MINCOR - Minimisation of crystal oscillator cosmic radiation effects

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INTRODUCTION

Quartz crystal oscillators for Space applications, due to their specific features, give high signal spectral purity, very good short-term and long-term frequency stabilities. These features are required in Navigation systems, science but also radar and telecom applications. As “timekeeper”, quartz crystal oscillators are designed to minimize their sensitivity to the environment and one of them is the ionizing radiation which generates frequency drift (short-term and long term).

To ensure that the quartz crystal oscillators are achieving the required level of performance for every space application and remain in its specifications during the duration of the satellite mission, resonators are manufactured using specific processes. These processes may add additional costs or delays.

In the traditional space sector, mainly in GEO with long missions, the heritage and the reliability of the components are the drivers of their selection process. However, with the emergence of New Space, low-cost LEO satellites are now designed. The selection of the components is a key driver and it is required to design oscillators using quartz crystal resonators manufactured at the right cost while achieving the targeted performance.

It is in this frame that the project MINCOR, funded by ESA, was started. It aims to bind the real needs and the right processes. It aims also to identify potential improvement paths for reducing the radiation sensitivity.

This paper follows and concludes the work presented at SPCD 2024 [1].

REMINDER

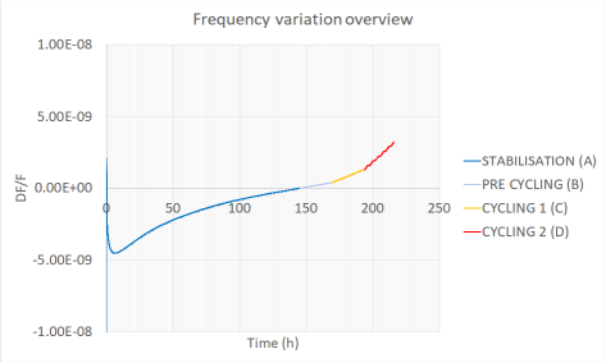
Radiation may affect the resonator and oscillator performance (essentially frequency variations) in different manner considering Dose Rate, Total Ionization Dose (TID) or Total Non-Ionizing Dose (TNID). In the study, a quite exhaustive analysis of the space environments was done with different missions. Several orbits and durations were considered based on existing space projects.
After reviewing, in the design or process of the resonator, the potential root causes of resonators radiation sensitivity, different manufacturing options were considered. Based on this analysis, 15 groups of 10, 50 or 100MHz resonators with different design and process options were defined. In total, 200+ resonators were produced on RAKON ESCC 3501 qualified line with all corresponding data packages. In each group, 4 pieces were selected as considered to be representative of their corresponding group leading to 60 resonators in total available for analysis (24x 10MHz, 32x 100MHz and 4x 50MHz).
A test plan was proposed consisting of successive gamma rays low dose rate (LDR) cycling measurements in oscillator and high dose radiation depositions on the resonator to see resonator sensitivity and its evolution,
A test system was developed consisting of oscillators designed to permit applying radiation of the resonator only, a moveable lead wall permitting the radiation cycling ON/OFF for LDR assessment and a frequency measurement bench permitting the measurement of the frequency during the radiation cycle.

COURSE OF ACTIVITIES

Tests were performed over a quite long period and were adjusted as per the initial results to improve the sensitivity of the measurement. Especially, the initial 1-day stabilisation period before LDR test was extended to 1 week. In total, 108 oscillator measurement tests under LDR were conducted, all 60 resonators were submitted to TID, however instead of 60krad applied in two steps, after discussion with project stakeholders, 100krad in one step was applied. Frequency variation due to 100krad radiation was assessed furthermore the most relevant resonators (24 pieces) were measured once again in LDR after TID to see the evolution of this sensitivity.

