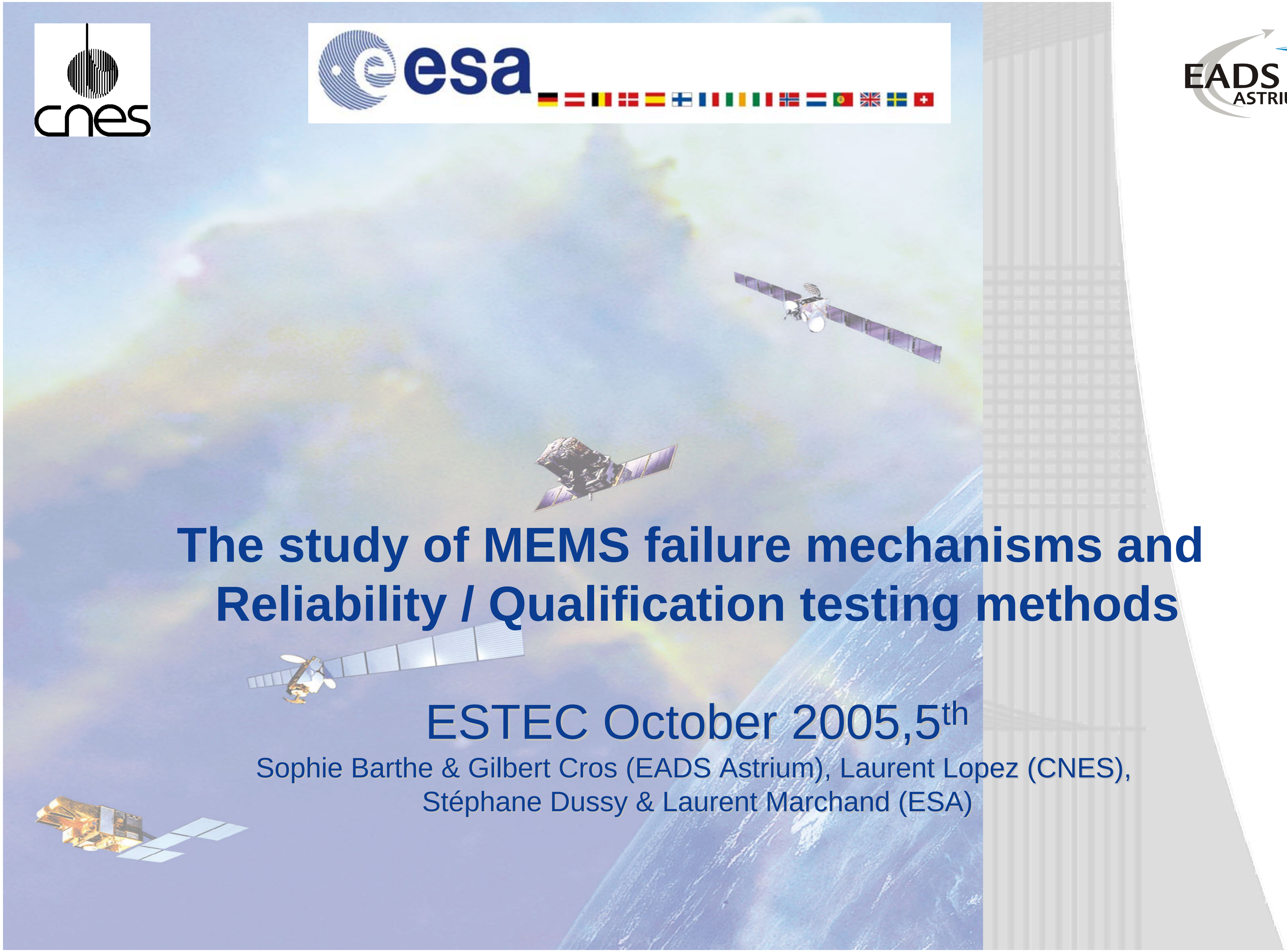

The study of MEMS failure mechanisms and Reliability / Qualification testing methods

ESTEC October 2005,5th

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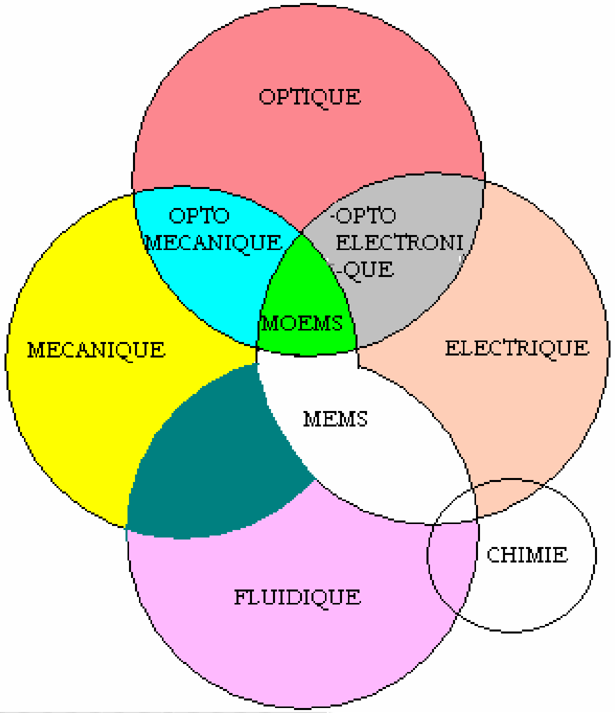
Content

- Overall project overview
- Presentation of the ESA/CNES Physical Analysis
- Presentation of the test plan
- Presentation of the test results
- Presentation of CNES FailureAnalysis
- Conclusion of the activity

1. Aim of the study



- To understand the issue related to MEMS
  Assess MEMS based Gyro Reliability
  Define the tight experiments and testing
- MEMS (MicroElectroMechanicalSystems) :
  10µm size intelligent systems
- Miniaturisation of platform electronics by the use of MEMS
  Interest for CNES, ESA and ASTRIUM
- MEMS overview : applications in space, MEMS technology, failure mechanisms, MEMS reliability test methods.
- Elaborate testing of MEMS : the micro-gyroscope
- Guideline redaction for the evaluation of MEMS

MEMS: Interest for space

Launch cost

Mass production methods

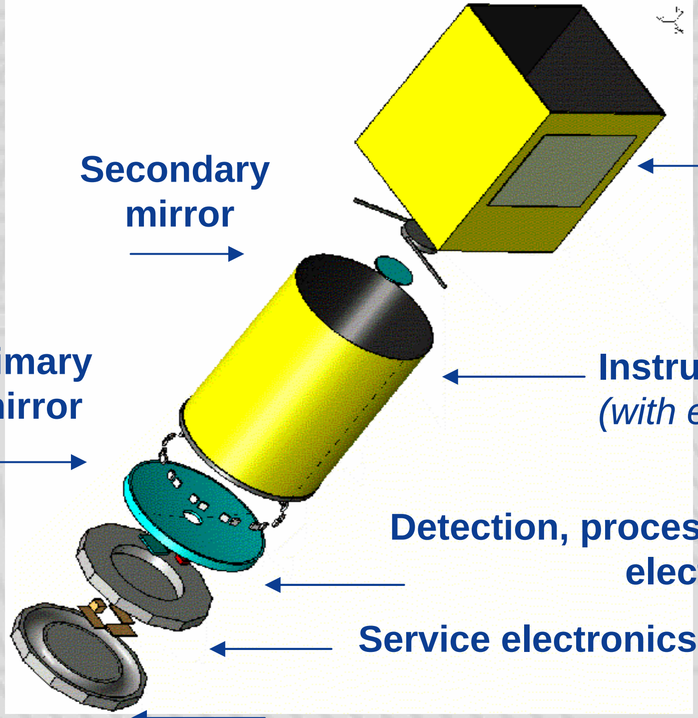
Weight reduction

Low power consumption

Satellite miniaturisation

Easy manipulation

Which micro-devices in a satellite?



Baffle *(with embedded RF electronics & Antennas)*

Solar array *(with embedded power management & distribution electronics)*

Secondary mirror

Primary mirror

Instrument Structure *(with embedded thermal control)*

Detection, processing & data storage electronics

Service electronics

Propulsion module (2x1/2 tank halves & Thrusters)

Micro reaction wheel

Millimotor

Nano gear

Magnetometer

Micro gyroscope

Tank

Pipes

Thruster

Possible space applications for MEMS

- The space industry is not a major player in the MST field but a “fast follower”.

TODAY (not in space)	FUTURE (in space)	
Pressure sensors	Micro gyroscopes and magnetometer (in AOCS)	**MEAN TERM**
Airbag accelerometers	Optical instrumentation	
Printers	RF components	
Read/Write heads for hard disk drives		
	Power supply	**LONG TERM**
	Cooling system	
	Optical payloads	

Gyroscopes: Sensor used to detect inertial angular motion.

- *Mechanical gyros*

  RIG (Rate Integrating Gyro) now replaced by

  Eurostar 2000

  DTG (Dynamically Tuned Gyro) ➘

  Eurostar 2000^+/3000 - ATV - Spot5 / Helios2 / Metop

- *Optical gyros*

  RLG (Ring Laser Gyro) ➔

  Ariane – Rosetta / Mars express

  FOG (Fibre Optic Gyro) ➚

  Will replace current techno. On new developed S/C (Pleiades, Aeolus, Astrobus,…)

- *Resonant gyros*

  HRG (Hemispherical Resonant Gyro) ➔

  Rocsat, Kompsat

  µVSG (Vibrating Silicon Gyro) ➚

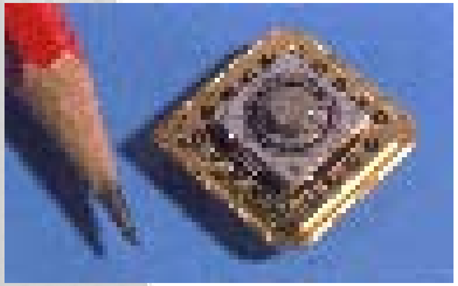
  (Micro satellite)

Gyroscopes performances status

		Bias stability	Angle Random Walk	Scale factor
		RF	ARW	SF
Mechanical gyros	RIG / DTG	0,1°/h → 0,001°/h	0,1°/√h → 0,001°/√h	1000 ppm
Optical gyros	RLG	1°/h → 0,01°/h	0,1°/√h → 0,01°/√h	10 → 1 ppm
	FOG	10°/h → 0,001°/h	0,01°/√h → 0,0001°/√h	1000 → 20 ppm
Resonant gyros	HRG	10°/h → 0,001°/h	0,01°/√h → 0,0001°/√h	200 → 50 ppm
	VSG	0.1°/s → 5°/h	1°/√h → 0,1°/√h	1% → 1000 ppm

The accuracy and bias stability of µ-gyros do not yet meet the requirements of satellite inertial systems.

