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SPACE QUALIFIED 5MHz ULTRA STABLE OSCILLATORS

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ESA/SCC/3501 qualified / quartz crystal resonators

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ABSTRACT

New demanding targets have been specified for on board Ultra-Stable Oscillators (USO) in the frame of new programs. The aim was to reach the highest feasible frequency stability performance over life-time, with the USO operating within all space environmental conditions.

Immediate applications are dedicated to accurate orbitography (new DORIS equipment) and frequency metrology (PHARAO/ACES project); further ones will cover fine positioning equipment (navigation or localization) and time-keeping systems.

This paper summarizes :

- Xtal qualification plan and test results,
- USO qualification test plan;
- Qualification & Flight Models data,

Main performance measured and validated on these USO models :

- aging slope better than 1.10^{-11} / day at early stage operation,
- mid ' term / **TDEV** lower than **3 ns over 24 hours**,
- short-term stability / Allan standard deviation from **5 to 7.10^{-14}/1s to 10 s**, (measured with a Sapphire reference),
- thermal stability better than 3.10^{-13} / °C,
- irradiation sensitivity below 5.10^{-13} / rad for on- board devices,
- magnetic field sensitivity below 5.10^{-13} / gauss,

USO mechanical robustness has been validated under vibration up to 30 grms (from 20Hz to 2000Hz), and shocks (200g/0.5ms).

Space USO @ 5MHz is now available with the same performance as the best CFPO-US1 ground base models with addition of all environmental conditions linked to Space applications.

INTRODUCTION

In this paper, we present the background and development leading to the qualification of a 5 MHz quartz crystal resonator for space applications. We have modified our 10 MHz space ultra stable oscillator, OUS NG, for the new developments suggested by the French Space Agency, CNES : DORIS, PHARAO, and Navigation on board clocks.
The 5 MHz ultra stable oscillator performance of the qualification model and of two flight models are analysed.

1. NEW NEEDS in VERY ULTRA STABLE SPACE USOs

1.1. DORIS Precise Orbit Determination

DORIS (Doppler Orbitography and Radiopositioning Integrated In Space) is a CNES, IGN and GRGS French space program able to very accurately determine (within 1-2 cm) the position of satellites and ground beacons [1]. The DORIS O.B. payload has been integrated into several satellites since 1990, SPOT 2 to 5 series, TOPEX, Jason 1, Envisat, and will be embarked on Cryosat, Jason 2,…. Spot series and Envisat are at 830 km, TOPEX and Jason 1 are at 1300 km. Presently, 6 DORIS O.B. payloads are in orbit, based on a one way bi frequency Doppler technique with O.B. very accurate measurements from a network of 55 ground transmitted beacons. Localization and orbitography are performed by several entities (CNES-SOD, IGN, NASA-JPL, IERS,…) [2]. The Doppler measurement precision needed to achieve the 1 cm radial orbit error is less than 0.3 mm/s or 1.10-12, including short term noise over 10s, medium term over 10 minutes, and contributions from all instruments (OB and Ground USO, transmitter and receiver). This budget allows a short and medium stability in the 10^{-14} to 10^{-13} range taking into account the space environment conditions [3].

1.2. PHARAO Cold Atom O.B. clock

PHARAO is a cold cesium atom space clock developed by CNES, based on experience gained from BNM-SYRTE, and ENS-LKB laboratories in PARIS. The Pharao frequency stability is expected to be better than $\sigma_Y(\tau) = 10^{-13} . \tau^{-1/2}$ for $\tau = 1s$ to 10^6 s. To achieve this performance necessitates a very stable USO in the 5 to 7.10^{-14} range from 1 to 10s [4].

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1.3. Navigation O.B. Clocks

In navigation systems, each satellite should broadcast all OB parameters (clocks,…) to allow users to determine their position. In Galileo, the User Range Error (URE) specification is < 65 cm (1σ) , composed of 45 cm for ephemeris error, and 45 cm (1.5 ns) for synchronization error. The 1.5 ns should be considered as the extrapolation error over TP = 6000 seconds following TM= 10^4 seconds used to determine the clock coefficient model. This necessitates a TDEV of less than 1.5 ns, or $\sigma_Y(\tau) = 2.6 .10^{-13}$ over 10^4 seconds [5].

2. SPACE USOs SPECIFICATIONS

The main requirements for DORIS and for PHARAO on board USOs are given in the table 1, taking account of the state of the art in manufacturing technologies. They are five times more rigorous, in terms of the short term stability, than at the beginning of the DORIS program [8],

The long term performance of 10 MHz on board USOs, measured by CNES using DORIS instrument in different orbital environments, is given by the figure 1 and the table 2.

The ageing is compliant with the requirement. But the short-term stability performance is not sufficient to meet the new specification [5].

