Quartzlock Model A7-MX Close-in Phase Noise Measurement & Ultra Low Noise Allan Variance, Phase/Frequency Comparison

Measurement of RF & Microwave Sources

Cosmo Little and Clive Green
Quartzlock (UK) Ltd, Gothic, Plymouth Road, Totnes, Devon, TG9 5LH, UK.

Tel: +44 1803 862062
cgreen@quartzlock.com

www.quartzlock.com

SCOPE

This presentation describes the measurement of time domain stability of microwave and RF sources and passive devices between 20MHz and 40GHz. An outline of a suitable measurement instrument is proposed.

INTRODUCTION

The A7MX frequency/phase difference comparator is a Quartzlock product for measuring a wide range of frequency standards, isolation amplifiers, frequency multipliers and dividers, and passive devices such as cables. The frequency reference can be either 5MHz or 10MHz.
The high resolution input operates on 5MHz or 10MHz with only a small deviation from the nominal frequency being permitted. The time resolution on the high resolution input is 0.125fs. The actual achievable resolution is noise limited.
The high resolution input is intended for the measurement of frequency standards and atomic clocks with outputs of either 5MHz or 10MHz.

The low resolution input operates between 50kHz and 65MHz with a basic time resolution of 12.5ps. This input cannot give an Allen variance noise floor lower than 3E-11 at tau=1second due to the resolution limit.

There are three possibilities for extending the instruments frequency range to the high RF and microwave domains. These are:

a) Construct a high resolution downconvertor which converts the input frequency to 10MHz for input to the high resolution input of the A7MX. Because of the narrow band of frequencies the high resolution input will accept, the downconvertor local oscillator (LO) would have to have 0.01Hz resolution . This is extremely difficult to do.

b) Construct a low resolution downconvertor which converts the input frequency to an IF in the range 10MHz to 65MHz for input to the low resolution input of the A7MX. The step size of the LO can then be equal to the IF bandwidth, ie for LO synthesizer steps of 10MHz, the IF bandwidth would be 10MHz. There is plenty of room in the FXQ measurement range to accommodate the IF bandwidth. The disadvantage of this approach is that it is difficult to provide a range of measurement bandwidths, important for getting the best possible time resolution.

c) Construct a high resolution downconvertor using double conversion. The first IF would be in the range 15 to 25MHz. The first LO would only need 10MHz steps as in approach (b). The second LO would tune over the range 15 to 25MHz and would have a high resolution of sub 1Hz. The final IF could be 100kHz. At this frequency filtering is much easier, and in fact the FXQ could provide the narrow measurement filters . This has already been proposed for the A7000. (lower cost version of the A7MX)

The general problem with downconvertors is that noise and phase instabilities in the LO are indistinguishable from noise and phase instabilities on the measured signal. Thus the LO synthesizer needs impeccable performance, both as regards phase noise and Allen variance noise floor. The Allen variance noise floor at taus greater than 10seconds will be largely determined by phase variations due to temperature gradients . Between 0.1 and 10 seconds there will be a contribution from both temperature instabilities and phase noise. Below 0.1 seconds the LO phase noise will dominate.

COMPARISON WITH OTHER INSTRUMENTS

Before deciding on an ideal specification of a microwave phase and frequency measuring instrument, it would be useful to consider different types of competing instruments.

a) Frequency counters

There are many types of frequency counter, however what is common to all instruments in this category is that they make time measurements of the zero crossing of the signal to be measured. An older generation reciprocal counter will make two measurements of the zero crossings, at the start and end of the gate period. By also counting the number of zero crossings between time tags, the frequency can be calculated. The total phase advance between time tags can also be calculated. The time resolution cannot be better than that of a single time tag. This is typically 80ps to 1ns .
More modern counters make multiple time tag measurements during the gate period, at a rate up to 250ks/s. The intermediate time tags can be used to improve the resolution by root(N), where N is the number of measurements available.

Some counters such as the most advanced made by Pendulum can store and output a large number of time tags for external processing. External processing can identify and measure phase modulation on the original signal, and can calculate Allen variance.

Counters can be extended to microwave signals by either downconverting or prescaling. Prescalers are now available up 20GHz. Downconverting using a sampling mixer is more complicated, but can extend the frequency up to 50GHz. The advantage of the downconversion approach is that the basic time resolution of the counter is improved by the ratio of the input frequency to the IF frequency that is measured. A prescaler does not affect the time resolution.

