nature portfolio

Peer Review File

Pathfinder Experiments with Atom Interferometry in the Cold Atom Lab onboard the International Space Station

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REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

This manuscript reports on several recent PI-led atom interferometry experiments using the Cold Atom Lab (CAL). Atom interferometry in space is an exciting and rapidly emerging new frontier, the advantages of which the authors clearly and convincingly articulate in their introduction. Experiments of this type have the potential to make revolutionary advances in tests of fundamental physics as well as practical applications such as geodesy. However, to reach these goals, it is critical to advance the technology. Atom interferometry on earth has been matured over decades, but making these experiments suitable for a space environment is a major challenge.

Fortunately, led in large part by many of the authors of this manuscript, progress in addressing this challenge has been rapid and impressive. The work presented in this manuscript represents an essential next step in making high-precision quantum sensors based on atom interferometry in space a reality. Given the broad-ranging impact that these sensors could have, it is important for a broad audience to be kept aware of the latest developments. Also, this work is especially timely given that both NASA and ESA are in the process of evaluating ideas for next-generation experiments with cold atoms, and other technologies, in space. The advances presented in this manuscript will provide essential input to the NASA and ESA processes and should be widely publicized.

The authors have chosen to present the results of three experiments together in this manuscript: the first three-pulse Mach-Zehnder interferometer in orbit, long-duration shear wave interferometry which provides interesting possibilities for characterizing phases that arise between different parts of the atom distribution, and a demonstration of a photon recoil sensitive atom interferometer. I support the authors’ decision to present these results together, as together they show advancement in the range of atom interferometry techniques that can now be implemented in space.

For the reasons I explained above, I believe that this manuscript would be an excellent contribution to Nature Communications. Below, I include some comments for the authors to consider about how the manuscript could be further improved.

-The authors independently measure the ISS vibrations and show that they are consistent with the observed loss of visibility of the Mach-Zehnder interferometer. However, it is possible that other factors, such as dipole forces across the atom cloud, could be contributing to visibility reduction as well. If the predominant effect is indeed due to vibration, the statistics of the interferometer output counts should follow a particular distribution, as shown in Geiger et al., Nature Communications 2, 474 (2011). Can the authors include a similar analysis as in Geiger et al.?

-Could the authors comment on whether CAL might be able to implement a gradiometer scheme in the future to suppress noise from vibrations?

-The authors briefly mention that photon recoil measurements in space could be useful for determinations of the fine structure constant. It would provide additional motivation for the photon recoil measurement demonstration in this paper if the authors could elaborate on this point. What would be the advantages of doing such a measurement in space? By allowing a larger ratio of free-fall time to time the atoms spend interacting with the light, could certain systematic errors be eased? Does space offer prospects for reducing systematic errors associated with the laser’s phase front, maybe by allowing for BECs with very low expansion rates?

-The shear wave interferometry technique shown by the authors could be a very useful tool for diagnosing phase shifts that vary in space across the atom cloud, such as those due to dipole forces from the Bragg beams. I suggest that the authors add emphasis of this point.

-It would be interesting if the authors could perform a principal component analysis of the multiple images from shear wave interferometers taken for a given time of flight. This could help to reveal persistent patterns versus the effects of shot-to-shot fluctuations. See Sugarbaker et al., PRL 111, 113002 (2013) as an example reference.

Reviewer #2 (Remarks to the Author):

In the article "Interferometry of Atomic Matter Waves in the Cold Atom Lab onboard the International Space Station," the authors present a series of three experiments in the field of atom interferometry with ultra-cold atoms (in this case 87Rb) for precision measurements carried out using the new scientific module SM3 installed at the International Space Station.

After an introduction on the importance and interest in utilizing matter wave interferometry in space for experimental physics tests, the results of three experiments are presented: demonstration of a Mach-Zehnder interferometer, realization of a Ramsey interferometer to perform a double-slit experiment with Bose-Einstein condensate, and the same Ramsey interferometer to conduct a proof-of-principle measurement of the recoil frequency of 87Rb. The discussion of the results and description of the methods follow.

