State Key Laboratory of Advanced
Optical Communication Systems and Networks

北京大學

A Fiber Optic Gyroscope Prototype with High Bias Stability for Rotational Seismology Phenomena Measurement

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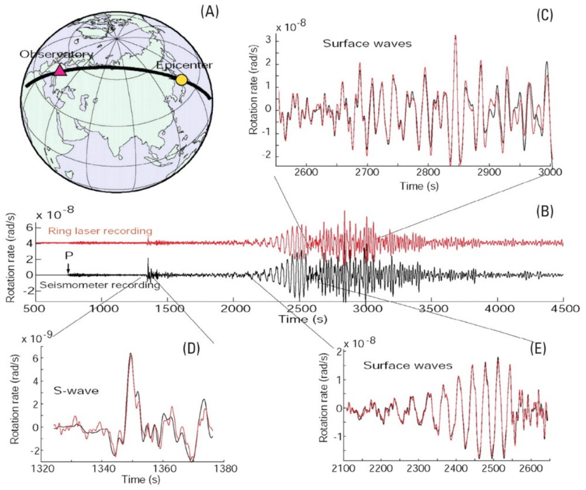
Outline

- Rotational Seismometer
- High Performance Gyroscope Principle
  - Optic system with large fiber coil
  - Depolarizer optimization for PN error reduction
  - Frequency modulation for ${}^{1}/_{f}$ noise reduction
- Indoor Testing
- Future Work

Rotational Seismology

- Rotation seismology phenomena have been observed for centuries
  - Rotation of a tomb, India, 1899
- Seismic motion is composed of translation and rotational motion (6 DOF)
- Rotational motion is significant for seismology but lack of study before RLG development

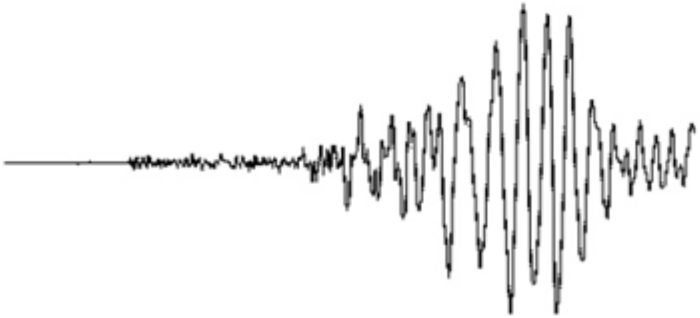


Lee, William H. K., Heiner Igel, and Mihailo D. Trifunac. "Recent Advances in Rotational Seismology." Seismological Research Letters 80.3 (2009): 479–490.

Seismology Rotational Motion

- Wide amplitude range
  - A few rad/s near seismic source (Nigbor 1994)
  - 10^{-11}rad/s at tele-seismic distances (Igel *et al*. 2005; Schreiber *et al.* 2005, 2006)

Contrast
High accuracy navigation-grade gyroscope (e.g. navigation for spacecraft)
Bias stability: around 10^{-8}rad/s



Igel, Heiner et al. "Broad-Band Observations of Earthquake-Induced Rotational Ground Motions." *Geophysical Journal International* 168.1 (2007): 182–196.

