Characterizing Small Changes in Gravity Using Cold Atom Interferometry

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A gravimeter is a specialized accelerometer that measures variations in local gravity, allowing for the characterization of subsurface geographic features such as underground tunnels and magma build-up [1]. Quantum gravimeters use atom interferometry, a process that uses laser pulses to split and recombine a group of atoms to measure the acceleration due to gravity with greater resolution. Atoms in a quantum gravimeter must be trapped and cooled to reduce thermal noise. The atom population is then split by a Raman pulse, and the gravitational field causes a phase shift of the quantum states. This phase shift causes the two momentum states of the atoms to interfere when they recombine, and the interference fringes reveal the effects of gravity on the state of the atom. Atom interferometers provide high resolution measurements and are well-suited for long-term measurements because they require minimal upkeep [2]. Methods such as Magneto-Optical Trapping (MOT) cool and trap atoms, improving the measurement accuracy of the atom interferometer [3]. The beam delivery for an atomic rubidium MOT can be miniaturized onto a silicon nitride photonic circuit, allowing the quantum gravimeter to use less bulky equipment [4].

I. INTRODUCTION

Gravimeters allow researchers to investigate local acceleration due to gravity. This technology allows researchers to study the shape and structure of the Earth, allowing many useful applications such as soil water content measurements to characterize landscape-level drought stress, ongoing research into military-grade inertial navigation systems, and magma flow tracking [5, 6]. Gravimeters are characterized in two broad categories: absolute and relative gravimeters. Absolute gravimeters measure gravitational acceleration in absolute units by using a free-falling mass, and relative gravimeters measure gravity relative to the extension of a spring [1]. Some of the best gravimeters in current technology are relative (e.g., superconducting gravimeters) because absolute classical gravimeters are bulky and expensive [7]. However, relative gravimeters are susceptible to drift due to environmental factors and must be recalibrated often. Quantum gravimeters provide absolute gravity measurements with a far more accurate resolution without the bulk of its classical counterparts or the drift of the competing superconducting gravimeter technology.

Planck and Einstein theorized that light was quantized to explain inaccuracies in the classical interpretation of phenomena such as the ultraviolet catastrophe and the photoelectric effect [8]. Inspired by this theoretical development, De Broglie theorized that not only do photons have wavelike and particle-like behavior, but also all matter can be described using wave-particle duality. He tested this theory by demonstrating that electrons diffract when scattered off a crystal structure [9]. Since photons and atoms can both be described using a wave function, quantum atomic optics and quantum photonic optics behave the same on a fundamental level. However, certain aspects of photons versus atoms create key differences that allow atoms to measure gravitational acceleration in a much more compact, efficient package.

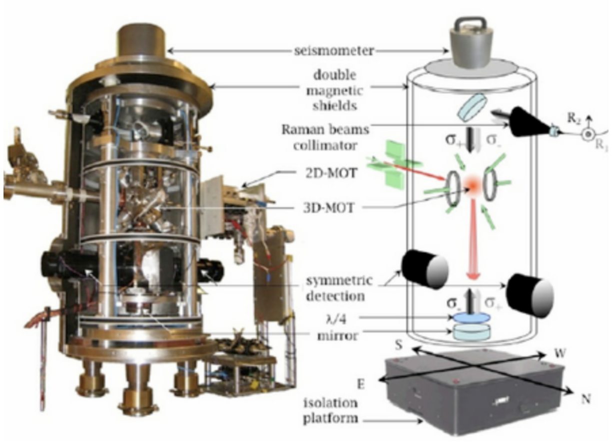

FIG. 1. An atomic gravimeter characterizes small changes in local gravity by interfering cold atoms. This figure shows how theoretical components, such as the cooling Magneto-Optical Trap (2D-MOT, 3D-MOT), map to a physical atomic gravimeter. Other notable components protect from vibrational displacement (seismometer), protect from the magnetic field of the earth (double magnetic shields), introduce the interference effect (Raman beams colliminator), detect interference (symmetric detection), and protect the system from movement (isolation platform) [10].

