Dual IQ for Complex RF Demodulation

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Abstract

In-phase and Quadrature (IQ) time referencing of Digital Sampling Oscilloscopes (DSOs) can correct for jitter and timebase nonlinearity and can also be used to demodulate both simple and complex RF waveforms. At high frequencies/jitter levels, however, IQ alone can be insufficient. We outline preliminary tests of a dual IQ scheme in which an additional slower IQ reference is introduced to resolve these issues. We also discuss its application to sampler nonlinearity and to the progression towards traceable waveform metrology.

I. Introduction

IN-PHASE and Quadrature (IQ) correction is starting to prove its worth in an increased number of digital sampling oscilloscope (DSO) applications. By using sine signal and cosine signals on two of the DSO channels as timing references it is possible to correct acquired waveforms for jitter and timebase errors and so achieve reduced errors and uncertainties in the measured waveform parameters. This has been demonstrated for generic correction for jitter [1], correction of eye diagrams [2] and demodulation of amplitude-modulated signals [3], underlining its wide range of uses. IQ correction is typically carried out at frequencies with periods of the order of the epoch being measured (MHz range), but can also be used at higher frequencies to provide phase information at each point in a signal waveform, enabling the determination of AM and FM components. Unfortunately the nature of the technique means that timebase correction is unobtainable when these high IQ frequencies are used, which can lead to timebase-induced errors when attempting RF demodulation.In this paper we propose a method to enable timebase correction during RF demodulation through the use of a second pair of IQ reference signals at low frequency applied as a form of modulation of the original IQ pair, which we term *dual IQ*. As with single IQ, only two oscilloscope channels are required and the combined high and low frequency references provide both phase and timebase information. This provides greater accuracy when extracting the modulation parameters from a measured waveform: As an example we demonstrate the identification of nonlinearity within the sampler.

Section II explains the principle of IQ referencing as applied to both timebase corrections and phase determination, discussing the limitations that arise at different frequencies, Section III explains the proposed dual IQ technique and Section IV presents some modelled data that illustrates the relative performance of the different techniques. Application of dual-IQ to sampler nonlinearity is used as a real measurement example in Section V.

II. In-Phase Quadrature correction

A. Principles of IQ correction

A sampling oscilloscope measures the waveform of a repetitive signal by sampling it at various times, each time related to a trigger event. There will normally exist some timing error between each trigger event and the sampling event, and this error is commonly known as the jitter σ_j. The probability distribution function of the jitter convolves with the waveform during the waveform

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measurement, increasing errors in parameters such as rise-time or eye width. Additionally, there may be systematic errors introduced as the time interval between the trigger event and the sampling event increases. These errors, too, distort the resulting measured waveform. IQ correction, however, can compensate for each of these.

The key to IQ correction is a sampling oscilloscope architecture where all sampling channels are triggered by the same event. (Note that this is not true for all oscilloscopes.) When this is the case the jitter between the sample events of two individual channels, σ_s, is very much less than σ_j. This means that a signal on one channel can be used as a reference for another channel (the signal channel), greatly reducing the timing errors in that channel. Of course, this requires that the timing of the reference signal itself is known, yet this will also be subject to timing errors. Therefore some way of knowing the true timing of the reference signal is required.

The answer is to use two reference signals, each an equal single frequency tone f_{IQ}, $\frac{\pi}{2}$ out of phase with each other, i.e. one, in-phase, one at quadrature. Plotted parametrically, these two signals will (if perfect) produce a circle. Therefore for any sampling event driven by a trigger event there will be, in addition to the signal point(s), a pair of IQ points that locate the sampling event in time on the circle $t_i = t_\theta$, where t_i is the time ascribed to the sampling event and t_θ is the time corresponding to the vector to the unit circle with angle θ (in radians) in the parametric co-ordinate system, i.e.

$$t_\theta = \frac{\theta}{2\pi f_{IQ}} \tag{1}$$

This reduces the uncertainty of the sampling event to σ_s(typically in the region of 200 fs) rather than σ_j.

