# ELISA: an Ultra-Stable Oscillator for ESA Deep Space Antennas

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## I. INTRODUCTION

Deep space tracking requires frequency references exhibiting excellent frequency stability. The frequency standards currently implemented in the European Space Agency (ESA) ground stations are based on an ultra-stable X-tal oscillator stabilized at long term on an hydrogen Maser. The short term frequency stability of this system is typically of $1 \times 10^{-13}$ for integration times $\tau \leq 100$s resulting from the performance of the state-of-the-art X-tal oscillator. For longer integration time the frequency stability is improved by the locking on the hydrogen maser. In order to validate new experiments in the field of radiosciences or space navigation, the short term performance of the ground station frequency reference must be improved. ESA has founded a project called ELISA with the objective to get a short term frequency stability of $3 \times 10^{-15}$ over time intervals between 1 s and 1000 s. The project is realized in collaboration between the FEMTO-ST Institut (prime), the National Physical Laboratory (NPL) and Timetek GmBh.

ELISA consists in a Sapphire Whispering Gallery Mode Resonator maintained at low temperature ($\approx$ 6K) in a pulse tube cryocooler. The system is completed by a classical sustaining circuit with Pound and Power controls implemented at room temperature. A synthesis chain will later be added to generate 10GHz, 100 MHz and 5 MHz outputs signals. In this paper, we describe the resonator design and the preliminary tests realized at different modul level.

## II. SAPPHIRE RESONATOR DESIGN

Since more than 10 years, the technology of cryogenic whispering gallery mode resonator [1] has proved its ability to produce ultra-stable microwave frequency references. Q-factors up to 1 billion are currently obtained in X-band and at the liquid helium temperature [2], [3]. Moreover intrinsic paramagnetic impurities contained in low concentration in high purity Sapphire monocrystal leads to suppress at first order the natural frequency sensititivity of the resonator modes to temperature fluctuations [4]. Records in short term [5], [6] and mid-term frequency stability [7], [8] have been obtained with such microwave references operating generaly in liquid helium dewar.

The resonator size and WG mode order determine the resonant frequency and the loss, thus the parameter $Q$. Experience shows that the best results are obtained with WG mode order between 13 and 18. The energy confinement in the dielectric improves as the mode order increases. This fact has two practical consequences: 1) $Q$ is progressively degraded at lower-order modes (less than 13) because of electromagnetic radiation, and 2) high order modes (greater than 18) are difficult to exploit because the couplers needs too sharp adjustment. Another difficulty connected with high-order modes is the presence of many spurious modes, which makes the frequency selection difficult. For reference, a liquid-He sapphire resonator of diameter $\Phi = 50$ mm and height $H = 20$ mm measured at FEMTO-ST has the $WG_{15}$ mode at $\nu_0 \approx 10.9$ GHz. The quality factor of this mode is $Q = 2 \times 10^9$. For practical reasons the resonator size can not be too large. A diameter of about 50 mm is comfortable for mechanics and cryogenics. This means that the resonant frequency should not be lower than some 9 GHz (see Fig.1).

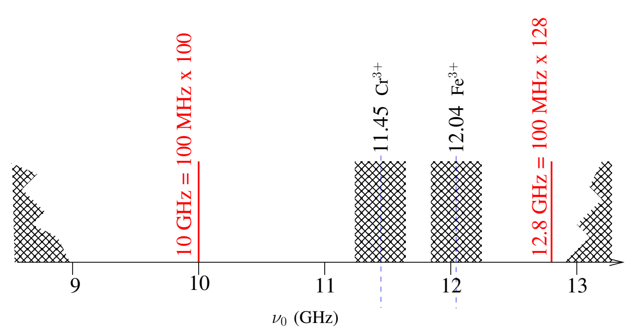


Fig. 1. The choice of the sapphire resonator frequency

Dielectric dissipation in sapphire increases as frequency increases. This phenomenon sets a soft upper limit at some 13 GHz. Finally, the resonance of the $Cr^{3+}$ ion at 11.45 GHz, and the resonance of the $Fe^{3+}$ ion and 12.04 GHz are to be avoided. A margin of $\pm$200 MHz is recommended.