This is not to say that atoms and photons behave identically; the differences in behavior are exploited to create better gravimeters (though it should be noted that competition is primarily from dropped-reflector and not optical gravimeters in the case of absolute gravimetry). While atoms can be reflected using atomic mirrors, there is no real equivalent to the beam-splitter in atomic optics, suggesting that substantially different designs are necessary to build the same types of interferometer. The reduced De-Broglie wavelength and coherence lengths of atoms changes the requirements for diffraction gratings. However, atoms can also move much more slowly than photons, so for time-dependent effects (such as acceleration on relative phase in an interferometer) there is a significant advantage. When compared to dropped-reflector gravimeters, the high rate and semi-solid-state nature of atom sources allow for more data points per second in a smaller package with dramatic decreases to power requirements and minimal maintenance.

II. METHODS

A. Kassevich-Chu Gravimetry

The earliest neutron gravimeters were developed by Coella et. al. in 1975 using a diffraction grating interferometer [11]. In 1988, Clauser used laser-generated standing waves to diffract atoms in the first atomic gravimeter, but his separation methods were effectively replaced by Kasevich and Chu with vertical Raman-scattering based separation [12, 13]. The paradigm developed there remains the basis for most contemporary atomic gravimeters.

In a Kasevich-Chu type gravimeter, a single laser is used to induce Raman scattering in a population of vertically free-falling cold atoms. The laser induces momentum changes in the z-direction using three precisely timed laser pulses. These pulses use precise phase control and a mirror at the bottom of the experimental chamber to create a differential frequency as required for stimulated Raman scattering. The frequency of the laser is rapidly modulated so that the reflected beam with frequency ω_1 and direct beam with frequency offset up to ω_2 interact with the atoms for the required amount of time to change the momentum state [13]. As gravity accelerates the atoms, the effective frequency difference of these lasers is changed due to the Doppler effect. While it is necessary in the original Kasevich-Chu design for expected gravitational acceleration (by changing ω_1 and ω_2 for expected velocity), more modern designs do not seem to require this. In any case, the Doppler-effect induced change to the laser frequency is the physical reason that there is a phase shift that is different to the phase shift in free space. The process of taking a measurement is the application of these concepts. One $\frac{\pi}{2}$ pulse splits the momentum states. After a time of flight T, a π pulse swaps the momentum state of each atom from state $|i\rangle$ to state $|j\rangle$ and vice versa, meaning that the wavepackets of atoms are in close enough proximity to interfere when another $\frac{\pi}{2}$ pulse is applied. A quick-and-dirty analysis suggests that the first pulse contributes nothing, the second pulse contributes a phase shift $-\Delta\phi_{ex}$, and the third pulse contributes $2\Delta\phi_{ex}$, to get the final result.

The critical behavior of the system is best described by its mathematical results. The first critical result is the population fraction as a result of phase shift, as shown in Eq. 1.

$$\hat{Z}\,|1\rangle = \frac{1}{2}(e^{-i\Delta\phi} + 1)\,|2\rangle + a_1\,|1\rangle \tag{1}$$

Where $\hat{Z}$ is the operator representing the action of the interferometer, $|1\rangle$ is the initial state of all particles in the population, and $|2\rangle$ is the state that some particles reach due to the effects of interference [13]. a_1 is derivable, but can also be found just by normalizing. The critical result here is that the phase shift controls the fraction of particles that will end up in state two. The detection system counts particles in state 2, mean-

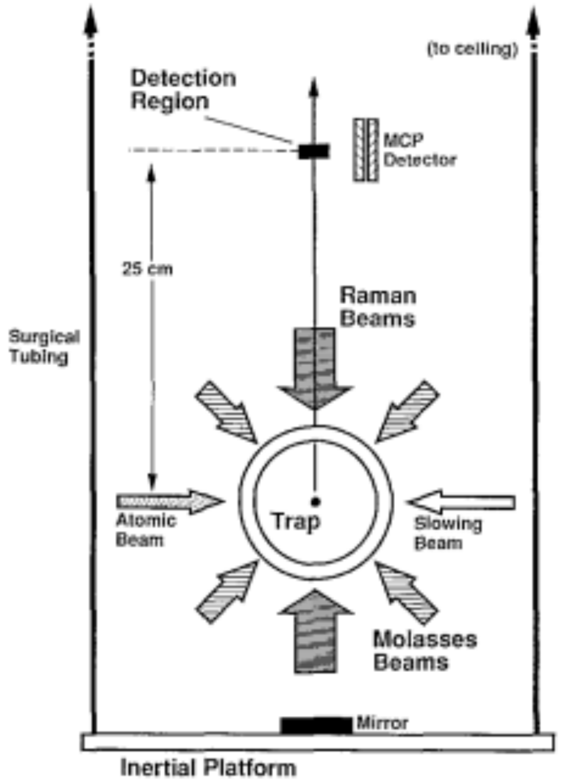

FIG. 2. Schematic of the Kasevich-Chu gravimeter. Note how the primary beam uses a mirror and time-shifting to cut down on the number of lasers requiring alignment. [13].