A parametric circle will only occur if the IQ signals are perfect, i.e. match exactly in amplitude, offset and have the precise $\frac{\pi}{2}$ phase difference. In practice there will be errors that distort and offset the circle, producing an elliptical plot. These effects can be corrected for by calculating the parameters of the ellipse that best fits the plot and then computing the appropriate transformation of that ellipse to a unit circle. (Note that noise in the IQ reference will 'thicken' the plot, increasing the number of possible parameter solutions and so introducing added uncertainty to the result.) This transformation is then applied in turn to the IQ reference waveforms obtained. Computation of the transformation requires as complete an ellipse as possible, so at least one cycle of the IQ waveforms should be present in the measurement, i.e. $f_{IQ}^{-1} \leq T$, where T is the total duration of the oscilloscope timebase.

(N.B. Corresponding parameters of the I and Q reference signals and their measured waveforms, such as their frequency or amplitude, are normally equal or approximately equal to each other. For clarity then we shall use singular terms such as "the frequency of the IQ reference waveform", and it is understood that in reality this applies to both.)

B. Limitations of the single IQ scheme

With IQ referencing, jitter and timebase nonlinearities can be corrected for and the time of each point in the signal waveform calculated to within σ_s, which sets the noise floor of the measurement. It should be apparent that the technique is dependent on the time error (jitter and nonlinearity combined) between successive points being less than a single cycle of the IQ reference, i.e. in terms of phase

$$\phi_{\Delta t} \leq 2\pi \tag{2}$$

If $\phi_{\Delta t} > 2\pi$ then there will be ambiguity in the referenced time, since events separated by $\frac{n}{2\pi f_{IQ}}$ will be located in the same place on the ellipse and so be indistinguishible. This can be avoided by using a frequency as low as possible (within the limit that $f_{IQ}^{-1} \leq T$). However, there is an added complication related to voltage noise σ_V. Voltage noise can be mistaken for jitter according to

$$\sigma_{j'} = \frac{\sigma_V}{2\pi f_{IQ}} \tag{3}$$

(j' has been used to indicate equivalent, not real, jitter). For long T (which will exhibit large σ_j) using too low a value for f_{IQ} may result in this equivalent jitter increasing the phase error beyond the $\phi_{\Delta t} \leq 2\pi$ constraint. This will necessitate the use of a higher f_{IQ} that is still within the limits of this constraint. Selection of f_{IQ} must clearly be considered carefully when long timebases are involved, and it is wise to limit σ_V as much as possible, e.g. through reducing the sampler bandwidth setting.

C. Reported-time method

It might seem that the need to avoid ambiguity mentioned above means that there is also a requirement that the period of the IQ reference is greater than the time difference Δt between successive points. However, provided Equation 2 is met, it is still possible to calculate the IQ corrections in a single IQ system using the *reported-time* method, which is simply based on Δt as reported by the oscilloscope. Multiple cycles (circuits of the ellipse) are accounted for within Δt and the so time t_i of a point is simply

$$t_i = \Delta t + t_\theta \tag{4}$$

where t_θ can be positive or negative. Note though that this is dependent on Δt being approximately correct — large errors in Δt, such as glitches in the timebase, will cause this method to produce incorrect results.

D. IQ correction scheme

The schematic for a typical measurement with IQ correction is shown in Figure 1. A synthesiser, synchronised to the source of the signal of interest, is used to produce the basic reference tone. This is split using a power divider or similar and some form of delay (usually variable for fine adjustment) introduced to produce two signals at quadrature which then provide the IQ reference. Acquisition is in single-shot mode (i.e. no averaging) and typically at the maximum number of points the oscilloscope can provide, creating a data file that contains the waveform measured by each channel. Multiple files (acquisitions) are taken to improve the final signal to noise ratio. These files are loaded at a separate time by software (at NPL we use a MathCAD sheet) that computes the transformation to the unit circle for the IQ references, then uses these transformed IQ references to calculate the correct timings of each point in the signal waveform.

It should be apparent that one of the main limitations in IQ correction is the amount of data acquired. Fifty measurements using three channels, each at 4096 points, equates to well over half a million data points. All these points need to be loaded simultaneously to compute the IQ corrections. Frequently the limitation on the number of points that can be processed is within the computer memory — the vast majority of programming languages require sufficient congruent memory space to store arrays or matrices.