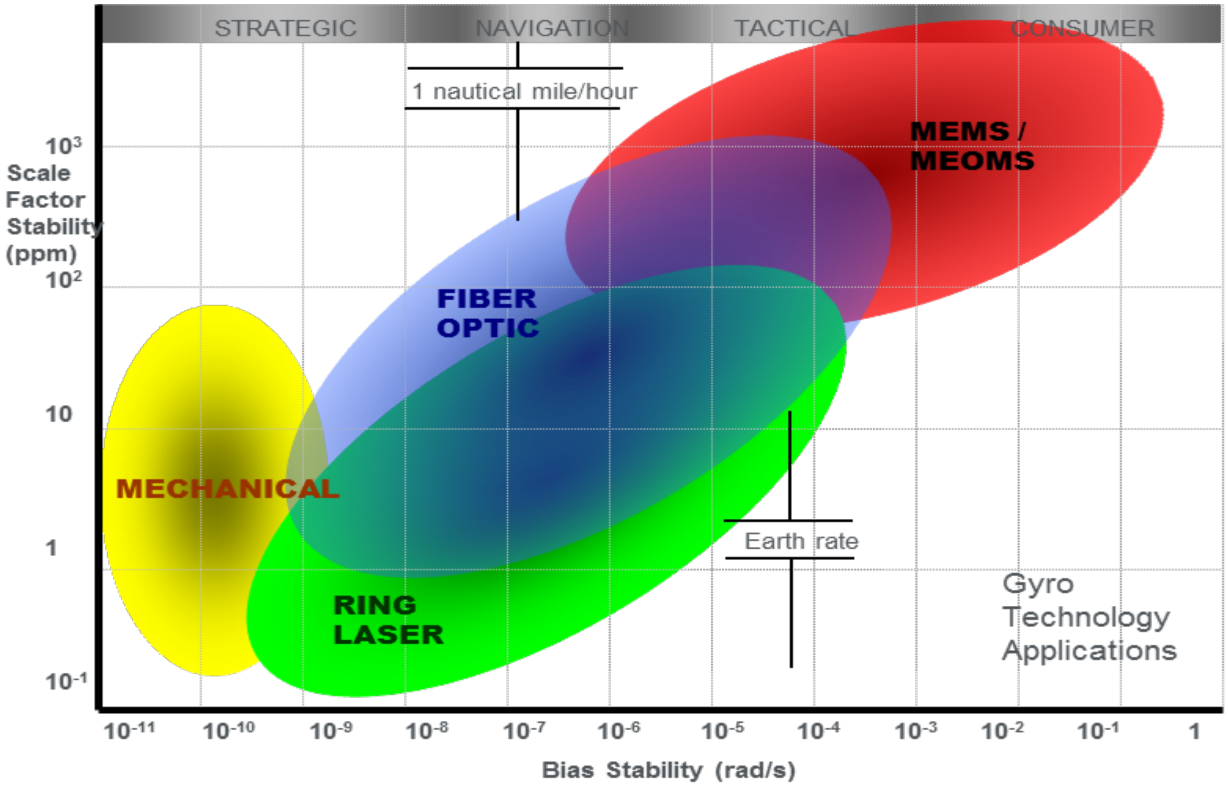
Rotational Seismometer Requirements

- **High sensitivity and high bias stability**
- **Wide amplitude range and frequency range**
  - $10^{-11} \sim 10^{0}\ \mathrm{rad/s}$
  - $10^{-3} \sim 10^{2}$ Hz
- Scale factor linearity
- Immunity to environmental influences
- Low cost (for widely usage)
- Portable (for outdoor usage)

How?

Potential Solutions

- Mechanical
- Fiber Optic
- Ring Laser
- MEMS
- ……



Fiber Optic Gyroscope may be one of the most suitable solution

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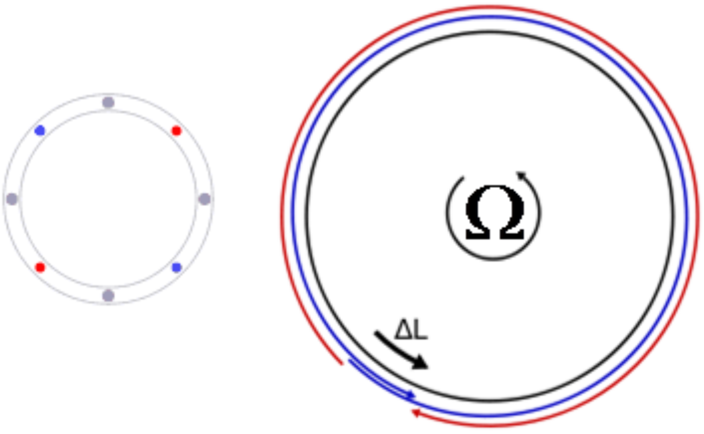
G. Zhang, "The Principles and Technologies of Fiber-Optic Gyroscope" National Defense Industry Press. Beijing. 2010

