application note 6689 AN-09

Frequency stability of Rubidium references vs. off-air receivers

Introduction

A stable frequency reference standard in a calibration lab, can be achieved in many possible ways. Examples are units based on atomic resonance principles, like Cesium-beam or Rubidium-lamp oscillators. Also high-stability oven crystal oscillators can be used, depending on the lab's certified accuracy.

Except for Cesium-references, these in-house references are subject to a slow change in the output frequency, known as aging. Typical yearly aging is 2×10^{-10} for Rubidium-oscillators and 2×10^{-8} for high-end crystal oven oscillators. Due to this aging the in-house frequency references need to be calibrated - at more or less frequent intervals - against a traceable standard. The frequency calibration can be made at e.g. other cal labs possessing a Cs-beam reference. To maintain a total uncertainty (at the "2 sigma" level) of let's say 2.5×10^{-8}, a high-end crystal oven reference needs to be calibrated every year. And to maintain an uncertainty of 5×10^{-10}, a typical Rubidium-reference should be calibrated every second year.

It has been increasingly popular to use off-air receivers to generate a reference frequency in the cal. lab. Examples are the DCF-77 long-wave transmitter in Mainflingen, Germany, the North-Atlantic navigation system Loran-C and recently the GPS (Global Positioning System). Common for all three systems is that they transmit a very high-stable time reference or carrier frequency, derived from a Cs-oscillator at the transmitter side. The reference receivers contain a receiver circuit and a tunable ("disciplined") oscillator, that is locked to the received reference. These units employ an excellent *long-term* frequency accuracy

Using an off-air reference to monitor the in-house frequency reference standard, is an excellent way to perform a *traceable calibration* of the "house" frequency reference. See figure 1.

As said above, the long term stability (the mean value of the output frequency over days or weeks) of these off-air receivers are in general excellent. But what about using such receivers as the *only frequency reference standard* in a cal. lab? Very often the frequency reference standard in the cal. lab is used to calibrate high-stability timebases of measuring instruments, like frequency counters or synthesizers, using a measuring time in the order of seconds. In this case one needs to be very careful, *because the short-term stability of off-air receivers is inferior to stand-alone Rubidium or crystal oscillator references*!

The Cs-reference stability on the transmitter side is transferred to the receiver *only after integration over a long period of time (hours or days)*. To ensure also a good short-term stability, a very careful (= expensive) design of the "disciplined" (receiver-controlled) integrated oscillator in the off-air receivers is needed. When this is not the case, the *short-term* stability will not be adequate, and a good crystal oven or a Rb-reference is needed anyway.

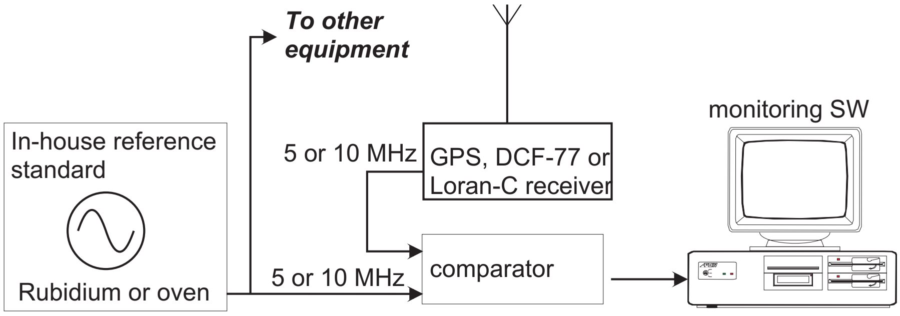

Figure 1 Use of an off-air frequency reference to monitor the in-house reference standard, ensures traceability

Short-term stability of a DCF-77 receiver

Figure 2 shows a typical DCF-77 receiver. It contains the LF-radio receiver (77,5 kHz) and a tunable oscillator that is phase-locked to a multiple of the received frequency. The short-term instability comes partly from variations in the received frequency, due to varying atmospheric conditions, sky and ground wave interference etc., and partly from loop instabilities.

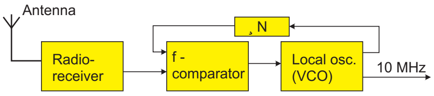

Figure 2 Simplified block diagram of a DCF-77 receiver

Figure 3 shows the output from a popular brand of DCF-77 receiver, in the "modulation domain" (frequency vs time). Each frequency measurement has a measuring time of 1 s. The measurement equipment in this recording is a CNT-81 Timer/Counter/Analyzer (Pendulum). The graph is generated via the *TimeView*™ SW, which turns the measurement front-end (CNT-81) into a *modulation domain analyzer*.

The CNT-81 has a frequency resolution of 5×10^{-11} for 1s measuring time. The time base used, has a specified short-term stability (Allan Deviation) of $<3\times10^{-11}$ over 1 s.

The max. and min. frequency values during the observation period are marked with cursors. The cursor values (beneath the graph area) shows that the difference δy (max-min) is 91.6 mHz or 9×10^{-8}. A calculation of Root Allan Variance of this data, results in 9×10^{-10} (τ = 1 s).

