

Adaptive robust high-precision atomic gravimetry

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Atomic gravimeters are the most accurate sensors for measuring gravity, yet a significant challenge lies in achieving high precision while also maintaining high dynamic range and robustness. Here, we develop a protocol for achieving robust high-precision atomic gravimetry based upon adaptive Bayesian quantum estimation. Our protocol incorporates a sequence of interferometry measurements taken with short to long interrogation times and offers several crucial advantages. Firstly, it enables a high dynamic range without the need to scan multiple fringes for pre-estimation, making it more efficient than the conventional frequentist method. Secondly, it improves robustness against noises, allowing for a significant improvement in measurement precision in noisy environments. The enhancement can be more than 5 times for a transportable gravimeter [Sci. Adv. **5**, eaax0800 (2019)] and up to an order of magnitude for a state-of-the-art fountain gravimeter [Phys. Rev. A **88**, 043610 (2013)]. Notably, by optimizing the interferometry sequence, our approach can improve the scaling of the measurement precision (Δg_{est}) versus the total interrogation time ($\bar{T}$) to $\Delta g_{\text{est}} \propto \bar{T}^{-2}$ or even better, in contrast to the conventional one $\Delta g_{\text{est}} \propto \bar{T}^{-0.5}$. Our approach offers superior precision, increased dynamic range, and enhanced robustness, making it highly promising for a range of practical sensing applications.

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Introduction. Atom interferometry has become a prominent inertial-sensing technique, in particular, gravimetry. Atomic gravimetry [1–9] plays a vital role in inertial navigation [10–13], geophysics [14–17], and fundamental research [18–25]. It is important to improve precision, stability, and efficiency of atomic gravimeters [26–32]. The gravitational acceleration g is usually determined using Mach-Zehnder interferometry. This method utilizes a $\pi/2 - \pi - \pi/2$ Raman pulse sequence to coherently split, reflect, and recombine the atomic wave packets, as depicted in Fig. 1(a). The beam-splitters and mirrors are achieved by state-changing Raman transitions, which are achieved with two counter-propagating laser pulses coherently coupling two internal states $|g, \mathbf{p}\rangle$ and $|e\rangle$. The first $\pi/2$ pulse transfers the atoms from $|g, \mathbf{p}\rangle$ ($\mathbf{p}$ labeling the momentum) into an equal superposition of states $|g, \mathbf{p}\rangle$ and $|e, \mathbf{p} + \hbar\mathbf{k}_{\text{eff}}\rangle$, obtaining an effective momentum of $\hbar\mathbf{k}_{\text{eff}} = \hbar k_{\text{eff}}\hat{\mathbf{z}} = \hbar(\mathbf{k}_1 - \mathbf{k}_2) = 2\hbar k\hat{\mathbf{z}}$, where $\mathbf{k}_1 = -\mathbf{k}_2 = k\hat{\mathbf{z}}$ are the wave vectors of two lasers along the gravity direction $\hat{\mathbf{z}}$. The π pulse then completely exchanges the two atomic

states, and the second $\pi/2$ pulse recombines the atoms. Finally, one can perform the population detection to determine g according to $\mathcal{L}_u = \frac{1}{2}[1 + (-1)^u \cos \Phi]$, where $\Phi = k_{\text{eff}}gT^2$ is the accumulated phase, T represents half of the interrogation time, and $u = 0$ or 1 stands for the atoms occupying $|g, \mathbf{p}\rangle$ or $|e, \mathbf{p} + \hbar\mathbf{k}_{\text{eff}}\rangle$, respectively [33].

