FIRST-TF project : Practical Work

Topic : atomic clocks

Rb discharge lamp atomic clock : from resonances to (in)stabilities

1 Introduction

Atomic clocks are since decades used as frequency standard for time keeping purposes as well as for fundamental research and/or synchronization techniques, to mention the most known applications. It is yet possible to realize optical references characterized by a relative stability of 10^{-17} at 1 second. Depending on the required characteristics (compactness, space compatibility, high stability, ...), one kind of atomic clock is more suitable than another. Examples of atomic clocks are : Cs beams, cold atom fountains, vapor cell devices, and, the last generation, optical clocks (with ions or neutral atoms).

The performance of an atomic clock (especially its stability and uncertainty) can be measured by direct comparison with another atomic clock or oscillator, used as reference and whose known characteristics are better than the clock to be characterized. The literature on atomic clock is very rich and we will recall here only a few details concerning the atomic clock that is used; students may refer to books and papers on frequency standard metrology for an exhaustive presentation of this matter.

The aim of this practical work is the study of an experimental setup that allows one to observe the atomic resonance of a Rb discharge lamp atomic clock and the measurement of the stability of this clock compared with another atomic clock used as reference.

2 Principle of the experiment

Fig. 1 gives a basic overview of the different blocks of the Rubidium atomic clock. It consists of three different packages. The optical elements, which include the Rb absorption cell and microwave cavity, form the atomic resonator, while the electronics package is constituted of the generator and the detection circuitry. The princi-

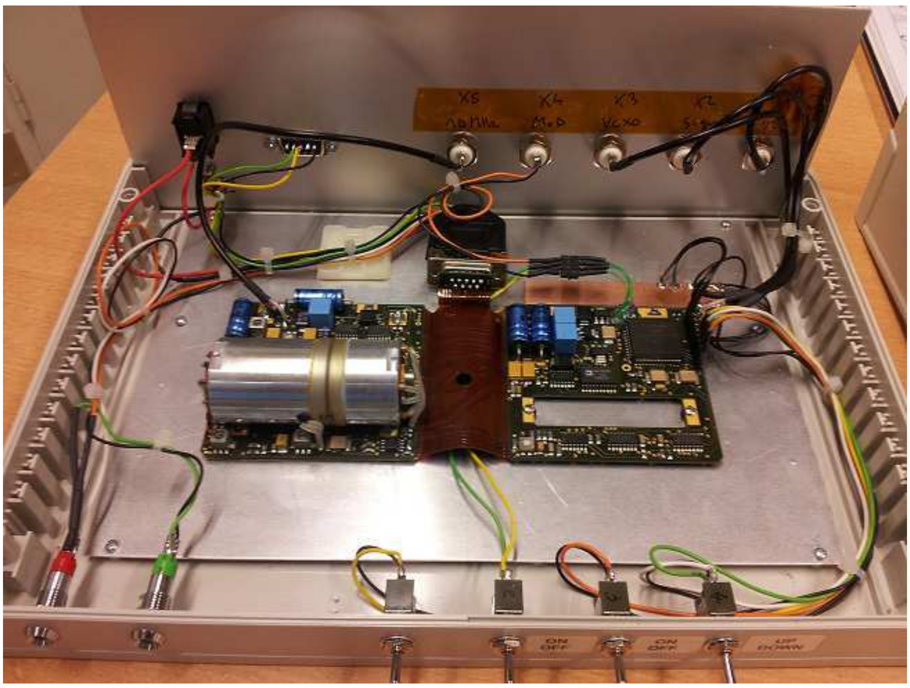

Figure 1: Rb discharge lamp atomic clock : picture of the ensemble.

ple of this kind of atomic clock is the following. A voltage-controlled crystal oscillator (VCXO) is locked to a highly stable atomic transition in the ground state of the Rb87 isotope. While the frequency of the VCXO is at the convenient standard frequency of 10MHz, the Rb clock frequency is at about 6.834GHz in the microwave range. The link between the two frequencies is done through a phase-stabilized frequency multiplication scheme.

The Rb atoms are confined in a vapor cell at an elevated temperature. The cell is placed in a microwave resonator to which the microwave power derived from the VCXO is coupled. The Rb87 atoms in the cell occur with equal probability in the two hyperfine energy levels of the ground state (F=1 and F=2). In order to detect the clock transition between these two levels, the atoms need to be manipulated in such a way that most of them occur in only one level. This is done by optical pumping via a higher excited state.