Sagnac Effect and Large Length FOG



Sagnac Effect

Sagnac phase shift

$$\Delta\phi_{sagnac} = \frac{4\pi R \cdot L}{\lambda c} \vec{n} \cdot \vec{\Omega}$$

λ: wavelength of light source

R, L : radius and length of fiber coil

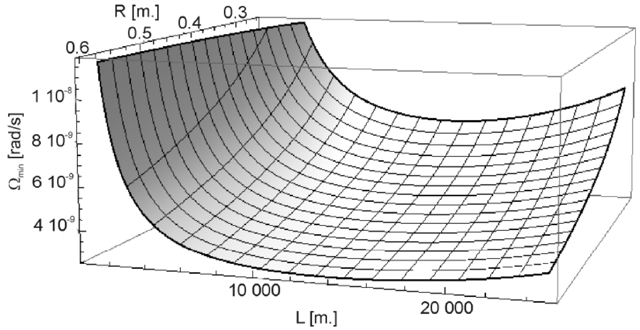
To increase R·L to improve sensitivity and stability

Two FOGs were demonstrated:

- A 15km-long SMF coil of 0.3m in diameter
- A 10km-long SMF coil of 0.2m in diameter

But, noise also increased

e.g. SNR drops due to loss increasing (L. R. Jaroszewicz, et al., 2008)

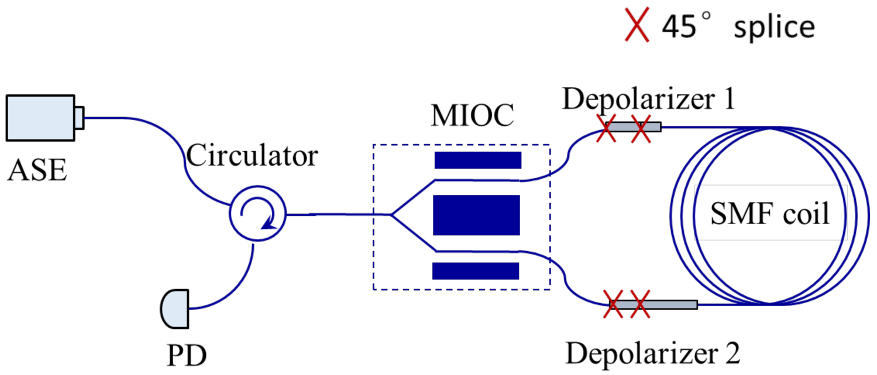


L. R. Jaroszewicz, et al., in R.Teisseyre, H. Nagahama, E. Majewski (eds.), Physics of Asymmetric Continuum: Extreme and Fracture Processes, Spinger-Verlag, Chap. 2, 2008.

Design Principles

- High sensitivity
  - Upgrade the products of R and L to increase sensitivity
  - SMF fiber with longer length preferable
- Main noise increases with large length
  - **Polarization non-reciprocity error**
  - **1/*f* fractal noise**
  - Shupe effect
  - SNR drops due to loss increasing
  - ……

Optical System Design



- Open-loop depolarized system under minimum polarization reciprocal configure
- Broadband ASE light source with bandwidth 40nm to overcome Rayleigh scattering
- MIOC with PMF pig tail for polarizing, modulating and coupling light into fiber coil
- SMF coil with 10km or 15km, for high sensitivity and low cost

For polarization non-reciprocity error
Use two depolarizers to ensure reciprocity
DOP < 0.5%