Counters are almost never specified in terms of Allen variance noise floor (phase stability) or long term drift. Resolution is usually specified, and is dominated by trigger noise, as the input bandwidth is very wide. For this reason counters can never achieve the lowest Allen variance noise floors.

Counters are usually dual channel. They can make time difference measurements between the channels with one channel acting as the start gate, and the other the stop gate. By using a single source with a power splitter, time domain stability of passive devices such as amplifiers can be measured by placing the device in the path between one output of the power splitter and the counter channel. The resolution of this technique is limited to the basic time resolution of the counter.

b) Modulation domain analysers

Modulation domain analysers are frequency counters with very rapid measurement rates, and a deep measurement memory. Measurement rates go up to 80Ms/s. The frequency resolution inversely depends on the measurement rate (reciprocal of gate time). The single shot time resolution is usually around 100ps.
Modulation domain analysers are useful for measuring phase/frequency modulation and drift on CW or pulsed sources. because of their rapid measurement rate, they can measure very short pulses used in pulse compression radar.

c) Signal source analysers

These instruments are quite new, and combine a number of measurement types into one instrument. They basically work by downconverting the input signal to either baseband or a lower IF. This is then sampled by a high rate ADC (250Ms/s). A digital phase or frequency lock loop is used to lock the LO at the correct frequency.
They usually have 2 channels, each with its own reference oscillator and synthesised LO. By making cross correlation measurements between the channels, the reference and LO noise can be eliminated leaving only the noise from the source. This enables quite low phase noise floors irrespective of the reference noise.
They can also make rapid frequency measurements and can replace modulation domain analysers. In fact Agilent have now discontinued all their modulation domain analysers. The frequency resolution is not particularly good, reaching 10^{-12} for 1 second gate time at 1GHz, but does not increase with gate time in the usual way. The frequency resolution is a complicated function of the down convertor bandwidth and gate time, for more information refer to the data sheet for the E5052B.

d) Vector network analysers

Network analysers cannot measure sources, but are very good at measuring phase or group delay (rate of change of phase with frequency, equal to the time delay of the device) in amplifiers or other passive devices. Because they have a narrow resolution bandwidth, they have very good phase resolution. Typical resolution for differential phase measurements is 0.1 degrees, with a temperature stability of 0.2degrees / degC. At 10GHz this is a resolution of 30fs, with a stability of 60fs. A vector network analyser can also measure absolute delay, this is called group delay and is calculated from the rate of change of phase over a known frequency sweep. Group delay resolution can be 10ps over 100MHz sweep range.

e) Frequency/phase analysers

Instruments such as the A7MX are quite rare, and really require their own category. They are

basically counter based instruments, but the input signal receives considerable modification, including down conversion, before being measured.
Most instruments of this type use a dual channel downconvertor with a single LO. The most basic form measures the phase difference between two signals of the same nominal frequency. In this situation the IF frequencies are the same, and time difference measurements may be made between the channels using a frequency counter in its time difference mode. The counter time resolution is multiplied by the downconversion ratio (the ratio of the input signal frequency to the IF frequency). The advantage of the basic form is that to a first approximation the noise and drift of the LO cancels out.
The problem with the basic form is that as the common IF is made lower in frequency, with the intention of increasing the time resolution, the available measurement bandwidth gets less. The other problem is that the phase jitter in the required zero crossing detectors increases as the slew rate of the IF decreases. Very narrow bandwidth zero crossing detectors have been developed to avoid this.

The Quartzlock A7MX actually has two downconversions and two PLL multipliers in each channel in order to get the required time resolution multiplication without the final IF becoming too low in frequency. The multiplication is either 10^3 or 10^5, with a final IF of 100kHz. The channels are subtracted to remove noise on the common LO using an offset mixing scheme before the frequency counter, so only a single channel counter is required.

Extension of the basic instrument to measurement of an input frequency substantially different from the reference frequency means that the downconversion LO must be different for the two channnels. This immediately means that the condition for cancellation of the LO phase jitter and drift is lost. The characteristics of the LO will be measured as well as the input signal.

If one examines the block diagram of the Picotime, for example, one can see that it is essentially a single channel downconvertor. The 10MHz reference is used to generate two LOs using DDS synthesisers which downconvert the input to an IF of 1kHz. (double conversion). All the drift and spurii of the LOs will be measured along with the input signal.

