A COST-EFFECTIVE TIME AND FREQUENCY REFERENCE

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Abstract

Current market requirements emphasize the need for compactness of and significant cost reduction on time and frequency references, capable of reaching the highest achievable stabilities (within a temperature range over the short term, mid term, and long term, etc.).

These requirements are found in applications such as orbitography, timekeeping, frequency reference equipment, and positioning and localization systems.

The new C-MAC miniature ultra-stable ground-based oscillator CFPO-US and the new flight model OUS NG, as time and frequency references, achieves the piezo state of the art for overall high stability and provide a competitive alternative to atomic clocks.

Industrialization of recent designs (directly derived from space references) and process control improvements have made possible a cost-effective solution, which reaches very high levels of performance, using standard and industrial structures and readily available components.

The main characteristics, obtained at 5 and 10 MHz with the CFPO-US and OUS NG devices, fitted with C-MAC SC-cut quartz crystal resonators, are:

- *thermal stability better than 2.10 x 10^{-11} from -20 to +60°C,*
- *ageing at less than a part in 10 x 10^{-11} per day*
- *short-term stability (Allan deviation) at a few parts in 10 x 10^{-14} for τ = 10 s*
- *package style 67 x 60 x 40 mm^3 (about 0.15 liter leaded package), for the CFPO-US*
- *compatibility with 12 v/15 v/24 v supply voltage*
- *timekeeping (mean square error of prediction): $\leq$ 2 ns over 3 hours; best 20 ns/50 ns typical over 24 hours.*

This paper presents measurement data and analysis of these devices.

1 INTRODUCTION

Telecommunication and measurement systems require more and more demanding performances from ultra-stable oscillators (USO) in all types of application (Space, Avionics, and Civil Telecom).

A new generation of Ultra Stable Oscillator has been designed and developed with the aim of attaining highest frequency stability at reduced cost : the CFPO-US OCXO, and a new generation of USO for space applications : the OUS NG. This was qualified in 1998 and first flight models have now been delivered.

This paper describes the main characteristics of these two oscillator types and presents their comparison with a rubidium standard. The use of these USOs in time–keeping applications is discussed.

2 RELATIONSHIP BETWEEN REQUIREMENT AND PERFORMANCE

Localization systems require especially demanding short-term and temperature stability (σ_y (10s) < 5.10^{-13} and $\Delta F/F$ < 5.10^{-11} within the operating temperature range) [1], [2]. Telecommunication and measurement systems require, in particular, long-term stability and absence of frequency jumps (daily ageing less than 2.10^{-11} and frequency jumps < 5.10^{-11}) [3], [4], [5]. The CFPO-US and the OUS NG have been developed with these objectives. In the rest of the paper, the CFPO-US will be referred to as a GB (ground-based) oscillator and the OUS NG an OB (on-board) oscillator.

3 PRODUCT DEFINITION AND CONFIGURATION

The USO for ground-basedstations at 5 MHz is based on a single oven structure. The definition of the GB oscillator is described in [2].The core of the GB oscillator OCXO has been designed to be compatible with different mechanical interfaces and packages, resulting in greater modularity. The design of the electronic and thermal aspects minimizes the number of adjustments. All performance criteria are maintained whatever the humidity rate and ambient pressure.

The performance for each class of model is obtained by sorting for ageing and by optimizing adjustment for temperature stability. Likewise, sorting and readjustment may be carried out to address specific short–term stability requirements. The on–board USO is based on a structure with a double oven and with dewar vessel, presented in [2], and is larger. Figures1 and 2 illustrate the two types of USO.

The material of the resonator blanks is swept quartz for the on–board USO and a high quality quartz having an IR absorption lower than 0.02 cm^{-1} for the ground-based model.

The mechanical structure for the 10 MHz resonator in the OB oscillator is self-suspended (QAS - BVA 4 type), which now insures compatibility with the ARIANE 5 mission profile (vibration 26 g rms/10 - 2000 Hz, shocks 200 g/0.5 ms).

The resonators used are packaged in an HC 40 U holder and are SC-cut/3rd overtone.

The manufacturing process of the QAS - 10 MHz resonator is in accordance with ESA requirements described in CEPE PID for space applications.

Concerning the on-board USO internal components, most of them are procured with an ESA-SCC C quality level for flight models. However, due to the performances required for critical components, we procured some commercial components, which were then qualified for use in space applications.

Measurements on the two types of USO are described in the next section.

4 PERFORMANCE

All of the main characteristics of these two USOs are given in Table 1. Greater detail concerning the methods of measurement may be found in references [2] and [6].

Figures 4 and 5 show the Allan standard deviation and Picinbono standard deviation [7] for the GB USO at 5 MHz (measured with a MASER [2]) and the OB USO at 10 MHz. Table 1 compares the characteristics with a typical rubidium standard, which has the same dimensions as the USOs. One notable difference is the short-term frequency stability. Below 10000s, the USOs are better than rubidium standard. Above 10000s, the reverse is true. Figure 3 illustrates this fact.

For warm-up time, retrace, and accuracy the rubidium standard obtains a better result. However, in terms of the frequency stability versus the environment (especially with temperature and with magnetic field), the USO outperforms the rubidium standard.

