Self-calibrated atom interferometry for absolute rotation measurement

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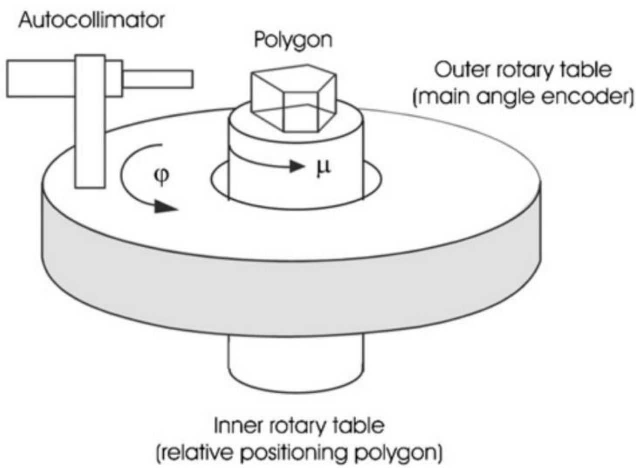
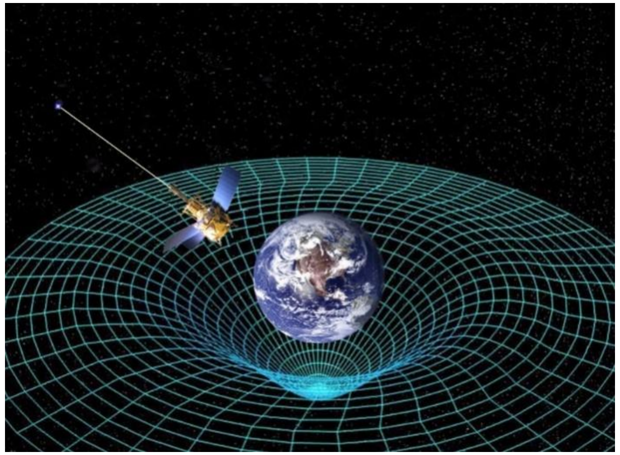
Outline

1. The absolute rotation measurement
2. Calibration of atom interferometer gyroscope
3. Improvement of scale factor stability
4. Conclusion and prospect

The absolute rotation measurement





- The relative rotation measurement
  - Movement between different platforms
- The absolute rotation measurement
  - Relative to inertial frame
  - Gimble, Sagnac interferometer, Vibration gyro

R. D. Geckeler, Meas. Sci. Technol. **17** (2006) 2811
https://www.nasa.gov

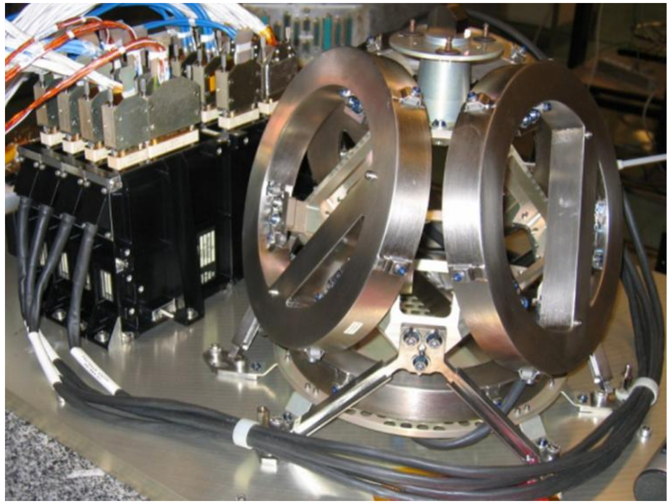
Atom interferometer gyroscope

TABLE I. Compared and contrasted are different properties of matter-wave and optical gyroscopes in terms of their sensitivity to phase differences—or equivalently—rotation rates. We see that the high mass of atoms initially contributes an increase of sensitivity of 10^{10}, but that the low atomic beam intensity, compared to photon beams, removes some of this advantage, as does the reduced number of round trips possible in an atom interferometer. Nevertheless, a typical factor of a 10^4 increase in rotation sensitivity can still be expected using atoms rather than photons.

	Matter	Laser	Matter-to-light sensitivity factor
Mass factor	$\sim 10^4$ MeV	~ 1 eV	$\sim 10^{10}$
Flux	$\rho v A \sim 10^{10}\times 10^4\times 10^{-2}$ $=10^{12}\,\frac{\text{particles}}{\text{sec}}$	$\frac{P}{\hbar v}\sim\frac{10^{-3}}{10^{-19}}$ $=10^{16}\,\frac{\text{photons}}{\text{sec}}$	$\sim 10^{-2}$
Round trips	~ 1	$\sim 10^4$	$\sim 10^{-4}$

$$\phi_\Omega = \frac{4\pi A\Omega}{\lambda v}$$

$$\frac{\phi_{dB}}{\phi_{Photon}} = \frac{\lambda c}{\lambda_{dB} v} \sim 10^{10}$$

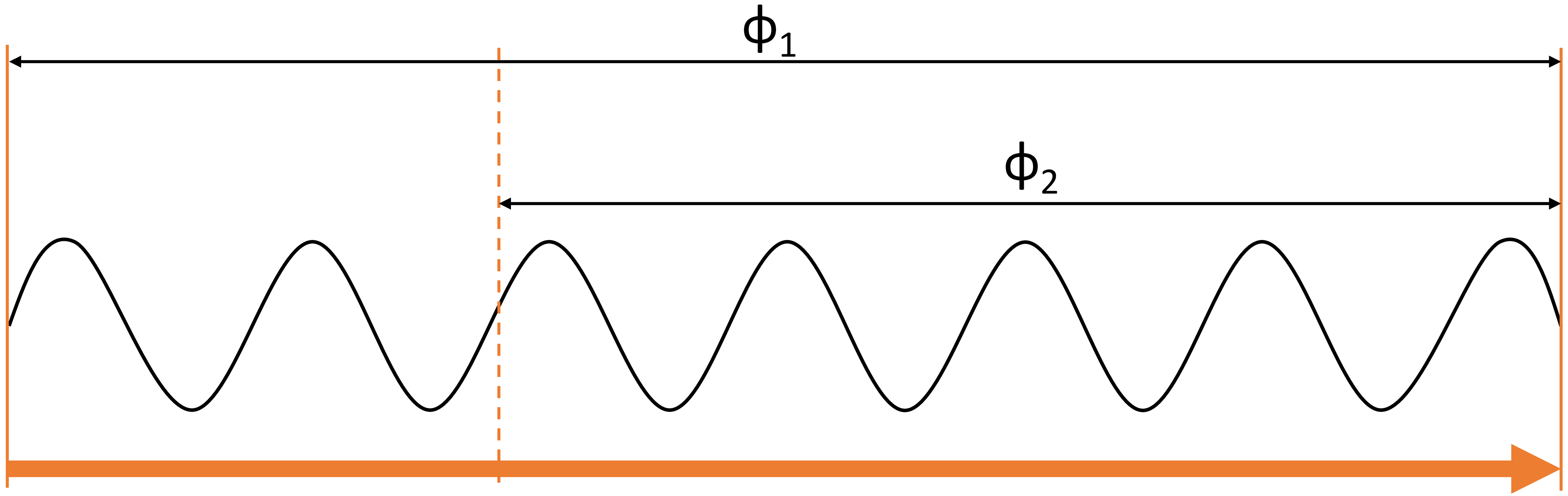


one million of kilometers, it means the measurement of the 15°/h of Earth rotation rate is performed with a relative stability of one millionth, i.e. a 1.5×10^{-5} °/h error combining bias and scale factor. The gyro fiber coils of this experiment being 3 km long over a diameter of 200 mm and the wavelength being 1550 nm, this 1.5×10^{-5} °/h error correspond to a phase difference error of only 5×10^{-10} radian. Compared to the absolute phase of $2\times10^{+10}$