High Order Eigen Frequency Modulation for 1/f Noise Reduction

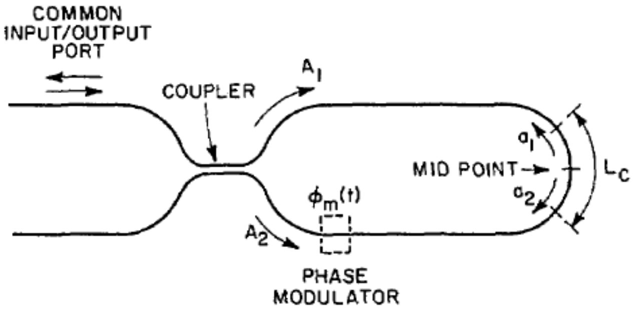
- The gyroscope needs a eigen frequency modulation to reduce Rayleigh backscattering error

- The backscattering beams should not be modulated

$$\sin(2\pi f t) = -\sin\left[2\pi f\left(t + \frac{c}{L_e}\right)\right]$$

$$f_e = (2n+1)\frac{c}{2L_e} \quad n = 0,1,2,\cdots$$

1st order eigen frequency: $f_e = \frac{c}{2L_e}$

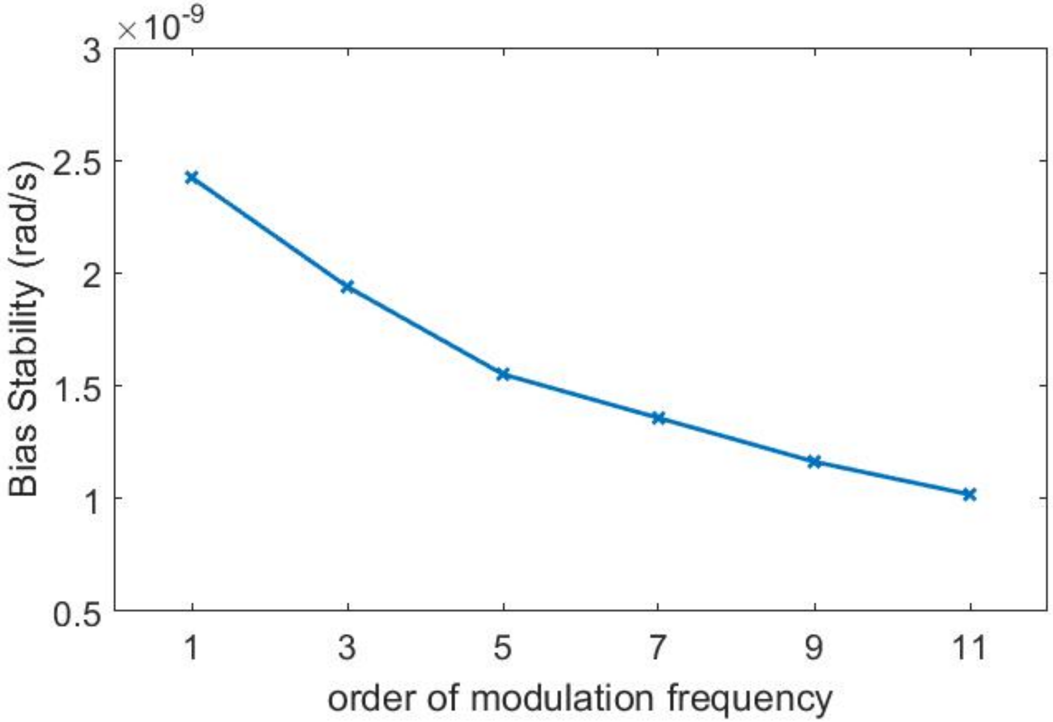


- High order eigen frequency can reduce $^1/_f$ noise

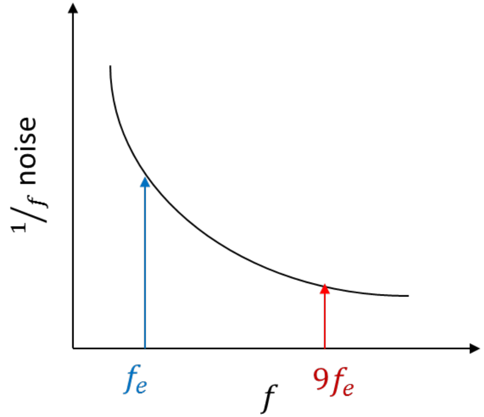
Lefevre, H. C., R. A. Bergh, and H. J. Shaw. “All-Fiber Gyroscope with Inertial-Navigation Short-Term Sensitivity.” *Optics Letters* 7.9 (1982): 454.