Once the correct timings have been determined, subsequent processing is dependent on the application. Currently at NPL we are concentrating on harmonic content of RF-type waveforms. A

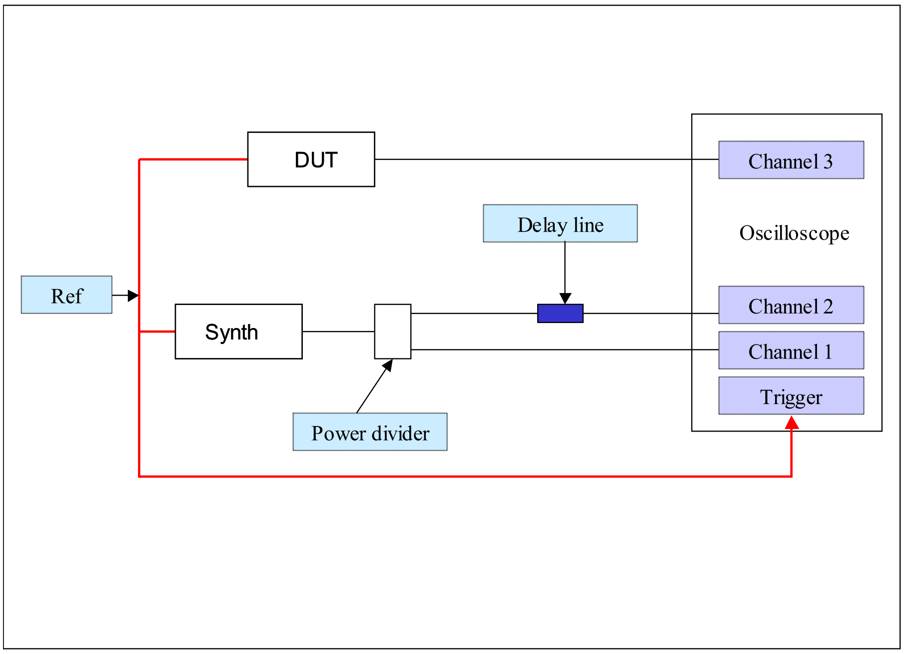

Fig. 1. Schematic showing a basic measurement using IQ correction. By splitting the output from a synthesiser and delaying one with respect to the other, two signals at quadrature are produced. If all oscilloscope channels trigger off the same event, these signals can be applied to two channels to provide a reference for a third.

least-squares-fit routine determines the sine and cosine components that produce the signal waveform — the amplitudes and frequencies of the calculated components thus producing the frequency spectrum of the signal. Without IQ correction, timing errors would produce distortions that would be incorrectly interpreted as modulations of the signal.

E. IQ for waveform demodulation

In the case where $f_{IQ} >> f_{DUT}$, the frequency of the signal of interest, one or more cycles of the IQ waveform will correspond to a 'point' on the signal waveform. The effect of jitter means that repeated sampling will produce the cycle(s), from which the phase of the signal point in question can be determined (since it will be equal to the phase of the IQ cycle, within the bounds of σ_s). This provides a method for retrieving the phase of the signal waveform at every point, enabling demodulation of the signal waveform to be carried out.

For low signal modulation frequencies ($\sim 10^5$ Hz) f_{IQ} can be high enough to provide the phase information without disrupting Equation 2. At higher modulation frequencies, however, this constraint is typically exceeded and so timebase corrections cannot be made. Timebase errors are interpreted as modulations in the signal waveform, adding to the uncertainties. Even so, IQ demodulation is a powerful technique for retrieving amplitude and frequency modulation components with the potential for traceability through the sampling oscilloscope: Reduction of the uncertainties would make it even more attractive.

