

Wavefront Mapping for Absolute Atom Interferometry

Joseph Junca,^{1,2} John Kitching,¹ and William McGehee^{1,*}

¹*Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA*

²*Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*

(Dated: April 10, 2026)

Wavefront distortions are a leading source of systematic uncertainty in light-pulse atom interferometry, limiting absolute measurements of gravitational acceleration at the 30 nm/s^2 level. Here, we demonstrate *in situ* spatially resolved measurement of the interferometer phase in a Mach-Zehnder atom interferometer as a tool to characterize and correct wavefront bias. By introducing controllable curvature of the Raman light using an adjustable collimation retro-reflector, we show that the bias due to parabolic wavefront curvature can be measured with 1 mrad uncertainty and that finite-size corrections impact the measured phase curvature. This measurement process could be adopted in optimized atom interferometer gravimeters to reduce wavefront bias uncertainty below the nm/s^2 level.

Introduction—Light-pulse atom interferometry (LPAI) [1, 2] is used to make precise measurements of inertial effects [3–5], to determine the values of fundamental constants [6, 7], and to probe physics beyond the standard model [8–10]. Applications in inertial sensing have been pursued for decades, as atom interferometry offers a path to high sensitivity measurements with low absolute uncertainty. LPAI gravimeters exemplify this trend, reaching stability levels matching the best cryogenic relative gravimeters [4] and approaching the absolute uncertainty of falling corner-cube gravimeters of $\approx 20 \text{ nm/s}^2$ [11, 12]. Fieldable LPAI gravimeters and gravity gradiometers could impact a broad range of geo-science applications including ground water monitoring, resource extraction, and measurements of volcanic activity [13–16].

The lowest reported absolute uncertainties in LPAI gravimeters are approximately 30 nm/s^2 [3, 17, 18], limited by several effects including Coriolis phases, magnetic shifts, light shifts, and wavefront aberrations. Many of these biases can be characterized with low uncertainty or rejected using differential measurements [19, 20]. Wavefront non-ideality of the interferometer light can directly bias the interferometric phase due to unequal sampling of the wavefront phase as the atoms expand or move during the measurement sequence [17, 18, 21]. Significant wavefront biases can be generated by wavefront curvature at the 10 km scale, strained vacuum windows, and Gouy phases—requiring *in situ* characterization to realize the lowest absolute wavefront uncertainty.

Quantifying the systematic effects of wavefront imperfections on LPAI measurements is a difficult task [22–27] and often relies on estimations of surface flatness of the optical elements and *ex situ* characterization of the interferometer beam. Zero-temperature extrapolation of the wavefront bias has shown that low-order Zernike wavefront analysis is insufficient for bias correction and that the bias can vary non-monotonically with gas temperature [25]. Recently, progress has been made on *in situ* wavefront characterization in Ramsey-Borde interferom-

eters, with demonstrations of 1D mapping of the relative integrated atomic phase [28] and the k-vector magnitude [29], both measured by translating the position of the atoms in the optical field. Mapping of the interferometer phase within a single expanding gas is commonly used in point-source atom interferometry [30] and has been demonstrated in a Bragg interferometer using principal-component analysis and ellipse fitting [31].

In this work, we demonstrate *in situ* 2D mapping of the interferometer phase in a Raman LPAI to measure and correct the wavefront bias. Imaging of the atoms in the plane transverse to the interferometer’s k-vector enables direct measurement of the transverse-motion biases including phases from magnetic gradients and wavefront curvature. To demonstrate accurate measurement of the wavefront bias, we introduce controlled wavefront curvature by varying the collimation of the retro-reflected Raman beam. We combine spatially resolved maps of the interferometer phase with k-reversal [19] to isolate the systematic error due to wavefront distortion, and we demonstrate that the measured wavefront curvature bias can be characterized at the mrad level.

Experimental description—Spatial wavefront mapping is demonstrated in a Mach-Zehnder ($\pi/2 - \pi - \pi/2$) atom interferometer using laser-cooled ^{87}Rb atoms in the apparatus described in Ref. [32]. Briefly, $\sim 10^7$ atoms are cooled to $\approx 3 \mu\text{K}$ using a 3D magneto-optical trap and optical molasses cooling. The atoms are allowed to fall under the influence of gravity, and Doppler-sensitive Raman transitions between the $F = 1, 2$ ground state levels are used to recoil the atoms by $\hbar k_{\text{eff}}$ as shown in Fig. 1(a), where $k_{\text{eff}} = 4\pi/\lambda$ is the Raman k-vector and $\lambda \approx 780 \text{ nm}$ is the wavelength of the Raman light.

