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Fluke PM 6681R Time Analyzer and Rubidium frequency reference

Application Note

Short-term frequency stability of Rubidium vs. off-air receivers

A stable frequency reference in a calibration lab can be achieved in various ways. Atomic resonance can be used to build reference oscillators based on cesium beams or rubidium lamps, for example. Alternatively, the lab may use high-stability oven crystal oscillators. The most appropriate method depends on the lab's certified accuracy.

Except for cesium (Cs) references, such in-house reference frequencies will slowly drift, an effect known as aging. Typical yearly aging is 2×10^{-10} for rubidium-oscillators and 2×10^{-8} for the best crystal oven oscillators. This requires them to be regularly calibrated against a traceable reference with a very good long-term frequency accuracy: for example, by another calibration lab that has a Cs-derived reference. To maintain a measurement inaccuracy within 1×10^{-7}, say, a 'normally good' crystal oven reference needs to be calibrated every year, while a typical rubidium-reference needs to be calibrated every other year to remain within 1×10^{-9}.

Off-air receivers are increasingly being used to provide excellent long-term stability in the calibration lab. Examples are the DCF-77 long-wave transmitter at Mainflingen (Germany), the North-Atlantic Loran-C navigation system, and recently GPS (Global Positioning System). Each of these three systems transmit a highly stable time reference or carrier frequency that is derived from a Cs-oscillator at the transmitter. A receiver circuit and a tunable (or 'disciplined') oscillator is locked to the reference received.

An off-air reference is an excellent way of monitoring the in-house reference continuously to maintain a traceable calibration of the long-term accuracy. See Figure 1.

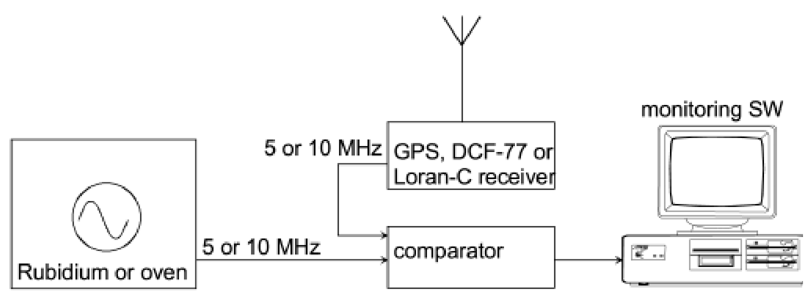

Figure 1 Using an off-air frequency reference to continuously monitor the in-house primary reference ensures traceability.

As noted, the long-term stability (expressed as the mean value of the output frequency over hours, days or weeks) of these off-air references is in general excellent. However, can such receivers be used as the primary (and only) frequency reference in a calibration lab? Here, the frequency reference is often used to calibrate the time base of frequency counters or synthesizers equipped with an oven oscillator, using a measuring time of about a second. These cases demand great care, since the short-term stability of off-air references is not very good, and can often be worse than simple stand-alone crystal oscillators!

The Cs-reference stability is transmitted to the receiver only when integrated over a long time period. A good short-term stability demands a very careful (and expensive) design of the 'disciplined' (receiver-controlled) integrated oscillator in the off-air receivers. The only commonly available in-house primary references with a guaranteed high short-term stability (over minutes, seconds or milliseconds) are cesium, rubidium or stand-alone crystal oven oscillators.

Short-term stability of a DCF-77 receiver

Consider a typical DCF–77 receiver. It contains an LF–receiver (77.5 kHz) and a tunable oscillator that is phase–locked to a multiple of the frequency received. The short–term instability arises partly from frequency fluctuations caused by varying atmospheric conditions, sky wave interference caused by ionosphere reflections and so on, and partly from the loop instabilities (Figure 2).

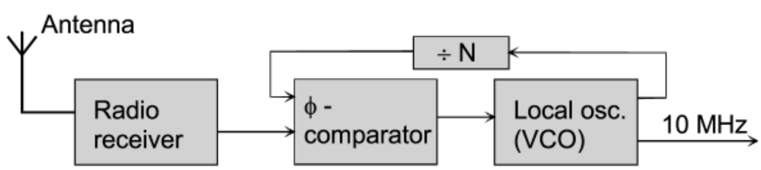

Figure 2 Simplified block diagram of a DCF–77 receiver.