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To simplify as much as possible the synthesis chain design, we can choose between two round frequencies: 10 GHz or 12.8 GHz. So that the synthesis relies (almost) only upon divide-by-two, multiply-by-two components and a RF interpolation synthesizer. 10 GHz was eventually choosen mainly because it corresponds to a lower order mode and then the resonator coupling should be easier and also because at such a frequency there are low-flicker SiGe amplifiers commercially available [9].

Due to machining tolerance (few to 10 MHz), the round frequency can not be obtained. As the tolerance can not be nulled with temperature or with electrical tuning, it will be compensated with a RF synthesizer operating at a comfortable low frequency $\delta\nu_{RF}$. The objective is then to design the resonator to get a high-Q whispering gallery mode at 10GHz-$\delta\nu_{RF}$ with $\delta\nu_{RF}$ = 10MHz ±5MHz which is a fairly good low-noise operation condition for a Direct Digital Synthesizer (DDS).

The resonator design is represented in the figure 2. It consists in a sapphire resonator with a spindle placed in the center of a copper cavity.

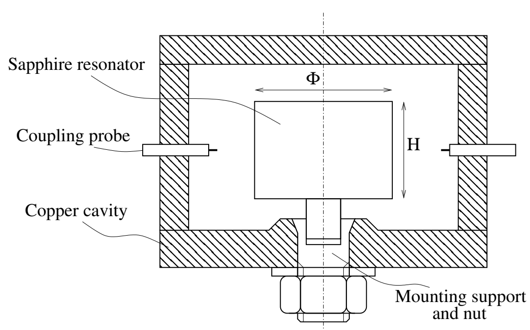


Fig. 2. Sapphire resonator geometry

The resonance frequency is mainly determined by the resonator diameter $\Phi$ and a for a smaller extent by its height $H$. The spindle diameter and height as well as the metallic cavity dimensions have a negligible influence on the resonator frequency. The spindle constitutes the thermal and mechanical interface with the cavity. We alrady tested such a configuration in some previous studies. We get with $\Phi = 50$mm and $H = 30$ mm a high-Q $WGH_{15,0,0}$ mode at 10.810 GHz. This previous experience constitutes the starting point for the new resonator design which has been refined with the help of Finite Elements simulation (Figure 3).

The key parameters to accuratly determine the modes frequencies are the values of the sapphire tensor permittivity components used for the calculation. By comparating experimental frequencies of available crystals and simulation results, we deduced the values of the permittivity components at 4K to be: $\epsilon_{\perp} = 9.270,688$ and $\epsilon_{//} = 11.340,286$. Eventually, we get a $WGH_{15,0,0}$ mode at 9.989,89 GHz with $\Phi = 54.2$ mm and $H = 30$ mm. Taking account the machining posibilities

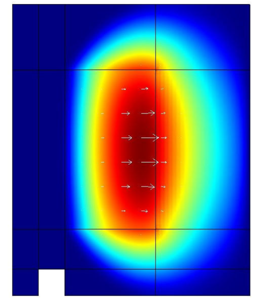

Fig. 3. $WGH_{15,0,0}$ magnetic field configuration simulated by F.E..

and the cost, we eventually ordered two sapphire pieces with:

$$\Phi = 54.2\text{mm} \pm 10\mu\text{m} \quad \text{and} \quad H = 30\text{mm} \pm 20\mu\text{m}: \qquad (1)$$

The resonator frequency is then defined as $9.989GHz$ $\pm 3.5MHz$.

The complete set of the resonator frequencies has been obtained through another model based on the mode matching technique (Figures 4 and 5).