Table 1 : DORIS and PHARAO O.B. USOs specifications

Parameters	DORIS USOs specs	PHARAO USOs specs
Frequency	5 or 10 MHz	5 MHz
Short term stability	$\le 1.10^{-13}$ $\tau = 10$s	$\le 1.10^{-13}$ $\tau = 1$ to 10s goal: 7.10^{-14} $\tau = 1$ to 10s
Medium term stability	$\le 1.10^{-13}$ / min over 10 min pass including noise, temperature, magnetic field and radiation	$\le 2.10^{-11}$ pp over 90 min orbit including noise, temperature, magnetic field and radiation
Long term aging	$1. 10^{-10}$ / day	$1. 10^{-10}$ / day
Phase noise L(f) in dBc/Hz	• 1 Hz N.A. • 10 Hz - 120 • 100 Hz N.A. • 1 KHz - 140 • 10 kHz - 150	• 1 Hz - 131 • 10 Hz - 147 • 100 Hz - 156 • 1 KHz - 156 • 10 kHz - 156
Temperature sensitivity	$\le 4. 10^{-10}$ pp in -15 to + 50°C	$\le 1. 10^{-11}$ pp over 0 to 48°C
Magnetic sensitivity	$\le 5. 10^{-13}$ / gauss	$\le 5. 10^{-13}$ / gauss
Radiation sensitivity	$\le 1. 10^{-12}$ / rad	$\le 1. 10^{-12}$ / rad
Acceleration sensitivity	$\le 1. 10^{-9}$ / g	$\le 3. 10^{-10}$ / g
DC power	3.5W @ 0°C in vaccum	3.5W @ 0°C in vaccum
Random vibration	20 G rms	11 G rms
Sine vibration	20 G	N.A.
Shock	300 G, 11ms	200G, 0.5 ms
Radiations	50 krad	1 krad
Reliability	300 fit	300 fit
Masse; Volume	1 kg; 1 liter	1 kg; 1 liter

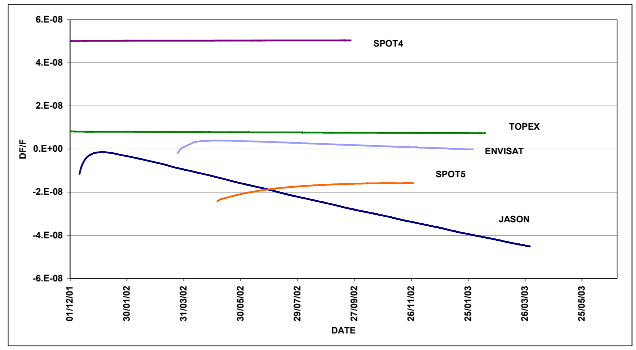


Fig. 1. 10MHz QAS flight model USOs frequency drift in orbit for different programs

Table 2 : Ageing slope per day of different 10 MHz QAS USOs in orbit

Satellite	SPOT 4	SPOT 5	TOPEX	JASON 1	ENVISAT
T0 : date of USO turn on	March 23 1998	May 4 2002	Dec 23 1998	Dec 8 2001	March 14 2002
Aging per day	+ 1.0 E-12	+ 4.2 E-11	- 1.8 E-12	- 1.0 E-10	-1.7. E-11
After	54 months	4 months	45 months	10 months	6 months

3. USOs DEVELOPMENT and SPACE QUALIFICATION

3.1. Development

We have proved that to obtain a short-term stability below 7.10^{-14}, a 5 MHz SC cut quartz crystal is more appropriate [7]. We have qualified the 5 MHz quartz resonator in a HC40 U package for space application.

With the new USO requirements, we have also adapted the electronic design to the 5 MHz crystal characteristics.

We have integrated new components to replace obsolete ones and to minimise the transfer of noise to the quartz resonator near the spectral carrier.

The components are procured with an ESA-SCC C level for flight level. The computed reliability with the application of MIL HDBK 217 F is 210 fit in a space flight environment at 50°C.

The fixing of the resonator holder is achieved by soldering. A soldering with a lower melting point than previously used was qualified. This minimises the constraints of assembling and limits the retrace and ageing. The USO mechanical structure resonances remain the same.

The other elements of the USO are the same as those in the 10 MHz USO, described in reference [6].

The figure 2 shows a photograph of the 5 MHz USO.

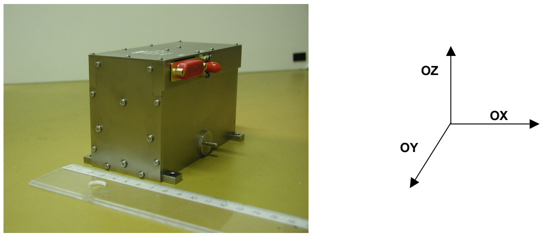
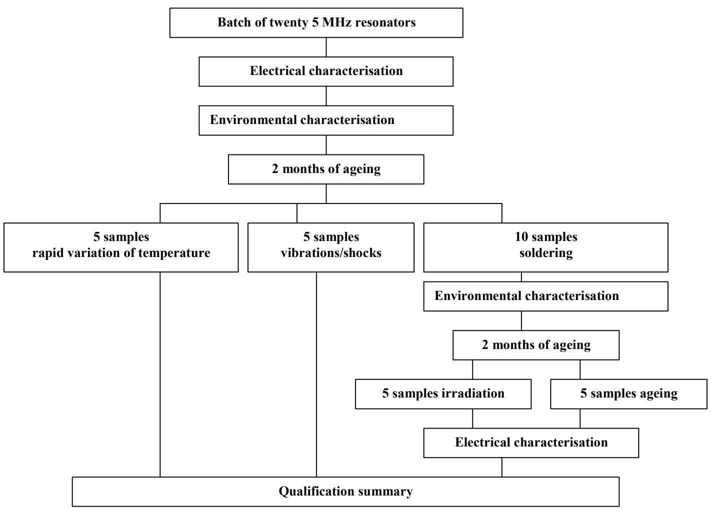


Fig. 2. 5 MHz space ultra stable oscillator with axis orientation

3.2. 5 MHz resonator qualification

For the 5 MHz resonator, the qualification was carried out following the program below:



The environmental characterisation consisted of :

- Short-term stability
- Magnetic field sensitivity
- Barometric sensitivity
- Acceleration sensitivity

300 cycles of rapid variation of temperature (RVT) were performed, from - 40°C to 100°C, with 30 minutes of stabilisation at both temperatures, with the two chambers method. The shocks applied were 300 g, 1000 g and 2000 g during 1 ms, semi-sine, six by axis.