ing that if gravitational acceleration of the atoms introduces an additional phase shift, it will be possible to determine the acceleration.

It turns out that by evaluating the same equations used to determine the phase shift due only to the lasers with a laser frequency separation generated by the Doppler effect, we actually find Eq. 2 [13].

$$\Delta\phi = (\mathbf{k}_1 - \mathbf{k}_2) \cdot \mathbf{g}T^2 \tag{2}$$

Where $\mathbf{k}$ is the wavenumber of the oncoming laser, T is the time of flight of the particle, and $\mathbf{g}$ is the acceleration. With the statistics provided by the population counting system, this allows for the local gravitational acceleration to be measured. There are a number of mathematical subtleties wallpapered over that provide critical implementation detail, but the functional behavior that allows us to extract gravitational acceleration is encompassed by these two equations. It also notably explains why cool atoms are greatly preferred for atomic gravimeters: warm atoms move faster, meaning that times of flight are much shorter. Because system sensitivity to acceleration differences is based on the size of the change of $\Delta\phi$ in response to a change of g, longer times of flight dramatically improve system sensitivity.

While atomic gravimeters have started to move out of the lab, they are still largely considered research-grade systems, meaning that there is no universal description. It is likely that Kasevich-Chu gravimeters are not the only design in use. However within the bounds of Kasevich-Chu systems there are a few universal requirements. Frequency synthesis and phase locking techniques are used to control the frequency of the primary laser, which is required to compensate for the changing speed of the atom cloud. Mirror vibrations can cause Doppler shift of the laser beam, leading to systematic error. While there are methods to compensate for this, mechanical isolation of the mirror is one conventional solution. The detection system also deserves some discussion. A pulse from the primary laser is used to ionize the atom cloud using resonant ionization. Resonant ionization can be tuned to be highly selective of state, meaning that it is possible to ionize almost all of the atoms in state 2, and almost none of the atoms in state one. From there, a microchannel plate is used to count the number of ionized atoms. These features can be examined in FIG. 2, in addition to the cooling system.

B. Atom Cooling and Trapping

A magneto-optical trap (MOT), shown in FIG 3, cools and traps atoms, reducing thermal noise and improving accuracy of atomic systems such as atomic clocks, neutral atom quantum computers, and quantum gravimeters. Significantly, atom cooling increases time of flight in atomic gravimeters, improving sensitivity and accuracy. A MOT uses Doppler cooling and the Zeeman effect to slow and localize atoms. However, the MOT cooling system has a minimum temperature determined by the Doppler limit. We can use other cooling techniques to cool the atoms below the Doppler limit, creating a Bose-Einstein condensate, which can further improve gravimetry measurements. For more information on sub-doppler cooling, refer to Appendix A.

A MOT uses symmetrical laser geometry to apply a scattering force on the atom cloud from all directions. Certain laser frequencies will excite an atomic transition in an atom, increasing the scattering force. Since the doppler effect changes the effective frequency of the photons based on the direction of the atom's motion, we can detune our lasers to excite an atomic transition in atoms moving toward the laser.

The Zeeman effect changes the frequency required for an atomic transition for different spin states in a magnetic field. As an atom drifts toward peripheral areas with a stronger magnetic field, the frequency required for an atomic transition will shift closer to the effective frequency of the laser. Therefore, the magnetic component of a MOT traps the atom.

Recently, researchers have created a MOT with lasers deployed from a photonic integrated circuit [4]. Photonic integrated circuit MOT, or PICMOTs, introduce several improvements over free-space MOTs. Individual lasers in free space may experience differences in vibration, and can easily become misaligned. On a PICMOT, the vibrations of all laser components are correlated, maintaining the integrity of the cross-section. Photonic integration also miniaturizes the components, reducing the mass and bulk of the system.

