Postdoc Research

Atom Interferometer Fringe Fitting Simulation for Imaging Setup Characterization

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Background

Atom interferometers (AI) have demonstrated exceptional precision and accuracy in measuring gravitation acceleration, gravitational gradient, and distortion by gravitational waves, due to the inherent stability of atomic states as well as advanced phase locking techniques. The inclusion of a quantum gravity gradiometer is expected to improve the orbital cross-track data of a space-based gravity gradiometer like GRACE-FO [1]. In addition, the AIs are researched at JPL also for dark energy detection in microgravity [2].

Objective

Given that atom interferometry relies on capturing fringe images produced by atom fluorescence, which are then collected by optics and captured by a camera, gaining insights into the impact of the imaging parameters to the phase uncertainty can help clarify the required constraints for an AI experiment. We develop a start-to-end simulation scheme incorporating a realistic lens to assess a realistic fringe image. We explore in simulation to understand the influence of various imaging parameters to the extracted phase using different fitting methods, using fringe images generated from 1D and 2D atomic distributions and ray tracing.

Approach and results

With initial studies of imaging parameters given an AI fringe image traced by Zemax, we have explored possibilities to use Python RayTracing package to develop a start-to-end sequence. Then, we analyzed phase errors given different fitting methods and various imaging parameters (population fluctuation, white noise, binning, bitdepth, rotation, translation) based on 1D and 2D atomic distributions.

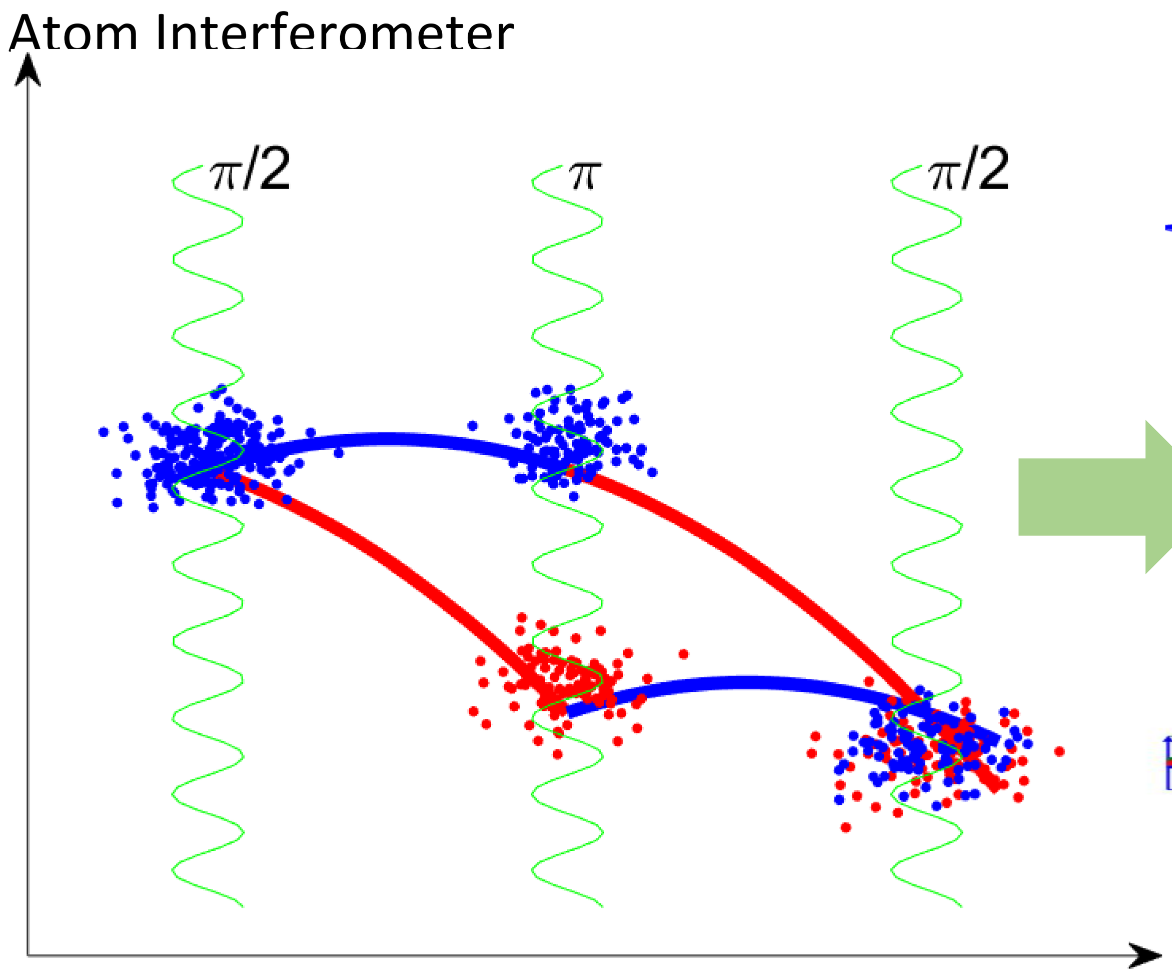
Significance of Results/Benefits to NASA/JPL