- Fiber optical gyro： A=150 m^2， K=5.96 rad/(rad/s), 4.3×10^{-10} rad
- Atom gyro： A=1.2 cm^2， K= 3×10^5 rad/(rad/s), 0.3 mrad

M. O. Scully, Phys. Rev. A **48**, 3186(1988)
H.C. Lefèvre, Optical Fiber Technology **19**, 828(2013)

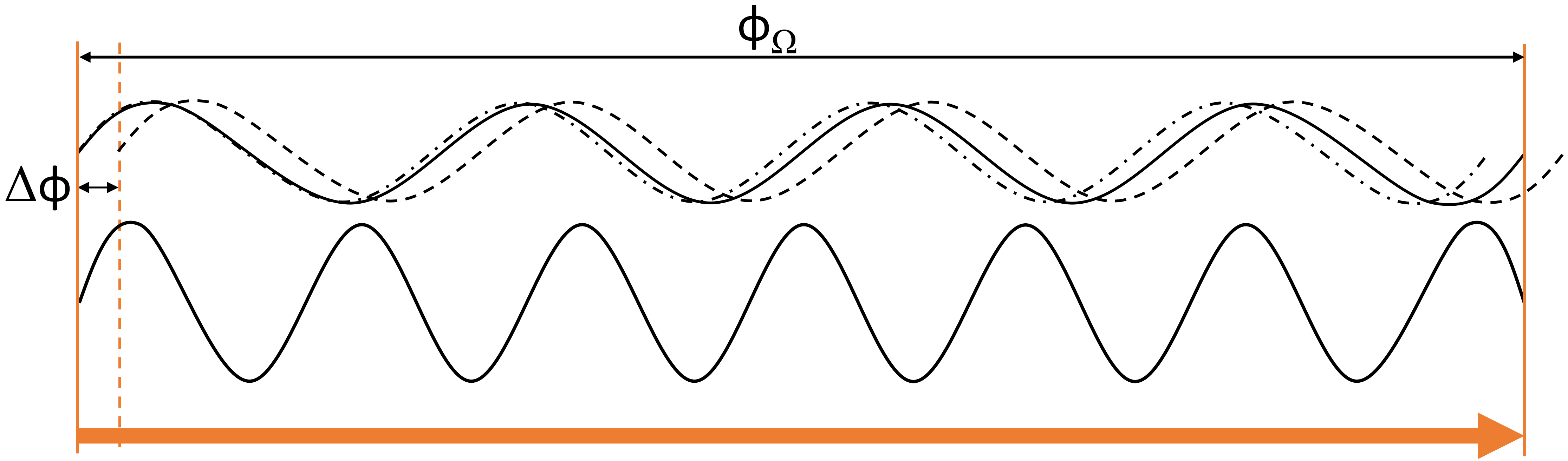
Interference-based gyroscope



$$P=\frac{1}{2}\left(1+C\cos(\phi)\right)$$

- How to determine the period number：ϕ_1 or ϕ_2？
- The phase ambiguity in large scale factor gyroscope

Absolutely phase extraction



- Multiple scale factors to calibrate the absolute phase shift
- Precisely measurement of scale factor： ΔK
- Evaluation of the phase accuracy： $\Delta\phi$

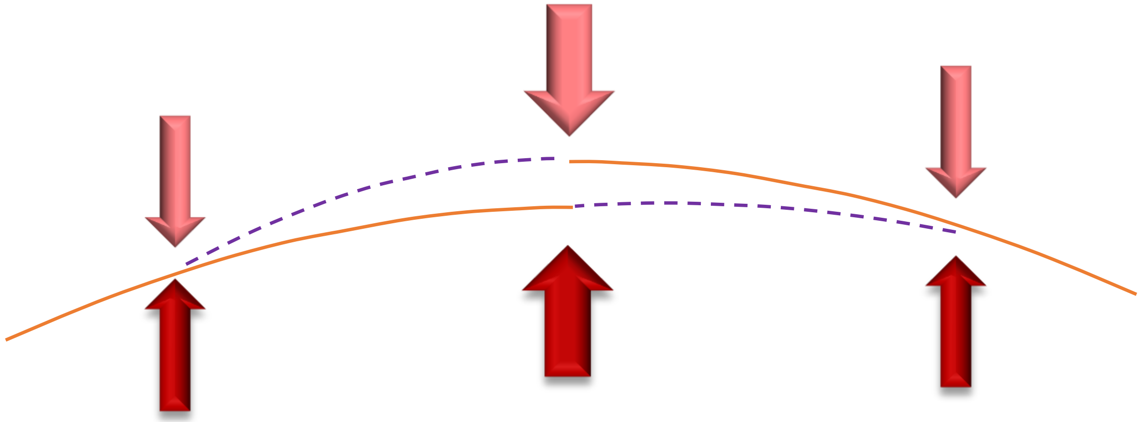
$$\lambda_{dB} = \frac{h}{mv}$$

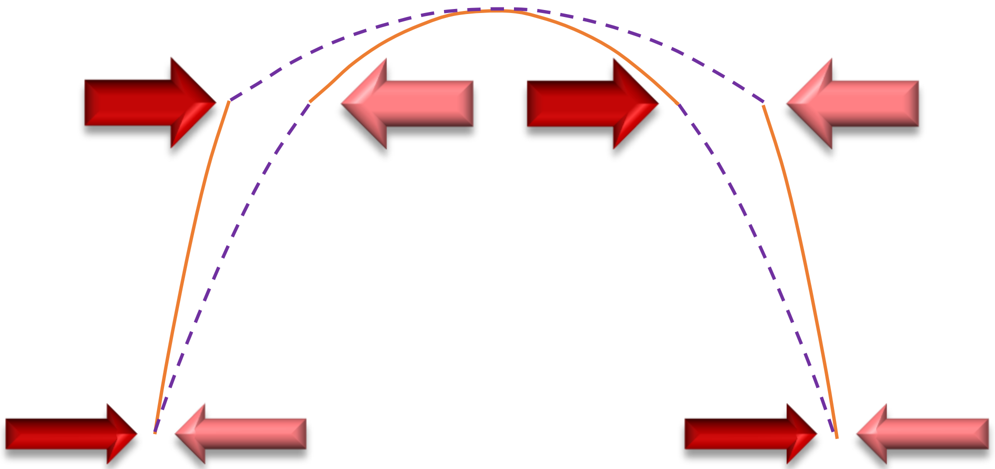
A. Bonnin, Applied Physics B **124,** 180 (2018)
D. Yankelev, Sci. Adv. **6** : eabd0650 (2020)

