The Challenges of Precision Analog Modulation Measurement

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Abstract - In today's digital world, many established analog techniques are being replaced by modern digital alternatives. Digital modulation is now commonplace, particularly in mobile communications, but traditional analog amplitude and frequency modulation are still in widespread use. Laboratories performing RF calibration report that analog modulation meters and analyzers are a part of their workload that cannot be ignored. When a new RF calibration source was designed, precision analog modulation was included to address this workload. This paper describes the digital signal processing based techniques used to measure its modulated outputs, and explores the challenges in assessing modulation measurement uncertainties and validating the results obtained.

Introduction

The need to measure analog modulation has existed since the invention of radio communications and still remains in today's predominantly digital world. For example, measuring analog modulation is commonplace in the broadcast and civil aviation industries. Making accurate analog modulation measurements is a requirement in many applications. Analog modulation features are found in the majority of signal generators, often alongside digital modulation in the more sophisticated instruments. Consequently, one might expect obtaining traceability for modulation measurements at low levels of uncertainty would be easy. In practice, it is not. The oldest and simplest modulation technique, amplitude modulation (AM), is the most difficult to measure accurately and several measurement definitions exist for some of its parameters. A number of techniques can be employed, providing uncertainties for modulation index (AM depth) ranging from a few percent down to just below 0.5% at best. Frequency Modulation (FM, developed in the 1930s), is theoretically more complicated but does have the advantage of a mathematical relationship (the Bessel function) that can be exploited to provide an extremely precise determination of modulation index. However, even when this relationship is exploited, the best uncertainties achieved in practice are often a few tenths of a percent.

During the development of a new RF source instrument[1] intended for calibration applications with design goals for analog modulation accuracy of better than 0.1% and distortion <0.05% (-66dB), it became rapidly evident that the traditional modulation measurement techniques would not provide the desired levels of uncertainty. The instrument provides amplitude, frequency, and phase modulation from an internal source. Operation with an external modulation source is included, but is not the primary mode of operation. In summary, there are two key aspects to the measurement requirements:

- Accuracy of the modulation – to determine the accuracy of the AM depth or Frequency/Phase modulation deviation and the accuracy of the modulation rate.
- Quality of the modulation – to determine the amount of distortion present on the modulation and the amount of incidental modulation produced (for example, unwanted AM produced when generating FM).

Determining the amount of unwanted (residual) modulation present on the unmodulated output signal is also important. The techniques used for measuring low levels of intentional modulation can also be applied to measuring residuals.

A measurement technique based on digital signal processing is described, used for the following modulation characteristics:

- AM depth accuracy
- AM Distortion
- FM deviation accuracy
- FM Distortion

In practice, the same techniques are used to measure the residual and incidental modulation characteristics, but detailed discussion is beyond the scope of this particular paper.

A new modulation measurement technique employing in-phase and quadrature referencing is under development and an overview of the technique and preliminary AM measurement results are included.

Digital Measurement Demodulator

The technique chosen employs one of the new high performance spectrum analyser/measuring receiver based instruments featuring a measurement demodulator. The digital signal processing in the spectrum analyzer, used in the analyzer mode for digital IF filters, is also ideally suited for demodulating FM or AM signals. The block diagram of the analyzer signal processing below (Figure 1) shows the analyzer's hardware from the IF to the processor.

