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Phys. Rev. A **92**, 063613 — Published 7 December 2015

DOI: 10.1103/PhysRevA.92.063613

Laser-Ranging Long Baseline Differential Atom Interferometers for Space

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(Dated: October 22, 2015)

High sensitivity differential atom interferometers (AIs) are promising for precision measurements in science frontiers in space, including gravity field mapping for Earth science studies and gravitational wave detection. Difficulties associated with implementing long baseline differential AIs have previously included the need of high optical power, large differential Doppler shifts, and narrow dynamic range. We propose a new configuration of twin AIs connected by a laser ranging interferometer (LRI-AI) to provide precise information of the displacements between the two AI reference mirrors and also to phase-lock the two independent interferometer lasers over long distances, thereby drastically improving the practical feasibility of long baseline differential AI measurements. We show that a properly implemented LRI-AI can achieve equivalent functionality to the conventional differential AI measurement configuration.

PACS numbers: 03.75.Dg, 06.30.Gv, 07.87.+v

I. INTRODUCTION

Atom interferometry exploits the wave nature of neutral atoms for precision metrology: The wave property allows each atom to interfere with itself resulting in modulation of the probability of populating a discrete state, associated with the environment that the atom traverses [1]. In a light-pulse atom interferometer (AI), an atomic matter wave is split, reflected, and recombined by laser pulses, and during each pulse the optical phase is registered by the atom. The output phase of the AI, the probability distribution among possible states, depends on the optical phases and the evolution of the atomic wave under the influences of environmental perturbations, including electromagnetic fields, gravity, etc. Due to the inherent stability and identicality of atomic properties for same species, the accuracy of an AI is fundamentally limited by the stability of the interrogating laser, and the understanding and control of the environment. This is in contrast to classical sensors, which drift over time and possess bulk effects that depend on their shape and composition. The repeatability and thorough understanding of atomic systems make cold-atom based instruments ideal candidates for precision measurements, including: local gravity acceleration g [2], photon recoil measurement of $\hbar/m$ and the fine structure constant α [3], rotation [4], the gravitational constant G [5, 6], etc. The power of AI-based precision measurements is illustrated in Ref [2]: An AI gravimeter not only surpasses the short-term sensitivity of a state-of-the-art classical falling corner cube gravimeter, but also agrees with global/regional gravity models over 4 years, thus restricting local Lorentz variance in gravity and electromagnetism to unprecedented levels.

The applicability of atom interferometry is further extended by a widely used technique, differential measurements between two simultaneous AIs [7–10] as depicted in Fig. 1(a). In this scheme, two AIs are interrogated by a common laser, using either the same or different spectral components of the beam [9]. The instrument sensitivity increases proportional to the baseline, while the contribution of baseline uncertainty to measurement error decreases. The vibrations of optics in the laser beam path, as well as the laser phase noise, are largely common to the two AIs, thanks to the relatively short propagation delay for a laser pulse to go from one AI to the other [11]. Common mode noise suppression of vibrations is demonstrated to exceed 140 dB [12]. Differential measurements allow instrument sensitivity beyond the abilities to control and quantify systematic errors of individual AI. In particular, AI gravity gradiometers [5, 6, 10, 13]

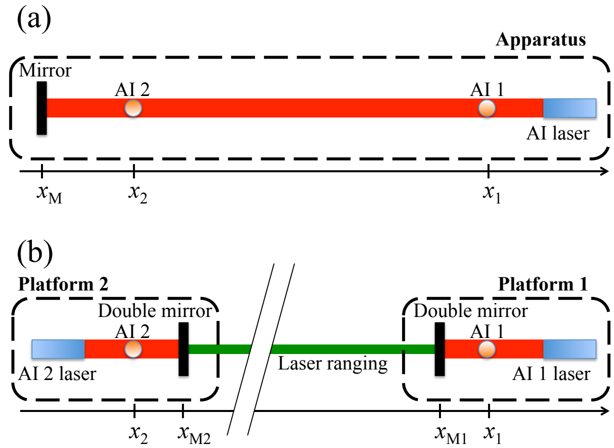

FIG. 1. (Color online) (a) Conventional differential AIs hosted in one apparatus. x_i is the position of the corresponding element. The instrument baseline $L = x_1 - x_2$. (b) Twin AIs linked with a laser ranging interferometer (LRI-AI). A double mirror has a reflective surface serving as the retroreflection mirror for AI on one side and serving as the retroreflection mirror for LRI on the other side.