The performance of different order eigen frequency modulation

Bias stability of 10km prototype using different order of modulation frequency

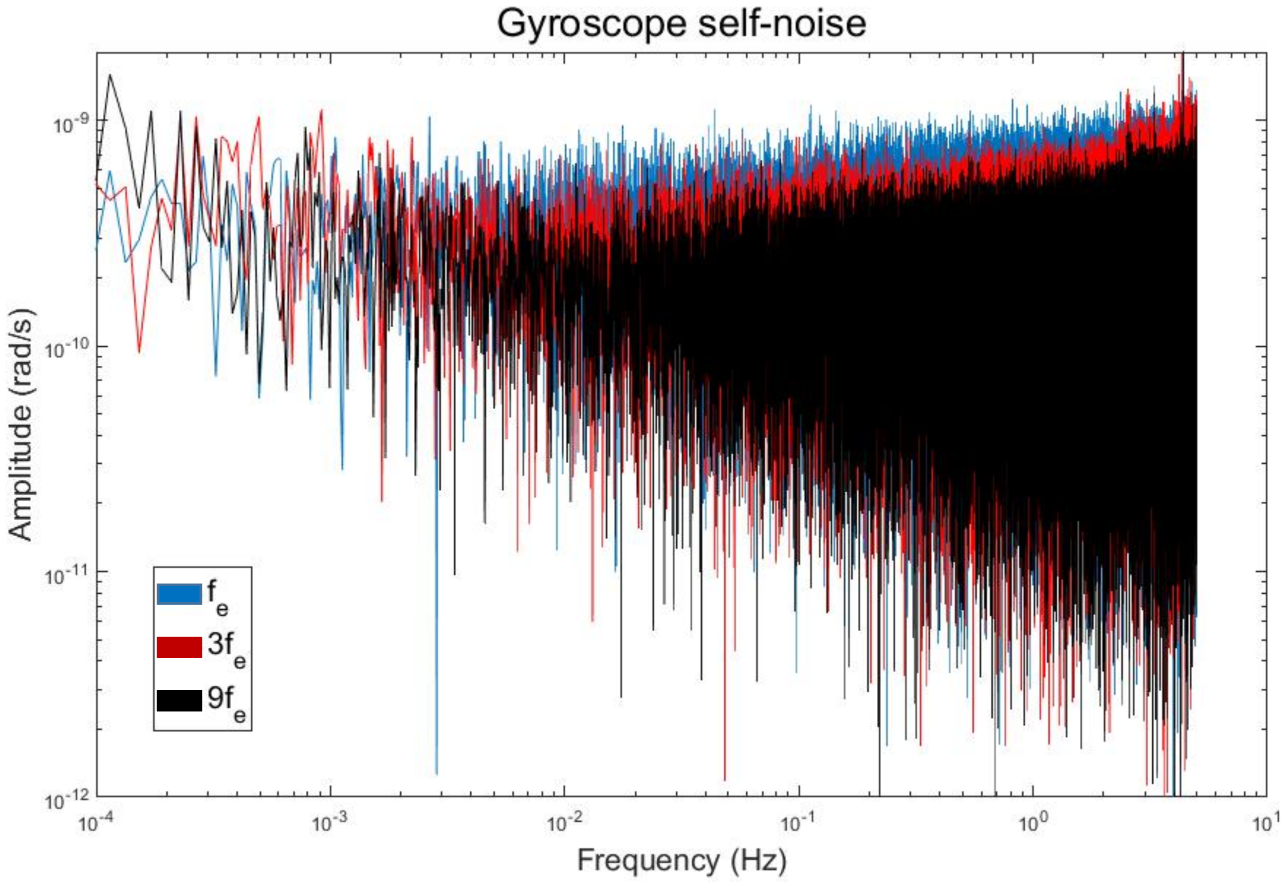


Prototype1
L = 10km
D = 0.2m



$^1/_f$ fractal noise

