Calibration of rotation sensors for application in seismology

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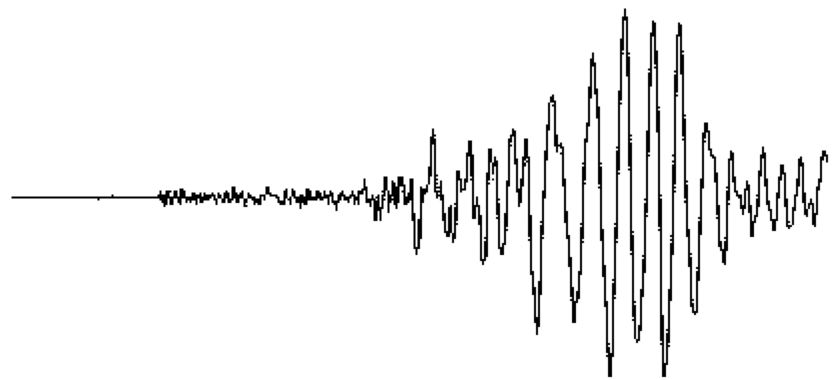
Motivation

- Seismic rotations in general possess relatively low amplitudes: corresponding sensor resolution required
- Pure rotation measurements are preferable, which imposes certain limitations on the sensor type application
- Sensors must be calibrated in order to deliver reliable information about the rotations

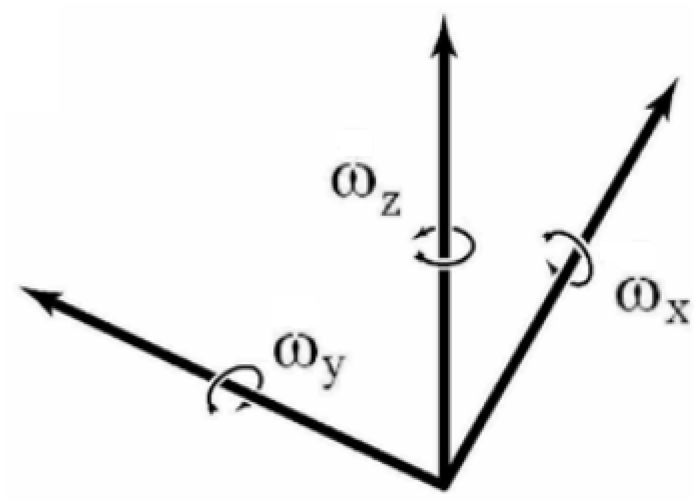
Seismic rotation signals of interest

$10^{-11} \ldots 1\,\mathrm{rad/s}$

$10^{-3} \ldots 100\,\mathrm{Hz}$



- Quasi-periodic signal
- Variable frequency
- Wide amplitude range

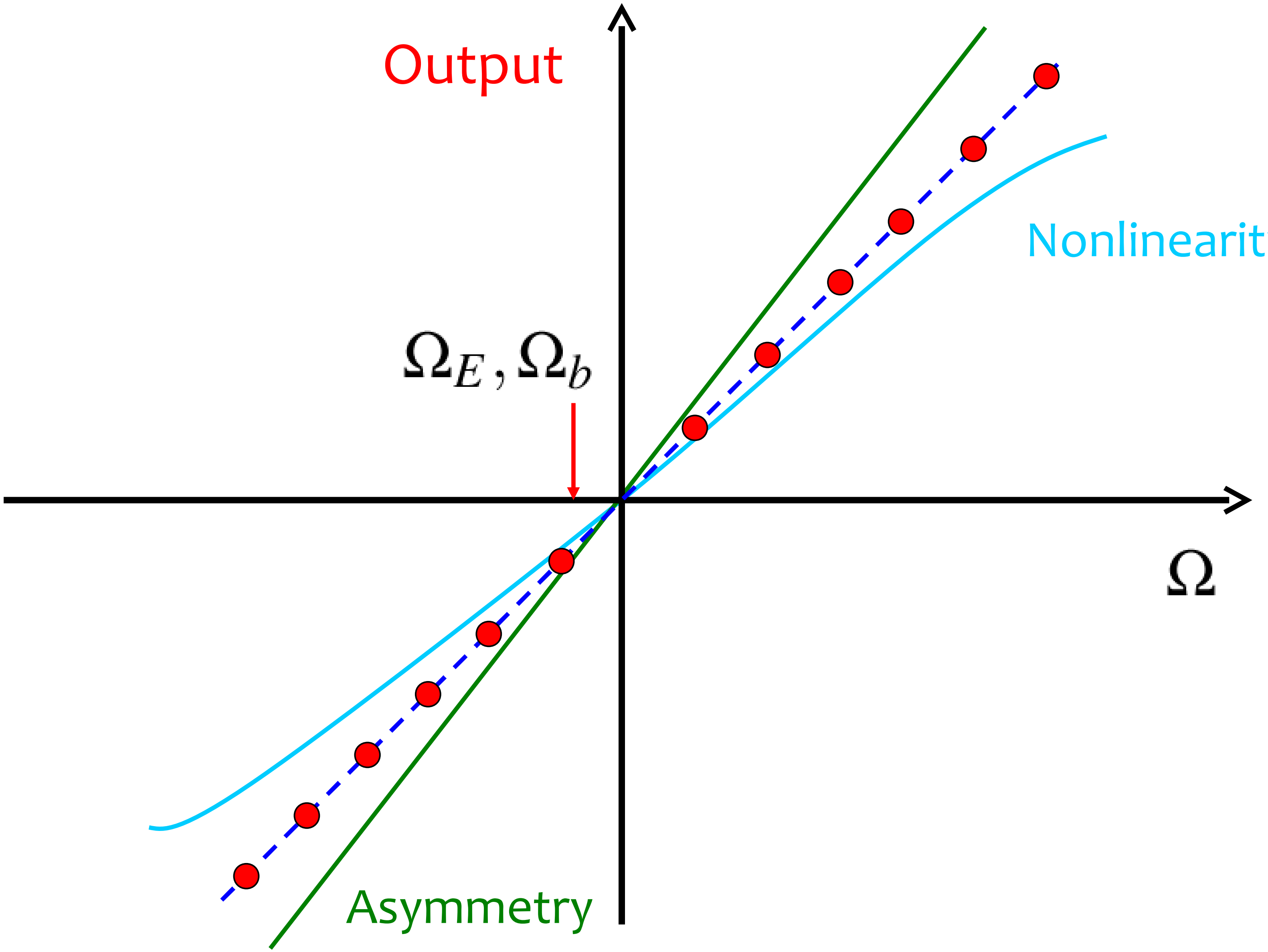


Rotation sensors requirements

- Scale factor linearity (flat or well known amplitude frequency response)
- Low self-noise level (resolution according to the application) and drift
- Low cross-axis sensitivity (misalignment in 3D units)
- Immunity to environmental influences (by design or after estimation)
- Translation insensitive