4.1 Temperature

This is being the case, with 10 degrees of variation over a day. The daily frequency stability is equivalent or better than the rubidium standard and the short-term stability is not affected. Figures 6 and 7 show frequency variation in the temperature range (- 15°C, 60°C) for a GB USO. The temperature rate is 15°C/hour. Figure 8 gives the Allan standard deviation with and without the temperature variation of Figure 6 for the GB USO. The ageing is the only remaining factor influencing the mid-term stability.

4.2 Magnetic Field

The use of appropriate components and redesign of the quartz crystal mounting allows us to reduce the frequency sensitivity of the USO to below the 1.10^{-12}/gauβ limit.

For satellite applications, the influence on frequency due to magnetic fields, generated by the actuators, has been reduced on the OB USO. This eliminates the need for extra shielding.

4.3 Ageing

Figure 9 shows the ageing over the first 5 months for thirty pieces at 10 MHz. Figures 10 and 11 give the first and fifth month ageing distributions respectively. For a typical curve as in Figure 12, the A and B values for the MIL-0-55310D mathematical model (below) may be determined.

$$\frac{\Delta F}{F} = A \log_N (Bt + 1)$$

The resulting 10-year ageing prediction extrapolated from the curve in Figure 12 is presented in Figure 13.

4.4 Short-term Stability and Ageing

The influence of ageing on the OB USO frequencv stability is given in Figure 14, with the distribution at the fifth month corresponding to Figure 11. The influence of ageing on the OB USO frequency stability as a function of the number of years in service is given in Figure 15, using the prediction model as shown in Figure 13.

We can cancel out the effect of ageing on the short-term stability calculation by using the Picinbono standard deviation $\sigma_{yp}(\tau)$ as illustrated in Figure 16 for an GB USO at 5 MHz. It is equivalent to correcting the frequency of its ageing, as shown in Figure 17. The comparison of the two methods is shown in Figure18 with the short-term frequency stability standard deviation.

4.5 Phase Stability

For navigation and time-keeping applications, the important parameter is the difference of phase, $\varphi(t)$, between the measured phase and a model of the phase variation [9]. It may be quantified by the mean time interval error (MTIE) with the variance, given in [11] :

$$MTIE^2(\tau) = \left\langle \left[x(to+\tau) - \hat{x}(to+\tau) \right]^2 \right\rangle \qquad (1)$$

with $\hat{x}(to+\tau) = x(to) + [x(to) - x(to-\tau)]$ (2)

and $x(t) = \dfrac{\varphi(t)}{2\Pi Fo}$ (3)

where Fo is the frequency of the clock, to is the initial time for phase prediction and $\hat{x}(to+\tau)$ is the predicted clock error.

We obtain from [8] : $MTIE^2(\tau) = 2\tau^2 \sigma_y{}^2(\tau)$ (4)

where τ is the integration time,
and $\sigma y^2(\tau)$ is the Allan variance.

By application of Equation (4) on the frequency stability obtained in 4.4, we obtain Figure 19, which gives typical curve of MTIE for the OB USO, GB USO, and the curve of a typical rubidium standard. Equation (4) can be used with a Picinbono variance or with a corrected Allan variance, $\sigma_{yc}(\tau)$, obtained with suppression of the ageing, as in 4.4. This yields the Picinbono MTIE, MTIEp(τ), and the corrected MTIE, MTIEc(τ) :

$$MTIEp^2(\tau) = 2.\tau^2 \sigma_{yp}{}^2(\tau) \qquad (5)$$

$$MTIEc^2(\tau) = 2.\tau^2 \sigma_{yc}{}^2(\tau). \qquad (6)$$

Figure 20 shows the MTIEP(τ) characteristic and it s comparison with the MTIE(τ). A direct measure of the phase difference has been carried out at C-MAC and it confirms the result shown in Figure20. The MTIEP(τ) between τ = 1s and τ = 1 day is near the limit imposed by the frequency short-term stability floor (frequency flicker noise). Values of a few nanoseconds can be obtained for the MTIEP(τ) over a 3-hour period and values between 20 ns and 50 ns for a day. Further research on the measurement of quartz crystal frequency flicker noise [10] will permit us , next year, to obtain a better short-term stability floor and a better MTIEP(τ).

5 CONCLUSION

The on-board and ground-based USOs presented in this paper provide, in continuous operating conditions, better environmental stability than a typical rubidium standard having the same volume. Values of some ns on 10000s can be obtained for the mean clock error of prediction. This means that these ultra-stable oscillators are now available as a cost-effective alternative to a rubidium standard. One of the ground-based type USOs at 5 MHz will be characterized in the near future by the Jet Propulsion Laboratory. The French Space Agency (CNES) is currently analyzing the clock time deviation exhibited by both of these C-MAC USO's.

Ongoing improvements on the manufacturing process will allow us to double the yield.

In conclusion, the performance achieved by these ultra-stable oscillators, coupled to a predictive method of time error analysis, offer an optimized solution to the time-keeping market at a very competitive cost.