SiRSS: Vibrating Structure Gyroscope (BAe)

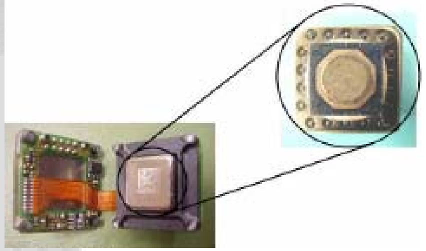


Solid state sensor based on the coriolis effect.
Single axis sensing element (less than one centimetre in diameter) and electronics in the same package (135g in weight).

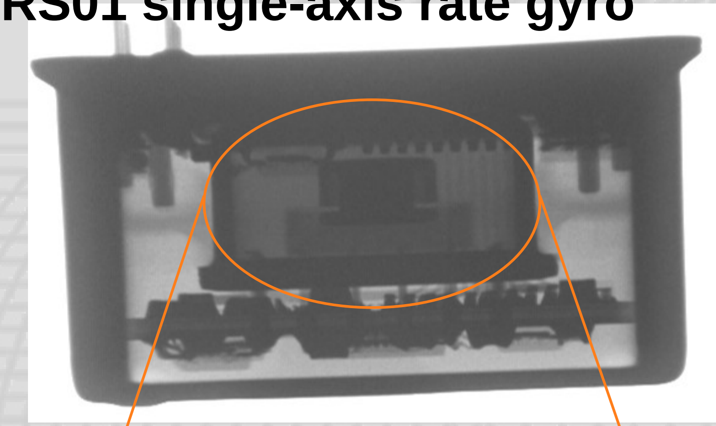
Performance : **Scale factor variation…… within +3% to – 3%**
Zero bias……………………..+2°/sec to –2°/sec
Axis alignment……………..+/- 0.5°

Performance tests over temperature: (- 40°C / + 70°C)

Output noise
Bias
Scale Factor Variation
Axis alignment



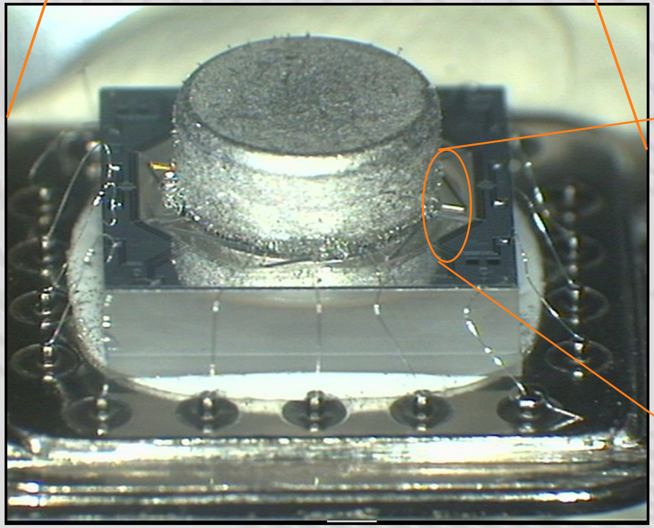
SiRRS01 single-axis rate gyro



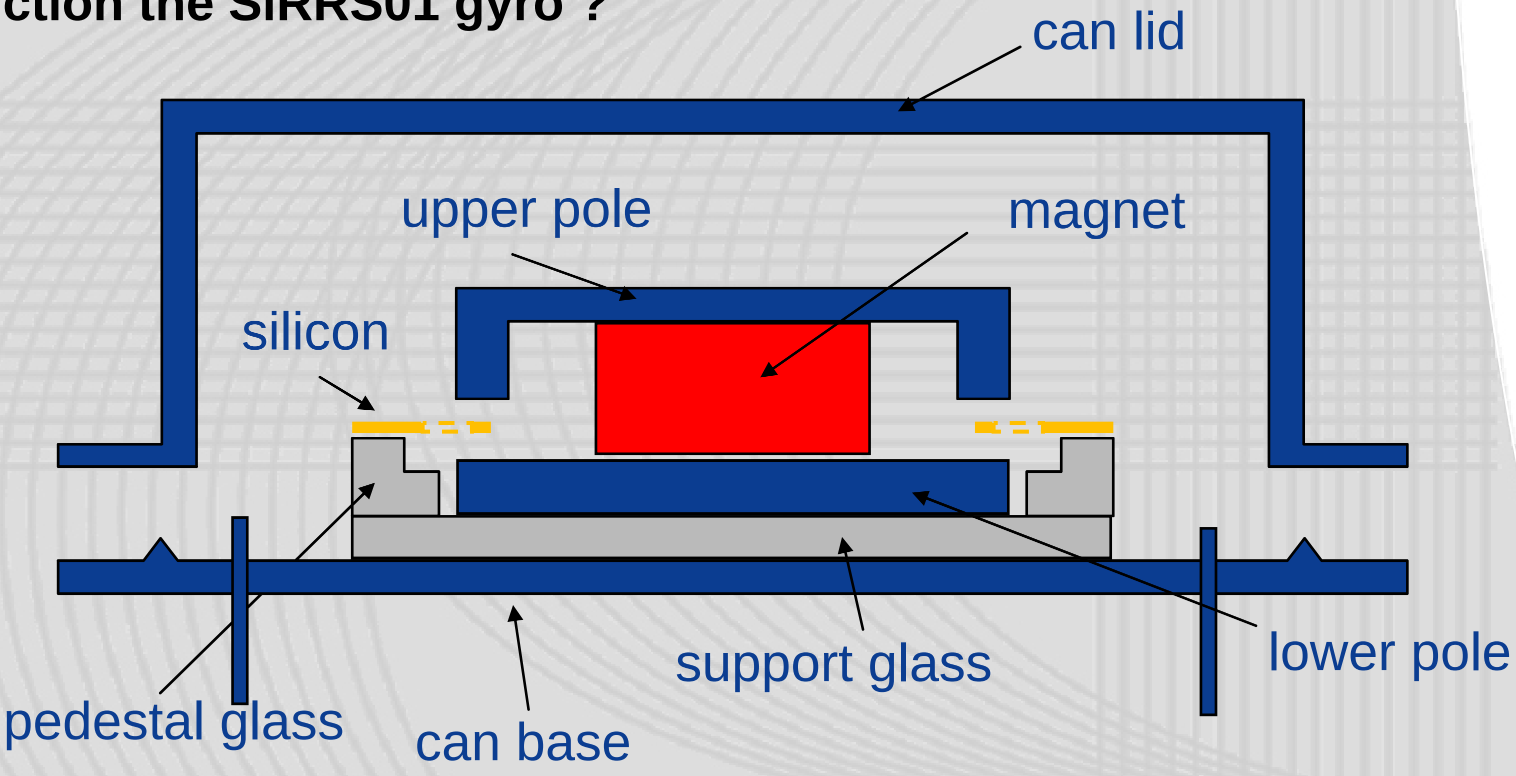
✓ Gyro made of a mechanical part, the 'sensor head', and an ASIC to put the gyro into vibration, control the vibration and measure the rate of turn.

✓ Vibrating Structure Gyro based on the coriolis effect.

✓ 'Deep trench etching' process enabling the production of the tiny micro-machined silicon ring.

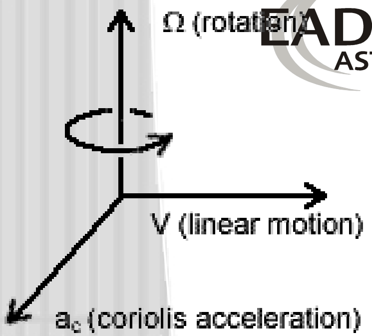


Construction the SiRRS01 gyro ?

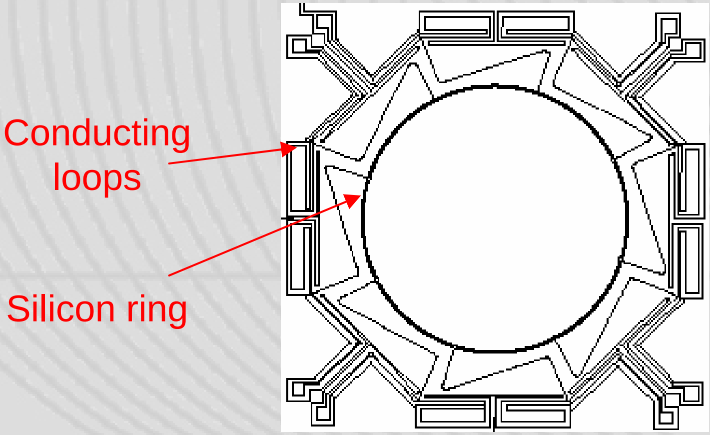


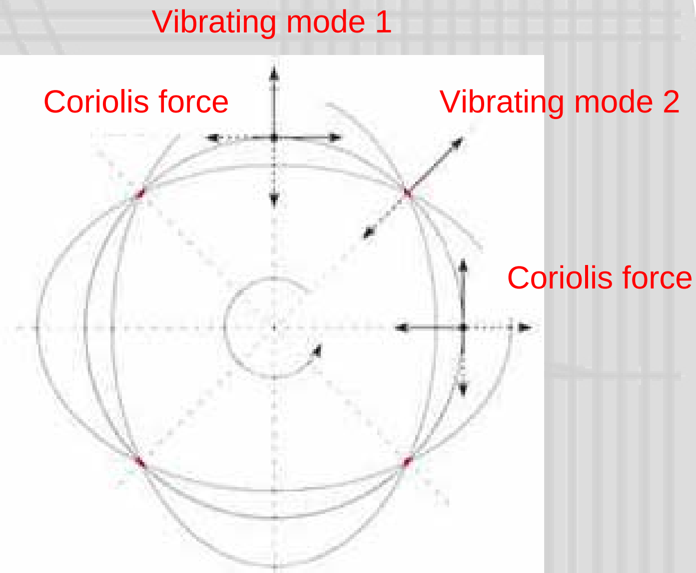
- ✓ Bulk micro-machining technology: silicon etched to create the sensor ring
- ✓ Silicon-on-insulator (SOI) substrate: silicon anodically bonded to a glass support

Functioning principles of the SiRRS01 gyro?