However, it is a great challenge to simultaneously achieve high precision and high dynamic range. On the one hand, although long interrogation time leads to high precision, it will bring phase ambiguity leading to inaccuracy. Typically, one can tune the laser frequency with a chirp rate α to introduce an auxiliary phase. Consequently, the accumulated phase becomes $\Phi = (k_{\text{eff}}g - 2\pi\alpha)T^2$. By scanning at least three fringes with different interrogation times, one can obtain a common α_0 and uniquely determine $g = 2\pi\alpha_0/k_{\text{eff}}$ [34–38]. However, this pre-estimation process requests more measurement times in experiments. On the other hand, the dynamic range becomes narrower for longer interrogation times and the corresponding robustness decreases. While a short interrogation time offers higher dynamic range but lower precision and a long interrogation time offers higher precision but lower dynamic range, *can we combine measurements taken with short and long interrogation times to simultaneously achieve high precision and high dynamic range?*

Bayesian quantum estimation may combine measurements taken with different interrogation times by updating the probability distribution with Bayes' theorem. It simultaneously provides excellent robustness, high precision, and wide dynamic range. This intriguing feature attracts increasing

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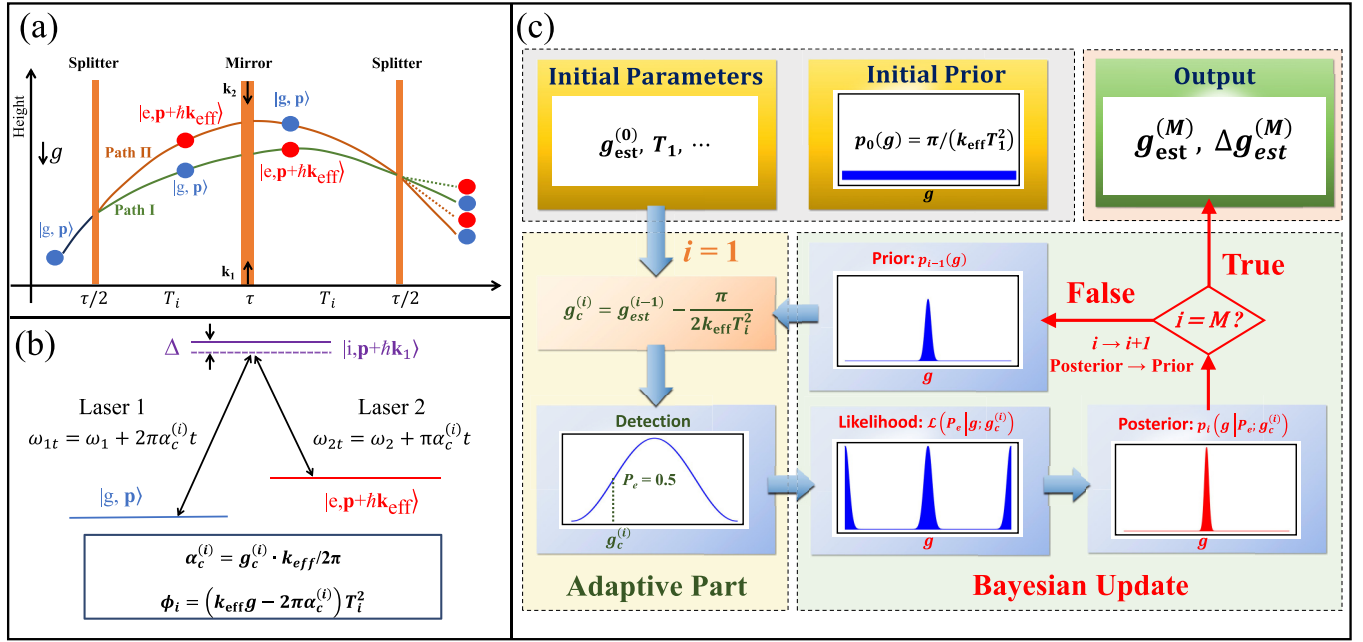


FIG. 1. (a) Bayesian atomic gravimetry incorporates a sequence of measurements taken with short to long T_i . Here, T_i is the separation time between neighboring pulses in i^{th} iteration. (b) Two Raman lasers couple two states $|g, \mathbf{p}\rangle$ and $|e, \mathbf{p} + \hbar \mathbf{k}_{\text{eff}}\rangle$ with frequencies $\omega_{1t} = \omega_1 + 2\pi\alpha_c^{(i)}t$ and $\omega_{2t} = \omega_2 + \pi\alpha_c^{(i)}t$. (c) Schematic of our adaptive Bayesian gravity estimation. Given a prior distribution p_{i-1} and the likelihood function, the posterior distribution p_i is updated through the Bayes' formula. The estimation value of $g_{\text{est}}^{(i)}$ and its standard deviation $\Delta g_{\text{est}}^{(i)}$ can be computed with p_i . Then, $g_c^{(i)}$ is adaptively given and then used to determine $\alpha_c^{(i)}$. Generally, the initial prior p_0 is an evenly distributed function.