The pump light comes from a Rb resonance lamp which emits the light of Rb87 atoms. This light, which intersects the absorption cell, is filtered in such a way that mainly one optical frequency, which corresponds to a transition out of one of the two ground state levels, enters the principal absorption region. The pump light excites Rb87 atoms which are in the lower hyperfine level (F=1) to the short-lived excited state from which they decay to the two ground state levels (F=1,2) with equal probability. Since pumping occurs continuously out of the F=1 level, after some time, almost all atoms are found in the F=2 level and no further absorption occurs. The transmitted light level is detected by a photodiode after the cell. The absorption cell is filled with metallic vapor which contains Rb85 and Rb87 isotopes and a buffer gas. Filtering of the pump light is achieved in the entrance region of the cell by absorption with Rb85 atoms which have an accidental overlap with one of the Rb87 resonance transitions. If now a microwave field resonant with clock transition F=2, m=0 $\rightarrow$ F=1, m=0 is coupled to the interaction region, the level F=1 is repopulated and light absorption is enhanced. A sweep of the microwave field over the resonance is detected as a small dip in the transmitted light level after the cell. This signal is fed into a synchronous detector whose output generates an error signal which corrects the frequency of the VCXO when its multiplied frequency drifts off the atomic resonance maximum.

The principal function of the buffer gas is to keep the Rb atoms away from the cell walls and restrict their movements. As a result they are practically frozen in place for the interaction time with the microwave field. In this way the Doppler-effect is virtually removed and a narrow line width results. The cell region is also surrounded by a so-called C-field coil which generates a small axial static magnetic field to resolve the Zeeman sub-transitions of the hyperfine line and select the clock transition, *i.e.* the one with the least magnetic sensitivity. To further reduce the magnetic sensitivity, the complete physics package is placed into nested magnetic shields.

3 Procedure

1 Check that both clocks are switched on, otherwise do it and wait a few minutes before starting the measurements (discharge lamps need some time to reach a stable regime). Visualize then the 10MHz output of the two clocks on the frequency counter. In a second step, look at the two signals on the picoscope : by triggering on one signal, the second one show a phase shift. Explain why.

2 In this step the reference clock is not used. Consider the atomic clock to be characterized (called here therein TP clock). Set it on mode LOCK OFF and MOD OFF (*i.e.* the clock is free running and no modulation is applied). Several output can be monitored; they are accessible on the back panel of the clock. Connect to the picoscope the atomic signal (named SIGNAL) on channel A and the voltage applied to the VCXO on channel B (named VCXO). You can now sweep manually the microwave by using the switch UP-DOWN; once that you have found the atomic clock resonance (an example is given in fig. 2), adjust the scales of the picoscope both in time and amplitude. Evaluate approximatively the width of the resonance, FWHM, by knowing the calibration of the microwave frequency sweep : 600kHz/V (or, in the time scale, 137kHz/s).

Then, add the squared modulation (MOD ON) and visualize on the picoscope the atomic signal (channel A) and the 137Hz modulation (channel B). Sweep again the microwave frequency to find the square modulated resonance (see fig. 3); save the data in CSV format on the desktop and name the file as `Resonance`. From this kind of signal the electronics extracts the error signal and, through PI's adapted parameters, sends the correction signal to the VCXO. Practically, this signal processing is made numerically by the FPGA that drives the clock and one has not access to this analysis; we can however make the same work and calculate the error signal from the square modulated atomic resonance. To do this, open the IgorPro file on the desktop. You can visualize the routine, already written, that calculates the error signal (CTR+M to open the procedures window). Execute the procedure by typing `LoadSignal()` on the terminal. It

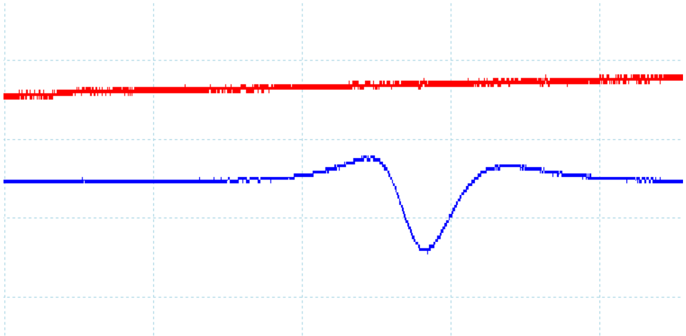

Figure 2: Atomic clock resonance: in red the ramp to sweep the microwave frequency, in blue the atomic resonance.

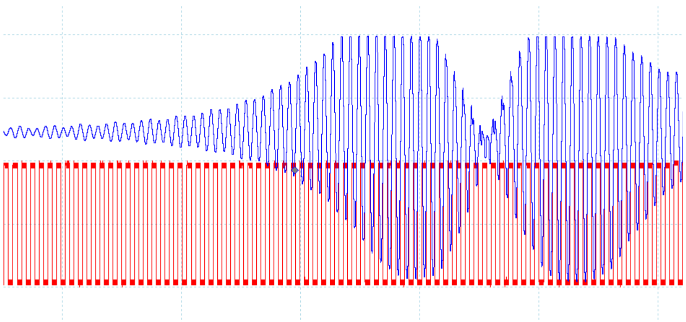

Figure 3: Atomic clock modulated resonance: in red the squared modulation at 137Hz, in blue the atomic resonance with the superposed modulation. From this signal the error signal is extracted.

can take some time due to the size of the data file, wait while the software is running. The result is a dispersive signal centered on the center of the atomic resonance; take the time to understand how this signal has been obtained.