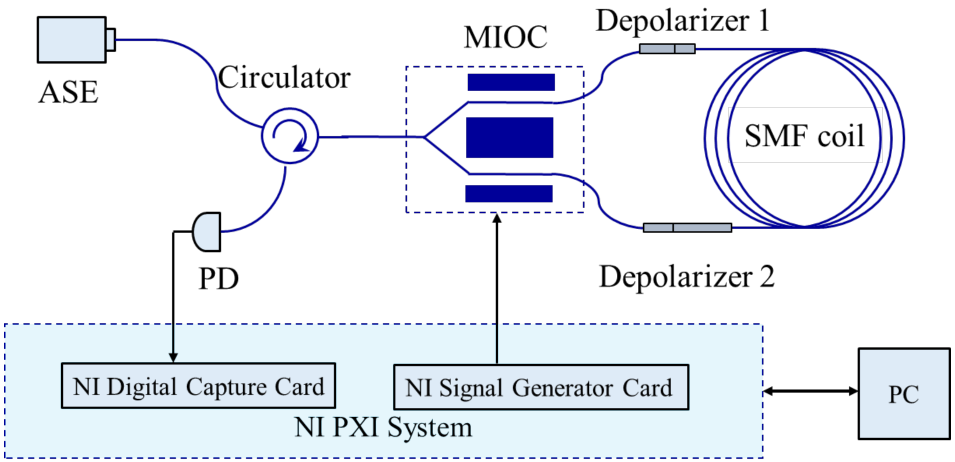
The performance of different order eigen frequency modulation

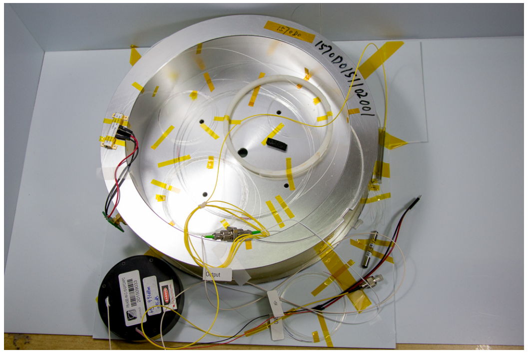


Prototype2
L = 15km
D = 0.3m

Self-noise at 1Hz, in rad/s/ √Hz : $1.1 * 10^{-9}$ (f_e) Vs. $0.7 * 10^{-9}$ ($9f_e$)