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are constructed for terrestrial and space oriented applications. Furthermore, spaceborne gravitational wave detection using differential AIs are proposed for frequency bands and sensitivities unachievable on Earth [14–17].

As the instrument baseline L increases for demanding sensitivity requirements, however, associated technical challenges may become prohibitively expensive to overcome for the conventional configuration, if at all possible. For instance, as discussed in detail in [15], the Rayleigh range $z_R = \pi w_0^2/\lambda$ of a Gaussian beam with waist w_0 and wavelength λ should be larger than L to efficiently deliver optical power from one site to the other, $2z_R \geq L$. Thus a longer baseline demands larger beam waist $w_0 \propto \sqrt{L}$, correspondingly bigger high quality optics. Similarly, the laser power required to maintain the same intensity at z_R for AIs is proportionally larger. Moreover, if the twin AIs are hosted inside one single vacuum chamber, the baseline is limited to $\ll 1$ km even with the help of a boom system [16]. In the configuration where twin AIs are housed in different spacecraft with the common laser passing through free space using complex optics systems, static and stochastic wavefront aberrations may be of serious concern [18, 19].

II. THE LRI-AI CONFIGURATION

Here we propose an alternative approach for differential AI measurements, which drastically improves the practical feasibility of long baseline differential AIs. As depicted in Fig. 1(b), instead of a common interrogation laser for both AIs, our approach is constituted of twin local AIs driven by independent lasers, and a laser ranging interferometer to link the AIs (LRI-AI). A similar concept using independent AIs for gravitational wave detection was previously proposed [20].

Conceptually, LRI-AI can be pictured as using phase-locked lasers to replace the common laser in the conventional differential AI configuration, thus the fundamental measurement concept is the same for both: atomic motions are interrogated by a coherent classical light field. In a conceptual dual AI arrangement, the readout phase of a Mach-Zehnder AI is $\psi_i = k_{\text{eff}_i}(\ddot{x}_i - \ddot{x}_{Mi})T^2 + \phi_{li}$, where $i = (1,2)$, k_{eff} the effective wavenumber, T the pulse separation time, and x_{Mi} and ϕ_{li} indicate the mechanical reference point and the combination of AI laser phases. The differential acceleration experienced by the two atomic ensembles is revealed by taking the phase difference:

$$\begin{aligned}\psi_1 - \psi_2 = &(k_{\text{eff}_1}\ddot{x}_1 - k_{\text{eff}_2}\ddot{x}_2)T^2 \\ &-(k_{\text{eff}_1}\ddot{x}_{M1} - k_{\text{eff}_2}\ddot{x}_{M2})T^2 + (\phi_{l1} - \phi_{l2}).\end{aligned}$$

In the conventional configuration (Fig. 1(a)), both AIs share a single AI laser and a common mechanical reference point, thus k_{eff_i}, $\ddot{x}_{Mi}$ and ϕ_{li} are common (neglecting the propagation delay). $\delta\psi = \psi_1 - \psi_2 = k_{\text{eff}}(\ddot{x}_1 - \ddot{x}_2)T^2$, with both the mechanical acceleration and laser phase noise terms canceled out [7, 8]. In LRI-AI (Fig. 1(b)), x_{M1} and x_{M2} are different, but LRI provides $\ddot{L} = \ddot{x}_{M1} - \ddot{x}_{M2}$ measurement. The combination

$$\psi_1 - \psi_2 + k_{\text{eff}}\ddot{L}T^2 = k_{\text{eff}}(\ddot{x}_1 - \ddot{x}_2)T^2 \qquad (1)$$

yields identical differential phase to that of the conventional configuration, provided that k_{eff_i} and laser phases are precisely known. Note that the positions x_{Mi} of the retroreflection mirrors drop out of the differential measurement as expressed in Eq. (1) and need not be actively controlled.