attentions in quantum phase estimation [39–46] and its applications in quantum magnetometers [47–53] and atomic clocks [54,55]. It has been demonstrated that the precision scaling with respect to the total interrogation time may surpass the standard quantum limit (SQL) [56] or even approach the Heisenberg scaling [57–59]. Unlike typical quantum phase estimation, where the accumulated phase has a linear dependence on interrogation time $\Phi \propto T$, in atomic gravimetry, the accumulated phase exhibits a quadratic dependence on interrogation time $\Phi \propto T^2$. Up to date, it is still unknown that how Bayesian quantum estimation can be utilized to improve the performance of atomic gravimetry.

In this Letter, we propose an adaptive Bayesian gravity estimation (BGE) protocol to achieve robust and high-precision atomic gravimetry. On one hand, our protocol enables a high dynamic range without the need to scan at least three fringes for pre-estimation. On the other hand, our protocol enhances resilience to noise, enabling over a tenfold improvement in gravity measurement precision in practical noisy conditions. Moreover, by optimizing the interferometry sequence of growing interrogation times, the scaling of the measurement precision Δg versus the total interrogation time $\tilde{T}$ can be improved from $\Delta g \propto \tilde{T}^{-0.5}$ to $\Delta g \propto \tilde{T}^{-2}$ or even $\Delta g \propto \tilde{T}^{-2.25}$. Our BGE protocol can be readily applied to enhance the performance of all existing interferometry-based atomic gravimeters.

Bayesian gravity estimation. Below we show how to employ Bayesian quantum estimation to determine the gravity g without the need to scan three different fringes. The key idea is using the measurement taken with short interrogation time (which has high dynamic range) for rough estimation and

then utilizing the measurement taken with long interrogation time for high-precision estimation. We use Bayesian update to combine the measurements taken with different interrogation times T_i , where $i = 1, 2, \dots, M$ is the iteration index and M denotes the total steps. To perform the adaptive BGE, we introduce an auxiliary parameter $g_c^{(i)} = 2\pi\alpha_c^{(i)}/k_{\text{eff}}$, which is realized by varying the two laser frequencies according to $\omega_{1t} = \omega_1 + 2\pi\alpha_c^{(i)}t$ and $\omega_{2t} = \omega_2 + \pi\alpha_c^{(i)}t$, see Fig. 1(b). Therefore, the corresponding likelihood function reads

$$\mathcal{L}_u = \frac{1}{2} \{1 + (-1)^u \cos[(g - g_c^{(i)})k_{\text{eff}}T_i^2]\}. \quad (1)$$

Different from conventional schemes, the adaptive BGE can search the optimal $g_c^{(i)}$ for each iteration. This ensures that the atomic gravimeter operates under the optimal condition with sharpest slope, see Fig. 1(c). In the beginning, if there is no prior knowledge of g , the first prior distribution can be set as a uniformly distributed function. For an ensemble of R atoms, the likelihood function can be approximated as a Gaussian function [60] $\mathcal{L}(P_e|g; g_c^{(i)}) = \frac{1}{\sqrt{2\pi}\sigma} \exp[-\frac{(P_e - \mathcal{L}(1|g; g_c^{(i)}))^2}{2\sigma^2}]$, with $\sigma^2 \approx P_e(1 - P_e)/R$ and P_e denoting the probability of atoms occupying the state $|e, \mathbf{p} + \hbar \mathbf{k}_{\text{eff}}\rangle$. The information of g can be updated through Bayes' theorem, resulting in a posterior distribution,

$$p_i(g|P_e; g_c^{(i)}) = \mathcal{N}\mathcal{L}(P_e|g; g_c^{(i)})p_{i-1}(g), \quad (2)$$

where $\mathcal{N}$ is the normalization factor, p_i and p_{i-1} denote the posterior and prior distributions, respectively. According to the posterior distribution, the estimation of g can be given as $g_{\text{est}}^{(i)} = \int g p_i(g|P_e; g_c) dg$ with a standard deviation $\Delta g_{\text{est}}^{(i)} = \sqrt{\int g^2 p_i(g|P_e; g_c) dg - (g_{\text{est}}^{(i)})^2}$.

