Principle of Pulsed-Interrogation Automatic Cavity Tuning for the ACES Hydrogen Maser

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***Abstract*— The output frequency of the Space Hydrogen Maser (SHM) developed by the Observatoire de Neuchâtel (ON) as reference clock in the Atomic Clock Ensemble in Space (ACES) experiment on-board of the International Space Station (ISS) shall guarantee a relative long-term frequency stability of $\sigma_y(10000s) = 1.5 \cdot 10^{-15}$. For this purpose, its microwave cavity resonance frequency is to be actively stabilized at 0.1-Hz level, in order to compensate for the cavity pulling effect. The associated electronics developed by ON uses a novel Pulsed-Interrogation Automatic Cavity Tuning (PI-ACT) principle. Details of the design and performance results of the ACT shown on a laboratory demonstrator are given.**

I. Introduction

In Hydrogen Masers (HM), long-term frequency stability is limited by the cavity pulling effect. Various ACT methods have been proposed and implemented to compensate for this limitation. Some are based on modulating the atomic quality factor ("spin-exchange") ([3]). Others derive an error signal by modulating the cavity quality factor ([4]). A third auto-tuning concept is based on an interrogation signal feeding the cavity. The response of this interrogation signal gives direct information on the cavity resonance frequency. The third method, which has also been referred to as “fast cavity auto-tuning” concept ([6], [7]), combines a number of advantages: it requires no second HM and allows long-term stability improvement with only minimal short-term stability degradation.

The Pulsed-Interrogation Automatic Cavity Tuning (PI-ACT) developed at the Observatoire de Neuchâtel (ON) for the Space Hydrogen Maser (SHM) belongs to third group but introduces a number of novelties ([8]). Unlike conventional ACT systems, that continuously interrogate the cavity resonance frequency by using for example square-wave frequency modulation, the PI-ACT principle, in addition to jump periodically between two frequencies, lower resp. higher than the cavity resonance frequency, also shows regular periods where no power is injected into the cavity. This greatly reduces any residual cavity pulling introduced by the interrogation signal. The interrogation signal is time-multiplexed with the atomic signal detection: typically 50% of the time is used for the ACT and 50% for the main Phase-Locked Loop (PLL), where the master Oven-Controlled Crystal Oscillator (OCXO) is locked to the atomic signal.

II. SHM for ACES

The “Atomic Clock Ensemble in Space” (ACES) is an ESA mission in fundamental physics based on high-performance clocks in the microgravity environment of the International Space Station (ISS). At the heart of the ACES system is the laser-cooled cesium clock “Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite” (PHARAO) provided by CNES, which is frequency-referenced by the SHM provided by ON. In order to overpass the medium-term performance of PHARAO, the SHM is mandatory. ON is currently developing this maser. After the development of the ACT and its performance demonstration with a laboratory demonstrator, ON is presently focusing on the atomic resonator, while the development of the control and frequency locking space electronics has been assigned to the co-contractor Oerlikon Space Zurich (OSZ).

The SHM for the ESA ACES mission is presented in more details in two other EFTF-IFCS 2007 papers ([1] in general, and [2] for the Physics Package (PP) especially).

Feasibility demonstration of the SHM, operated with a space-worthy electronic breadboard, has been shown, and will enable, in next project phases, development for meeting ACES-level required specifications.

III. PI-ACT Design

A. General

The PI-ACT design was driven by the following major requirements of the ACES mission and constraints of the PP design:

- $\sigma_y(1s) \le 1.5 \cdot 10^{-13}$.
- $\sigma_y(10s) \le 2.1 \cdot 10^{-14}$.
- $\sigma_y(100s) \le 5.1 \cdot 10^{-15}$.

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- $\sigma_y(1000s) \le 2.1 \cdot 10^{-15}$.
- $\sigma_y(10000s) \le 1.5 \cdot 10^{-15}$.
- SHM base-plate temperature following a sine-wave (1.5-K peak-to-peak amplitude and 1.5-h period).
- Sapphire-loaded microwave cavity temperature stabilized at millikelvin level, corresponding to 100-Hz resonance frequency stability.

Then, the ACT electronics shall further improve the cavity resonance frequency stability at 0.1 Hz.