It is not always necessary to phase lock AI lasers to the ranging laser, as in the conceptual picture, to establish the equivalence to the conventional configuration, where the purpose of phase locking is to remove differential k_{eff} and laser phase noise in ϕ_l. For a conventional AI using counter-propagating Raman or Bragg beams, as opposed to those using single photon beam-splitters proposed in [14, 17], the laser phase noise in the AI measurement ϕ_i is determined by the relative phase noise between the counter-propagating beams, i.e., the phase noise of the rf source that generates the counter-propagating beams [23]. Thus, sufficiently low uncertainty of k_{eff} and laser phase ϕ_l beyond fundamental noise floor (such as atom shot noise) can be guaranteed without such phase lock. For instance, with an assumed AI phase resolution of 1 mrad, and $T \sim 1$ s for Earth gravity measurements, the requirement on the local oscillator is ~ -60 dBc/Hz in phase noise, or $\sim 1 \times 10^{-13}$ frequency stability at 1 s for a 10 GHz local oscillator. Existing ultra stable oscillators can provide such noise performance. Similarly, sufficient knowledge of the acceleration sensitivity coefficient $k_{\text{eff}}T^2$ is easily achieved, where the requirement on its accuracy is the same as in the conventional configuration. Without the need of phase-locking, the ranging laser can have very different wavelength from AI lasers, thus making LRI-AI easily integrable to existing implementations, as proposed for gravitational wave detection [20]. For very long baselines such that propagation delay is not negligible for the stability of the ranging laser, variations of Time-Delay Interferometer can be used [14, 24, 25].

III. COMPARISON OF LRI-AI WITH CONVENTIONAL AI SCHEME

LRI-AI is advantageous over the conventional configuration in several aspects. First of all, LRI technology is well-developed in GRACE-FO for Earth gravity measurements [21] and in LISA for gravitational wave detection [26]. LRI-AI does not impose more stringent requirements on the ranging laser than already developed, because the ranging laser is used only to deliver the phase information such that a small amount of the received laser power (<nW) is sufficient, where beam collimation and wavefront aberrations are not critical as well. Mitigating the otherwise required large AI laser beam size

Atom source	AI interrogation time T (s)	AI acceleration sensitivity (nm/s^2/$\sqrt{\text{Hz}}$)	LRI ranging sensitivity (nm/$\sqrt{\text{Hz}}$) [21]	LRI acceleration sensitivity (nm/s^2/$\sqrt{\text{Hz}}$)
Thermal AI	0.16 [6]	30 [6]	80	$31.6 \times (f/0.1)^2$
BEC AI	1.15 [22]	0.3 [22]	80	$31.6 \times (f/0.1)^2$

TABLE I. Performance of LRI-AI using demonstrated technologies. While conventional differential AIs will be limited by AI sensitivity only, LRI-AI performance will also be limited by AI sensitivity at frequencies $f < 0.1$Hz for thermal AIs, and at frequencies $f < 0.01$Hz for BEC AIs.

for delivering the beam over long distance, local AI laser beams in LRI-AI can be tailored for local atomic sample size, optimization and systematic control. Higher intensity for large momentum transfer beam splitters will also be more affordable in LRI-AI [27–31]. Furthermore, one of the operational difficulties of using common laser for two spacecraft-based AIs is to accommodate the relative Doppler shift between distant spacecrafts, which can be on the order of MHz [21] and may prevent simultaneous operation of distant AIs using a single common laser without further mitigation strategy. In the LRI-AI configuration, local AIs are relatively stationary to the spacecraft, while the large Doppler shift is registered by heterodyne measurements in LRI [21].