The interferometer operates with a time $T = 16 \text{ ms}$ between each pulse, and the first Raman pulse is delayed 8 ms after release to resolve the desired Doppler-sensitive transitions. The resonant Raman light fields are detuned by $\approx 210 \text{ MHz}$ below the $F' = 3$ excited state and have the same circular polarization [33]. The Raman π transition time is $\sim 5 \mu\text{s}$, and the atoms expand for

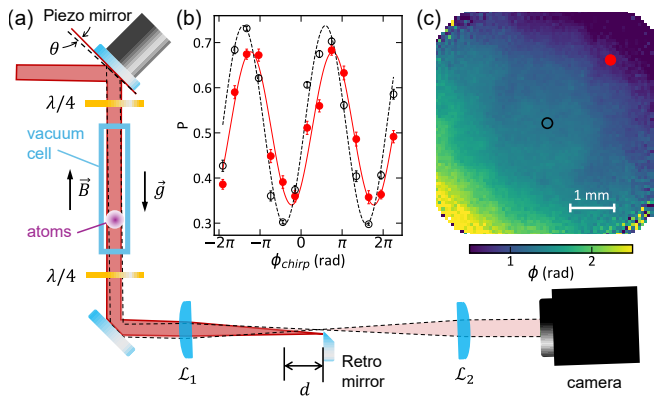


FIG. 1. *In situ* phase mapping. (a) An experimental schematic shows that the Raman interferometer light (red) is retro-reflected using a pick-off mirror placed near the center of a 4-f imaging system. The wavefront curvature of the retro-reflected Raman beam is controlled by translating the retro-reflecting mirror by a distance d away from the focus of lens \mathcal{L}_1 . Deflection of this beam path (dashed) allows for imaging in the transverse plane of the interferometer. (b) The local interferometer phase is inferred by spatially measuring the interferometer transfer probabilities as the global interferometer phase is varied. Two characteristic interference fringes are shown (black and red) from the spatial interferometer phase map in (c) for $+k_{\text{eff}}$. Error bars indicate the standard uncertainty of the mean.

$T_{\text{ex}} \approx 45$ ms. The experimental drop time, Raman beam size (≈ 4.5 mm $1/e^2$ radius), and T are limited by the cm-scale of the vacuum vessel used in this work. The total experimental cycle is ~ 1 s, dominated by the time used to capture atoms in the MOT.

During the interferometer sequence, the two-photon Raman detuning is linearly swept to follow the Doppler shifted resonance as the atoms are accelerated by gravity. The phase of the interferometer is $\phi = (\mathbf{k}_{\text{eff}} \cdot \mathbf{g} - \alpha)T^2 + \phi_{\text{sys}}$, where \mathbf{g} is the gravitational acceleration vector, $\alpha \sim \pm 2\pi \cdot 25.1$ MHz/s is the Raman chirp rate, and ϕ_{sys} are the phases generated from other sources including magnetic fields, light shifts, and Coriolis phases. By changing the sign α , we select which pair of counter-propagating Raman fields is resonant and change the sign of the momentum kick imparted to the atoms [19]. The atoms are detected using absorption imaging along the Raman \mathbf{k} -vector using 4-f imaging optics $\mathcal{L}_{1,2}$ with focal lengths $f = 150$ mm.

The Raman light is retro-reflected in a “cat-eye” geometry using a pickoff mirror located near the center of the 4-f imaging system. This geometry maintains a constant intensity ratio of the $F = 1, 2$ frequency components of the Raman light as there are no polarization sensitive elements. The intensity ratio is chosen to minimize differential light shifts [34], and residual light shifts are largely common mode between the $\pm k$ transitions. Imaging is achieved by deflecting this beam path using

a piezo-actuated mirror so that the imaging light passes the pickoff mirror and is recorded on a camera. The beam is deflected by ≈ 2.5 mrad, and this process introduces a 6.8 ms delay between the last Raman pulse and detection.

Phase mapping—The spatially-resolved interferometer phase is measured using pixel-by-pixel fitting of the interferometer signal [35]. To enable local determination of the interferometer phase ϕ_i and contrast c_i , the global phase of the interferometer is scanned over a range of $\approx 4\pi$ by varying α ; the corresponding Raman frequency chirp phase is $\phi_{\text{chirp}} = (\alpha - \alpha_0)T^2$, where α_0 is the chirp rate which nulls the gravitational phase shift. The spatially-resolved, fractional interferometer transfer probability P_i is fit to a sinusoidal function $P_i = [1 - c_i \cos(\phi_{\text{chirp}} + \phi_i)]/2$ to infer ϕ_i at each pixel i as shown in Fig. 1(b).

An example of the resulting phase maps is shown in Fig. 1(c). The atomic absorption signal is recorded at $9 \mu\text{m}$ spatial resolution, and the data is processed after 8×8 binning of the data such that each pixel is $72 \mu\text{m}$ by $72 \mu\text{m}$. In the center of the gas, each pixel detects ~ 6000 atoms and the interferometer contrast is $\approx 40\%$. For the recorded data, the single-shot phase noise from uncompensated vibrations is ≈ 70 mrad and dominates the projection and measurement noise except near the edges of the gas.

Phase variation across the atomic sample is observed at the radian level due to a combination of inertial and non-inertial phases. To aid in isolating the wavefront phases, we perform \mathbf{k} -reversal to reject differential light shifts and magnetic gradients that are common-mode to both \mathbf{k} -vectors. The $\pm k$ phase maps ϕ_{+k} and ϕ_{-k} are combined to separate these signals, forming the differential and common-mode signals $\phi_{\Delta} = (\phi_{+k} - \phi_{-k})/2$ and $\phi_{\Sigma} = (\phi_{+k} + \phi_{-k})/2$, respectively, as shown in Fig. 2.

