Review Report 1

Originality/Novelty

This paper treats an important question concerning the measurement of the gravitational constant G by atom interferometry. The treatment involves quantum corrections which are treated by calculating the Wigner representation of the density matrix and I am not aware of the use of such an extensive use of Wigner representation to describe atom interferometry experiments. The correction phi_Q was not discussed in the previous papers I know on the subject and I think that the paper must be published but, as explained below, important improvements are needed.

The novelty of the paper would not be reduced if the authors had quoted previous works on the same subject or using the same technique:

The first example is the result announced in Equation (4), concerning the phase shift due to the gravity gradient gamma. This effect was first calculated by Wolf and Tourrencin Physics Letters A 251 (1999) pp 241–246 and discussed with more details in A. Peters, K.Y. Chung and S. Chu, Metrologia 2001, 38, 25–61. Moreover, the authors call this effect a quantum correction probably because it is proportional to hbar but it would be more clear to explain that, the leading term of the gravitation phase being independent of hbar because of a cancellation (hbar appears in the numerator and denominator of the quantity giving the phase), the term linear in gamma is also proportional to the recoil velocity which itself is proportional to hbar.

A second example is the equation 9b for Wigner function: the associated quotation is ref. 17 by one of the authors and M.A. Kasevich in Phys Rev A (2006). A brief search on the web proves that a similar equation was used by Hongyi Fan Phys Rev A 656, 064102 (2002) who quotes two references dating from 1984 and a book published in 1994. I am not sufficiently aware of the use f Wigner function but I am sure that there are better and more useful references to quote in addition to ref 17!

In my opinion, phi_Q is the real quantum correction due to the spreading of the wavepacket during propagation. If I am correct, this should be explained.

Significance and Quality of Presentation

The paper is quite difficult to read, because of very many bulky equations. I do not see how to reduce the number of equations but I think that some more comments would help the reader.

For instance, the equations 12 to 14 were not clear for me but I found an explanation at Equation (37).

The meaning of the three x_C, x_qC and x_QC (Equation (99)) is far from obvious but it is very surprising that the leading term in T^2 is different?

The paper contains only one figure with 28 panels presenting the results of the calculations. I think that this figure is very difficult to read! I do not understand clearly why results are plotted with y < y_min if this not physical: please explain!

A figure explaining the geometry of the experiment would also help.

Scientific Soundness

There are several approximations which are not discussed, all of them related to atom diffraction (see for example Equation (32)):

- The process is calculated as if the gravitational forces can be neglected during the diffraction laser pulses. This is probably an excellent approximation but please comment it!
- The diffraction probability is assumed to be exactly ½ for the pi/2 pulses, with no dependence with x or p. Is this justified?

- The fountain is assumed to be exactly symmetric (see line after Equation (100)). It is well known that with symmetric fountains diffraction with retro-reflected laser beams produces stray interferometers...

Minor Remarks

I noted an error after Equation (1): ... the gravitational potential is constant... I assume that the authors meant acceleration g, not the potential.

Authors' response

We would like to thank the referee for his/her careful reading of the manuscript and the helpful comments. The response to these comments and changes to the manuscript in response to these comments is given below:

1. We added references to the Wolf and Tourrencin and A. Peters, K.Y. Chung and S. Chu articles. The latter of these articles does not address the quantum corrections
2. The referee implies that the leading term is not a quantum correction owing to the cancellation of a numerator proportional to hbar and a denominator in the spatial phase factor that is also proportional to hbar. This is, is some respect, a question of semantics, and has a long history in discussions of quantum effects in atom interferometry. Basically this term is a Doppler shift, which is clearly of classical origin, with no need to impose arguments related to cancellations of hbars in numerators and denominators. In the approach we follow using the Wigner representation, there are no numerators and denominators; the leading term has no hbar.
3. The density matrix in the Wigner representation has been widely used in problems related to the recoil effect and laser cooling. For some mysterious reason it hasn't used in much in problems involving atom interferometry. Of course there are hundreds of articles (maybe more) and books on the Wigner representation; however here we are concerned mainly with its application to calculations involving atom interferometry. The only examples we know of are the ones referred to in the paper.
4. The article by Fam is devoted to the use of Wigner representation for the two-particle density matrix, which is outside the scope of our article. Moreover, in contrast to that article, we do not use an expansion of the equation for the Wigner distribution in powers of hbar. For both these reasons, we do not include a reference on this article
5. As far as we can tell, the phi_Q term is not related directly to the spreading of the wave-packet. It arises as a quantum correction to phase factors during periods of free evolution. At this point, we do not have any other physical interpretation. We do not know yet how this term would manifest itself in the other approaches (path-integrals, ABCD theorem and etc.). This remains an interesting topic for future work, but is outside the scope of our article.
6. We added a paragraph re-emphasizing the choice of x_C, x_qC and x_QC just after Equation (99); these terms do not have to the same leading terms in T^2.
7. Several additional paragraphs have been added near the figures to help explain the plots appearing in these figures. For the stationary atom case, the limits on y_{m0} are determined from inequality (106) and it is indeed possible for y_{m0} to be less than y_{min}. The manner in which we arrived at the regions of validity of the approximations is now described in more detail.
8. In the article we obtained results that are specific for the parameters of the atom interferometer and test mass' shape and trajectory. We think for the each case one should generate one figure

to answer all questions regarding the validity and role of different parts of the phase and approximate expressions for them. Instead of using a lot of dashed curves, we decided to use a panel of figures. Although each plot is difficult to read at "normal" magnification, the online reader can easily magnify any plot when accessing the article in PDF format. We have added a note to this effect.

9. We added a schematic figure of the geometry of our problem.
10. In the paragraph after Equation (30) we added a list of requirements that will insure that the signal does not depend critically on the initial atomic state phase space distribution. These requirements minimize the corrections arising from diffraction to which the referee refers
11. Difficulties related to stray interferometers exist and are important, but are not addressed in our paper, as the referee points out. We are assuming that the effects can be minimized in a fountain geometry using a variety of experimental techniques. In any event, a discussion of these effects is beyond what we are able to discuss in this article.
12. The word "potential" has been changed to "acceleration" in the sentence after Equation (1).

Again, we would like to thank the referee. We know that this paper is "equation-rich", but we have tried to provide some physical guidance for the reader.

Review Report 2

In this manuscript, the influences of an external test mass on the phase of the signal of an atom interferometer are studied theoretically. Two processes are considered, one occurs during the interaction between the cold atom cloud and the Raman beams, the other occurs during the free evolution of the cold atom cloud in vacuum. The results obtained seem reasonable, although I have no time to verify all the derivations. These results are interesting to the people working in the field of atom interferometer, because the test mass are often used in the practical experiment. I recommend accepting this manuscript, provided the following points are clarified:

The relative location of the test mass to the cold atom cloud should be clearly stated during the calculation, as the gravitational force is a vector. If the test mass is not located in the direction of the evolution trajectory of the atom cloud, the applicability of some formulas (e.g. Equation (3)) need to be verified. It will be helpful to the readers if a figure is provided to show the locations.

The cloud is assumed to be characterized by a Wigner distribution function. What are the advantages to use Wigner distribution function instead of wave function?

In the Introduction, quite a lot of papers are cited concerning the applications of atom interferometer in varies fields. Just for the note of the authors, there are some new applications of atom interferometer, e.g., in the accurate measurement of the quadratic Zeeman coefficient [J. Phys. B: At. Mol. Opt. Phys., 47(1): 015001, 2014].

Author response

We would like to thank the referee for his/her careful reading of the manuscript and the helpful comments. The response to these comments and changes to the manuscript in response to these comments is given below:

1. A figure has been added to clarify the geometry of the problem. Moreover, additional discussion of the trajectories involved are now given in paragraphs that were added to help explain the plots given in Figures 2 and 3.
2. The wave function cannot be used when we know only some statistical properties of the initial phase space distribution.
3. We thank the referee for pointing out this additional reference and have added it to the references.