Calibration: scale factor

- Zero rotation record – bias (Earth rate/drift) removal
- A sequence of constant rotations in CW and CCW directions over the whole measurement range – nominal scale factor
- Estimations of scale factor asymmetry, nonlinearity and stability
- Estimations of environmental sensitivity: temperature, magnetic field etc.

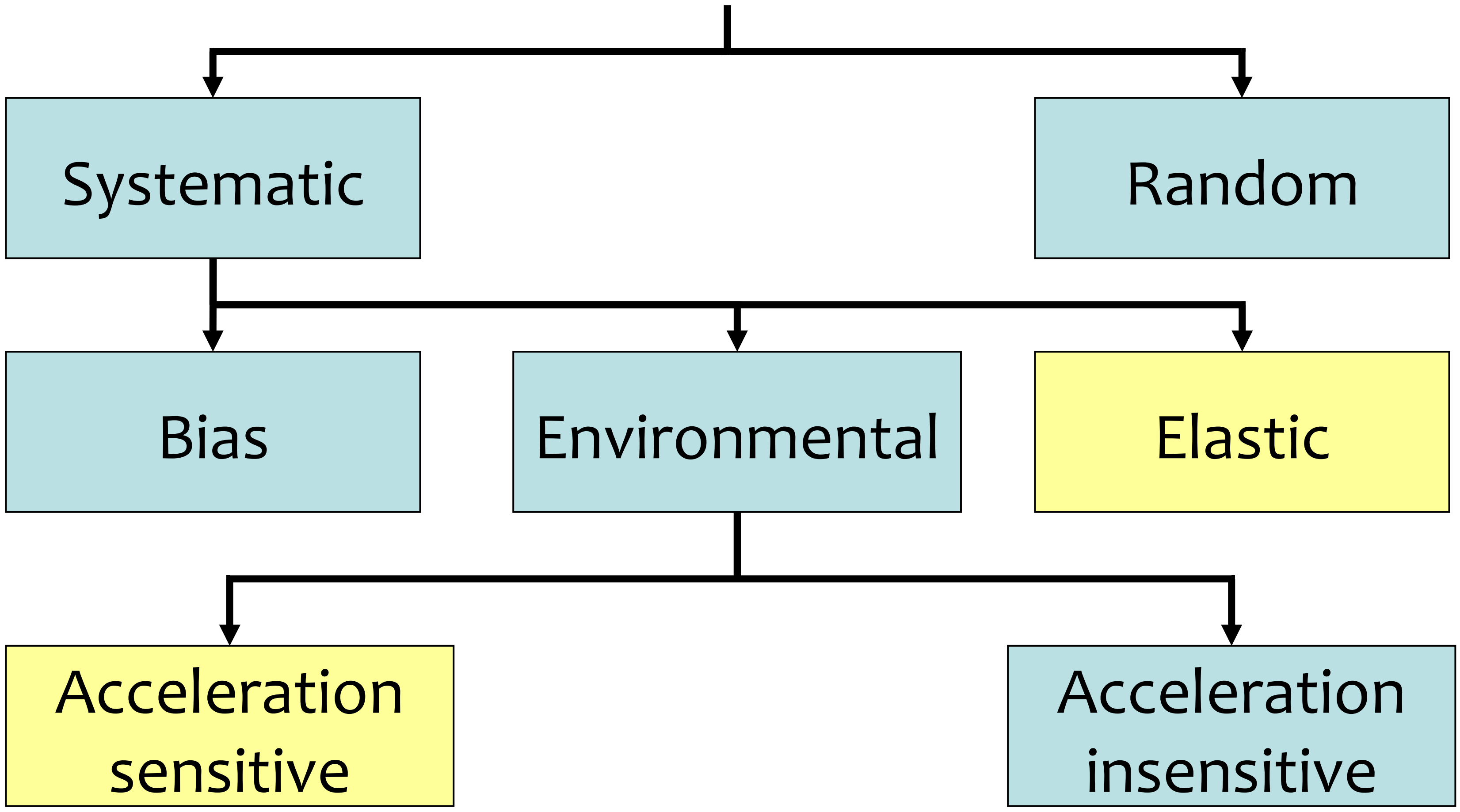


Output
Nonlinearity
Ω_E, Ω_b
Ω
Asymmetry

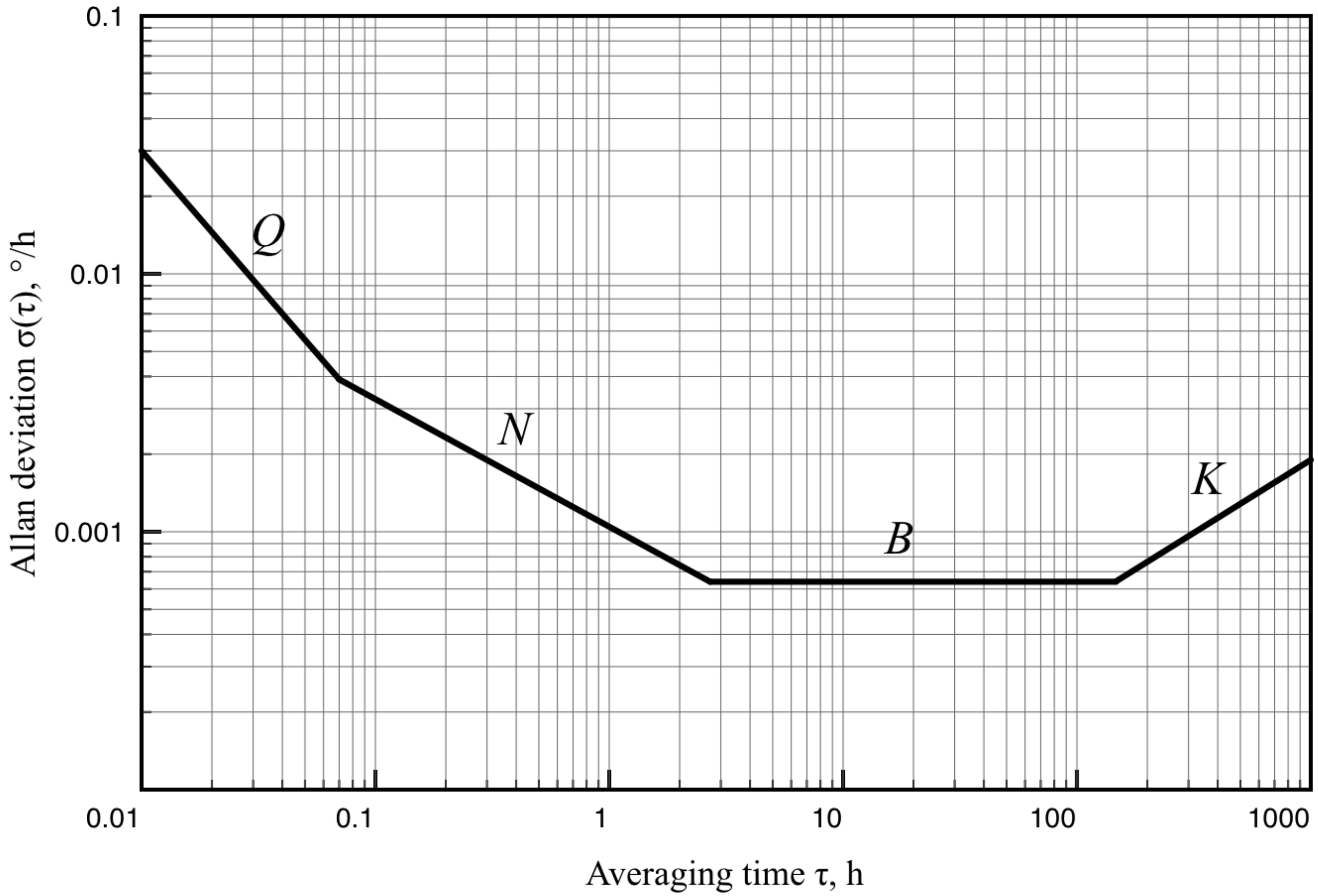
Calibration: noise level

- Precise positioning of the unit (within few arcsec) relative to the ENV frame
- Output signal measurements without rotation
- Estimation of noise and various drift components