As a final step, lock now the TP clock (LOCK ON, MOD ON). The led in the front panel, red when the clock is free running, becomes green. Look again on the picoscope at the atomic signal (channel A) with the modulation on channel 2; choose a convenient time scale and explain the behavior of the signal.

3 Let's now compare the uncertainty of the TP-clock by comparison with the reference clock. For this purpose, by using the phase/frequency electronic box in open loop, one can measure the frequency beat between the 10MHz output of the two clocks. The output of the box is low frequency filtered, so the 20MHz is cut. The beat note can be measured on the picoscope. With respect to the setup shown in fig. 4, use the output of the 10MHz reference clock that is minded to be sent to the external reference of the frequency counter (not used in this measurement).

Because the uncertainty depends on electric and magnetic fields, you can see how the beat note is perturbed by approaching a small magnet to the TP-clock.

4 This is the last step of the practical work. We want to measure the (in)stability of the TP-clock in comparison to the reference clock. Because we expect the two clocks to be stable in the 10^{-11} range, a common frequency counter usually has not the good resolution. One can however down convert the 10MHz of the TP-clock by using the circuit of fig. 4 and measure on the counter a lower frequency (in this case 90kHz). Open the AD5930 software to communicate with the DDS and set the following parameters :

- Output signal : Sine
- DAC status Enabled, MSB status Enabled
- External clock (MCLK frequency) at 40MHz
- Output frequency (START frequency) at 10.090MHz
- Frequency increment at 0Hz
- Click on Program and then on Control

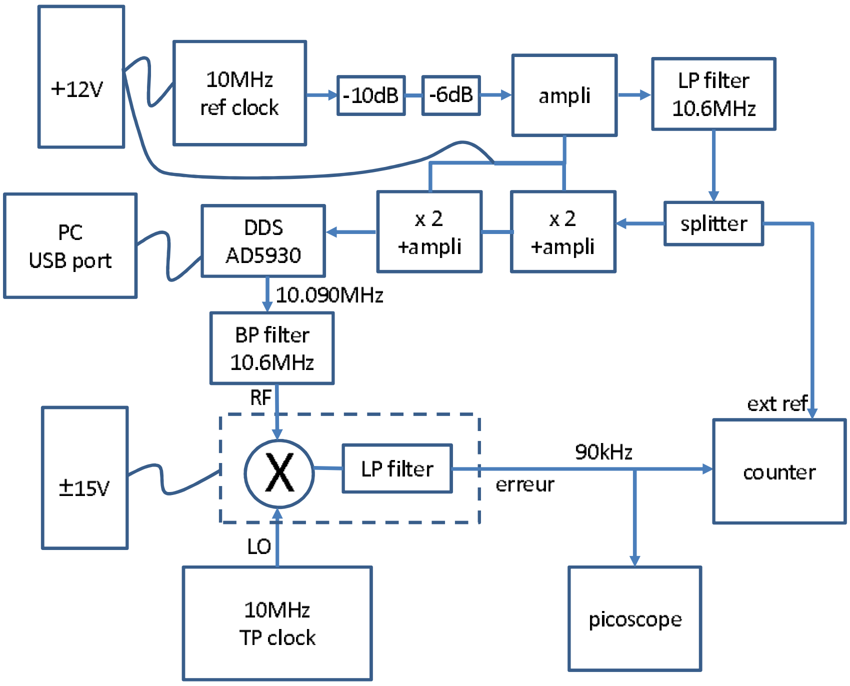

Figure 4: Scheme of the electronic setup to compare the TP clock frequency output with the one of the reference clock. The beat note between the two clocks is down-converted to low frequency in order to measure a high stability by using a low cost frequency counter.

The interface DDS windows looks like in fig. 5. If the window is partially cut on the desktop and the Control button is not visible, after clicking on Program, tape **two** tabs and then click on Enter. Check on the picoscope the output frequency of the DDS; repeat the operation if there is no output or the output frequency is wrong. Once the DDS is set, you can close the Picoscope application as well as the AD5930 interface (keep the USB cable used for power supply), to minimize the RAM consumption of the laptop. Check the 90kHz beat note output on the counter (referenced on the external 10MHz clock). The setup is displayed in fig 4. Open the BK_Counter LabView application to communicate with the frequency counter (through USB-R232 interface). Set the gate at 10s, the Refresh at 10s, and start a data acquisition, with the TP-clock locked; stop the measurements after 5 minutes (we are interested on short term stability ad probably the time that you can spend on this experiment is run away fast). Save the data in `.dat` format. To analyze the Allan deviation of the measurement, open Stable32, import the saved file and normalize the data. Take care of the gate time τ and the scale factor. Plot the graph of the measured stability. If you have still time, run a similar measurement with the TP-clock unlocked and compare the two Allan deviation graphs.