The differential signal ϕ_{Δ} includes the desired inertial phases, wavefront biases, and other asymmetries which exist in the atom interferometer; a representative image is shown in Fig. 2(a). The inertial phases include the linear acceleration phase as well as the Coriolis phase gradient $\mathbf{k}_{\Omega} = 2(\mathbf{k}_{\text{eff}} \times \Omega_{\oplus})T^2/T_{\text{ex}} \sim 9.7$ rad/m, where Ω_{\oplus} is the Earth rotation rate [36]. The Coriolis phase has an odd symmetry relative to the transverse velocity, and they do not contribute to the integrated acceleration bias in most LPAIs, except through asymmetrical sampling. Other common asymmetries could bias ϕ_{Δ} including two-photon light shifts [20], residual Doppler shifts [37], and other effects which limit the symmetry of the \mathbf{k} -reversal measurement. The inertial phase gradients is small in this measurement, and the spatial variation of ϕ_{Δ} arises primarily from wavefront aberrations.

The measured ϕ_{Δ} have a strong anti-symmetry around the center of the transverse velocity distribution, as visible in Fig. 2(a), arising from the -1 magnification ratio of the “cat-eye” retro-reflector. In this geometry, any wavefront structure in the incident Raman laser beam is

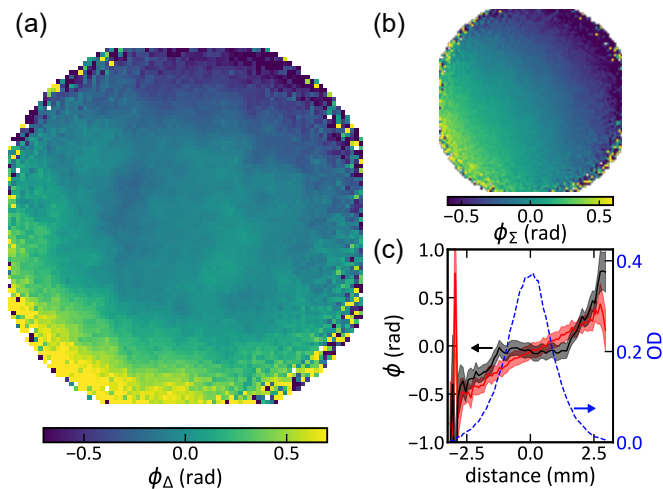


FIG. 2. Phase mapping with k-reversal. Maps of ϕ_Δ (a) and ϕ_Σ (b) show phases which are differential and common mode under k-reversal, respectively. (c) Traces of ϕ_Δ (black), ϕ_Σ (red), and the optical depth (OD) of the gas (blue) are shown along a diagonal of the maps. The field of view in (a,b) is 5.8 mm \times 5.8 mm with near zero applied wavefront curvature.

spatially inverted upon retro-reflection and contributes to the odd symmetry of the ϕ_Δ maps. The odd components of ϕ_Δ do not bias the integrated phase measurement used in gravimetry but would bias measurements made in point-source atom gyroscopes [30, 35]. We isolate the even, phase-biasing signal by symmetrizing the images according to $\phi_{\text{even}}(\mathbf{r}) = (\phi_\Delta(\mathbf{r}) + \phi_\Delta(-\mathbf{r}))/2$, where \mathbf{r} is the position vector relative to the center of the final gas; example of these maps are shown in Fig. 3.

The common mode signal ϕ_Σ shown in Fig. 2(b) includes effects which do not depend on the sign of the k-vector. Here, ϕ_Σ is dominated by a magnetic gradient estimated at $\approx 0.6 \mu\text{T}/\text{mm}$. This gradient generates an interferometer phase gradient $\phi' \approx -2\gamma B|B'|T^2/T_{\text{ex}}$ where γ is the 2nd-order Zeeman shift coefficient, $B \approx 70\mu\text{T}$ is the field strength, and $|B'|$ is the field's spatial gradient in the transverse plane. Magnetic gradients along the Raman k-vector are not resolved in this signal and could contribute to ϕ_Δ since the atoms travel on slightly different trajectories for $\pm k$.

Wavefront characterization—To demonstrate wavefront characterization, we vary the Raman wavefront curvature and measure the impact on ϕ_{even} as shown in Fig. 3(a). The curvature is introduced by controllably varying the collimation of the retro-reflected Raman light by translating the pickoff mirror within the “cat-eye” retro-reflector as indicated in Fig. 1(a). This generates a Raman wavefront difference with a radius-of-curvature $R_{\text{light}} = f^2/2d$, where d is the displacement of the mirror from the focal plane of lens \mathcal{L}_1 .