A Rubidium- or a good crystal oven oscillator, would have a frequency deviation that were about 50-1000 times less, typically within the interval 5×10^{-11}… 1×10^{-12} (τ = 1 s).

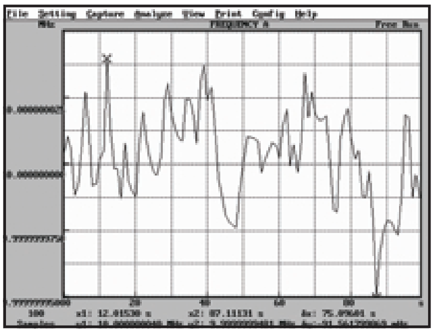

Figure 3 Modulation domain measurement (frequency vs time) of the DCF-77 output, using CNT-81 and TimeView

Short-term stability of a Rubidium Reference

Let's look at the short term stability of a stand-alone Rubidium-reference, the *6689 Rubidium Frequency Standard*, from Pendulum.

In figure 4, the corresponding modulation domain graph is shown. Note the much smaller frequency variations over the 100 s observation period (The X- and Y-axis scaling are identical to figure 3). The δy (max- min) is only 1 mHz or 1×10^{-10}. A calculation of Allan Deviation of this data, results in 2×10^{-11} (τ= 1s).

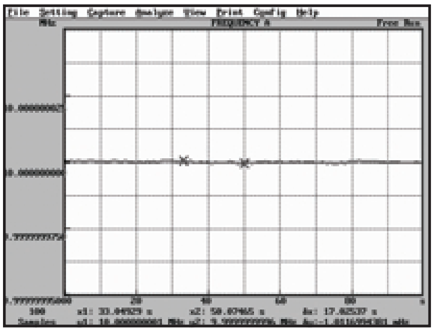

Figure 4 Modulation domain measurement (frequency vs time) of the 6689 Frequency Standard output, using PM 6681 and TimeView

Measurement on a faulty DCF-77 receiver

Off-air receivers must be carefully monitored for possible malfunctions, preferably via modulation domain analysis (frequency vs. Time). See figure 5 which shows the variation of the instantaneous frequency during approx. 0.8 s in a faulty DCF-77-receiver.

The output frequency exhibits very large variations of 114 Hz peak-to-peak. The Allan deviation is 13.5 Hz (τ = 100 μs).

But worst of all, the mean value over approx. 1s is 12 Hz higher than the nominal 10 MHz (a deviation of 1.2×10^{-6}). This is an unacceptable value when calibrating e.g. crystal oven oscillators, which require in general 0.01 to 0.1Hz calibration adjustment tolerance!

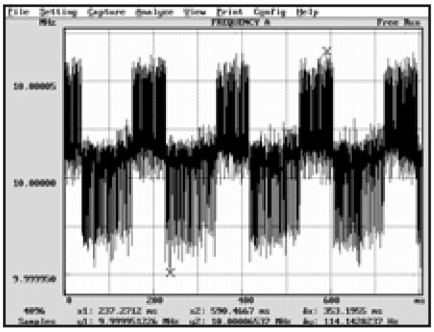

Figure 5 This modulation domain measurement (CNT-81 and TimeView) directly exposes a faulty DCF-77 receiver

Conclusion

Off-air receivers are excellent tools for monitoring the cal lab's reference standard to ensure traceability

A frequency monitoring system, like the one shown in figure 1, is the optimum solution for stability and traceability. The system employs *two independent* frequency sources, which makes it very reliable.

But off-air receivers, should normally NOT be used as *only* frequency standard where *short-term stability* is important. As a "one-box solution" in the lab, a Rubidium reference, like the 6689, is preferred, because of its much higher stability.

A comparison of typical stability is shown in the table below, between a DCF-77 receiver, 6688 (oven) and 6689 (Rubidium timebase).

	Frequency stability:		
Type of standard	***1s (Allan dev.)***	***1 month aging***	***1 year aging***
6689	3×10^{-11}	5×10^{-11}	2×10^{-10}
6688	5×10^{-12}	3×10^{-9}	2×10^{-8}
DCF-77	1×10^{-9} (*)	$<1\times10^{-11}$	$<1\times10^{-11}$

(*) based on actual measurements

Another important conclusion is that an off-air receiver, just like any other lab reference, must be checked regularly for possible malfunctions. Unlike a monitoring system with two independent sources as in figure 1, the receiver control of the built-in oscillator is "hidden inside the box" (figure 2), and not obvious for the user. There is no built-in warning system if the receiver is faulty. The faulty receiver in figure 5 is easy to detect when you have the proper equipment, that can perform modulation domain analysis.

An excellent solution and an exception to the rule that an off-air receiver must be continuously monitored, is the GPS controlled frequency standards 910 or 910R from Pendulum Instruments. They contain the complete monitoring HW and SW and is contained in one compact box.