Standardization training program
E-60 discipline: Control

Gyro terminology and performance specification standard

E-ST-60-21C (Febr. 2017)

The ECSS E60 branch

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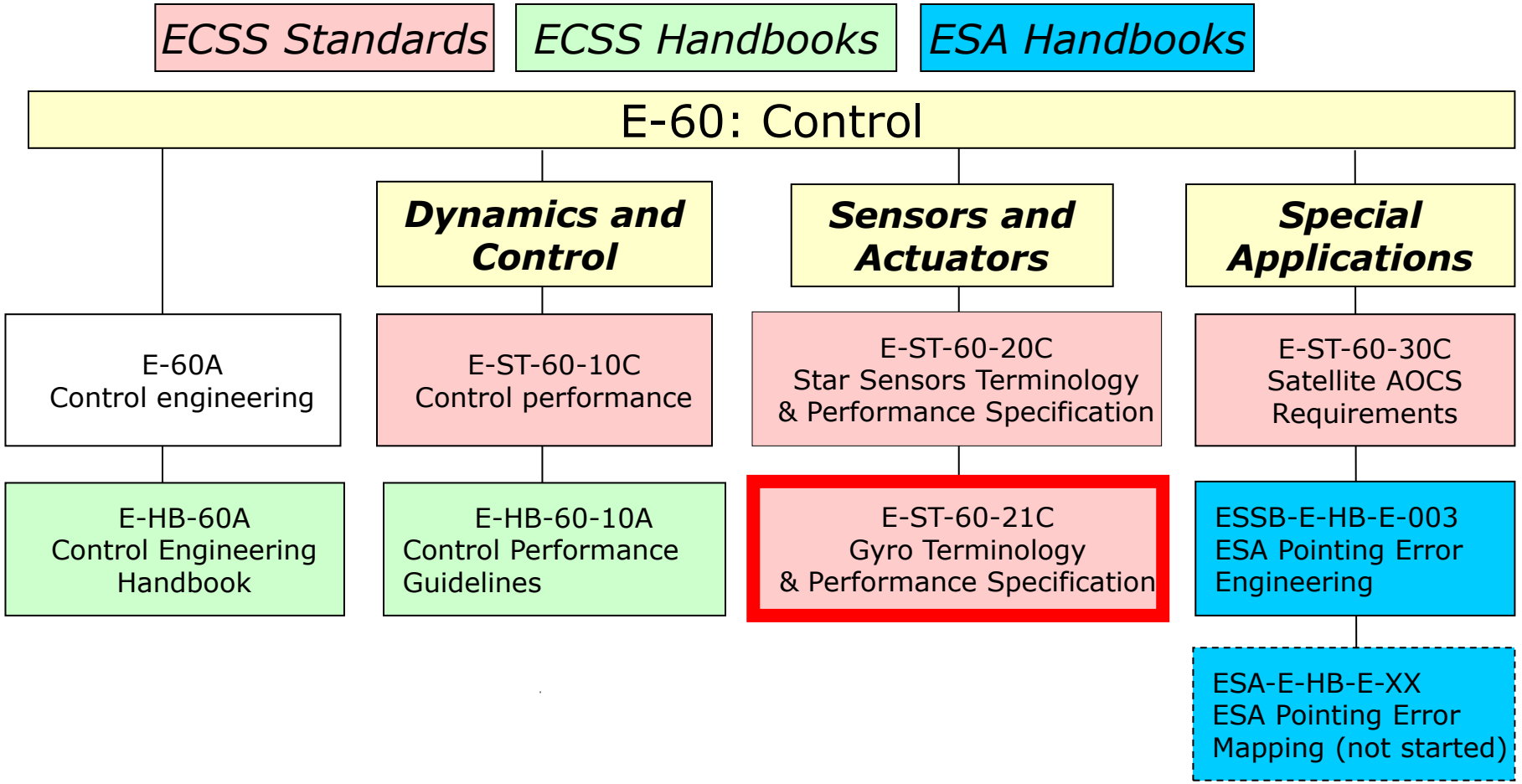

Background and motivation

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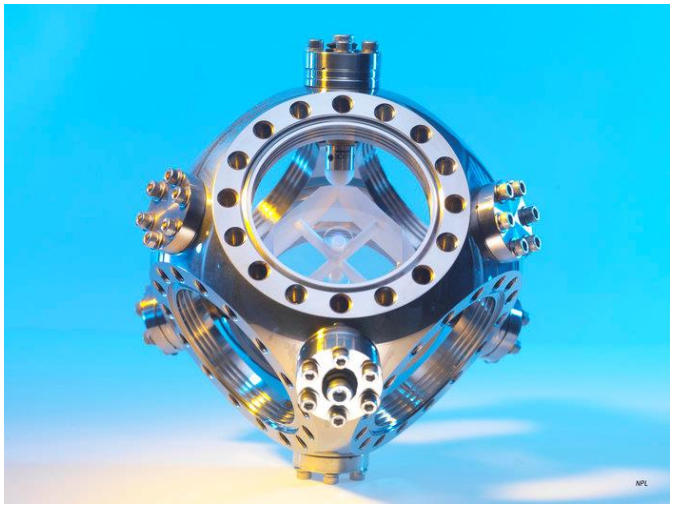
IF YOU ASK 10 PEOPLE WHAT BIAS IS, YOU GET 11 ANSWERS



- Gyros are used on almost all spacecraft
- Often used in **mission-critical functions**:
  - Detumble and rate damping
  - Safe mode, Sun acquisition mode
  - High accuracy gyrostellar estimation
  - Star tracker blinding coverage
- Different **technologies** exist:
  - Optical gyros (Ring Laser Gyro, Fibre Optic Gyro)
  - Coriolis Vibratory Gyros (Hemispherical Resonating Gyro, Tuning Fork Gyro,…)
  - Mechanical gyros (single-axis/dual-axis mechanical gyro, Dynamically Tuned Gyro,…)
  - MEMS gyros
- Despite the different technologies, a **common understanding** of the performance of gyros is needed.
- Often the **IEEE** standards (952-1997 FOG and 1431-2004 CVG) were referred to.