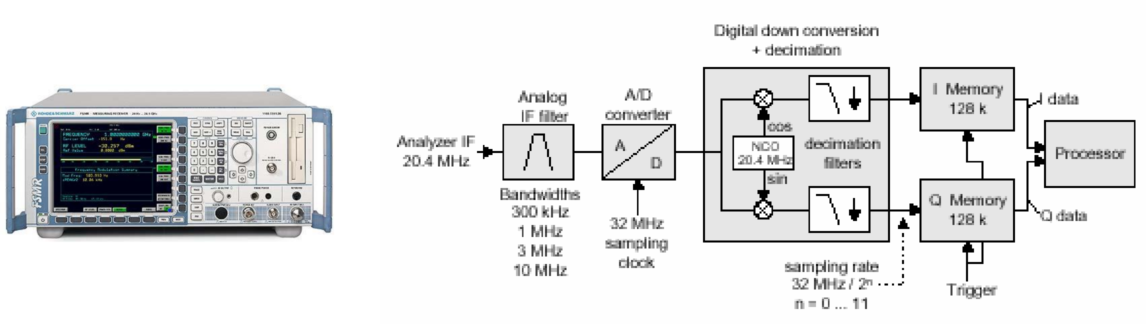

Figure 1. The R&S FSMR Measuring Receiver/Spectrum Analyzer and its IF to processor hardware[2].

The IF filter is the resolution filter of the spectrum analyzer, with a bandwidth range from 300 kHz to 10 MHz. The A/D converter samples the IF (20.4 MHz) at 32 MHz. Lowpass filtering and reduction of the sampling rate follow the downconversion to the complex baseband. The decimation depends on the selected demodulation bandwidth (DBW) setting. The DBW setting is not a 3dB bandwidth but is the range of frequencies for which amplitude and phase errors are negligible. The output sampling rate is set in powers of 2 between 15.625 kHz and 32 MHz. Useless oversampling at narrow bandwidths is avoided, saving computing time and increasing the maximum recording time.

By sampling (digitization) at the IF and digital downconversion to the baseband (I/Q), the demodulator achieves maximum accuracy and temperature stability. The accuracy and stability is maximized by minimizing the analog circuitry prior to the IF analog to digital converter. For this reason only the 10MHz IF filter setting is selected when using the analyzer for modulation measurements.

There is no evidence of commonplace errors of analog downconversion and demodulation like AM/FM conversion, deviation error, frequency response or frequency drift at DC coupling. Only the characteristics of the analog IF filter ahead of the A/D converter need to be taken into consideration.

The software demodulator runs on the main processor of the analyzer. The demodulation process is shown in Figure 2, the block diagram of the software demodulator. All calculations are performed simultaneously with the same I/Q data set. Measurements results can be displayed as time domain or frequency domain traces, numeric data, and results are also available via the analyzer's remote interface.

