High Stability Cryocooled 10 GHz Oscillator For The European Space Agency

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Abstract— **This paper reports on a 10 GHz ultra-stable Cryocooled Sapphire Oscillator (CSO) developed for the European Space Agency. This CSO presents a frequency stability better than 3×10^{-15} between 1 s and 1,000 s and a phase noise lower than -100 dBc/Hz at 1 Hz.**

I. Introduction

The ever increasing need for better tracking data and scientific return in deep space missions calls for the development of new frequency references of improved stability. Ground stations of the European Space Agency (ESA) are conventionnaly equipped with hydrogen masers (HM) which are the most stable commercial atomic clocks around 1000 s – 1 day timescales ($\sigma_y(\tau \approx 1000\text{s}) < 10^{-15}$) but limited at $2 \times 10^{-13}\tau^{-1/2}$ for $\tau < 1000$s.

The Elisa project founded by the ESA has as main objective the realization of a microwave CSO with 3×10^{-15} short term frequency stability associated with the use of a cryocooler as cold source to cool down the sapphire resonator. The autonomy of the cryoccoler has to be of one year or more.

Cryogenic Sapphire Oscillators (CSO) offer unbeatable stability performances in timescales ranging from milliseconds to a few hundred seconds, and therefore extremely low phase noise close to the carrier. A combined CSO and HM system in ESA deep space stations would allow to benefit from excellent short term and long stabilities. Compared to the current performances available from hydrogen masers and state of the art quartz oscillators, CSO would provide the means to improve the orbit determination and would open the field to new radio science experiments.

II. ELISA sub-systems

The scheme in figure 1 describes the main subsystems constituting the Elisa frequency reference.

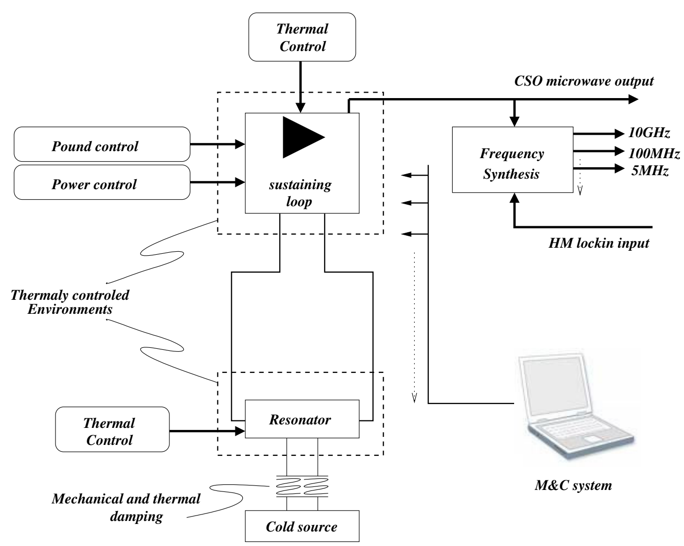

Fig. 1. ELISA sub-systems. The frequency reference is a sapphire resonator maintained at a low temperature ($\approx$ 6K) in a closed cycle cryocooler. The CSO delivers a signal at the frequency ν_0 which serves as reference for a frequency synthesis subsystem delivering the useful frequencies

The heart of the system is a whispering gallery mode sapphire resonator made of a large and thick high purity sapphire crystal (HEMEX grade [1]) cylinder placed in the center of a copper cavity (see section III). This assembly is thermally connected to the second stage of a pulse tube cryocooler. A special "soft" thermal link and a thermal ballast (see section III-B) were designed in order to filter the vibrations and the temperature modulation at about 1 Hz induced by the gas flow in the cryocooler.

Low thermal conductance coaxial cables are used to connect the Sapphire resonator to the sustaining loop placed at room temperature. The oscillating circuit is completed by two servos stabilizing the phase along the loop and the power injected into the resonator. These control loops use the same principle as those described in the reference [2] (see section IV). Apart from the CSO signal at a frequency ν_0, we have to generate three other frequencies required for ESA applications: 10 GHz, 100 MHz and 5 MHz. Moreover these useful signals should be phase locked at long term on a 100 MHz reference coming from a Hydrogen Maser (HM). A frequency synthesis was then designed to transfer the CSO's frequency stability to these useful signals with a slight degradation at 5 MHz as a result of the performance of typical RF components.

III. Cryocooled Sapphire Resonator

A. Sapphire Resonator

High purity sapphire resonators, excited on Whispering Gallery (WG) modes are well known to exhibit unloaded Q factor as high as 1 billion at the liquid helium temperature. One problem of this project was to design our sapphire resonator in order to obtain a "round" resonant frequency to simplify the development of the frequency synthesis chain. Moreover the presence of paramagnetic impurities, such as Cr^{3+} and Fe^{3+} with Electronic Spin Resonance (ESR) of 11.45 GHz and 12.04 GHz, leads us to avoid frequencies in the range 11.2 GHz-12.3 GHz. Finally the resonator was designed to obtain a frequency around 10 GHz.