General Comment:

From a formal point of view, the manuscript is well-written and organized. The described methodologies are convincing, and the data analysis is correctly executed and presented. Regarding the obtained results, I commend the authors for their work: being able to perform such complex experiments in a space environment is a clear demonstration of the high TRL level achieved by the instrument, which also demonstrates remarkable operational flexibility, similar to what can be achieved in a standard laboratory on Earth. However, I have serious doubts that Nature Communication is the appropriate journal for this work, for the following reasons:

- I believe the strength of the work lies in the ability to create condensates in a space environment and their use in an atom interferometer in micro-gravity. These results (undoubtedly groundbreaking) have already been widely reported by the same authors in [6], which makes the present work an extension/appendix of the latter.

- None of the experiments reported demonstrate in any way the benefit of operating in space, which should primarily be the ability to achieve long free evolution times (>10 s) as also noted by the authors themselves in the introduction.

For these reasons, despite considering the manuscript of absolute interest to the relevant community, I believe it is more suitable for a more specialized journal.

Minor Comments:

- Fig 1a: It could be useful to include information on the dimensions of the payload so that the reader can appreciate the compactness of the apparatus.
- Why was it chosen to use square pulses to drive Bragg transitions? Usually, Gaussian profiles are used to avoid losses in other orders (which, by the way, have been found in the Mach-Zender interferometer).
- In section 2.3, it is stated that the contrast of the Ramsey interferometer is limited by the size of the trapped condensate, which is 8 μm. I wonder if the effective temperature of the atomic sample also contributes to this reduction.

Response to Reviewer #1

Thank you for your feedback and the thorough list of comments and questions. Below we include our responses as well as identify where we made related changes to the paper (in blue). In order to clearly identify each of our responses, we numbered your comments in the order they appeared in your review.

1. The authors independently measure the ISS vibrations and show that they are consistent with the observed loss of visibility of the Mach-Zehnder interferometer. However, it is possible that other factors, such as dipole forces across the atom cloud, could be contributing to visibility reduction as well. If the predominant effect is indeed due to vibration, the statistics of the interferometer output counts should follow a particular distribution, as shown in Geiger et al., Nature Communications 2, 474 (2011). Can the authors include a similar analysis as in Geiger et al.?

   Response We appreciate this suggestion because the inclusion of the probability distribution function analysis into the manuscript clarifies our assertion that phase noise is a leading cause of visibility degradation as AI interrogation time is increased to $T = 10$ ms. To support this discussion in the manuscript, a new section is included in the Methods, with the heading **Analysis of Mach-Zehnder Interferometer Output** and a corresponding new figure (**Figure 5: Histogram analysis of Mach-Zehnder interferometer signals**) is included. We also updated the text at the end of the **Mach-Zehnder Interferometer** section to include the new results as:

   Original text:
   Increasing T from 0.5 ms to 10 ms causes the interferometer visibility to drop to a value consistent with zero. However, the shot-to-shot signal variations are on par with the visibility observed at $T = 0.5$ ms, signifying that phase noise is dominating the signal [58]. This behavior is consistent with the simulated T-dependent visibility degradation, shown in the upper inset of Figure 2, which was modeled using ISS-SAMS 121F04 accelerometer data measured along the $\boldsymbol{z}$ direction. For details of the visibility degradation simulation, see Methods.

   New text:
   Increasing T from 0.5 ms to 10 ms causes the interferometer visibility to drop to a value consistent with zero. However, the effective contrast at longer T was determined by fitting the histograms of the excitation fractions at $T = 0.5$ ms and $T = 10$ ms with a Probability Distribution Function (PDF) for a double-peaked distribution indicative of a sinusoidal excitation fraction with Gaussian noise (given by Equation 5). The effective contrast decreases by approximately 30% as T is increased from 0.5 ms to 10 ms, signifying that phase noise is still dominating the signal at $T = 10$ ms [58], but other sources of visibility degradation are also growing as T is increased. The rising influence of phase noise with T is consistent with the simulated T-dependent visibility degradation, shown in the upper inset of Figure 2, which was modeled using ISS-SAMS 121F04 accelerometer data measured along the $\boldsymbol{z}$ direction. Details of the PDF fits and the visibility degradation simulation due to ISS vibrations are given in the Methods section.

2. Could the authors comment on whether CAL might be able to implement a gradiometer scheme in the future to suppress noise from vibrations?