The applied wavefront curvature modifies the interferometer phase as atoms sample different points in the

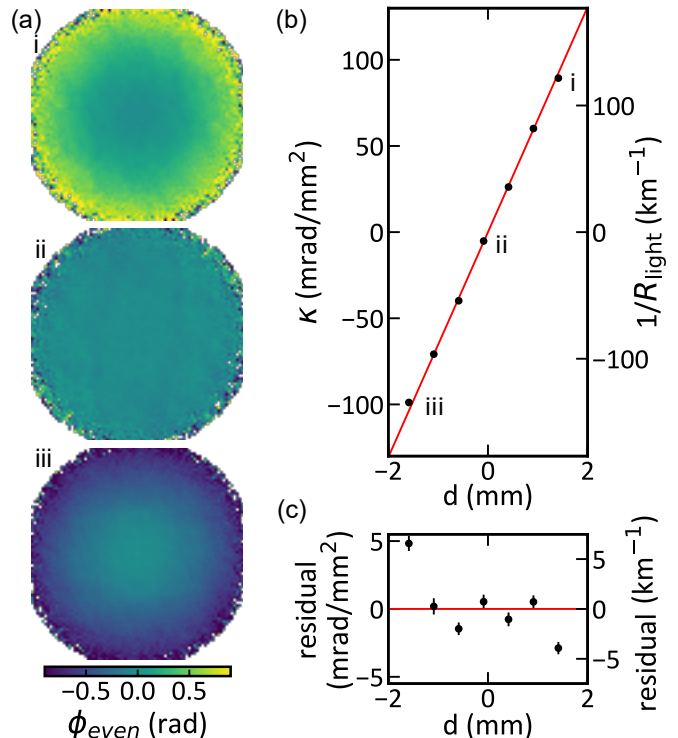


FIG. 3. Wavefront curvature measurement. (a) Maps of ϕ_{even} are recorded at varying Raman wavefront curvature set by the retro-reflecting mirror position d . (b) The curvature of ϕ_{even} is extracted from these maps (black points) and compared to the predicted curvature from Eq. (1) (red line). Labeled points correspond to the maps in (a) and residuals are shown in (c). The right axes in (b,c) are inferred using Eq. 1; some error bars are smaller than the markers.

Raman beam at each of the LPAI light pulses. A useful approximation for the wavefront phase in an LPAI is $\phi_{\text{atom}} = \phi_{\text{light}}(\mathbf{r}_1) - 2\phi_{\text{light}}(\mathbf{r}_2) + \phi_{\text{light}}(\mathbf{r}_3)$, where ϕ_{light} is the phase of Raman light and \mathbf{r}_i is the location of the atom at the i -th light pulse [36]. For the case of a parabolic wavefront, such as the kind generated by varying the collimation of the Raman light, $\phi_{\text{light}} = k_{\text{eff}}\mathbf{r}^2/4R_{\text{light}}$ and $\phi_{\text{atom}}(\mathbf{v}) = k_{\text{eff}}\mathbf{v}^2T^2/2R_{\text{light}}$ [38], where \mathbf{v} is an atom's transverse velocity vector.

Practical LPAIs have a spread of velocities at each \mathbf{r} due to the finite size of the initial, laser-cooled gas, and the observed wavefront curvature is reduced by the imperfect position-velocity correlation observed at the time of imaging. For a thermal gas with a Gaussian initial size σ_0 and final size σ_f , the expected wavefront is

$$\phi_{\text{even}}(\mathbf{r}) = \frac{k_{\text{eff}}T^2}{2R_{\text{light}}T_{\text{ex}}^2} (\beta^2\mathbf{r}^2 + 2\beta\sigma_0^2), \quad (1)$$

where $\beta = 1 - \sigma_0^2/\sigma_f^2$ [33]. Equation (1) is calculated by integrating the wavefront phase shifts over the atomic velocity and initial position distributions, similar to the calculation of finite-size corrections in point-source atom interferometry [39]. Equation (1) includes a phase offset

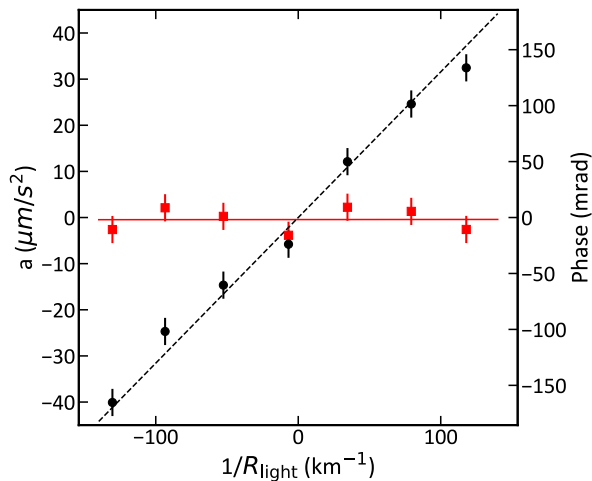


FIG. 4. Wavefront bias and correction. The integrated acceleration signal (black circles) is shown as the wavefront curvature is varied (same dataset as Fig. 3) and compared to the expected bias $\langle a_{\text{bias}} \rangle = \sigma_v^2/R_{\text{light}}$ (dashed black line). A bias-free signal (red squares) is extracted from the central ($|\mathbf{r}| < \sigma_0$) interferometer phase accounting for the finite size bias ϕ^* . A linear fit to the bias-corrected data (solid red line) is consistent with zero slope, implying strong suppression of wavefront curvature biases. The datasets are offset so that the a is approximately zero at $R_{\text{light}}^{-1} = 0$.