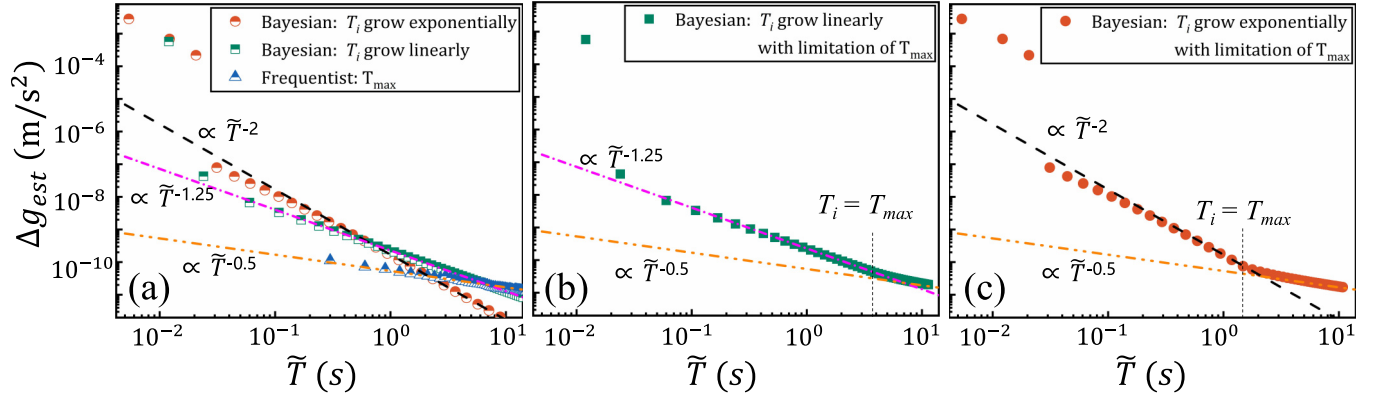


FIG. 2. Precision scaling with respect to total interrogation time. (a) T_i grow linearly ($b = T_1 = 12 \times 10^{-3}$ s) and exponentially ($a = 1.25$, $T_1 = 5.4 \times 10^{-3}$ s), respectively. (b) T_i grows linearly until it reaches $T_{\max}$. The precision follows $\tilde{T}^{-1.25}$ until T_i attains $T_{\max}$, then eventually converges to $\tilde{T}^{-0.5}$ as T_i remains $T_{\max}$ in the following. (c) T_i grows exponentially until it reaches $T_{\max}$. The precision follows $\tilde{T}^{-2}$ until T_i attains $T_{\max}$, then eventually converges to $\tilde{T}^{-0.5}$ as T_i remains $T_{\max}$ in the following. Here, $k_{\text{eff}} = 1.61 \times 10^7$ rad/m, $T_{\max} = 0.3$ s and $R = 5 \times 10^7$. The total measurement times for (b) and (c) is $M = 50$. Here, $k_{\text{eff}} = 1.61 \times 10^7$ rad/m, $T_{\max} = 0.3$ s and $R = 5 \times 10^7$ are chosen based on typical atomic fountain experiments.