By using a Finite Elements analysis, we get a $WGH_{15,0,0}$ mode at 9.990 GHz with $D = 54.20$ mm and $H = 30.00$ mm. Taking into account the machining possibilities and the cost, we ordered two sapphire pieces with $D = 54.20\mathrm{mm} \pm 10\mu\mathrm{m}$ and $H = 30.00\mathrm{mm} \pm 20\mu\mathrm{m}$. The resonator frequency is then defined as 9.990 GHz ± 3.5 MHz.

The resonator has a spindle (diameter 10 mm, length 22 mm) to be clamped from below. Such a mounting enables to reduce the mechanical stress on the region where the electromagnetic field is confined [3]. Two quasi identical resonators were machined from the same HEMEX sapphire boule by the Crystal System company. One of the two resonators named Elisa and Alizée are shown on the figure 2.

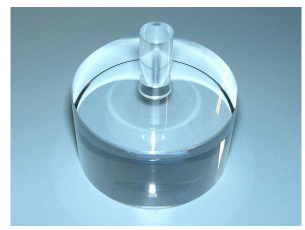

Fig. 2. *HEMEX high grade sapphire resonator.*

The resonator is clamped on the inferior plate closing the gold plated copper cavity. The latter is maintained in thermal contact with the cooling source through a copper piece in which a thermal sensor and a heater are anchored. To couple the resonator to the external circuit, we use two small magnetic loops intercepting the H_φ magnetic field component of the resonator.

Table I summarizes the main characteristics of the two resonators at their turnover temperature T_0. The adjustment of the coupling coefficients have been obtained after few cool-downs and we get input couplings (β_1) around 1 and output couplings (β_2) around 0.02.

TABLE I

Resonators parameters

	ν_0 (GHz)	T_0 (K)	Q_L
ELISA	$9.989,121$	6.13	7.4×10^8
ALIZEE	$9.988,370$	6.05	6.9×10^8

B. Cryocooler

The key point that made us opt for the cryocooler option is that unlike bath cryostat, they don't need regular refills of liquid helium. These refillings disturb the sapphire resonator which needs around two days to recover. Nevertheless two problems had to be solved: the vibrations level and the temperature fluctuations of the cryocooler cold stage. We measured temperature fluctuations of ± 100 mK on a Cryomech PT405 with a 1.3 Hz frequency corresponding to the gas cycle in the system. Oxford Instruments supplied a 4K Cryofree® cryostat modified to achieve the performance required by the ELISA project. This cryocooler fulfilled of a low displacement on the experiment plate (less than two microns in three axes) with a temperature stabilization of ± 1 mK over 1000 s and a cooling power at 4K of 50 mW. The cryocooler used by Oxford Instruments is a two-stage pulse-tube refrigerator with a rotary valve decoupled from the main dewar, eliminating the need for moving parts in the cold head. The cryostat design of the vibration reduction system is similar to those described in the references [4], [5]. The Oxford Instruments design is represented in figure 3.

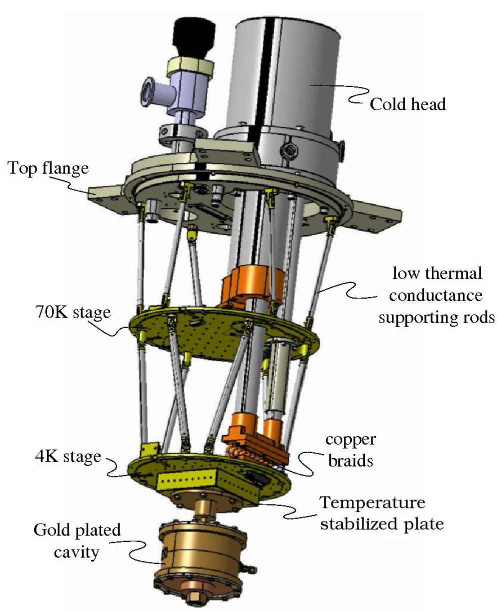

Fig. 3. *Crycooler internal design.*

The two stages of the cryostat (70K shield and 4K cold plate) are thermally linked to the cryocooler stages with floppy copper heat links. The support thin-wall tubes are mounted like an hexapod to give rigidity to the system. To limit the temperature fluctuations of the cold stage, a gadolinium gallium garnet (GGG) crystal [6] was mounted between this stage and a copper temperature stabilization block supporting the experiment using four legs. The four legs provided a tuned weak thermal link to optimize the temperature stability and cooling power of the cryostat. Few combinations of materials for the legs were used and the optimized performance was obtained when using two stainless steel and two brass/copper legs. A three axis accelerometer was fixed on the experimental plate and we measured less than 1 μm vibration in $x,\ y$ and z direction [7]. The base temperature at stabilization stage with the customer wiring is 6K with 50 mW applied to the stabilization stage for a maximum of fluctuations of 1mK.

