\lambda}{L}\cdot\left(\frac{\sqrt{T}}{f^{2}T^{2}}\right)SNR}$$

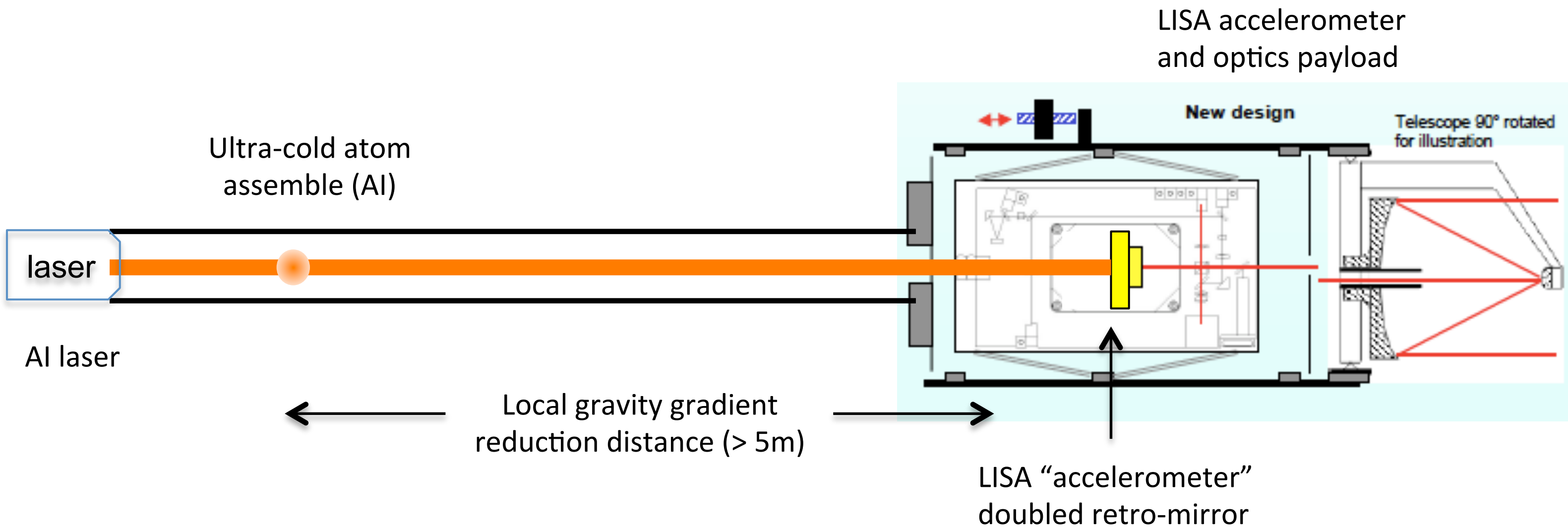
Example: *N*=20, *SNR*=1x10^{-4}, *T*=10 *sec*, *λ*=1 *µm*, *L*=5x10^{9} *m*, *we will have* $S_h(f)$=2x10^{-25}/f^2. This yields S_h(2mHz)=5x10^{-20}, indeed comparable to the current LISA DRS and IMS error budget.

Notional Strain Readout Sensitivity Spectrum Using AI

AI displacement readout noise budget



LISA chart from LISA-MSE-TN-0001 [ESA 2009]



Atom position jitters in the residual s/c gravity field gradient results in error.
Mitigation – By moving atoms away from main spacecraft mass [Hogan, 2011]:

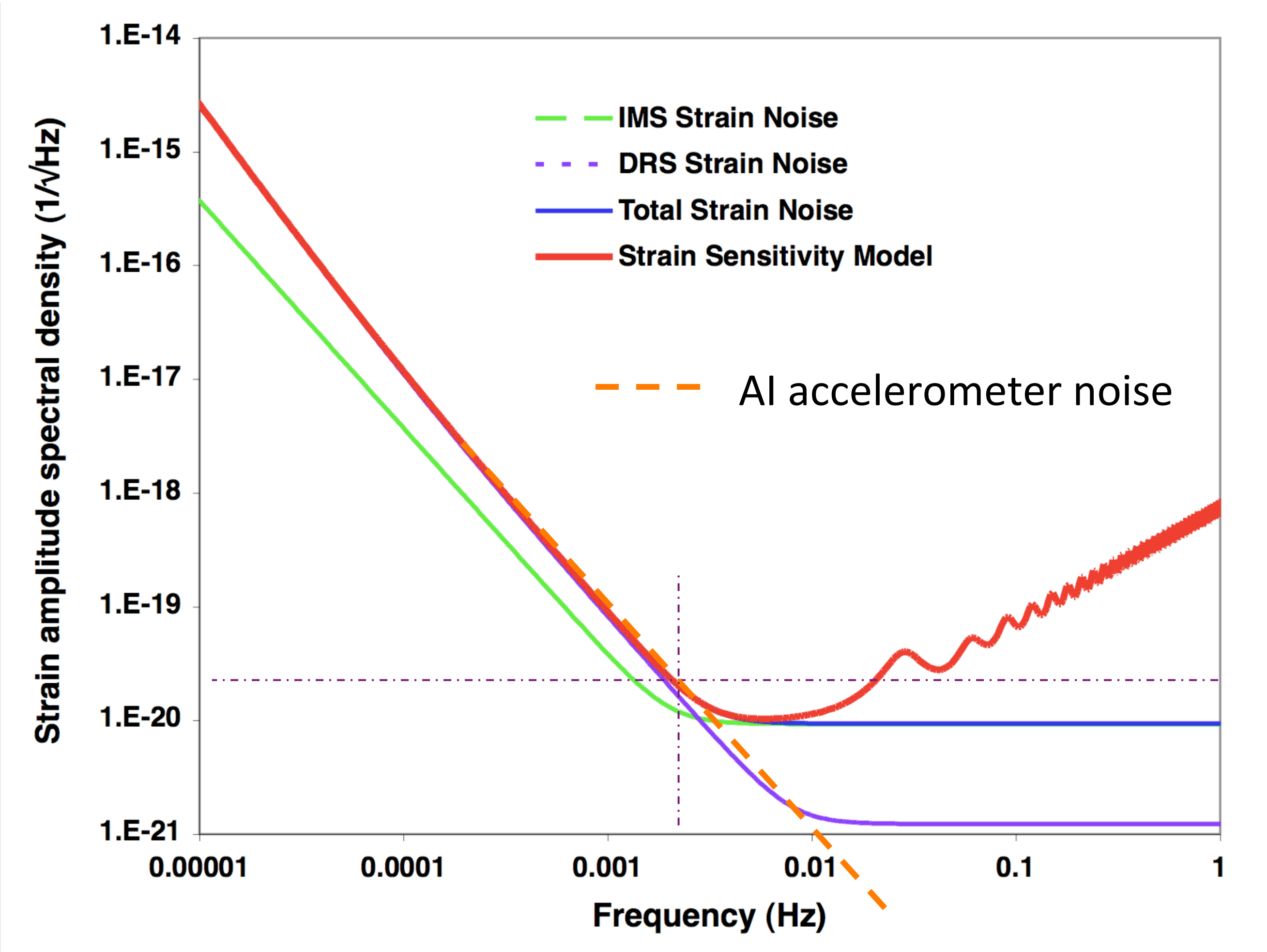
$$\Delta x_a = \iint (\Delta f / m) dt = \iint \Delta\left(\frac{GM_{sc}}{r^2}\right) dt = -\iint \frac{2GM_{sc}}{r_0^3} \Delta r(t)\, dt$$

$$S_x(f) = \left(\frac{2GM_{sc}}{r^3 f^2}\right) S_r(f) = \frac{3.4\times 10^{-10}}{f^2} S_r(f)$$

Assuming a 5-m distance away from a 300 kg spacecraft, < 3 μm/Hz$^{1/2}$ atomic position jitter would be sufficient to meet the LISA accelerometer noise budget requirement. (Specific s/c mass distribution design can reduce this requirement further.)