6 REFERENCES

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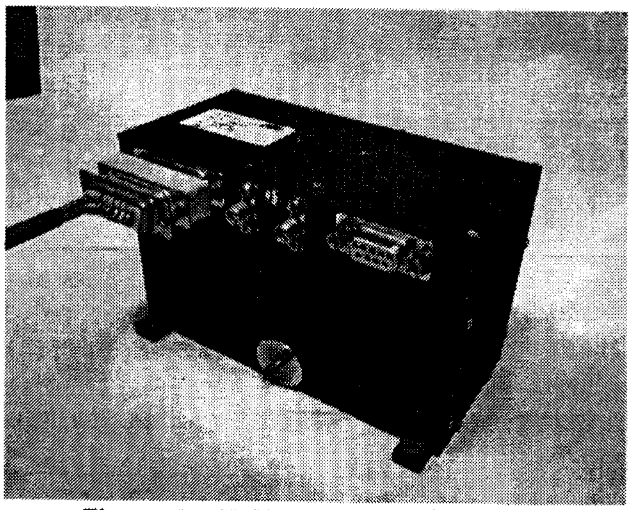

Figure 1 : 10 MHz OB USO (OUS NG)

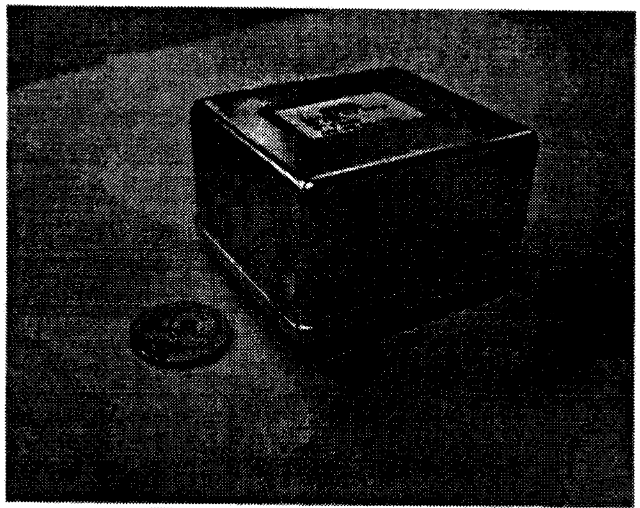

Figure 2 : 5 MHz GB USO
(CFPO-US - package 67A)

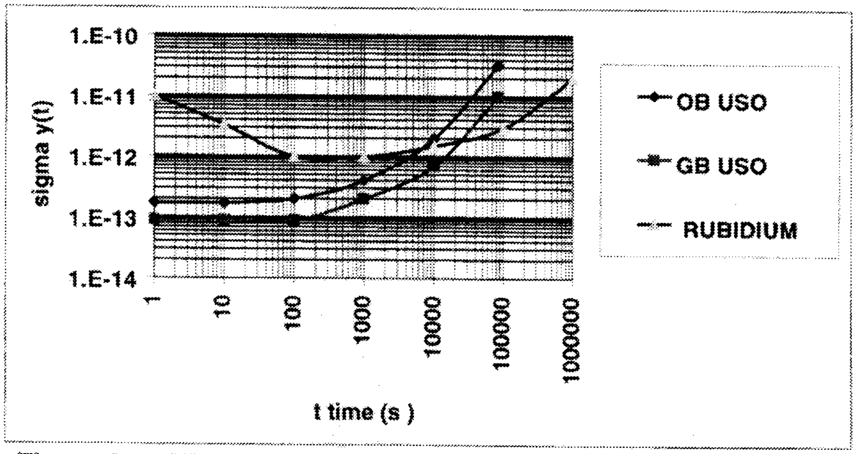

Figure 3 : Allan standard deviation, sigma y (t) for OB USO, GB USO and Rubidium standard

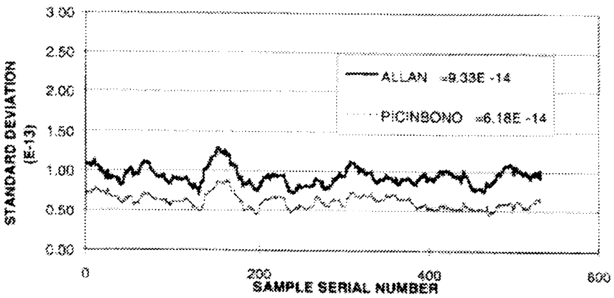

Figure 4 : 5 Mhz GB USO N° 69404 short-term stability (integration time : 10s)

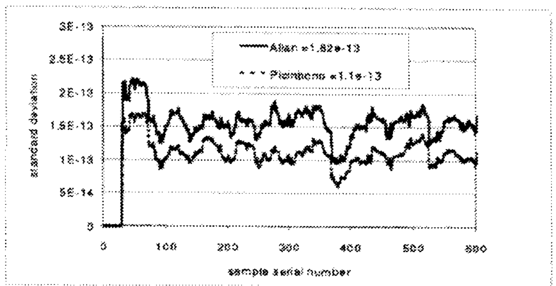

Figure 5 : 10 MHz OB USO short-term stability (Integration time : 10s)