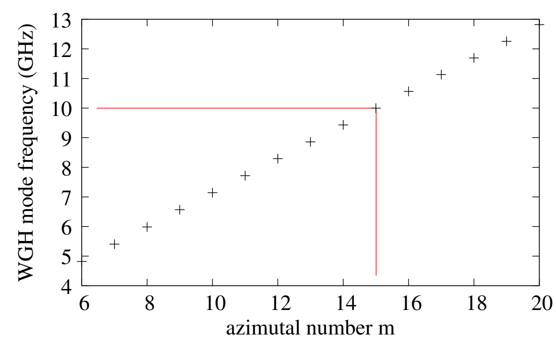


Fig. 4. Sapphire resonator frequencies for $WGH_{m,0,0}$ modes (4 K).

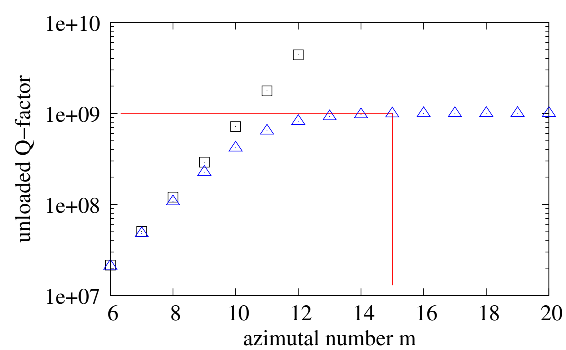


Fig. 5. △: Q-factor for $WGH_{m,0,0}$ modes; ⊡: contribution of metallic losses at 4 K

Although less accurate than F.E. model, the mode matching method enables to evaluate rapidly the frequency and Q-factor of the whispering gallery modes. For WGH modes with $m > 5$, resonance frequencies and Q-factor are determined with 1% and 10% accuracy respectively.

## III. RESONATORS PRELIMINARY TESTS

The coupling coefficient at each resonator port has to be adjusted at room temperature in order to get the optimal value at low temperature. The input coupling coefficient is the most critical. Its optimal value is $\beta_1 = 1$. $\beta_2$ has to be set to a low value to limit the loaded Q-factor degradation. As the coupling coefficient increases during cooling as the unloaded Q-factor, we can deduce the room temperature value of $\beta_1$ from the relation:

$$\frac{\beta_1^{4K}}{\beta_1^{300K}} = \frac{Q_0^{4K}}{Q_0^{300K}} \tag{2}$$

If we assume a $Q_0^{4K} = 1 \times 10^9$ and $Q_0^{300K} = 2 \times 10^5$, the coupling coefficient will be multiplied by 5,000. In order to get $\beta_{1_{4K}} = 1$, we have to adjust $\beta_1^{300K}$ to $2 \times 10^{-4}$. Assuming remains $\beta_2 \ll 1$, $\beta_1$ is simply related to the resonator input port reflection coefficient $S_{11}$ at resonance through:

$$S_{11} = \frac{1 - \beta_1}{1 + \beta_1} \tag{3}$$

That gives at room temperature $S_{11} = 0.9996$ (or $-3.5 \times 10^{-3}$dB) which is a very low value but that can be observed with good Network Analyser (NA).

Each resonator was mounted in its copper cavity and the coupling is adjusted by changing the probe penetration inside the cavity until getting the preceding value of $S_{11}$. Then the resonator is cooled down to 4K into a cryocooler. This first adjustment enables to approach roughly the right coupling value but nevertheless few cooling downs are required to optimize $\beta_1^{4K}$. Figures 6 and 7 shows the transmission $S_{21}^{4K}$ and reflexion $S_{11}^{4K}$ coefficients for our two resonators after this optimisation step.