The completion of this fringe simulation can be used as a reference for designing a similar AI system. The relation of each parameters and the correlations among them will be very useful when selecting each parameters to meet strict design requirements typical for space/science explorations.

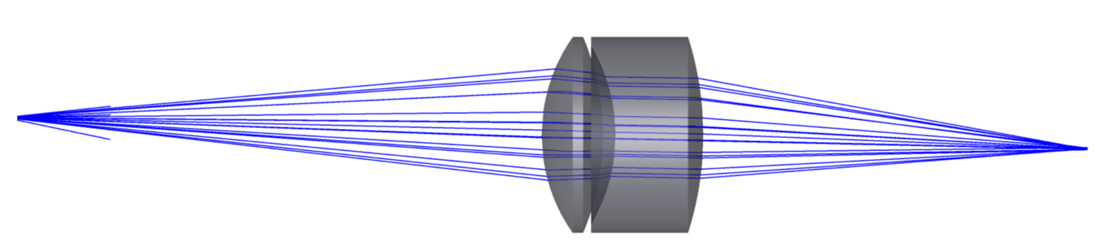
Future Work

The fringe simulation tools available in Matlab/Zemax and in Python will be used to study the impacts of various imaging parameters. After completing the influence of the parameters to the 1D and 2D models, we will use the results to understand the impacts of the parameters to the start-to-end fringe simulation.

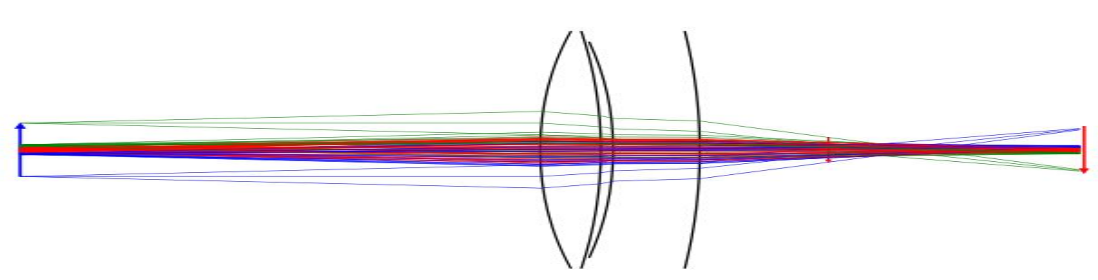
Atom Interferometer



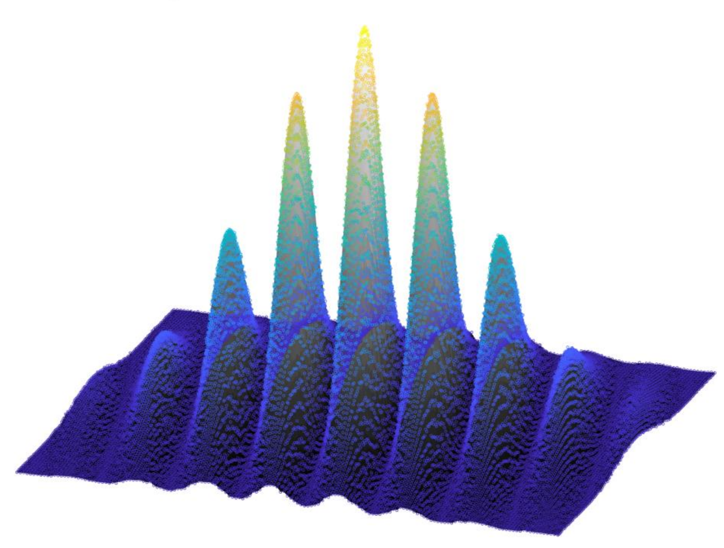
Zemax :