Gyro terminology & performance specification overview

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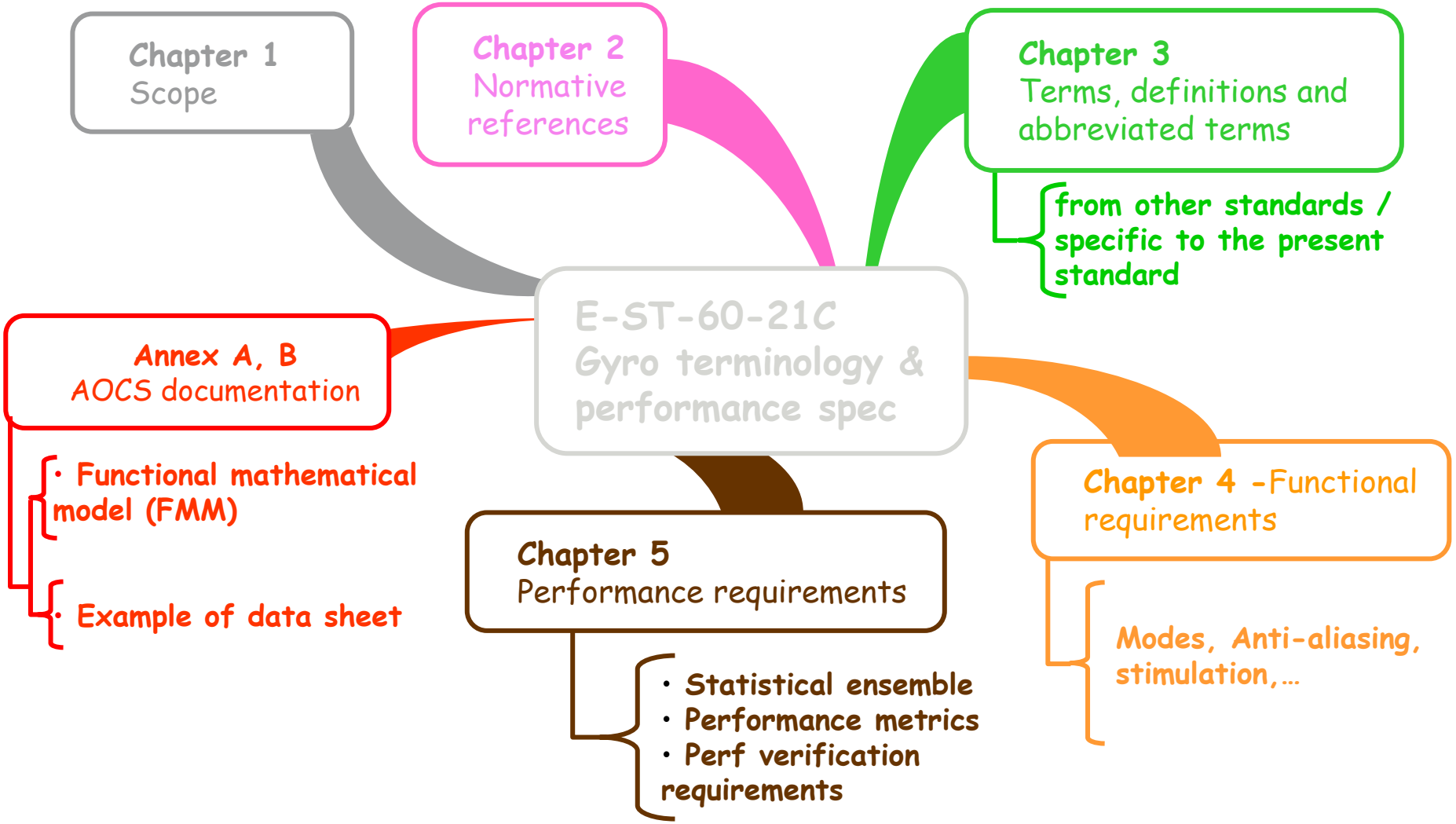

ECSS-E-ST-60-21C: Gyro terminology and performance specification

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1. Scope
2. Normative References
3. Terms, definitions and abbreviated terms
4. **Functional** requirements
5. **Performance** requirements

- Annex: functional mathematical model description
- Annex: example of data sheet

Chapter 4 : Functional requirements

- Operating Modes
  - Measurement mode
  - Auxiliary modes (test mode, programming mode,…)
- Start-up, Warm-up (durations)
- Alignment and scale factor (shall be provided by supplier)
- Anti-aliasing filter (shall be defined by supplier)
- Stimulation
- Lifetime and duty cycle

Perf. Req. Chapter 5.1, 5.2, 5.3: Statistical Ensemble, Verification req.