- Environmental influence estimation

Drift

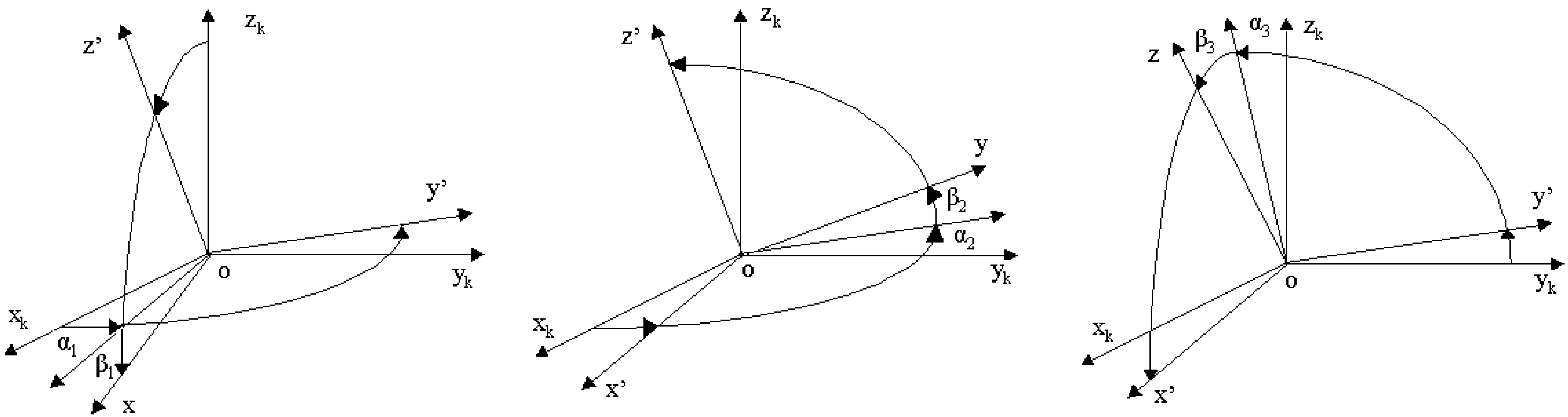

Systematic
Random
Bias
Environmental
Elastic
Acceleration sensitive
Acceleration insensitive

Allan deviation



$$\mathrm{ARW}\left(\frac{\mathrm{deg}}{\sqrt{\mathrm{h}}}\right) = \frac{1}{60}\sqrt{\mathrm{PSD}(\mathrm{deg/h})^2/\mathrm{Hz}}$$

Cross-axis sensitivity



$$D_g = \begin{bmatrix} \cos(\alpha_1)\cos(\beta_1) & \sin(\alpha_1)\cos(\beta_1) & -\sin(\beta_1) \\ -\sin(\alpha_2)\cos(\beta_2) & \cos(\alpha_2)\cos(\beta_2) & \sin(\beta_2) \\ \sin(\beta_3) & -\sin(\alpha_3)\cos(\beta_3) & \cos(\alpha_3)\cos(\beta_3) \end{bmatrix}$$