B. Principle (Fig. 1)

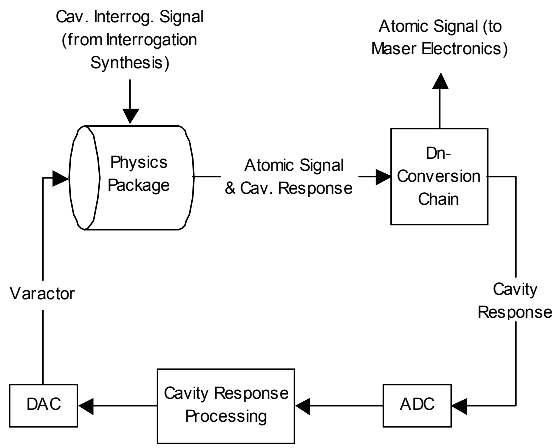

Figure 1. Principle of the method

A frequency-modulated microwave signal (interrogation signal), is injected into the cavity and transmitted through it. It has three states:

- Left (lower) frequency injection.
- Right (higher) frequency injection.
- No frequency injected.

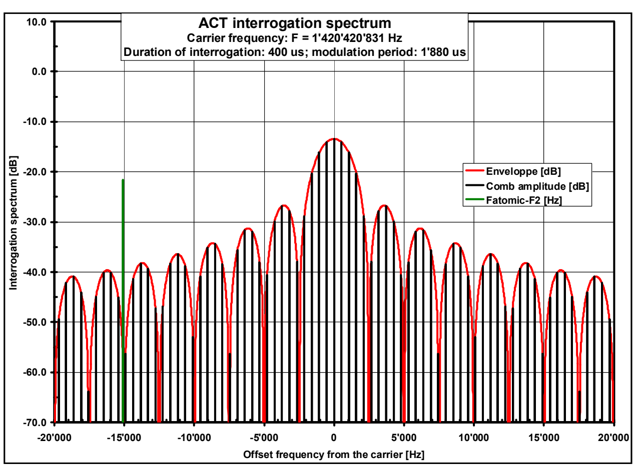

Figure 2. Typical interrogation signal composite spectrum (only right injected frequency considered)

A typical interrogation signal composite spectrum is shown in Fig. 2. On the Hz-axis, we have *e.g.*:

- At 0 Hz: the right injected frequency position.
- At about –15000 Hz: the atomic frequency spectral line.

Note that the numerous spectral lines presented are following a sin(x)/x envelope.

The spectral line shown at about –15000 Hz (Fig. 2), representing atomic frequency, shall in no way coincide with any interrogation signal spectral line (disturbance of the atoms). The atomic frequency shall then ideally stay on a sin(x)/x function zero-crossing, *i.e.*:

- Left frequency offset (w.r.t. atomic frequency) integer multiple of the left injection duration inverse value.
- Right frequency offset (w.r.t. atomic frequency) integer multiple of the right injection duration inverse value.

When the cavity resonance frequency is temporarily slightly different from the average of the two injected frequencies, the response signal from the cavity then returns different amplitudes for left and right. These two amplitudes are separately computed by means of a non-coherent correlation amplitude detection algorithm ([10]). The left-minus-right amplitude value is then applied to a high-gain integrator, and the output signal sent to the varactor diode controlling the cavity resonance frequency. The so-implemented control loop allows cavity resonance locking to the average of the two injected frequencies.

C. Features

- Cavity resonance frequency adjustable to the spin-exchange tuned frequency of hydrogen atoms.
- No hazardous spectral lines at maser frequency.
- No second maser needed.
- Fast cavity-control loop, in order to compensate for ACES medium-term temperature variations in orbit.
- In the chosen PI scheme, the injected power duty-cycle is 50%. This allows the main PLL to be totally insensitive to the interrogation signal, thanks to its hold state of 50% duty-cycle too.

D. *Main Design Drivers*

1) Modulation Depth (Fig. 3)

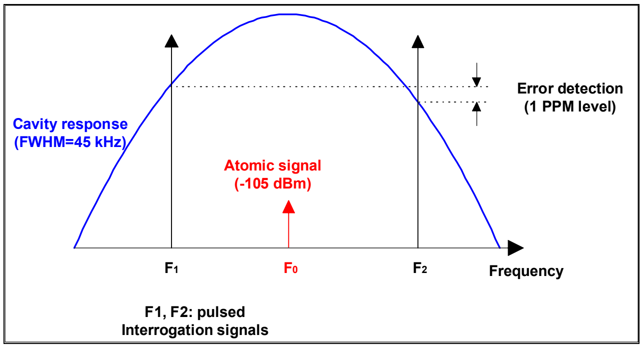

Figure 3. Cavity response to the interrogation signals

Ideally, the modulation depth shall be selected so that left and right injected frequencies coincide with cavity power gain-vs-frequency normalized response curve maximum slope.