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- **Statistical interpretation**
  - Variation in time → temporal interpretation (e.g. noise), use worst-case sensor
  - Variation from sensor-to-sensor → ensemble interpretation (e.g. switch-on bias)
  - Mixed interpretation (do not use this as a default)

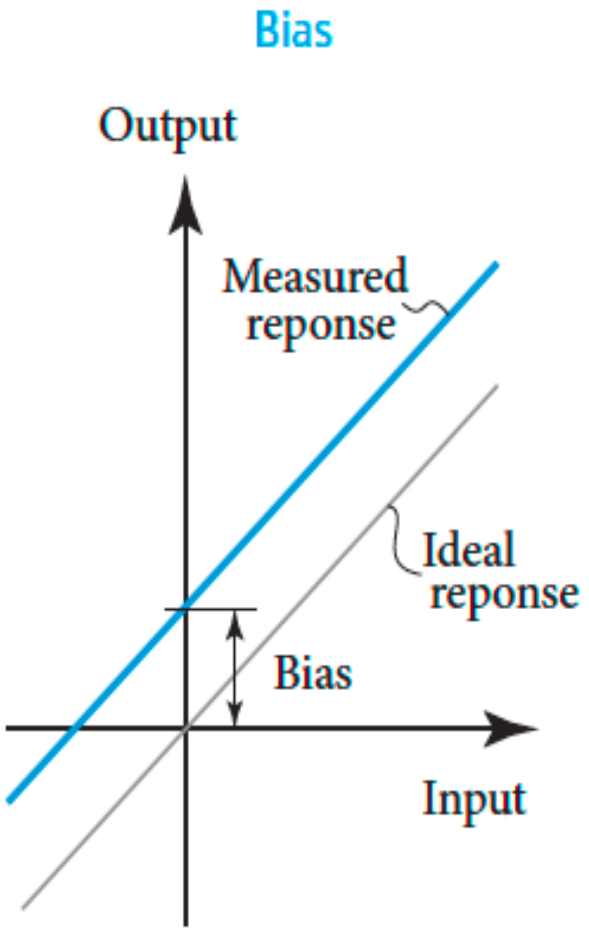
- **Confidence level** is to be agreed with the customer for each of the error source
  - (1σ, 2σ or 3σ only applies for Gaussian distributions)

- **Performance verification**
  - To be specified whether this applies to compensated (calibrated) or uncompensated measurements
  - Adequate test equipment is required
  - Earth rotation rate (approx. 15°/h) shall be taken into account

- Performance requirements shall indicate **conditions**:
  - EOL vs BOL
  - Environmental effects
  - Warm-up effects
  - Acceleration, 1g 0g effects
  - Temperature effects

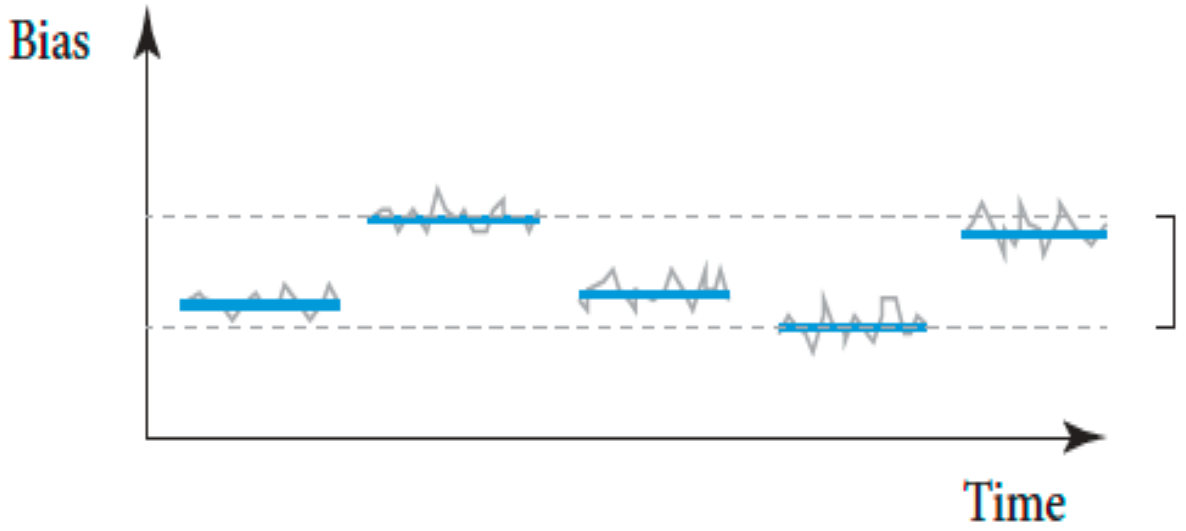
Gyro bias

- Bias is the measured output for a zero rate input
- Errors can be split in 2 parts:
  - Systematic
  - Random
- ECSS: not rate dependent, average rate error, over a defined time period
- The absolute value of bias does not dominate, as long as it is systematic
- A bias of 0.001°/h misses on full revolution in 41 years!