RESULTS

As a basis for the presentation, a very typical example of frequency monitoring during the Low Dose Rate Sensitivity assessment is presented in Fig. 1, 2 and 3 for oscillator n°1 @ 10MHz.
In this example, the gamma ray, as seen from the part, was set to 6 rad/h. The frequency was measured during 7 days with the moveable lead wall placed in front of the gamma ray. It must be noticed that the lead wall is not fully opaque to gamma rays and a radiation of 10% remains behind the wall.
The one-week period permits to stabilize the part before switching to irradiation cycling. Two cycles were then performed consecutively. The first one consisted of 20 minutes irradiation (referred as irradiation ON) followed by 100 minutes no radiation (referred as irradiation OFF). 11 cycles were performed for a total duration close to 24 hours.
The second one consisted of 120 minutes ON and 120 minutes OFF, 5 and a half cycles were performed over approximately 22 hours.
In the analysis, the last 24 hours of the stabilization were isolated to extract the frequency slope just before the cycling periods. This led to 4 periods (Fig. 1 left): Stabilisation (A), Pre-Cycling (B), Cycling 1 (C) and Cycling 2 (D).
Period B, C and D can be drawn on the same graph taking each period initial point as reference for time and relative frequency change (Fig. 1 right). Linear trend can be drawn.



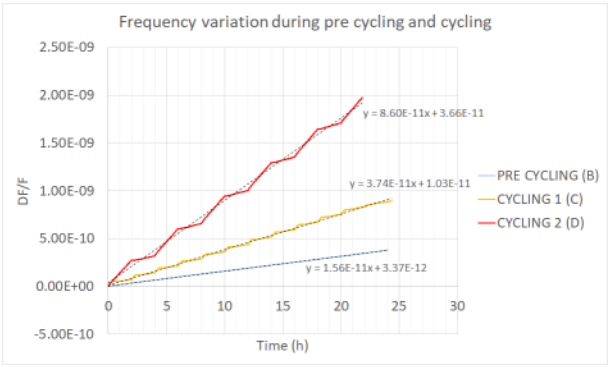
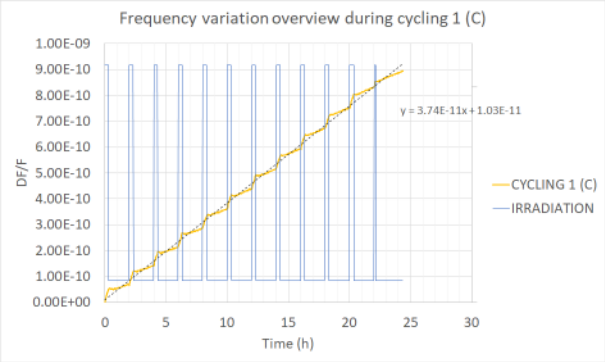


Fig. 1: Frequency variation overview (left) and slopes comparison (right) for Osc. 10MHz n°1

On these graphs it can be seen a linear trend that is, furthermore, cumulative i.e. after stopping the radiation the frequency does not come back to its previous value.
Cycling period C and D can be drawn separately along with the indication of radiation ON and OFF (Fig. 2).



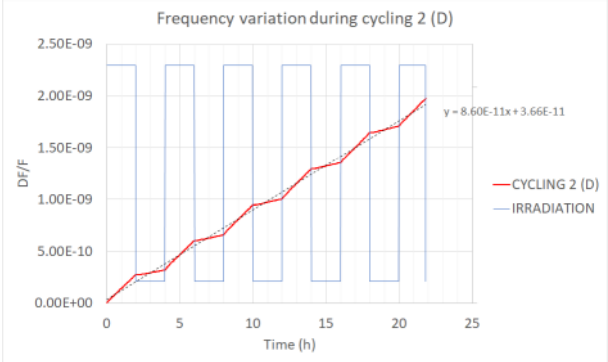


Fig. 2: Frequency variation during irradiation cycling 1 (left) and 2 (right) for Osc. 10MHz n°1

At last, every single ON or OFF section of each cycling period can be drawn on the same graph using their initial point as reference for time and relative frequency change (Fig. 3). Linear trends can be drawn.