The control parameter $g_c^{(i)}$ is gradually calculated and adjusted based on the measurement results at each iteration step. Using the Bayes update, it is possible to achieve high sensitivity [48,50,51,59,61,62] and high robustness against noises [40,41,63–65] within a limited number of measurements. With the prior information, the initial $g_{\text{est}}^{(0)}$ can be preset as a constant. The value of g_c for the i -th iteration is designed as

$$g_c^{(i)} = g_{\text{est}}^{(i-1)} - \pi / (2k_{\text{eff}} T_i^2), \quad (3)$$

which is determined by the estimated value $g_{\text{est}}^{(i-1)}$ given by the posterior distribution p_i and the interrogation time T_i . One can lock $P_e \approx 0.5$ to perform the optimal slope detection for each step [59]. Different from other adaptive methods that require complex calculation of auxiliary parameters [42,47,54], our design is straightforward and efficient without large amount of calculations, which is of great significance in the cases with large atom number (about $10^5 \sim 10^7$) in atomic gravimeters.

Analytically, one can find that the likelihood function is a Gaussian function versus g with a standard deviation $\sigma_i = \frac{1}{\sqrt{Rk_{\text{eff}} T_i^2}}$ [66]. Then, the i -th posterior can be given by the multiplication of a series of Gaussian functions so that the final posterior reads

$$p_M(g|P_e; g_c^{(M)}) = \frac{1}{\sqrt{2\pi}\sigma_M} \exp\left[-\frac{(g - \mu_M)^2}{2\sigma_M^2}\right], \quad (4)$$

where $\mu_M \approx g$ and $\sigma_M = \frac{1}{\sqrt{Rk_{\text{eff}} \sum_{i=1}^M T_i^2}}$ when M is sufficiently large [66]. Obviously, the standard deviation decreases as the square root of the sum of T_i^4 and different sequence of T_i would result in different precision scaling versus the total interrogation time $\tilde{T} = \sum_{i=1}^M T_i$.

Precision scaling with respect to the total interrogation time. Theoretically, if one increase $T_i = T_1 + (i-1)b$ linearly from T_1 with the increment interval b , according to the final posterior, the final measurement precision can be given as

$$\Delta g_{\text{est}}^{(M)} \approx \frac{\sqrt{5}}{\sqrt{Rk_{\text{eff}} \tilde{T}_M^{1.25} b^{0.75} 2^{1.25}}} = \frac{\mathcal{B}(b)}{\sqrt{Rk_{\text{eff}}}} \frac{1}{\tilde{T}_M^{1.25}}. \quad (5)$$

Here M is the total iteration number, the total interrogation time $\tilde{T}_M = \sum_{i=1}^M T_i \approx M^2 b/2$ ($M \gg 1$), and the factor $\mathcal{B}(b) = \frac{\sqrt{5}}{b^{0.75} 2^{1.25}}$. Thus, the corresponding measurement precision Δg_{est} versus the total interrogation time $\tilde{T}$ scales as $\Delta g_{\text{est}} \propto \tilde{T}^{-1.25}$, see Fig. 2(a).

In contrast, if one increase $T_i = T_1 a^{i-1}$ exponentially from T_1 with the increment ratio $a > 1$, the measurement precision scaling can be improved [51,56,61,67] and the final measurement precision becomes

$$\Delta g_{\text{est}}^{(M)} \approx \frac{\sqrt{a^4 - 1}}{\sqrt{Rk_{\text{eff}} \tilde{T}_M^2 (a-1)^2}} = \frac{\mathcal{A}(a)}{\sqrt{Rk_{\text{eff}}}} \frac{1}{\tilde{T}_M^2}, \quad (6)$$

where $\tilde{T}_M = \sum_{i=1}^M T_i \approx a \tilde{T}_M / (a-1)$ with $M \gg 1$ and the factor $\mathcal{A}(a) = \frac{\sqrt{a^4 - 1}}{(a-1)^2}$. The corresponding measurement precision versus the total interrogation time scales as $\Delta g_{\text{est}} \propto \tilde{T}^{-2}$, see Fig. 2(a). If $T_i = T_{\max}$ in all measurements, the corresponding measurement precision versus the total interrogation time scales as $\Delta g_{\text{est}} \propto \tilde{T}^{-0.5}$. More interestingly, if one use exponential increasing with time-dependent $a(t)$, the precision scaling can even attain $\Delta g_{\text{est}} \propto \tilde{T}^{-2.25}$ [66]. Typically, the fast increasing T_i may lead to erroneous peaks and we can apply the point identification method [68] to eliminate with more details shown in [66].