Measurements using Earth rate

$$\begin{bmatrix}\Omega_{x1}\\ \Omega_{y1}\\ \Omega_{z1}\end{bmatrix} = D_g \begin{bmatrix}\Omega_{\xi}\\ \Omega_{\eta}\\ \Omega_{\zeta}\end{bmatrix} \qquad \mathrm{O}x_k y_k z_k = \mathrm{O}\xi\eta\zeta$$

$$\begin{bmatrix}\Omega_{x2}\\ \Omega_{y2}\\ \Omega_{z2}\end{bmatrix} = D_g \begin{bmatrix}\Omega_{\eta}\\ -\Omega_{\xi}\\ \Omega_{\zeta}\end{bmatrix} \qquad \mathrm{O}x_k y_k z_k = \mathrm{O}\eta\xi\zeta, \circlearrowleft 90^\circ$$

$$\begin{bmatrix}\Omega_{x3}\\ \Omega_{y3}\\ \Omega_{z3}\end{bmatrix} = D_g \begin{bmatrix}-\Omega_{\xi}\\ -\Omega_{\eta}\\ \Omega_{\zeta}\end{bmatrix} \qquad \mathrm{O}x_k y_k z_k = -\mathrm{O}\xi\eta\zeta, \circlearrowleft 180^\circ$$

Misalignment angles

$$\begin{cases} \alpha_1 = \arctan \dfrac{\Omega_{x1} - \Omega_{x3}}{2\Omega_{x2} - \Omega_{x3} - \Omega_{x1}} \\ \beta_1 = \arccos \dfrac{\Omega_{x1} - \Omega_{x3}}{2\Omega_\eta \sin \alpha_1} \end{cases}$$

$$\begin{cases} \alpha_2 = \arctan \dfrac{\Omega_{y1} - 2\Omega_{y2} + \Omega_{y3}}{\Omega_{y1} - \Omega_{y3}} \\ \beta_2 = \arccos \dfrac{\Omega_{y1} - \Omega_{y3}}{2\Omega_\eta \cos \alpha_2} \end{cases}$$

$$\begin{cases} \alpha_3 = \arcsin \dfrac{\Omega_{z3} - \Omega_{z1}}{2\Omega_\eta \cos \beta_3} \\ \beta_3 = \arcsin \dfrac{2\Omega_{z2} - \Omega_{z1} - \Omega_{z3}}{2\Omega_\eta} \end{cases}$$

Environmental influences

- Temperature dependencies
- Magnetic field impact
- Vibration tests
- Shock tests
- Humidity tests
- Radiation resistance
- Acceleration sensitivity

Equipment required

- Rate tables (1, 2, multi-axis)
- Precise mounting fixture
- Positioning means (theodolite etc.)
- Centrifuges
- Vibration/shock machines
- Environmental chambers
- Data acquisition (ADC, counters, PC etc.)
- Brains

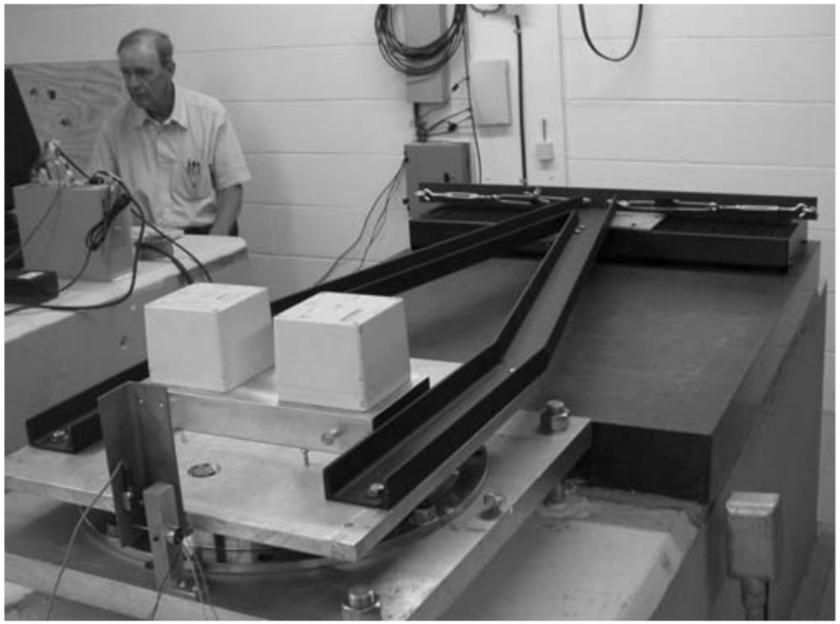
Problems with traditional test methods

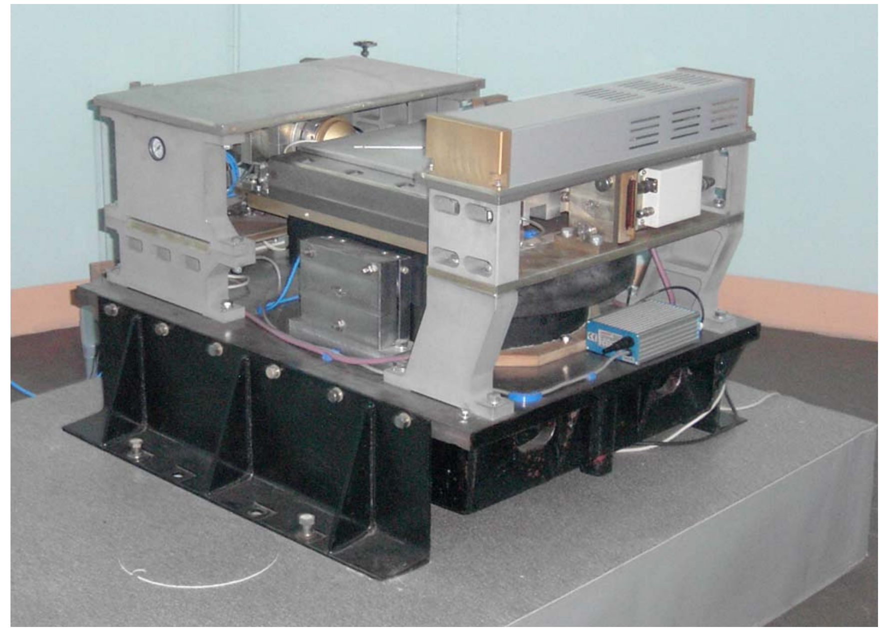
- Tables are big, heavy and very expensive
- Barely available periodical motion regime
- Control sensor resolution might not be enough for testing in the lower range of rotational amplitudes
- No metrological methods exist for certification of periodical motion simulators (unless it’s a specifically built standard)

Problems with traditional test methods (cont.)