ϕ^* at $\mathbf{r} = 0$; this offset is maximally $\phi^* = k_{\text{eff}}\sigma_0^2/8R_{\text{light}}$ in the limit of large expansion where $\beta = 1$ and $T_{\text{ex}} = 2T$.

In our LPAI, the spatial phase mapping procedure with k -reversal was repeated as R_{light} was varied over a range of ≈ -8 m to $+8$ m as shown in Fig. 3. For these measurements, 480 runs of the interferometer sequence were used at each mirror position, and the maximum variation of the retro-reflected light intensity from the applied curvature is $< 10\%$ at the atoms. The resulting maps of ϕ_{even} were fit to parabolic surfaces [33] as

$$\phi_{\text{even}} = \kappa \mathbf{r}^2 + \phi_{\text{offset}}. \quad (2)$$

The extracted values for κ are shown in Fig. 3(b), and the data agree with Eq. (1) with no free parameters as shown in the residuals plotted in Fig. 3(c). The ratio $\sigma_0/\sigma_f \approx 0.33$ for this data.

Bias correction—The effect of wavefront curvature on the measured acceleration signal is quantified using the data in Fig. 3. The average acceleration across the measured ϕ_{Δ} maps is calculated as

$$\langle a \rangle = k_{\text{eff}}T^2 \langle \phi_{\Delta,i} \rangle, \quad (3)$$

where the brackets indicate a weighted averaging over the phases measured at each pixel i . The weights are set by the occupation of each pixel N_i , analogous to the averaging that occurs in integrated fluorescence detection in conventional LPAIs. The results are shown in Fig. 4, where the data are plotted against R_{light}^{-1} from Fig. 3.

The measured acceleration depends linearly on the inverse of the wavefront curvature [34], and the values are consistent with the expected bias for a thermal gas as

$$\langle a_{\text{bias}} \rangle = \sigma_v^2/R_{\text{light}}, \quad (4)$$

where $\sigma_v = \sqrt{k_B\tau/m}$, $\tau = (3.3 \pm 0.2) \mu\text{K}$ is the gas temperature, and m is the atomic mass. The acceleration bias is independent of the interferometer time T as the scale factor and phase bias both scale with T^2 . The bias is independent of finite size effects, but does depend on the distribution of atomic velocities. The uncertainty of the bias characterization is set by the measurement uncertainty of R_{light} and of the gas temperature. For the measurement in Fig. 3(ii), $R_{\text{light}}^{-1} = (-6.83 \pm 0.68) \text{ km}^{-1}$ and the acceleration bias is $(-21.5 \pm 2.5) \times 10^{-7} \text{ m/s}^2$, equivalent to $(-8.9 \pm 1.0) \text{ mrad}$ in phase bias.

A “bias-free” inertial signal can also be extracted from ϕ_{even} by evaluating the central phase $\phi_{\text{even}}(\mathbf{r} = 0)$ and subtracting the finite-size phase offset ϕ^* as in Eq. (1). The central phase can be extracted using surface fitting of the phase maps, but we evaluated this phase numerically using the central 10% of the atoms and the weighting used in Eq. (3) to avoid potential artifacts from higher-order wavefront curvature. Here, the phase offset $\phi^* = \beta\sigma_0^2k_{\text{eff}}(T/T_{\text{ex}})^2/R_{\text{light}} \approx 150 \mu\text{rad km}$, equivalent to $\approx 36 \text{ nm/s}^2 \text{ km}$ for $T = 16$ ms. The resulting inertial signal $a = k_{\text{eff}}T^2(\phi_{\text{even}}(\mathbf{r} = 0) - \phi^*)$ rejects the wavefront curvature bias and is shown as the red squares in Fig. 4. A line fit to this data of form $a = \alpha R_{\text{light}}^{-1}$ produces a slope of $\alpha = (0.2 \pm 13) \text{ nm/s}^2 \text{ km}$, consistent with zero. Whereas, the sensitivity of the uncorrected acceleration signal to wavefront curvature from Eq. (4) is $\alpha = \sigma_v^2 \approx 290 \text{ nm/s}^2 \text{ km}$.