In practice, since the interference cavity length of an atomic gravimeter is finite, there always has a limited interrogation time $T_{\max}$ so that $T_i \leq T_{\max}$. To design a practical sequence of T_i , we set the last interrogation time $T_M = T_{\max}$ and derive the previous ones. If the interrogation time increases linearly, the sequence of T_i can be given as

$$T_i = \begin{cases} T_{\max} - (M_b - i)b, & 1 \leq i < M_b, \\ T_{\max}, & M_b \leq i \leq M. \end{cases} \quad (7)$$

Given the minimum interrogation time $T_{\min}$, one needs M_b steps to increase from $T_1 = \max\{T_{\min}, T_{\max} - (M_b - 1)b\}$ to $T_{\max}$. Once T_i reaches $T_{\max}$, it keeps fixed at $T_{\max}$ for the remaining $M - M_b$ steps.

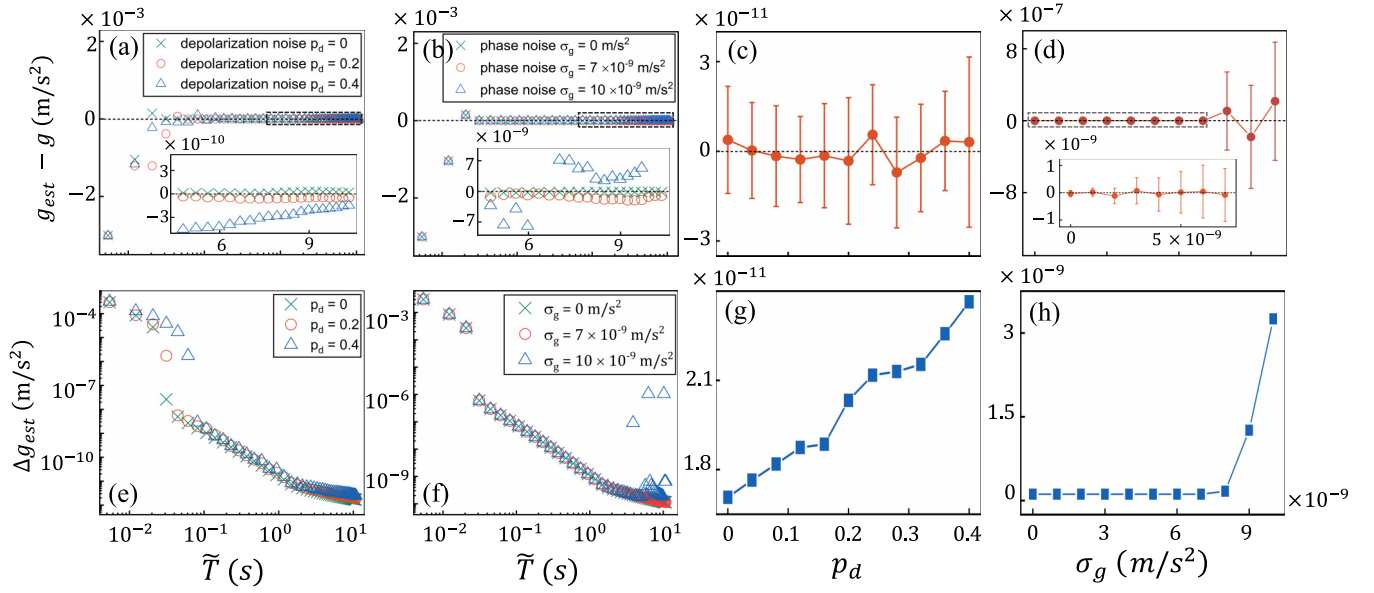


FIG. 3. Performance of Bayesian atomic gravimetry in the presence of noises. The error $g_{\text{est}} - g$ versus the total interrogation time $\tilde{T}$ for different strengths of (a) depolarization noise and (b) phase noise. The final error $g_{\text{est}} - g$ versus (c) the depolarization noise strength p_d and (d) the phase noise strength σ_g with error bars denoting their fluctuations for 30 repetitions. The precision Δg_{est} versus $\tilde{T}$ for different strengths of (e) depolarization noise and (f) phase noise. The final precision Δg_{est} versus (g) p_d and (h) σ_g . In our numerical simulation, $M = 50$ and $R = 5 \times 10^7$, $T_{\text{max}} = 0.3$ s, $C = 0.15$ are chosen based on typical atomic fountain experiments [69].