III. Dual IQ scheme

To provide timebase correction for high modulation frequency waveform demodulation using an IQ reference, we propose the use of a second pair of IQ signals to provide an additional, low

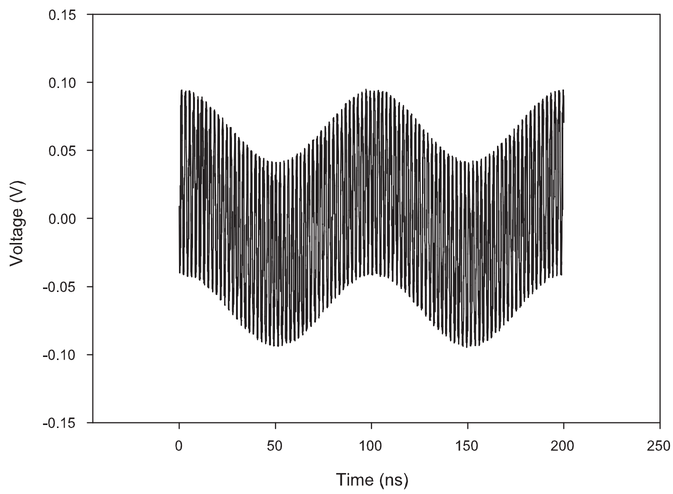

Fig. 2. Captured waveform of one half of a dual IQ reference. The high frequency is 20 GHz and the low frequency 10 MHz.

frequency, reference. To avoid the use of additional channels (as indeed there would be no channel left for the signal!) the second IQ pair is applied as an addition to the first. To implement dual-IQ, a suitable source set to provide a much lower frequency tone, such as a second synthesiser or similar, is synchronised with the first and has its output divided and a delay introduced as required to obtain I and Q components. (For clarity, we refer to the original IQ pair as 'high IQ' and the second IQ pair as 'low IQ', in reference to their relative frequencies.) The low IQ pair is combined additively with the high IQ pair, each component being combined with its corresponding partner. (Figure 2 illustrates a typical pair of waveforms produced in this manner.) When plotted parametrically, the high IQ reference signals still produce an ellipse, but the centre of this is located by the low IQ reference signals and so describes another ellipse.

To solve the transformations for both ellipses, we implement an iterative method that moves between the two. First the low IQ ellipse is determined approximately by calculating the centre of each of the smaller ellipses — typically a simple geometric average of the points is sufficient at this stage — and a corresponding IQ timebase correction found from this. This correction is then applied to the high IQ waveforms, and the newly-corrected ellipses produced can then be used to determine the larger ellipse once again. In this way the algorithm moves back and forth between the two until a suitable solution for both is reached.

IV. Modelled Comparison of Single and Dual IQ measurements

A MathCAD model written at NPL simulates a two-tone (two single frequencies with a relatively small separation added together) measurement with IQ reference signals. The model is capable of simulating effects such as voltage noise and jitter in both the signal and the IQ references, as well as nonlinearity in the timebase. Correct calculation of the IQ ellipse transformations is assumed by the model. The model produces the following: The results returned without any form of IQ correction (reported values); the results returned using a high frequency single IQ reference (differential phase); the results returned using dual IQ; the results returned using single IQ corrected using the reported time; and finally the true results (true time).

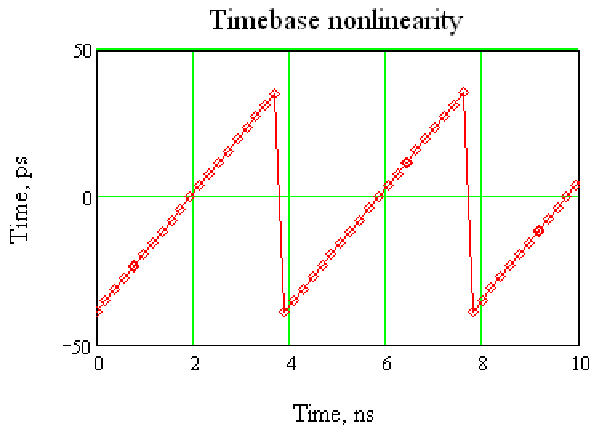

Fig. 3. Modelled timebase linearity, including the simulation of a glitch every 3.9 ns. Such glitches are found in some sampling oscilloscope timebases.