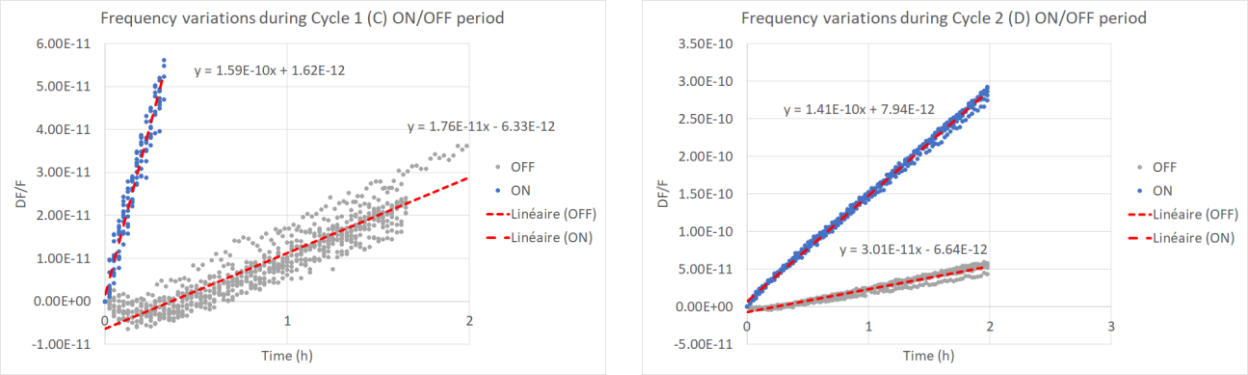


Fig. 3: Frequency variation during ON/OFF periods for cycle 1 (left) and cycle 2 (right) for Osc. 10MHz n°1

Based on data presented in Fig 1 right, frequency slope can be assessed to a mean value of 1.56e-11/h during the pre-cycling period (B), 3.74e-11/h during the cycling period 1 (C) and 8.60e-11/h during the cycling period 1 (D).

Considering that the lead wall is not fully opaque to gamma ray (10% transparency), it means that during the pre-cycling period the part is subjected to 0.6rad per hour constantly. During the cycling period 1, the part is subjected to 6rad/h during the ON part of the cycle (20min) and 0.6rad/h during the OFF part (100min). This means a mean value of 1.5rad/h. The same reasoning for the cycling period 2 leads to 3.3 rad/h in average.

On this basis, converting the relative frequency variation per hour in variation per rad leads to 2.60e-11/rad for the period B, 2.51e-11/rad for the period C and 2.58e-11 for the period D.

Additionally, based on data presented in Fig 3, during the cycling period 1, the mean relative frequency slope is 1.59e-10/h when irradiation is ON and 1.79e-11 when it is OFF. Similarly, during the cycling period 2, the mean relative frequency slope is 1.41e-10/h when irradiation is ON and 3.01e-11/h when irradiation is OFF. Converting these values in relative frequency variation per rad, leads respectively to 2.51e-11/rad, 2.63e-11/rad, 2.35e-11/rad and 4.55e-11/rad.

All these results are very consistent with each other and tends to demonstrate that the apparent time to stabilize the part (Period A and B) is mainly due to the remaining radiation behind the lead wall.

This can be seen also when we draw the mean frequency slope during cycling vs mean frequency slope during precycling for different resonators.

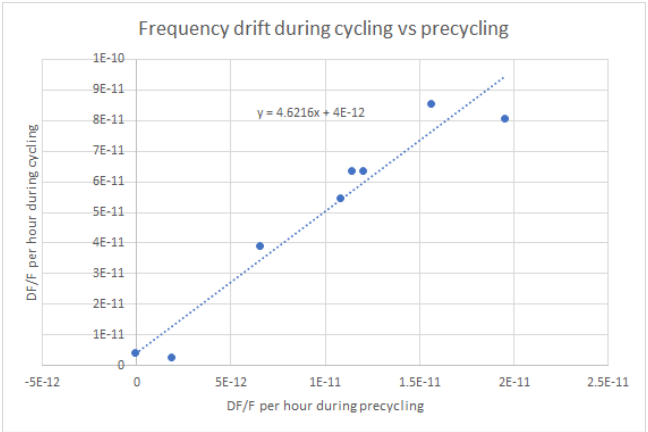


Fig. 4: Frequency drift correlation between pre-cycling (B) and cycling 2 (D)

During the first phase of the study a lot of measurement were done (84 in total). The cumulative phenomenon presented above exhibits different amplitudes and, when measurable, the effect is mainly positive.
However, the very typical result presented above for Osc. n°1 is not always so linear. As example, in the Fig. 5 is presented the Cycling period 1 and 2 of Osc. n°2 at 10MHz.