Similarly, if the interrogation time increases exponentially, the sequence of T_i can be given as

$$T_i = \begin{cases} T_{\text{max}}/a^{M_a-i}, & 1 \leq i < M_a, \\ T_{\text{max}}, & M_a \leq i \leq M. \end{cases} \quad (8)$$

Here, T_i needs M_a steps to increase from $T_1 = \max\{T_{\text{min}}, T_{\text{max}}/a^{M_a-1}\}$ to T_{max} , and subsequently stays constant at T_{max} for the remaining $M - M_b$ steps. As shown in Figs. 2(b) and 2(c), in the presence of T_{max} , the measurement precision scales as $\Delta g_{\text{est}} \propto \tilde{T}^{-1.25}$ for linear increasing T_i and $\Delta g_{\text{est}} \propto \tilde{T}^{-2}$ for exponentially increasing T_i . Subsequently, after T_i reaches T_{max} and remains fixed, the precision reverts to $\Delta g_{\text{est}} \propto \tilde{T}^{-0.5}$.

Robustness against noises. – One significant feature of our adaptive BGE is the robustness against noises. The key is that our protocol uses the measurement taken with short T_i for rough estimation, while relying on large quantum fluctuations in short T_i interferometry to effectively mitigate the impact of noise sources [66]. There are two typical noises [42,44,70] in atomic gravimetry: depolarization noise and phase noise. Depolarization noise leads to contrast loss, while phase noise introduces random errors. With depolarization noise, the likelihood function becomes $\mathcal{L}_u = \frac{1}{2}[1 + (1 - \tilde{p}_d)(-1)^u \cos(g - g_c^{(i)}k_{\text{eff}}T_i^2)]$, where $\tilde{p}_d \sim |\mathcal{N}(0, p_d^2)|$ is a Gaussian distribution with $0 \leq p_d \leq 1$. While in the presence of phase noise, the likelihood function becomes $\mathcal{L}_u = \frac{1}{2}[1 + (-1)^u C \cos(g - g_c^{(i)} + \tilde{\sigma}_g)k_{\text{eff}}T_i^2]$, where the contrast C is always less than 1, and $\tilde{\sigma}_g \sim \mathcal{N}(0, \sigma_g^2)$ is a Gaussian distribution with $\sigma_g \geq 0$.

We first analyze the error $g_{\text{est}} - g$ and the measurement precision Δg_{est} versus the total interrogation time $\tilde{T}$. In the case of depolarization noise, the error convergence speed and the measurement precision decrease when the noise strength increases, see Figs. 3(a) and 3(e). In the case of phase noise, the errors and measurement precision almost remain un-

changed for small σ_g . However, when strong noise is present, such as $\sigma_g = 1 \mu\text{Gal}$, g_{est} and Δg_{est} will abruptly change because of the significant shift between the center positions of the likelihood function and the prior distribution. Therefore, the corresponding estimation becomes unreliable, see Figs. 3(b) and 3(f). In our calculation, we set $C = 0.15$ and $R = 5 \times 10^7$ based upon the typical atomic fountain experiments [1,69,71,72].

Then, we analyze how the measurement results depend on noise strength by averaging 30 samples. In the case of depolarization noise, the errors $g_{\text{est}} - g$ and their fluctuations (denoted by errorbars) are slightly changed for small p_d [see Fig. 3(c)], and the measurement precision Δg_{est} slightly increases with p_d [see Fig. 3(g)]. In the case of phase noise, the errors $g_{\text{est}} - g$ and their fluctuations (denoted by errorbars) are significantly changed for σ_g [see Fig. 3(d)], and the measurement precision Δg_{est} is almost unchanged for small σ_g [see Fig. 3(h)]. However, errors and measurement precision may deteriorate, leading to unreliable results when there is significant phase noise, as observed in cases where $\sigma_g \geq 0.9 \mu\text{Gal}$.