ELECTRICAL PERFORMANCE	RUBIDIUM	OCXO	
STRUCTURE	CLOCK	OB (space qualified)	GB
Frequency	5 MHz	10 MHz	5 MHz
Standard deviation frequency			
Allan 1s	1×10^{-11}	2×10^{-13}	1×10^{-13}
10s	3.1×10^{-12}	2×10^{-13}	1×10^{-13}
100s	1×10^{-12}	2×10^{-13}	1×10^{-13}
1000s	1×10^{-12}	3.5×10^{-13}	3.5×10^{-13}
10^4s	1.1×10^{-12}	3.5×10^{-13}	3.5×10^{-13}
10^5s	5×10^{-12}	3×10^{-11}	3×10^{-11}
SSB 10 HZ	- 125 dbc/Hz	- 135 dbc/Hz	
100 HZ	- 155 dbc/Hz	- 150 dbc/Hz	
1000 Hz	- 155 dbc/Hz	- 150 dbc/Hz	
10^4 Hz	- 155 dbc/Hz	- 150 dbc/Hz	
10^5 Hz	- 155 dbc/Hz	- 150 dbc/Hz	
Retrace	$\pm 2 \times 10^{-11}$	$\pm 2.10^{-9}$	
Accuracy	$\pm 5 \times 10^{-11}$	$\pm 5.10^{-9}$	
Power (at 25°C)	13 W	2.4 W	
Warm up	(at 10 min 2×10^{-10})	(at 120 min 2×10^{-11})	
Aging per month	4×10^{-11}	5×10^{-10}	
Frequency trim range	$\pm 2 \times 10^{-9}$	$\pm 3 \times 10^{-8}$	
Environmental performance			
Operating temperature range	(- 25°C/65°C)	(-20°C/60°C)	
Temperature sensitivity	1.1×10^{-12}/°C	2.5×10^{-13}/°C	
Magnetic field sensitivity	3×10^{-11}/gauβ	1.5×10^{-12}/gauβ	
Pressure sensitivity	-1×10^{-11}/bar	5×10^{-9}/bar	1×10^{-12}/bar
Relative humidity	95%	95%	
Power supply voltage sensitivity (±10%)	$< 1 \times 10^{-11}$	$< 1 \times 10^{-12}$	
Load sensitivity (50Ω±10%)	$< 1 \times 10^{-12}$	$< 1 \times 10^{-12}$	
Acceleration sensitivity	4×10^{-12}/G	5×10^{-10}/G	5.10^{-9}/G
Irradiation sensitivity	5×10^{-15}/rad	1×10^{-12}/rad	
Physical characteristics			
Weight	1.3 Kg	1.0 Kg	0.5 Kg
Volume	1000 cm^3	840 cm^3	161 cm^3
Dimensions	100 x 100 x 100 mm^3	80x80x130 mm^3	67x60x40mm^3
Cost	2	10	1

Table 1 : Electrical performance comparison between Rubidium standard, on-board USO and ground-based USO

