HIGH PERFORMANCES FROM A NEW DESIGN OF CRYSTAL OSCILLATOR

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ABSTRACT

This paper describes new designs developed and applied in order to increase the performance of crystal oscillators for military and space applications, requiring high performances.

The following performances have been reached :

- at frequencies of 10 MHz or 10,230 MHz : long term stability 10^{-10} per month ; drift in temperature range (from -40 to +70°C) some parts of 10^{-10} ; short term 5.10^{-13}; spectral density < 160 dBc/Hz, g-sensitivity $< 2.5.10^{-10}$ per g, which allows high immunity against induced side bands under vibrations.

These results have been obtained from :

- the developments of a new technology applied to crystal resonators
- the use of a low noise design of the electronics associated with the resonator
- highly miniaturized oven with PID control
- assembly of these elements have met these specifications during mechanical environment tests.

INTRODUCTION

Since several decades, oven controlled crystal oscillators in a large range of frequencies from 1 MHz to 200 MHz, offering high performances in stability and spectral density, have been improved by CEPE. From this large experience for research, development and manufacturing OCXO and other kinds as XO, TCXO, VCXO ; with the contribution of new techniques on resonators and with the support of precise systems of measurements, a new generation of ultra stable oscillator, (USO), is now under development to satisfy the requirements during the next decade.

These USO are designed for a nominal frequency of 10 MHz ; frequencies about 10 MHz, for example 10.230 MHz can be also achieved. The domain of stability involved is 10^{-10} per month and under environmental conditions. According to the environment, it has been defined three types corresponding to the fields of application (fig 1).

1. USO for fixed equipments : continuous operation; easy environmental conditions, volume and power consumption are not critical.
2. USO for transportable or airborne equipments : intermittent operation, severe operating conditions, volume and possibly power consumption to be minimized.
3. USO for satellite applications : performances to be maintained after launch, volume and power consumption to be minimized.

Considering these different domains which could lead to contradictions, it has been nevertheless possible to define a basic design, with extensions suitable for specific requirements.

The study and development have been done on the following elements which are described in the first part :

- High Q resonators

- Circuits of the oscillator and the oven
- Mechanical assembly.

In the second part, tests results of following parameters are presented :

- Long term stability
- Mean term stability
- Short term stability
- Spectral density
- Influence of environmental conditions
- Turn on time and retrace.

DESCRIPTION OF INCORPORATED ELEMENTS

An ultra stable oscillator had to be considered as a sub-assembly in an equipment ; each function is depending of the others. Nevertheless, three main subjects can be considered as shown in block diagram (fig 2).

Crystal resonators

In this field, CEPE has now the capability of manufacturing high Q resonators at 10 MHz or 10.230 MHz standard frequencies ; it is also possible to provide other frequencies in the range of 5 MHz to 20 MHz, having a product Q x F of 12×10^{12} with the support of the following facilities :

- choice of the overtone : 3rd or 5th
- choice of the doubled rotated cut : SC ...
- choice of the assembly technologies : classic means with plated electrodes and mounted on springs: QAS plated electrodes, isolated from the active part of the plate by quartz bridges ; BVA electrodes separate from the quartz active

plate, using quartz bridges as QAS and assembled by clips.

- improved experience on technics of machining and polishing the plates, of metallisation, outgasing and closing procedures.

In other respects, the facilities of measurment of the achieved resonators have been completed by precision test sets allowing short term 0,1 to 1000 s and g-sensitivity measurments at the operational temperature of the oven adjustable between 50 and 90°C.

These facilities and capabilities allow the choice of the resonator adapted for each domain of utilization and improved before mounting in the oscillator in the oven.

Electronic circuitry

Two main parts can be distinguished :

- the oscillator (fig 3)
- and the oven (fig N° 4)

The oscillator includes the following elements :

- the transistorized oscillator which is a Clapp giving a low drive level of about 30 μW on the resonator. The components must have a low noise level especially the transistor.
- the varactor, in series with the resonator, permits the adjustment of the frequency by a control voltage.
- the voltage regulator has to be designed for a low noise and effective protection against the ripple of the power supply.
- the additional buffer amplifiers give an insulation between the oscillator and the external mismatch of the frequency output.

