A7 Summary

With the huge advance in accuracy and stability of modern atomic clocks, the need for a very precise method of detecting instabilities in their signals has arisen. For example, with two hydrogen masers with a 1 in 10^{15} frequency difference, the drift rate of phase due to the frequency difference will be 1fs per second or 3.6ps per hour. No ordinary universal counter would be capable of resolving the difference between the two signals. It is vital therefore that the modern metrologist has knowledge, and control, of the measurement system drift rate if very small, but important, frequency differences are to be measured.

Quartzlock have developed an innovative instrument, based around the KVARZ frequency difference multiplier, which is capable of resolving 1.5 parts in 10^{15} with 10^{14} accuracy. The A7 frequency and phase comparator is a 2U rack or bench mount unit with inputs and controls on the front panel. The A7 is interfaced to a computer via a GT200 time interval counter card capable of 100ps resolution without averaging. To complement the device, software has been written to enable the user to perform powerful statistical analysis on the data obtained. The company believes the A7 meets the needs of even the most demanding application.

The Device

The frequency difference multiplier from IEM KVARZ is the heart of the device. It takes two input signals at either 5 or 10 MHz, multiplies their fractional frequency difference by 1000 (frequency mode) and 10000 (phase/time difference mode), outputting a 5 MHz sine wave with this fractional frequency difference multiplied by 1000 superimposed and 1 Hz pulse with fractional frequency difference multiplied by 10000 superimposed.

The rest of the A7 provides a 10 MHz reference signal to the counter, providing a 1 Hz reference pulse and provides automatic level switching and monitoring (enabling 5 or 10 MHz inputs to be applied).

The reference chain starts with a 10 dB directional coupler, which samples the reference signal applied to the freq. difference multiplier. The counter reference is provided by a doubler if the input is 5 MHz, and a direct amplifier / limiter if the input is 10 MHz. The presence of a 5 MHz output from the low pass filter is detected and used to automatically switch between the doubler and the direct path.

The 1 Hz reference is obtained by division by 5E6 or 10E6 depending upon the input frequency. Again the switch over is automatic. The divider used has a reclocked output latch, which removes the effect of the divider propagation delay from the reference path. This reduces the effect of temperature changes on the delay. The divider constant may be changed higher or lower by the phase adjust push buttons. This enables the phase of the 1 Hz reference to be slewed.

Level monitoring is provided on both inputs by AC detectors and window comparators.

Distribution Amplifier

The A7 is fitted with a 4-way distribution amplifier as standard. This is a linear distribution amplifier designed for standard frequency distribution between 1 MHz and 100 MHz. It is therefore more than capable of distributing the 5 or 10 MHz signals applied to the input on the front panel. If the user has a valuable signal from a hydrogen maser, they would apply it to the distribution amplifier input, enabling then to use one output for the reference input, leaving 3 outputs free for use elsewhere within the lab. This eliminates the need for a costly stand-alone distribution amplifier.

Rubidium Frequency Standard

The A7 has a rubidium oscillator fitted as standard within the device. Due to the need to have a suitable reference signal at all times, the decision was made to incorporate one of the companies P line rubidium oscillators into the A7. The advantages conferred thereby are obvious. Due to its small size, low weight, high accuracy and stability and low cost, the Rb provides an ideal reference signal suitable for most applications. The Rb typically has a frequency stability of parts in 10^{12} over 100s averaging time. This makes the A7 a complete instrument, capable of providing, distributing and analysing frequency standards. Whilst the Rb will cover most requirements, the user should be aware that to maximise the resolution and accuracy of the A7, a signal from an active hydrogen maser is required. When used in a temperature-controlled environment, the A7 is the capable of the quoted 1.5 E-15 resolution. Obviously when measuring devices like GPS-DOs or other rubidium oscillators, a hydrogen maser reference is crucial if unambiguous results are to be obtained

GT200 Time Interval Counter Card

The signals carrying the frequency difference information are output to, and measured by, the GT200 universal counter using the most accurate technique available, reciprocal counting coupled to time interpolation [2]. The GT200 is a PC based counter card, which fits into one of the spare ISA slots. It has a configurable address (settable in either HEX or decimal) to avoid conflict with other ISA cards (like SoundBlaster or internal Modems). The GT200 has associated software, which provides the virtual counter front panel. This enables the user to operate the counter like a normal universal counter, with the normal range of functions totalise, trigger, arming, pacing, calibration etc.). Communication errors between the driver and windows force the user to operate the program under DOS. Data is saved in ASCII format, with the appropriate DOS path and .DAT file extension (to avoid data read in errors in Mathcad

Modes of Operation

There are two ways to acquire data using the A7 and depend upon which mode the frequency difference multiplier is operated in.

4.1 Frequency mode

This is most useful for adjustment purposes, as a short gate may be used with sufficient resolution to adjust even high quality atomic frequency standards, like Rubidium. It is also ideal for very short gate times (τ less than one second) where the phase time difference mode cannot be used. . The longer the gate time, the greater the number of significant figures in the result and the greater the potential accuracy. The gate time defines the averaging time of the measurement. A long gate time will provide average frequency, but will also hide any short-term variation, whereas short gate-times enable characterisation of the short-term frequency variations. The gate time for the GT200 may be set to any desired value between 1 ms and 3200s. In phase/time difference mode the minimum gate time is 1s, a point worth remembering if extremely long run times are to be avoided. The necessary software routines are presently under development and will be tested when ready. It is hoped that these will provide the user with a method for very short-term characterization of signals, highlighting details often hidden when using longer gate time- although these improve resolution.