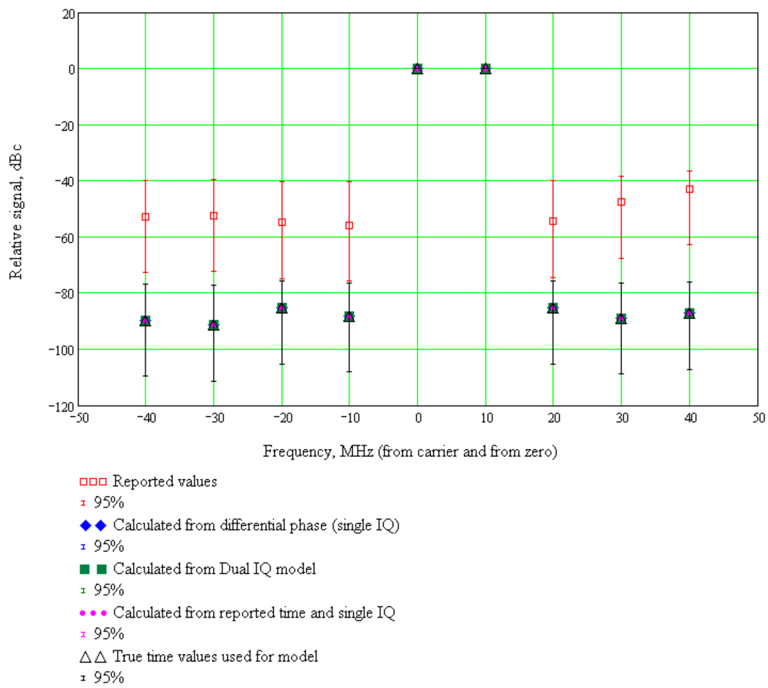

Fig. 4. Output from the MathCAD model for a typical two-tone measurement. It can be seen that the use of IQ correction improves sensitivity over the uncorrected measurement.

For a typical result from the model, five 200 ns traces of 1024 points were generated, based on two-tone signals at 1 GHz and 1.01 GHz. Also simulated was a timebase nonlinearity of 2% occuring every 3.9 ns, as illustrated in Figure 3. Figure 4 shows the results: The higher noise floor in the sideband region is clearly evident for the uncorrected values, demonstrating that the use of IQ can increase system sensitivity.

Figure 5 demonstrates what happens when higher IQ (and corresponding tone) frequencies are

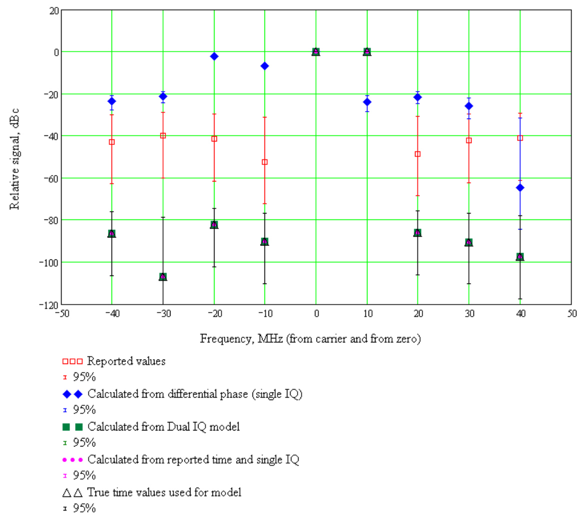

Fig. 5. Output from the MathCAD model for a two-tone measurement at higher frequency (3 GHz). The basic IQ correction method fails at these higher frequencies.

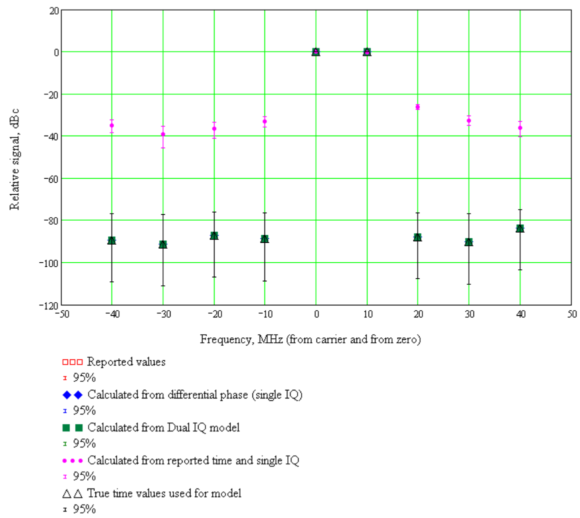

Fig. 6. Output from the MathCAD model for a two-tone measurement at with a timebase scaling error. The reported-time method mis-interprets the error has harmonics in the signal. The uncorrected results are not even returned correctly.