   Response Indeed, a differential interferometry scheme would lead to strong suppression of vibration noise in the differential phase and enable gradiometric measurements with longer interferometer times. As mentioned in the discussion section of the manuscript, CAL allows in principle for such schemes and they are being implemented by some of the authors in an ongoing campaign. The results are planned to be published independently in the future. Naturally, the results of the present manuscript are very helpful for preparing and performing such differential interferometry measurements. We updated the following statement to make this point clearer:

Additional text in the third paragraph of the Discussion section:
Significant advancements and new sensing capabilities are expected to arise as differential interferometry (using either spatially-separated atom interferometers with the same atomic species in a gradiometer configuration or simultaneous interrogation of two distinct atomic species) is further explored with CAL.

3. The authors briefly mention that photon recoil measurements in space could be useful for determinations of the fine structure constant. It would provide additional motivation for the photon recoil measurement demonstration in this paper if the authors could elaborate on this point. What would be the advantages of doing such a measurement in space? By allowing a larger ratio of free-fall time to time the atoms spend interacting with the light, could certain systematic errors be eased? Does space offer prospects for reducing systematic errors associated with the laser's phase front, maybe by allowing for BECs with very low expansion rates?

Response We have updated the text at the beginning of the **Photon Recoil Measurement** section to attempt to make this point more clear.

Original text:
The two-pulse Ramsey interferometer configuration described in the previous section can also be used to perform a proof-of-principle recoil frequency measurement. Notably, in between the two Bragg pulses, the atomic wave packets develop a phase difference that depends on the recoil frequency $\omega_r \equiv \hbar k^2/2m$. High-precision terrestrial measurements of ω_r are used to determine the fine structure constant [28,29]. The long interrogation times available in microgravity could support such efforts, and even a lower-precision recoil frequency measurement could provide a useful method to calibrate the Bragg wave number k in a space environment where no conventional wavemeter instrument is available.

New text:
The two-pulse Ramsey interferometer configuration described in the previous section can also be used to perform a proof-of-principle recoil frequency measurement. Notably, in between the two Bragg pulses, the atomic wave packets develop a phase difference that depends on the recoil frequency $\omega_r \equiv \hbar k^2/2m$. High-precision terrestrial measurements of ω_r are used to determine the fine structure constant [28,29]. These efforts could be supported in microgravity by the availability of long interrogation times and low atom-cloud expansion rates. Many systematic errors are reduced for atoms remaining in a fixed position relative to the apparatus, and the impact of errors that impart a fixed phase shift (including laser phase errors [64]) is reduced at longer interrogation times where the recoil phase is larger. Alternatively, even low-precision recoil frequency measurements could provide a useful method to calibrate the Bragg wave number k in a space environment where no conventional wavemeter instrument is available.

4. The shear wave interferometry technique shown by the authors could be a very useful tool for diagnosing phase shifts that vary in space across the atom cloud, such as those due to dipole forces from the Bragg beams. I suggest that the authors add emphasis of this point.

Response We thank the referee for pointing out the additional applications for the shear-wave interferometry and have added the following new text relating to this topic at the start of the **Shear-Wave Atom Interferometry** section in the manuscript. Performing such an analysis with the current data set is unfortunately out of reach due to the rather limited statistics of 3-5 shots for each time-of-flight and overall small signal strength.

Additional text at start of Shear-Wave Atom Interferometry section:
In Figure 1(c) a two-pulse Ramsey interferometer geometry [59] is illustrated. Here, two $\pi/2$

pulses of the Bragg laser beam are applied in relatively rapid succession so that the atomic wave functions split from the first laser pulse still sufficiently overlap as to interfere and reveal a spatially resolved interference pattern at imaging. Depending on the expansion energy of the atoms and the freefall time after the second pulse t_{TOF}, as well as the timings of the interferometer sequence and ϕ_{laser}, such shear-wave interferometers [60] can provide direct information about both the atoms and the experimental apparatus. In particular, the spatially resolved interference pattern can in general be a very useful tool for diagnosing phase shifts that vary across the atom cloud as for instance induced by optical dipole forces from the Bragg beam or further diffraction from stray laser light [52].