The uncertainty of the corrected phases in Fig. 4 are dominated by laboratory vibration noise to ≈ 10 mrad at 8 minutes of integration time, and the mrad-level wavefront bias uncertainty exceeds the stability of the interferometer signal. This level of phase bias uncertainty would allow for $\approx 5 \text{ nm/s}^2$ wavefront bias uncertainty at $T = 100$ ms, which could be reduced below 1 nm/s^2 using longer averaging times and vibration rejection. The quantum projection noise (QPN) limit [40] to wavefront curvature measurement is calculated using a least-squares approach [41] as $\sigma_{R_{\text{light}}^{-1}} = 1/k_{\text{eff}}T^2\sqrt{2N}\sigma_v^2$, where N is the total number of atom in the interferometer. The QPN limit on the associated wavefront bias uncertainty is

$$\sigma_{\langle a_{\text{bias}} \rangle} = \frac{d \langle a_{\text{bias}} \rangle}{dR_{\text{light}}^{-1}} \sigma_{R_{\text{light}}^{-1}} = \frac{1}{\sqrt{2N}k_{\text{eff}}T^2}, \quad (5)$$

which is independent of R_{light} and similar to the QPN-limited acceleration uncertainty $\sigma_a = 1/\sqrt{N}k_{\text{eff}}T^2$ [33]. This implies that wavefront systematics could be evaluated at the level needed to reduce absolute acceleration uncertainty in leading atom interferometers.

Conclusion—Transverse spatial phase mapping in LPAI, as demonstrated in this work, enables *in situ* evaluation of wavefront biases and reduction of the absolute uncertainty of the inertial atom interferometer phase. This approach is complimentary to methods that strongly suppress the gas temperature and associated transverse motion biases using evaporative cooling or δ -kick cooling, which may not be feasible in compact or transportable atom interferometers. Here, we show that evaluation of the parabolic wavefront phase at the ≈ 1.0 mrad level, which would enable optimized atom interferometers to reduce the wavefront bias from the 30 nm/s^2 level to below 1 nm/s^2 .

This study focused on the parabolic wavefront bias, but higher-order wavefront analysis is likely necessary to capture the full absolute bias on inertial phases for more complex wavefront profiles [37]. This analysis would involve fitting of ϕ_Δ to Zernike polynomials and involve corrections to the gravimetric phase for each of the even-order terms. The higher order terms do not have constant curvature, and measuring the final position of the atoms in the gas with respect to the wavefront would be necessary to correct these biases. We have performed this Zernike analysis up to 8th-order for our measurements of ϕ_Δ , and the resulting curvature values are consistent with the ϕ_{even} analysis presented in Fig. 3.

Transverse phase mapping is a direct method for measuring the wavefront biases and could be incorporated into many LPAI systems as a calibration step or as the primary phase measurement. The “cat-eye” retro-reflection approach used here enabled imaging in the transverse plane and provided a convenient method to control the curvature of the wavefront, but other methods for retro-reflection may be more practical in fieldable gravimeters and large-scale interferometers, including use of dichroic optics or partially-reflective mirrors, without the need for a rapid mirror motion. Spatial wavefront mapping may prove useful in a broad range of LPAI systems including gyroscopes, long-baseline interferometers [42], and other measurements where mrad-level phase accuracy is needed [43].

Acknowledgment—This work was supported by the National Institute of Standards and Technology and the “NIST on a Chip” program. JJ acknowledges the financial assistance award 70NANB23H027 from U.S. Department of Commerce, NIST. We thank Greg Hoth and Stephen Eckel for helpful suggestions on this manuscript, and we thank Elizabeth Donley for her years of support as chief of the Time and Frequency Division at NIST.