- ✓ Based on the Coriolis Effect: Coriolis acceleration experienced by a particle undergoing linear motion in a rotating frame of reference.
- ✓ Resulting acceleration directly proportional to the rate of turn.
- ✓ Vibratory motion coupled from a primary vibrating mode into a second mode when sensor experiencing angular rate.





Potential failure mechanisms of the SiRRS01 gyro

Focus made on the sensor head : {silicon ring / metallic resonator / glass bonded}

Sensor head

Fracture

Single-crystalline Si (anisotropic material)

Fatigue

Not in glass and Si: brittle materials

Yes in coatings and polySi

Stiction / Wear

No surfaces in contact

Delamination

At interfaces such as Can base/ support glass

Dampening effects

Not operating at resonant frequency and hermetically sealed

Radiation

Expected to be sensitive

Particulates

Dust particles from iron can

Temperature changes

Mechanical properties affected ?

Potential weaknesses also assessed by ESA/CNES Constructional Analyses

Failure mechanisms vs testing

- SiRRS01 silicon rate sensor more sensitive to fracture and delamination.

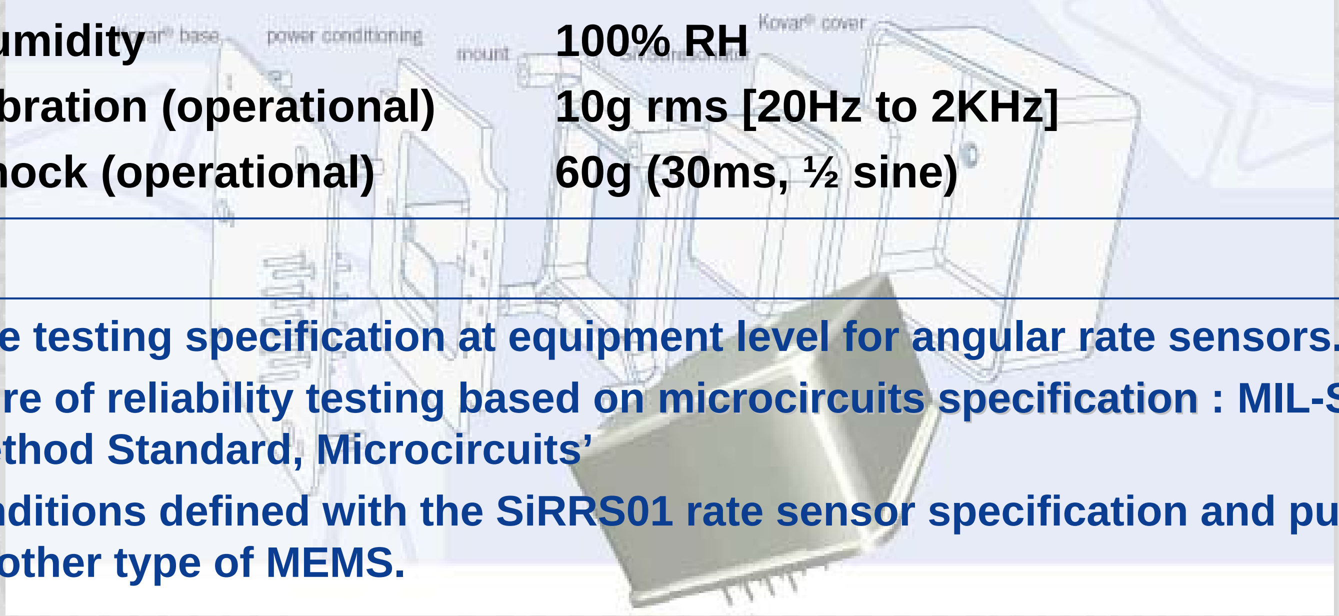
- **Thermo-mechanical** tests and even life-test may evidence these failure mechanisms.

  - Shocks and temperature testing may induce fracture and delamination
  - Shocks could lead to early end of life of the structure, as vibrations do by inducing distortions or bending of the structure.
  - Symmetry of the ring design offer excellent rejection of linear vibration.

- Electronics in a closed loop around the sensing part and may prevent the system from reaching its functional limits even under harsh conditions.

  - Radiation testing will be performed separately on the sensor head alone (but previous testing at ESA demonstrated MEMS gyroscope (sensor and electronic sensitivity to TID)

Performance and reliability testing

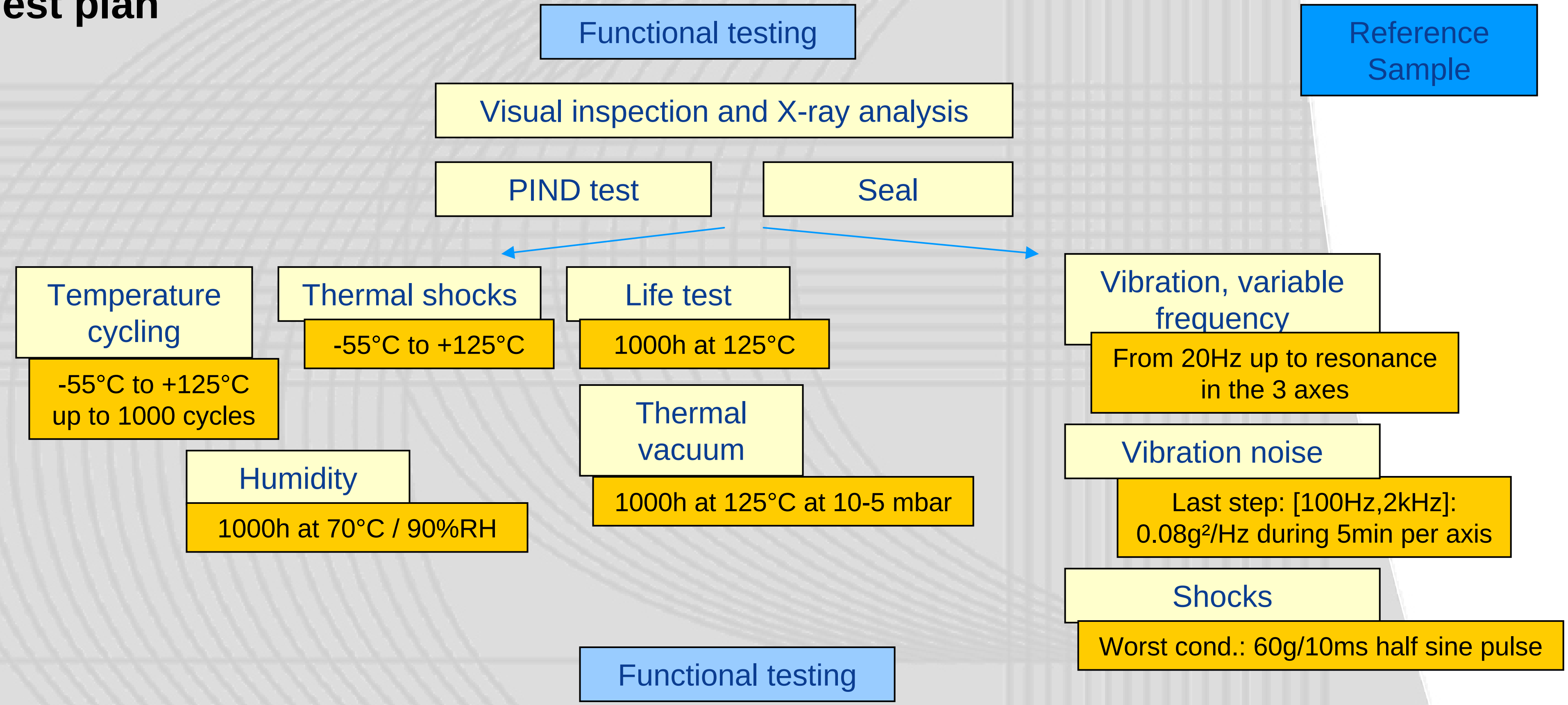


Operating temperature	- 40°C to + 75°C
Humidity	100% RH
Vibration (operational)	10g rms [20Hz to 2KHz]
Shock (operational)	60g (30ms, ½ sine)

- No space testing specification at equipment level for angular rate sensors.
- Procedure of reliability testing based on microcircuits specification : MIL-STD-883E ‘Test Method Standard, Microcircuits’
- Test conditions defined with the SiRRS01 rate sensor specification and published data on other type of MEMS.

- Mechanical shocks performed on a sample up to destruction.
- Failure Analysis to be performed in case of anomalous parameter measurements or destructive events.
- Limited number (7) of gyros including a sample of reference to perform reliability testing.
- Sensor and electronics kept together in the same package during tests.