Evaluate approximatively the signal to noise ratio S/N from the width of the resonance, the parameters of the squared modulation and the measured stability.

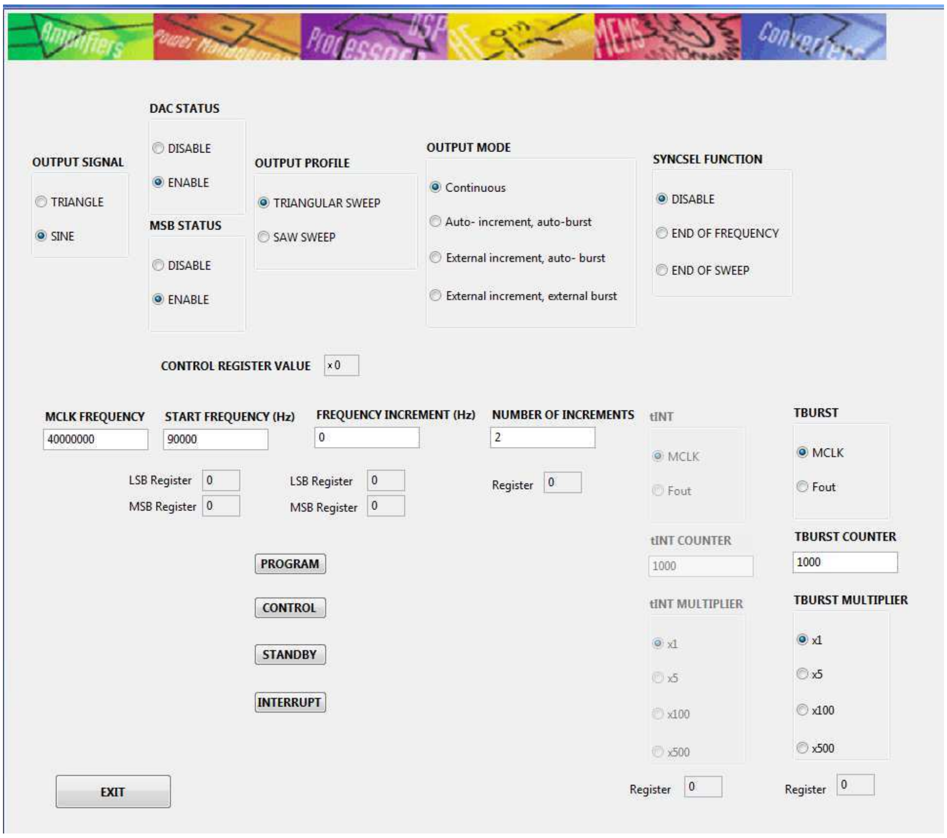

Figure 5: Interface window to communicate with the Analog Devices DDS.

4 Appendix : components list and softwares

4.0.1 Setup components

- Commercial discharge lamp Rb atomic clock, Spectratime LPFRS-01 (used as reference clock); voltage supply : +12V.
- Mini-Notebook HP-4210.
- Rb atomic clock to be characterized, supplied by Spectratime.
- DDS Analog Devices EVAL-AD5930EBZ.
- Phase-Frequency Lock electronics, supplied by the electronic pool of SYRTE (used here only for filtered frequency beat analysis).
- Two-channel Picoscope 3205B.
- Frequency counter BK Precision 1823A.
- 2x frequency doubling + amplifiers (Voltage supply : +12V), supplied by the electronic pool of SYRTE.
- Amplifier (Voltage supply : +12V), supplied by the electronic pool of SYRTE.
- 10dB and 6dB attenuators.
- 10.7MHz low pass filter and 10.7MHz band pass filter.
- Splitter Mini-Circuits ZX10-2-12-S+, 2-1200MHz.
- Symmetrical DC power supply 0 - ± 15V, 500mA, MCP lab electronics SPN 15-05C.
- Stabilized voltage supply 0 - 15V, 3A, Selectronic SL1709SB.

4.0.2 Software for analysis and hardware interfaces

- Picoscope 6.0 USB interface, software down loadable from Internet.
- Igor Pro, signal analysis software, license required.
- BK_Counter USB-R232 interface, executable file form LabView9.0 (written by N. Castagna).
- AD5930 USB interface, software down loadable from Internet.
- Stable32, stability measurement software, license required.