used. At 3 GHz the single IQ method struggles due to violation of Equation 2, raising the noise floor compared to the uncorrected results. Including the reported time, as can be seen, rescues the single IQ method. On the introduction of a scaling error in the timebase, however, the reported time method produces spurious errors (Figure 6) as distortions are interpreted as real harmonic distortion in the signal.

It is seen then that only the dual IQ method appears to be capable of dealing with every type of likely timebase error, as well as providing the phase information of the signal for demodulation. A model of this type is very useful in understanding how the various errors in timing can contribute to errors in the returned values for the signal harmonics, as well as for identifying the most appropriate IQ method for a given experimental system.

V. Determination of sampler nonlinearity

As an example of the application of dual IQ, we present here some preliminary tests that demonstrate the improved system sensitivity leading to identification of a potential sampler nonlinearity. Such nonlinearity of response with frequency in samplers can introduce significant errors into measured waveforms but can be extremely hard to measure due to the difficulty of distinguishing between errors in voltage and errors in time. By applying IQ correction to remove the timebase errors the remaining distortions in voltage can be attributed (where appropriate) to nonlinearity effects. We showed this previously using IQ-corrected measurements of single tone frequencies with DC offsets applied [4]. Here we apply a fuller treatment using mixed tones which we IQ-correct and then use a component-fitting algorithm to determine the harmonic components and any residual nonlinearities in the system.

Figure 7 shows the experimental set-up used. A two-tone signal is created by using a power splitter to mix the output from two synthesisers, synchronised via their 10 MHz references. The normal IQ reference is provided by a third synchronised synthesiser which has its output split by a power divider. A variable delay line in one arm of the output shifts the references to quadrature. To implement dual-IQ, the 10 MHz reference is also split out using a standard T-connector, and passed through some suitable low-pass filters before being split by a third divider. Quadrature can be achieved using an appropriate length of cable on one output if necessary. Attenuators should also be used in at least one IQ arm to avoid reflections which can create sidebands in the system. These second low-frequency IQ components are then applied to their respective high-frequency IQ components using bias tees. The 10 MHz reference from the synthesisers is also used to trigger the oscilloscope.

Measurement of the two-tone signal was made by 40 single-shot acquisitions at 4050 points, generating 486,000 points of data for each measurement. Two dual-channel sampling heads were present in the oscilloscope, one of 50 GHz bandwidth and the other of 70 GHz. To minimise noise in the IQ reference it was measured using the 50 GHz sampler at its lower bandwidth setting of 26 GHz. The signal of interest was measured on the 70 GHz sampler at full bandwidth. Initially a two-tone signal comprising of a 1 GHz tone and a 1.01 GHz tone at -20 dB was measured, using 1 GHz for the high IQ frequency. The retrieved results are shown in Figure 8.

The expected low noise floor, around -75 dBc, is immediately apparent. Also apparent are the unexpected signal components present 10 and 20 MHz from the carrier, around -63 dBc. It was put forward that these were due to nonlinearity in the sampler but the difficulty is that similar effects would be expected if any nonlinearity were present due to the dual IQ reference itself — as the high frequency component of the IQ reference is at the same frequency as the carrier, such nonlinearities could mask those in the sampler. To ascertain this, single IQ measurements were made of the two-tone signals, as the cause of single IQ reference nonlinearities are more easily identified. The two-tone signals were shifted to 900 MHz and 910 MHz to avoid any masking effect. Figure 9 shows the result: The 10 MHz sideband at -63 dBc is still present. As a final check, this measurement was repeated with the signal of interest on the 50 GHz sampler and the single IQ reference on the 70 GHz sampler, set to 50 GHz bandwidth (Figure 10). The 10 MHz sideband is no longer evident, further supporting the suggestion of nonlinearity in the 70 GHz sampler. Note also the higher noise floor due to the use of a higher bandwidth sampler for the IQ reference (as expected from Section B). We suggest, then, that the appearance of this sideband on changing the configuration