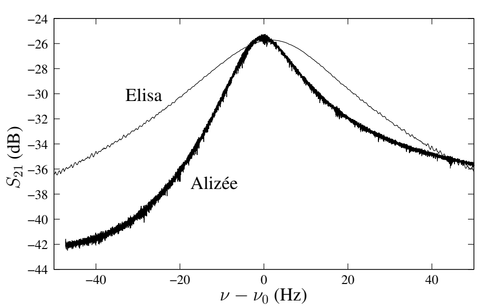


Fig. 6. Transmission coefficient $S_{21}$ for the two resontors. Resonance frequencies have been shifted for comparison.

we get:

| | $\nu_0 (GHz)$ | $Q_L/10^6$ |
|---|---|---|
| ELISA | $9.989, 125$ | 330 |
| ALIZEE | $9.988, 370$ | 690 |

The two resonator frequencies are in accordance with our prediction taking account the machining tolerances and differ from 755kHz. For a direct comparison of the two oscillators, this beatnote frequency is still compatible to be counted with a sufficient resolution with state-of-the-art frequency counters. The Q-factor of Elisa is two times lower and that certainly results from a cleanness defect of this resonator which has not been cleaned after the phase of the coupling adjustment during which it was submitted to few pression and temperature cycles.

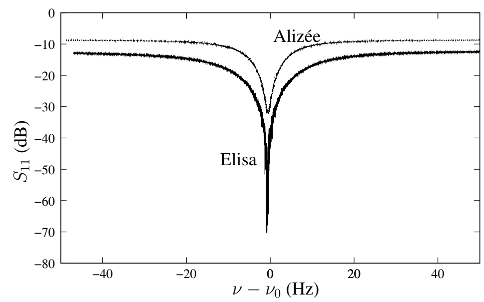


Fig. 7. Input port reflexion coefficient $S11$ for the two resontors. Resonance frequencies have been shifted for comparison

The couling coefficients have been determined from these measurements and we get: $\beta_1^{4K} = 1.09$ for Alizée and $\beta_1^{4K} = 1$ for Elisa. We also checked the turnover temperatrue by slowly increasing the resonator temperature and recording its resonance frequency: $T_0 = 5.9$K and 6.1K for Alizée and Elisa respectively.

## IV. CRYOGENIC SAPPHIRE OSCILLATORS PRELIMINARY VALIDATION

The objective of ELISA project is to design a frequency reference that does not require the use of liquid helium and then eventually the resonator has to be cooled in a cryocooler. However, at this stage of the project, we need to validate all the oscillator sub-systems in a stable environment and then we conducted preliminary tests with the two resonators placed in two separated liquid helium dewars as represented in the figure 8.

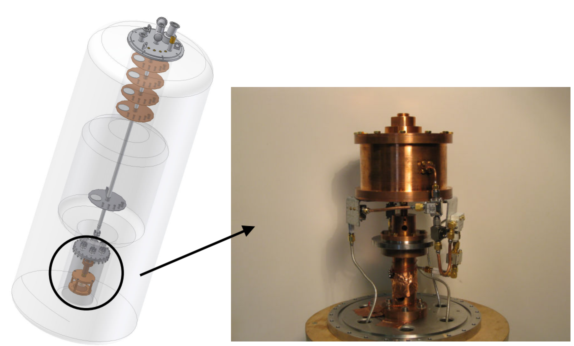

Fig. 8. Picture of the 100l L-He dewar, vaccum chamber and cavity with resonator

Figure 9 shows the typical circuit that has to be implemented to get the optimal performance.

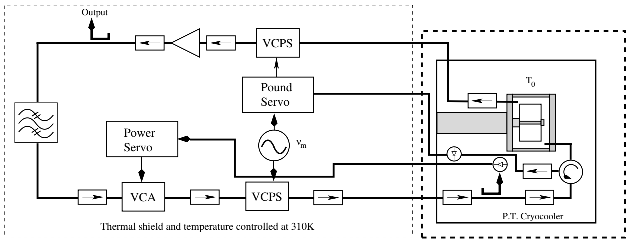


Fig. 9. Scheme of the oscillator circuit. The bold lines are the oscillator loop. The thin lines refer to the electronic controls required to get a high frequency stability

The oscillator operation is ensured by a classical sustaining loop consisting in two microwave amplifiers and a filter 100MHz bandwidth to select the $WGH_{15,0,0}$ mode. This microwave circuit is completed by two servos loops, i.e. a Pound servo to correct the phase fluctuations along the loop and a power servo stabilizing the power injected into the resonator. All these electronic circuits are placed at room temperature.