The circuits of the oven are constituted by thermistors, DC proportional amplifier and heating elements. The thermistors located near the crystal case, are glass welded small size type because they have a good long term stability. The proportional amplifier associated with integrator and derivator circuits ensures with a high sensibility, a good stability without ondulation. The heating elements are made with power transistors on which it is possible to adjust the required power.

Mechanical assembly

The purpose was to reduce as much as possible the volume to be maintained within several hundredths of degree centigrade. For this reason the elements to be in the oven: crystal and the oscillator and some other parts of the electronics have been designed in mini electronic or hybrid assembly (fig N° 5).

Also specific hybrid circuits including the thermistor and a chip of power transistor were developed on BeO substrate to ensure a tight thermal coupling between these elements and the crystal housing.

Mechanical design of the assembly takes in account the thermal losses corresponding to the optimization between a fine regulation and a power consumption as low as possible fig N° 6).

Thermal insulation can be eccofoam, or still air between non radiative walls, or vaccum. If necessary , in particular requirements, a second oven can be added.

RESULTS OF THE PERFORMANCES

In this section, the key parameters of the performances are presented.

Long term stability

This parameter is measured in stable conditions : continuous operating, supply voltage, load and external temperature are constant at the moment of the measurement. For this type of USO, in the performance of $\pm$ 10^{-11} per day is obtained after 10 days of continuous operation. The level of some 10^{-10} per month is obtained after 2 months of continuous operation and we expect $\pm$ 1.10^{-9} per year.

These measurements are done on a fully automatic testing equipment referenced by a Cesium standard (figure 7) on which the result of stability per day is given on the last ten days.

Mean term stability

This domain concerns the stability between 100 s and one day, in continuous operation, taking into account the drifts due to slight changes in power supply, load and temperature. This requirement is specifically expressed by the drift of the external temperature at about 5 or 10°C / per hour related to the kind of the mission.

The measurments are made with a programmable test chamber and the the frequencies are recorded each 10 s during 15 minutes, the slope p and the dispersion σ are calculated with goal of $p = 1.10^{-12}$/ min. and $\sigma = 3.\ 10^{-12}$.

Short term stability

This parameter, also designed by stability in time domain, can be achieved by comparaison of two or three USO of the same type running in continuous operation. The measurments are made on a specific test system including a low noise mixer, a low noise amplifier, a low band pass filter giving a resolution better than 10^{-11} over 10 ms and 5.10^{-14} over 100 s. The results are expressed by $\sigma_y(\tau)$ as function of τ by the formula of Allan or Pincibono variance. The results are given on fig N°8.

Spectral density

The spectral density $\mathcal{L}$(f) is defined as a ratio between the power of the phase noise in a bandwith of 1 Hz at the frequency f from the carrier and the total power of the signal. Because of the high Q factor of this oscillator, the spectral density will be at -130 dBc/Hz at 10 Hz and -160 dBc / Hz at 1 KHz (fig N° 9). The measurment set has the basic configuration of the previous one, coupled with a low frequency analyzer and a graphic plotter; the resolution reaches - 170 dBc / Hz.

Influence of the environment

The characteristics of stability and spectral density have to be maintained in the proper environmental conditions specified for each application. The following parameters have been taken into consideration :

a) - external temperature

by using SC crystals and a precision electronic compact design for the oven, the stability of $2. 10^{-11}$ peak-peak from + 10 to + 40°C or 2.10^{-10} peak-peak from - 40 to + 70°C in the total temperature range (fig N° 10).

b) - g-sensitivity

due to the new developments on crystal, a stability as low as $3. 10^{-10}$ per g in all directions is achieved. This value drops to $5. 10^{-11}$ per g in all directions, if required.

c) - vibrations and shocks

by a ruggedized conception of PCB and assembly, the USO is able to support high levels of mechanical stresses :

- under sine vibration 20 g up to 2000 Hz
- under random vibrations 25 g rms up to 2000 Hz
- under shocks 100 g - 11 ms

c) - pressure

the performances under vacuum are also guaranteed by a specific design due to thermal losses.

Turn-on time and retrace

The performances in this domain are mostly important in intermittent operational conditions. In order to make comparative measurements, the following procedure is applied : after the measure of the slope p_1 ΔF / F per day before turn off, the oscillator is stored at ambient temperature during 24 hours and the frequency is recorded after turn-on at t_o. The retrace is defined as the gap of frequency between the frequency before turn-on and the frequency obtained when the slope p_2 is equal to p_1 (fig N° 11).