Notional Strain Readout Sensitivity Spectrum Using AI

AI displacement readout noise budget



LISA chart from LISA-MSE-TN-0001 [ESA 2009]

Key points of using atomic reference:

- Free fall atoms are naturally drag-free
- Measurements relative to the spacecraft accelerometers
- Maintain LISA mission concept and science objectives
- Reduced self-gradient effect
- Reduced spacecraft thermal sensitivity
- Reduced magnetic field sensitivity
- No charge effect
- No pressure noise (vacuum required for reducing collisional loss)
- No micro thruster noise
- Risk reduction and cost savings

Major Noise Sources

Three major types of atomic reference error source

- *Fundamental noise* – white phase noise
  - Atomic state projection noise (or atom shot noise), $n^{1/2}$, determined by the total number of atoms, *n*.

  Mitigation: increased number of cold atoms.

- *AI phase noise* – Random phase noise and drifts
  - Due to various field effects on atoms, magnetic Zeeman shift, electric field Stark shifts
  - Due to optical wave front
  - Due to atomic assemble inhomogeneity

  Mitigation: reduced various field effects, can be well controlled as in atomic clocks.

- *Parasitic force noise* – $1/f^2$ noise
  - Coriolis force due to rotation disturbances
  - Random residual local gravity gradient noise

  Mitigation: atomic test mass far away from spacecraft.

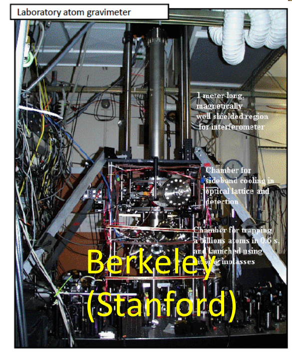
1. Vacuum package
a) Non-magnetic housing
b) Large aperture high quality optical windows
c) Sealed vacuum package without active pump

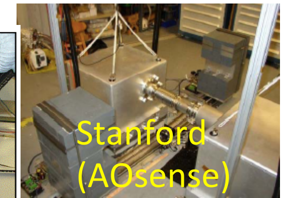
2. Laser and optics
a) Master lasers
b) Amplifiers
c) Agile laser frequency and intensity switching
d) Beam alignments

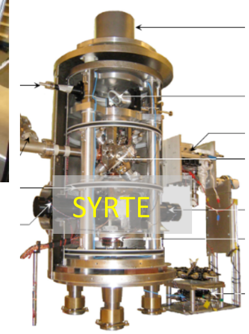
3. Environmental control
a) Magnetic field management
b) Vibration reduction
c) Platform rotation
d) Drag-free systematics reduction

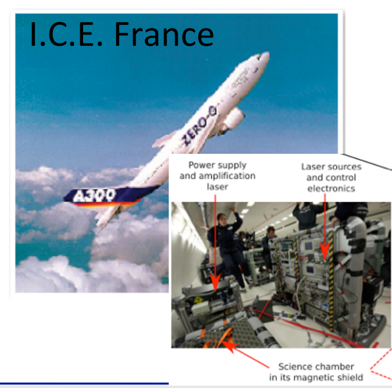
4. Microgravity operation
a) Ultra cold atom source
b) Atomic ensemble dynamics

AI development activities

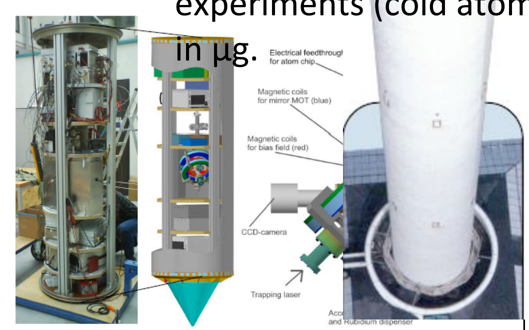








DRL Drop tower experiments (cold atom in µg.



Summary Points of the RFI Input

- Keep overall LISA mission concept
  - Replace LISA DRS with atomic DRS (aDRS)
  - Address the LISA Disturbance Reduction System (DRS), the most challenging part of the LISA mission
- Using truly drag-free atomic proof masses
  - Quantum inertial sensor technology of atom interferometry
  - Ground-proven atom interferometer measurement technique is sufficient for LISA mission application [Peters 2001][McGuirk 2002][Mueller 2009][Wu 2009][Yu 2011]
- Reduction of the DRS test mass requirements
  - Reduced drag-free requirement by > x1000
  - Significantly reduce the complexity, risk and cost of the current LISA DRS
- Key risk assessment
  - Atom interferometer technology validation in microgravity at long measurement time

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