5. It would be interesting if the authors could perform a principal component analysis of the multiple images from shear wave interferometers taken for a given time of flight. This could help to reveal persistent patterns versus the effects of shot-to-shot fluctuations. See Sugarbaker et al., PRL 111, 113002 (2013) as an example reference.

Response We have looked into the principal component analysis (PCA) carefully and applied it to our current data set. The expectation would be to see one main component of the PCA corresponding to the envelope of the atom clouds and two other components (one symmetric one anti-symmetric) that built up the stripe pattern of the shear-wave interferomter. The remaining components would then correspond to additional patterns or noise effects. However, since we only have data corresponding to 3-5 experimental shots for each time-of-flight, such an analysis is not very meaningful and the resulting PCA components are too few to clearly reveal the desired information. The mentioned paper by Sugarbaker et al., PRL 111, 113002 (2013) typically used 20 experimental shots for their PCA which then allowed to clearly identify the relevant components and separate them from noise effects.

Nevertheless, we already utilized other PCA methods to reduce the background noise in the atom density plots. For this approach we analyzed the difference between the beam and atom image for all experimental shots independent of the expansion time and used this knowledge to remove background stripes from the density plots. This method led to an improved contrast of the fringe spacing. We slightly adapted the present discussion in the Methods section to make our approach clearer.

Original text for Method section - Fringe Detection and Data Analysis:
For the shear Ramsey atom interferometer measurements, absorption images were first processed using principle component analysis [Phys. Rev. A 81, 053601 (2010)] to remove background imaging noise, and are then fit to the Ramsey fringe model described in the main text.

New text for Method section - Fringe Detection and Data Analysis:
For the shear Ramsey atom interferometer measurements, absorption images were first processed using a principal component analysis of the whole data set to remove background imaging noise [74]. The resulting density profiles were then fitted to the Ramsey fringe model described in the main text.

We also added a reference [60] for Sugarbaker et al., PRL 111, 113002 (2013) in the first paragraph in the **Shear-Wave Atom Interferometry section** relating to shear-wave interferometers.

Response to Reviewer #2

Thank you for this thorough list of comments and questions and for detailing your concerns with our manuscript. We have made every effort to understand and address your concerns and to provide arguments for why our manuscript is well-justified for publication in *Nature Communications*. In the following, we include our responses as well as identify where we made related changes to the paper (in blue). In order to clearly identify each of our responses, we numbered your comments in the order they appeared in your review.

General Comments: From a formal point of view, the manuscript is well-written and organized. The described methodologies are convincing, and the data analysis is correctly executed and presented. Regarding the obtained results, I commend the authors for their work: being able to perform such complex experiments in a space environment is a clear demonstration of the high TRL level achieved by the instrument, which also demonstrates remarkable operational flexibility, similar to what can be achieved in a standard laboratory on Earth. However, I have serious doubts that Nature Communication is the appropriate journal for this work, for the following reasons:

1. I believe the strength of the work lies in the ability to create condensates in a space environment and their use in an atom interferometer in micro-gravity. These results (undoubtedly groundbreaking) have already been widely reported by the same authors in [6], which makes the present work an extension/appendix of the latter.

   Response We do not agree that the strength of this work lies solely in the ability to create condensates in a space environment or in the direct demonstration of atom interferometry in microgravity. As mentioned by the reviewer, the realization of Bose-Einstein condensates and atom interferometry in space has been reported previously [52, 6]. However, these prior demonstrations were insensitive to influences from the ISS acceleration environment and did not directly serve for remote sensing on the ISS. Note, that even the recent ^{87}Rb and ^{41}K dual-species AI publicized by our team in [6] concentrated heavily on the demonstration and study of dual-species quantum gases in space but only gave a brief demonstration of differential atom interferometry, relying on short interrogation time and differential comparisons between simultaneously interrogated condensates to be effectively immune to external influences including the ISS environment.

