Quantum Gravity Gradiometer Sensor for Earth Science Applications

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Abstract - **Quantum gravity gradiometers based on atom interferometry hold the promise for greater sensitivity and suitability for Earth science applications. Such instruments can potentially provide not only high resolution mapping of mass distribution both above and below the surface of the planet, but also temporal monitoring of its dynamical processes. These capabilities will significantly advance our knowledge of the solid Earth, the oceans, and under ground water.**

The underlying principle of atom-interferometry is the quantum particle-wave duality. According to quantum mechanics, atoms behave as waves, as does light. One can therefore construct an interferometer based on atom-waves much like laser interferometers. Because of the finite mass of the atom, matter-wave interferometers are intrinsically extremely sensitive to the gravity. Advances in laser cooling of neutral atoms and atom optics in recent years have made such atom-wave interferometers more practical than ever.

We are developing a quantum gravity gradiometer (QGG) sensor towards a portable and eventually flyable system. In our ground-based gradiometer implementation, two atom-interferometer-based accelerometers will be placed one above the other vertically. Each accelerometer is realized in an atomic fountain, where cold atoms are first produced in a magneto-optical trap by laser cooling. The atoms are then launched out of the trap and subsequently divided in two paths by laser light, and then recombined to form a Mach-Zehnder-type interferometer. Gravity, acting on the moving atoms, distorts the phase of the matter waves and therefore changes the interference pattern, which can be readily detected via laser resonance fluorescence.

In this paper, we will describe some of the underlying principles of QGG, discuss its potential capability, and report on the progress of our hardware development to date. We will also discuss the development of a new data recovery algorithm as part of the QGG sensor, which is required in view of the new hardware capability.

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I. INTRODUCTION

A comprehensive model of our planet is the key to understand the solid Earth, ice and oceans, and dynamic processes that have direct effects from global phenomena to our everyday life. There are at least two major ingredients for the realization of such a comprehensive model: geometry measurement and gravity field mapping. While the former has been progressing extremely well, particularly with the advent of GPS and laser and radar altimetry, the latter has been relative scarce and insufficient. There exist only a few very-limited terrestrial gravity monitoring networks. Gravity mapping has been carried out in space through GPS tracking of satellite orbits. Most significant change will come from the most recently launched GRACE mission. By tracking the distance between two dedicated satellites, GRACE will be able to recover the gravity data of the Earth with high precision for long wavelength measurement and monitoring.

We are developing a novel atom interferometer-based quantum gravity gradiometer (QGG) for space application. J. Clauser first proposed using an atom interferometer as a gravity sensor in 1988 [1]. This idea could not be fully realized until subsequent advances in laser cooling and manipulation of atoms. S. Chu's group at Stanford first experimentally demonstrated the measurement of g using a light-pulse atom interferometer in 1992 [2]. The technologic approach of the new gravity measurement device is drastically different from the satellite-tracking scheme. In fact, it is fundamentally different from any previous mechanical methods of gravity measurement. In a quantum gravity gradiometer, we use atoms themselves as test masses. At the same time, we utilize the quantum nature of atom as matter-wave to carry out interferometric measurement of the effect of gravity on the atoms. The exquisite sensitivity potentially achievable with atom-wave interferometry holds great promise for new gravity mapping and monitoring capabilities — higher measurement sensitivity, finer spatial resolution, and shorter-time temporal monitoring. All these will provide new gravity measurement

opportunities for the Earth Observing System in understanding the planetary inner structure and dynamics, changes in ice sheets and ocean currents, changes in underground water storage, and in overall scientific geodesy study.

In this paper, we will describe briefly the underlying principles of QGG, discuss its potential capability and applicability in space environments, and report on the progress of our hardware development to date. We will also discuss the development of a new data recovery algorithm as part of the QGG measurement system.

II. Principle of Atom Interferometry

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 [1].

In our quantum gravity gradiometer, we will employ the light-pulse atom interferometer technique. The full theory of this approach has been discussed in details in literature [3]. We will only briefly describe the ground-based operation as it is being implemented in our system setup.