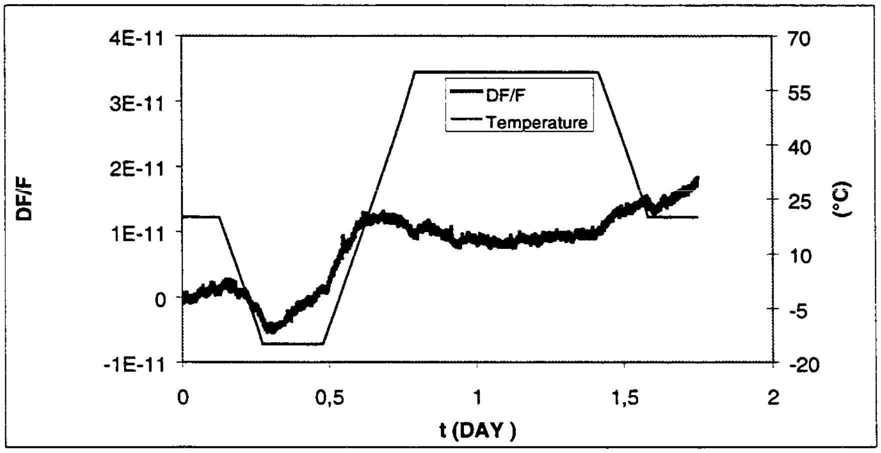

Figure 6 : 5 MHz GB USO frequency variation in temperature range

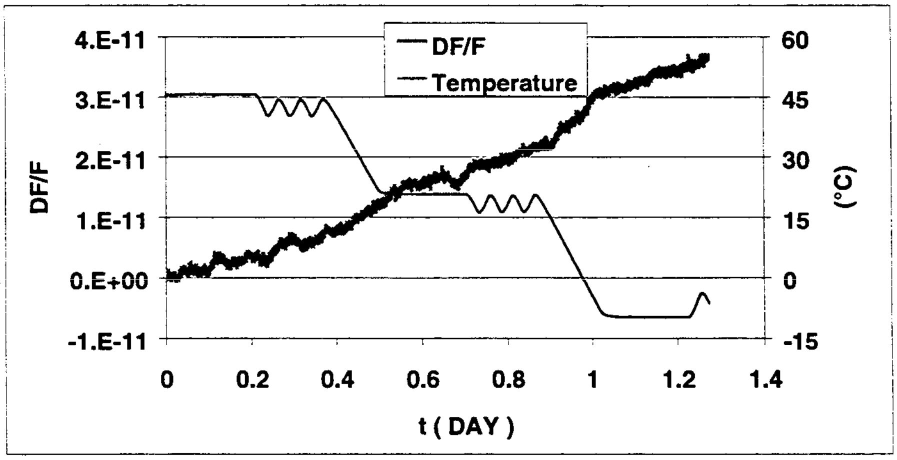

Figure 7 : 10 MHz OB USO frequency variation in temperature range

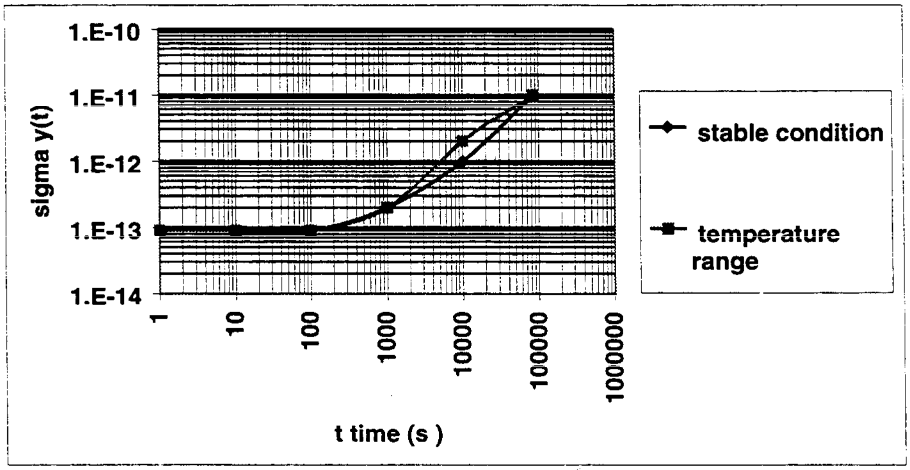

Figure 8 : Allan standard deviation sigma v (t) with and without temperature variation of Figure6 for GB USO