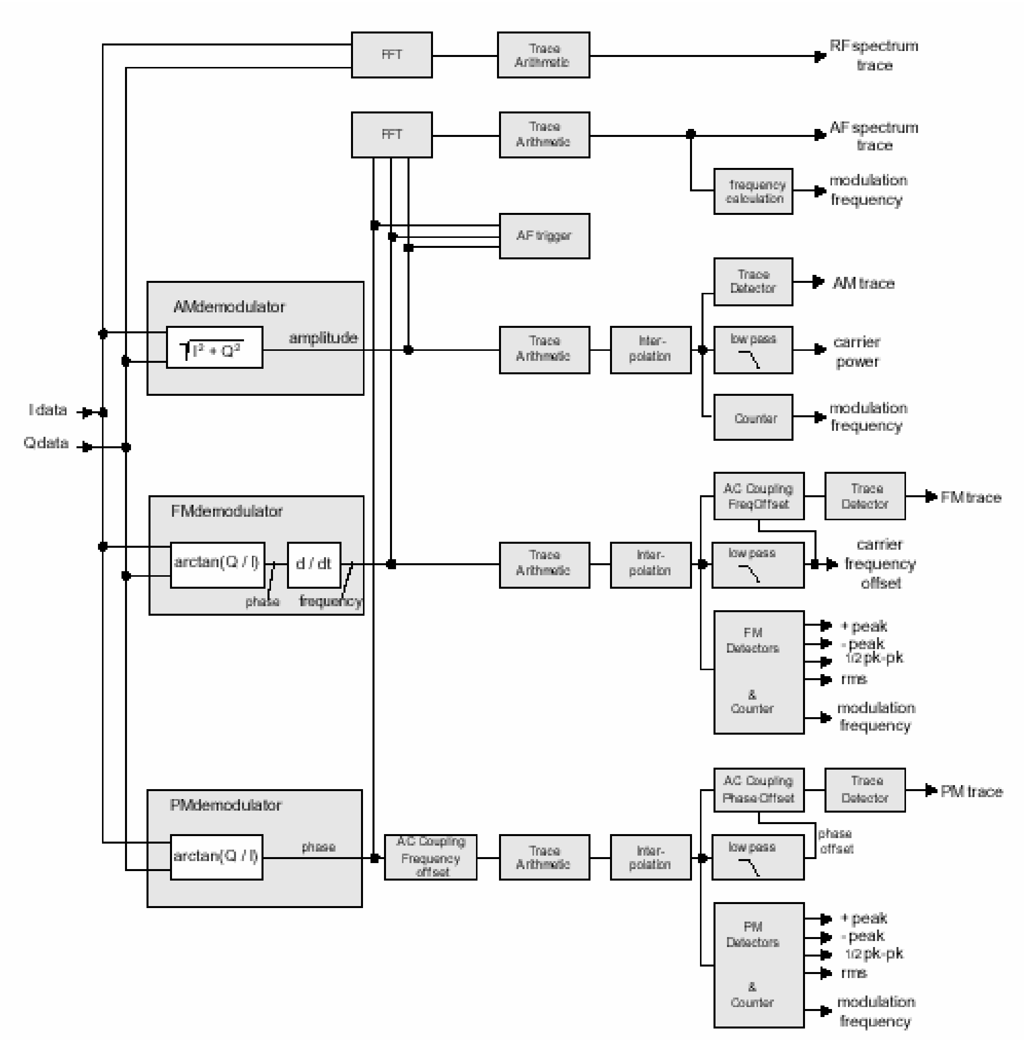

Figure 2. Block diagram of the software demodulator[2].

AM Measurements

An illustration of an amplitude modulated signal is shown in Figure 3. In the time domain, the amplitude of the carrier varies with the modulating signal, where V_p describes the peak to peak amplitude at the peak of the envelope, and V_t describes the peak to peak amplitude at the trough of the envelope. In the frequency domain, modulation sidebands of equal amplitude are located at the carrier frequency (F_c) plus and minus the modulation rate frequency (F_r).

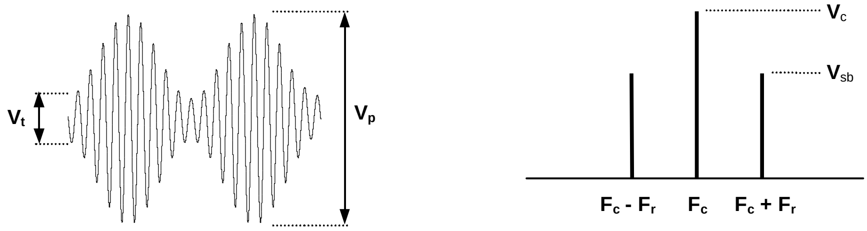

Figure 3. Time domain (left) and frequency domain (right) representations of an AM signal.

The modulation index (AM depth) is usually defined as $m = \frac{V_p - V_t}{V_p + V_t} \times 100\%$. The ratio of the modulation sidebands to the carrier amplitude depend on the modulation index, allowing a value for modulation index to be obtained by measuring the carrier and sideband amplitudes in the frequency domain. In this case $m = 2 \times \frac{V_{sb}}{V_c} \times 100\%$, where V_c is the amplitude at the carrier frequency and V_{sb} is the sideband amplitude. The example in Figure 3 shows an undistorted sinewave modulating the carrier. If distortion is present, additional sidebands will appear in the spectrum at $F_c \pm nF_r$, with n corresponding to the relevant harmonics involved, and the envelope will become distorted. Even harmonics produce asymmetric peaks and troughs, odd harmonics modify peaks and troughs equally. Other definitions of the modulation index are possible (based on detecting the positive or negative peaks and troughs, etc) and will result in different values for modulation index when distortion is present.

If the modulation process introduces unwanted FM, the sideband amplitudes will become unequal. (The sidebands introduced by the unwanted FM at $F_c \pm nF_r$ are of opposite phase, adding to and subtracting from the AM sidebands creating unequal sideband amplitudes).