The random vibration level was 45 g (rms) between 10 Hz to 2000 Hz.

The irradiation accumulated dose was 10 krads with a rate of 5 krad per hour.

3.2.1. 5 MHz resonator batch performances

The figures 3 to 15 and table 2 give performances results of the 5 MHz resonator batch that was used for the qualification. The 5 MHz resonator is packaged in HC 40 U holder. It is SC cut quartz crystal , third overtone, and it is mounted on four points. The average Q factor of these resonators (QHS) is 2.6 million.

The quartz material employed is the new type as presented in [7] for the 10 MHz QAS resonator. The first mechanical structure resonance is above 2200 Hz. The mechanical axis, Z, is perpendicular to the quartz blank. The axis X, Y are in the plane of the quartz blank.

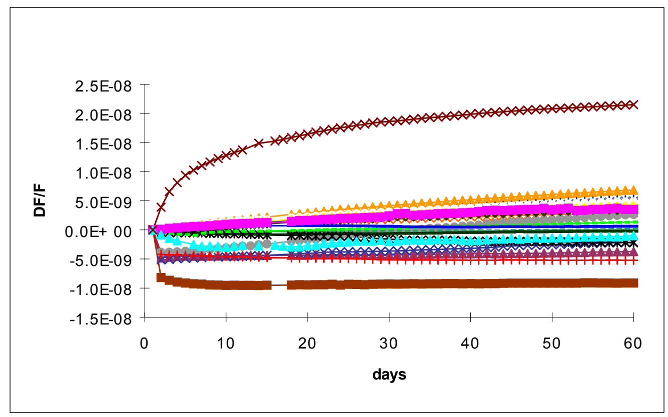


Fig. 3. 5 MHz QHS two month ageing curves

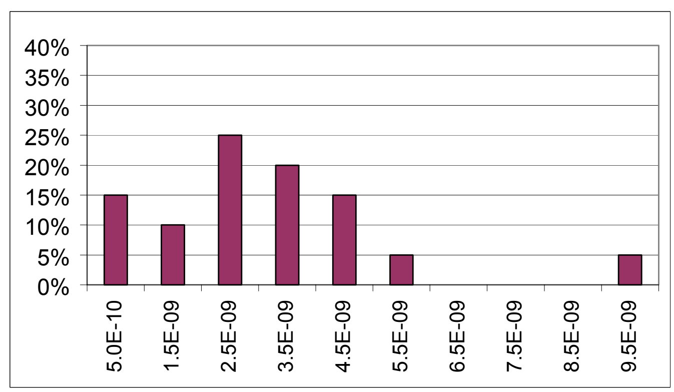


Fig. 4. 5 MHz QHS first month ageing distribution

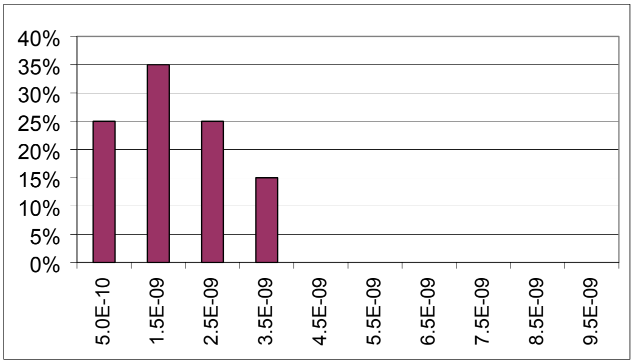