III. DISCUSSION

Current absolute and relative gravimeters are accurate to the 10nm/s^2 scale [15, 16]. However, relative gravimeters will always suffer from drift

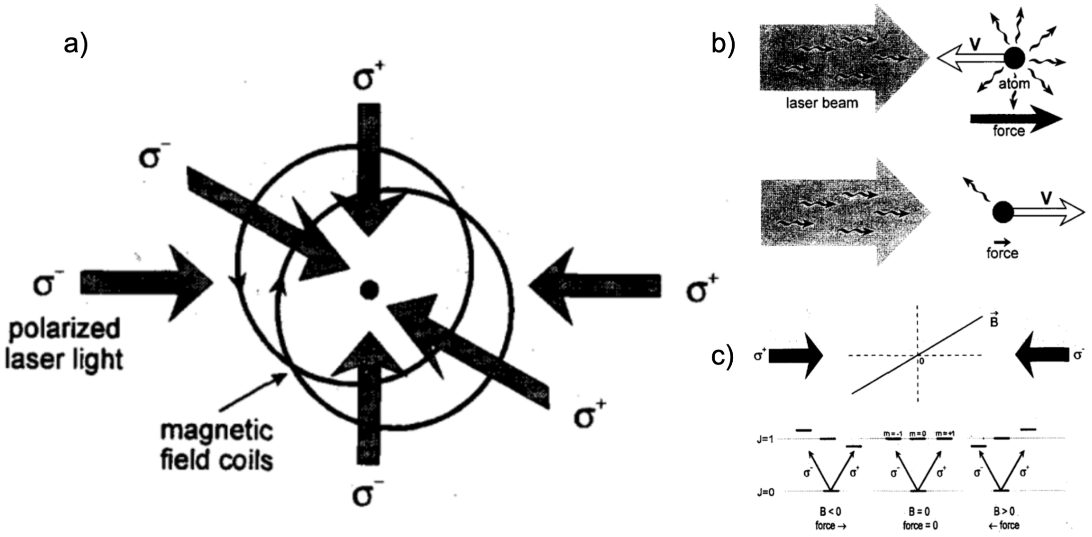

FIG. 3. Schematic and conceptual design of a magneto-optical trap (MOT). (a) The geometry of the trap includes 3 pairs of counterpropogating lasers and two coils with opposite currents, which create a magnetic field. (b) Doppler cooling occurs when the effective frequency of the laser excites an atomic transition when the atom is moving toward the laser, increasing the scattering force. (c) The Zeeman effect splits the atomic transition in a magnetic field. [14].

in accuracy, leading to frequent recalibration. Therefore, absolute gravimeters are the best choice for long term monitoring because they require minimal maintenance. The top commercial option for gravimetry is the MuQuans Absolute Quantum Gravimeter, which leverages laser cooled atoms instead of the traditional spring-mass system. The use of fiber-friendly 1560 nm lasers ensures no need for optical alignment, and reliability is improved due to the lack of mechanical components, allowing the gravimeter to run continuously for years.

Gravimeters are useful in many fields of science related to observing the Earth and its features. Gravimeters have been used to measure water levels on multiple occasions, both on the ground and from space. NASA's GRACE mission, which ran from 2003 to 2011, sent gravimeters into orbit on a satellite and was able to perform measurements all over the globe. In particular, the GRACE mission analyzed the changing water levels in Africa, where certain regions suffer from long-term droughts [17]. In addition, the gravimetric data revealed the water and rock composition beneath the surface of glaciers by their density difference, allowing scientists to analyze the rate that glaciers are melting and their contribution to ocean levels rising [18]. Gravimeters are also used in the Hebei region of China to monitor surface and groundwater levels. Due to the extreme amount of water used for agriculture and industry, groundwater in the region is being depleted at a dangerous rate. The water depletion contributes to land subsidence and a water crisis, making the research conducted with gravimeters key to the future of the region [19]. Additionally, the Hawaiian Volcano Observatory acquired a MuQuans Absolute Quantum Gravimeter in 2022 for its advantages over non-atomic gravimeters in tracking volcanic activity. Constantly monitoring volcanic activity is crucial to the safety of Hawaiians, and the purchase of an atomic gravimeter ensures that Hawaiians will have accurate and reliable data for years to come [20].