   Our manuscript instead reports on a series of experiments in which CAL investigators utilized the unique ISS environment to perform pathfinding investigations with single-species ^{87}Rb BECs to explore atom interferometry and associated quantum sensing for the first time on an Earth orbiting platform. In addition to the demonstration of a single-species Mach-Zehnder interferometer (MZI), our results include signatures of atom interferometer sensitivities and visibility degradation due to the ISS vibration environment, the use of shear-Ramsey atom interferometry to extract contrast and phase shifts in a single experimental run, observation of interference fringes persisting for greater than 150 ms during freefall in the compact CAL science cell, and the use of the CAL atom interferometer to perform a photon recoil measurement to demonstrate its utility as the first quantum matter-wave sensor in space. Our results are therefore unique from any work published previously and their impact extends far beyond an extension/appendix to prior publications. We assert that they represent a critical milestone towards high-precision quantum sensing via atom interferometry in space.

   We believe that the original title of the paper and a confusing discussion in the Introduction and Discussion sections led to the reviewer's assessment that this paper was limited in scope. To clarify these points, we have made the following changes:

   Title:
   The title was changed from "*Matter Wave Interferometry in the Cold Atom Lab onboard the International Space Station*" to "*Pathfinder Experiments with Atom Interferometry in the Cold Atom Lab onboard the International Space Station*"

Introduction:

- The first paragraph of the introduction was updated so that all published CAL results, that don't rely on AI, are compiled together:

  Additional text in the first paragraph of the introduction
  Initial commissioning efforts for the flight instrument used laser and evaporative cooling of rubidium gases to produce Bose-Einstein Condensates (BECs) in orbit and characterized these quantum gases after freefall times exceeding 1 second [2]. Subsequent science demonstrations by the CAL investigators included enhanced techniques for cooling, manipulation, and control for quantum gases such as decompression cooling via adiabatic relaxation [3], shortcut to adiabaticity and delta-kick collimation techniques for preparing atoms with effective temperatures as low as 52 picokelvin [4], as well as the development of RF-dressed potentials and the study of ultracold rubidium gases in bubble-shaped geometries [5]. Recently, sympathetic cooling of bosonic potassium using evaporated ^{87}Rb gases as a reservoir has also been utilized in CAL to produce ultracold gases of either ^{41}K or ^{39}K and coexisting and interacting BECs of ^{41}K and ^{87}Rb [6].

- The second paragraph was simplified to remove information that was not relevant and had been reported previously. It changed from:

  Original text:
  Accommodation on the ISS not only provides the unique infrastructure, support, and effective real-time download of science data needed for daily operations of CAL, but also allows for on-orbit repair and upgrades by the resident astronaut crew. Two key upgrades have significantly expanded the scientific capabilities of the flight instrument: (i) A replacement science module (SM3) was launched to ISS onboard the commercial resupply services mission SpaceX-19 and was installed into CAL by astronauts Christina Koch and Jessica Meir. SM3 was equipped with a new optical beam path to enable experiments with atom interferometry. (ii) An upgraded microwave source was brought to the ISS onboard SpaceX-22 and was installed into CAL by astronaut Megan McArthur. The enhanced microwave source enabled species-specific evaporative cooling of ^{87}Rb gases to ultracold temperatures to provide a reservoir for sympathetic cooling of bosonic potassium gases. Recent commissioning efforts of these hardware upgrades have produced ultracold gases of either ^{41}K or ^{39}K, coexisting and interacting BECs of ^{41}K and ^{87}Rb, and simultaneously interrogated ^{41}K and ^{87}Rb atom interferometers using the single-laser atom interferometer beam [6]. This article details the design of the CAL atom interferometer upgrade and the first PI-led experiments utilizing matter-wave interferometry with ultracold ^{87}Rb gases in orbit.

  New text
  Accommodation of CAL on the ISS not only provides the unique infrastructure, support, and effective real-time download of science data needed for daily operations, but also allows for on-orbit repair and upgrades by the resident astronaut crew. Notably, a replacement science module (SM-3) was launched to ISS onboard the commercial resupply services mission SpaceX-19 and was installed into CAL by astronauts Christina Koch and Jessica Meir. SM-3 was equipped with an optical beam path to enable experiments with atom interferometry. This article details the

initial pathfinder experiments by CAL investigators utilizing matter-wave interferometry with ultracold ^{87}Rb gases in orbit.