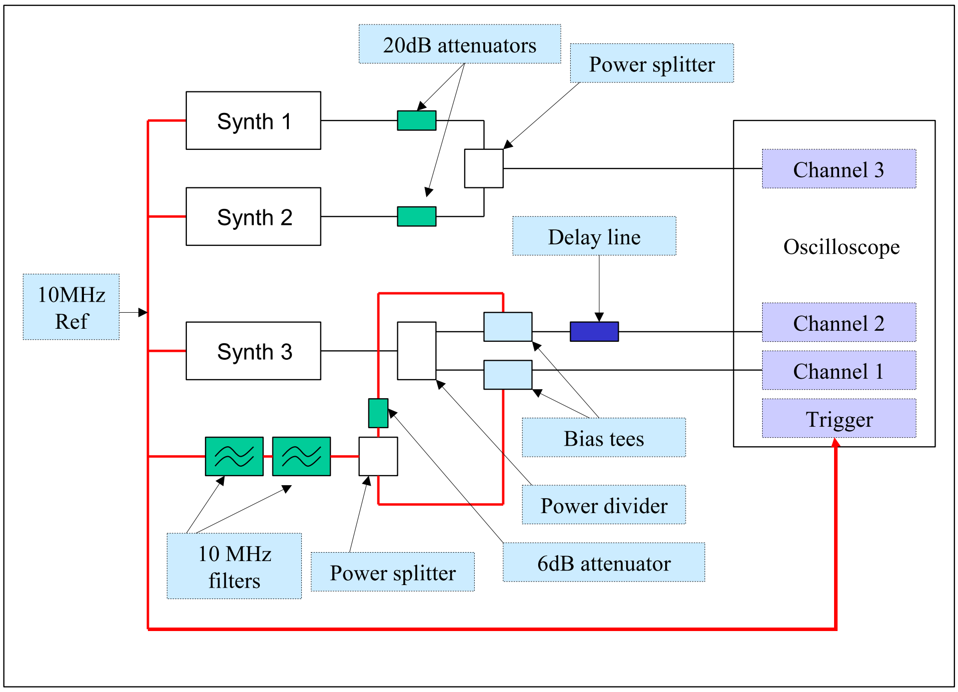

Fig. 7. Experimental arrangement using a two-tone signal and a dual IQ reference to examine nonlinearity in an oscilloscope sampler.

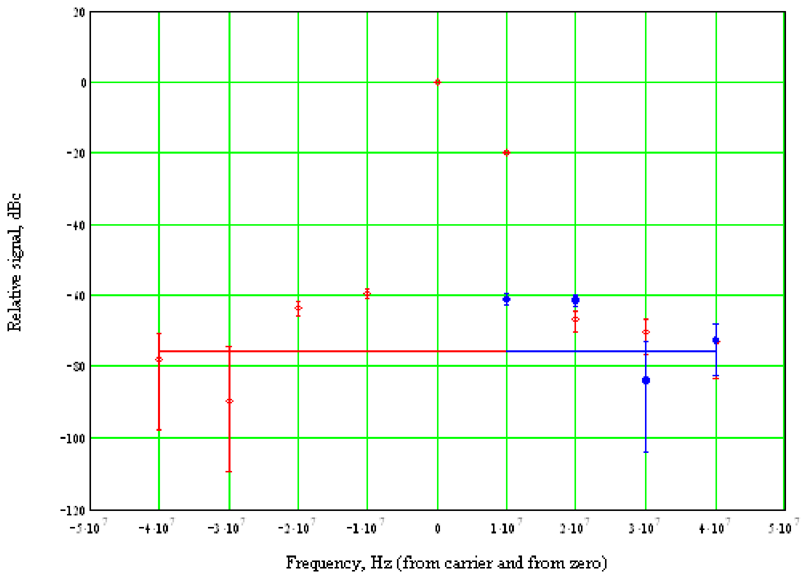

Fig. 8. Two tones at 1 GHz and 1.01 GHz on a 70 GHz sampler with IQ references on a 50 GHz sampler (set to 26 GHz bandwidth). The additional sidebands at around -63 dBc are clearly apparent.