LRI-AI is readily implementable with compelling performance by adopting matured technologies in LRI and compact AI, in comparison to extensive technology development and validation effort on conventional long baseline AI configuration for space applications. AI-based measurements are fundamentally limited by atom shot noise, and we argue that LRI technology maturity [21, 26] can support atom-shot-noise limited LRI-AI with baseline $>$ 100 km, of which the feasibility is rather questionable in the conventional configuration. Table I summarizes hypothetical combinations of LRI and AIs demonstrated to-date, based on the LRI development for GRACE-FO [21] and state-of-the-art terrestrial AIs [6, 22]. It is clear that an LRI system similar to that developed for GRACE-FO of a baseline up to 270 km, including the expected influences of thermal, acoustic, and vibrational effects on the optical path length, would have the same AI-limited performance as conventional differential AIs at time scales longer than 10 s for thermal sources, and at time scales longer than 100 s for BEC sources, while the technology for such long baseline AIs in the conventional configuration is still under development. For LRI to support AIs at shorter time scales, advanced LRIs can be adapted such as that demonstrated for the LISA mission with 1000$\times$ better performance [21]. Indeed, current LRI can support state-of-the-art AIs, which is at best what a conventional AI configuration can achieve.

IV. IMPLEMENTATION OF LRI-AI

As an example to illustrate the power of LRI-AI, a combination of a terrestrial demonstrated thermal AI and the GRACE-FO LRI with a baseline of 200 km will have a gravity gradient sensitivity of 150 μE/$\sqrt{\text{Hz}}$ (E is Eötvös=$10^{-9}/s^2$), which compares favorably to the gradiometers of $\sim$ 1mE/$\sqrt{\text{Hz}}$ in GOCE [32]. The achievable sensitivity can be further enhanced with the use of BEC sources and longer T available under microgravity. Again, using the demonstrated BEC AI sensitivity and a baseline of 200 km, one can achieve 1.5 μE/$\sqrt{\text{Hz}}$. Such a gravity gradient measurement system is expected to improve over the current GRACE gravity measurement significantly, though detailed gravity recovery simulation is required for its ability to recover gravity through the gradient measurements. In addition to improved sensitivity, LRI-AI also provides atomic clock grade stability, which is lacking in current gravity missions. Uncertainty in the scale factor calibration and variations associated with the mechanical accelerometers used in GRACE and GOCE are potential error sources. On the other hand, the AI technique has demonstrated unprecedented long-term stability [2, 4].

LRI-AI also mitigates systematics in gravity measurements associated with self-gravity gradient (SG) of spacecrafts. SG influences accelerometers on-board depending on relative position of the spacecraft and the test mass, and thus generates error in acceleration measurements. To completely remove the spacecraft self-gravity gradient error, the spacecraft can fly drag-free, similar to GOCE or LISA mission concept, where the spacecraft is servoed to follow the free-falling test mass using thrusters. However, at lower Earth orbit altitude drag-free flight is difficult and has very limited mission lifetime due to fuel consumption. On the other hand, in the LRI-AI approach, the atoms on each platform will serve as an ideal drag-free references in the presence of the spacecraft self-gravity gradient when the interrogation time is kept relatively short, which renders drag-free flight unnecessary [33].