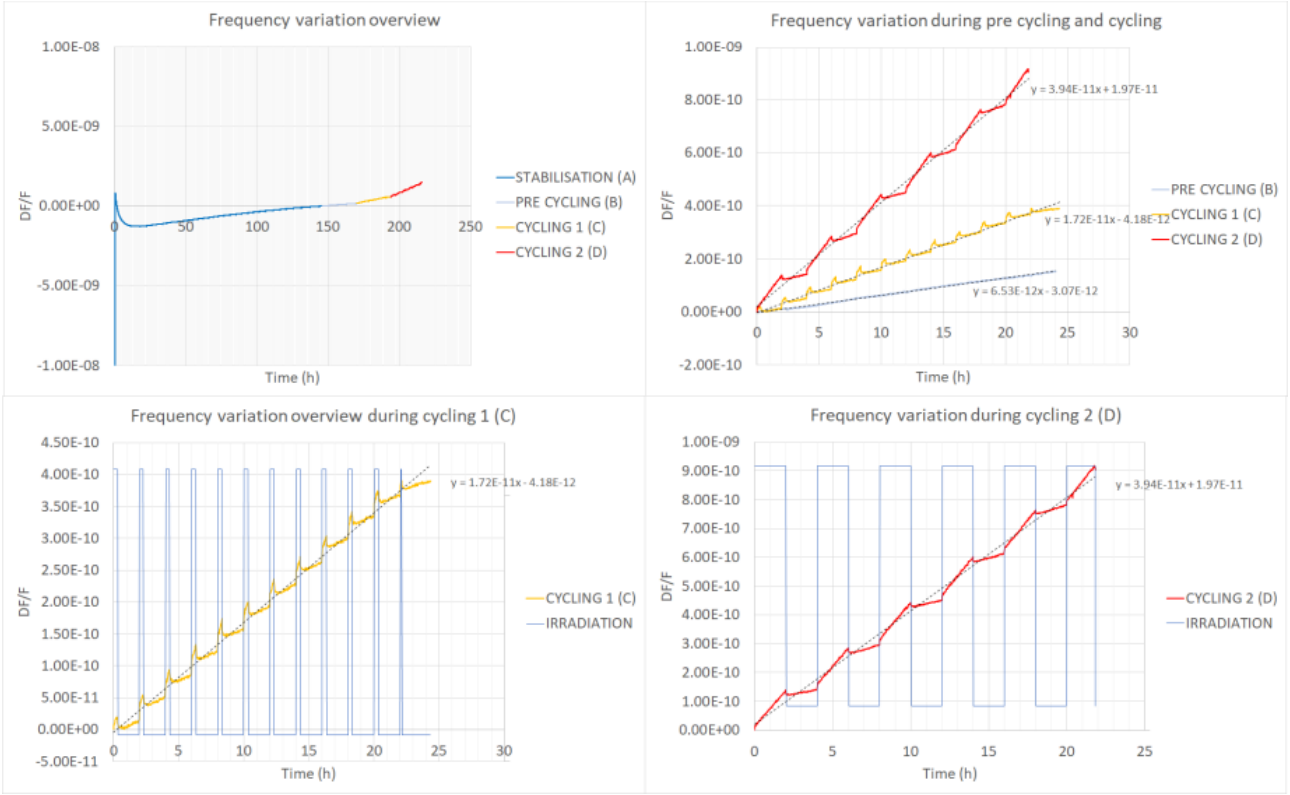


Fig. 5: Frequency variation during stabilization and irradiation cycling for Osc. 10MHz n°2

In this example, as for Osc. n°1, a positive, cumulative and quite constant linear frequency drift occurs during the radiation. However, superimposed on this main phenomenon, a specific positive and sudden frequency drift is occurring in the early stage of the ON period. On the contrary to the previously described effect this phenomenon is not cumulative i.e. the frequency comes back in relaxation-like behaviour within few minutes. The effect seems also to saturate as the frequency shift is the same for cycling 1 and 2 (around 2.5e-11 in this example). This effect is remarked on some resonators and can be positive or negative.