The short–term stability of rubidium and oven oscillators expressed as the Root–Allan variance over 1 s are typically in the 5×10^{-11} to 1×10^{-12} range. Now consider the output from a common brand of DCF–77 receiver, plotted in the 'modulation domain' (frequency vs. time), Figure 3. Each frequency measurement lasts 1 s. A Fluke PM 6681R Time Analyzer/Frequency Reference takes the measurements, with the graph being generated by the TimeView™ PC software, which turns the measurement front–end (PM 6681) into a modulation domain analyzer. The PM 6681R has a built–in rubidium timebase reference, and a frequency resolution of 5×10^{-11} for a measuring time of 1 s.

The maximum and minimum frequency values during the observation are marked by cursors. The cursor values (below the graph area) show that the difference (dy, max – min) is 91.6 mHz or 9×10^{-8}. A calculation of the Root–Allan variance of this data gives 9×10^{-10} ($t = 1$ s). The measuring equipment (PM 6681R) contributes a 0.5×10^{-10} resolution uncertainty to the measurement. A rubidium or good crystal oven oscillator would have a frequency deviation about 50–1000 times lower.

Measurements on a faulty DCF–77 receiver

Another important point is that a DCF–77 receiver must be carefully monitored for possible malfunctions. The best way to monitor the 'health' of such a receiver is to use time and frequency analysis in the modulation domain (frequency vs. time), for example via TimeView and the PM 6681. Figure 4 shows the extreme instability of a faulty DCF–77–receiver.

The output frequency exhibits very large variations of 114 Hz peak–to–peak. The measuring time is very short in this measurement (100 ms), but the measuring equipment contributes a resolution uncertainty of only 5 Hz (5×10^{-7}). The Root–Allan variance is 13.5 Hz ($T = 100$ ms) but, worst of all, the mean value over almost one second is 12 Hz higher than the nominal 10 MHz (1.2×10^{-6}). This is unacceptable when used for calibrating crystal oven oscillators for example, which generally require calibration adjustment tolerances in the range 0.01 to 1 Hz.

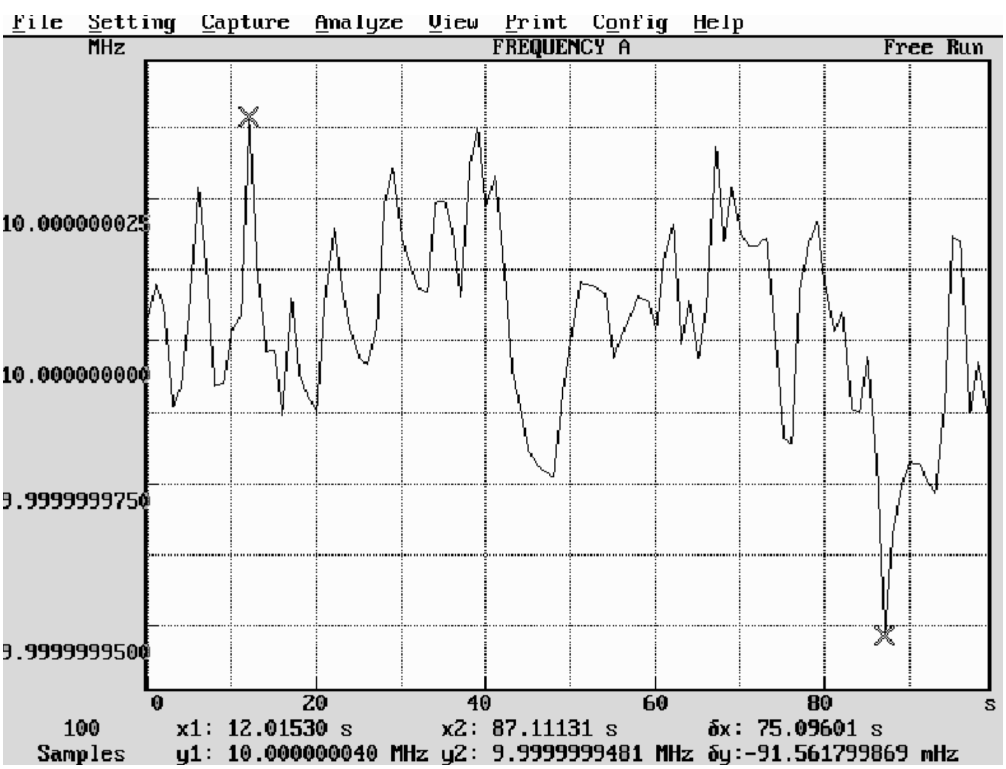

Figure 3 Modulation domain measurement (frequency vs. time) of the DCF–77 output, using PM 6681R and TimeView software.