Fig. 5. 5 MHz QHS second month ageing distribution

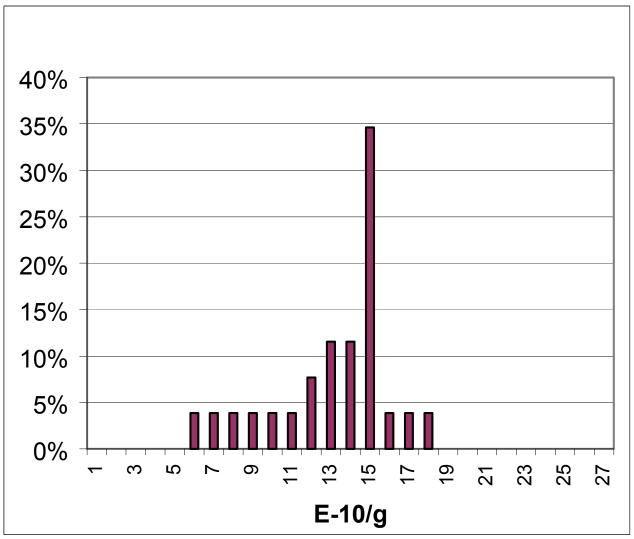


Fig. 6. 5 MHz QHS X axis acceleration sensitivity distribution

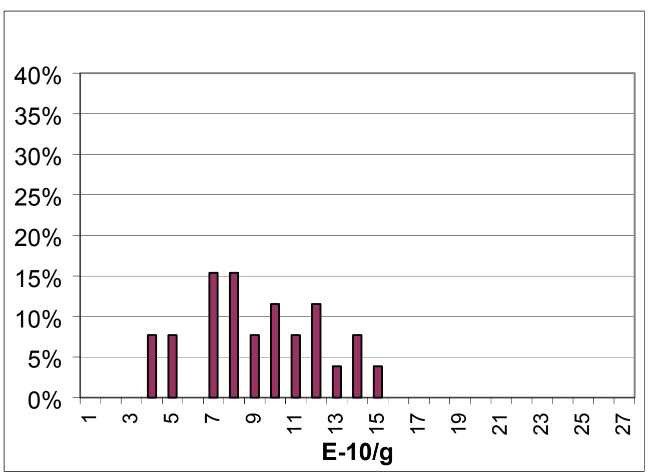


Fig. 7. 5 MHz QHS Y axis acceleration sensitivity distribution

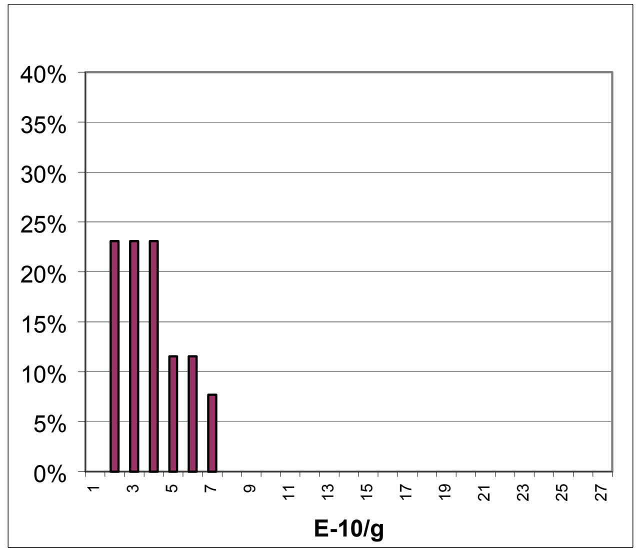


Fig. 8. 5 MHz QHS Z axis acceleration sensitivity distribution

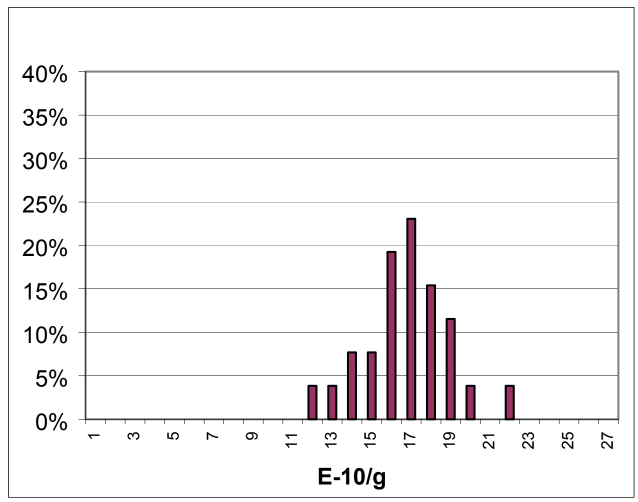


Fig. 9. 5 MHz QHS worst case axis acceleration sensitivity distribution

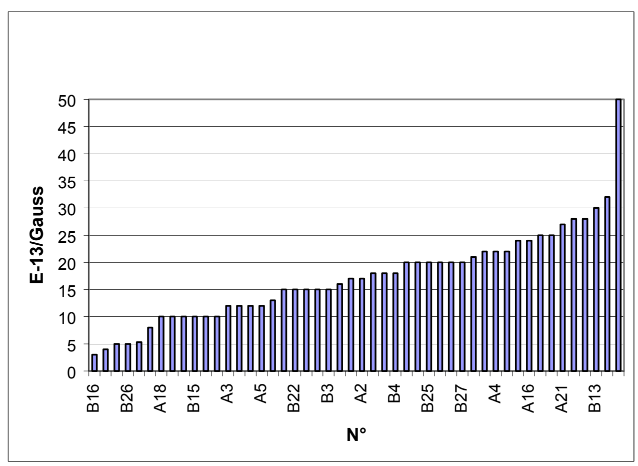


Fig. 10. 5 MHz QHS X axis magnetic field sensitivity

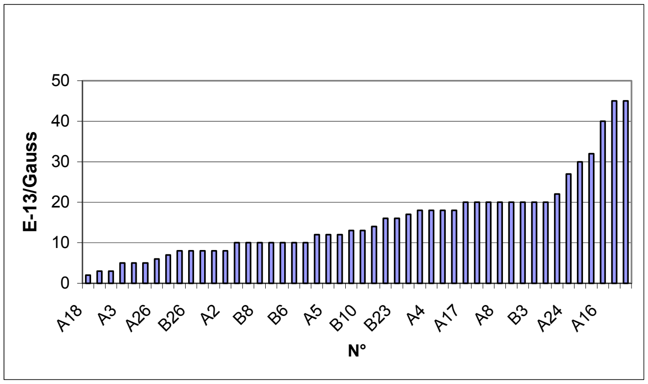


Fig. 11. 5 MHz QHS Y axis magnetic field sensitivity

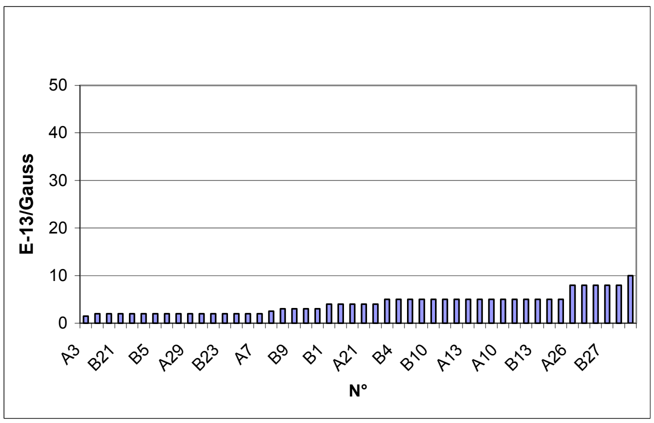


Fig. 12. 5 MHz QHS Z axis magnetic field sensitivity

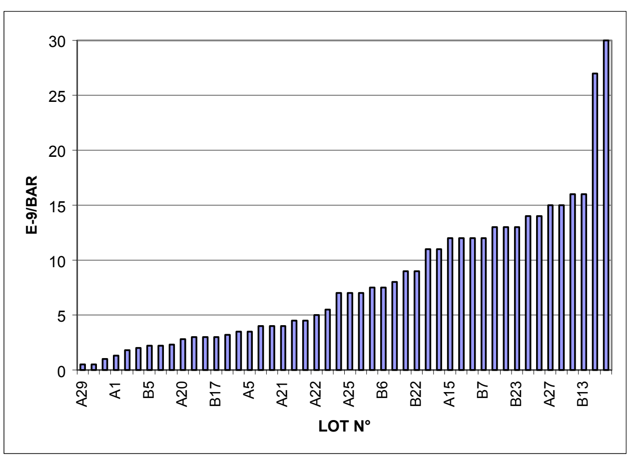


Fig. 13. 5 MHz QHS barometric sensitivity

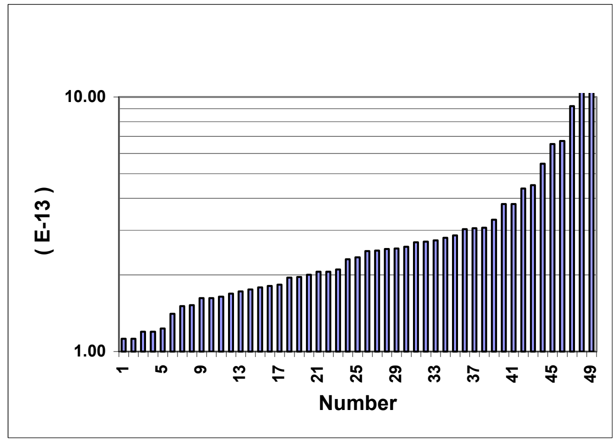


Fig. 14. QHS 5 MHz Allan standard deviation with integration time of 10s