Test plan



Functional testing

Reference Sample

Visual inspection and X-ray analysis

PIND test

Seal

Temperature cycling

-55°C to +125°C
up to 1000 cycles

Thermal shocks

-55°C to +125°C

Life test

1000h at 125°C

Thermal vacuum

1000h at 125°C at 10-5 mbar

Humidity

1000h at 70°C / 90%RH

Vibration, variable frequency

From 20Hz up to resonance
in the 3 axes

Vibration noise

Last step: [100Hz,2kHz]:
0.08g^2/Hz during 5min per axis

Shocks

Worst cond.: 60g/10ms half sine pulse

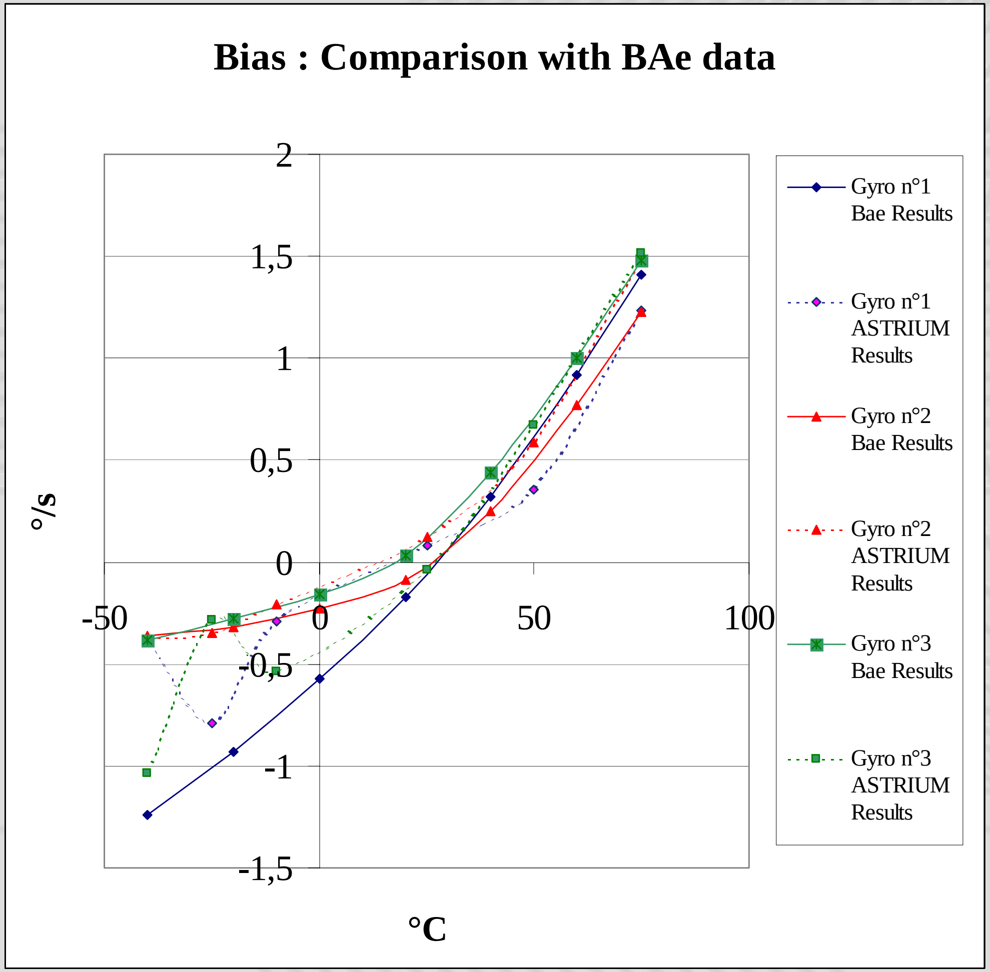
Functional testing

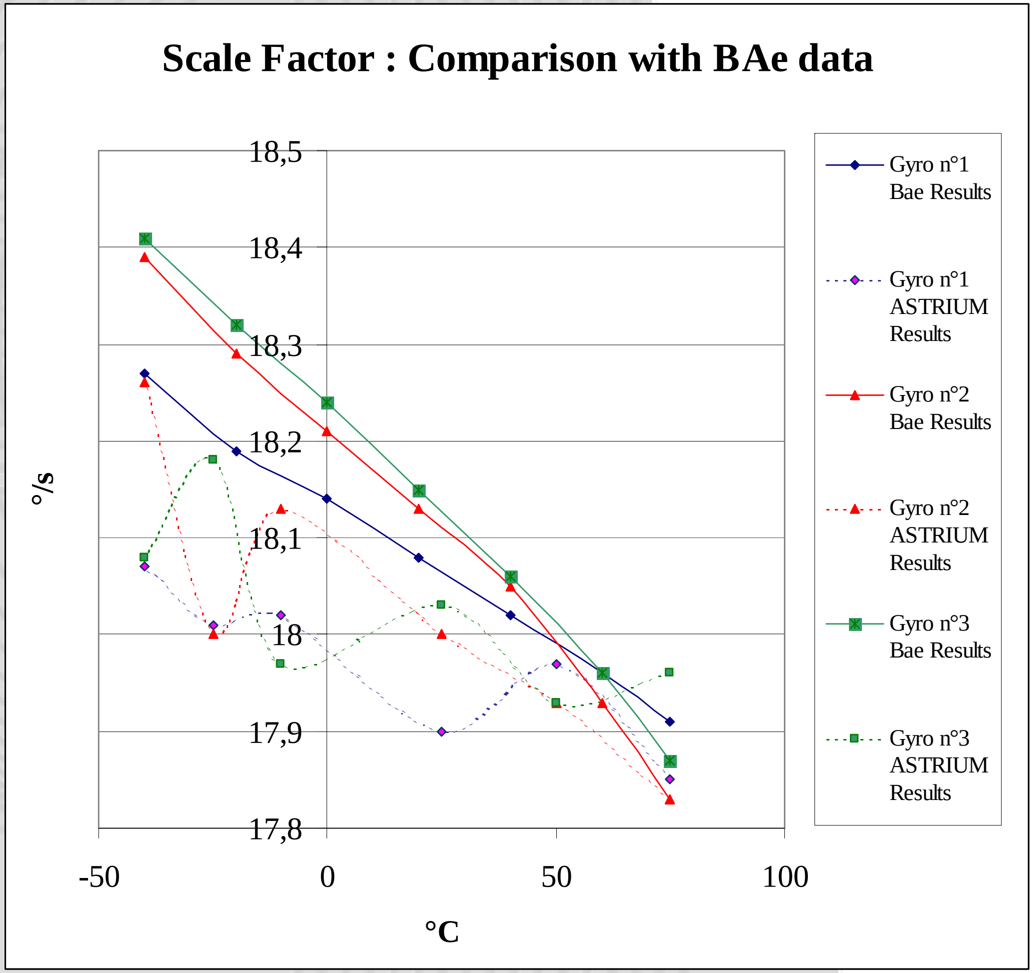
- **Basic performances (Bias / Bias repeatability / Noise) to be performed between each tests.**
- **3 gyros will undergo temperature testing while 3 others mechanical testing.**

Test sequence per part

S/N	
10805	1000 thermal cycles + life test (1000 h@+125°C)
10880	Technical hitch [too high temperature seen by the component]→PIND test
10882	Life test+ thermal vacuum + life test
20580	Mechanical test : vibrations and shocks
20582	Mechanical test : vibrations and shocks
20592	Mechanical test : vibrations and shocks
20760	ESA destructive DPA
20762	ESA reference part. (S/N ESA)
21048	1000 thermal cycles + life test (1000 h@+125°C)
21050	Technical hitch [wrong polarization]→ PIND test

Functional testing: Astrium initial measurements


Bias : Comparison with BAe data


Scale Factor : Comparison with BAe data

- ❑ Gyros show a rather stable behaviour over temperature

INITIAL TEST RESULTS : Comparison with BAE results: Main differences

- NOISE

Measured (ASTRIUM & CNES) : > 0.7 °/√h

SiRSS datasheet : < 0.2 °/√h

Difference not understood. Measurement method?

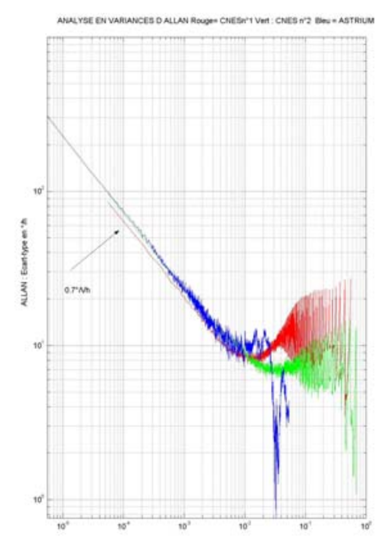


Figure : comparison between ASTRIUM and CNES VA measurements

- DRIFT STABILITY

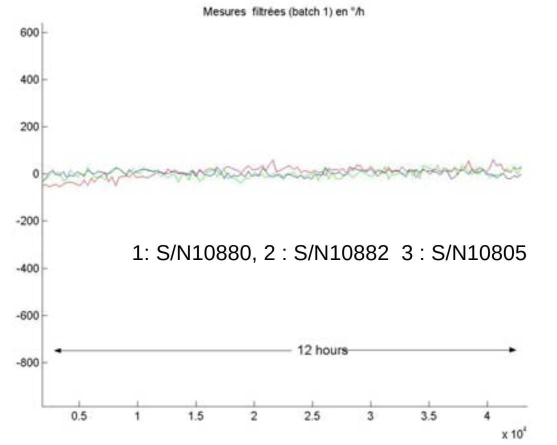
Two family of gyros !