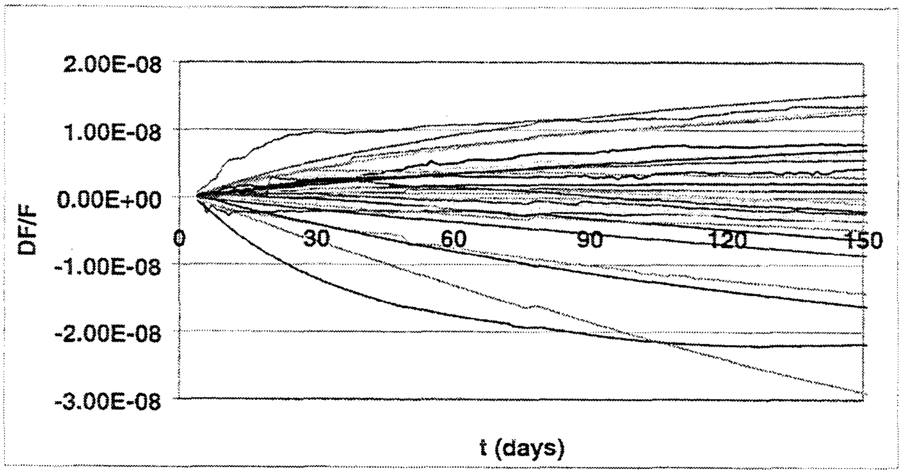

Figure 9 : 5 first months ageing of thirty 10 MHZ devices

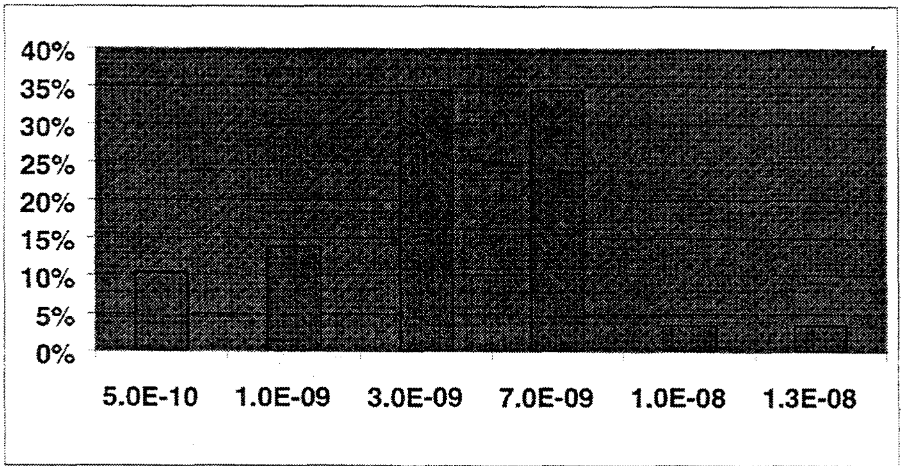

Figure 10 : First month ageing distribution of 10 MHz CFPO1 OCXO

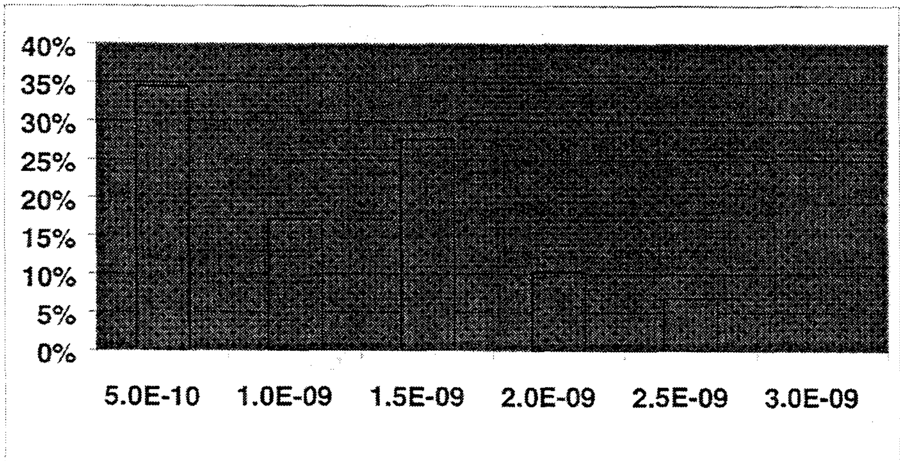

Figure 11 : Fifth month ageing distribution of 10 MHz CFPO1 OCXO

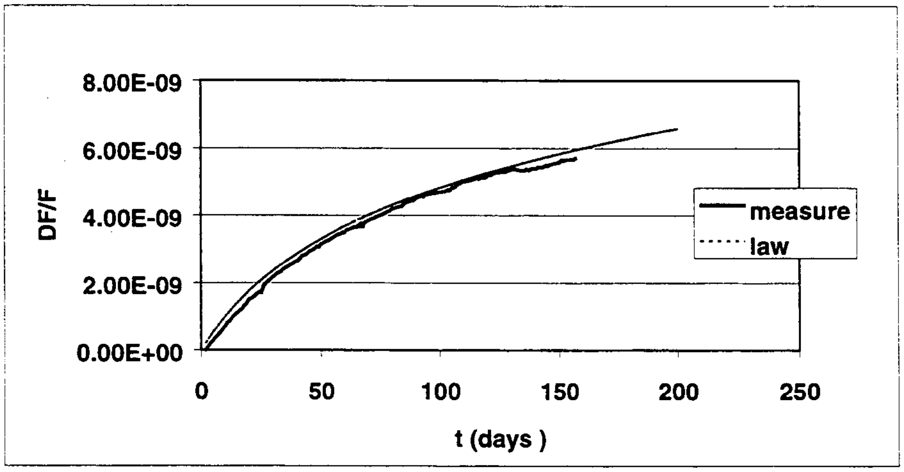

Figure 12 : Comparison between a typical measured curve ageing and the MIL-0-55310D law