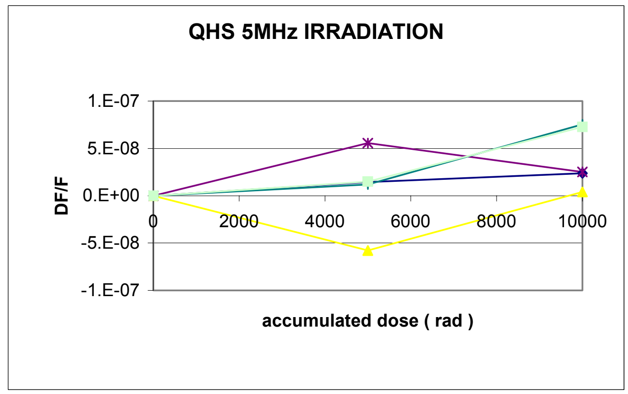


Fig. 15. 5 MHz QHS frequency versus irradiation accumulated dose with 5Krad/Hour rate

TABLE 3
5 MHz QHS irradiation sensitivity at different accumulated dose

(DF/F / rad)	DF/F/rad (at 0 rad)	DF/F/rad (at 10Krad)
mean	6.18E-12	4E-12
max	1.16E-11	7.5E-12

3.2.2. 5 MHz resonator qualification results

The maximum relative frequency drift obtained after thermal shocks cycling test was 1.6E-7. After random vibration test and 1000 g shocks test, it was below 1E-8. After irradiation exposure at 10 krad, the frequency drift is between – 8E-8 to 8E-8. The qualification was concluded with success.

3.3. 5 MHz USO Qualification

For the 5 MHz USO qualification, the USO was exposed to sine vibration (20 g peak, 2 oct/min swept up and down between 11 to 100 Hz). After that, a random vibration spectrum, as shown in figure 16, was applied during 1 minute per axis. To finish, we applied one shock (200 g sine 0.5 ms) along the six directions.