When negative, this effect if superimposed on a positive cumulative phenomenon will lead to quite jagged curves as presented on Fig. 6 for Osc n°11.

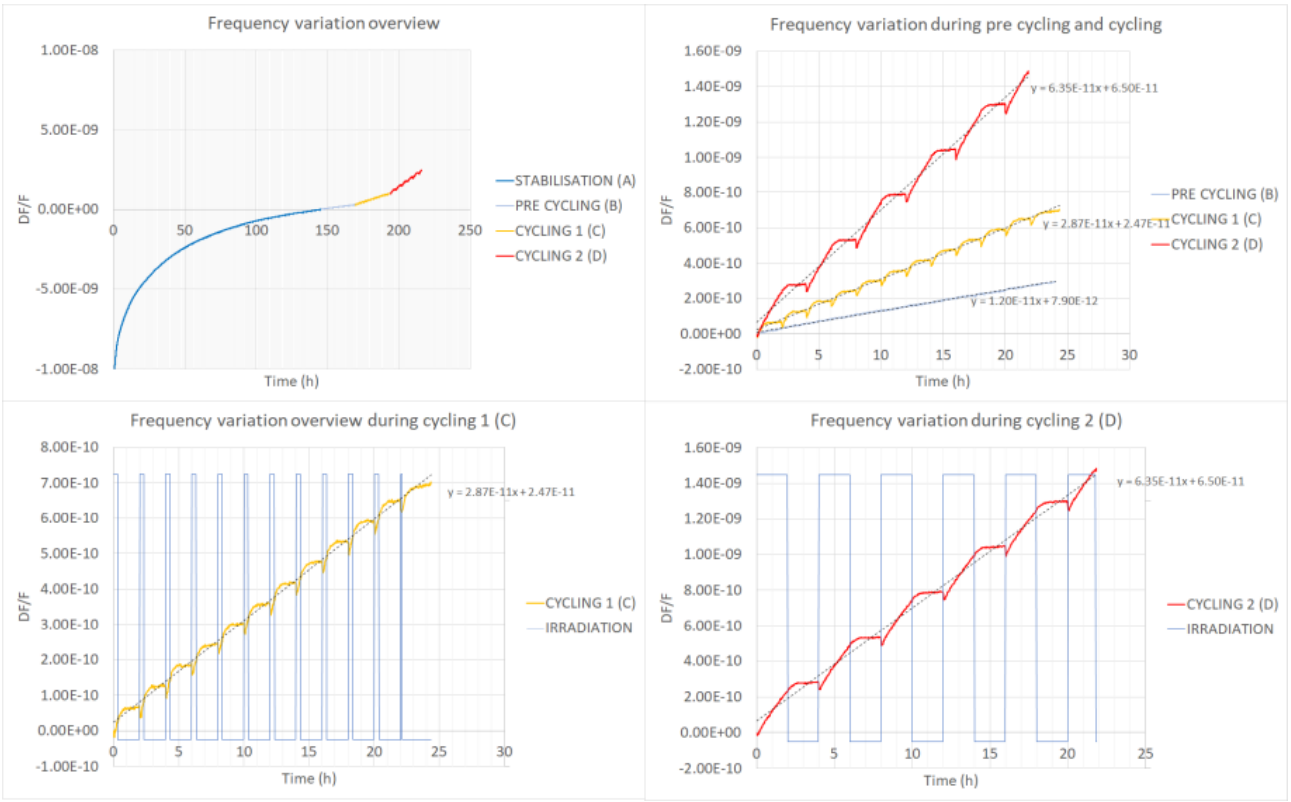


Fig. 6: Frequency variation during stabilization and irradiation cycling for Osc. 10MHz n°11

At last, in some cases the first main behaviour is not cumulative. This can be seen on Fig. 7 below for Osc. n° 5 at 10MHz.