Two configurations of atom gyroscope

- Three pulses: velocity dependent(counter propagating)

- Four pulses: gravity dependent



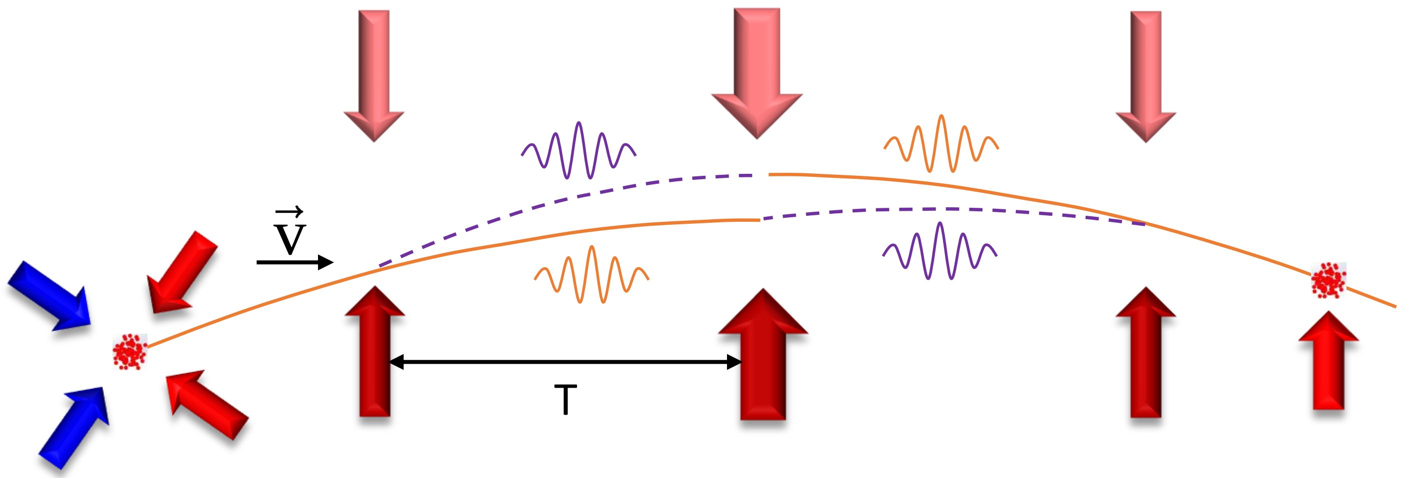


$$\Delta\phi_{\pi/2-\pi-\pi/2}=\vec{k}_{eff}\cdot\vec{g}T^2\text{-}2\vec{k}_{eff}\cdot\left(\vec{\Omega}\times\vec{v}\right)T^2-2\vec{k}_{eff}\cdot\left(\vec{\Omega}\times\vec{g}\right)T^3-\vec{k}_{eff}\cdot\left(\left(\vec{\Omega}-\vec{\Omega}_E\right)\times\vec{g}\right)T^3$$

$$\Delta\phi_{\pi/2-\pi-\pi-\pi/2}=-4\vec{k}_{eff}\cdot\left(\vec{\Omega}\times\vec{g}\right)T^3-2\vec{k}_{eff}\cdot\left(\left(\vec{\Omega}-\vec{\Omega}_E\right)\times\vec{g}\right)T^3$$

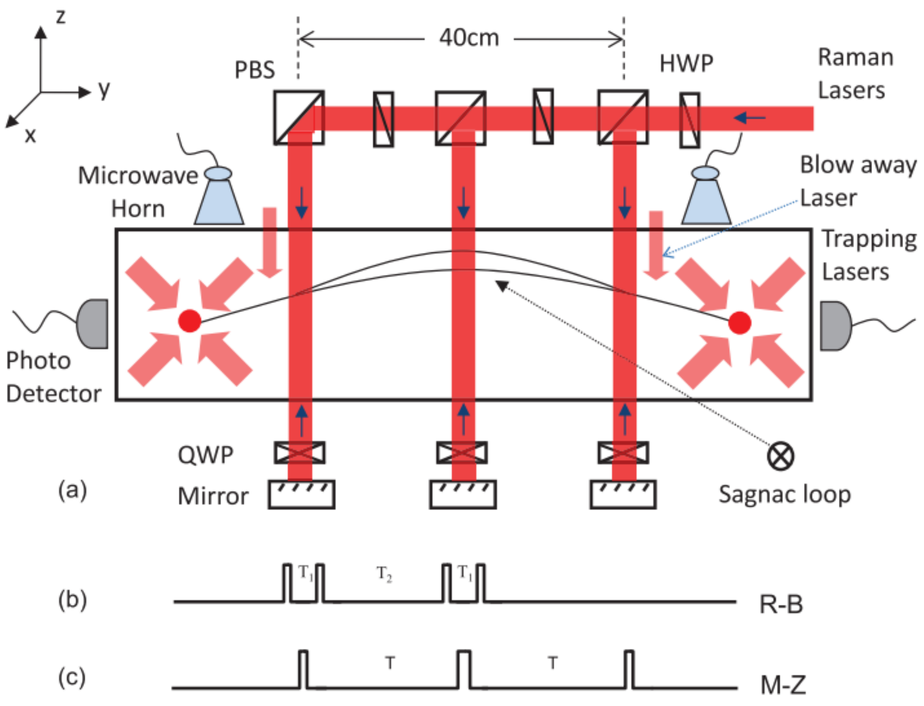
K. P. Marzlin, PRA **53**, 312 (1996)
K. Takase, PhD thesis, Stanford University (2008)

Atom interference



- Magnetic optical trap: μK order
- Moving molasses: $v=\delta f\cdot\lambda\cos\theta$
- Mach-Zehnder interferometer: $\Delta\phi_{\pi/2-\pi-\pi/2}=2\vec{k}_{eff}\cdot\left(\vec{\Omega}\times\vec{v}\right)T^2$
- Fluorescence detection: $P=\frac{1}{2}\left(1+C\cos\left(\phi_\Omega+\phi_g+\phi_B+\ldots\right)\right)$