2) Modulation Frequency

Goal of optimizing the interrogation signal modulation frequency is to have all spectral lines distant from f_{maser} = 1420.405751 MHz, in order not to disturb the atoms. A favorable situation is shown in Fig. 4.

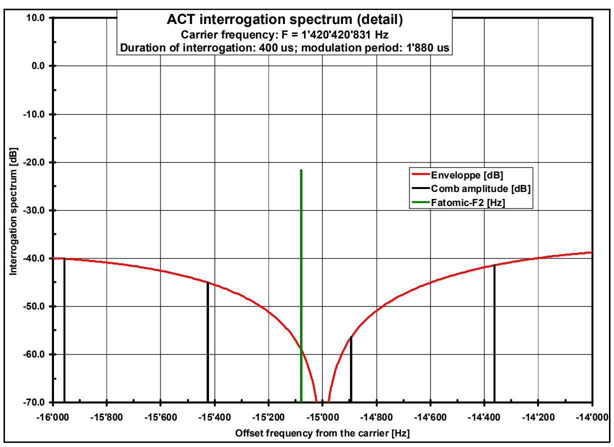

Figure 4. Interrogation signal composite spectrum (detail of Fig. 2)

Note that in Fig. 4, the atomic frequency line is not precisely, as recommended in Chap.IIIB, on a sin(x)/x function zero-crossing. But the 60-dB noise attenuation shown can be considered as large enough.

For modulation frequency optimization, frequency values of the spectral lines present in the interrogation signal shall be known. They can be determined at least in following ideal cases:

- Interrogation sine-wave phase random w.r.t. the modulating signal. Interrogation signal spectrum is continuous, and no hazardous spectral lines are to be expected.
- Interrogation sine-wave phase as if left resp. right sine-wave would be permanent for itself. The interrogation signal spectrum contains potentially hazardous spectral lines of frequency $f_{left}+n\bullet f_{modulation}$ and $f_{right}-n\bullet f_{modulation}$ (product, in the time domain, of f_{left}-carrier resp. f_{right}-carrier with the on/off signal of repetition frequency $f_{modulation}$).
- Left resp. right interrogation sine-wave phase always the same at the beginning of a new left resp. right sine-wave burst. The interrogation signal is periodic with repetition frequency $f_{modulation}$. The interrogation signal spectrum then contains the spectral lines of frequency $n\bullet f_{modulation}$.
- Interrogation sine-wave phase as if sine-wave would be permanent for itself, with continuous phase, and 50% duty-cycle for left resp. right frequency. It can be shown in this case that the interrogation signal spectrum contains *dominating* spectral lines of frequency $(f_{left}+f_{right})/2 + n\bullet f_{modulation}$ and $(f_{left}+f_{right})/2 - n\bullet f_{modulation}$. Converging interpretation: square-wave frequency modulation spectrum with carrier frequency $(f_{left}+f_{right})/2$ and modulation depth $(f_{right}-f_{left})/2$ (see also [9]).

Although the type of Direct Digital Synthesizer (DDS) used in the ON demonstrator corresponds to the fourth ideal case above, it is safer to check more generally that, in the four cases considered, all interrogation signal spectral lines are distant from the f_{maser} spectral line.

3) Modulating Signal Slopes

As already said, the frequency modulating signal has three states, and the switching times from one state to the next are ideally zero. This results into a spectrum in sin(x)/x around f_{left} resp. f_{right} (Fig. 2). The sin(x)-function envelope, in $1/f_{offset}$, is a –20dB/decade asymptote.

Now, in the case of non-zero switching times (*e.g.* linear ramps of duration $\tau_{switching}$), the spectrum asymptote shows a knee ([11]) at offset frequency $f_{knee} = 1/(\pi\bullet\ \tau_{switching})$ for changing to –40 dB/decade. This assures at f_{maser} practically 3 dB of additional spectrum attenuation w.r.t. $\tau_{switching} = 0$.