- Calibration of rotation sensors requires a real controllable rotary motion
- For rotation sensors there is no such procedure as estimation of transfer function (basically only DC test)
- No simple electronic tests possible

Test benches and rate tables





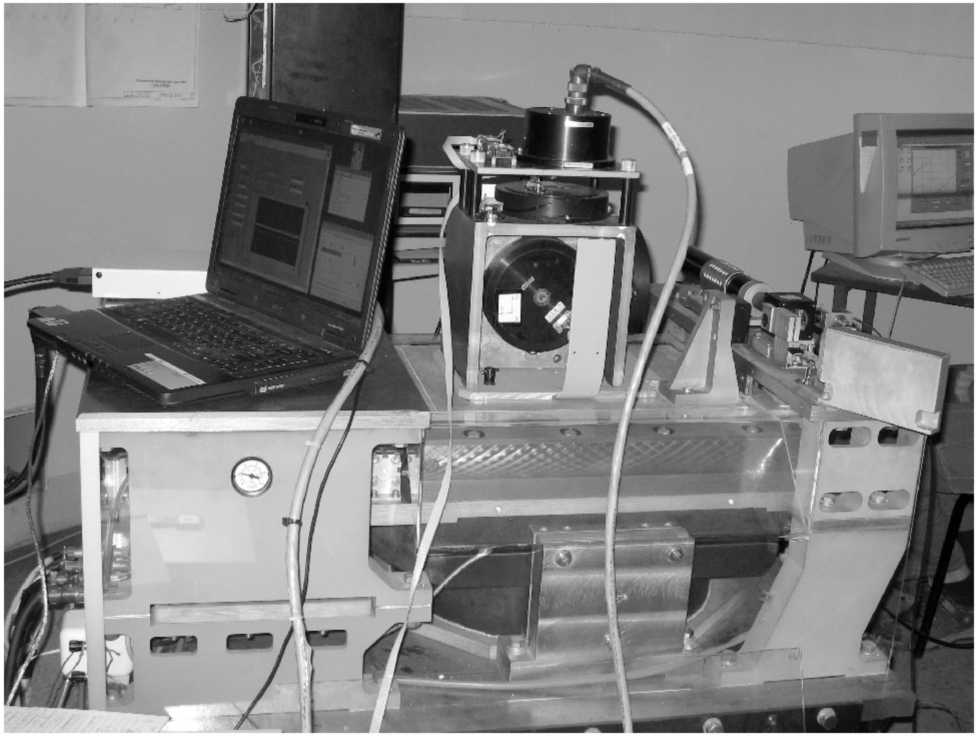
Example

$$A = 10^{-6} \dots 10^{-2}\, m$$
$$f = 10^{-3} \dots 1\, Hz$$

$$L = A_0 \sin(2\pi f t)$$

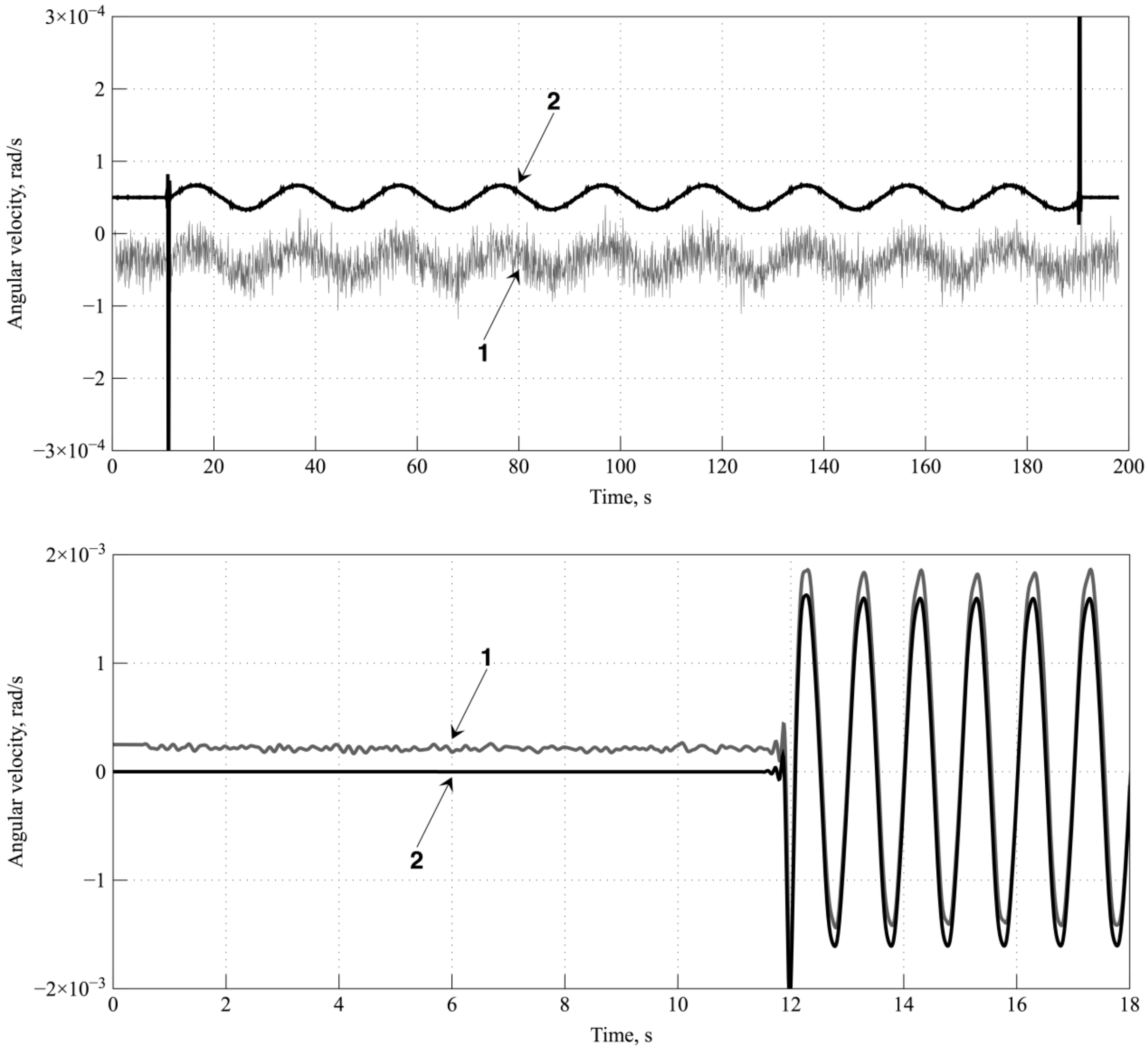
$$\varphi = \frac{L}{R} = \frac{A_0}{R} \sin(2\pi f t)$$