The various outputs from the frequency difference multiplier carry the frequency difference information between the reference and the DUT as an offset from the nominal frequency. The fractional frequency difference between the inputs is multiplied by 1000 for the 1 and 5 MHz outputs and by 10000 for the 1 Hz outputs

4.2 Phase/time difference mode

When stability of signals with τ from 1 second to 10000 seconds (or longer) is required, operation of the frequency difference multiplier in phase/time difference mode is recommended. As detailed below, software is supplied allowing simple but powerful analysis using all the common statistical measures for characterisation of frequency and time signals. One benefit of this method is that the frequency difference information can always be obtained by differentiating time difference over a required τ (averaging time)

A divider on the auxiliary board provides a suitable frequency reference at 1 Hz. This is at an identical nominal frequency to the frequency output at the 1 Hz output of the frequency difference multiplier. This second frequency is the one carrying the frequency difference information. The GT200 card then measures the time interval between a rising edge of the frequency difference signals and that of the reference. The rate of change of time interval divided by the previously mentioned fractional frequency difference multiplication factor for the 1 Hz output (10000) will give the fractional frequency difference between the inputs. If the rate of change of time interval is 100ms/s (1 part in 10^4), when divided by 10000, gives a fractional frequency difference between the DUT and the reference of 1 part in 10^8. The maximum allowable frequency difference between the sources, if the results from the comparator are to be 100% reliable, is 1 part in 10^9. For a 10 MHz signal, this is an offset in the DUT of 0.01 Hz. Whilst this may seem restrictive, it is important to remember that if devices are being tested with greater offsets than this, a normal universal counter would be sufficient. The A7 is designed for high-end measurement, where the likely offsets will very often be much smaller than this (a hydrogen maser has a typical offset of parts in 10^{13})

Software

Development of the A7 frequency and phase comparator, necessitated accompanying software so that data gained from the A7 during a phase/time interval run could be analysed.

The decision was made to write several routines in Mathcad. One of the advantages of this method was that the user had full control over the routines he was using. Therefore should he require additional features they were easy to add into the existing worksheet. In addition due to the capability of Mathcad, unlimited data entry is possible. This allowed long data runs, which enable characterisation of signals out to longer averaging times

5.1 First difference variances take into account frequency offsets between the sources. This is useful for checking the calibration of a source before it is sent out to a customer. There are two such first difference variances

i) **Fractional Frequency Offset** at an averaging time τ will give the same result as the average of a large number of frequency counter readings will a gate time of τ

ii) **Mean Fractional Frequency Offset** is similar but will calculate a mean slope over τ using intermediate data point

5.2 Second difference variances are concerned with frequency stability and will ignore a fixed frequency offset. There are many of these but we have confined ourselves to the 3 most commonly used.

i) **Allen Variance**, abbreviated $\sigma^2_y(\tau)$ or AVAR is the most commonly used measure of frequency stability.

$$s^{2}_{y}(t) = ½t^{2} <(D^{2}x)^{2}> \qquad (1)$$

This was originally developed in 1966 by D.W.Allan because of the realisation that frequency standards do not generate a constant frequency output contaminated only by white noise and the output of such a frequency standard cannot be averaged to get rid of the noise. Therefore the usual statistical measures like standard deviation and mean cannot be used to characterise frequency standards. AVAR is excellent at characterising the intermediate to long-term stability of clocks and oscillators. This will be the variance most often used when using the A7.

ii) **Modified Allen Variance**, abbreviated $MOD\sigma^2_y(\tau)$ or MVAR, is similar to Allen Variance, except that it calculates mean slopes using intermediate data points in a similar way to mean fractional frequency offset.

$$s^{2}_{y}(t) = ½t^{2} <(D^{2}\bar{x})^{2}> \qquad (2)$$

One of the advantages confered thereby, is that MVAR can distinguish between white noise PM and flicker noise PM, whereas AVAR cannot.

Both of the above are very suited to the characterisation of frequency standards, especially looking at the frequency stabilities of such standards.

iii) **Time Variance**, abbreviated $\sigma^2_x(\tau)$ or TVAR is for use when the measurement of time is the issue, rather than that of frequency.

$$s^{2}_{x}(t) = 1/6 <(D^{2}\bar{x})^{2}> \qquad (3)$$

In many ways TVAR is similar to MVAR, and has many of the improvements over AVAR. TVAR is directly related the MVAR and is used for the characterisation of clocks. TVAR is the recommended method of charcterisation of frequency standards intended for use within the telecommunications industry

Results

Noise floor measurements are possible in both frequency and phase/time difference modes. It is far easier to measure the noise floor in phase/time difference mode, since in frequency mode a separate run must be made for each value of τ required. However, simplified noise floor measurements in frequency mode reveal a peak-to-peak jitter of +/- 2E-12 and 2E-13 for 100ms and 1s gate times respectively. This is useful for calibrating a frequency standard against a master standard frequency and may be done with additional statistical analysis.

The specifications state a short-term stability of 1.5E-13/τ, resulting in 1.5E-13, 1.5E-14 and 1.5E-15 for 1s, 10s and 100s gate times (τ). Initial results suggest even better performance than this with Allen variances of 5E-14, 8E-15, 1.5E-15 and 3.5E-16 for 1s, 10s, 100s and 1000s gate times (τ).

Assuming a constant ambient temperature, the A7 has been observed to drift only 2ps/hr, with the contribution of a 1-°C temperature change being less than an additional 10ps. A single shot rms resolution of 0.3ps was also measured, a remarkable result enabling the A7 to easily resolve the 3.6ps/hr drift rate between two hydrogen masers. The primary benefits of the A7 frequency and phase comparator are improved accuracy and reduced measurement time. Fast measurements with high accuracy permit greater knowledge of the stability of the signal.

The applications for an instrument capable of such resolution are anticipated to be numerous, ranging from national standards and calibration laboratories, through Cesium, Rubidium and Quartz production to time transfer measurements.