Obtaining valid and accurate amplitude modulation measurements depends on setting the spectrum analyzer/measurement demodulator mixer level with appropriate choice of its RF input attenuator settings. The mixer is inherently a non-linear device, used to shift the input signal in frequency while preserving its amplitude characteristics. If the input signal level at the mixer is too high, the signal will be compressed and distorted resulting in AM depth measurement errors and incorrect THD readings. (Compression is the effect where as the input signal is increased the mixer output becomes progressively smaller in proportion as the mixer begins to be overloaded. As the input is increased further and the mixer is overloaded, intermodulation will occur resulting in sum and difference frequency products being generated, dependent on the frequency content of the input.)

The effect of mixer compression can easily be envisioned by considering the envelope of an AM signal. At the peaks of the modulation, the signal is closer to the mixer compression point than at the troughs, and therefore when compression takes place the carrier level at the peaks is reduced in relation to that at the troughs, effectively changing the modulation depth. For a 100 % modulated AM signal the peak carrier level is 6 dB above the level of an unmodulated carrier. For a signal with low AM depth, the peak carrier level is much closer to the unmodulated carrier level. Consequently, the effect of compression becomes worse at higher modulation depths and for a given amount of compression (non-linearity) a higher signal level can be tolerated than at low modulation depths.

The non-linearity introduced by compression also affects the distortion content of the modulated signal. The distortion introduced by the non-linearity may not be in phase with the distortion already present in the input signal, so distortion cancellation may occur. (As the signal level at the mixer input is increased toward compression the measured distortion may decrease rather than increase). The analyzer RF input compression is at least +13 dBm with 1 dB compression. For compression of a linear amplifier, the amount of compression reduces by a factor of 10 per 10 dB level decrease. For a signal at about -16 dBm mixer level (or -10 dBm for the peak), this will result in a 0.01 dB compression (or about 0.1 %). This would be 60 dB distortion. Lowering the mixer level will reduce distortion introduced by the spectrum analyser further, and tests have been made to assess the effect of mixer level on AM distortion and assist with mixer level setting.

Figures 4 and 5 show the effect of increasing the signal level at the mixer of the analyzer/measurement demodulator on the measured value of AM depth and distortion, using a Fluke 9640A RF Reference Source as the modulated signal source. Figures 6 and 7 show the analyzer displays from which the measurements are taken. Figure 4 shows results for 90 % AM depth and Figure 5 for 10 % AM depth. The square (pink) dots are for depth measurement using the analyzer's spectral display based on an FFT measurement, and the triangular (yellow) dots are for depth from the analyzer's time domain display based on a peak measurement. The depth value from the spectral display using FFT is less sensitive to noise and remains constant at lower signal levels approaching the noise floor. The diamond (blue) dots are distortion, and in both cases show a reduction in distortion at higher mixer levels as compression begins (distortion cancellation taking place), followed by an increase in Figure 4 as mixer level increases further.

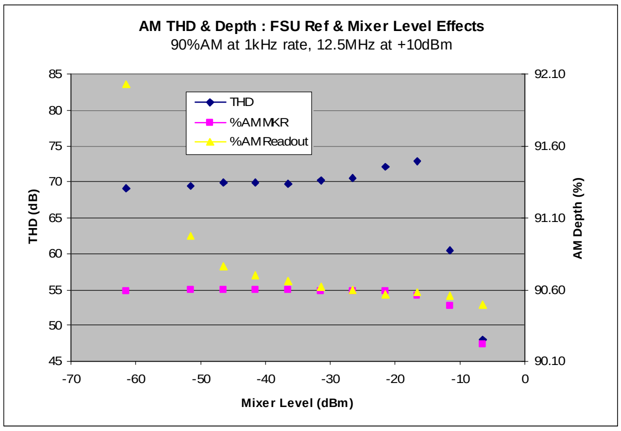

Figure 4. Effect of analyzer mixer level at 90% AM.