Cesium 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 up to 10^9 atoms from a beam or a background vapor. After these atoms are collected, further laser-cooling brings the atoms' temperature down to 2–5 μK, corresponding to an rms velocity of a few cm/s. The cold atoms are launched vertically by introducing a slight frequency shift between pairs of lasers to create a moving "rest frame" for the atom ensemble. This so-called "atomic fountain" allows us twice the available interaction time with the atoms in an apparatus of given height. The atom interferometry is then performed during the subsequent free fall of atoms in the atomic fountain.

The atom interferometer uses a $\pi/2$–π–$\pi/2$ pulse sequence of stimulated Raman transitions between the two ground hyperfine states. The two counter-propagating Raman laser beams are oriented along the vertical launch axis, parallel to the direction of gravitational acceleration. The first $\pi/2$ pulse 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 lightly different velocity, realizing the first beam splitting of a traditional Mach-Zehnder-like interferometer. Similarly, subsequent π and $\pi/2$ pulsed redirect and recombine the atom waves to complete an interferometer loop. In the absence of gravity, the two paths of the interferometer would be identical and no relative phase shifts result. If, on the other hand, atoms experience an acceleration g during this time, a net phase shift difference is accumulated. This phase is given by $\Delta\phi = 2kgT^2$, where T, the interrogation time, is the time between the light pulses, and k is the Raman laser wave number.

The fringe of the interferometer can be read out by monitoring the relative populations of the two hyperfine states in the recombined atoms via laser-induced fluorescence. Knowing the laser wave number and the interrogation time, the gravity acceleration g can be determined. To see the resulting sensitivity in this kind of device, consider commonly used Cs atoms (transition wavelength λ at 852 nm): with a 1 s interrogation time, a mere $7 \times 10^{-9}\ g$ of gravity acceleration will cause a fringe phase shift of one full radian in a single measurement. The overall measurement sensitivity will depend on the readout signal-to-noise ratio (SNR), which is primarily determined by atom number shot-noise. A shot-noise-limited SNR of greater than 1000 per atom launch has been demonstrated [4]. This would imply a sensitivity better than $10^{-11}\ g$ for $T = 1$ s. One laboratory g measurement has already demonstrated a sensitivity of about $2 \times 10^{-8}\ g/\mathrm{Hz}^{1/2}$ and $1 \times 10^{-10}\ g$ resolution after two days integration [5]. The interrogation time was only 60 ms in that experiment, and the absolute accuracy was a few ppb.

Although the gravitational acceleration can be measured directly as described above, this measurement requires an inertial frame of reference which is very difficult to realize even in a laboratory environment. This roots to the fundamental physics of Einstein's Equivalence Principle, which states that one cannot distinguish the reference frame acceleration from the gravitational acceleration in a local measurement. Gravity gradiometry provides a more fundamental measure of the gravitational fields. A gradiometer measures the gravitational acceleration difference between two locations with a common reference frame. Other inertial

accelerations will be rejected as common mode noise. The simplest implementation of a QGG consists of two atom-interferometer accelerometers separated by some distance. The two acceleration measurements are performed simultaneously and by using the same Raman laser beams, so that the common-mode noise and uncertainties are effectively cancelled [6], as illustrated in Fig. 1. With this configuration in a laboratory setting, a gravity gradient sensitivity of 10 $E/Hz^{-1/2}$ (gravity gradient unit 1 E $=10^{-9}$ s^{-2}) has been demonstrated with an effective common-mode rejection of 140 dB [7].

III. Quantum Gravity Gradiometer in Space Environments

Impressive as the laboratory demonstrations were, the most significant sensitivity gain will come from the operation of QGG in space. There are several important operation differences between a ground-based system and a space-borne version. As it turns out, most of them will enhance the performance. We discuss some of the issues below.

As discussed before, the gradiometer sensitivity increases with the *square* of the interrogation time, in