$$\omega = 2\pi f \frac{A_0}{R} \cos(2\pi f t)$$



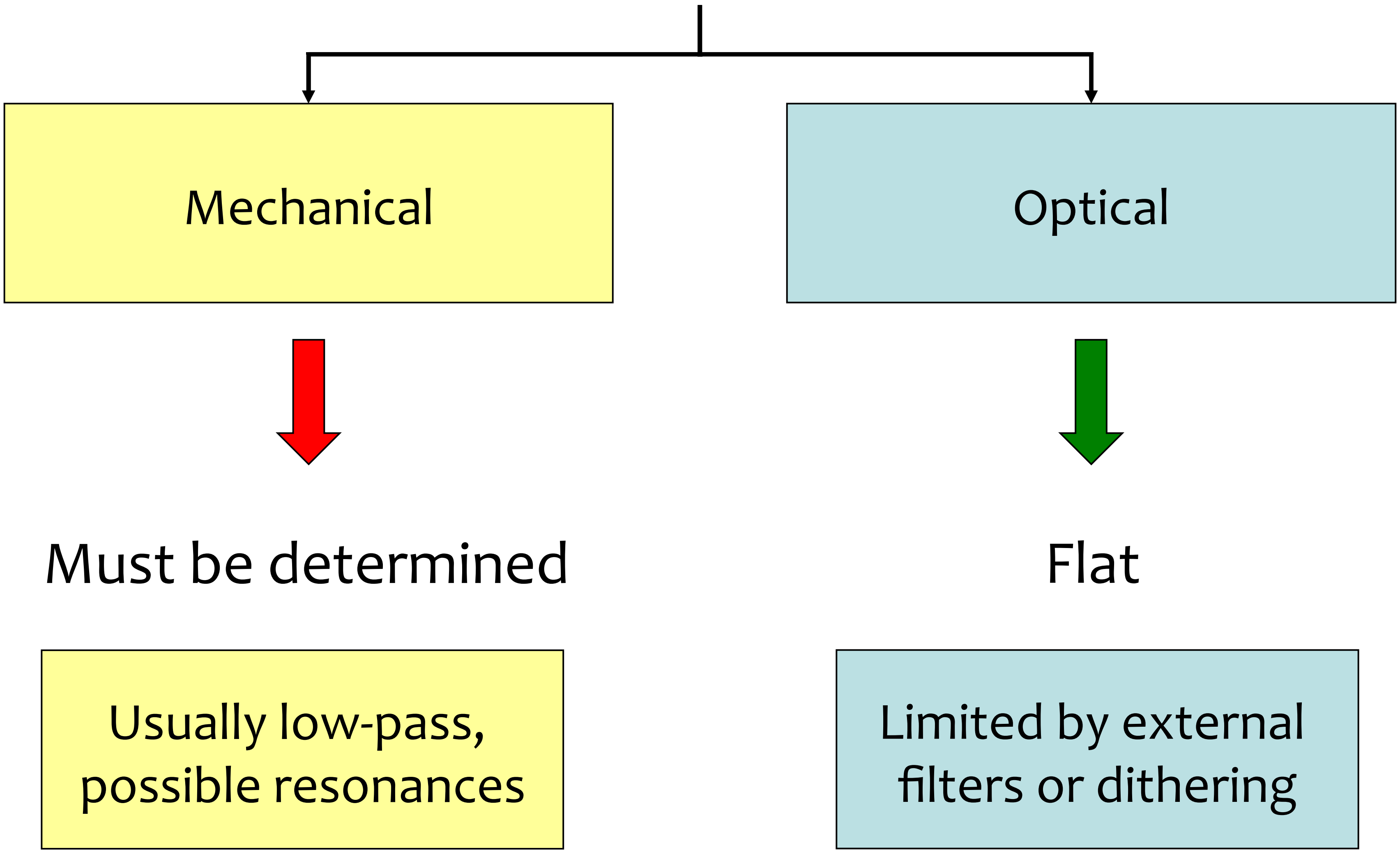
Good precision but limited amplitude and frequency range