4) Signal-to-Noise Ratio

Thermal noise added to the cavity response signal is a critical topic in this ACT concept. Signal-to-Noise Ratio (SNR) shall be strictly controlled all along the down-converting chain. This is because, at the end, additive noise present at cavity response amplitude difference high-gain integrator input shall be compensated to zero by an equal (but opposite in sign) parasitic left-minus-right amplitude value. This difference can only be produced by a cavity resonance frequency jitter, which obviously modulates the maser output signal by white frequency noise. Following parameters are playing a major role in SNR:

- Interrogation signal level has a direct influence on SNR. But a too high level would disturb the atoms.
- The interrogation signal is following the four-state sequence ... — LEFT SINE — NO INJECTION — RIGHT SINE — NO INJECTION — ... As practical compromise, all four states have approximately equal durations (exact values need to be determined by the

two formulas in Chap.IIIB). This means of course that the non-coherent correlation amplitude detection algorithm cannot observe left resp. right sine-wave longer than a quarter of the time. This represents an absolute minimum of 6-dB SNR loss.

- The down-converting chain is composed of a certain number of Radio Frequency (RF) mixers. In front of each of them, there is a filter. One task of this filter is to reject image noise that adds to the existing noise by aliasing effect in the RF mixer.

5) Left-Minus-Right Amplitude Stability

Detected left-minus-right amplitude stability is another critical topic in this ACT concept. Stability shall be strictly controlled all along the electronic stages, in the order of 10^{-6}. This is because, at the end, cavity response amplitude difference high-gain integrator input fluctuations shall be compensated to zero by an equal (but opposite in sign) parasitic left-minus-right amplitude value. This difference can only be produced by a cavity resonance frequency jitter, which modulates in frequency the maser output signal according to the unwanted fluctuations. Following parameters are playing a major role in the detected amplitude difference stability:

- Keeping down-converting chain gain flat vs frequency is extremely important. This is because left and right injected frequency values are not the same. Then, same gain at both frequencies means, for instance, that comparable gain-vs-temperature coefficient at both frequencies can be expected.
- Keeping left and right cavity response amplitudes identical all along the down-converting chain.
- Keeping ACT electronics temperature fluctuations low: thermal control of some components.

E. Non-Conventional Implementation Features

1) Interrogation Signal Synthesis

The interrogation signal generation needs only one up-conversion (Fig. 5).

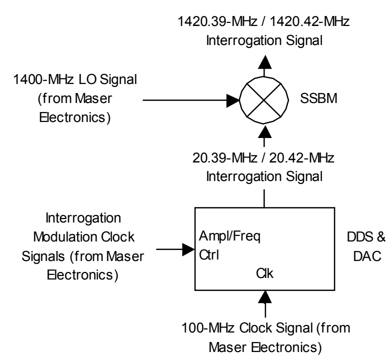

Figure 5. Interrogation signal synthesis

A 100-MHz clock signal, delivered by the maser timing electronics, is used as reference clock for the DDS (using phase accumulation principle). Left resp. right frequencies generated by the DDS are typically 20.39 MHz resp. 20.42 MHz. In other words, the DDS is generating the needed frequency-modulated interrogation signal, but at lower frequency. Modulation frequency is typically 498 Hz.

Above signal is then up-converted to 1420.39 MHz resp. 1420.42 MHz by means of a Single-Sideband Mixer (SSBM).

2) Cavity Response Processing

The response signal from the cavity feeds the Low-Noise Amplifier (LNA), feeding itself the down-converting chain. Note that the down-converting chain is common to cavity response and atomic signal, as far as the two higher converting stages are concerned. At this point, two signals are present:

- 4.594-MHz down-converted atomic signal.
- 4.610-MHz resp. 4.580-MHz down-converted cavity response signal.

About half of the power is sent to the maser electronics for locking the master OCXO to the atomic signal. The main PLL operation is not influenced by the cavity response signal because, during active injection (half-time in the average), the main PLL can stay in hold state.

The other half is sent to an additional down-converting stage − with 4.594-MHz Local Oscillator (LO) – in order to convert to Direct Current (DC) the unwanted atomic signal. At the output of this stage, we have a typically 16-kHz resp. 14-kHz down-converted cavity response signal.

At such low frequency, the cavity response processing can be done by software (Fig. 6), with highest amplitude stability in temperature and time:

- LO generation (cosine/sine tables).
- Non-coherent correlation amplitude demodulation (products).
- Filtering (accumulation).
- Squaring.
- Square root.
- Proportional Integral Differential (PID) controller.