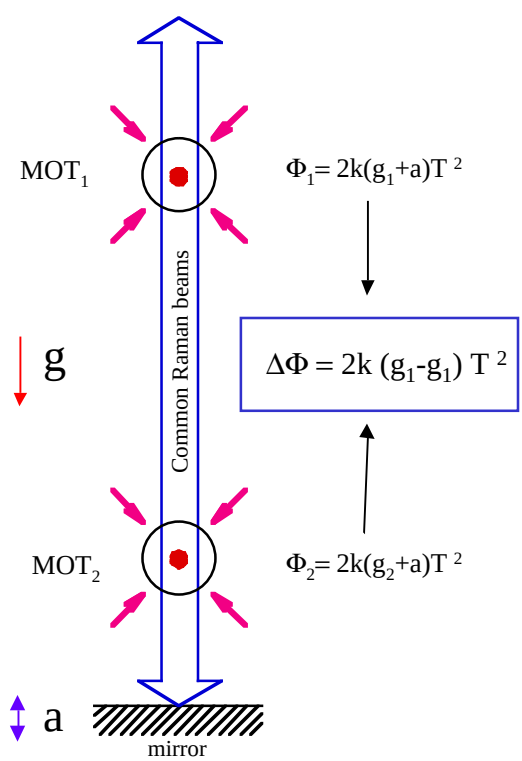

Fig. 1. Illustration of two magneto-optical traps and the configuration as a gravity gradiometer. The small shaded arrows designate the counter-propagating MOT beams with the dots as trapped atom clouds. They share the same Raman laser beams for high common-mode noise rejection.

contrast to the $1/T$ increase in precision with most other precision measurements such as atomic clocks. This results from the fact that first-order phase shifts due to accelerations are symmetric in the two interferometer arms, and they therefore cancel out. It is the second-order term in the Doppler-induced phase shifts that gives the net phase difference. In a ground-based experiment in an atomic fountain, the interrogation time is limited to a fraction of a second due to practical limitations in the height of the apparatus. When operating a similar experiment in a microgravity environment, no launch is necessary. The atoms will be drag-free in the frame of spacecraft, and will have little overall drift velocity. This allows interrogation times much longer than that is possible on the ground. For example, a 10 s interrogation time in space is feasible, which in principle gives more than 3 orders of magnitude improvement over ground-based fountains. As a result, a full radian phase shift corresponds to only a 7×10^{-12} g of acceleration. Assuming a modest SNR of 100 at 10 s interrogation time, one achieves 10^{-13} g in a single measurement sequence of about 20 seconds for each accelerometer. A gradiometer with a baseline separation of 10 m would give a corresponding sensitivity about 3×10^{-4} E per single measurement, or roughly 0.001 $E/Hz^{1/2}$.

It should be pointed out that the current interferometer operates in a pulsed mode. Only a single phase-readout can be made within each measurement sequence which is about twice the interrogation time plus the atom loading time. With a space-borne device, the measurement device is constantly moving at the orbiting speed. So each measurement data is an averaged acceleration value over the path of the spacecraft. There will be a trade off between the sensitivity of each measurement and the spatial resolution of the overall measurement. Fortunately, the interrogation time is an operation parameter that can be adjusted as needed in real time.

Microgravity operation of the quantum gravity gradiometer also makes multi-component gradient sensor measurements possible. In the Raman laser pulse scheme we use, the acceleration is always sensed in the direction of the Raman beams. On the ground, the large gravitational acceleration of the atoms makes the vertical direction the only possible measurement. In the microgravity environment, on the other hand, it is equally possible to measure other components. It is relatively straightforward to measure three diagonal components of the gravity gradient tensor. The three diagonal components are not independent, and the additional component provides a valuable crosscheck. The measurement of

the cross-terms of the gradient tensor is also conceivable. Implementation of such a system requires multiple-axis gradiometers, however, adds significantly to the complexity of the instrument.

IV. Experiment

We are developing a ground-based atom interferometer gravity gradiometer system with emphasizes on the technology development towards a portable and eventually a space-flyable system. We have so far demonstrated an atom interferometer in a laboratory atomic fountain. The experimental setup consists of ultra-high vacuum enclosure with a background pressure at about 5×10^{-10} Torr in the interaction region. Part of the vacuum enclosure serves as the Cs vapor cell from which atoms are collected. Three counter-propagating pairs of laser beams for the MOT are delivered via polarization-maintaining fibers though a set of six homemade collimator modules. All necessary laser beams are generated from semiconductor lasers and are frequency locked to various atomic transitions. We were able to collect about 10^8 atoms in 1 s MOT loading time. At the end of the loading, the MOT magnetic field was turned off and the trapping lasers were further detuned to allow optical cooling to below 5 μK. The atoms were then launched as an atomic fountain.