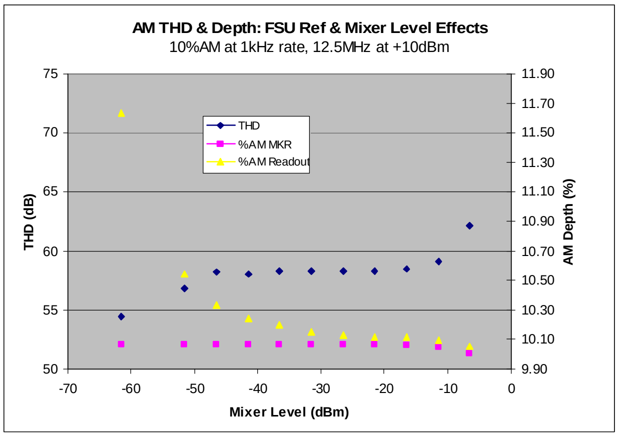

Figure 5. Effect of analyzer mixer level at 10% AM.

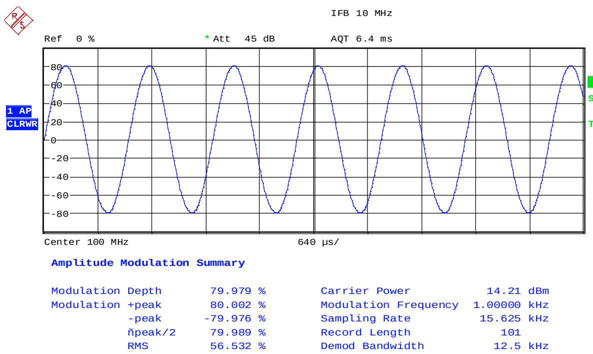

Figure 6. Demodulated AM time domain display.

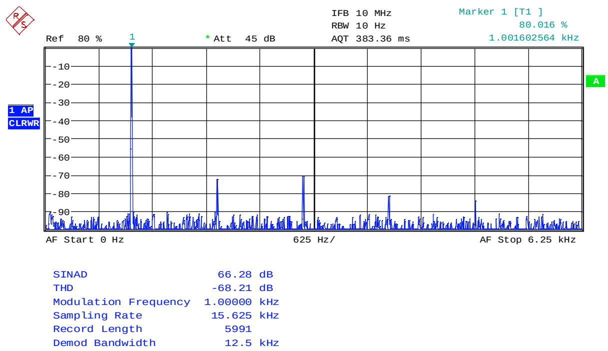

Figure 7. Demodulated AM frequency domain display

Example AM Depth Results and Preliminary Uncertainty Estimates

Example results obtained using the measurement demodulator for an AM signal generated by the 9640A:

Carrier level +14 dBm, frequency 100 MHz.
Modulation depth of 80 % at 1 kHz rate.

Measurements of AM depth and distortion are taken from the analyzer demodulated AM frequency domain display, shown in Figure 7 above. The measured depth value is 80.016 %, an error from the nominal 80 % of 0.02 % of setting (200 ppm). The distortion is predominantly 2nd and 3rd harmonic, at 70 dB below the fundamental modulation rate frequency. These 2nd and 3rd harmonic signals can be seen in Figure 7. The analyzer employs a THD calculation algorithm that operates on the data in the demodulated spectral display. It automatically identifies the fundamental modulating rate frequency and determines signal content at the fundamental and all harmonics within the frequency span setting for the display, and calculates the total harmonic distortion. (The span is chosen to include harmonics up to the 5th).

Such a small depth error together with such low distortion is extremely encouraging. The agreement in depth value between the 9640A and the measurement demodulator is very good. In addition to the effect of compression in the analyser/demodulator and the choice of mixer level setting discussed above, other sources of measurement uncertainty must also be considered:

- The linearity of the A/D converter within the analyser/measurement demodulator.

  The spectrum analyser is configured to use minimal analog circuitry prior to the IF analog to digital converter and employ digital log conversion. The 14bit A/D converter also uses large scale dithering to ensure that linearity does not degrade at low levels, even below the LSB. Measured analyzer linearity errors are generally much less than the estimated uncertainty of the test, and show typical non-linearity < 0.005 dB for a 50 dB range.