At the time of the conference, the two power servos were not be put into operation. The two oscillators were comparated directly by beating the two microwave signals. The observed frequency stability is represented in the figure 10:

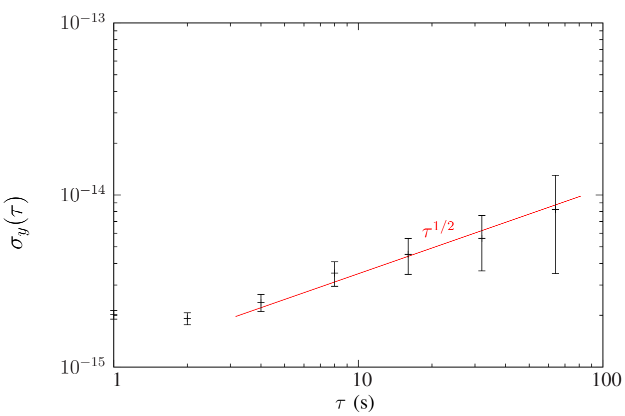


Fig. 10. Allan Deviation as measured directly by beating the two cryogenic oscillators

The measured short term frequency stability is $2 \times 10^{-15}$ at 1s and a randow walk of frequency is observed from few seconds. We attributed this frequency stability degradation to the lack of power servos. The microwave cable linking the resonator to the external circuit pass through the liquid He which evaporates continously. The cables are then never in thermal equilibrium and their losses vary with time.The measured resonator frequency sensitivity to power is about $4 \times 10^{-11}$/mW and then any power variation will induce a oscillator frequency change. The two power servos will be implemented in a second step in order to solve this issue.

## V. CRYOCOOLER

As previously mentioned the Elisa cryogenic oscillator should be implemented in a ESA ground station and then it should have a large autonomy. The use of liquid Helium dewar requiring refilling every week or even every month should be absolutly avoided. The Elisa Resonator should then be placed into a cryocooler.

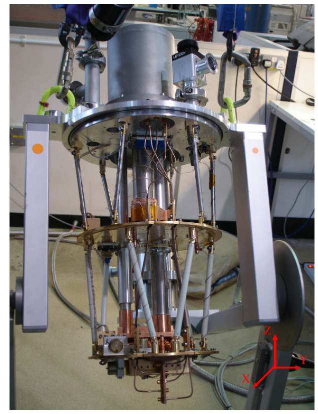

Fig. 11. Oxford Instruments cryocooler

Such an instrument are know to generate large mechanical vibration that can impact on thefrequency performance of the CSO. In a previous paper we presented the evaluation of the acceleration sensitivity of the sapphire resonator [10]. Thsi sensitvity is $-3.21 \times 10^{-10}/g$. To meet ESA's frequency stability target of $3 \times 10^{-15}$, with a pulse-tube cooler shaking at its characteristics/fundamental frequency of 1 Hz, this sensitivity translates into demanding that the resonator's vertical amplitude of deplacement (at 1 Hz) be less than 2 $\mu$m. Indeed, if we assume that the deplacement $x\left(t\right)$ of the resonator takes the form

$$x\left(t\right) = A_0 sin\left(\omega t\right) \quad (4)$$

then the acceleration is given by

$$\frac{d^2x}{dt^2} = -\omega^2 A_0 sin\left(\omega t\right) \quad (5)$$

With cryocoolers the main source of vibrational noise is at the drive frequency of cooling cycle, typically about 1 Hz. Therefore, equation 5 simplifies to