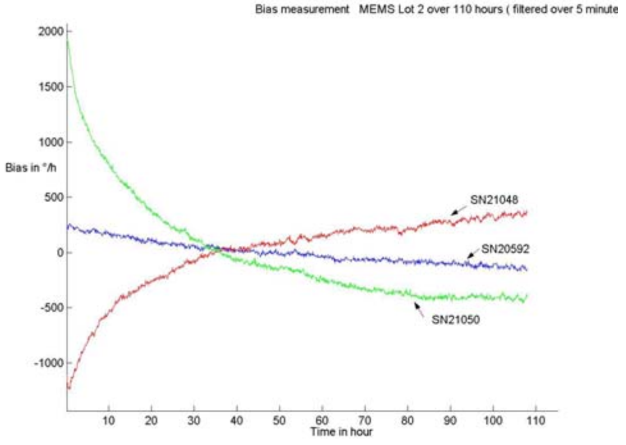
1st LOT : rather stable typ. ±50°/h

(data sheet : < 2 °/h !!)

2nd LOT : very unstable

(up to 1500 °/h per day)





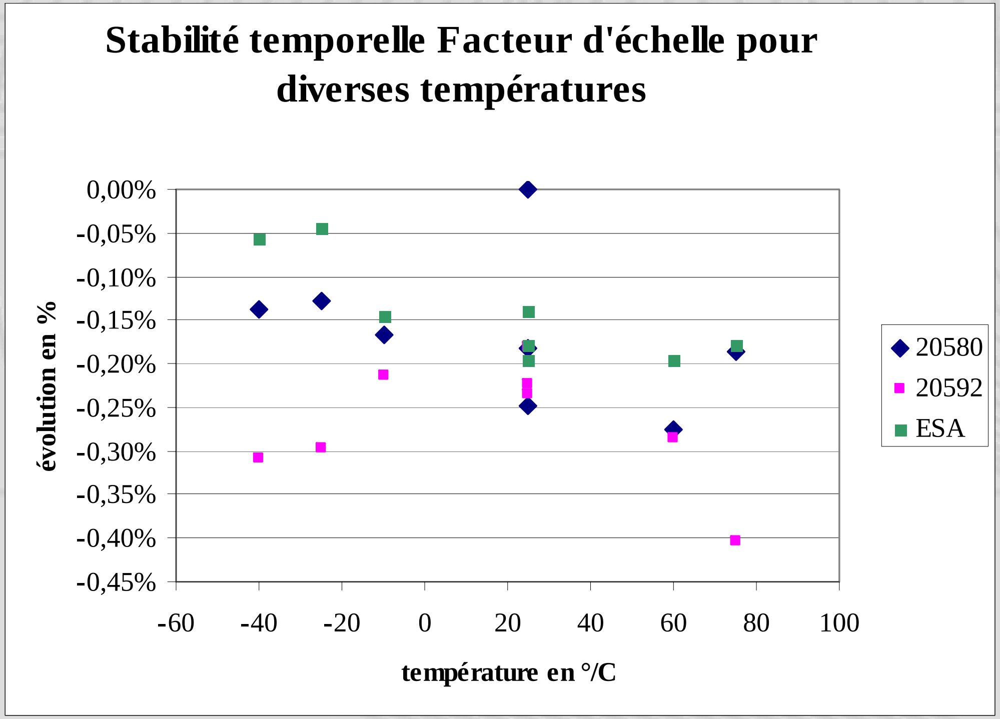
Test Results: SCALE FACTOR STABILITY OVER TIME

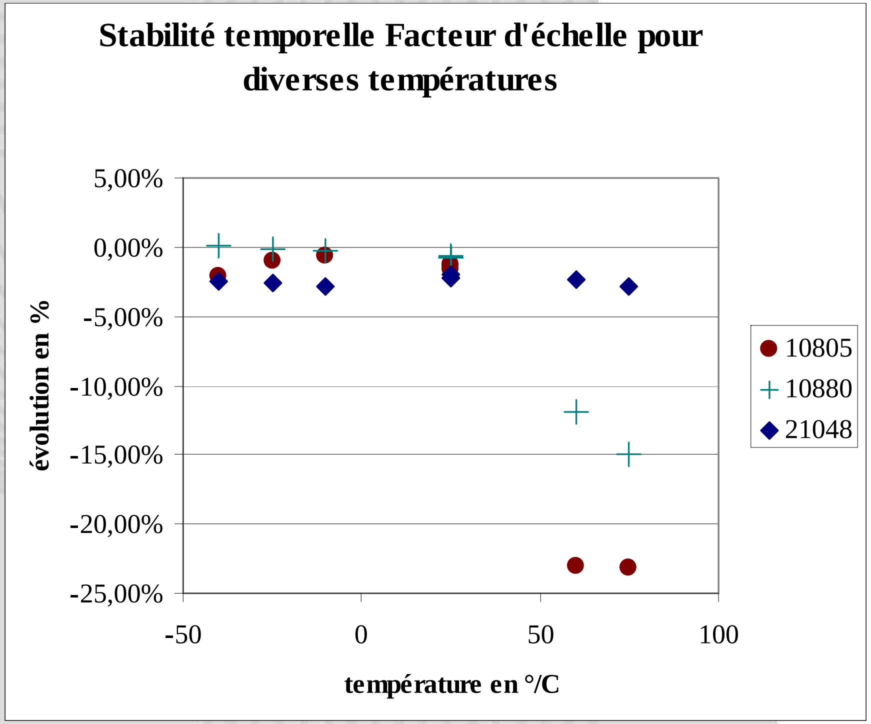
- **Data sheet BAe :**

Nominal : 18.2 mV/°/s
Repeatability : +/-1% (1 sigma)

OK : n° 20580, n° 20592, n° ESA

NOT OK : n° 10805, n° 10880, n° 21048





Test Results: SCALE FACTOR LINEARITY

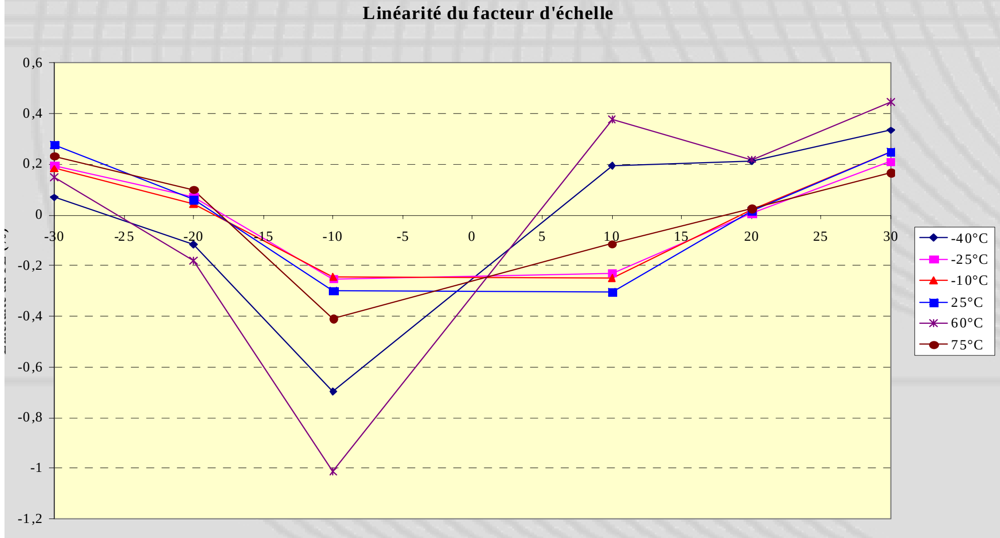
- Data sheet BAe :

  Linearity +/-1% of full scale

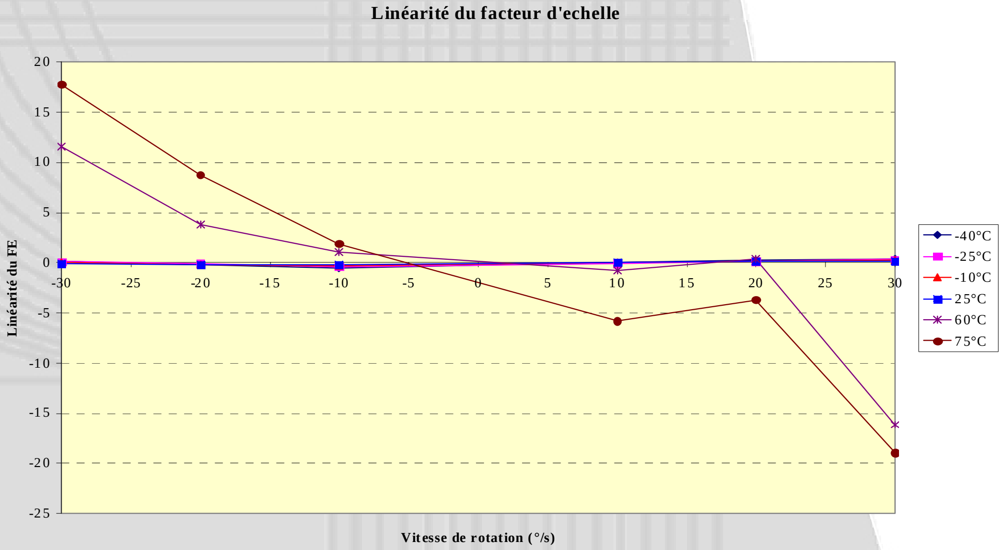
OK : n° 20580, n° 20592, n° ESA

NOK : n° 10805, n° 10880, n° 21048

		20580	20592	21048	ESA	10805	10880
Final	**Facteur d'échelle linéarité (max)**	+/-0,4%	+/-0,5%	+/-4%	+/-1%	+/-15%	+/-20%