- The frequency response of the IF and RF circuits over the demodulation bandwidth.

  The measured sideband level is influenced by spectrum analyser frequency response close to the carrier (combination of RF and IF responses). The configuration used with the 10 MHz IF filter minimises the IF filter response contribution. The IF filter response is smooth, with no significant ripple and there is no ripple in the digital filters (the YIG preselector is automatically bypassed below 3.6 GHz). Tests suggest 0.01 dB/300 kHz is an appropriate contribution.

- The repeatability of the measured result.

  This is evaluated in the usual manner by repeating measurements many times.

Table 1 shows the effect of these uncertainty estimates at representative measurement points. For a signal similar to that used in the above example, the uncertainty is estimated at around 0.1 % of the nominal AM depth. The measured error in the 9640A signal is about five times less than this uncertainty estimate. The measurement demodulator specifications published by its manufacturer for absolute depth measurement accuracy is 1 %, and for frequency response (flatness) is 0.3 %. This measurement result and uncertainty analysis suggest these specifications are conservative.

Preliminary Uncertainty Contribution Estimates			
10dBm Carrier		**1kHz Rate 90% Depth** **-30dBm Mixer**	**100kHz Rate 10% Depth** **-25dBm Mixer**
IF Freq Response (0.01dB/300kHz)	Rect	0.003%	0.035%
Compression (0.01dB, -16dBm mixer)	Rect	0.01%	0.0001%
Linearity (0.005dB over 50dB)	Rect	0.06%	0.06%
Repeatability	1 σ	0.0001%	0.002%
Summation	95%CL	0.09%	0.10%

Table 1. Example uncertainty contribution estimates for AM depth measurement.

Frequency Modulation

The RF spectrum of an FM signal depends on the modulation rate and deviation frequencies. The mathematical relationship is complicated and involves the Bessel function. Theoretically, an FM signal has an infinite number of sidebands, with the amplitude of the sidebands determined by the Bessel function. A useful approximation for the RF bandwidth of an FM signal is given by Carson's rule:

For narrowband FM, where the modulation index (ratio of deviation to rate) is low the bandwidth is approximately twice the rate frequency. (The RF spectrum resembles an AM spectrum with two visible sidebands).

For wideband FM, where the modulation index (ratio of deviation to rate) is high the bandwidth is approximately twice the deviation frequency. (The RF spectrum has many visible sidebands, spaced at the modulation rate).

Figure 8 is the RF spectrum display obtained for an FM signal with a moderate value of modulation index. For very high modulation index signals, it would not be possible to distinguish the individual sidebands in such a display.

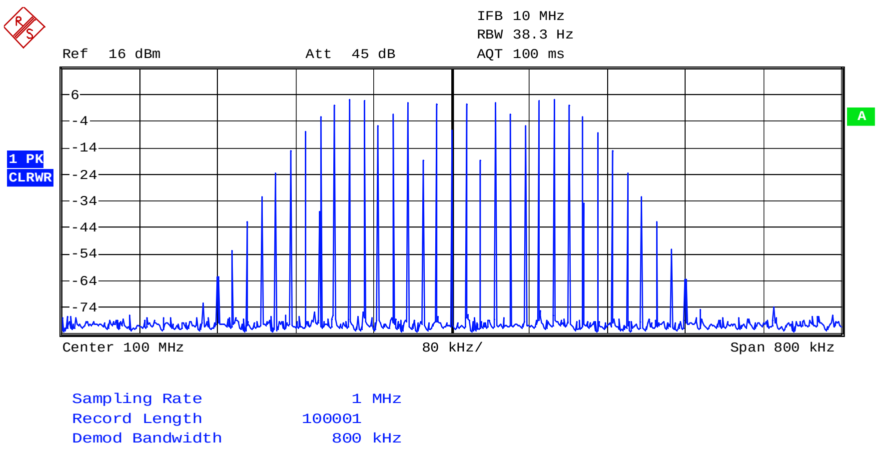

Figure 8. RF spectrum of a 100MHz carrier frequency modulated with 125 kHz deviation at 15 kHz rate.