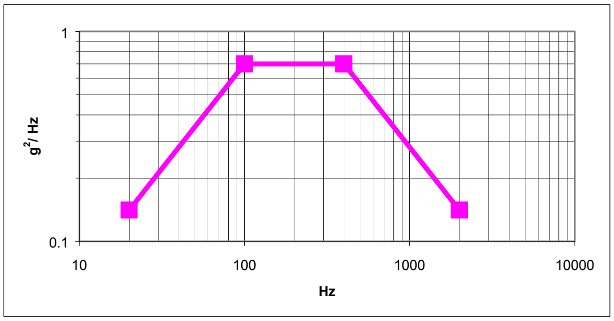


Fig. 16. Random vibration spectral density (30 g rms)

During the vibration test, the USO was operable and put on a shaker in our vibration bunker as shown in figure 17. The figures 18, 19 and 20 give the phase noise measurement during random vibration on the three axes. The axes are as presented in figure 2. We can see the USO structure resonances at 400 Hz and 1500 Hz and the resonator structure resonance at 2800 Hz and 3500 Hz.

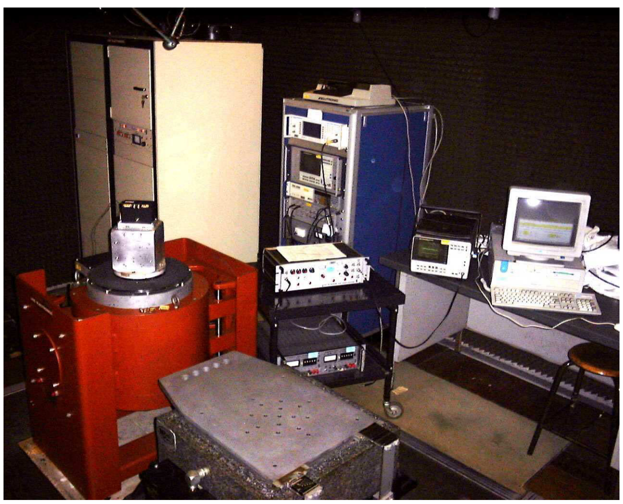


Fig. 17. USO mounted on the shaker during vibration test

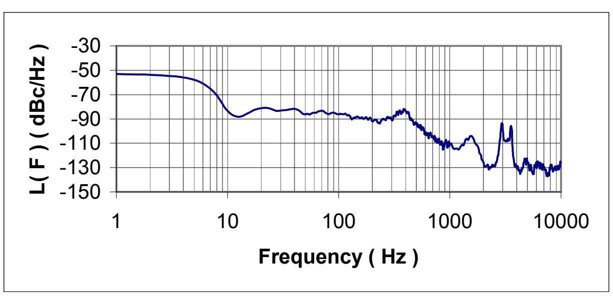


Fig. 18. MIQ 33 Phase noise under 30 grms random vibration on axis X

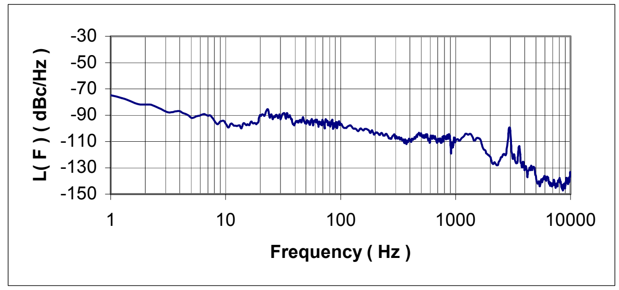


Fig. 19. MIQ 33 Phase noise under 30 grms random vibration on axis Y

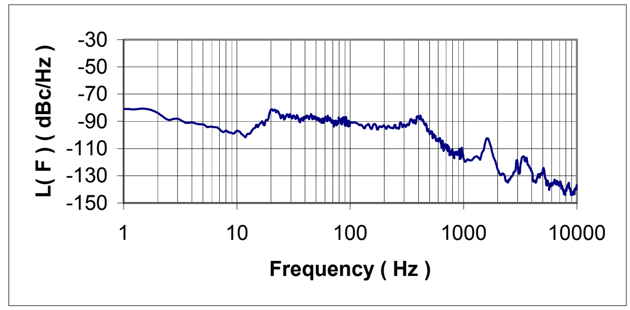


Fig. 20. MIQ 33 Phase noise under 30 grms random vibration on axis Z

4. 5 MHz USO PERFORMANCES

One qualification model, MIQ 33, and two PHARAO flight models (FM34, FM35) were measured.

The typical frequency drift versus temperature under vaccum is shown in the figure 21, the thermal sensitivity of frequency is about 3.10^{-13}/°C.

The time delay (TD) is typically 300 ns over a 24 hour period as shown in figure 22.

The time internal error standard deviation between the time delay and a quadratic model over 24 hours is with in 1 ns to 3.4 ns and that is with 4°C of temperature cycling (Fig. 23). The double side band phase noise density, L (f), is just on the PHARAO specification (Fig. 24). Nevertheless, the short-term stability between 1s to 10s with temperature variation (Fig. 25 and Fig. 26) is below to 1.10-13. That was confirmed by the measurement at BNM-SYRTE. The measurement bench (Fig. 27) used a cryogenic sapphire oscillator with a good stability (below 1.10^{-14} between 1 s to 100 s). The results for flight models FM 34 and FM 35 are better than expected (Fig. 28 and Fig. 29). The performance of these 5 MHz USOs are compliant for DORIS and PHARAO applications.