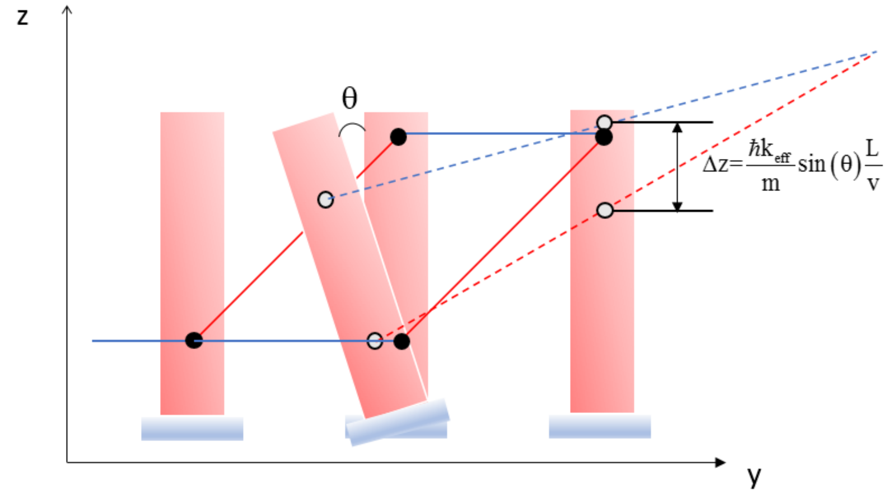
Large area Atom interferometer gyroscope

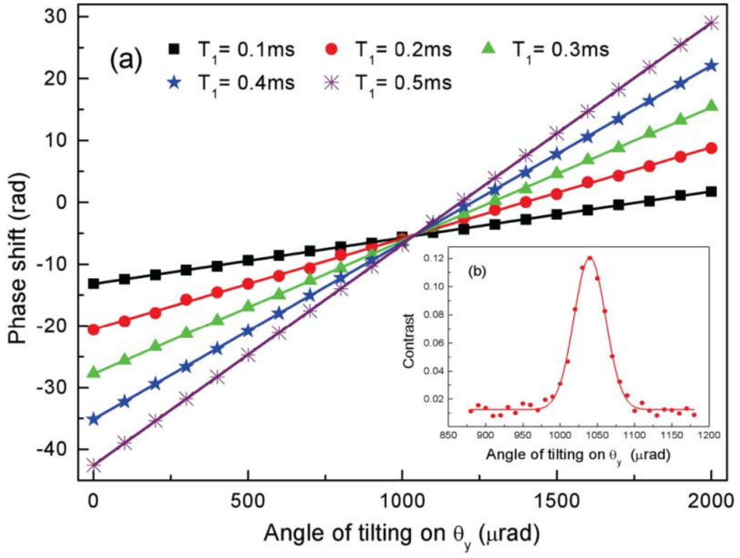


- Coherence length> Separation distance

$$\Delta l = \hbar / 2\Delta p$$

- Phase calibration to align laser beam



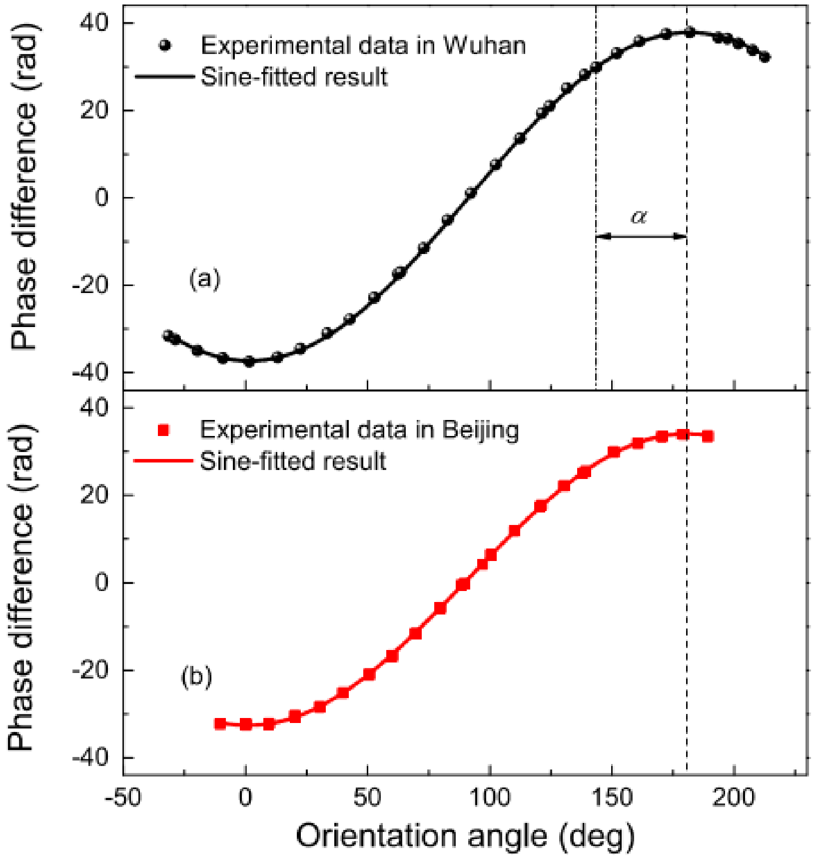


Atom interferometry, Paul R. Berman, (1997)
Z. Yao, Phys. Rev. A **103**, 023319 (2021)