Research and development of absolute quantum gravimeters (AQG) continues to make smaller and lighter gravimeters. The Muller Group at Berkeley created a compact atomic gravimeter that achieved a sensitivity of 37 nm/s^2, competitive with current gravimeters [21]. The total mass of the Muller gravimeter is only 70 kg, 30% less than the MuQuans. By reducing the size and mass, they could theoretically mount it onto a drone, opening possibilities in field research.

[1] R. P. Middlemiss, A. Samarelli, D. J. Paul, J. Hough, S. Rowan, and G. D. Hammond, en"Measurement of the Earth tides with a MEMS gravimeter," Nature **531**, 614–617 (2016), number: 7596 Publisher: Nature Publishing Group.

[2] Jiaqi Zhong, Biao Tang, Xi Chen, and Lin Zhou, "Quantum gravimetry going toward real applications," The Innovation **3**, 100230 (2022).

[3] Jongmin Lee, Roger Ding, Justin Christensen, Randy R. Rosenthal, Aaron Ison, Daniel P. Gillund, David Bossert, Kyle H. Fuerschbach, William Kindel, Patrick S. Finnegan, Joel R. Wendt, Michael Gehl, Ashok Kodigala, Hayden McGuinness, Charles A. Walker, Shanalyn A. Kemme, Anthony Lentine, Grant Biedermann, and Peter D. D. Schwindt, eng"A compact cold-atom interferometer with a high data-rate grating magneto-optical trap and a photonic-integrated-circuit-compatible laser system," Nature Communications **13**, 5131 (2022).

[4] Andrei Isichenko, Nitesh Chauhan, Debapam Bose, Jiawei Wang, Paul D. Kunz, and Daniel J. Blumenthal, en"Photonic integrated beam delivery for a rubidium 3D magneto-optical trap," Nature Communications **14**, 3080 (2023), number: 1 Publisher: Nature Publishing Group.

[5] Min Zhang, Ziwei Liu, Qiong Wu, Yuntian Teng, Xiaotong Zhang, Feibai Du, and Ying Jiang, "Hydrologic changes of in-situ gravimetry," Geophysics **87**, B117–B127 (2022).

[6] Maurizio Battaglia, Joachim Gottsmann, Daniele Carbone, and José Fernández, "4D volcano gravimetry," GEOPHYSICS **73**, WA3–WA18 (2008), publisher: Society of Exploration Geophysicists.

[7] John M. Goodkind, "The superconducting gravimeter," Review of Scientific Instruments

70, 4131–4152 (1999).

[8] Virendra Singh, "Einstein and the Quantum," (2005), arXiv:quant-ph/0510180.

[9] en-US"The Nobel Prize in Physics 1929," ().

[10] F. Arias, Z. Jiang, Lennart Robertsson, Leonid Vitushkin, Diethard Ruess, Christian Ullrich, Dave Inglis, Jacques Liard, Ian Robinson, Wangxi Ji, Wu Shuqing, Chiungwu Lee, Vojtech Palinkas, Jaakko Mäkinen, Franck Pereira dos Santos, Quentin Bodart, Sébastien Merlet, Shigeki Mizushima, In-Mook Choi, and Baki Karaböce, "Final report of key comparison CCM. G-K1: International comparison of absolute gravimeters ICAG2009," Metrologia **49** (2012), 10.1088/0026-1394/49/1A/07011.

[11] R. Colella, A. W. Overhauser, and S. A. Werner, "Observation of Gravitationally Induced Quantum Interference," Physical Review Letters **34**, 1472–1474 (1975), publisher: American Physical Society.

[12] John F. Clauser, "Ultra-high sensitivity accelerometers and gyroscopes using neutral atom matter-wave interferometry," Physica B+C **151**, 262–272 (1988), aDS Bibcode: 1988PhyBC.151..262C.

[13] Mark Kasevich and Steven Chu, "Atomic interferometry using stimulated Raman transitions," Physical Review Letters **67**, 181–184 (1991), publisher: American Physical Society.

[14] Carl Wieman, Gwenn Flowers, and Sarah Gilbert, "Inexpensive laser cooling and trapping experiment for undergraduate laboratories," American Journal of Physics **63**, 317–330 (1995).