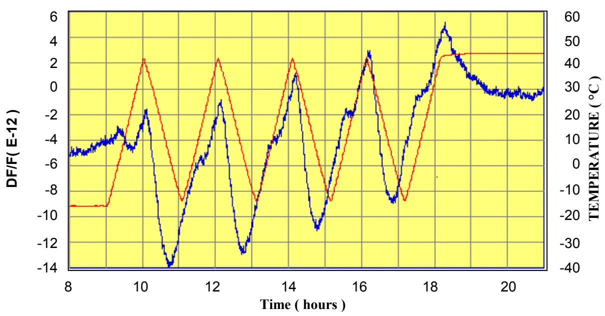


Fig. 21. Typical frequency drift versus temperature under vacuum

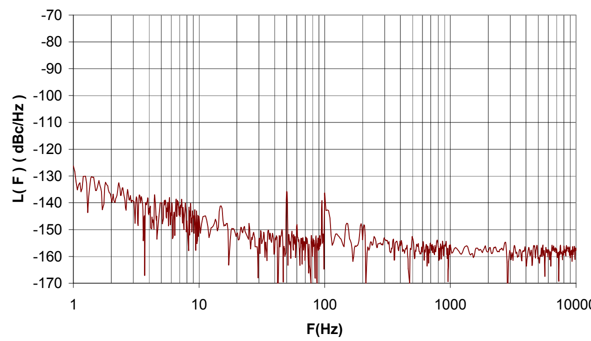


Fig. 24. MIQ 33 double side band phase noise density L(f)

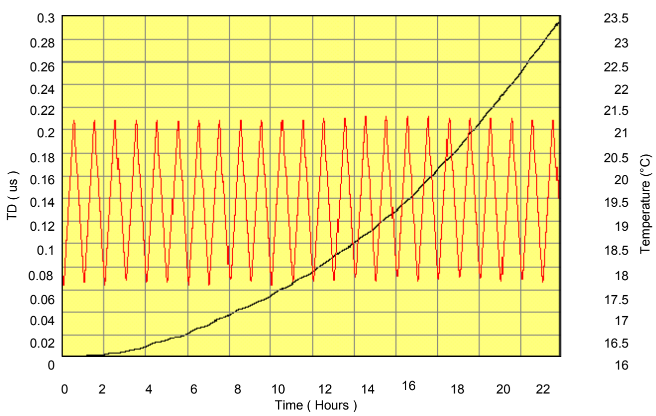


Fig. 22. Time delay during 24H with 4°C of temperature cycling and under vacuum

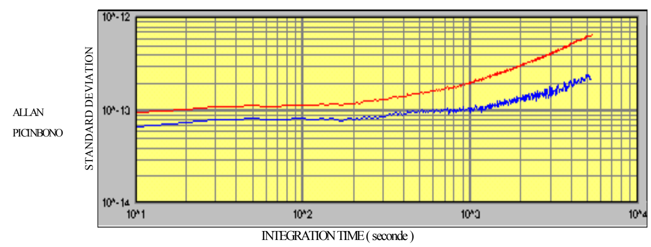


Fig. 25. Allan and Picinbono standard deviation with an integration time between 10s to 10000s

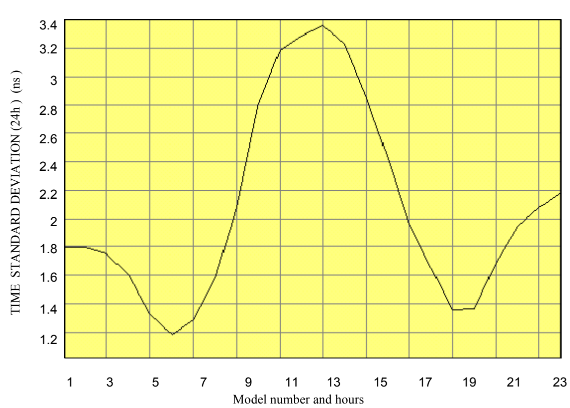


Fig. 23. Time interval error standard deviation between time delay curve and quadratic 24 hours model for 24 tests shifted of 1 hour

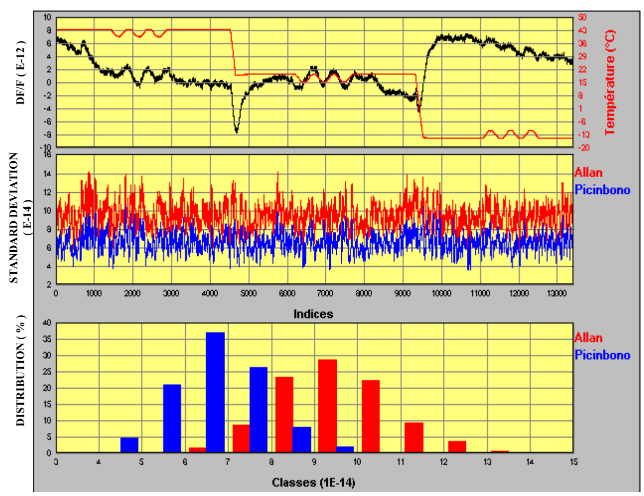


Fig. 26. MIQ 33 Allan and Picinbono standard deviation with an integration time of 10s and during temperature variation of 60°C