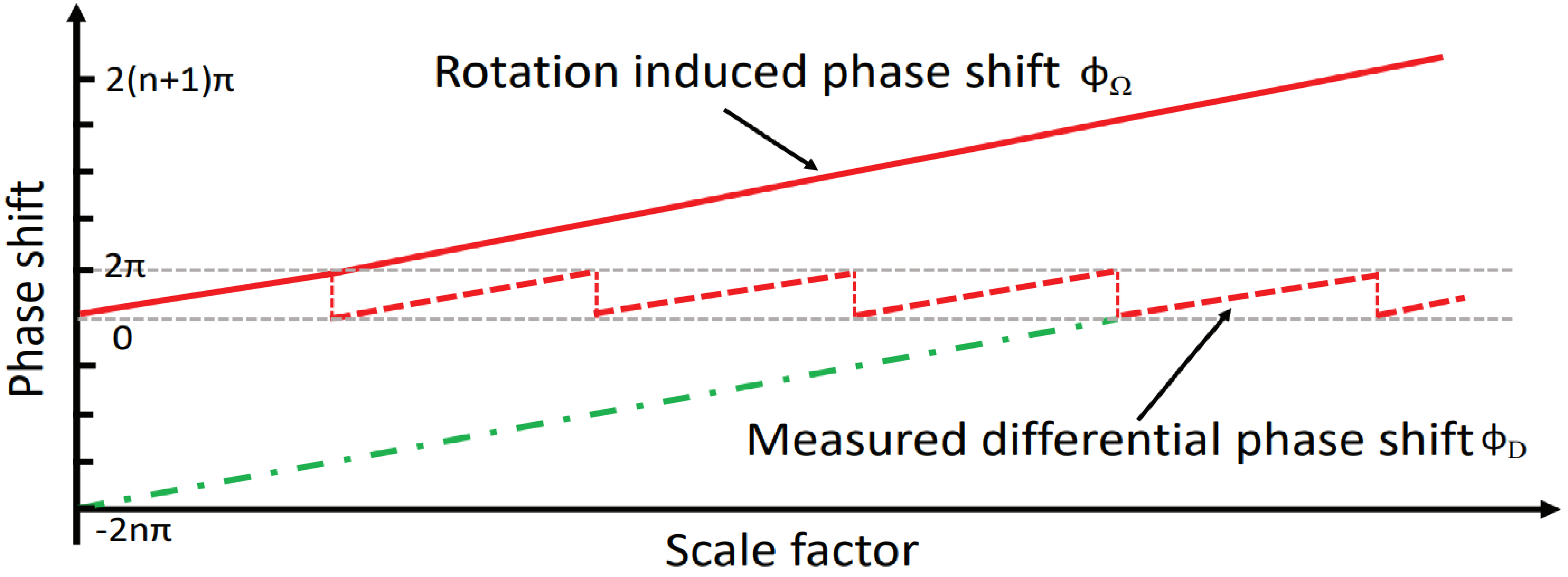
The absolute rotation measurement

- Phase resolution: QPN, Vibration noise, phase noise
- Absolute phase shift
  - Modulation of rotation rate(rotation table)
  - Modulation of atomic velocity
- Scale factor accuracy: atomic velocity
- Systematic error: wave front, Zeeman shift, light shift

$$\Delta\phi = K\Omega$$

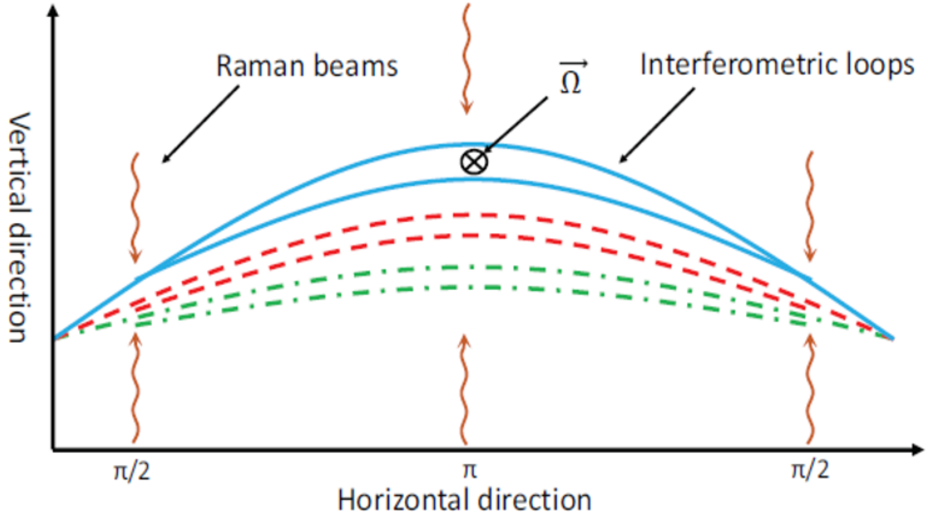


Absolute phase calibration



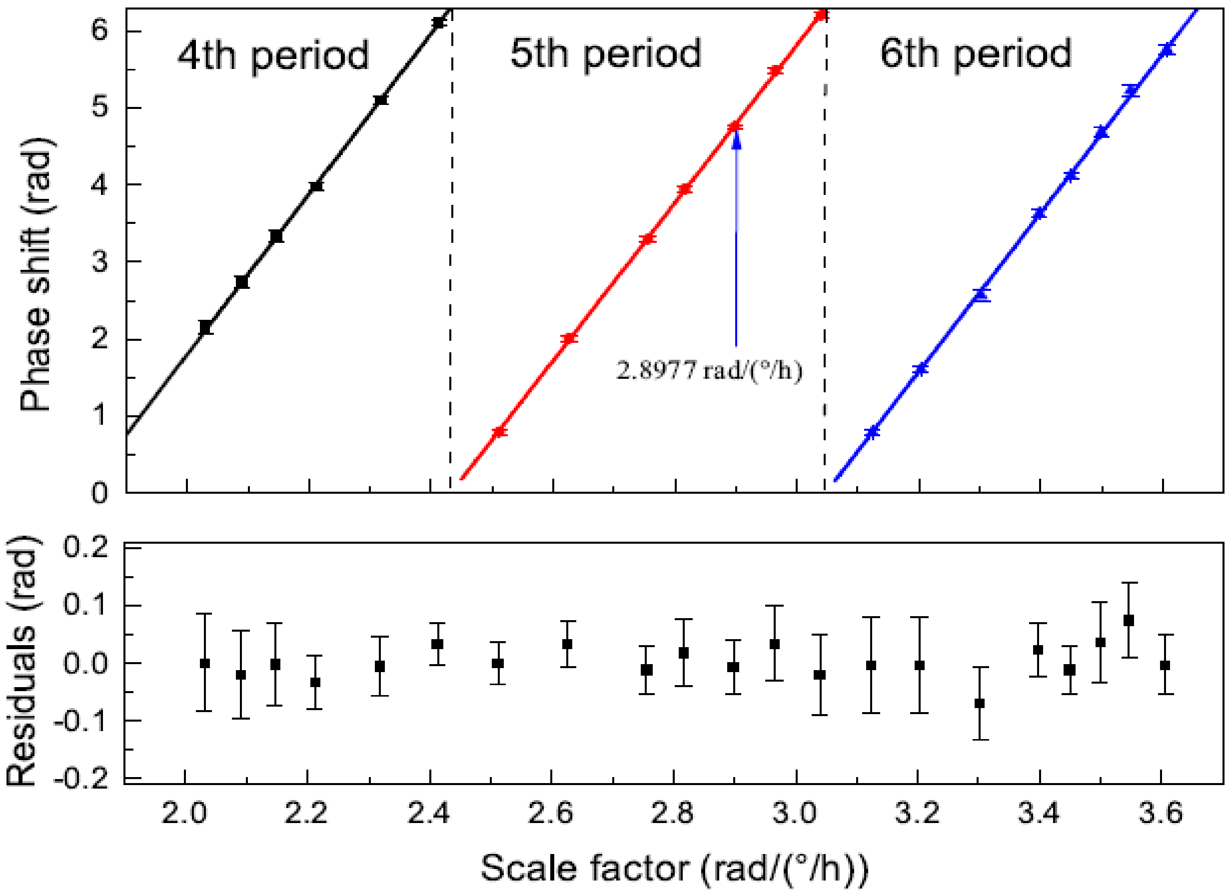
$$\Omega = \frac{\partial \phi}{\partial K}$$