This gap depends on the power available, on the capability of resonators and the miniaturization of the oven. The influence of the number of retraces and of the temperature of storage will be also measured.

The results obtained with a power consumption of 5 W during less than 1 min., with a QAS resonator is shown in fig N° 12 which gives retrace of $\pm 2 . 10^{-10}$ after 100 min. and even the stability of $\pm 1 . 10^{-9}$ have been reached after 10 min. operation.

CONCLUSIONS

Since the USO are tuneable by external adjustment of voltage applied on the varactor, the long term drift can be permanently or periodically compensated by the external circuitry shown on fig N° 13 .

By combination of QAS and BVA resonators and new design of the electrical and mechanical parts of the ovenized oscillator, it is now possible to define a new generation of USO (fig N° 1bis) giving at great improvement to the different fields of application.

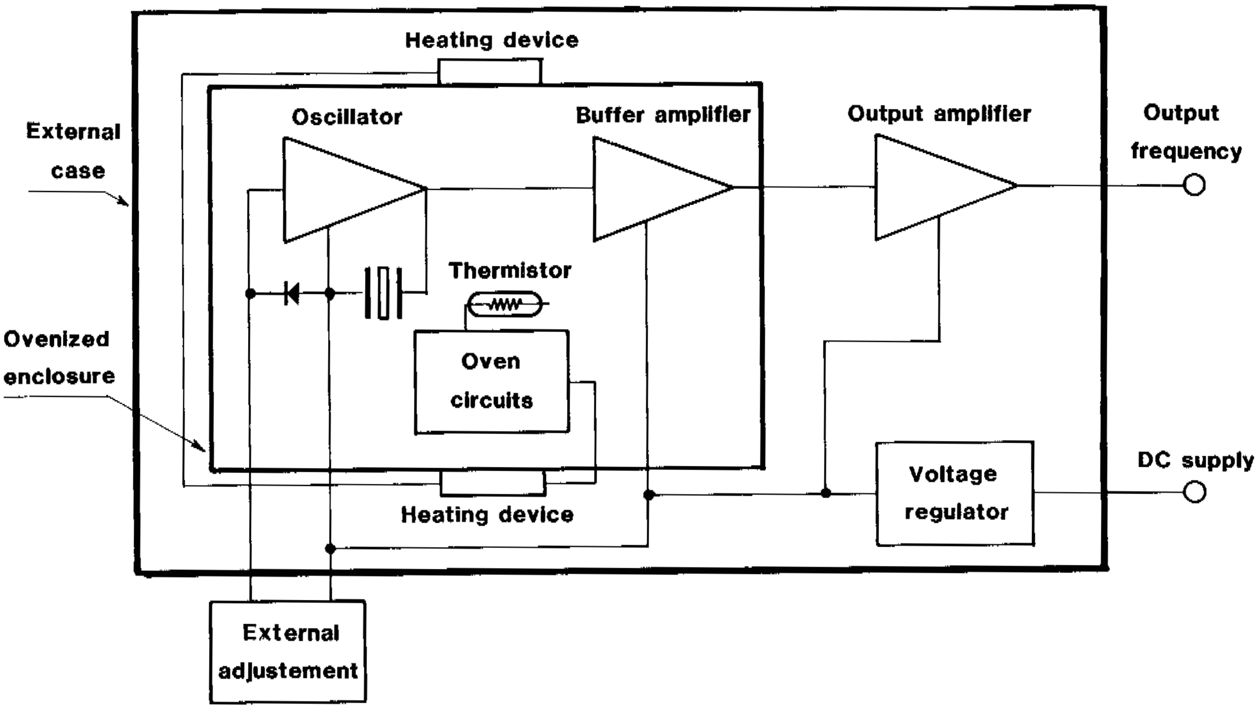
Thus, these USO offer with an expected duration of life of ten years, performances comparable and even better, than those offered by other secondary references of frequency.