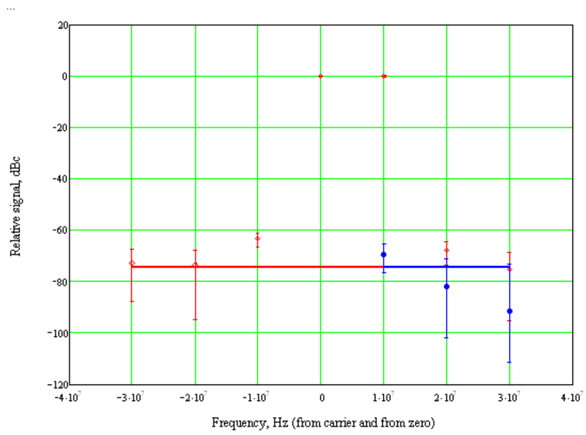

Fig. 9. Two tones at 900 MHz and 910 MHz on a 70 GHz sampler with IQ references on a 50 GHz sampler (set to 26 GHz bandwidth). The 10 MHz sideband at -63 dBc is clearly apparent.

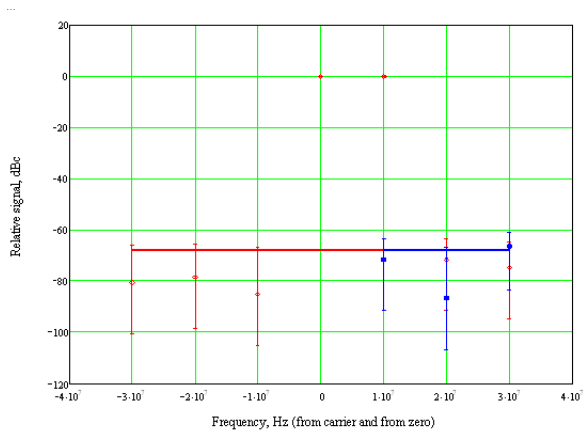

Fig. 10. Two tones at 900 MHz and 910 MHz on a 50 GHz sampler with IQ references on a 70 GHz sampler (set to 50 GHz bandwidth). No 10 MHz sideband is visible now. Noted the raised noise floor (compared to Figure 9) due to the higher bandwidth of the IQ sampler.

implies a nonlinear characteristic in the 70 GHz sampler.Identification of this type of subtle feature (down at the -65 dBc level) would not be possible using conventional measurement methods and demonstrates the potential power of dual IQ for improving sensitivity and reducing uncertainty in demodulation metrology.

VI. Towards fully traceable waveforms

Characterisation of an instrument is often distilled to a solitary value, for example the risetime of a pulse generator or sampler response, and its associated uncertainty. Such a single value is useful for simple corrections and assessments but does not tell the whole story. The value will have been calculated from a waveform such as the measured pulse generator output or derived sampler impulse response, and will only provide gross information about that waveform. Finer details, ringing in the response for instance, are not captured by the value yet can be an important feature of instrument performance when more exacting measurements are required. At NPL we are currently working towards providing a service that provides a fully traceable waveform as the characterisation of an instrument's output or response. The point-by-point corrections that dual IQ can provide are seen to be an important stage in the development of this.

VII. Conclusions

We have proposed an extension to the IQ correction technique that we term dual IQ, in which low-frequency IQ reference signals are added to high-frequency IQ references. This enables simultaneous phase determination and timebase error correction for the individual points of a waveform measured using a sampling oscilloscope. Modelled data demonstrates the advantages of this technique over single IQ and preliminary data, and we have presented some preliminary results using dual IQ to identify nonlinearity in a high-bandwidth sampler. Further measurements will be given at the conference. It is anticipated that this technique will be developed at NPL as part of the advancement of ultrafast measurements towards providing full, traceable, waveform metrology.

VIII. Acknowledgements

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