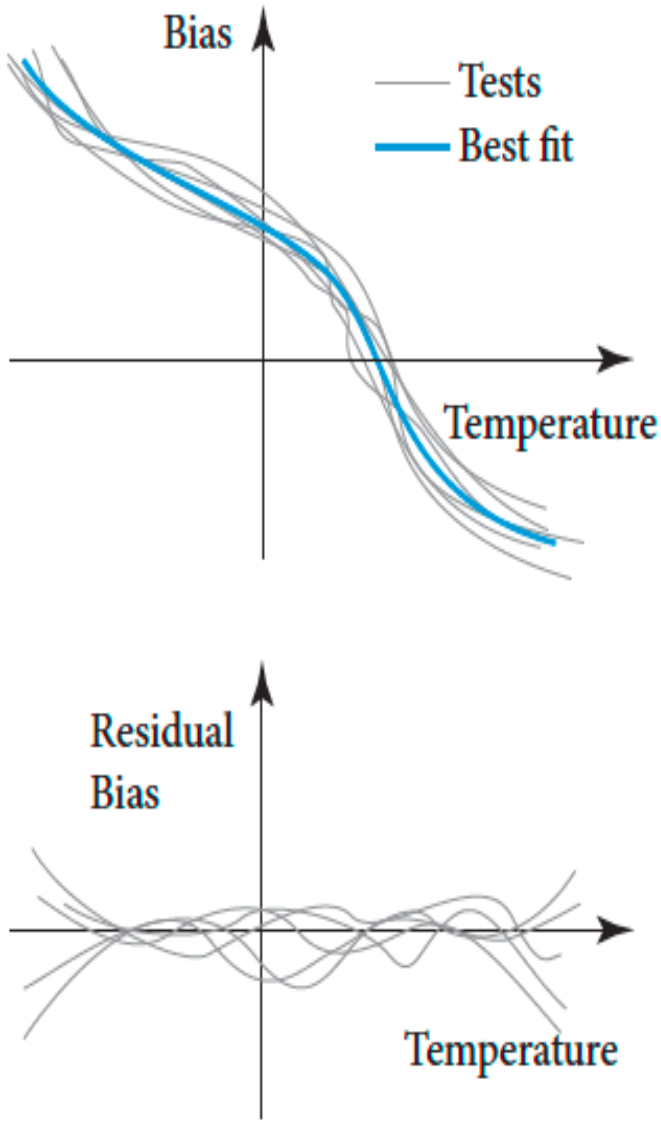
Bias repeatability

- Degree of closeness of test results taken during different periods of operation
- Random in magnitude, but constant in time. Variations between switch-on to switch-on; or before and after environmental conditions



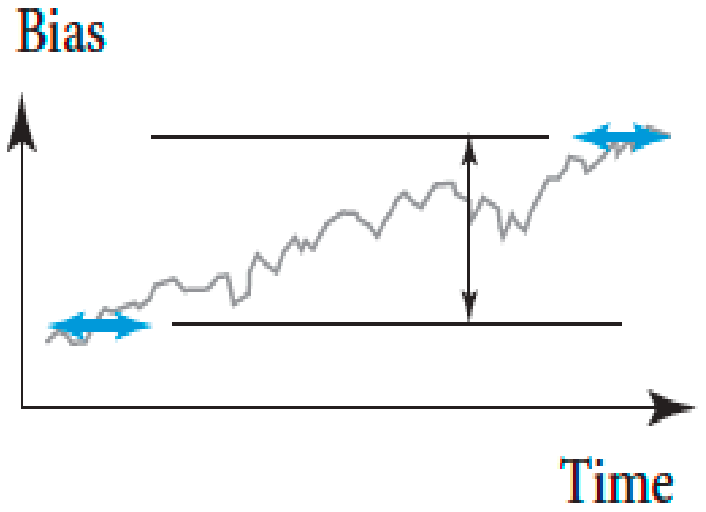
Bias thermal sensitivity

- Usually, a polynomial fit (e.g. 4th order) is used to calibrate the systematic effects
- Factory calibration can be stored in EEPROM
- The relevant error source is then the residual after calibration, measured in °/h (not °/h/K)
- ECSS: noise contribution must be <1/3 of target accuracy, preferably <1/10



Bias stability

- Variation of defined time period
- Constant environmental conditions, no switch-off
- Also known as:
  - Bias drift
  - In-run bias
  - Bias in-run drift
  - Bias random walk
  - Rate random walk
- ECSS: agree with customer to specify averaging period and observation period, but no default values given



Perf. Req. Chapter 5.4: Performance metrics

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→ BIAS

- Bias **repeatability**
  - Switch-on to switch-on repeatability
  - Repeatability before and after mechanical environment
  - Repeatability before and after thermal vacuum cycling
  - Repeatability before and after radiation
- Bias **stability**
  - E.g. maximum over life, time intervals to be specified
  - See also: rate random walk, flicker noise, long term drift, bias drift
- Bias **thermal sensitivity**
  - Before calibration or residual after calibration
  - Sensitivity to thermal gradient (spatial or temporal) to be specified
- Other bias **sensitivity**:
  - Magnetic flux density
  - Specific force (non-gravitational acceleration)
  - Vibration
  - …
- **Verification**: on marble block, thermal chamber

Noise: Power Spectral Density (PSD) introduction

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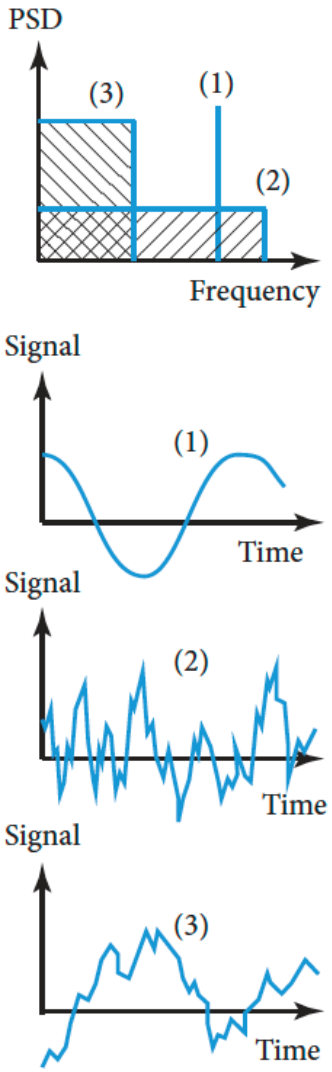
- Power spectral density (PSD) describes the frequency content of a random process
- The mean square value of the signal is equal to the integral under the PSD curve:

$$E[x^2] = \int_0^\infty S_x(f)df$$

- White noise has a flat PSD curve
- Propagation through a transfer function H:

$$S_y(\omega) = |H(i\omega)|^2 S_x(\omega)$$



Perf. Req. Chapter 5.4: Performance metrics

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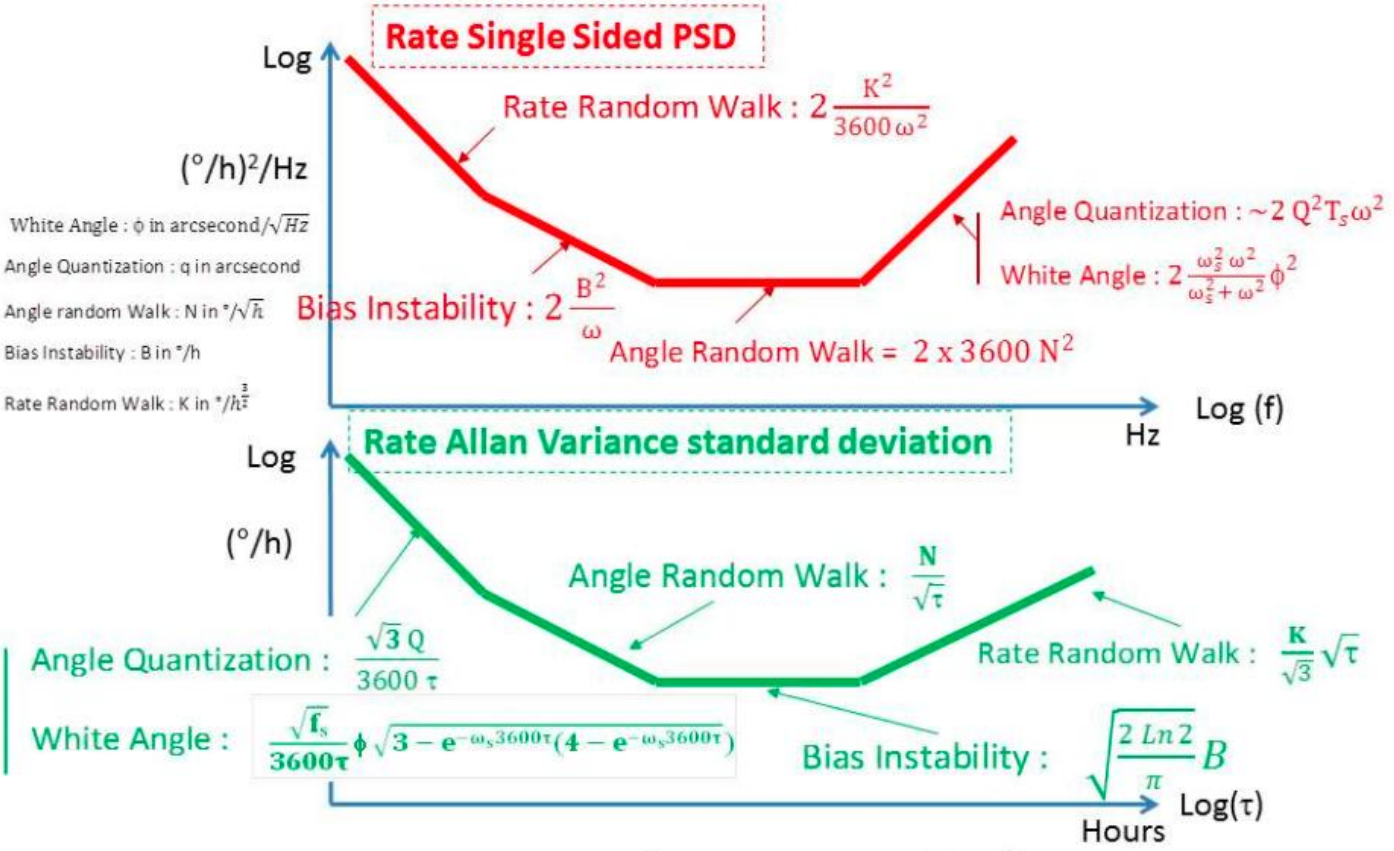