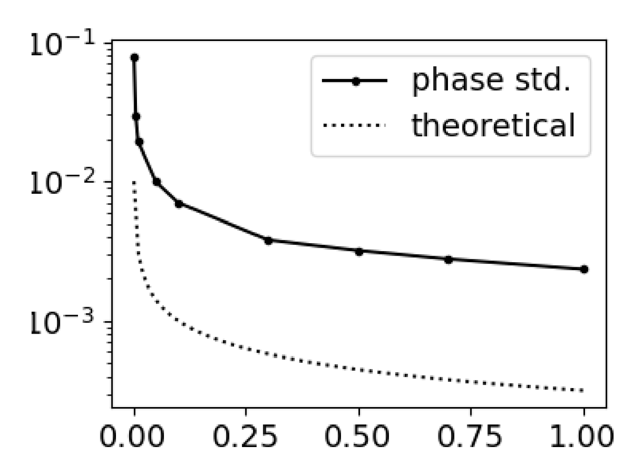
Python Ray Tracing [3] :



2D Fringe Fitting



Start-to-end Simulation at different #atoms

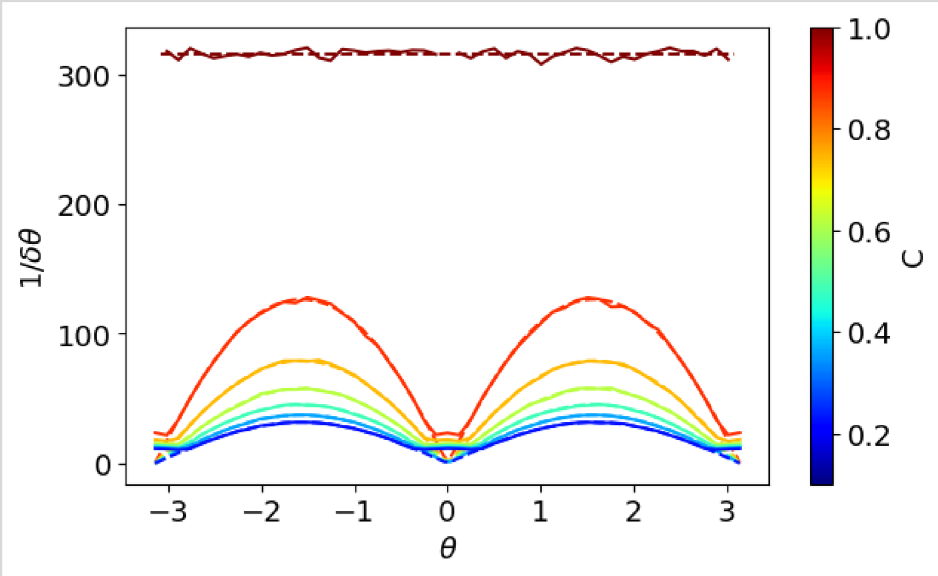


Two – state Transition Probability

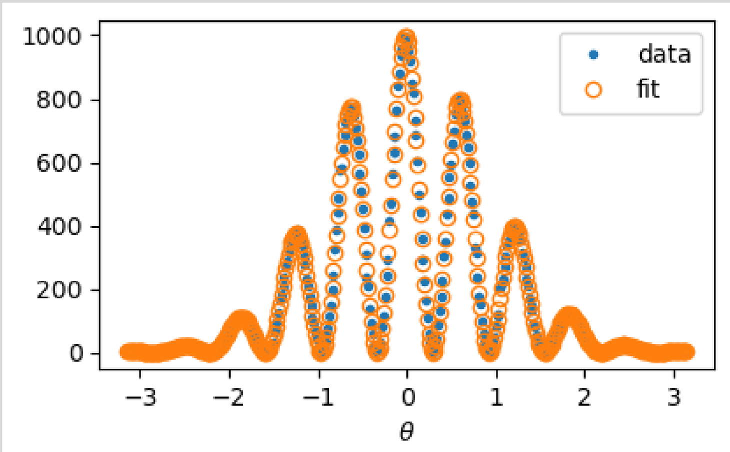
$$P = \frac{1}{2}\left(1 + C\cos(kx+\phi)\right)\exp\left(-\frac{x^2}{2\sigma_g^2}\right) \qquad (1)$$