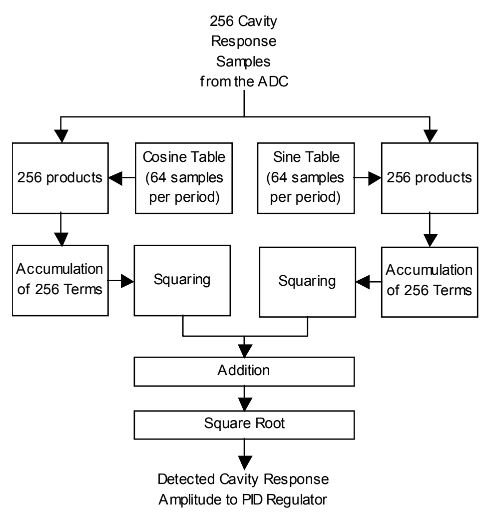

Figure 6. Non-coherent correlation left resp. right amplitude detection

Note (Fig. 6) that even if one cavity response amplitude difference sample is computed every 2 ms (interrogation signal modulation period), a new sample is sent to the cavity varactor Digital-to-Analog Converter (DAC) only about each 1.7 s, rendering possible cavity resonance frequency drift not corrected fast enough. Therefore a double integrator was implemented in the ACT loop filter, to cancel potential cavity resonance frequency drift.

IV. ACT Demonstrator Measurement Results

A. *Stability Measurements with Physics Package Prototype Engineering Model*

1) *Device Under Test*

The Device Under Test (DUT) is the Physics Package Prototype Engineering Model (PP-PEM). The PP-PEM is representative of the Physics Package Engineering Model (PP-EM), with the main difference that it can be operated at ambient pressure, thanks to its autonomous secondary vacuum system.

2) *Experimental Setup (Fig. 7)*

- DUT (PP-PEM and PP Controller).
- Heterodyne Receiver.
- ACT Demonstrator and PC.
- ON Maser Reference.
- Commercial Frequency Comparator (Vremya VCH-307).

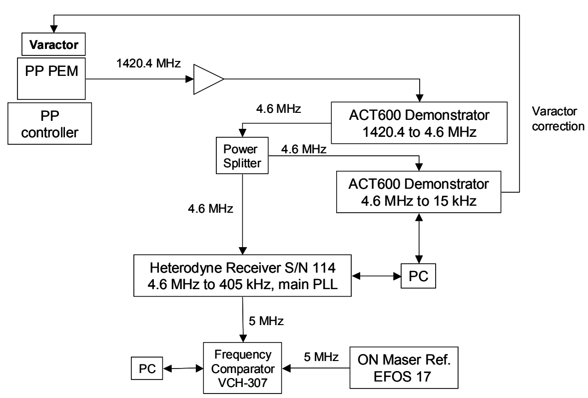

Figure 7. ACT measurement setup with PP-PEM

Note that the down-converting chain from 1420.4 MHz to 4.6 MHz is common to the maser signal and the interrogation signal.

3) *Measurement Results*

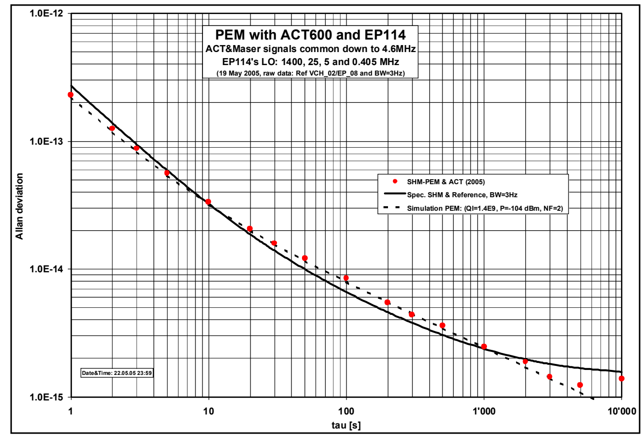

Figure 8. ACT measurement results with PP-PEM

The three items shown in Fig. 8 are:

- Curve giving frequency stability limits specified for the ACES SHM, corrected for the 3-Hz system measurement bandwidth.
- Discrete points corresponding to the measurements. These measurements are within specifications, except in 10s-to-1000s τ-range. This can be explained by PP-PEM degraded performance (cavity teflon coating contamination).
- Curve obtained by lower-Q_{cavity} simulation. Correspondence with the measured values is good.

B. *Stability Measurements with Physics Package Engineering Model*

1) *Device Under Test*

The DUT is the PP-EM, representative of the future flight model.

2) *Experimental Setup*

The measurement setup is the same as for the measurements with the PP-PEM. In addition, the PP-EM is operated in a Thermal Vacuum Chamber (TVC) with a temperature-regulated base-plate.