N° ESA



N°10880

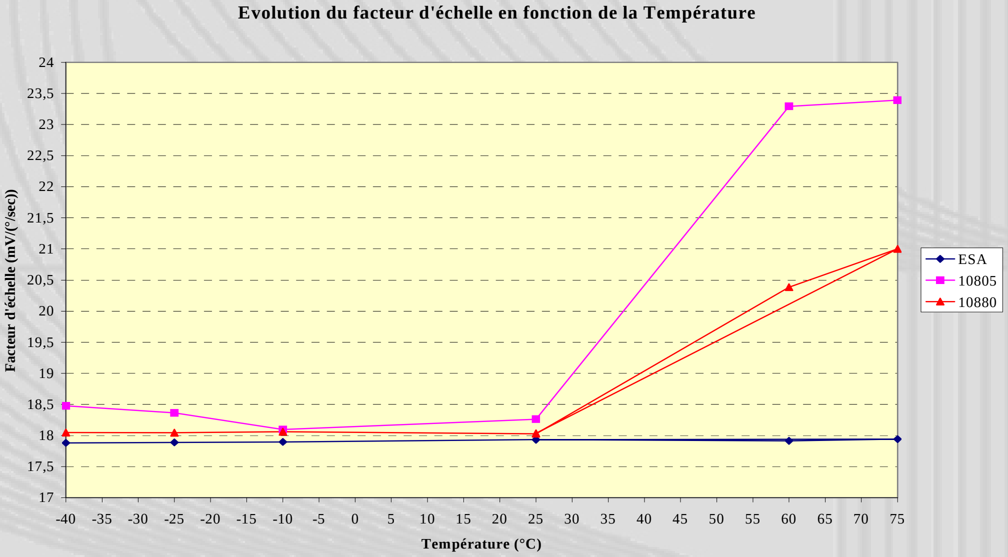
Test Results: SCALE FACTOR SENSITIVITY TO TEMPERATURE

- Data sheet BAe :
  Variation with temperature : +/-3%

OK : n° 20580, n° 20592, n° ESA

NOK : n° 10805, n° 10880, (n° 21048)

	20580	20592	21048	ESA	10805	10880
Facteir d'échelle en température Stabilité (max-min)	0,58%	1,37%	2,37%	0,35%	28,89%	16,52%



Test Results: BIAS STABILITY OVER TIME

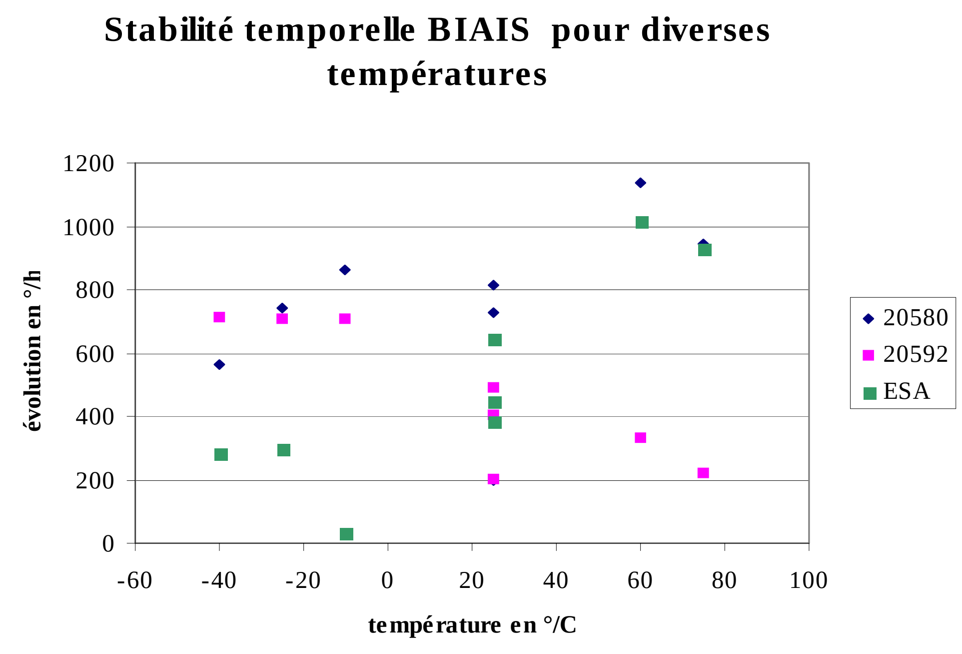
- **Data sheet BAe :**

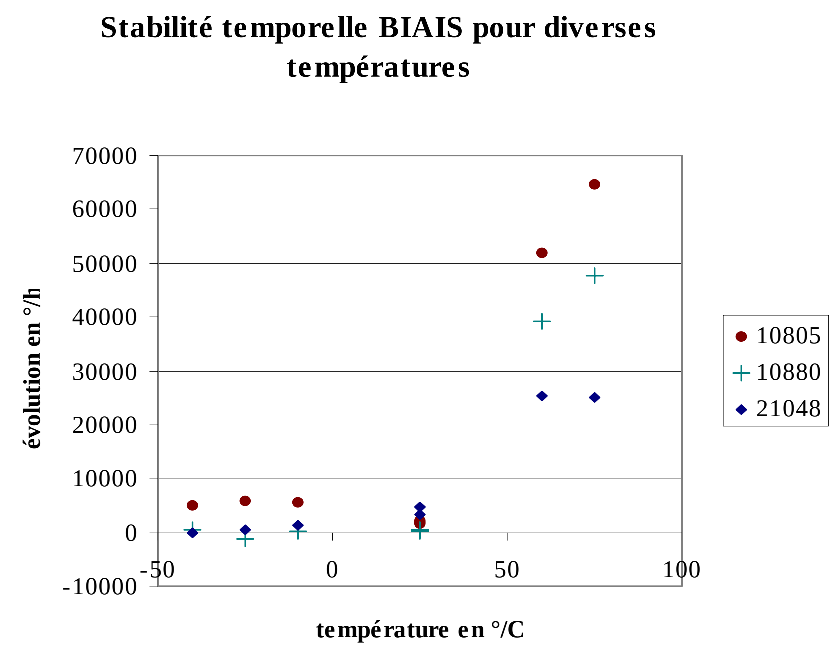
  Setting@20°C) :+/- 0.3°/s

  Repeatability : 0.1°/s = 360 °/h (1 sigma)

OK : n° 20580, n° 20592, n° ESA

NOK : n° 10805, n° 10880, n° 21048


Stabilité temporelle BIAIS pour diverses températures


Stabilité temporelle BIAIS pour diverses températures

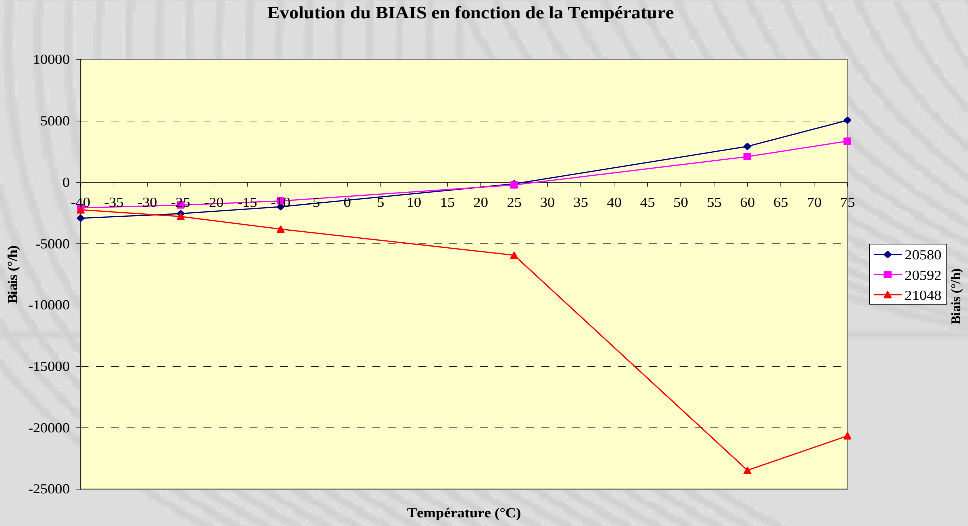
Test Results: BIAS SENSITIVITY TO TEMPERATURE

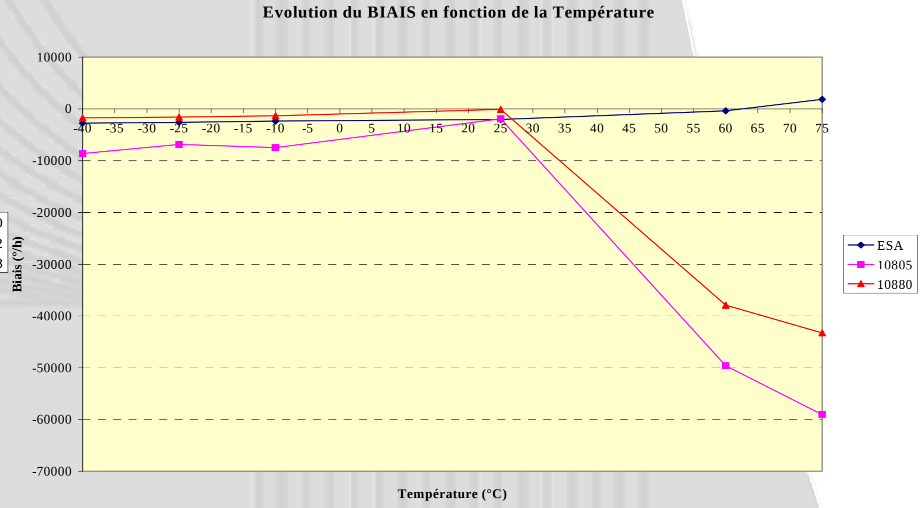
- **Data sheet BAe :**
  Variation with temperature : +/-0.2°/s (or 720 °/h)

≈OK : n° 20580, n° 20592, n° ESA

NOK : n° 10805, n° 10880, (n° 21048)

	20580	20592	21048	ESA	10805	10880
Biais en température Stabilité (max-min) en °/h	7975	5442	21234	4616	57422	43276





DRIFT STABILITY OVER 1 HOUR

- Data sheet BAe :

  Stability : 3°/h

Drift stability over 1 hour , in °/h						
	20580	**20592**	**21048**	**ESA**	**10805**	**10880**
25°C initial	-214	-325	-6340	-2508	-2353	-244
25°C final	87	-164	-9342	-2226	-1715	-31
Stability over 1 hour	301	161	-3001	282	638	213