- The following statement was added at the end of the fifth paragraph to co-localize all previously published AI measurements in space: "As part of the commissioning efforts for SM-3 in the CAL instrument, a dual-species atom interferoemter in space was also recently demonstrated using simultaneously interrogated ^{41}K and ^{87}Rb atoms with a single-laser atom interferometer beam [6].
- To further clarify the focus of our work, the first sentence of the sixth paragraph was changed from

  Original text:
  In this article, we report on the first PI-led experiments exploring atom interferometry on an Earth orbiting platform.

  New text:
  We report on a series of seminal experiments in which CAL investigators performed pathfinding investigations with single-species ^{87}Rb BECs to mature atom interferometry and quantum sensing on an Earth orbiting platform.

2. None of the experiments reported demonstrate in any way the benefit of operating in space, which should primarily be the ability to achieve long free evolution times (> 10 s) as also noted by the authors themselves in the introduction.

Response There is no mention in our manuscript of the need to achieve 10 second free evolution times to benefit from operation in space. Instead, we outline in the introduction three benefits that come from exploring atom interferometry in space: "(i) access to essentially unlimited freefall time in a compact instrument, (ii) enabling novel schemes such as extreme adiabatic cooling and delta-kick collimation for achieving ultra-low effective temperatures in atomic gases, and (iii) implementation and maturation of this quantum technology on a flight platform to support upcoming space missions where high-precision inertial sensing will be needed, including Earth observers and missions to test fundamental physics". Each benefit opens up new science capabilities or allows experimenters to understand limitations from the space platform, and are therefore uniquely important for enabling future mission concepts based on atom interferometry. However, significant efforts must be carried out, in the form of pathfinder experiments and technology demonstrations in space, to realize the full potential of space-based precision quantum sensors.

While the realization of free evolution times exceeding 10 seconds is a significant milestone for a number of proposed mission concepts, we contend that important milestones and capabilities arise with lower evolution times as well, including atom-interferometer-based tests of candidate theories to explain dark energy, high-resolution gravity sensing for Earth and planetary sciences, advanced navigation and drag-free referencing, and AI-based measurements to explore the nature of quantum matter at the unprecedented low temperature scales enabled in a persistent microgravity environment.

The demonstration of interferometer interrogation times > 10 seconds is therefore far out of scope of the present work. The absence of gravity is not the sole criteria for demonstrating this milestone with condensed gases. Even the realization of > 10 second freefall time is not a sufficient criteria for future demonstrations of precision atom interferometry with long interrogation times in space. Numerous technical advances and quantum sensing protocols must first be developed in the space platform and the environment (vibrations, vacuum, electromagnetic radiation, etc.) of the sensor must be understood at a level far-exceeding what is currently known even for the ISS. Hence, the experiments detailed in our manuscript benefit from operating in the relevant space environment by serving as pathfinder investigations in space for several technologies and platforms under consideration for future mission concepts.

The following paragraph was inserted into the Discussion section to further emphasize the unique importance of our work:

> **Additional text added to the Discussion section:**
> These efforts and findings serve as important milestones for maturing space-based atom interferometry for numerous mission concepts. Notably, observation of high-contrast interference fringes after long freefall times and within a single experimental run, as demonstrated here with shear-wave interferometry, is a technique that can be utilized for precision sensors [36], allowing for shot-to-shot determination of AI contrast and phase shifts. AI-based measurements of the photon recoil in space is also promising for multiple applications. Experiments to determine the fine structure constant [28,29] are expected to benefit from the extended freefall environment of microgravity for higher precision and reduced systematic errors by achieving long T in a relatively compact and freely-falling apparatus. Additionally, measuring the frequency of the AI laser via atomic feedback, as directly demonstrated in this article, will enable characterization and control over leading systematics for future missions and can remove the need for launching dedicated wave meters for the AI lasers. Finally, understanding the influence of ISS vibrations to the Rb-based AI allows researchers to understand limitations and optimize near-term experiments using differential interferometry for fundamental physics investigations on the ISS.

Minor Comments:

1. Fig 1a: It could be useful to include information on the dimensions of the payload so that the reader can appreciate the compactness of the apparatus.