3) Measurement Results

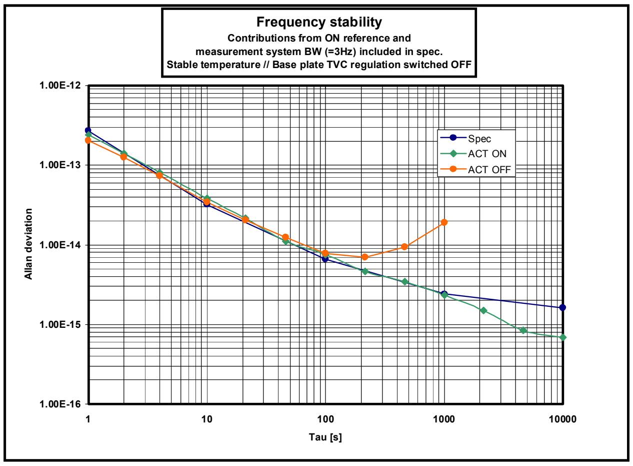

Figure 9. ACT measurement results with PP-EM

Fig. 9 shows three results:

- Curve giving frequency stability limits specified for the ACES SHM, corrected for the 3-Hz system measurement bandwidth.
- Curve corresponding to measurements with ACT off. The maser output stability is degraded for $\tau \geq 100$ s, due to cavity resonance frequency instability.
- Curve corresponding to measurements with ACT on. The maser output stability is no longer affected by the cavity resonance frequency instability, up to τ = 10000 s, and is fully in specifications.

V. Summary and Conclusions

The PI-ACT belongs to the fast microwave cavity auto-tuning category. The PI principle allows the main PLL to be totally insensitive to the interrogation signal, thanks to its 50% duty-cycle hold state. The price to pay is then a moderately degraded cavity response SNR.

On the other hand, the PI signal composite spectrum shall be such as not generating spectral lines close to the atomic frequency. Favorable conditions, theoretically understood, can be implemented by fine interrogation timing programming.

Frequency stability measurements have been done with two different PP models, and results show that the ACT demonstrator fulfills frequency stability performance required for the SHM.

The PI-ACT demonstrator development has succeeded in reaching its goal: demonstrate that an ACT for the ACES SHM is feasible, in order to support the electronics co-contractor OSZ in the development of their Elegant Breadboard (EBB). This mission is now completed.

Acknowledgment

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References

[1] H. Schweda *et al.*, "Performance Demonstration of the On-Board Active Hydrogen Maser for the ACES Space Mission of ESA", EFTF-IFCS 2007, Geneva (Switzerland), May 29th - June 1st.

[2] S. Zivanov, H. Schweda, D. Goujon, D. Gritti and G. Perruchoud, "Physics Package of the 35-kg Space Active Hydrogen Maser for the ACES Space Mission of ESA", EFTF-IFCS 2007, Geneva (Switzerland), May 29th - June 1st.

[3] L. J. Rueger, J. Inst. Electron. Telecomm. Eng. 27, 1981, p. 493.

[4] T. K. Tucker and G. J. Dick, "Performance of a Hydrogen Maser with Auto-Tuning Utilizing Cavity Q Modulation", Proceedings 41st AFCS 1987, p. 87-90.

[5] H. E. Peters, "Design and Performance of New Hydrogen Masers Using Cavity Frequency Switching Servos", 38th AFCS, June 1984.

[6] C. Audoin, "Fast Cavity Auto-Tuning Systems for Hydrogen Masers", Rev. Phys. Appl., Vol. 16, 1981, p. 125-130.

[7] C. Audoin, Rev. Phys. Appl., Vol. 17, 1982, p.273.

[8] G. Busca, L.-G. Bernier and P. Rochat, Observatoire de Neuchâtel (Switzerland), "Active Hydrogen Maser Atomic Frequency Standard", US Patent Number 5,838,206, 17th November 1998.

[9] R. Barillet, J. Viennet, P. Petit and C. Audoin, "Fast Cavity Auto-Tuning System for H-Masers: Experimental Results", 5th EFTF Besançon, March 12th-14th 1991.

[10] Reference Data for Engineers, 8th ed., Carmel: SAMS Publishing, 1993, p. 24-17.

[11] Clayton R. Paul, Introduction to Electromagnetic Compatibility, 1st ed., New York: John Wiley & Sons, Inc., 1992, p. 365.