NOISE

- **Data sheet BAe :**

  ARW : 0.2°/√h

≈OK : n° 20580, n° 20592, n° ESA,

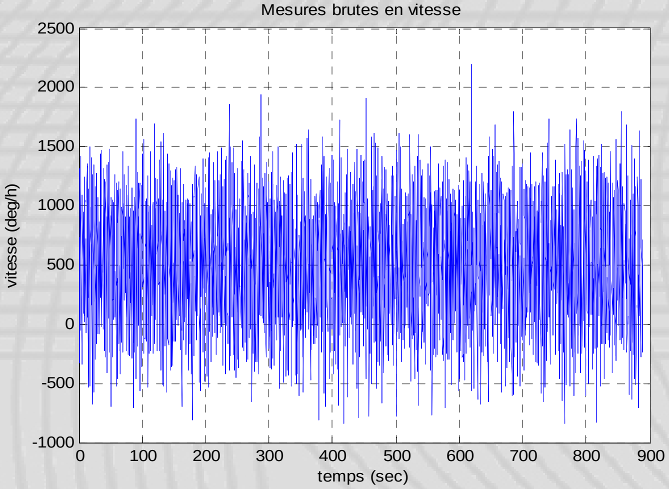
NOK : n° 10805, n° 10880 , n° 21048

ARW , in °/Vh						
	20580	**20592**	**21048**	**ESA**	**10805**	**10880**
25°C initial	0,75	0,75	0,83	0,7	1,44	1,44
25°C final	0,75	0,75	0,83	0,7	1,29	1,39