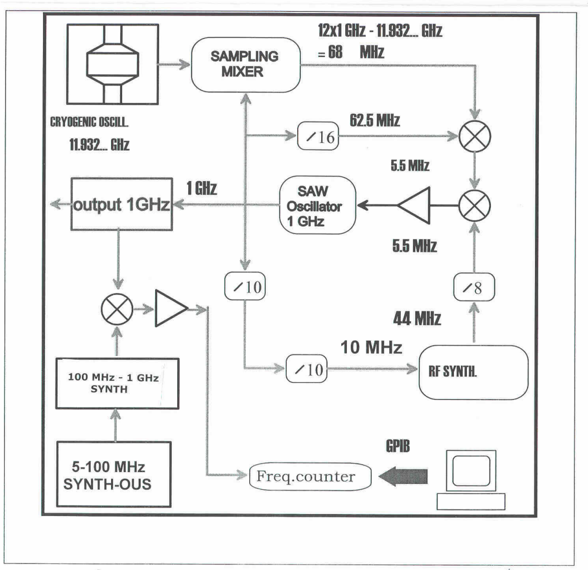


Fig. 27. BNM SYRTE short-term measurement bench synopsis with a cryogenic sapphire oscillator as frequency reference

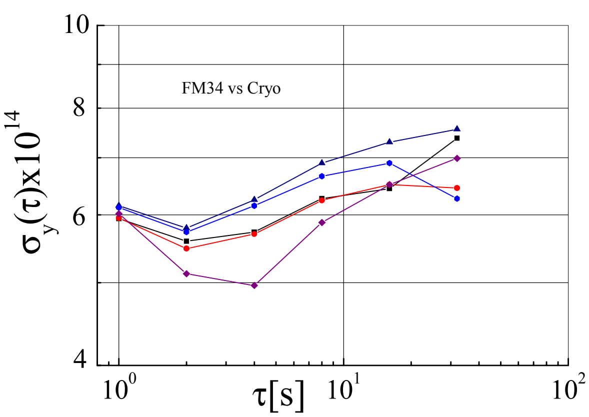


Fig. 28. PHARAO FM34 Allan standard deviation with an integration time between 1s to 100s

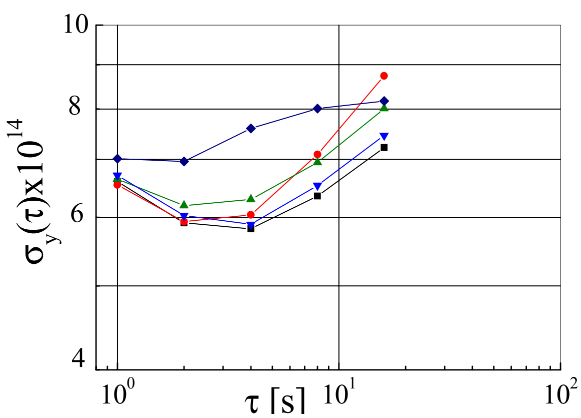


Fig. 29. PHARAO FM 35 Allan standard deviation with an integration time between 1s to 100s

CONCLUSION

The 5 MHz resonator and the 5 MHz USO were qualified for space applications, which require very low phase noise, frequency stability of a few 10^{-14} from 1s to 10s and very low environment sensitivities. Two flight models have been delivered to the PHARAO team and the new USO will be embarked on the DORIS on board equipment. Some actions are underway to increase the productivity of these products. To reduce the acceleration sensitivity of this 5 MHz quartz resonator, a BVA 4 (QAS) structure in a HC40U holder is being studied.

ACKNOWLEDGMENTS

We would like to thank the BNM-SYRTE for their time during the testing of several PHARAO USOs including the flight models. We would also like to thank the CNES DORIS team for providing us all the input data and in orbit OB drift data.

REFERENCES

[1] M.Brunet, "Doris precise orbit determination and localization system performances of Ultra Stable Oscillators" - 6th EFTF, march 1992

[2] M.Brunet, "Doris precise orbit determination and localization system description and USOs performances" - IEEE Frequency Control Symposium 1995

[3] M. Brunet, A. Auriol, J.P. Berthias, M. Costes, J.K. Issler, P. Sengenes, "DORIS precise orbit determination and localization - Performances in orbit and preliminary studies of DORIS-NG", 11th European Frequency and Time Forum Neuchâtel - March 1997.

[4] Ph.Laurent, E.Simon, G.Santarelli, A. Clairon, Ch. Salomon, P. Lemonde,P. Petit, N. Dimarcq, C. Audoin, F. Gonzalez, F. Jamin Changeart, "PHARAO: A Space clock with cold cesium atoms ", Proceedings of the 26 th Precise Time and Time Interval, Washington (USA), 1996.

[5] V. Candelier, G. Marotel, D. Thorax, C. Trialoup, ''Cost Effective Time and Frequency Reference'', Proceedings of the 31st Annual PTTI - December 1999.

[6] V. Candelier, J. Chauvin, C. Gellé, G. Marotel, M. Brunet, R. Petit, ''Ultra Stable Oscillators '', Proceedings of the 12th EFTF, March 1998.

[7] Vincent Candelier, Patrice Canzian, Jacques Lamboley, Gérard Marotel, Pierre Poulain, "State of the art in ultra stable oscillators for accurate/precise on board and ground applications" - IEEE International Frequency Control Symposium.Proceedings 2001

[8] André Debaisieux, Jean Pierre Aubry, Evelyne Gérard, Michel Brunet , "A satellite oscillator for very precise orbitography the DORIS program" , 39 th Annual symposium on frequency control proceedings. Philadelphia, 1985