Test results



1 – Single-axis FOG
2 – Reference

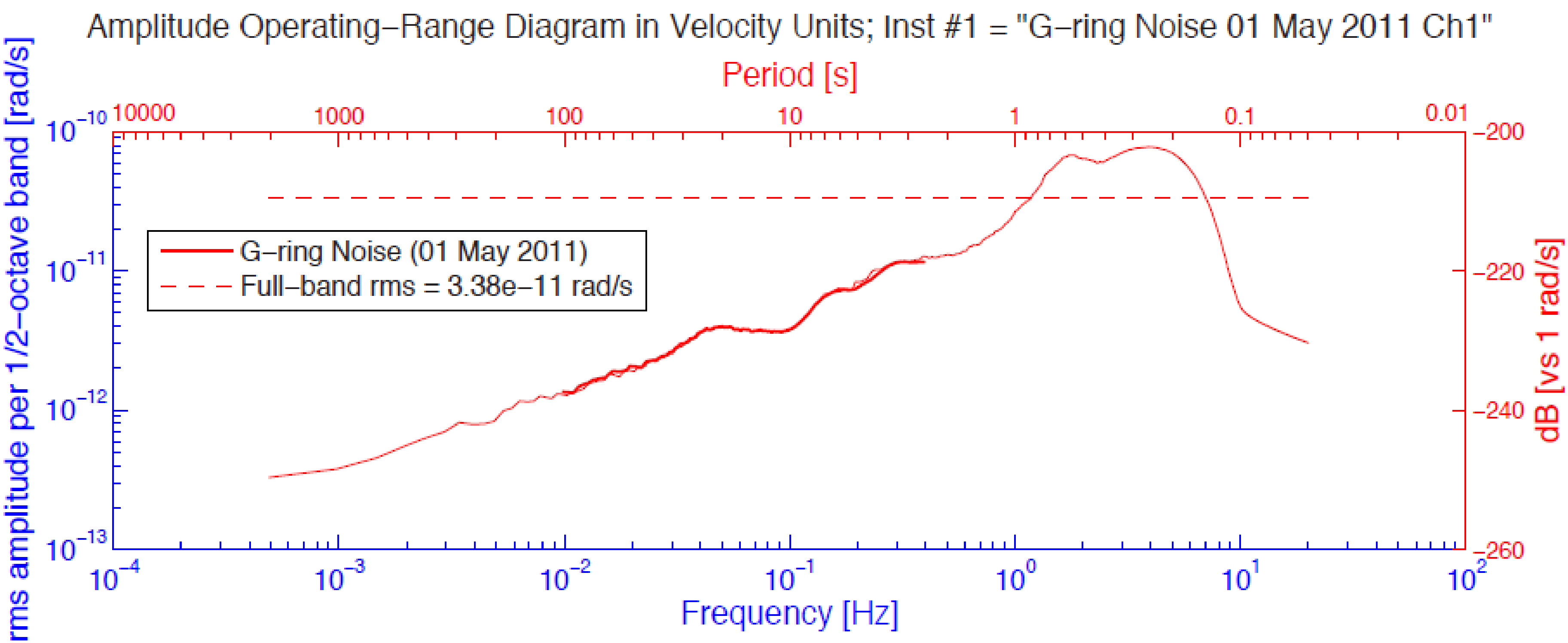
Gyro transfer function



Calibration option

- Rotational shake table (see Nigbor, Evans, Hutt 2009)
- Direct measurements of the platform angular position (high-accuracy angular encoder: ±1″)
- Controllable side motion (accelerometers)
- Reasonably high bandwidth

Self-noise: NLNM for rotations?



Courtesy of J. Evans: LNM based on G ring laser data

Single-axis sensor calibration

- Stationary test (self-noise, bias, ARW)
- Scale factor estimation (nominal, DC rotations)
- Transfer function estimation (3 dB test, variable frequencies)
- Environmental sensitivity (if required or susceptibility is critical)

What can be done without lab

- Self-noise estimation
- Bias estimation
- Traditional scale factor estimation
- Misalignment estimation (valid for sensors of higher sensitivity)

Experience so far

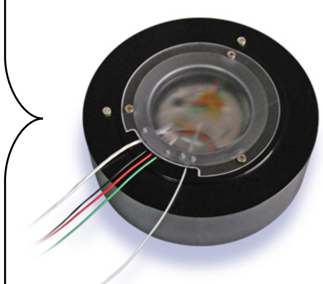
- Strong motion detection needs sensors with angle random walk about $3 \cdot 10^{-6}$ rad/s/√Hz (0.01 deg/√h) or higher
- For better accuracy and possibility of seismometer correction it needs to be less than 10^{-6} rad/s/√Hz
- Bias may not be an issue for short period observations (but lower is better)
- Scale factor stability is important (ppm level)
- Environmental fluctuations may severely affect certain type of sensors

Application grades

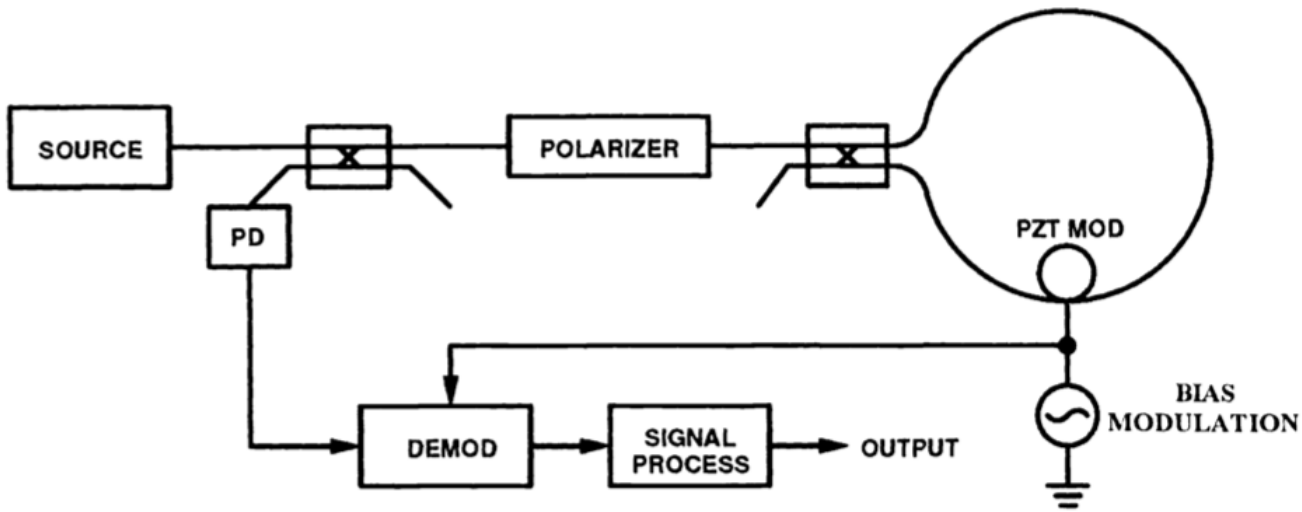
Gyro bias	Grade
100°/h	Commercial
10°/h	Commercial
1°/h	Tactical
0,1°/h	Tactical
0,01°/h	Inertial navigation
0,001°/h	Strategic
0,0001°/h	Strategic