Calibration for absolute phase measurement



$$\phi = \frac{4k_{eff}L^2}{v}\Omega$$

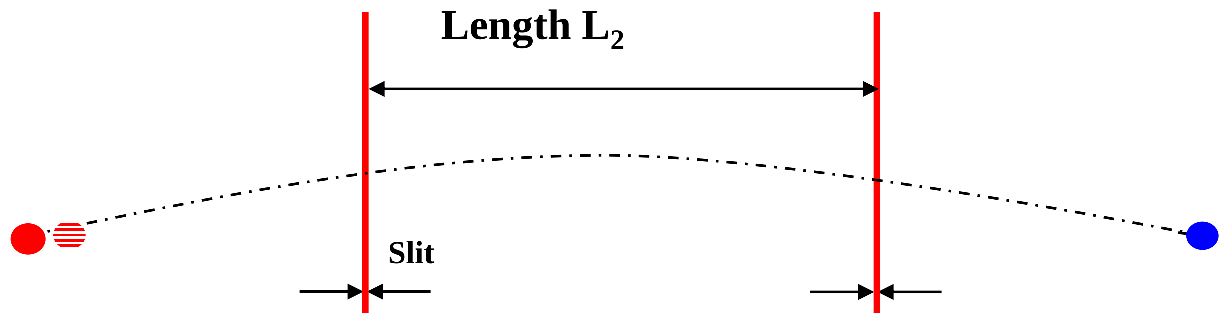
- Velocity modulation to adjust the scale factor
- Separately frequency control to ensure trajectory overlapping
- Scale factor modulation to determine the period number



H. H. Chen, Z. W. Yao, et al, arxiv 2303023319

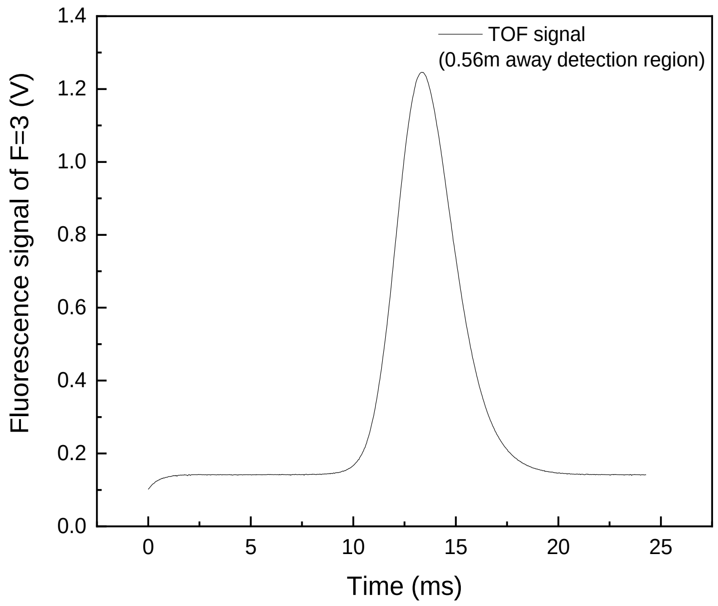
Atom velocity measurement

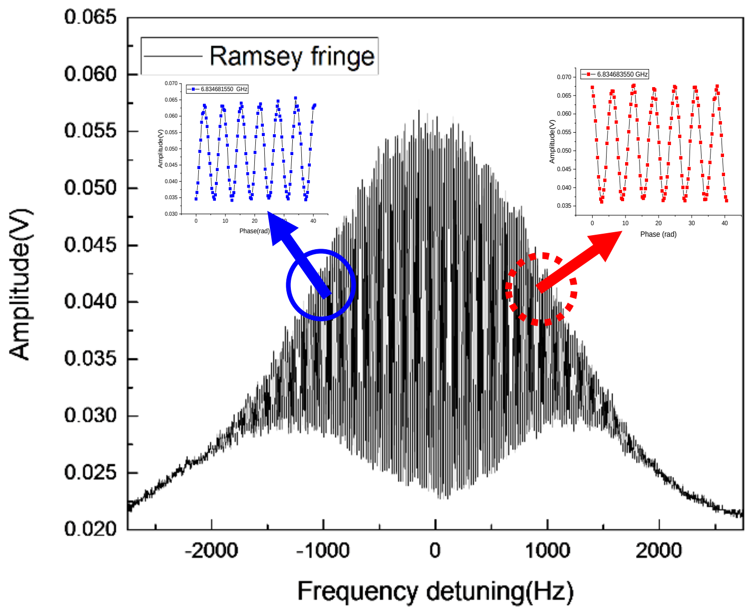
- TOF method
- Two slits Ramsey interferometer
  - Quasi-continuous laser
  - Differential measurement
  - Slit distance measurement
- Advantage
  - Position independent



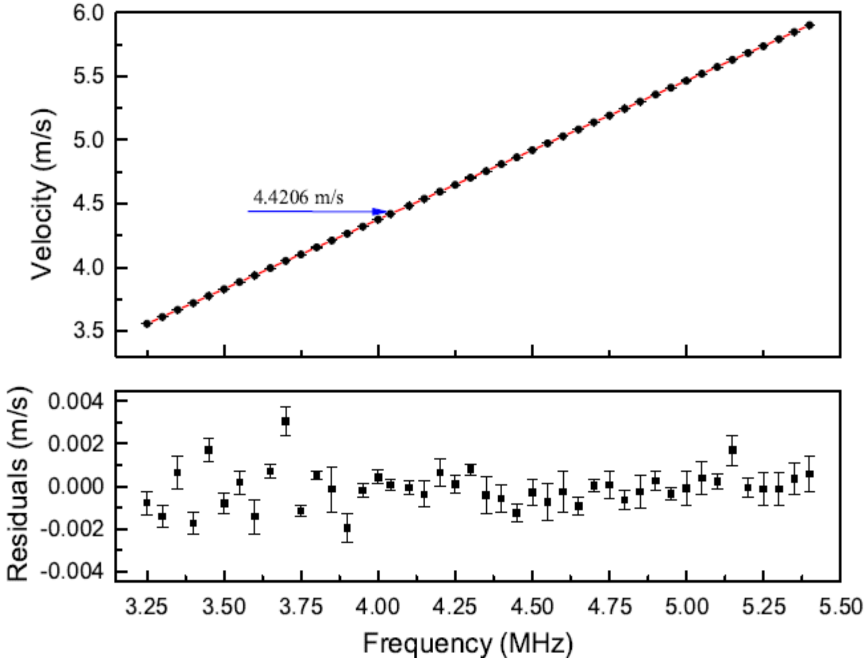
$$v = \frac{L_2}{T_2} = \frac{L_2(f_1 - f_2)}{(\phi_1 - \phi_2)}$$