To improve the fringe contrast, further velocity selection was performed using the Doppler sensitive Raman transitions [8]. Our Raman laser intensity produces about 30 kHz Rabi bandwidth. Atoms with Doppler shift larger than 30 kHz along the launch axis were deselected, leaving an ensemble of atoms with less than 400 nK equivalent longitudinal temperature.

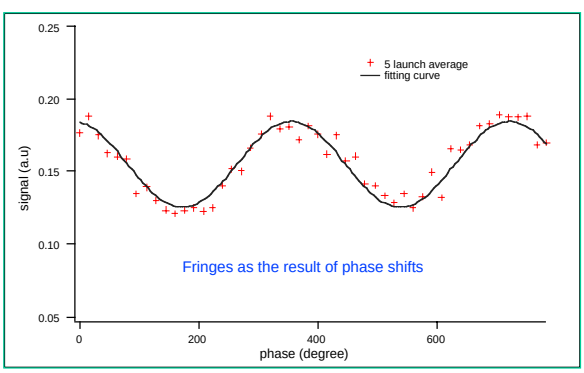

Fig. 2 An atom-interferometer fringe as the phase Raman laser is changed. The plot is the atom population signal (in arbitrary unit) vs. the Raman phase (in degree).

In subsequent interferometric measurements, a sequence of $\pi/2-\pi-\pi/2$ pulses is applied. The $\pi/2$ pulse duration is about 5 μs and π pulse 10 μs. The phase difference at the end of interferometer is then monitored by probing the population of one of the two hyperfine states. An interference fringe can be produced by simply changing the relative phase of the Raman pulses, as shown in Fig. 2. No signal normalization was performed in the experiment. In addition, the interrogation time is kept below 10 ms. This is because we have not implemented vibration isolation on the retro-reflecting mirror which acts as the frame of reference, and mirror vibrations and/or displacements affect the interference phase shift and degrade the fringe contrast. This is of course the reason why a gradiometer is necessary to cancel out the common of the reference frame vibration. When a full gradiometer system is implemented, suppression of such common mode effects can be greater than 140 dB

In an effort to develop a system beyond the laboratory setup, we have made progress toward a compact and robust laser system for the entire operation of the atom interferometer. This system is highly modularized using components used for fiber optical industrial whenever possible. Two master lasers are frequency-stabilized from which all other frequencies are derived using acoustic modulators. Laser frequency injection locking scheme is used to boost the power needed for the operation. The entire laser setup is reduced from a full $4' \times 8'$ optical table to a $2' \times 3' \times 1'$ box.

We are also in the process of developing a compact cold atom beam source for the atom-interferometer gravity gradiometer system. The use of the atom beam to load an UHV MOT allows fast loading times while still maintaining a low background of cesium atoms. The cold atom beam source is based on a 2D-MOT which extracts atoms from a separate high-pressure (10^{-7} Torr) Cs vapor cell. The slow cold atom beam from the 2D-MOT exits the source region though an aperture into the UHV region where they are captured by the 3D-MOT in the atomic fountain. The source will be a "bolt-on" modification to the main fountain chamber, with a single optical fiber connection for the trapping lasers and an electrical connection for the magnetic coils.

V. Inversion of Gravity Gradient Data

With the increased resolution promised by QGG, the associated inversion problem becomes computationally infeasible to address with classical global

inversion techniques, namely, the retrieval of spherical harmonic coefficients of the gravity potential. Even if the global problem were numerically tractable, the inversion would be dominated by 'nuisance' parameters characterizing the far field, of little interest for local phenomena. The unique value of the QGG sensor would be realized if we find localized inversion techniques that can retrieve the relevant features from the region of interest, be it volcano monitoring, aquifer depletion, underground structures or ocean bottom pressures.

The gravity gradient arising from a three-dimensional distribution of mass density $\rho(\vec{r})$ takes the form

$$\Phi_{ij}(\vec{r}) = \int K_{ij}(\vec{r}-\vec{R})\,\rho(\vec{R})\,d^3\vec{R}$$

This has the form of a convolution of the mass density, with translationally invariant kernel

$$K_{ij}(\vec{r}) = G\frac{r_i r_j - r^2\delta_{ij}}{r^5}$$

where r_i is the *i*-th component of the vector $\vec{r}$. The inversion problem is to recover useful information about the sources $\rho(\vec{r})$ from a set of measurements of the gravity gradient Φ_{ij}. As is well known, the unconstrained three-dimensional inversion is ill-posed; for example, any local spherically symmetric redistribution of mass leaves the exterior gravitational potential, and *a fortiori* the gradient, unchanged.