Simulation of expected phase error due to quantum projection noise fitted with

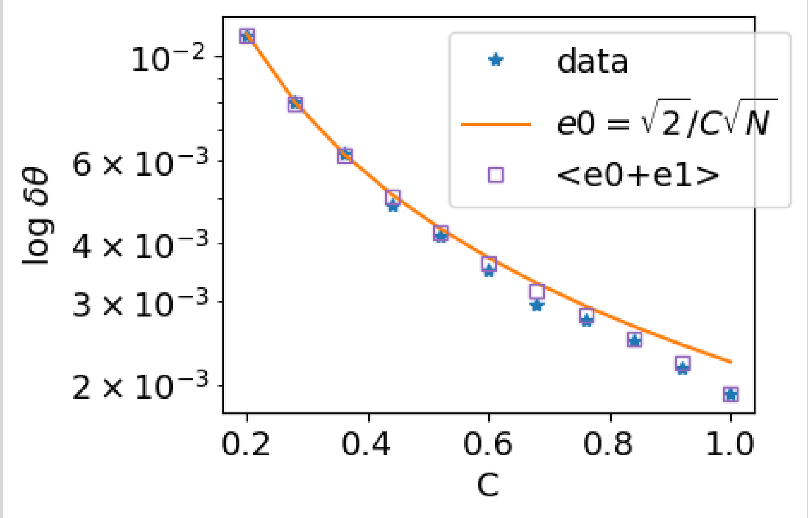
$$\delta\theta_{QPN}(\theta) = \frac{1}{C\sqrt{N}}\frac{\sqrt{1-C^2\cos^2\theta}}{\sin\theta} \qquad (2)$$



1D Fringe Fitting :



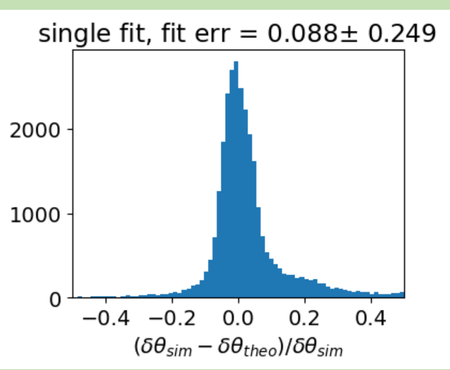
Phase error at different contrast, plotted with expected value derived from on Eq. 2



Expected phase error given various imaging parameters

$$\delta\theta = \sqrt{\left(\delta\theta_{QPN}p_0\right)^2 + \left(\frac{\theta_{m/n}}{C\sqrt{N_a}}p_1\right)^2 + \left(\frac{\sigma_N}{C\sqrt{N_a}}p_2\right)^2 + \left(\frac{\sigma_\lambda}{C\sqrt{N_a/n}}p_3\right)^2 + \left(\frac{1}{2^b-1}\,p_4\right)^2 + corr.} \qquad (3)$$

Difference between Eq. 3 and 1D simulation



National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
www.nasa.gov

Clearance Number: CL#00-0000

Poster Number: PRD-T-007

References:

[1] N. Yu, J.M. Kohel, J.R. Kellogg, and L. Maleki. Development of an atom interferometer gravity gradiometer for gravity measurement from space. Applied Physics B, 84(4):647–652, 2006.
[2] S. Chiow and N. Yu. Multiloop atom interferometer measurements of chameleon dark energy in microgravity. Phys. Rev. D, 97:044043, Feb 2018,
[3] V. Nö̈el, et al. Tools and tut*orial on practical ray tracing for microscopy. Neurophotonics, 8(1):010801, 2021 https://github.com/DCC-Lab/RayTracing*

Publications and Acknowledgements:

This work was funded by UFAS (Strategic R&TD) and by Dark energy/Matter (Fund. Physics Mgmt)

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