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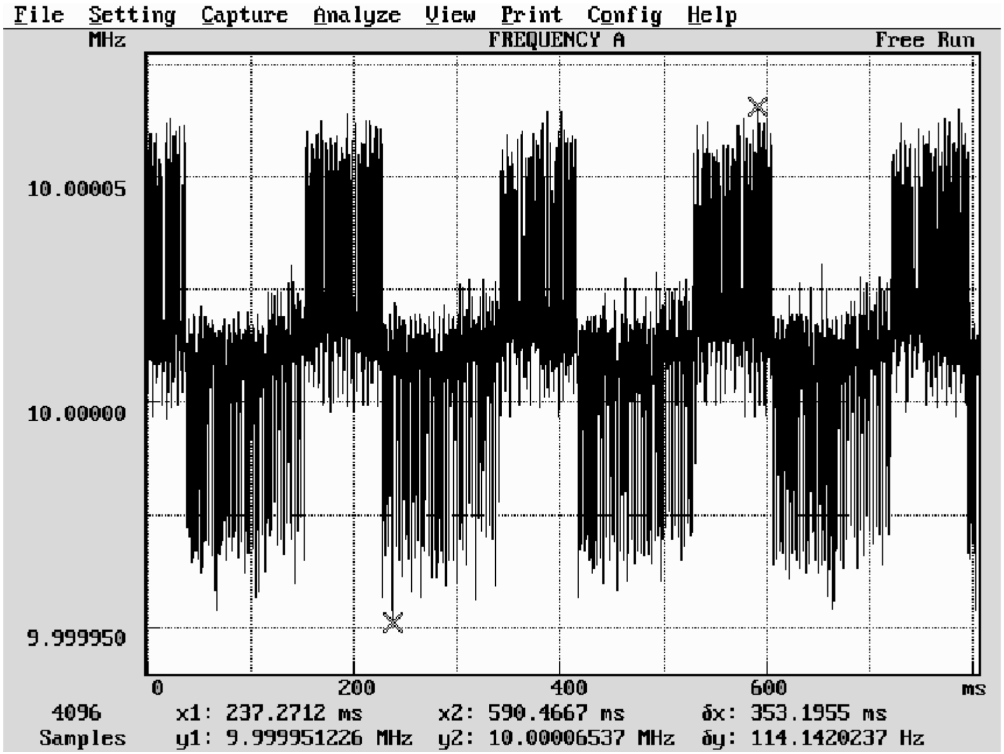

Figure 4 This modulation domain measurement (PM 6681 and TimeView) directly shows a faulty DCF-77 receiver.

Conclusion

Off-air receivers are excellent tools for:

- monitoring the calibration lab's primary reference to ensure traceability;
- calibrating other frequency sources for long-term accuracy.

Type of reference	Total uncertainty of 10 MHz over 1s	Stability over 1s (Root–Allan variance)	Stability over 1 month	Stability over 1 year
Rubidium	1 mHz	2.5 x 10^{-11}	5 x 10^{-11}	2 x 10^{-10}
High-end crystal oven	50 mHz	5 x 10^{-12}	3 x 10^{-9}	2 x 10^{-8}
DCF-77	500 mHz (*)	1 × 10^{-9} (*)	<1 x 10^{-11}	<1 x 10^{-11}

(*) based on actual measurements

Off-air receivers, and especially DCF-77 receivers, should however not be used as primary frequency references where short-term stability is important. In these cases a rubidium-based reference, such as that in the PM 6681R, is much more stable.

The table on the right compares typical stabilities. An example of a high-end crystal oven oscillator is the PM 9692 timebase oscillator (optional on the PM 6681); a rubidium timebase is included in, for example, the PM 6681R.

A DCF-77 receiver, just like any other lab reference, must be checked regularly for possible malfunctions. A faulty receiver like that shown in Figure 4 can be easily detected with suitable equipment. The PM 6681 with TimeView software, for example, can perform time and frequency analysis in the modulation domain.

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