RLG

FOG

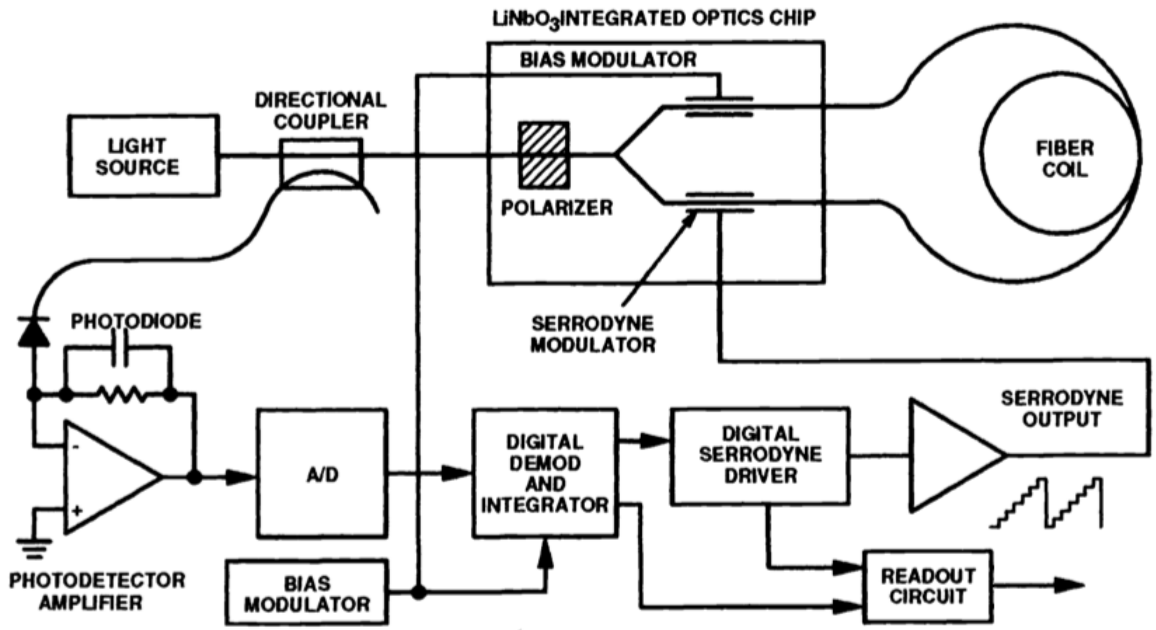


Open loop signal processing



- Preserves reciprocity
- Stable bias
- Limited range of accurate rotation rate measurements

Closed loop signal processing

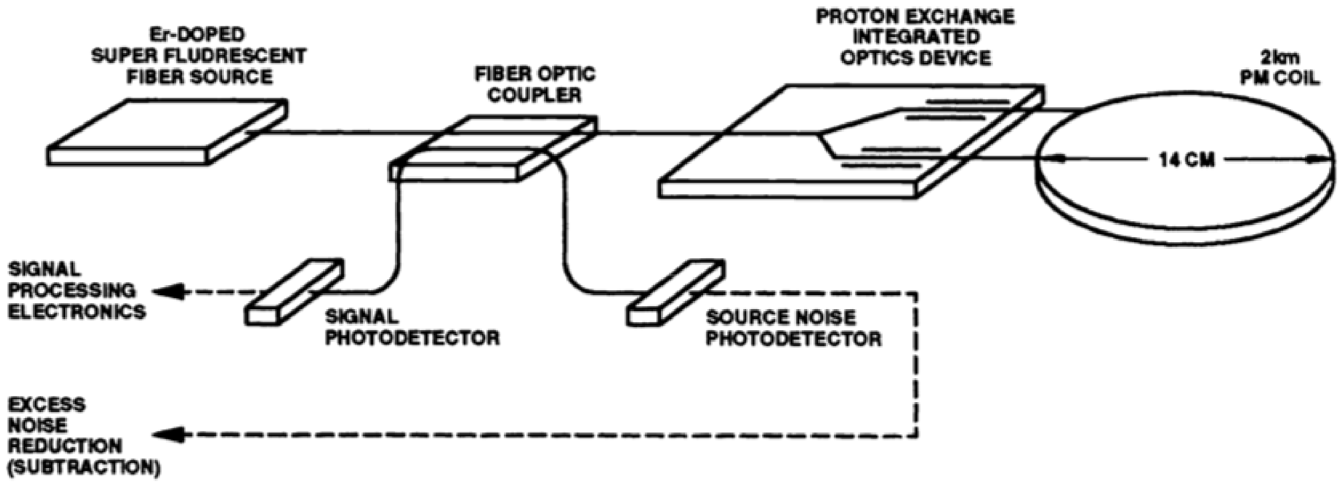


- Linearization & stabilization of scale factor
- Digital ramp ensures proper phase reset
- Simplicity of design

FOG error sources and countermeasures

Effect	Compensation
Backscatter induced noise	Broadband source
Birefringence induced nonreciprocities	PM fiber, broadband source
Shupe effect	Quadrupolar winding
Faraday effect	PM fiber, magnetic shielding
Kerr effect	Broadband source
Scale factor nonlinearity	Closed loop operation

Strategic grade FOG



- High power, stable wavelength, broadband light source (FLS)
- PM fiber coil
- Source noise subtraction
- Bias stability 0.0002°/h, ARW 0.00006°/ √h

Conclusions

- Some of the test are so complicated that should be done by OEM
- By ordering the custom designed sensor one should request an explicit calibration sheet from the manufacturer
- In case of building the sensor by yourself there is an access to calibration equipment required
- Suitable for seismology rotation sensors test methodology is still pending