Two-Dimensional Rotation Measurement with Point Source Atom Interferometry

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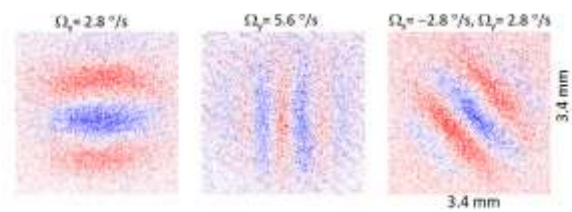
Abstract— **In analogy with a spinning rotor gyroscope, which precesses in response to a torque in the plane transverse to the axis of spin, point source atom interferometry (PSI) senses the components of rotation in the plane transverse to the direction of a pair of counter-propagating Raman laser beams. Based on the PSI technique, we demonstrate the two-dimensional measurement of a rotation vector projected into a plane. We characterize the sensitivity of the measurement, including the magnitude and the direction of the rotation vector component.**

Keywords— gyroscope; atom interferometer; quantum sensor

Rotation measurements with light pulse atom interferometry are typically more complex than acceleration measurements because both acceleration and rotation contribute to the interferometer phase shift. Two counter-propagating cold-atom sources or more complicated atom-optics are often used to obtain the rotation measurement from the interferometer phase shift [1]. In contrast, point source atom interferometry (PSI) [2] makes use of the thermal velocity spread of an isotropically expanding cloud of cold atoms to construct the rotation measurement. While dramatically simplifying the architecture of an atom interferometer gyroscope, the PSI's unique capability to simultaneously measure two components of the rotation vector with moderate to high bandwidth also opens up new applications. For instance, it may permit measuring time-varying rotation vectors, such as precessions, with atom interferometers.

In PSI, the most common Raman beamsplitter-mirror-beamsplitter pulse sequence is applied to a cold-atom cloud which expands within a pair of counter-propagating Raman laser beams. If the final cloud is much larger than the initial cloud, the latter is an approximation to a "point source" and the position of an atom in the final cloud is related to the velocity of the atom by $\vec{r} = \vec{v}T_{\text{ex}}$, where T_{ex} is the total expansion time of the cloud. This position-velocity correlation maps the interferometer phase shift of each atom into space as $\Phi(\vec{r}) = \vec{k}_{\text{eff}} \cdot \vec{a}T^2 + \vec{k}_{\Omega} \cdot \vec{r}$, where the first term is the acceleration phase and the second term is due to a phase gradient induced by rotation. The phase gradient is $\vec{k}_{\Omega} = (\vec{k}_{\text{eff}} \times \vec{\Omega})2T^2/T_{\text{ex}}$, where $\vec{\Omega}$ is the angular velocity, $\vec{k}_{\text{eff}}$ is the effective Raman wavevector, and T is the time between the Raman pulses. The population ratio is a sinusoidal function of the interferometer phase, so the phase gradient creates a spatial fringe pattern in the final cloud (Figure 1). The projection of $\vec{\Omega}$ into the plane transverse to $\vec{k}_{\text{eff}}$ is constructed from the fringes. The number of the fringes is proportional to the magnitude of the rotation projection. The orientation of the fringes is in the direction of the rotation projection. The acceleration in the direction of $\vec{k}_{\text{eff}}$ translates the fringes without affecting the number and orientation of the fringes.

Fig. 1. Rotation fringes obtained with a simulated rotation. Images are auto-scaled with red indicating population maxima and blue population minima. The Raman laser beams propagate parallel to the *z*-axis and the cold-atom cloud is imaged in the *xy*-plane. Here, $T = 8$ ms and $T_{\text{ex}} = 26$ ms.



With a single cloud of laser cooled ^{87}Rb atoms, we have previously demonstrated rotation measurements with PSI in the regime where the final cloud is only a few times larger than the initial cloud. We have characterized a systematic error due to this non-ideal point source [3]. In the current work, we focus on the two-dimensional rotation measurement of PSI. We demonstrate the measurement of a rotation vector projected onto the plane normal to the Raman laser beams and characterize the sensitivities of the measurement, including the magnitude and direction of the rotation vector projection in the plane (Figure 2).

In the presentation, we will present the details of the 2D rotation measurement with PSI and discuss our ongoing work on investigating the technical performance limitations and systematic errors in our compact setup, in which we have such a non-ideal point source. We will also discuss the applications of the PSI technique; for example, the 2D rotation measurement with PSI can be used to find geographic north (Figure 3).

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Fig. 2. Allan deviation of the magnitude and direction of the rotation vector measurement in a plane with simulated rotation. Here, $T = 8$ ms and $T_{\mathrm{ex}} = 26$ ms. Black lines are $\tau^{-1/2}$ power fits from $\tau = 1$ to 10 s. For a 1 s averaging time, the sensitivity of the magnitude is $0.033\ {}^{\circ}/\mathrm{s}$ and that of the direction is $0.27\ {}^{\circ}$. We estimate that, with an ideal point source limited only by atom shot noise, for 1 s the ultimate sensitivities could be as low as $1 \times 10^{-4}\ {}^{\circ}/\mathrm{s}$ and $3 \times 10^{-3}\ {}^{\circ}$, respectively.

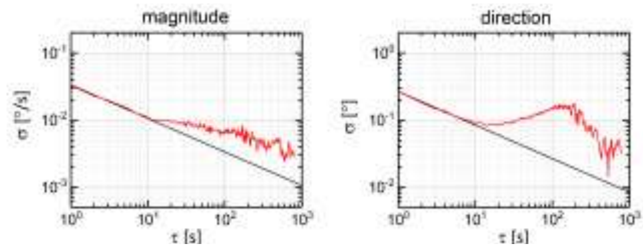
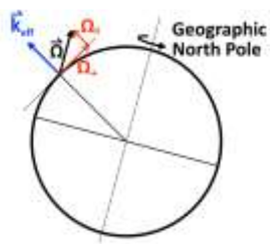


Fig. 3. Illustration of gyrocompassing with PSI. When the direction of the Raman laser beams ($\vec{k}_{\mathrm{eff}}$) is normal to the surface of Earth, PSI senses the projection ($\Omega_{\perp}$) of the Earth rotation ($\vec{\Omega}$) onto the Earth's surface. Since $\Omega_{\perp}$ points to the geographic north, the rotation fringes due to Earth's rotation points to the geographic north.



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