	① USO-Metrology	② USO-Transportable	③ USO-Satellite
Operation	continuous	alternative storage/continuous	storage + continuous
Environmental conditions			
-operating temperature	0 to 50°C	-40 to +70°C	10 to 40°C
- vibrations - shocks - accelerations	no	yes	yes in storage no in operation
Power consumption	no	no	yes
Small size	no	yes	yes

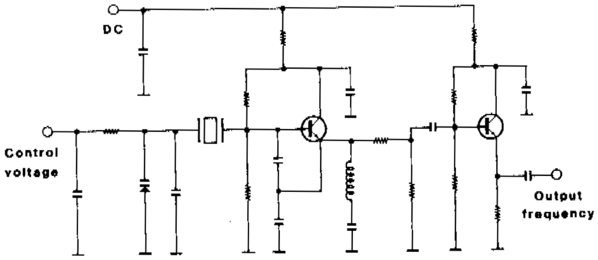
1 - Classification of Ultra Stable Oscillators

		OCXO PMT.P	USO
Long term stability	1day	$\pm 5.10^{-10}$ to $\pm 5.10^{-11}$	$\pm 5.10^{-11}$ to $\pm 1.10^{-11}$
	1month	$\pm 1.10^{-8}$ to $\pm 1.10^{-9}$	$\pm 1.10^{-9}$ to $\pm 2.10^{-10}$
	1year	$\pm 5.10^{-8}$ to $\pm 1.10^{-8}$	$\pm 1.10^{-8}$ to $\pm 2.10^{-9}$
Mean term stability	+ 10 to 40C	3.10^{-9} pp	5.10^{-11} pp
	− 40 to 70C	1.10^{-8} pp	2.10^{-10} pp
Short term stability	1ms	4.10^{-10}	4.10^{-11}
	1s	5.10^{-12}	6.10^{-13}
	10s	5.10^{-12}	5.10^{-13}
Spectral density dB/Hz	10 Hz	120	130
	100 Hz	135	147
	1 KHz	150	158
Retrace after turn on	10 mn	1.10^{-8}	1.10^{-9}
	100 mn	2.10^{-9}	2.10^{-10}
g-sensitivity	per g	5 to 2.10^{-9}	5.10^{-10} to 5.10^{-11}