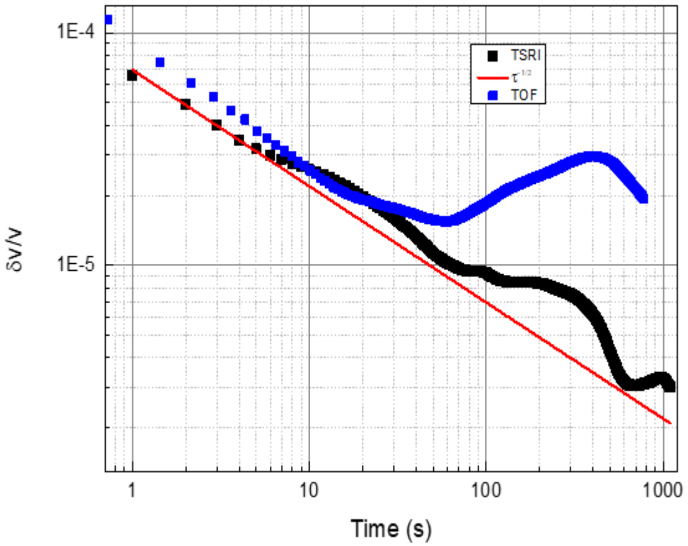
$$\Phi_{Ramsey} = \delta T_2$$

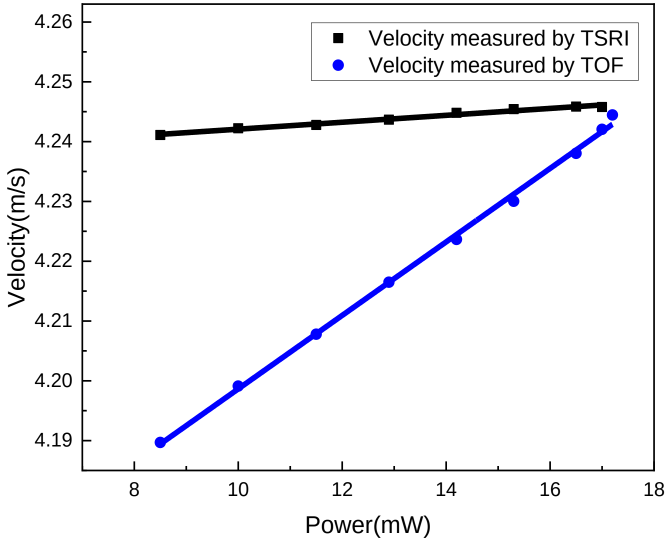




Scale factor measurement





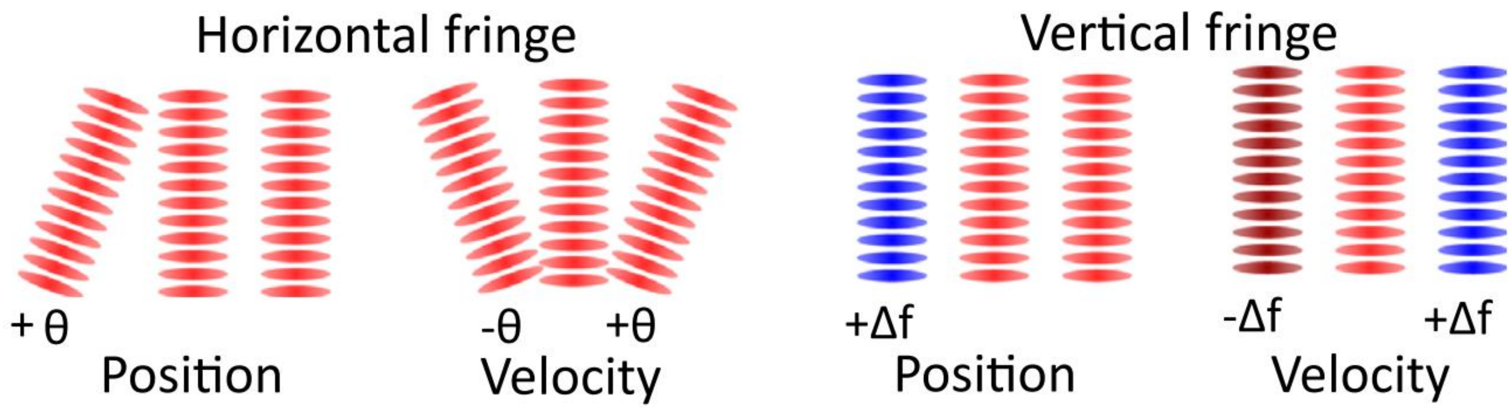


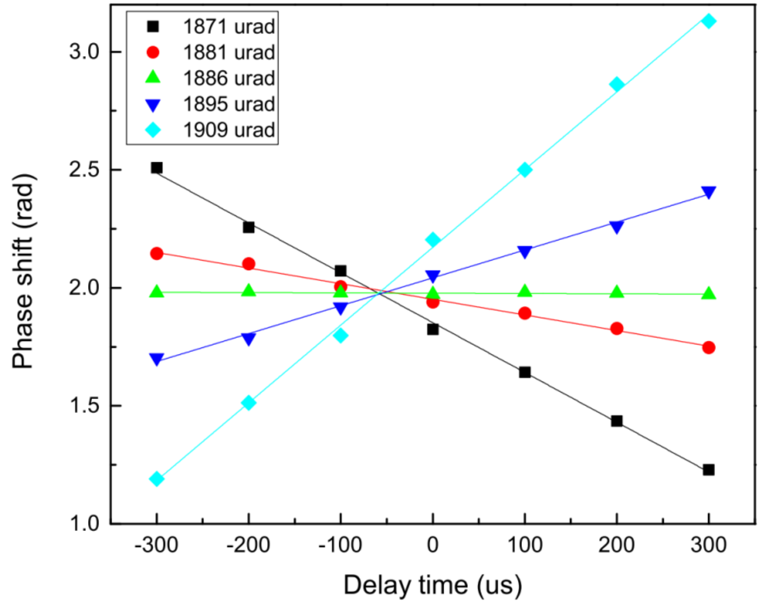
- The dependence on the laser intensity
  - TSRI: 4.6×10^{-4} (m/s)/mW
  - TOF: 6.1×10^{-3} (m/s)/mW
- Scale factor: **K** =2.8977 rad/(° /h)
- Stability of scale factor: 3 ppm

Parameter	Value (Unit)	Relative uncertainty (ppm)
Frequency	2007.200 (1) Hz	0.5
Phase	581.115 (40) rad	70
Length	203.693 (20) mm	100
Atomic velocity	4.4206 (5) m/s	122

$$K=4k_{eff}vT^2[1+(\frac{4}{\pi}-2)\frac{\tau}{4}]$$

Systematic error evaluation





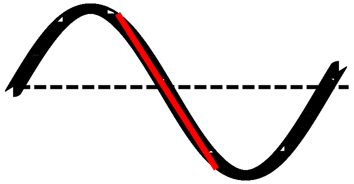
- Systematic error evaluation
  - Trajectory overlapping, Wavevector reversal
  - Phase uncertainty: 106 ppm
- Scale factor uncertainty: 122 ppm
- Rotation rate uncertainty: 162 ppm@10.3148 deg/ h