   Response We agree with this suggestion. We therefore updated Figure 1 with dimensions shown for the glass vacuum chamber that serves as our science cell. The reasoning for including these dimensions is that it both gives a sense of scale for the reader to appreciate the compactness of the physics package, and it also gives the relevant length scales and experimental constraints for the AI experiments. In addition to the figure update, the caption was updated to also give the volume and mass of the CAL payload as:

> **Original Caption for Figure 1:**
> **Atom interferometer set up onboard the ISS. a** Cut of the upper region of the physics package of SM3 to expose the interior components and the path of the retro-reflected Bragg beam (red) inside the vacuum system. The expanded region shows the beam entering the vacuum chamber through a window and between pairs of Z and U-traces (blue) and H-traces (yellow) on the atom chip. **b** Space-time diagram of an ideal Mach-Zehnder interferometer (MZI), where three retro-reflected laser pulses (red) are applied in a sequence of $\frac{\pi}{2}$-π-$\frac{\pi}{2}$ pulses, with pulse separation times T, to create a superposition and then recombination of the initial atom cloud into two motional states ($|p_+\rangle$ and $|p_0\rangle$ given by blue and yellow clouds respectively). **c** Ramsey atom interferometer diagram using a sequence of $\frac{\pi}{2}$-$\frac{\pi}{2}$ pulses to explore shear-wave atom interferometry at long time-of-flight t_{TOF}. For sufficiently short T, used for photon recoil measurements, the outputs are similar to that of the MZI.

> **New Caption for Figure 1:**
> **Atom interferometer set up onboard the ISS. a** Cut of the upper region of the physics pack-

age of SM-3 to expose the interior components and the path of the retro-reflected Bragg beam (red) inside the vacuum system. The expanded region shows the beam entering the vacuum chamber through a window and between pairs of Z and U-traces (blue) and H-traces (yellow) on the atom chip. Dimensions of the upper vacuum cell are given to illustrate the compactness of the science region accommodating our AI experiments. Note that the entire CAL payload occupies only 0.4 m^3 on the ISS with a mass of approximately 230 kg. **b** Space-time diagram of an ideal Mach-Zehnder interferometer, where three retro-reflected laser pulses (red) are applied in a sequence of $\frac{\pi}{2}$-π-$\frac{\pi}{2}$ pulses, with pulse separation times T, to create a superposition and then recombination of the initial atom cloud into two motional states ($|p_+\rangle$ and $|p_0\rangle$ given by blue and yellow clouds respectively). **c** Ramsey atom interferometer diagram using a sequence of $\frac{\pi}{2}$-$\frac{\pi}{2}$ pulses to explore shear-wave atom interferometry at long time-of-flight t_{TOF}. For sufficiently short T, used for photon recoil measurements, the outputs are similar to that of the MZI.

2. Why was it chosen to use square pulses to drive Bragg transitions? Usually, Gaussian profiles are used to avoid losses in other orders (which, by the way, have been found in the Mach-Zender interferometer).

Response We agree that Gaussian-shaped pulses are commonly used for Bragg spectroscopy to minimize broadening of the pulse spectrum and driving unwanted excitations to other states. Due to the design of the CAL laser and optical system, amplitude control of the Bragg beam is currently constrained to 10 microsecond granularity, which is limiting for approximating Gaussian pulses on the $\sim$ 100 microsecond timescale. Due to concerns and complications with implementing Gaussian-approximated pulses in the CAL system, it was decided to use square pulses for this work and explore Gaussian-approximated pulses in the future with lower temperature gases and longer pulse times where the effects of discretization of the pulse shape can be minimized. To make this clear, the manuscript was updated as:

> **Original text in the second paragraph of the "Mach-Zehnder Interferometer" section:**
> Note that a small population in the spurious exit port N_-, corresponding to atoms driven towards the atom chip via off-resonant transitions into the $|p_-\rangle$ state, was also produced as a result of the finite cloud temperature and moderate two-frequency detunings of the Bragg laser
>
> **New text:**
> Note that a small population in the spurious exit port N_-, corresponding to atoms driven towards the atom chip via off-resonant transitions into the $|p_-\rangle$ state, was also produced as a result of the finite cloud temperature, moderate two-frequency detunings of the Bragg laser, and hardware limitations that practically inhibited the use of smooth (e.g., Gaussian-shaped) pulses. [52,54,56]

3. In section 2.3, it is stated that the contrast of the Ramsey interferometer is limited by the size of the trapped condensate, which is 8 μm. I wonder if the effective temperature of the atomic sample also contributes to this reduction.