Obtaining valid and accurate frequency modulation measurements is dependent on setting the measurement demodulator bandwidth appropriately. Insufficient bandwidth will exclude some modulation sidebands resulting in inaccurate FM deviation measurements, and excessive bandwidth will increase wideband noise in the demodulated signal.

If Carson's rule is used to set the demodulation bandwidth the error in the measured deviation value is approximately 0.5 %, which is too large in this precision measurement. Using the relationship BW = 3 x {Rate + Deviation} reduces this error to approximately 0.02 %, which is acceptable.

Figure 9 shows the result of an experiment to determine the bandwidth of an FM signal by observing the sidebands visible above the noise floor 80 dB down on the unmodulated carrier level, at a variety of modulation indices (ratio of deviation to rate frequencies). This shows that for very low and very high modulation index values the observed bandwidth follows the factor of two from Carson's rule, but for in-between values the factor is much greater than 2.

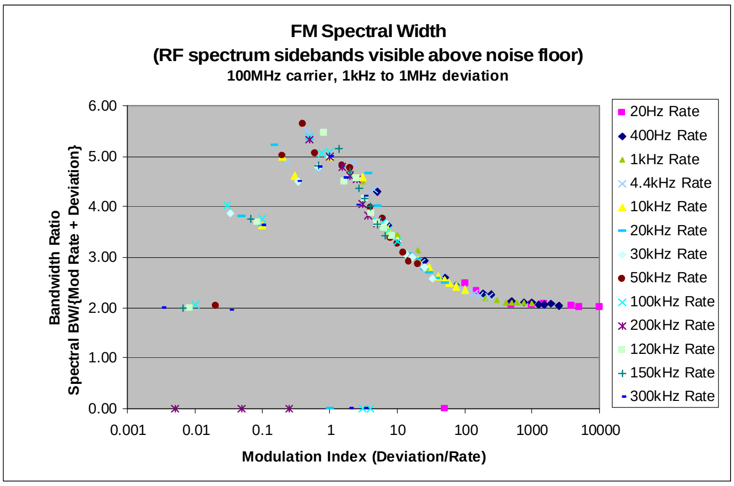

Figure 9. Relative bandwidth required to observe FM sidebands above noise floor ≥80 dB below unmodulated carrier.

Example FM Deviation Results and Preliminary Uncertainty Estimates

Example results obtained using the measurement demodulator for an FM signal generated by the 9640A.

Carrier level +13 dBm, frequency 100 MHz.
Frequency Deviation 125 kHz at 15 kHz rate.

Measurements of FM deviation and distortion are taken from the analyzer demodulated FM frequency domain display, shown in Figure 10 below. The measured deviation value is 124.9819 kHz, an error from the nominal 125 kHz of 0.0145 % (145 ppm). The distortion is predominantly 2nd harmonic, at 80 dB below the fundamental modulation rate frequency. This 2nd harmonic signal can be seen in Figure 10. This small deviation error together with low distortion is extremely encouraging, and there is good agreement between the 9640A deviation setting and the measured value.