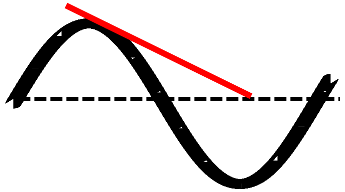
Error source	Relative uncertainty (ppm)
ac Stark shift	7
Zeeman shift	21
Gravity gradient	17
Wave front	23
Statistical error	100
Total	106

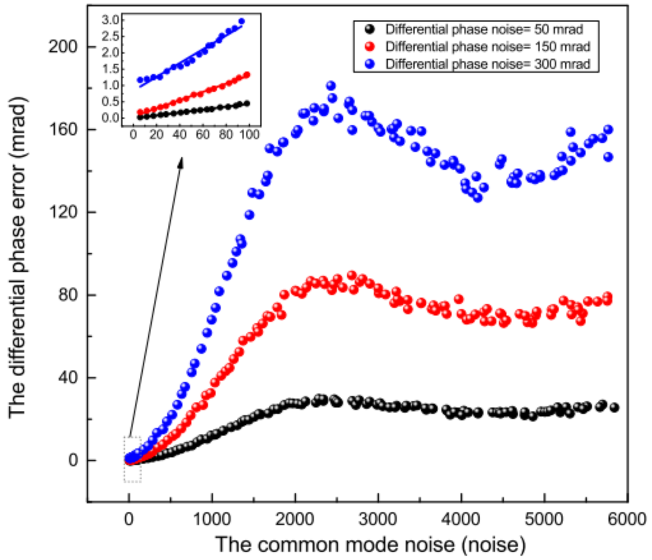
Peter Asenbaum, PRL **125**, 191101 (2020)

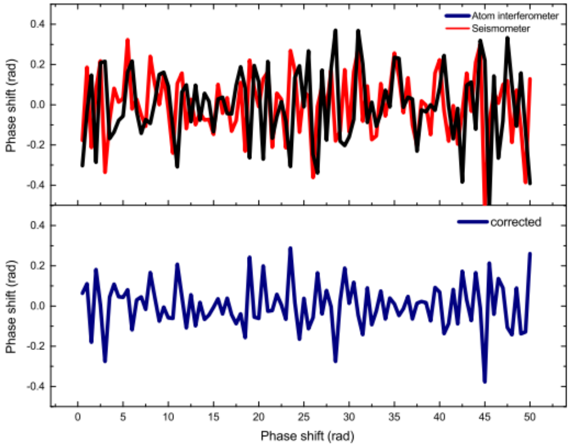
H. H. Chen, Z. W. Yao, et al, arxiv 2303023319

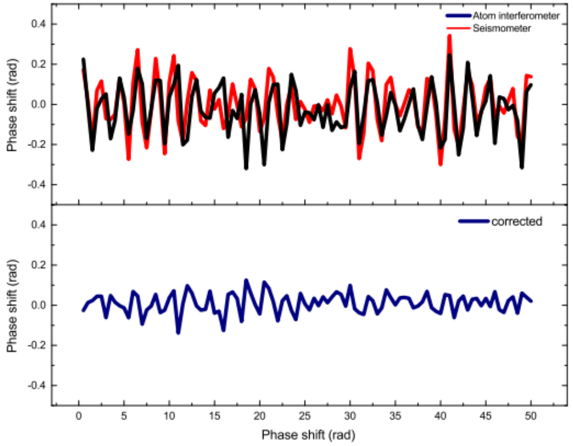
Improvement of the SF stability











$$P=\frac{1}{2}\left(1+C\cos(\phi)\right)$$

$$\Delta\phi_1=\phi_g+\phi_\Omega$$

$$\Delta\phi_2=\phi_g-\phi_\Omega$$

- The influence of the common mode noise
- The real-time compensation method

J. Lautier, APL. 105, 144102 (2014)

Proposal to improve SF stability

PHYSICAL REVIEW A **78**, 013638 (2008)

Dispersion compensation in atom interferometry by a Sagnac phase

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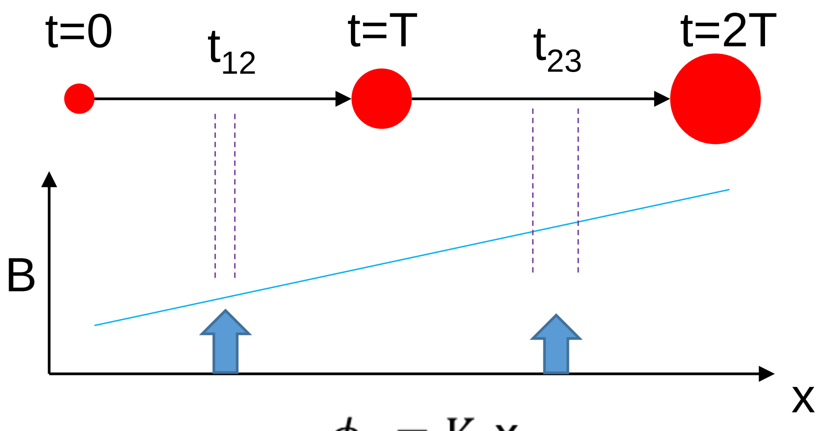
(Received 23 May 2008; published 31 July 2008)

We reanalyzed our atom interferometer measurement of the electric polarizability of lithium, now accounting for the Sagnac effect due to the Earth's rotation. The resulting correction to the polarizability is very small, but the visibility as a function of the applied phase shift is now better explained. The fact that the Sagnac and polarizability phase shifts are both proportional to v^{-1}, where v is the atom velocity, suggests that a phase shift of the Sagnac type could be used as a counterphase to compensate for the electric polarizability phase shift. This exact compensation opens the way to higher-accuracy measurements of atomic polarizabilities, and we discuss how this can be done in practice and the final limitations of the proposed technique.



$$\phi_B = K_B x$$

$$\delta\phi_B = K_B(t_{23}-t_{12})\,\delta v = k_B\delta v$$

- Stability of scale factor： 3 ppm
- Rotation phase compensation
  - Velocity dependent phase shift
  - Magnetic gradient field
- Stability improvement after compensation

$$\frac{\partial\phi}{\partial v} = k_\Omega\Omega - k_B B$$

$$\frac{\delta K}{K} = \frac{\delta v}{v}\frac{\delta\Omega}{\Omega}$$

Conclusion and prospect

- Conclusion
  - The calibration of AIG for absolute rotation measurement
  - The stability of atom velocity is dominated by the laser intensity
- Prospect
  - The improvement accuracy and stability of atom velocity
  - Dynamic rotation measurement: closed loop AIG and high data rate
  - Reducing the influence of environment noise

Group members： Sibin Lu, Shaokang Li, Min Jiang, Wei-Tou Ni, Runbing Li, Jin Wang, Mingsheng Zhan

Graduate students： Honghui Chen, Zexi Lu, Yinfei Mao, Xiaoli Chen, Chuan Sun, Yang Li

Thanks for your attention!