**Table 1.** Error budget for a typical velocity measurement with phase choppers.

| Parameter | Value (Unc.) | Uncertainty in $v_0$ (%) |
|---|---|---|
| Stat error in $v$ | | 0.04 |
| $L$ | 1270.68(25) mm | 0.02 |
| $\phi_{1DC}/\pi$ | 1.000(5) | 0.01 |
| $\phi_{2DC}/\pi$ | 1.000(5) | 0.01 |
| Beam width | 100(30) $\mu$m | 0.04 |
| Initial contrast $C_0$ | 25(2)% | 0.04 |
| Transit time | 2 $\mu$s | 0.005 |
| Switching time | 200 ns | 0.001 |
| Duty cycle | 50.0(3)% | 0.005 |
| Sagnac phase shift | 1.46(2) rad | 0.005 |
| Molecules | 10(10)% | 0.02 |
| Total | | 0.08 |

We measured the distance between the two choppers, $L$, by inserting the ends of a calibrated tape measure between the wire and ground plane of each chopper. We subdivided the millimeter markings on the tape measure by analyzing high-resolution digital photographs of the tape measure inserted into each chopper. We took care to take the pictures with the chopper wire centered in the frame and from normal incidence to the ground plane. Thermal expansion may change the distance between choppers by no more than 150 $\mu$m (0.01%), significantly less than the measurement uncertainty in $L$.

Adding the Sagnac phase shift from the Earth's rotation into the analysis also yields small corrections to the best fit $v_0$ and $r$. The corrections to $v_0$ and $r$ can be as large as 0.2 and 4%, respectively, for slower beams with smaller $r$. Holmgren *et al* [1] explains how we incorporate the Sagnac phase shift in our interferometer model. The uncertainty in this correction is negligible.

We add a correction to the phase chopper model to account for the nonzero width of the atom beam and additional interferometers formed by other diffraction orders. We model this correction by making $\phi_i(v, t)$ (equation (3)) a function of $x_0$ as well and then introducing an additional average over beam width ($x_0$) in equation (1). For the widest beams, the correction to $v_0$ and $r$ is less than 0.1%, and the uncertainty in $v_0$ due to the beam width is less than 0.04%.

Despite accounting for the averaging of fringe patterns from the velocity distribution and beam width, the measured reference contrast is systematically 1–2% larger than the best-fit contrast parameter $C_0$. Fixing $C_0$ at its measured value in a least-squares fit of the chopper frequency scan typically results in an unrealistically small $r$, which then requires slightly slower $v_0$ to fit the data well. We estimate the uncertainty from this parameter by taking the full difference in fitted $v_0$ when using the two different initial contrasts. Future work is needed to discover the source of this uncertainty.

The voltage switching time and the transit time for atoms through the choppers introduce additional mechanisms by which the phase shifts may be different than desired. The switching time can be thought of as making the phase shifts depicted in figure 1 have fuzzy edges in time, while the finite extent of the electric field causes fuzzy edges in space. Both these corrections are negligible at our level of precision (see table 1).