$\omega = 2\pi f$

with f = frequency in Hz

$\omega_s = 2\pi f_s = \frac{2\pi}{T_s}$

with f_s = sampling frequency in Hz

$Q = \frac{q}{\sqrt{12}}$

with q= angle quantization in arcsecond

Perf. Req. Chapter 5.4: Performance metrics

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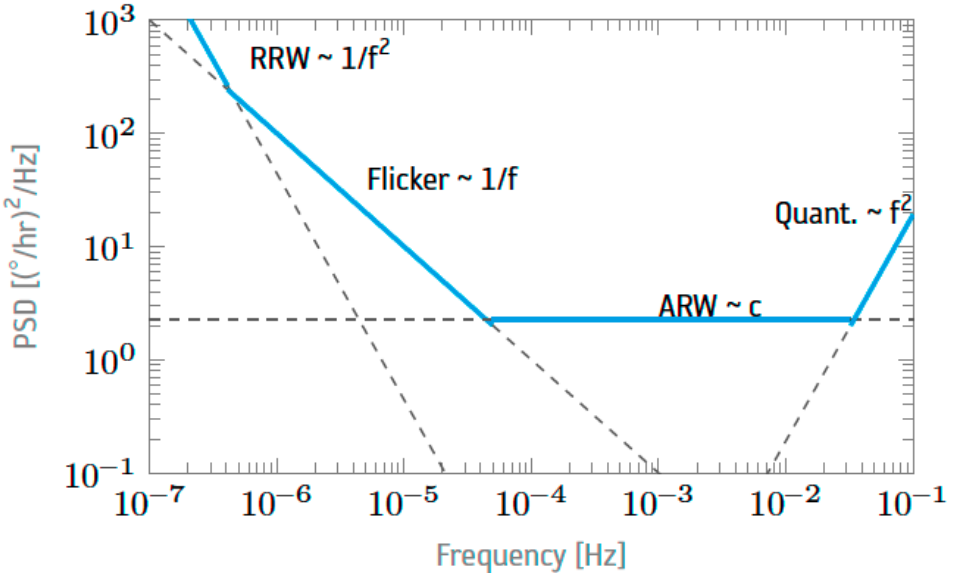
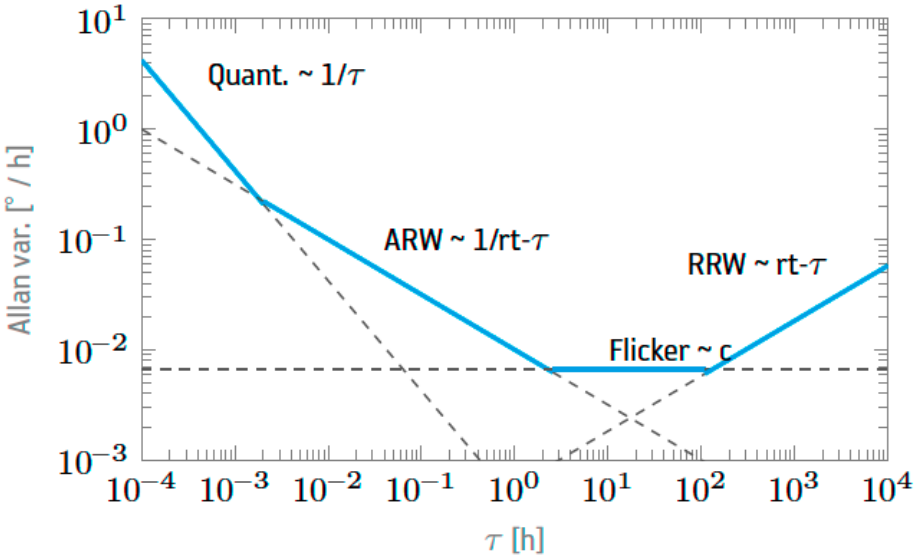
→ NOISE

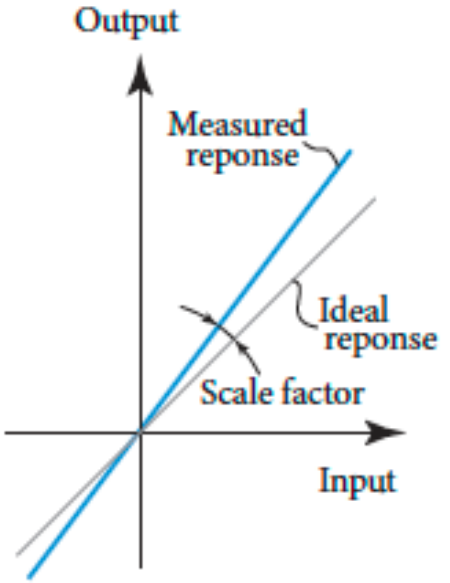
- Noise performance requirements (from high-frequency to low frequency)
  - Angle White noise (AWN)
  - Angular Quantization Noise (AQN)
  - Angle Random Walk (ARW)
  - Bias instability (flicker, 1/f noise)
  - Rate Random Walk (RRW)
  - Rate Ramp
- PSD versus Allan Variance

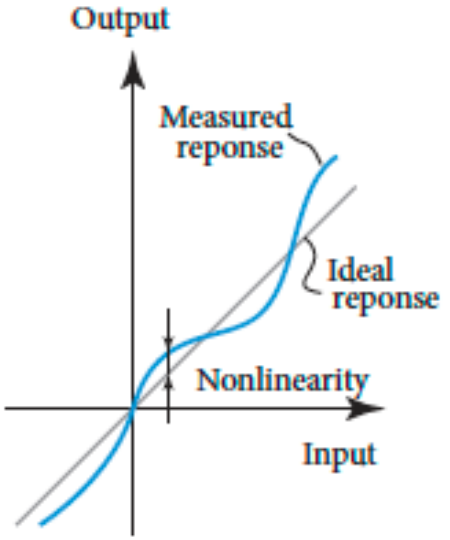




Performance metrics: scale factor

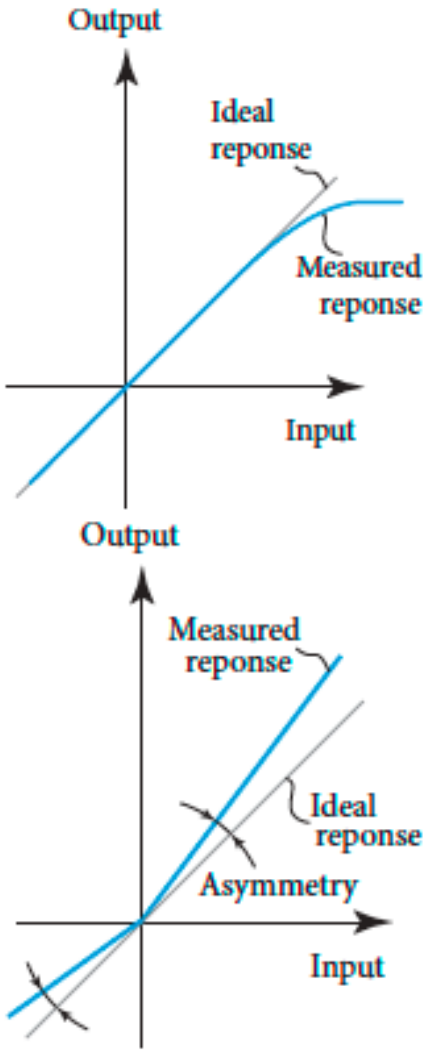
- Slope between input and output
- Non-linearity: depends on input rate
- Usually expressed as the ratio of the error to the full scale, in % or in ppm
- A scale factor error of 10 ppm loses one Earth revolution in 274 years!