IV. OSCILLATOR

The oscillator circuit is described in Fig. 4. It is a classical transmission oscillator circuit with two additional servo loops that control the phase and the power of the circulating signal. These two servos are mandatory to get a high frequency stability.

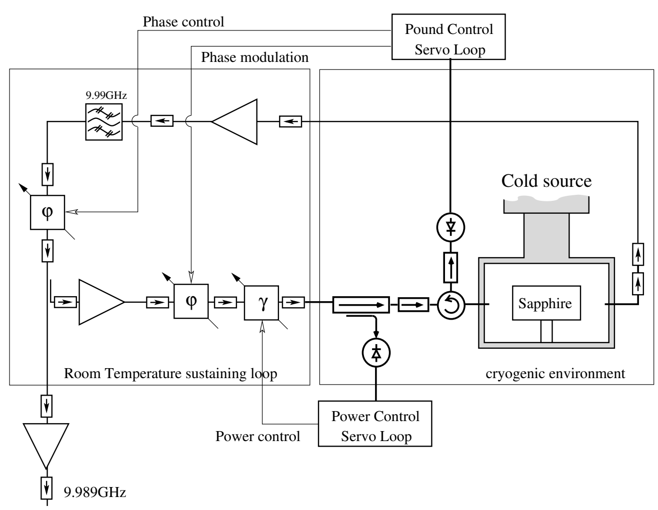

Fig. 4. *Elisa oscillator design. The sustaining loop is completed with two additional servo loops stabilizing the phase of the circulating signal and the power injected inside the resonator.*

The first servo loop is based on the Pound frequency discriminator principle [8]–[10], it ensures that the CSO oscillates at the resonator frequency ν_0 by compensating any variation of the phase lag along the loop.

Due to the radiation pressure and to the self resonator heating, the resonator frequency presents a power sensitivity of the order of 4×10^{-11}/mW. A power servo loop [11] is then used to control the injected power at the resonator input.

V. FREQUENCY SYNTHESIS

The frequency synthesis principle is given in Fig. 5. A Dielectric Resonator Oscillator is phase locked to the CSO. The frequency offset of the cryogenic oscillator is compensated with a low noise DDS. Commercial frequency dividers enable to reach the operational frequencies of 100MHz and 5MHz.

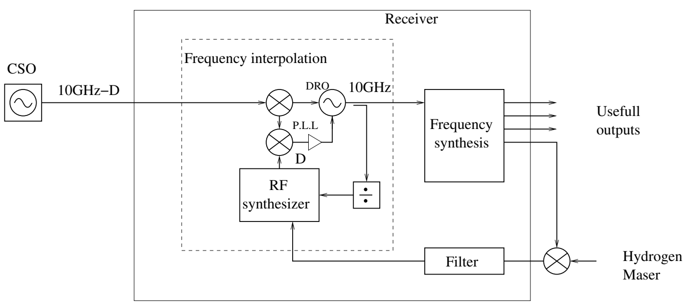

Fig. 5. *Scheme of the frequency synthesis developed by Timetech Gmbh.*

VI. PERFORMANCES

A. Frequency stability and phase noise measurement

To evaluate the relative frequency stability of Elisa, it has been compared with a second CSO build around the second resonator Alizée which is cooled in a liquid helium dewar. Apart from the cooling method, the two CSOs are quasi identical.

The time domain measurement technique is a standard one: the two oscillator signals are mixed to get a beatnote at the frequency difference which is of about 745 kHz. The beat signal is directly sent to a high resolution counter and the Allan deviation σ_y is computed from data averaged over 1s. The 3×10^{-15} frequency stability specification is almost met for $\tau \leq 1,000$ s limited by a flicker floor [12] (cf. Fig. 6). This result corresponds to a data recording of about 5 hours (15192 samples) without any post-processing applied to the raw data.