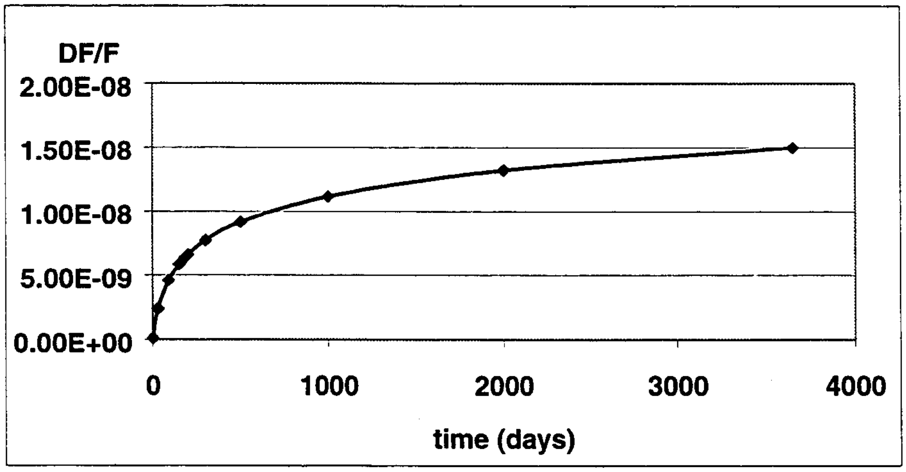

Figure 13 : Resulting 10 year ageing prediction extrapolated from typical curve

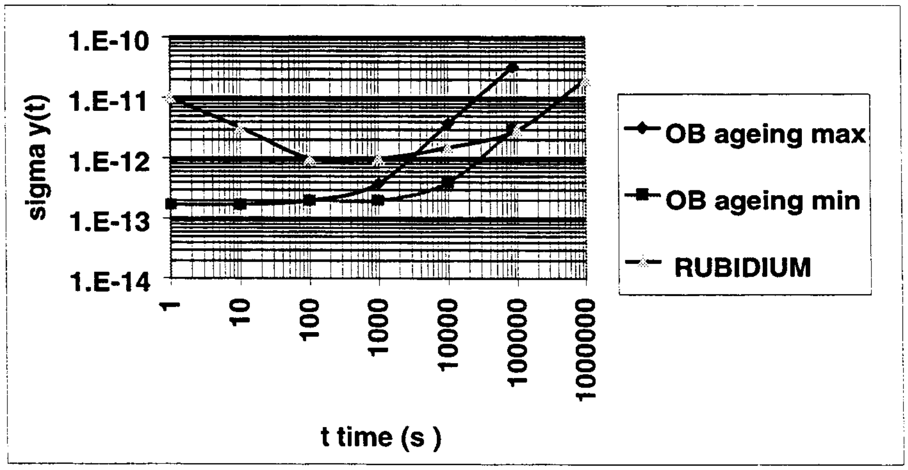

Figure 14 : Influence of initial ageing on Allan standard deviation sigma y (t) of the 10 MHz OB USO

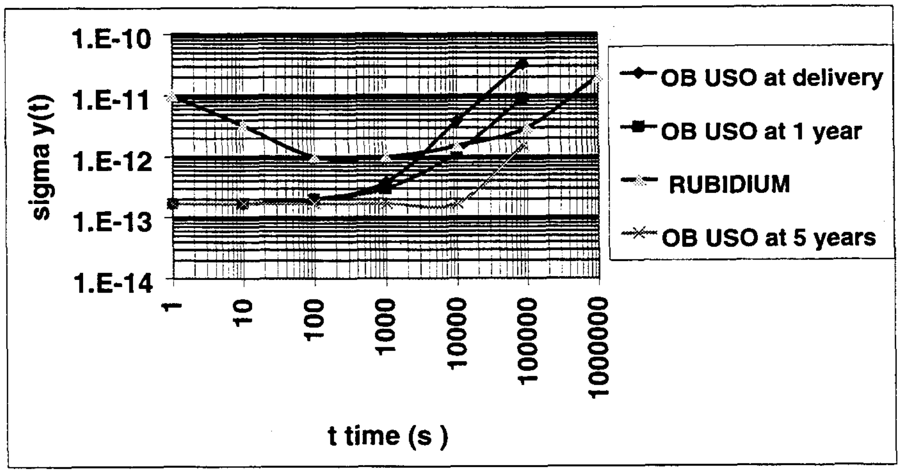

Figure 15 : Evolution of the Allan standard deviation sigma y (t) with the ageing of the OB USO

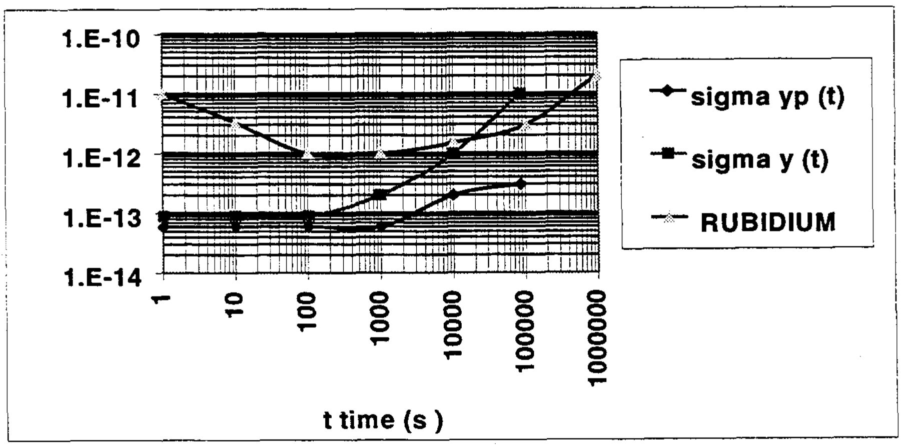

Figure 16 : 5 MHz GB USO Allan standard deviation and Picinbono standard deviation

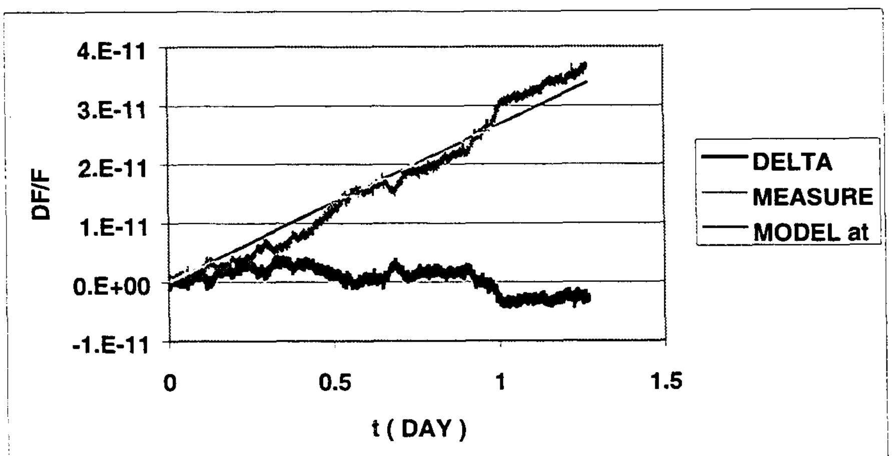

Figure 17 : OB USO frequency deviation corrected of the ageing by a linear model $\Delta F/F = a \times t$ (over temperature range)