Performance metrics: scale factor

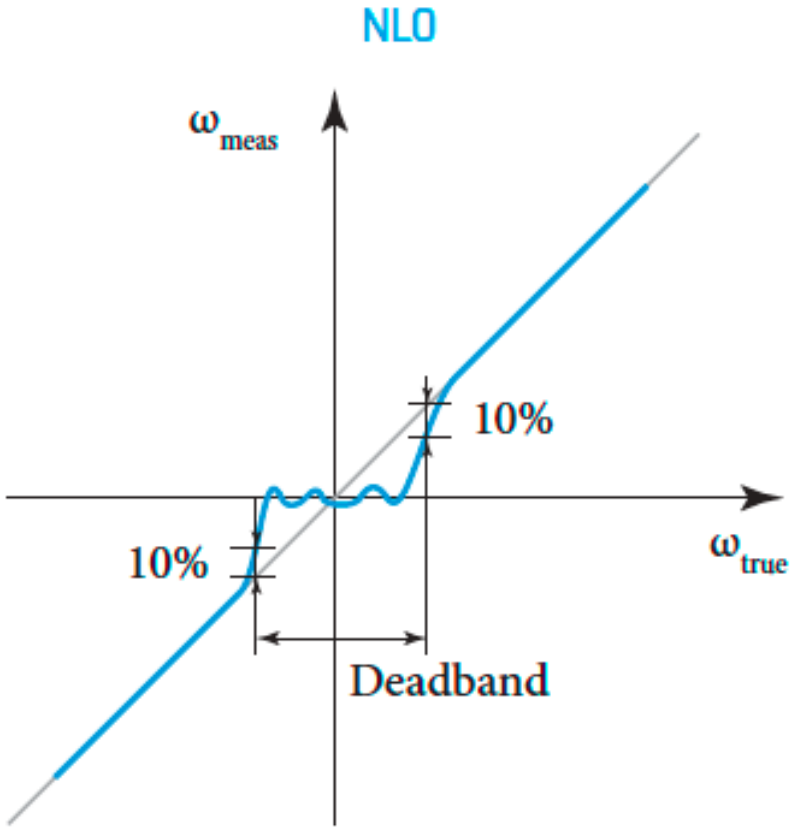
- Scale factor can have high non-linearity close to maximum output (saturation)
- An asymmetry error appears as a bias for oscillatory vehicle motion around zero input (e.g. vibration)



Performance metrics: scale factor

→ DEADBAND

- A.k.a. Non-linearity around zero (NLO)
- Caused by:
  - Stiction in mechanical gyros
  - Lock-in in RLGs
  - Reflections and electronics limitations in FOGs
- Often hard to measure with good accuracy (elimination of Earth rotation)



Perf. Req. Chapter 5.4: Performance metrics

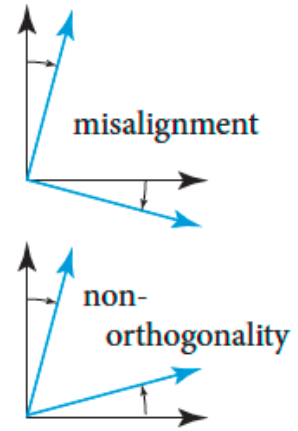
→ SCALE FACTOR ERRORS

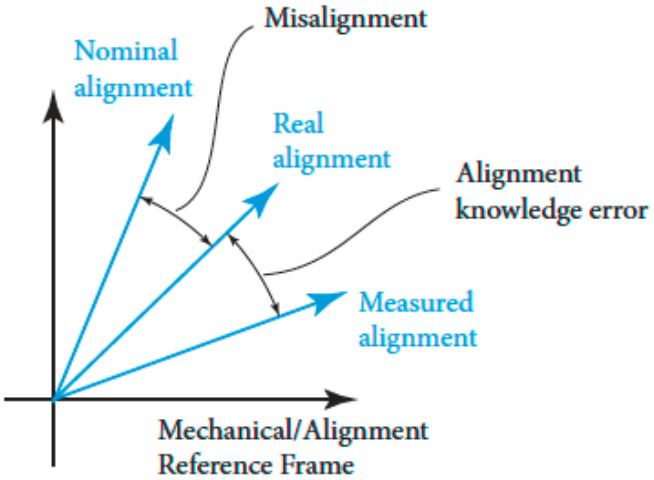
- Scale factor **initial value**
- **Deadband** (no Δ-value specified in ECSS), **non-linearity** and non-linearity error
- Scale factor **repeatability**
    - Switch-on to switch-on
    - Mechanical environment
    - Thermal vacuum
    - Radiation
- Scale factor **stability**
    - Time period to be specified
- Scale factor **thermal sensitivity**
- Verification:
    - Rate table
    - After bias compensation
    - Axis alignment errors
    - Noise effects must be <10% of scale factor error requirement

Perf. Req. Chapter 5.4: Performance metrics

→ MISALIGNMENT

- Absolute/relative **alignment** error
  - Absolute: angular error of sensitive axes wrt theoretical orientation
  - Relative: angular error between sensitive axes (non-orthogonality)
- Absolute/relative alignment **knowledge** error
  - Launch, micro-gravity, outgassing, moisture release, thermo-elastics,…
- Absolute/relative alignment **repeatability**
  - Mechanical environment
  - Thermal vacuum cycling
- Absolute/relative alignment **stability**
  - Specified time period
- Absolute/relative alignment **thermal sensitivity**
  - Operating temperature range and/or customer-specified temperature range