One useful constraint on the inversion, which usually results in a well-posed problem, is to restrict the sources to a two-dimensional surface. In the case of the full gravitational field, this is not a realistic *ansatz*, but if we are interested in changes in the gravitational field on time scales of days to months, it makes sense to model the changes as arising from mass redistribution within a relatively narrow layer about the surface of the Earth. We first consider approximating a localized region as a flat plane, with the gradient measurements taken on a horizontal plane at height h above the ground. With this regular geometry, the measurement model for any given component of the gravity gradient reads

$$\Phi_{ij}(\vec{r}) = \int K_{ij}(\vec{r}-\vec{R})\,\sigma(\vec{R})\,d^2\vec{R}$$

which is also a convolution with translationally invariant kernel K_{ij}. One formal approach to the inversion is to take the Fourier transform of each side. The convolution becomes a product in transform space:

$$\tilde{\Phi}_{ij}(\vec{k}) = \tilde{K}_{ij}(\overrightarrow{-k})\,\tilde{\sigma}(\vec{k})$$

where a tilde indicates the Fourier transform. Spectral deconvolution involves solving this equation for the Fourier transform of the source distribution:

$$\tilde{\sigma}(\vec{k}) = \frac{\tilde{\Phi}_{ij}(\vec{k})}{\tilde{K}_{ij}(\overrightarrow{-k})}$$

which directly yields the desired distribution of sources $\sigma(\vec{r})$, at least formally, upon taking the inverse Fourier transform. An instability arises for this approach when the kernel transform $\tilde{K}_{ij}$ in the denominator becomes small. A standard solution for this sort of problem is Tikhonov regularization, which involves introducing a small positive parameter α and regularizing the ratio according to

$$\tilde{\sigma}^{(\alpha)} = \frac{\tilde{\Phi}_{ij}\tilde{K}_{ij}^{*}}{\tilde{K}_{ij}\tilde{K}_{ij}^{*} + \alpha}$$

Fig. 3 (1) and (2) show examples of simulated recovery of gravitational sources using spectral deconvolution of space-based gravity gradient data.

V. Conclusions

Atom interferometry is a novel and emerging quantum technology that has the potential to provide new gravity measurement capability in Earth science applications. The new approach uses atoms as identical test masses, and measures gravitational fields directly. All necessary manipulations of atoms are accomplished using diode lasers, without any need for mechanical moving parts or cryogen. We are currently developing a ground-based demonstration device which will have state-of-the-art performance in gravity gradient measurements. By going to a microgravity environment in space, such a device will have much greater sensitivity because of the longer interrogation times possible. We believe that a 10^{-3} E/Hz$^{1/2}$ in space is realizable in the near future, with comparable long-time accuracy. This long-time performance is not possible with any mechanical device. The Quantum Gravity Gradiometer would significantly improve the Earth gravity monitoring capability, by complimenting and extending beyond GRACE-like missions. It is also conceivable to combine the QGG technology with satellite-to-satellite tracking methods to create a

