because phase shifts to atomic de Broglie waves depend on the time of flight for atoms propagating through an interaction region. Additionally, improved measurements of beam velocity can increase the accuracy of space-domain matter-wave inertial sensors [5, 6]. In this paper, we describe a novel and highly accurate method to measure the flow velocity and velocity distribution of atoms in an atom beam interferometer.

Many techniques exist to measure atom beam velocities, but few provide the 0.1% accuracy we demonstrate here using a new method. For comparison and background, we review a handful of velocity measurement techniques. First, two spinning mechanical choppers (slotted disks) separated by a distance $L$ and blocking the beam at frequency $f$ can transmit atoms with velocity $v = nLf$, where $n$ is an integer. Molecular beam velocity has been measured using this technique with 0.2% uncertainty [7, 8], but this requires moving parts inside a vacuum system and can cause unacceptable vibrations. Another approach uses the small gravitational free fall of an atom beam through separated apertures at different heights to define the velocity of transmitted atoms with 1% uncertainty [9]. Doppler shifts of an atomic transition observed with a resonant laser enable measurements of velocity with 0.8% uncertainty [3]. Similar uncertainty (0.8%) was obtained with Bragg diffraction from standing waves of light by analyzing rocking curves [3]. Atom diffraction using a nanograting has been used by our group to measure beam velocity with 0.3% uncertainty [1]. Finally, pulsed beams and time-resolved detection were recently used to achieve 0.03% uncertainty velocity measurements of pulsed metastable helium beams [10], but this technique is less applicable to continuous beams of ground state atoms.

Our new velocity measurement technique uses *phase choppers* to measure the velocity of atoms in an interferometer. Phase choppers do not block any atoms, do not require resolved diffraction, have no moving parts, work for continuous or pulsed beams, and work well for many types of atoms and molecules. Phase choppers are similar to the phase shifters described in [11] and their utility for measuring beam velocity was first proposed in [12]. This paper develops a significantly more thorough analysis of atom beam velocity measurements using phase choppers and we demonstrate velocity measurements with 0.1% uncertainty. We tested phase choppers with supersonic beams of Li, Na, K and Cs, and we use the velocity measurements as inputs to atomic polarizability measurements. To demonstrate the utility of phase choppers for precision measurements, we present consistent measurements of Cs polarizability with 0.1% precision using beams that had different velocities (spanning 925–1680 m s$^{-1}$).

## 2. Phase choppers theory

The principle behind phase choppers is similar to that behind mechanical choppers. An atom with velocity $v$ will travel a distance $L$ from the first chopper to the second chopper in a time $\tau = L/v$, corresponding to a fundamental chopping frequency $f_0 = v/L$. Mechanical choppers simply block or transmit atoms, leading to a maximum in the transmitted flux when the chopping frequency is any integer multiple of $f_0$. In the method we present in this paper, phase choppers are switched on and off by a function generator to periodically apply phase shifts to atomic de Broglie waves in an interferometer. We will explain how this leads to a maximum in the interferometer contrast, instead of the flux, when the chopping frequency satisfies $f = nf_0$. Additionally, the ability to control wavefunction phase, rather than amplitude, allows atoms to contribute to the interference fringes in unique ways and provides new measurement possibilities, as we describe next.

To explain how phase choppers enable velocity measurements, we will describe how the atom interference pattern changes when the phase choppers are switched on and off at several