Current methods of differential phase extraction between AIs rely on the constancy of the phase difference and high common mode rejection [7, 8] during stationary data acquisition in a laboratory environment. This requirement reduces the spatial-temporal resolution of an instrument in a dynamic moving platform such as in low

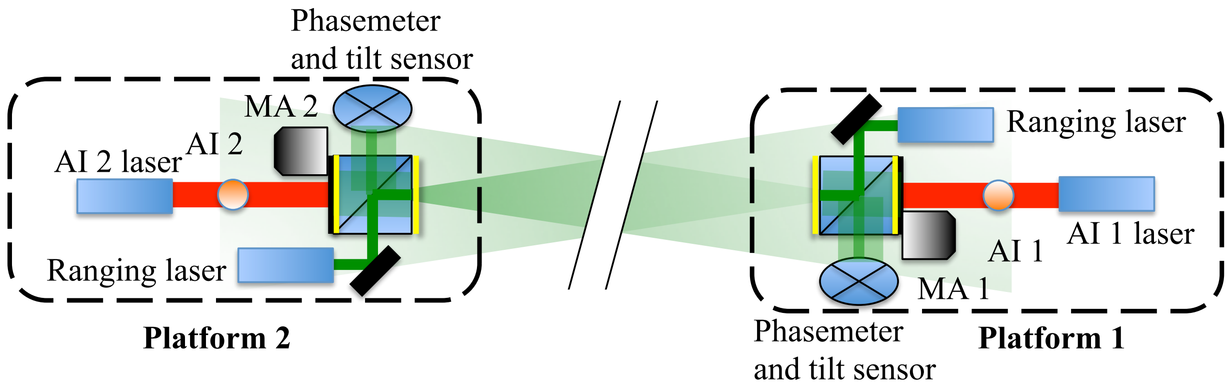

FIG. 2. (Color online) Schematic of LRI-AI with key components. Local forces measured by a mechanical accelerometer (MA) are used to feed back on the AI laser phase to compensate for excessive excursions of the retroreflection surface and thus to maintain the AI phase near zero, where the sensitivity is optimal. Ranging beams are circularly polarized with the quarter waveplates (yellow plates) after polarization beam splitting cubes. Beatnote between local and remote lasers is obtained after the remote beam is reflected off the back of the AI mirror (double-passing a quarter waveplate) and directed to the phasemeter by the polarization beam splitting cube. Relative tilt can be read off from the quadrant detector [21].

Earth orbit, where actual common phase AIs are unpredictable and random. The situation in LRI-AI may appear to be worse in that the phase difference between AIs also depends on the motion of the local inertial reference point; there is no commonality of the motions for the two inertial reference points on different spacecraft. A mitigation unique to the LRI-AI scheme can be implemented that greatly enhances the useful data rate (Fig. 2): Each local AI is operated near a phase zero-crossing (equal probability between two output ports) by controlling the AI beam splitter phase based on the reading of a mechanical accelerometer (MA) [34, 35]. In this scheme, the MA provides an estimate of the mirror acceleration, allowing AI laser phase adjustment to compensate for the anticipated phase excursion so as to maintain near-zero readout phase. Error of the estimate will manifest as the AI readout phase. After the AI completes, combining the AI phase and the applied phase adjustment gives a highly accurate and stable acceleration measurement of the reflection mirror relative to the free fall atoms, with greatly extended dynamic range of MAs. The AI differential phase can be easily calculated while LRI provides satellite ranging with high stability and sensitivity to accommodate shot-to-shot variation of differential signal, including Doppler shifts on the order of MHz.

V. CONCLUSION

In summary, we propose a new method for long baseline atom interferometers with laser ranging in space. This method adapts the state-of-the-art accurate atomic accelerometer technology and the technical advancement of laser ranging interferometry, allowing > 100 km baseline differential AIs with low optical power and a compact apparatus. With the assistance of mechanical accelerometers to keep the AIs operating at their most sensitive phase points, LRI-AI exhibits large dynamic range, fast data extraction, and low aliasing for high resolution spatial-temporal mapping. This method will be applicable in atom interferometer based spaceborne gravity measurements as well as in gravitational wave detection.

VI. ACKNOWLEDGEMENT

During preparation of the letter, we became aware of the manuscript by Hogan *et al.* discussing a similar configuration [36].

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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