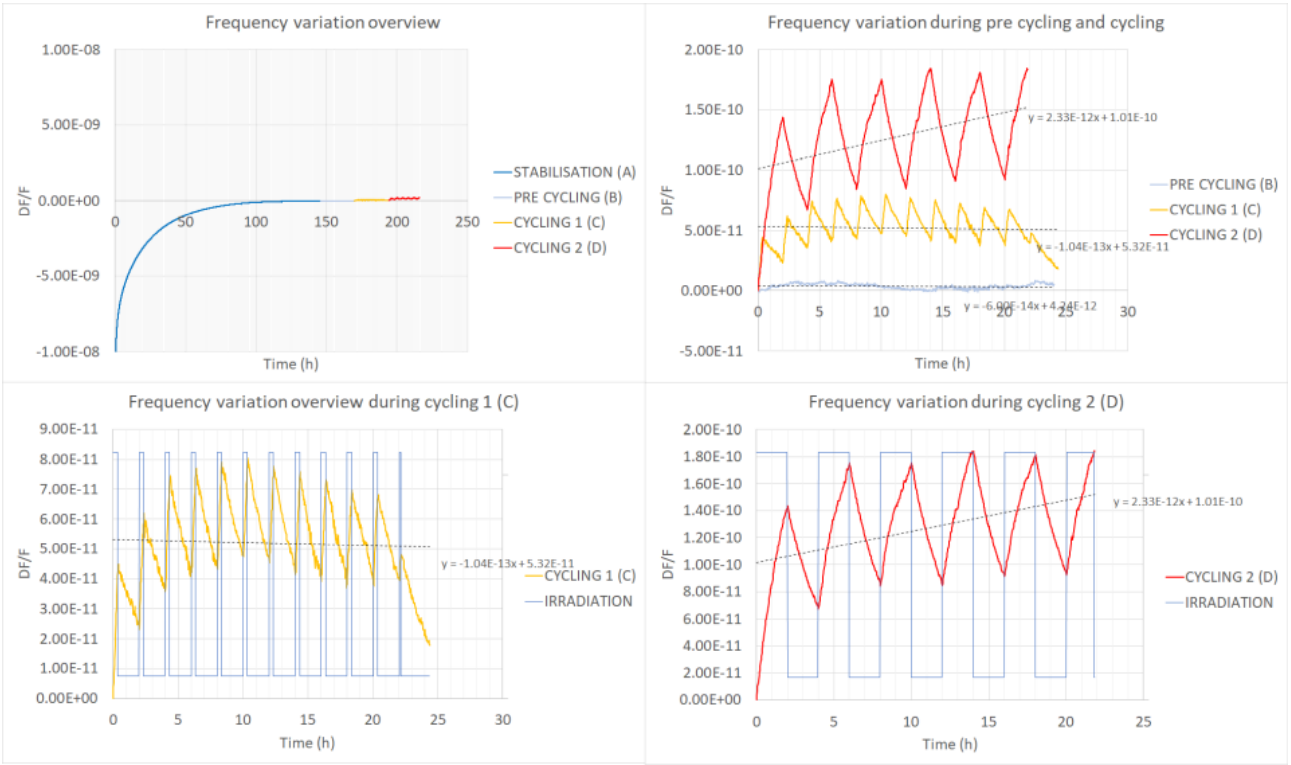


Fig. 7: Frequency variation during stabilization and irradiation cycling for Osc. 10MHz n° 5

In the above case, the frequency is rising during the ON period but comes back during the OFF period and the drift during this OFF period will compensate the drift during the ON period as presented on Fig. 8.