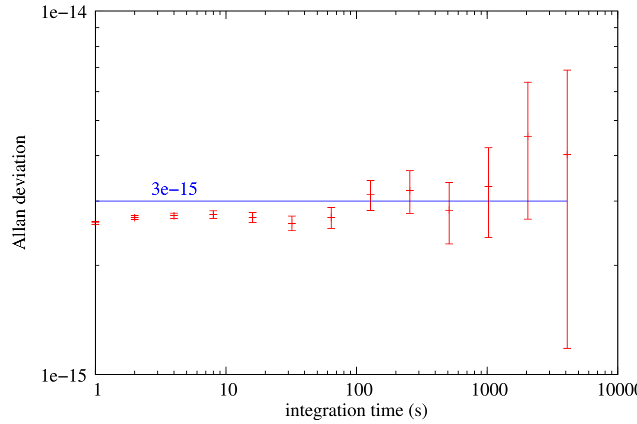

Fig. 6. *Maximal frequency instability of the cryocooled CSO Elisa measured by direct comparison with Alizée cooled in a liquid helium bath.*

The CSO's phase noise has been measured by demodulating the 745kHz beatnote with the signal coming from a divided RF synthesizer [13]

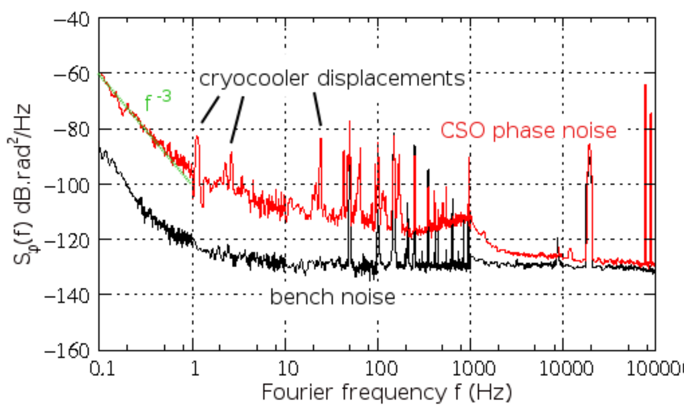

Fig. 7. *Phase noise of Elisa.*

At low Fourier frequencies, the measured phase noise is dominated by a flicker frequency noise (f^{-3} slope). For one CSO, we get $S_\phi(1Hz) = -98$ dB.rad^2/Hz equivalent at $\sigma_y(1s) \approx 1.5 \times 10^{-15}$ in the time domain. This result is coherent with the $\sigma_y(1s) \approx 2.6 \times 10^{-15}/\sqrt{2} \approx 1.8 \times 10^{-15}$ measured previously. On the same spectrum, bright lines resulting from the residual vibrations are clearly visible. from the power of first line at 1.14 Hz, we estimated that the residual displacement of the resonator is less than 1 μm.

A new tuning of the servo controls improved the short term frequency stability of Elisa and Alizée as indicated in red in Fig. 8. The flicker floor decreased until 1.5×10^{-15} reached at 20s. At longer integration times, the CSOs are limited by a random walk $\sigma_y(\tau) \approx 1.3 \times 10^{-16}\sqrt{\tau}$ due to the sensitivity of the liquid helium to the atmospheric pressure.

On the same plot we have also represented the performances of the 10 GHz and 100 MHz outputs of the frequency synthesis chain. As we can see there is just a small degradation at short integration time.

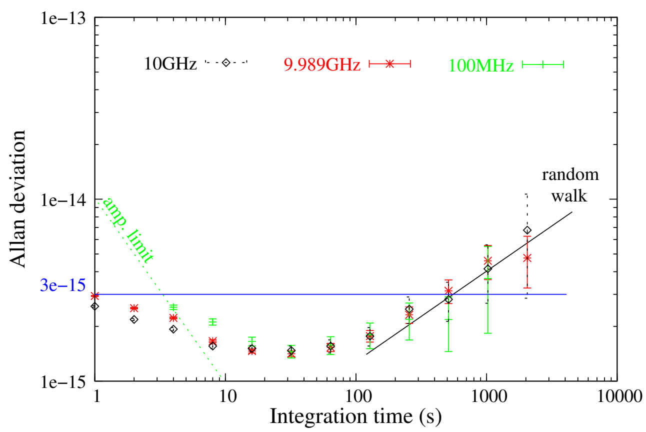

Fig. 8. *Allan deviation of the resulting beatnote signals at 10GHz (black curve), 9.989GHz (red curve) and 100MHz (green curve).*

VII. Conclusion

This article summarizes the latest results obtained on the Elisa project founded by the European Space agency. This study led to the development of a cryocooled sapphire oscillator named Elisa. Elisa shows an exceptional Allan deviation inferior of 3×10^{-15} for integration times ranging from 1s to 1000s for a phase noise of $S_\phi(1Hz) = -98$ dB.rad^2. Moreover, the frequency synthesis chain enables to transfer the performances of Elisa at the operational frequencies of 10GHz and 100MHz without degradations of the reference signal.

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