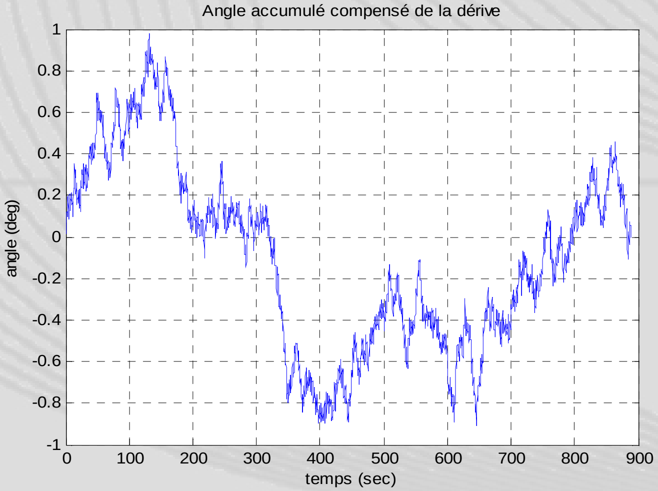
NOISE

N°20580 : ~OK

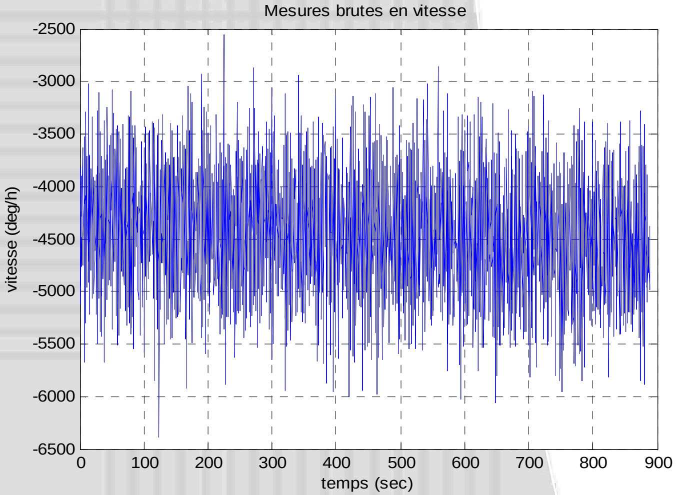
Vitesses

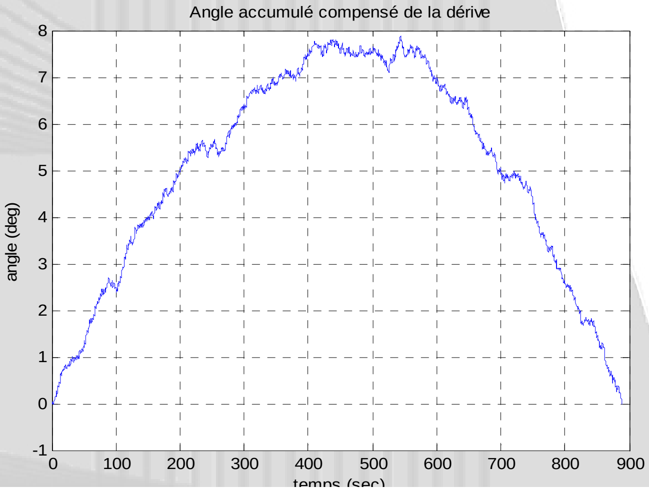

Mesures brutes en vitesse

Angles


Angle accumulé compensé de la dérive

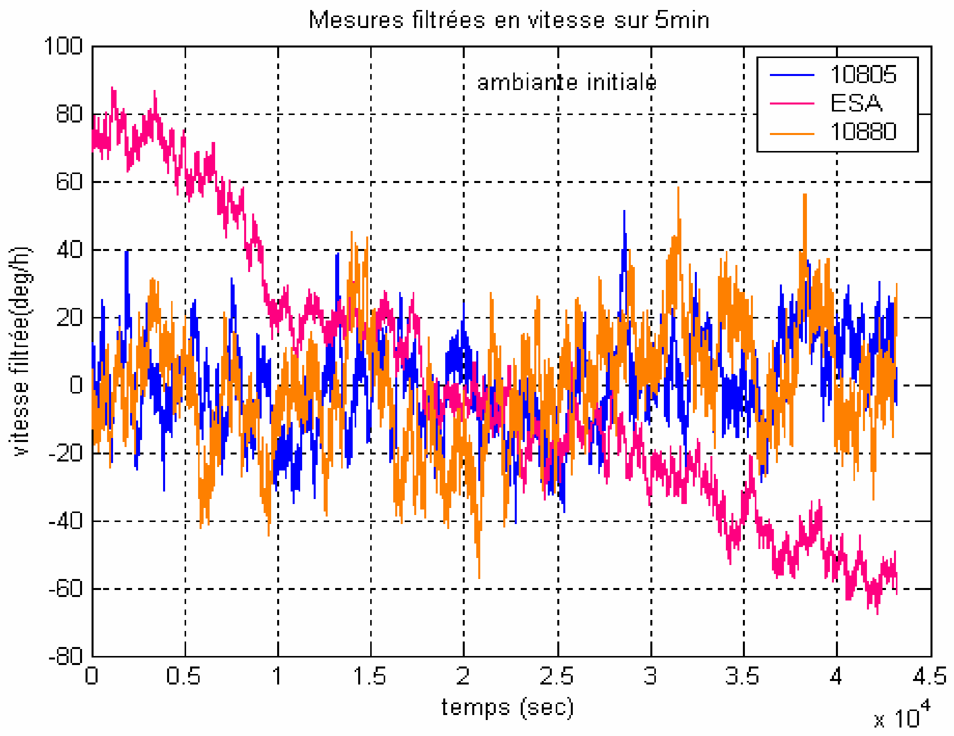
N°21048 gyro : NOK

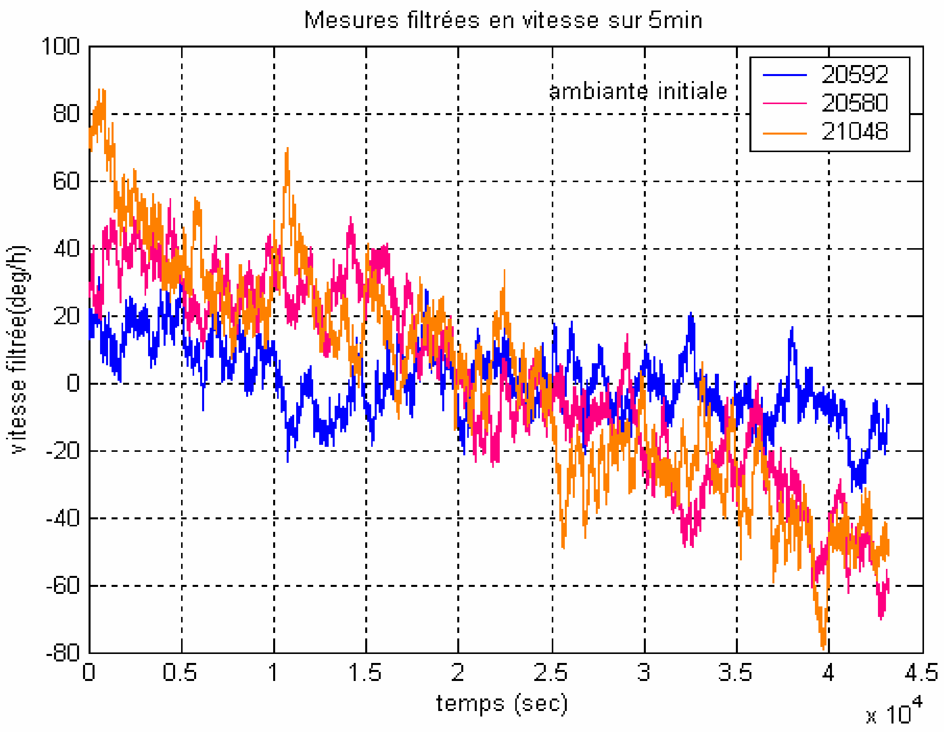

Mesures brutes en vitesse


Angle accumulé compensé de la dérive

Filtered (5 min) outputs versus time

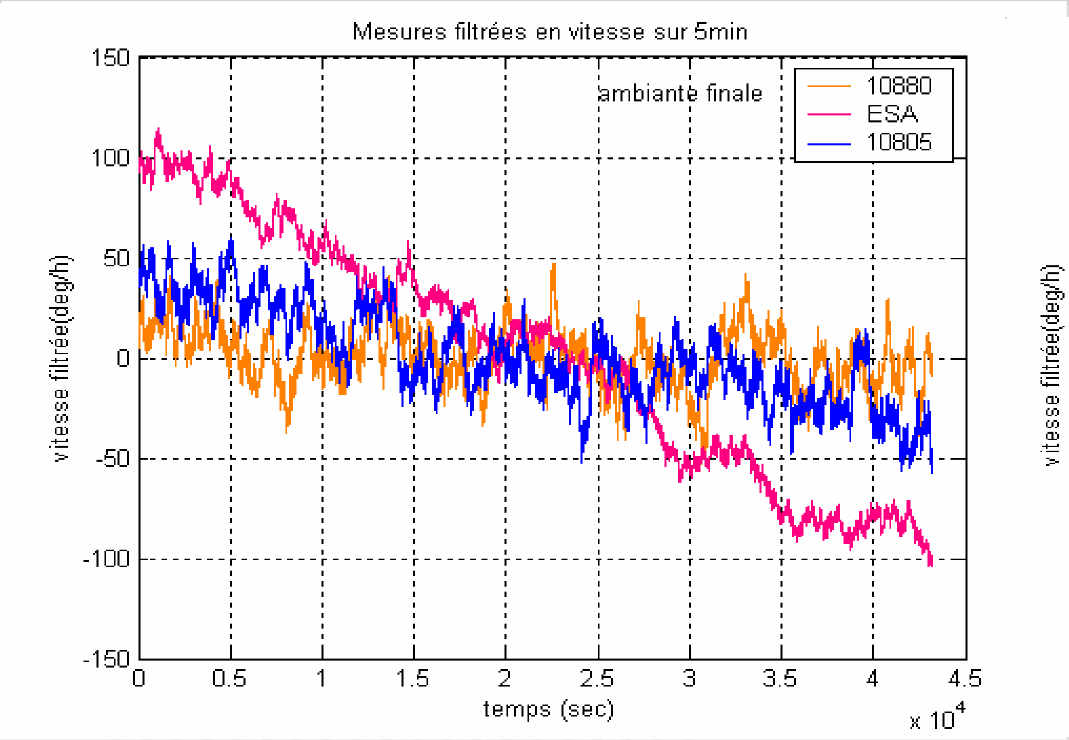
Rate variation wrt mean value



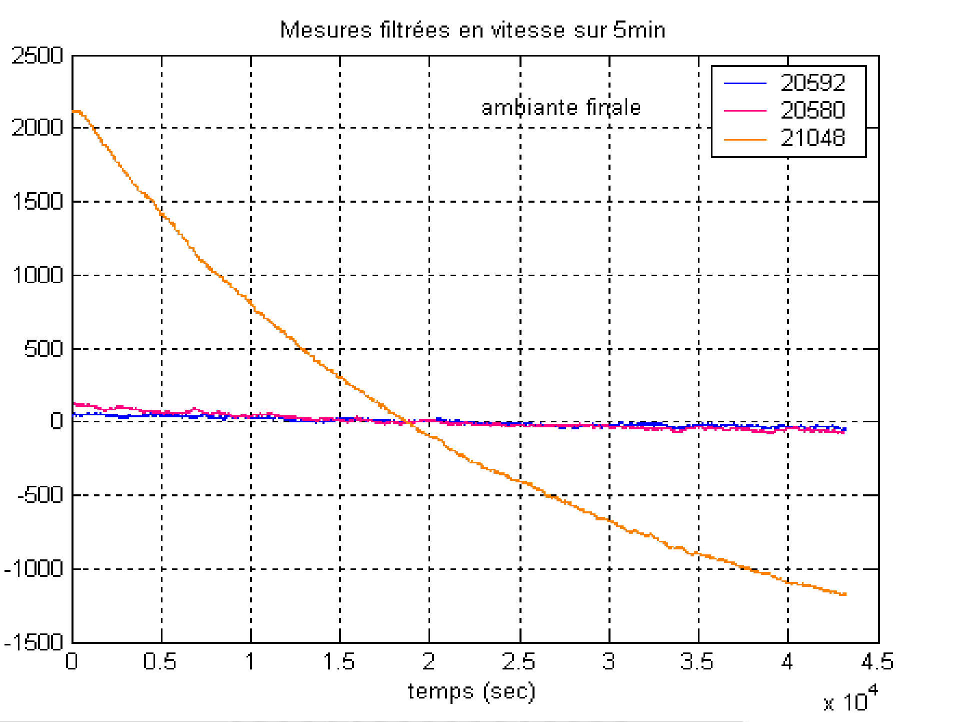


Initial tests @25°C (over 12 hours)

Filtered (5 min) outputs versus time



Rate variation wrt mean value



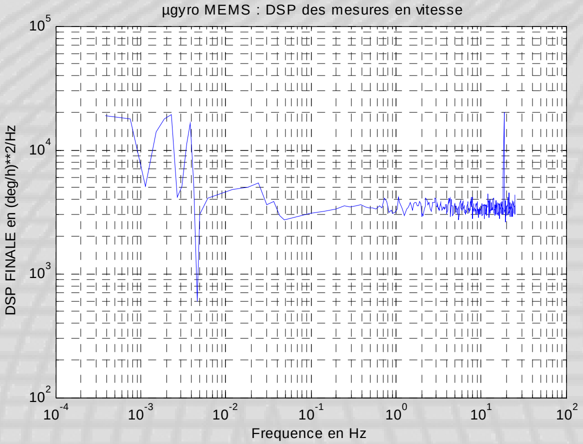
Final tests @25°C (over 12 hours)

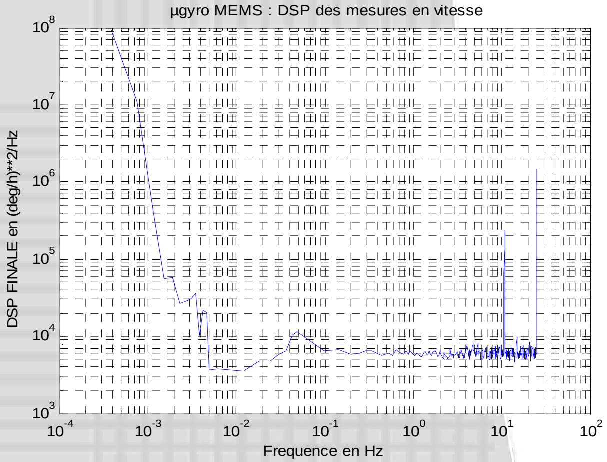
NOISE

ESA gyro : OK

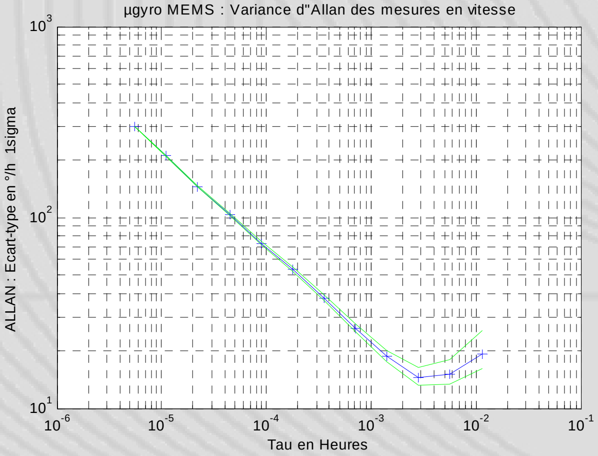
N°21048 gyro : NOK

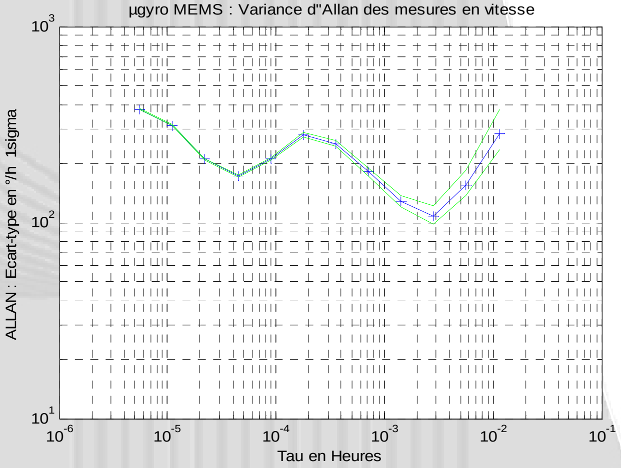
DSP





Allan Variances





Test results summary

- Initial Measurements:

  2 populations of gyro could be identified

- Mechanical environments (vibrations and shocks):

  Good survivability

  Rather low impacts on performances

- Thermal environments/thermal cycling (very severe : -55°C , +125°C) & life test @125°C:

  Important impacts on performance (at completion of testing, all gyroscopes exhibited erratic behaviour on drift)

  Failures observed

CONCLUSION

Findings:

- large disparity of the SiRSS in terms of performances, seems to be related to gyroscope disparity in terms of manufacturing (observed during Failure Analyses and additional X-Ray inspection @ Astrium); evolution of electronic design and COTS used observed
- degradation of performances was observed: erratic behaviour far above expectation (one or two order of magnitude) but difficult to associate this behaviour to MEMS or its electronics.

Follow-on discussion:

- first contacts with BAe confirmed a first set of measurements made by Astrium and acknowleged that disparity may be associated to changes in the fabrication process (use of different metallisation scheme)
- Crack identified during Failure Analysis confirmed by BAe as a possible cause of degradation (change of mechanical properties of the MEMS sensor)

Way Forward:

- New ESA activity starting with the Gyroscope Manufacturer:

Thanks to ESA ESTEC and CNES for their cooperation in this study