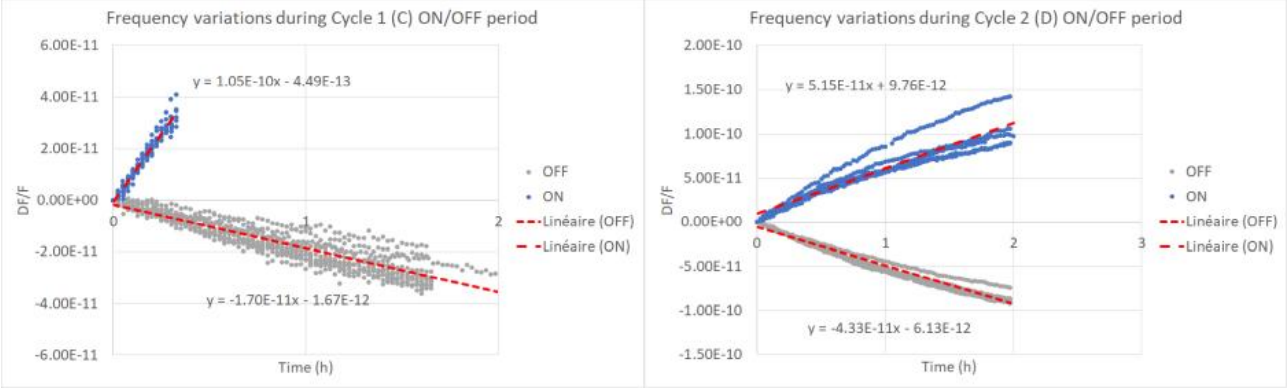


Fig. 8: Frequency variation during ON/OFF periods for cycle 1 (left) and cycle 2 (right) for Osc. 10MHz n° 5

At this level, the phenomena are not linear hence, depending on the duration of the ON cycle, the equilibrium is not reached with the same ON/OFF slopes. To be noticed that, before TID radiation, the non-cumulative behaviour is seen on quartz resonators made of swept materials.

For 10MHz resonators, the sensitivity to LDR is visible, with the specificities as described above, for all 24 parts whatever the material or process used. On the contrary, the effect is neither visible for 100MHz 5th overtone HC35 xtals nor for 50MHz 3rd SMD that were produced in the study as presented in Fig. 9 for Osc. 4 @ 100MHz and Osc. 4 @ 50MHz.

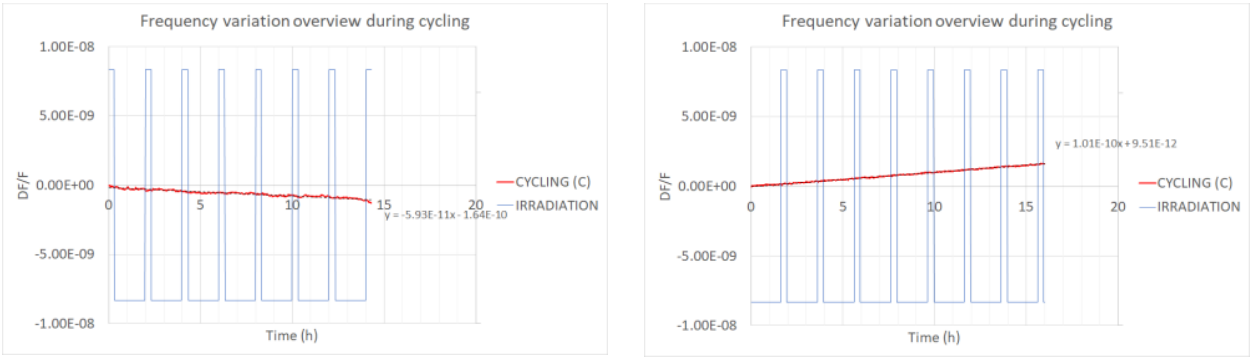


Fig. 9: Frequency variation during ON/OFF periods for Osc. 100MHz n°4 (left) and Osc. 50MHz n°4 (right)

As mentioned earlier, all parts were subjected to 100krad however, it must be noticed that the resonators were unmounted from the oscillator before TID to avoid affecting the oscillator. Resonators were mounted on a plate and submitted to a rate of 220rad/h during roughly 20 days (Fig. 10)

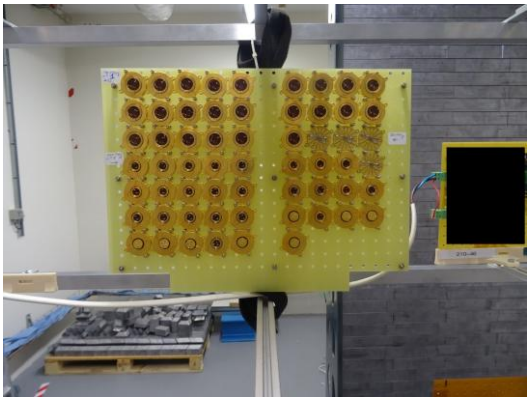


Fig. 10: Board with 60 resonators for 100krad TID

Comparison of the frequency before and after the 100krad TID could be done and calculation globally shows frequency variations that remain below few 10e-12/rad.