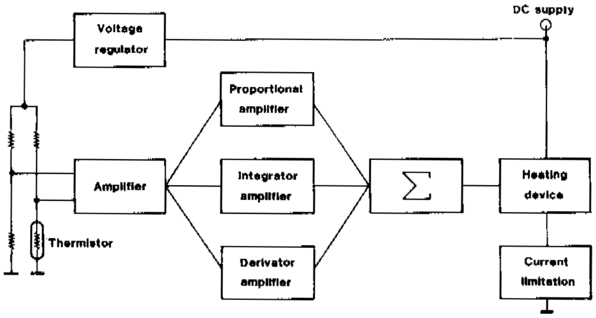
1bis - Comparaison between OCXO and USO



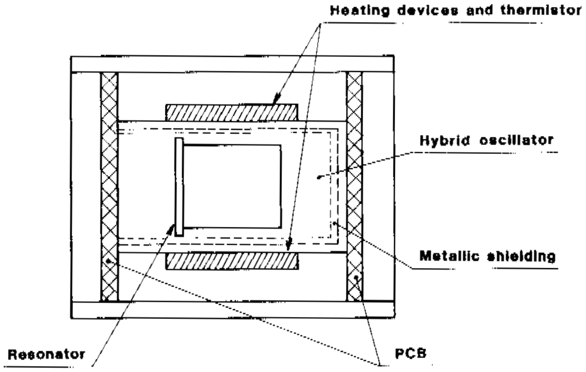
2 _ Block diagram



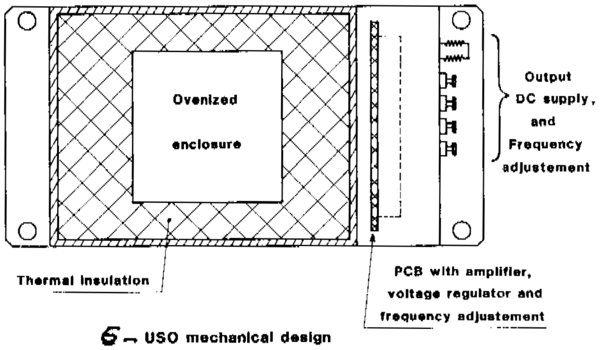
3 _ Clapp oscillator



4 → Oven circuits



5 _ Ovenized enclosure

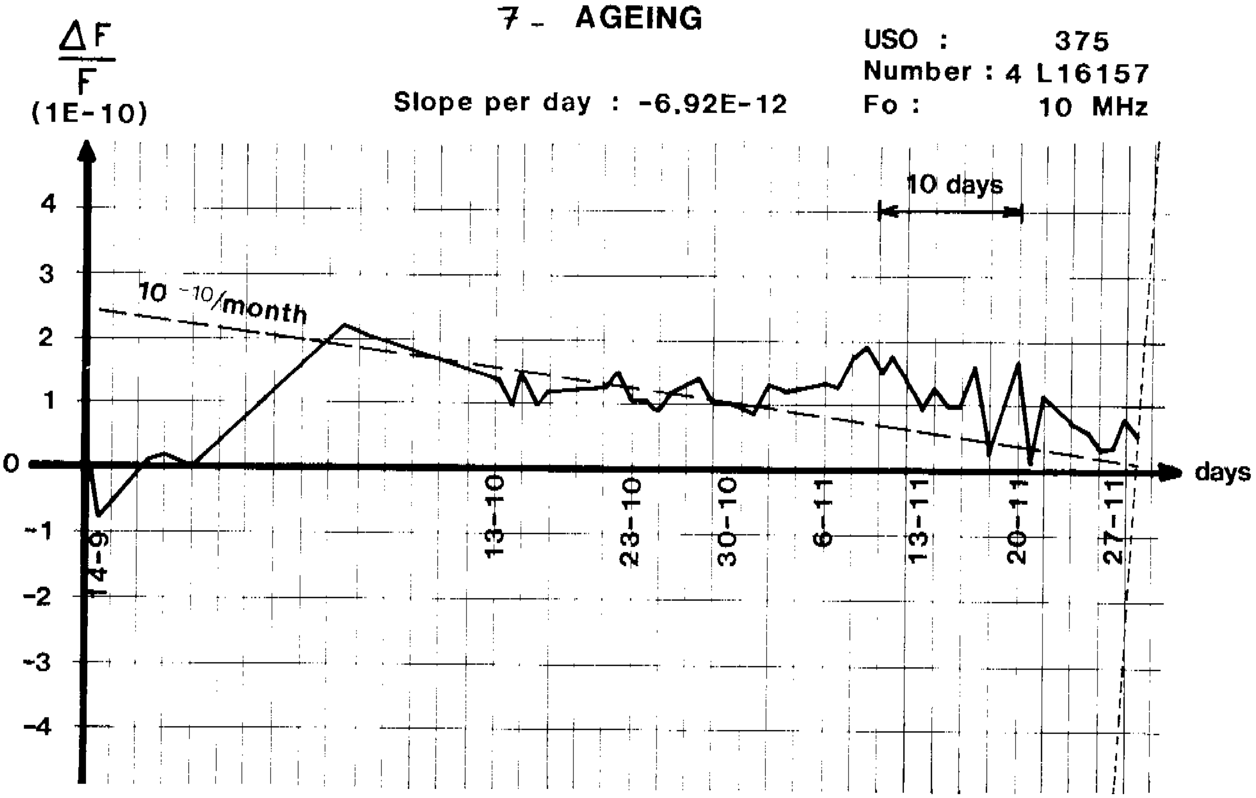


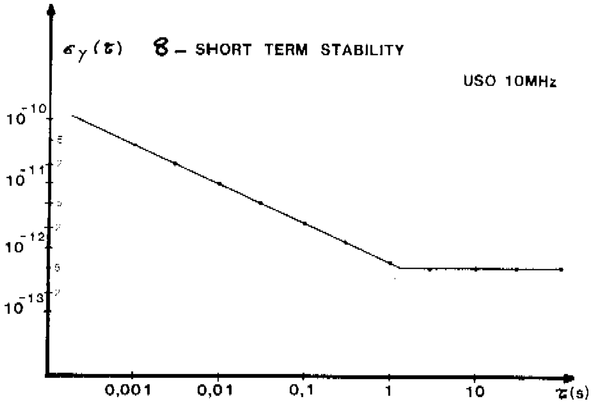
6 → USO mechanical design

7 – AGEING

USO : 375
Number : 4 L16157
Fo : 10 MHz

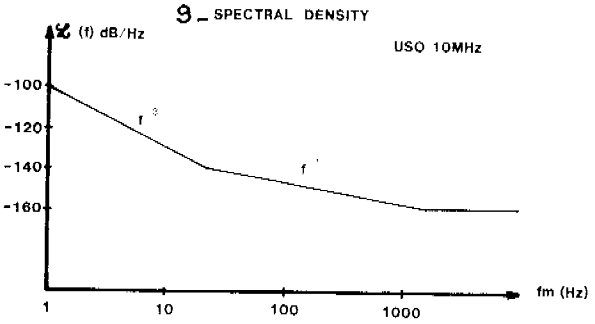
Slope per day : -6.92E-12

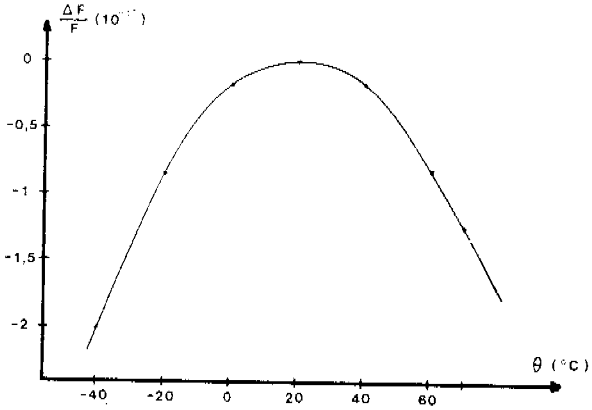




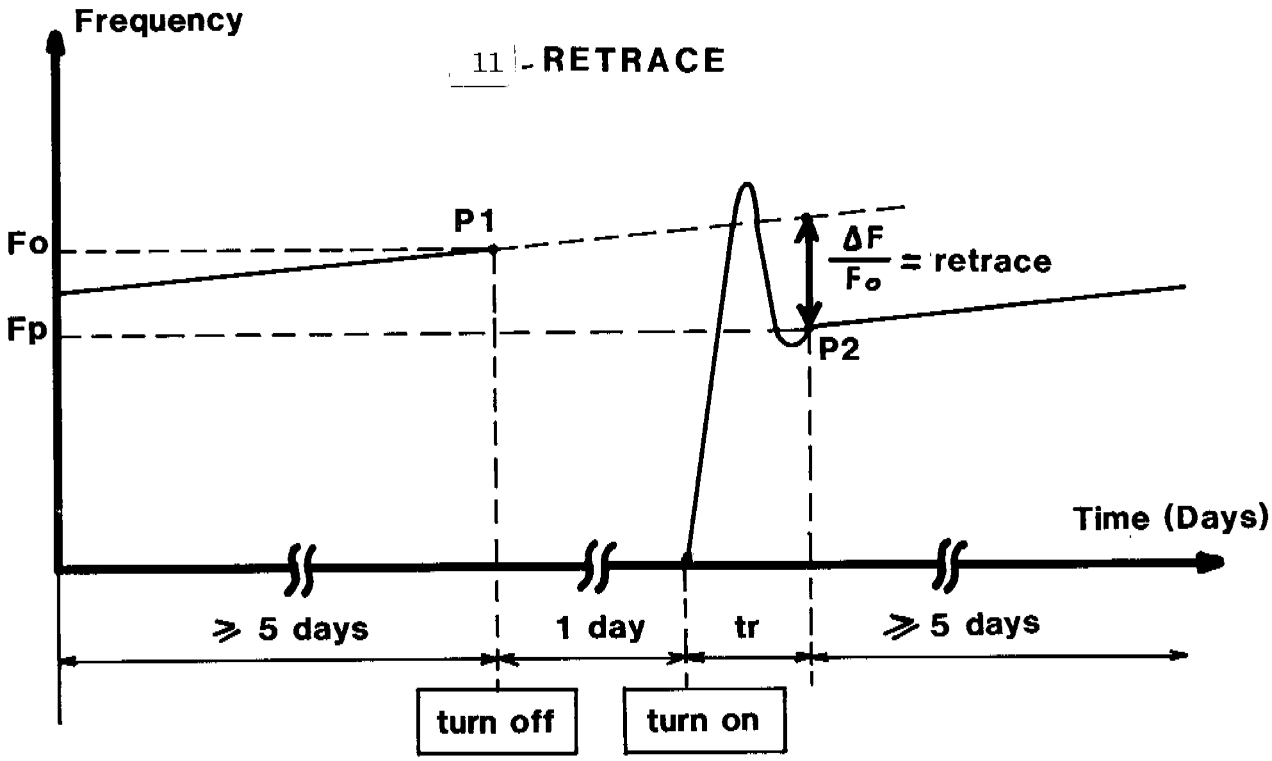
8 – SHORT TERM STABILITY

9 – SPECTRAL DENSITY

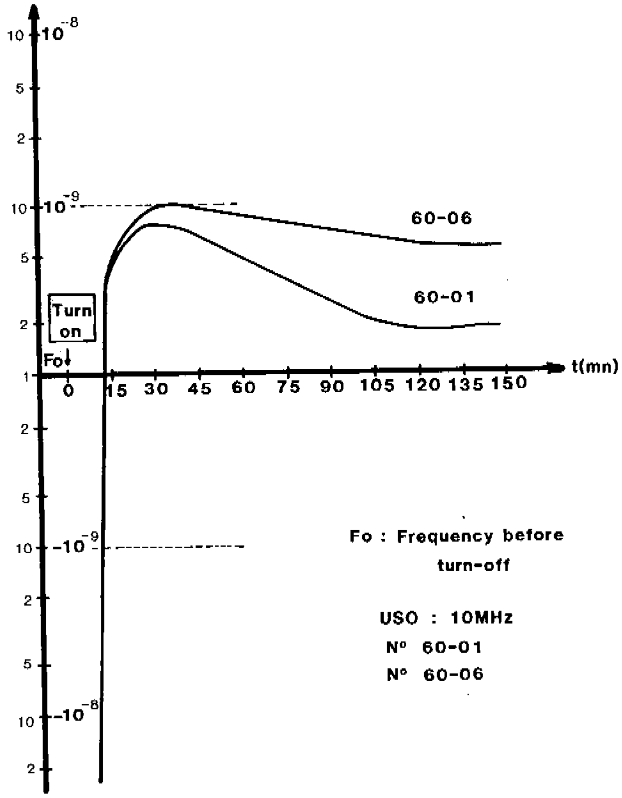




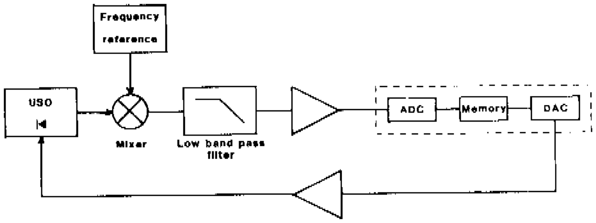
10 – TEMPERATURE STABILITY



11 - RETRACE



12 - MEASUREMENT OF RETRACE



13 - EXTERNAL ADJUSTMENT