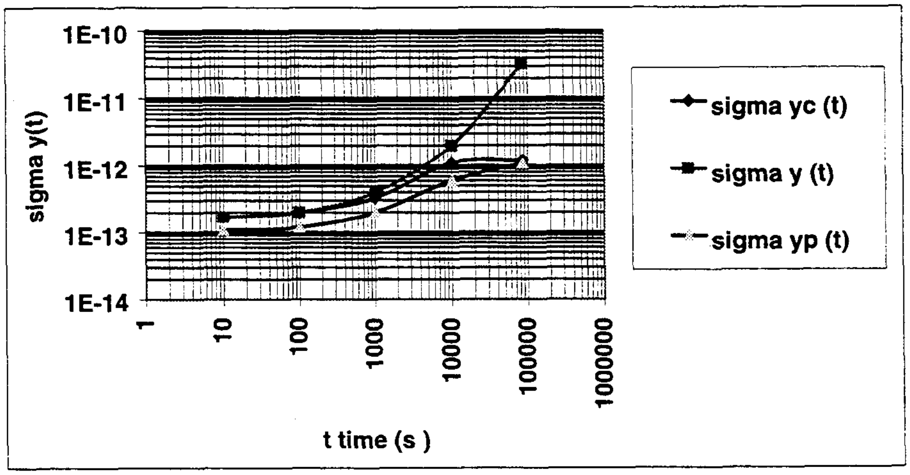

Figure 18 : OB USO relative frequency standard deviation
1/ $\sigma y(\tau)$
2/ $\sigma yc(\tau)$ with ageing correction by a linear relation
3/ $\sigma yp(\tau)$

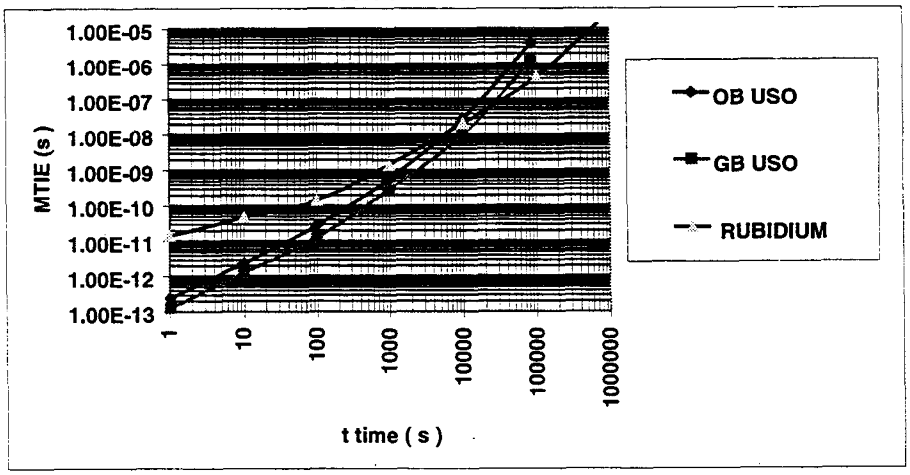

Figure 19 : MTIE sigma x (t)

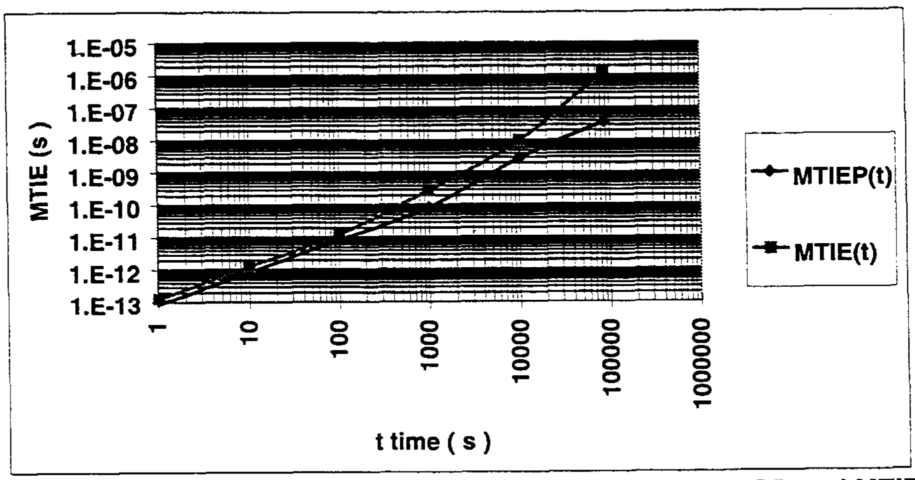

Figure 20 : 5 MHz GB USO Comparison between MTIEP and MTIE