Response We assume that the interference signal is predominantly due to atoms in the condensate. First, non-condensed atoms have a much lower density and so contribute little to the absorption image signals. Second, the higher velocity of the non-condensed atoms reduces the fidelity of the Bragg pulses and thus reduces the visibility of any interference that was observed. We therefore use a simple picture that the Thomas-Fermi condensate is the only source of interference signal. In a more realistic picture, the interferometer contrast is determined by the spatial coherence length of the original sample, which does in principle depend on temperature. However, as outlined by Dodd et al [Optics Express 1 284 (1997)], the average coherence in a situation like ours is normally dominated by the pure condensate fraction.

The reviewer might instead be referring to the mean-field expansion of the condensate as an ‘effective temperature.’ It is true that at the time of the interferometer, the condensate is larger than 8 μm due to this expansion, but the expansion process leads to correlations between velocity and position. If we try to recombine two packets that are separated by more than 8 μm, then the velocities will be mismatched and the visibility will be low for that reason.

REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

I thank the authors for their detailed response to the reviewers. The authors have satisfactorily addressed my suggestions. Moreover, I agree with the perspective offered by the authors in their response to reviewer 2 regarding the suitable of the manuscript for Nature Communications, and I support the authors' added emphasis of the point that this work represents pathfinder experiments that will provide essential guidance for upcoming atom interferometers in space.

As I argued in my first report, there are many technological challenges that must be overcome to mature atom interferometry in space, and this manuscript reports an important step in this journey. For example, I envision that the ability of the shear wave interferometry technique to diagnose phase shifts spatially varying across the atom cloud will be critical to ultimately realizing interferometers with >10 s of free evolution time. Such phase shifts become increasingly difficult to avoid as the different branches of the wave packet drift apart by larger distances, and so having a tool to directly characterize them will provide very important input for implementing appropriate mitigations. The potential benefits of a photon recoil measurement in space are also exciting, especially given the large disagreement between current ground-based measurements of this type and the importance of these measurements for precisely testing the Standard Model.

Additionally, as I mentioned previously, as the broader scientific community is now actively considering the next steps for cold atoms in space, it is important that these results be circulated to a wide audience.

In conclusion, I am now happy to recommend this manuscript for publication in Nature Communications.

Reviewer #2 (Remarks to the Author):

In this new version of the manuscript, the authors have correctly implemented the referees' suggestions, extending the experimental analysis with the addition of PDF analysis and enriching the text with new information.

While I believe the work is of very high quality, my doubts about its suitability for publication in Nature Communications remain. The introduction clearly lists the main results, namely:

"(i) the demonstration of high-visibility Mach-Zehnder interferometry (MZI) at relatively short times
(ii) signatures of atom interferometer sensitivities and visibility degradation due to the ISS vibration environment
(iii) the use of shear-Ramsey atom interferometry to extract contrast and phase shifts in a single experimental run
(iv) observation of interference fringes persisting for greater than 150 ms during free-fall in the compact science cell
(v) the use of the CAL atom interferometer to perform a photon recoil measurement, demonstrating its utility as the first quantum matter-wave sensor in space"

Regarding (i), I still believe that this result is somewhat already contained in [6]. Concerning (ii), the degradation due to vibrations was already clearly visible in Fig 4 of [6], as well as indications of instrumental sensitivity. Finally, regarding (iii) and (iv), in [42], a similar experiment was conducted in conditions of non-permanent micro-gravity with free evolution times well beyond 150 ms.

That said, I want to be clear that I do not intend to underrate the work done, which is certainly of excellent technical quality, and I agree that the results are of undeniable interest to the community. However, the fact remains that the impact of the work is diminished by previous publications on the subject, and the experiments reported are effectively proof of principle demonstrations of experiments already performed on Earth.

I have reservations that merely conducting these experiments in orbit, without any demonstration of having exploited the condition of permanent free-fall, is sufficient to warrant publication in a high-impact journal like Nature Communications.

Therefore, I leave the decision on this matter to the editor.