Data Availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

* william.mcgehee@nist.gov

- [1] A. D. Cronin, J. Schmiedmayer, and D. E. Pritchard, Atom Interferometers, *Reviews of Modern Physics* **81**, 1051 (2009).
- [2] S. Abend, M. Gersemann, C. Schubert, D. Schlippert, E. M. Rasel, M. Zimmermann, M. A. Efremov, A. Roura, F. A. Narducci, and W. P. Schleich, Atom interferometry and its applications, in *Foundations of Quantum Theory* (IOS Press, 2019) pp. 345–392.
- [3] A. Peters, K. Y. Chung, and S. Chu, Measurement of gravitational acceleration by dropping atoms, *Nature* **400**, 849–852 (1999).
- [4] T. Zhang, L.-L. Chen, Y.-B. Shu, W.-J. Xu, Y. Cheng, Q. Luo, Z.-K. Hu, and M.-K. Zhou, Ultrahigh-sensitivity bragg atom gravimeter and its application in testing lorentz violation, *Physical Review Applied* **20** (2023).
- [5] D. Savoie, M. Altorio, B. Fang, L. A. Sidorenkov, R. Geiger, and A. Landragin, Interleaved atom interferometry for high-sensitivity inertial measurements, *Science Advances* **4** (2018).
- [6] G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli, and G. M. Tino, Precision measurement of the newtonian gravitational constant using cold atoms, *Nature* **510**, 518–521 (2014).
- [7] L. Morel, Z. Yao, P. Cladé, and S. Guellati-Khélifa, Determination of the fine-structure constant with an accuracy of 81 parts per trillion, *Nature* **588**, 61–65 (2020).
- [8] S. Dimopoulos, P. W. Graham, J. M. Hogan, and M. A. Kasevich, Testing General Relativity with Atom Interferometry, *Physical Review Letters* **98**, 111102 (2007).
- [9] D. O. Sabulsky, I. Dutta, E. A. Hinds, B. Elder, C. Burrage, and E. J. Copeland, Experiment to detect dark energy forces using atom interferometry, *Phys. Rev. Lett.* **123**, 061102 (2019).
- [10] P. Asenbaum, C. Overstreet, M. Kim, J. Curti, and M. A. Kasevich, Atom-interferometric test of the equivalence principle at the 10^{-12} level, *Physical Review Letters* **125** (2020).
- [11] T. M. Niebauer, G. S. Sasagawa, J. E. Faller, R. Hilt, and F. Klocking, A new generation of absolute gravimeters, *Metrologia* **32**, 159 (1995).
- [12] O. Francis, H. Baumann, T. Volarik, C. Rothleitner, G. Klein, M. Seil, N. Dando, R. Tracey, C. Ullrich, S. Castelein, H. Hua, W. Kang, S. Chongyang, X. Songbo, T. Hongbo, L. Zhengyuan, V. Pálinkás, J. Kostelecký, J. Mäkinen, J. Näränen, S. Merlet, T. Farah, C. Guerlin, F. P. D. Santos, N. L. Moigne, C. Champollion, S. Deville, L. Timmen, R. Falk, H. Wilmes, D. Iacovone, F. Baccaro, A. Germak, E. Biolcati, J. Krynski, M. Sekowski, T. Olszak, A. Pachuta, J. Agren, A. Engfeldt, R. Reudink, P. Inacio, D. McLaughlin, G. Shannon, M. Eckl, T. Wilkins, D. van Westrum, and R. Billson, The European Comparison of Absolute Gravimeters 2011 (ECAG-2011) in Walferdange, Luxembourg: Results and recommendations, *Metrologia* **50**, 257 (2013).
- [13] T. Farah, C. Guerlin, A. Landragin, Ph. Bouyer, S. Gaffet, F. Pereira Dos Santos, and S. Merlet, Underground operation at best sensitivity of the mobile LNE-SYRTE cold atom gravimeter, *Gyroscope and Navigation* **5**, 266 (2014).