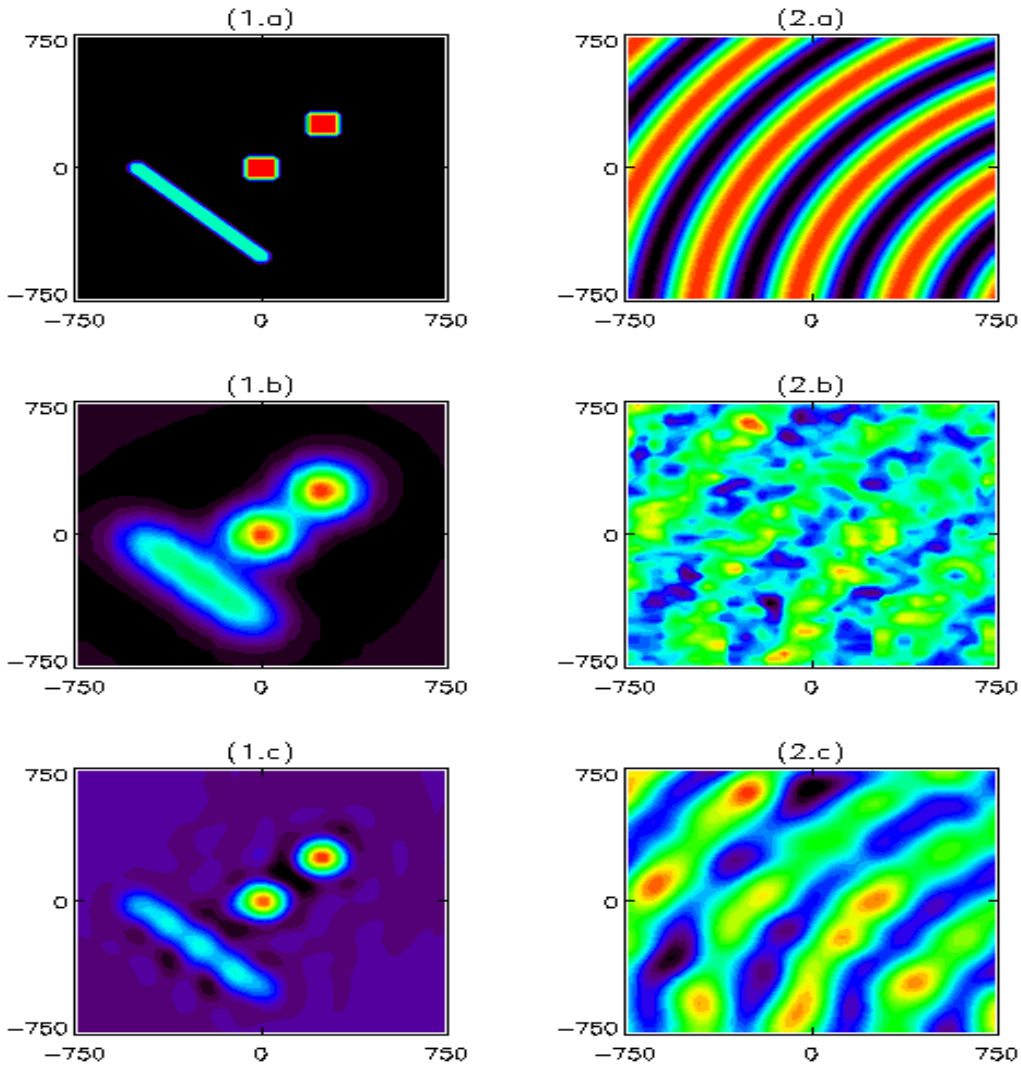

Fig. 3. (1) and (2) above show examples of inversion of simulated gravity gradient data by Fourier deconvolution. Part (a) in each shows a distribution of surface mass density; in figure (1) there are two arbitrary pointlike sources and one linelike source, while figure (2) is a "toy model" of ocean bottom pressure horizontal structure with length scale (half wavelength) 200 km (the units for the horizontal axes are kilometers; the regions are assumed to be in mid-latitudes). Part (b) shows the horizontal distribution of gravity gradient data, in each case taken from one month of passes by a polar orbiter at 200 km altitude. Finally, part (c) is the reconstruction of the sources by deconvolution, to be compared with (a). The inversions include the effects of data noise (modeled as white Gaussian); discretization to a finite 64×64 grid to implement the FFTs (only the interior region is shown); orbit height variations at the kilometer level; interpolation to data gaps; and geometrical distortion from performing the forward model with a curved Earth (while the deconvolution is done on a projected plane). Note that for the sharp sources (1a), the inversion (1c) manages to sharpen the spread-out "image" (1b); much of the remaining blurring is a result of the data noise. For the wider source (2a), the deconvolution has an opposite effect, tending to smooth out the noisy "image" (2b).

comprehensive gravity measurement system that neither technology alone can accomplish. It is worth pointing out that atom interferometry is still in its infancy relative to other inertial sensor technologies. There are already paths identified that will improve the QGG sensitivity further, even by orders of magnitudes. These paths are being investigated in our laboratory and others around the world. Finally, given the possibility of increased resolutions with QGG, we have invested local gradient inversion schemes rather global inversion which may become numerically inefficient or intractable.

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