Perf. Req. Chapter 5.4: Performance metrics

→ OTHER PERFORMANCE METRICS

- Measurement **datation and latency**
  - Datation accuracy (jitter) → verified by analysis
  - Latency: between measurement date and availability date on databus
- **start-up** performances
  - Max rate error or angle increment error during start-up period
- **Warm-up** performances
  - Bias
  - Noise
  - Scale factor error
  - Misalignment error
- Measurement output **bandwidth**
- **Anti-aliasing** filter (DC gain, max phase at frequency, max overshoot, max attenuation, min attenuation, sample frequency,…)
- Data **quantization**
- **Failure detection** efficiency
- **Stimulation**

Annex A:
Functional Mathematical Model (FMM)

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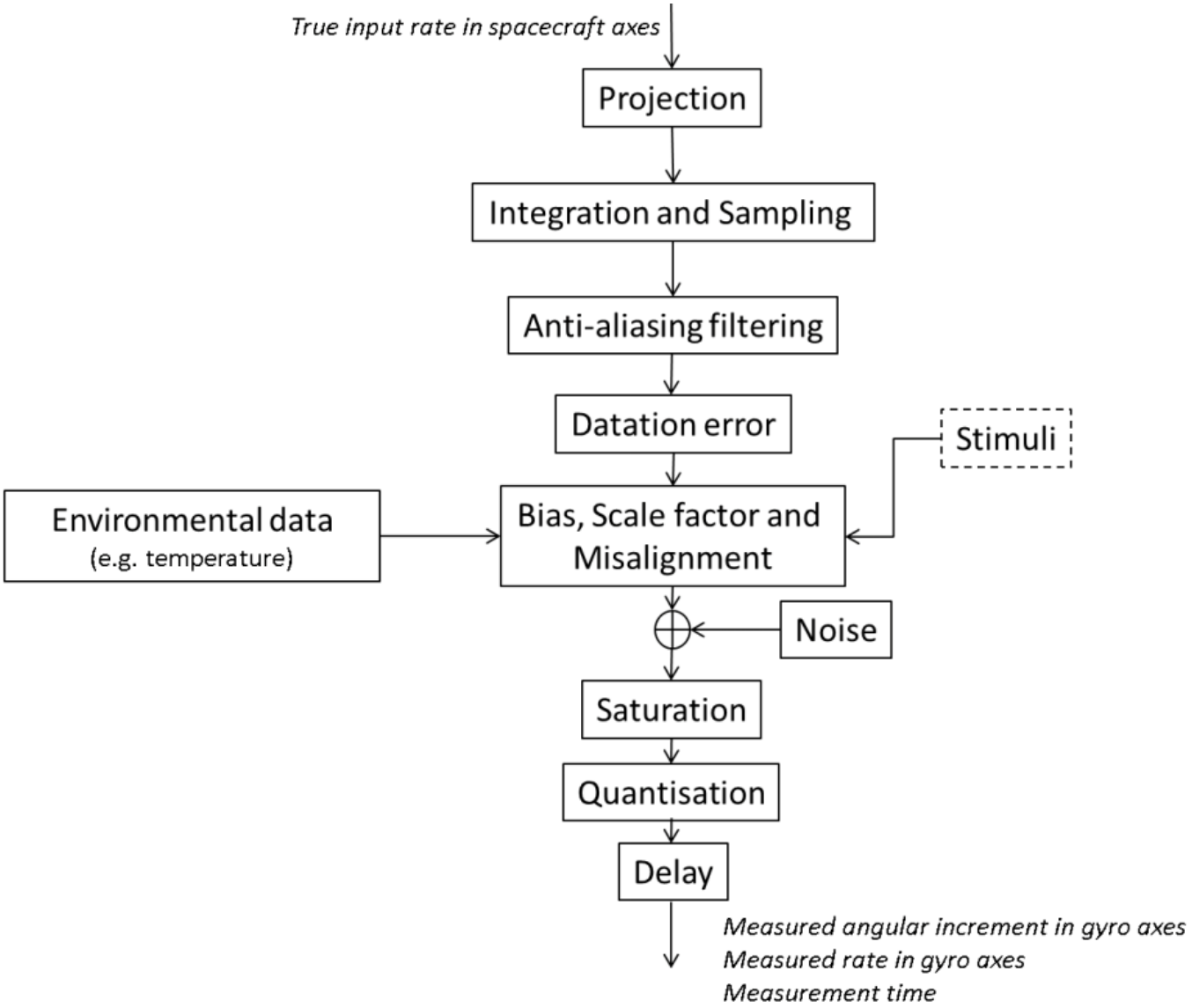

Conclusions

- A common **terminology**, performance specification and test methodology is specified for all gyro technologies to be used for spacecraft
- Gyro **performance specification** contains, at least:
  - Bias (repeatability, thermal, stability, sensitivity)
  - Noise (quantization, ARW, flicker, RRW)
  - Scale factor (repeatability, deadband, thermal sensitivity, stability)
  - Misalignment (absolute/relative, knowledge, repeatability, stability, sensitivity)
  - Others (datation and latency, bandwidth, start-up, warm-up,…)
- **Not** a specification for gyros for **launchers** (not treating e.g. coning effects, depressurization effects, transfer function, structural damping,….)
- A similar terminology and performance specification standard can be proposed for **accelerometers** (no working group formed yet)

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