Seismometer Prototype

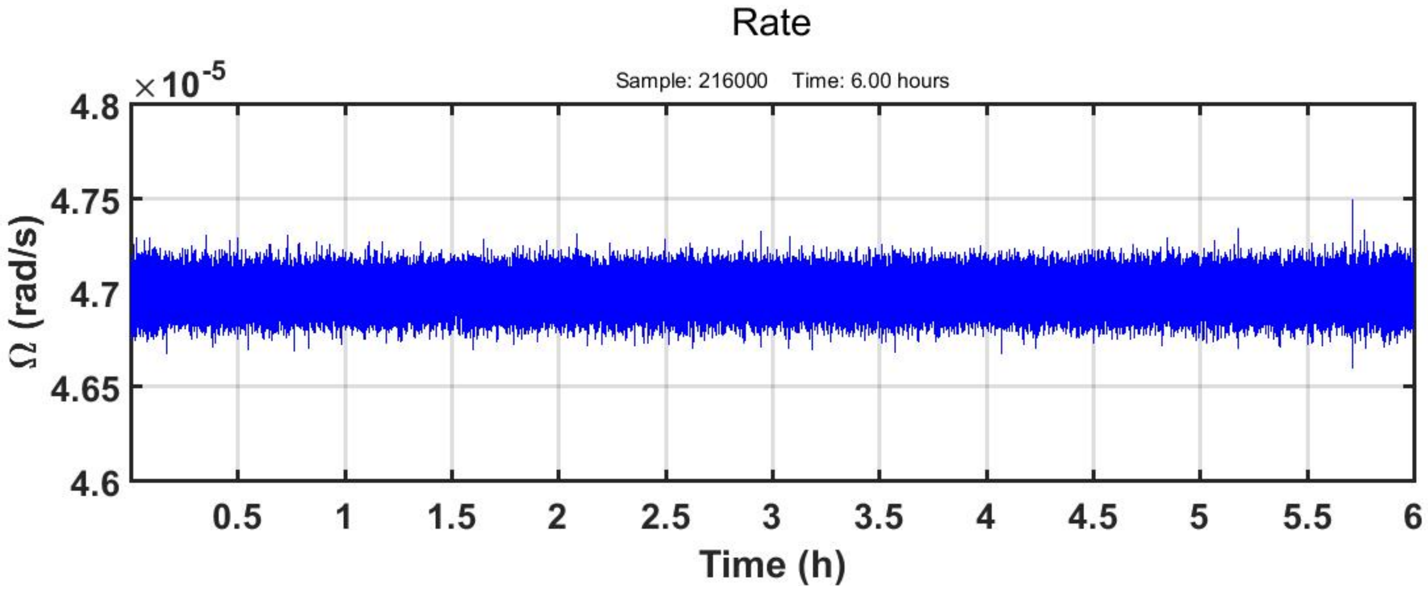


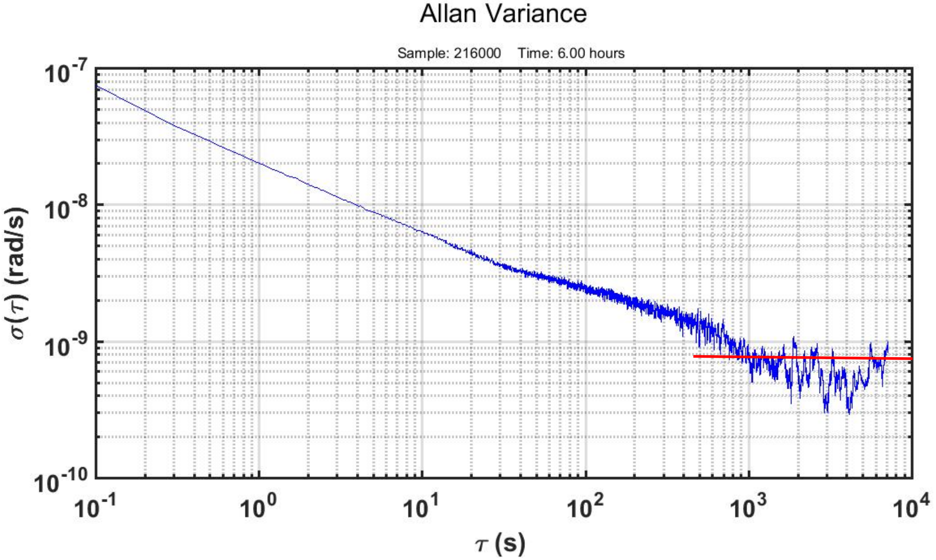


Detecting Earth rotation as static testing

Earth rotation in Beijing (N39.99°, $4.70 \cdot 10^{-9}$ rad/s)

Indoor Test Outcome





15km prototype
Output at 10Hz

The Allan variance
$< 8 * 10^{-10}$ rad/s

Future work

- Calibration
- Observing seismology rotational motions
- Engineering development
- 6 DOF seismometer development

Conclusions

- The prototype demonstrated can be a suitable choice:
  - High bias stability to detect tiny rotational motion
  - Enough frequency bandpass for seismic application
  - Relatively small size and low cost
- Necessary verification:
  - Fully test and field observation for seismology rotational motion
- Portable development is in progress

Thank you!