QUESTIONS AND ANSWERS

MR. CAMP:

The warmup time that you showed for SC seems to be relatively long. You mentioned one of the limits was the amount of power available. How long did it take for the oven to cut back on the power?

MR. BEAUVY:

This time was some three minutes, or something like that if you start at 20°C.

MR. GOLDBERG:

EGG. What is the size oscillator you showed?

MR. BEAUVY:

External, about ten centimeter cubic. Ten centimeters on each side.

MR. McCOUBREY:

To what extent is the spectral density of the noise performance and the short term stability achieved considering the theoretical limits?

MR. BEAUVY:

Do you mean the theoretical limits which are located about -130 db for spectral density?

MR. McCOUBREY:

Yes.

MR. BEAUVY:

There is some progress to be done, but there are also limitations due to the electronic circuits and also the loaded Q value of the resonator, and some things like that. So I think this improvement is one of the best that can be done today.

MR. McCOUBREY:

What is the most important source of noise now, is it the crystal or the electronics?

MR. BEAUVY:

I would say both of them, it depends if you are at a place near the carrier or far from the carrier. So for some radar applications, we build oscillators for 100 or 200 megahertz, and what is important, is not noise near the carrier, but noise far from the carrier.

We can achieve much better results, starting with a hundred megacycle direct, instead of starting with ten megacycles with multiplication, but of course you are not so good right near the carrier in this case.