$$\frac{d^2x}{dt^2} = -4\pi^2 A_0 sin\left(\omega t\right) \quad (6)$$

Hence, for vibration levels of $6 \times 10^{-6}$ g we require a maximum peak displacement $A_0$ of

$$A_0 \leq \frac{9 \times 10^{-6} g}{4\pi^2} \quad (7)$$

$$A_0 \lesssim 2\mu m \quad (8)$$

A task of designing a vibration free cryocooler was given to Oxford Instruments that just delivers the instrument (see figure 11).
Mechanical vibrations were measured by Oxford Instruments with accelerometers placed in accordance with the X, Y and Z axes (Figure 11). Figures 12, 13 and 14 show the power spectrum density of displacement ($\mu m_{RMS}/\sqrt{Hz}$).

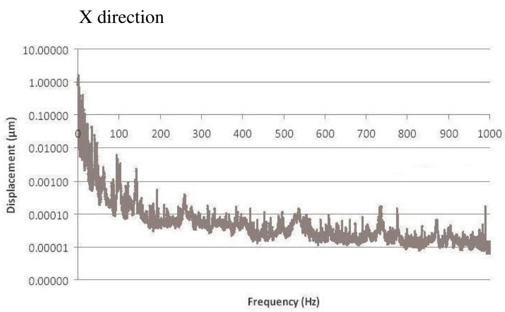


Fig. 12. X displacement

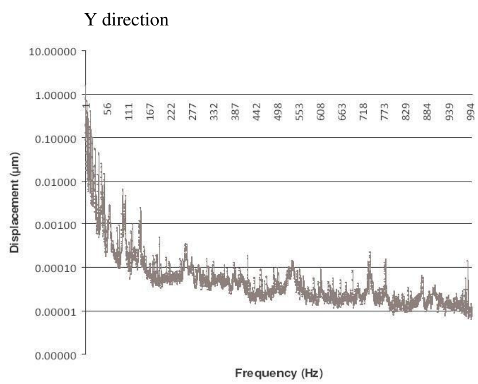


Fig. 13. Y displacement

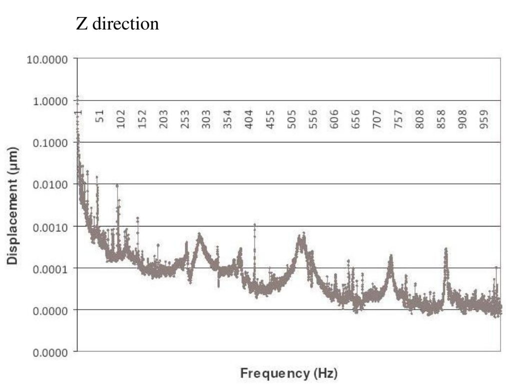


Fig. 14. Z displacement

We notice that, at 1Hz, for each directions, the displacement is inferior to $1\mu m$ which corresponds to the specification (eq. 8).

## VI. CONCLUSION

The technology of the Sapphire Whispering Gallery Mode Resonator allows to surpass the frequency stability of traditional ultra-stable oscillators, and then can be exploited in number of applications requiring a high frequency stability as a frequency standard for the ESA ground station for which the requirement in term of frequency stability is $\sigma_y(\tau) = 3 \times 10^{-15}$ for integration times $1 \leq \tau \leq 1000s$.

We presented here the different steps of our resonator design. Two almost equivalent resonators have been realised and characterised at low temperature. Two CSO have then be implemented around these two resonators cooled in a preliminary step in liquid helium dewars. Although the two CSO are not totally optimised, we get a short term frequency stability of $2 \times 10^{-15}$ at 1s. Power servos that will be implemented in a second step will improve the long term frequency stability which is at the present time degraded by a random walk of frequency of the order of $1 \times 10^{-15}\tau^{1/2}$.

The cryocooler that will be eventually used to cool the Elisa resonator was characterised for its mechanical vibrations. It has been confirmed that the displacement at the resonator level is less that $2\mu$m that should be sufficient to get the ESA requirement.

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