- [14] R. Geiger, A. Landragin, S. Merlet, and F. Pereira Dos Santos, High-accuracy inertial measurements with cold-atom sensors, *AVS Quantum Science* **2**, 024702 (2020).
- [15] L. Antoni-Micollier, D. Carbone, V. Ménéret, J. Lautier-Gaud, T. King, F. Greco, A. Messina, D. Contrafatto, and B. Desruelle, Detecting volcano-related underground mass changes with a quantum gravimeter, *Geophysical Research Letters* **49**, e2022GL097814 (2022).
- [16] F. A. Narducci, A. T. Black, and J. H. Burke, Advances toward fieldable atom interferometers, *Advances in Physics: X* **7**, 1946426 (2022).
- [17] P. Gillot, B. Cheng, A. Imanaliev, S. Merlet, and F. Pereira Dos Santos, The LNE-SYRTE cold atom gravimeter, in *2016 European Frequency and Time Forum (EFTF)* (2016) pp. 1–3.
- [18] C. Freier, M. Hauth, V. Schkolnik, B. Leykauf, M. Schilling, H. Wziontek, H.-G. Scherneck, J. Müller, and A. Peters, Mobile quantum gravity sensor with unprecedented stability, *Journal of Physics: Conference Series* **723**, 012050 (2016).
- [19] D. S. Durfee, Y. K. Shaham, and M. A. Kasevich, Long-term stability of an area-reversible atom-interferometer sagnac gyroscope, *Physical Review Letters* **97** (2006).
- [20] A. Gauguet, T. E. Mehlstäubler, T. Lévêque, J. Le Gouët, W. Chaibi, B. Canuel, A. Clairon, F. P. Dos Santos, and A. Landragin, Off-resonant raman transition impact in an atom interferometer, *Physical Review A* **78** (2008).
- [21] A. Gauguet, B. Canuel, T. Lévêque, W. Chaibi, and A. Landragin, Characterization and limits of a cold-atom Sagnac interferometer, *Physical Review A* **80**, 063604 (2009).
- [22] A. Louchet-Chauvet, T. Farah, Q. Bodart, A. Clairon, A. Landragin, S. Merlet, and F. P. D. Santos, The influence of transverse motion within an atomic gravimeter, *New Journal of Physics* **13**, 065025 (2011).
- [23] V. Schkolnik, B. Leykauf, M. Hauth, C. Freier, and A. Peters, The effect of wavefront aberrations in atom interferometry, *Applied Physics B* **120**, 311–316 (2015).
- [24] M.-k. Zhou, Q. Luo, L.-l. Chen, X.-c. Duan, and Z.-k. Hu, Observing the effect of wave-front aberrations in an atom interferometer by modulating the diameter of Raman beams, *Physical Review A* **93**, 043610 (2016).
- [25] R. Karcher, A. Imanaliev, S. Merlet, and F. P. D. Santos, Improving the accuracy of atom interferometers with ultracold sources, *New Journal of Physics* **20**, 113041 (2018).
- [26] L. Pagot, S. Merlet, and F. P. D. Santos, Influence of optical aberrations on the accuracy of an atomic gravimeter, *Optics Express* **33**, 18843 (2025), publisher: Optica Publishing Group.
- [27] Q. Luo, L. Li, H. Zhou, L. Chen, X. Duan, Z. Hu, and M. Zhou, Evaluating the effect of wavefront aberrations in an atom gravimeter, *Metrologia* **62**, 055006 (2025).
- [28] W.-J. Xu, J. Liu, Q. Luo, Z.-K. Hu, and M.-K. Zhou, *In Situ* measurement of the wavefront phase shift in an atom interferometer, *Physical Review Applied* **22**, 054014 (2024).
- [29] S. Gaudout, R. Si-Ahmed, C. Debavelaere, M. Door, P. Cladé, and S. Guellati-Khelifa, *Probing the spatial distribution of k-vectors in situ with Bose-Einstein condensates* (2025), arXiv:2507.19157.
- [30] S. M. Dickerson, J. M. Hogan, A. Sugarbaker, D. M. S. Johnson, and M. A. Kasevich, Multiaxis inertial sensing with long-time point source atom interferometry, *Phys. Rev. Lett.* **111**, 083001 (2013).
- [31] S. Seckmeyer, H. Ahlers, J.-N. Kirsten-Siemß, M. Gersmann, E. M. Rasel, S. Abend, and N. Gaaloul, Spatially resolved phase reconstruction for atom interferometry, *EPJ Quantum Technology* **12** (2025).
- [32] Y.-J. Chen, A. Hansen, G. W. Hoth, E. Ivanov, B. Pelle, J. Kitching, and E. A. Donley, Single-source multiaxis cold-atom interferometer in a centimeter-scale cell, *Physical Review Applied* **12** (2019).
- [33] See Supplemental Material at [url] for derivations of the main equations and additional experimental details.
- [34] A. Peters, K. Y. Chung, and S. Chu, High-precision gravity measurements using atom interferometry, *Metrologia* **38**, 25 (2001).
- [35] G. W. Hoth, B. Pelle, S. Riedl, J. Kitching, and E. A. Donley, Point source atom interferometry with a cloud of finite size, *Applied Physics Letters* **109**, 071113 (2016).
- [36] J. M. Hogan, D. M. S. Johnson, and M. A. Kasevich, Light-pulse atom interferometry, in *Atom Optics and Space Physics* (IOS Press, 2009) pp. 411–447.
- [37] P. Gillot, B. Cheng, S. Merlet, and F. Pereira Dos Santos, Limits to the symmetry of a Mach-Zehnder-type atom interferometer, *Physical Review A* **93** (2016).
- [38] D. S. Weiss, B. C. Young, and S. Chu, Precision measurement of \hbar/mc_s based on photon recoil using laser-cooled atoms and atomic interferometry, *Applied Physics B* **59**, 217 (1994).
- [39] G. W. Hoth, *Development and Characterization of an Interferometer Based on an Expanding Ball of Atoms*, Ph.D. thesis, University of Colorado Boulder (2016).
- [40] W. M. Itano, J. C. Bergquist, J. J. Bollinger, J. M. Gilligan, D. J. Heinzen, F. L. Moore, M. G. Raizen, and D. J. Wineland, Quantum projection noise: Population fluctuations in two-level systems, *Physical Review A* **47**, 3554 (1993).
- [41] J. Li, T. Kovachy, J. Bonacum, and S. M. Shahriar, Sensitivity of a Point-Source-Interferometry-Based Inertial Measurement Unit Employing Large Momentum Transfer and Launched Atoms, *Atoms* **12**, 32 (2024).
- [42] M. Abe, P. Adamson, M. Borcean, D. Bortoletto, K. Bridges, S. P. Carman, S. Chattopadhyay, J. Coleman, N. M. Curfman, K. DeRose, T. Deshpande, S. Dimopoulos, C. J. Foot, J. C. Frisch, B. E. Garber, S. Geer, V. Gibson, J. Glick, P. W. Graham, S. R. Hahn, R. Harnik, L. Hawkins, S. Hindley, J. M. Hogan, Y. Jiang, M. A. Kasevich, R. J. Kelleth, M. Kiburg, T. Kovachy, J. D. Lykken, J. March-Russell, J. Mitchell, M. Murphy, M. Nantel, L. E. Nobrega, R. K. Plunkett, S. Rajendran, J. Rudolph, N. Sachdeva, M. Safdari, J. K. Santucci, A. G. Schwartzman, I. Shipsey, H. Swan, L. R. Valerio, A. Vasonis, Y. Wang, and T. Wilkason, Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100), *Quantum Science and Technology* **6**, 044003 (2021).
- [43] J. M. Hogan, D. M. S. Johnson, S. Dickerson, T. Kovachy, A. Sugarbaker, S.-w. Chiow, P. W. Graham, M. A. Kasevich, B. Saif, S. Rajendran, P. Bouyer, B. D. Seery, L. Feinberg, and R. Keski-Kuha, An atomic gravitational wave interferometric sensor in low earth orbit (AGIS-LEO), *General Relativity and Gravitation* **43**, 1953 (2011).