Because of the absence of visible LDR sensitivity of 50 and 100MHz, only the 10MHz were remeasured once again in LDR cycling (after being remounted in their respective oscillator).
After TID, all the parts are presenting an improvement in their LDR sensitivity, furthermore, and more noticeably, the effect of radiation becomes non-cumulative and may present a change of slope as compared to the effect before TID radiation (Fig. 11)

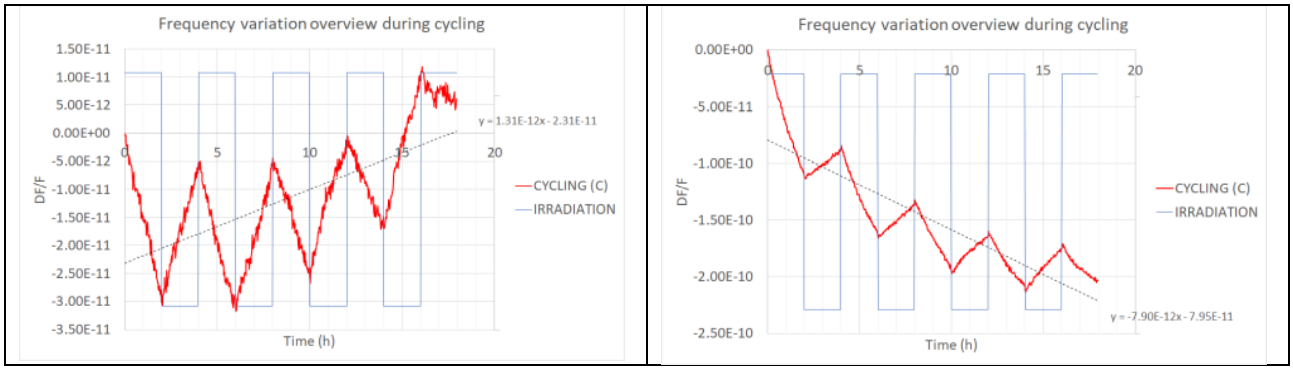


Fig. 11: LDR sensitivity after TID for Osc. 10MHz n°1 (left) and Osc. 100MHz n°2 (right)

CONCLUSION

In this paper we presented some of the results of the MINCOR project. We showed that the sensitivity to radiation can be seen on some resonator types. We showed that cumulative, non-cumulative, positive or negative frequency drifts may occur due to radiation and their intensities tend to decrease with increased exposure. This sensitivity can be more specifically of concern in LEO system because of the intermittent radiation exposure compared to other mission profiles where more constant radiation is applied, and where parts will tend to stabilize. However, levels of sensitivity presented in the study remain quite low, and, in most applications, it will not affect the overall performance of the system. Amongst processes variants, materials are showing differences in terms of behaviour and it must be noticed that, although their quality was not the same, their level of impurities was quite low (<1ppm) as shown in previous paper [1]. However, even if their materials are generally of good quality, not all quartz material suppliers are able to guarantee impurity levels although it is shown to mainly explain radiation sensitivity of quartz resonators.

ACKNOWLEDGMENT

This work is funded by ESA according to ESA contract No. 4000133592/20/NL/FE
Rakon would like to thank ESA for their continuity in supporting radiation studies since many years with special thanks to Joaquin Jimenez in the frame of this project.
Rakon would like to thank the CNES (National Center for Space Study) for the continuous collaboration especially on radiation since more than 20 years with a special thanks to Nicolas Vorobyev for his great support on the measurement system.
Also, Rakon thanks Cristal Innov for all the discussions related to quartz material and for their dedication to provide quartz resonator industry with very high and guaranteed low impurity level material.
At last, authors thank all contributors of this study working in the background at TRAD and RAKON.

REFERENCES

[1] N. Gufflet, L. Couteleau, F. Vittrant, Y. Padie, A. Rousset, “MINCOR - Minimisation of crystal oscillator cosmic radiation effects”, ESA/ESTEC Space Passive Component Day, 2024