Precision improvement of realistic atomic gravimeters. – In conventional frequentist estimation, one may choose T_{max} to achieve the highest precision, but the dynamic range becomes smallest due to phase ambiguities. In our BGE, one may choose a suitable minimum interrogation time T_{min} to ensure a high dynamic range, whereas increasing T_i improves the measurement precision. Moreover, there is no need to scan at least three different fringes to pre-estimate g . Notably, the measurement precision can be significantly enhanced under noisy condition, opening up promising practical applications.

In our simulation, we consider a transportable atomic gravimeter with Cs atoms [29] as an example. Fixing the

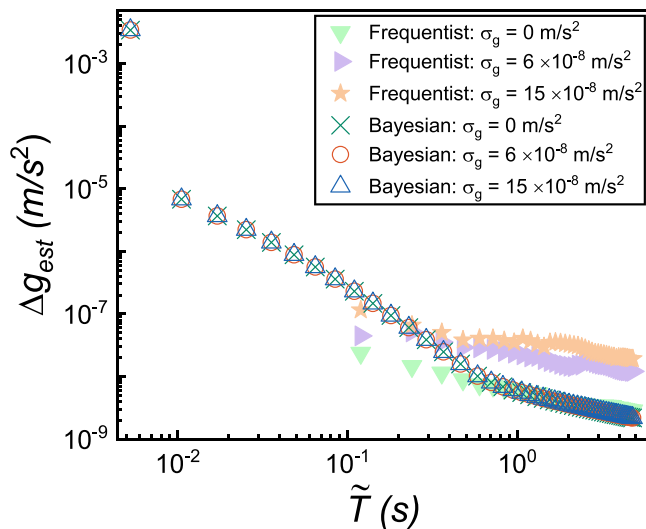


FIG. 4. Improvement of a transportable gravimeter under phase noise [29] via our Bayesian protocol. In our numerical simulation, we use an exponential increasing scheme with $a = 1.25$, $T_{\max} = 0.12$ s, $C = 0.16$, $R = 5 \times 10^6$, and $k_{\text{eff}} = 1.47 \times 10^7$ rad/m.

total interrogation time as $\tilde{T} = 40 T_{\max}$, we assume the conventional frequentist protocol takes 40 measurements with $T_{\max} = 0.12$ s, while our BGE performs 51 measurements with $a = 1.25$. Figure 4 shows the measurement precisions versus the interrogation time $\tilde{T}$. Although the precisions are almost the same when $\sigma_g = 0$, the improvement becomes

significant when noises appear. The precision of the conventional protocol rapidly decreases with the noise strength. When $\sigma_g = 6 \times 10^{-8}$ m/s², our BGE can achieve a precision that is 5 times greater than that of the conventional method. Moreover, the stronger the phase noise, the more significant this improvement will be. While for the state-of-the-art atomic fountain gravimeters, the precision enhancement offered by our BGE can be even up to an order of magnitude [66].

Conclusion and discussion. – We propose an adaptive Bayesian quantum estimation protocol to achieve robust high-precision gravimetry. Based upon a tailored sequence of correlated Mach-Zehnder interferometry taken with short to long interrogation times, our protocol allows us to incorporate prior knowledge of gravity and update it with Bayes' theorem to obtain high precision. Under noisy conditions, it is possible to improve the measurement precisions of state-of-the-art atomic gravimeters by an order of magnitude without compromising the dynamic range. Our protocol may also be suitable for real-time tracking, which not only has promising application for versatile gravity measurement necessities such as transportable gravimeters [7,73–77] for exploring mineral and oil resources, but also is applicable in various interferometry-based quantum sensors such as atomic clocks, quantum magnetometers, and atomic gyroscopes.

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