DISCUSSION OF REQUIREMENTS FOR NEW INSTRUMENT

The proposed microwave frequency and phase analyser will be used for the following measurement tasks:

a) Measurement of time domain stability of sources between 10MHz and 20(40) GHz referred to a reference source of 10MHz (single channel mode)
b) Measurement of time domain stability of two identical microwave sources with a relatively small frequency offset. (dual channel mode)
c) Measurement of time domain stability of microwave passive devices (not sources) (dual channel mode)

For requirement (a) the main competition is a conventional and relatively low cost microwave counter. The Pendulum CNT-91 offers a fixed single shot time resolution of 50ps, applicable up to 20GHz. It uses prescalers to cover the microwave range, rather than downconvertors, so there is no improvement in resolution at higher frequencies. The frequency resolution claims to be 12 digits in 1sec of measurement time. This is quite a vague specification, but implies resolution of 1ps after averaging. The counter makes multiple time tag measurements and

improves its resolution by linear regression of the time tags to obtain average frequency during the measurement period.
As with all counters, there is no specification on Allen variance noise floor or drift.The basic counter will show Allen variance at one gate time, but in order to produce a graph the counter must be used with a PC and the Timeview software.

A new instrument based on a downconvertor would certainly be able to get much better resolution than 1ps. An instrument based on approach (b) above at 10GHz would improve the basic resolution of the FXQ (the phase meter used in the A7MX) by 500 times, which would give a basic time resolution of 25fs. It is very difficult to estimate the usable noise limited resolution, however, as this will depend upon the noise performance of the LO.

One might question whether there are any free running sources to be measured at microwave frequencies. Most microwave sources are synthesized, in which case there is hardly any point in making Allen variance measurements at long averaging times as the performance will be equal to the synthesizer reference that is used, and this could be measured using a standard A7MX.

Conceivable microwave measurements using a 2 channel instrument might be the phase stability of cables and other passive (not sources) devices such as amplifiers, phase shifters, and power splitter/isolation devices. The phase performance of these is important for applications such as phased array radars. Unfortunately most labs seriously developing microwave devices will have a vector network analyser, and will use this to evaluate phase stability.

In single channel mode, the instrument could measure frequency stability against a 10MHz reference. By using the same sort of averaging techniques as the Pendulum counter (linear regression of multiple time tags) resolution of 10E-14 in one second of gate time could be achieved. The actual Allen variance floor will be determined by the stability of the local oscillators.

OUTLINE PERFORMANCE OF NEW INSTRUMENT

The proposed instrument will have the following features:

a) Two measurement channels with common local oscillators in order to measure identical frequency sources and passive devices. In this mode substantial cancellation of the local oscillator noise and drift can be expected.

b) A basic measurement range of 10MHz to 2GHz

c) An extended measurement range of 2GHz to 20GHZ (possibly 30GHz)

d) Measurement bandwidths of 10kHz to 0.1Hz provided by digital filters

e) Minimum single shot phase resolution of 125fs at 10MHz rising to 0.625fs at 2GHz.

f) A user interface similar to the existing A7MX, with displays of Allen variance and power spectral density.

OUTLINE OF DETAILED DESIGN

It is not possible to be too explicit about the design details at this moment. The following comments can be made:

a) The instrument will be double conversion on the basic range and triple conversion on the extended range

b) On the basic range the first IF will be tunable between 15MHz and 25MHz. The second IF will be 100kHz

c) On the extended range the first IF will be tunable between 1GHz and 2GHz (tbc)

d) In order to achieve the best possible phase stability, the design of the first LO synthesiser, which will cover the range 25MHz to 2GHZ in steps of 10MHz, will be optimised for phase stability with temperature and low noise. It is probable that a harmonic locking loop will be used with a sampling phase detector. This type of loop uses no digital dividers.

e) The second LO synthesiser covers the range 15MHz to 25MHz in steps of <0.1Hz. A fractional N loop will probably be used covering the range 960MHz to 1.6GHz followed by a digital divide by 64. The divider will reduce spurii and phase noise on the synthesiser by about 36dB. Drift and noise in the divider will probably be the limiting factor.

f) The extended range will be accomplished by a dual channel harmonic downconvertor using sampling mixers. The sampler drive will be at about 1GHz. Due to the wide tunable bandwidth of the first IF in this mode (1GHz to 2GHz) only two possible sampler drive frequencies will be needed to cover all the possible input frequencies. Thus the synthesiser used to drive the sampler will be quite simple.