[15] Zhong-Kun Hu, Bu-Liang Sun, Xiao-Chun Duan, Min-Kang Zhou, Le-Le Chen, Su Zhan, Qiao-Zhen Zhang, and Jun Luo, "Demonstration of an ultrahigh-sensitivity atom-interferometry absolute gravimeter," Physical Review A **88**, 043610 (2013), publisher: American Physical Society.

[16] O. Francis, en"Performance assessment of the relative gravimeter Scintrex CG-6," Journal of Geodesy **95**, 116 (2021).

[17] Guillaume Ramillien, Frédéric Frappart, and Lucia Seoane, en"Application of the Regional Water Mass Variations from GRACE Satellite Gravimetry to Large-Scale Water Management in Africa," Remote Sensing **6**, 7379–7405 (2014), number: 8 Publisher: Multidisciplinary Digital Publishing Institute.

[18] Karen Mohr, en"Gravity Recovery and Climate Experiment (GRACE) | Earth," Publisher: 610 Web Dev.

[19] Hongtao Hao, Hongliang Liu, Xinlin Zhang, Jin Wei, Bin Zhao, and Minzhang Hu, en"Terrestrial water storage variation in Hebei plain area of China, based on ground surface gravimetry," Geodesy and Geodynamics **12**, 190–196 (2021).

[20] "Volcano Watch — New instrument with new potential: the Absolute Quantum Gravimeter | U.S. Geological Survey," ().

[21] Storm Weiner, Xuejian Wu, Zachary Pagel, Dongzoon Li, Jacob Sleczkowski, Francis Ketcham, and Holger Mueller, "A Flight Capable Atomic Gravity Gradiometer With a Single Laser," (2020) pp. 1–3.

[22] Stuart S. Szigeti, Samuel P. Nolan, John D. Close, and Simon A. Haine, "High Precision, Quantum-Enhanced Gravimetry with a Bose-Einstein Condensate," Physical Review Letters

125, 100402 (2020), arXiv:2005.00368 [cond-mat, physics:physics, physics:quant-ph].

Appendix A: Sub-Doppler Cooling

Doppler cooling uses symmetrical lasers to excite an atomic transition in a moving atom and slow the atom in the cross-section of all incident lasers, When the atom returns to ground state, it will emit a photon, which provides a momentum kick. The momentum kick provides some velocity to the atom, creating a cooling limit, which we refer to as the Doppler limit. Different techniques can cool atoms below the doppler limit. Evaporative cooling and sisyphus cooling are notable because these methods can create a Bose-Einstein condensate. For more information on the applications of Bose-Einstein condensates in quantum gravimetry, refer to Appendix B.

Evaporative cooling selectively removes atoms with high kinetic energy, lowering the average velocity of the remaining atoms. In a MOT, the coolest atoms are found in the center while warmer atoms occupy peripheral areas. The magnetic field in a MOT is zero in the center and increases linearly in peripheral areas. The Zeeman effect changes the energy between the magnetic spin states, splitting the atomic transition into components. We can introduce a radiofrequency source to excite an atomic transition between m=-1 and m=1, removing warmer peripheral atoms that are impacted by the Zeeman effect.

Sisyphus cooling introduces a standing wave in polarization, which maximizes the potential energy and minimizes kinetic energy of the atom. We can create this standing wave using counter-propogating beams with orthogonal polarization.

To maximize cooling, we can remove the magnetic field in a MOT to create optical molasses, which cools but does not trap atoms. When we remove the magnetic trapping effect, the atom cloud immediately begins to fall out of the cooling mechanism. The system can cool the atoms for longer where gravity has less of an impact, such as on the international space station.

Appendix B: Bose-Einstein Condensate Gravimetry

In 2020 a group of researchers at the Australian National University tried another avenue on the path to miniaturizing AQGs [22]. They experimented with using a Bose-Einstein condensate (BEC), a boson gas at lower density and temperature than the atom cloud currently used in quantum gravimeters. While extreme cooling is impractical for most applications, early results show it reduces the required number of atoms by 96%. With current research in creating Bose-Einstein condensates at higher temperatures, this could be a possible avenue into making more compact or accurate gravimeters in the future.