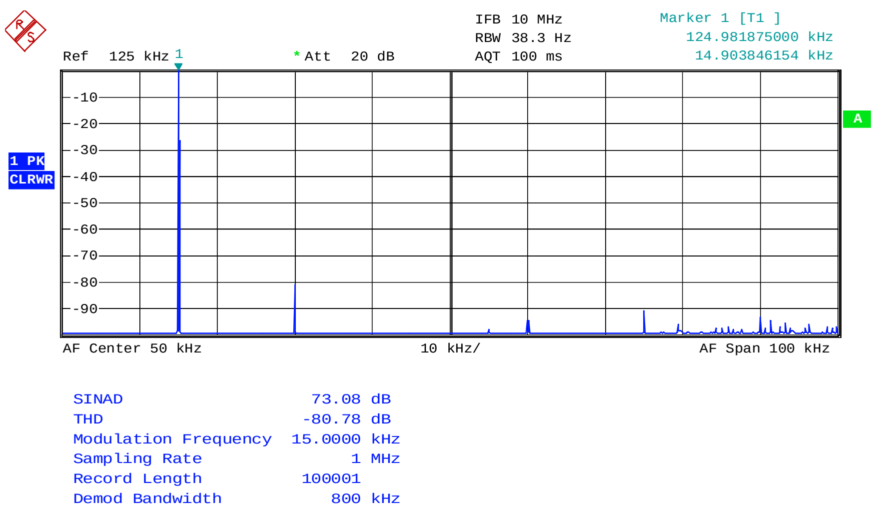

Figure 10. Demodulated spectrum of 100 MHz FM signal with 125 kHz deviation at 15 kHz rate.

Other sources of measurement uncertainty must also be considered, in addition to the effect of the demodulation bandwidth setting that cuts off some sidebands of the FM signal RF spectrum discussed above:

- The linearity of the A/D converter within the analyser/measurement demodulator.

  This effect was discussed in the AM depth section of this paper, and also applies to FM deviation measurement, since the FM deviation value is derived from the relative carrier and sideband levels.

- The frequency response of the IF and RF circuits over the demodulation bandwidth.

  This is also discussed in the AM depth section of this paper, and applicable to FM deviation measurement which depends on relative carrier and sideband level measurement.

- The repeatability of the measured result.

Table 2 shows estimates of these uncertainty contributions for typical measurement points. For a signal similar to that used in the above example, the uncertainty is estimated at around 0.15 %. The measured error in the 9640A signal is about ten times less than this uncertainty estimate. The measurement demodulator specifications published by its manufacturer for deviation measurement accuracy is 1 %. These measurement results and uncertainty contributions suggest this specification is conservative.

Preliminary Uncertainty Contribution Estimates				
		1kHz Rate 100kHz Devn	**10kHz Rate 200kHz Devn**	**100kHz Rate 1MHz Devn**
IF Freq Response (0.01dB/300kHz)	Rect	0.04%	0.08%	0.38%
Demod BW sideband cutoff	Rect	0.02%	0.02%	0.02%
Linearity (0.005dB over 50dB)	Rect	0.06%	0.06%	0.06%
Repeatability	1 σ	0.0001%	0.002%	0.002%
Summation	95%CL	0.11%	0.15%	0.57%

Table 2. Example uncertainty contribution estimates for FM deviation measurement.

FM Measurement Validation

There is a method for FM deviation measurement based on FM theory which is potentially very accurate - the Bessel Null or Disappearing Carrier method. The amplitude of an FM signal remains constant, but the amplitude of the spectral content at the carrier and sideband frequencies is related to the modulation index by the Bessel function.

Modulation index $b = \frac{F_d}{F_r}$, where F_d is the peak frequency deviation and F_r modulation rate frequency.

At certain values of modulation index the amplitude of the signal at the carrier frequency $J_0(\beta)$ and of the sidebands $J_n(\beta)$ nulls to zero (see Table 3), and this condition can be observed on a spectrum analyser. It is generally easy to provide a modulating signal with an accurately known frequency, and as the modulation index value is determined mathematically by the Bessel function, this technique can be used to accurately determine the FM deviation.

Null No.	Carrier Signal	Sidebands		
		First	Second	Third
	$J_0(b)$	$J_1(b)$	$J_2(b)$	$J_3(b)$
1	2.4048	3.8317	5.1356	6.3802
2	5.5201	7.0156	8.4172	9.7610
3	8.6531	10.1735	11.6198	13.0152
4	11.7915	13.3237	14.7960	16.2235

Table 3. Modulation Index values for carrier and sideband nulls.

The Bessel Null technique has been used to validate the FM deviation measurements made using the measurement demodulator. For example, Figure 11 shows the RF spectrum of the 9640A FM output for a +13 dBm 100 MHz carrier modulated at a rate of 23.113 kHz, which produces a carrier null when the deviation is set to 200 kHz (corresponding to the third order null with $J_0(\beta) = 8.6531$).

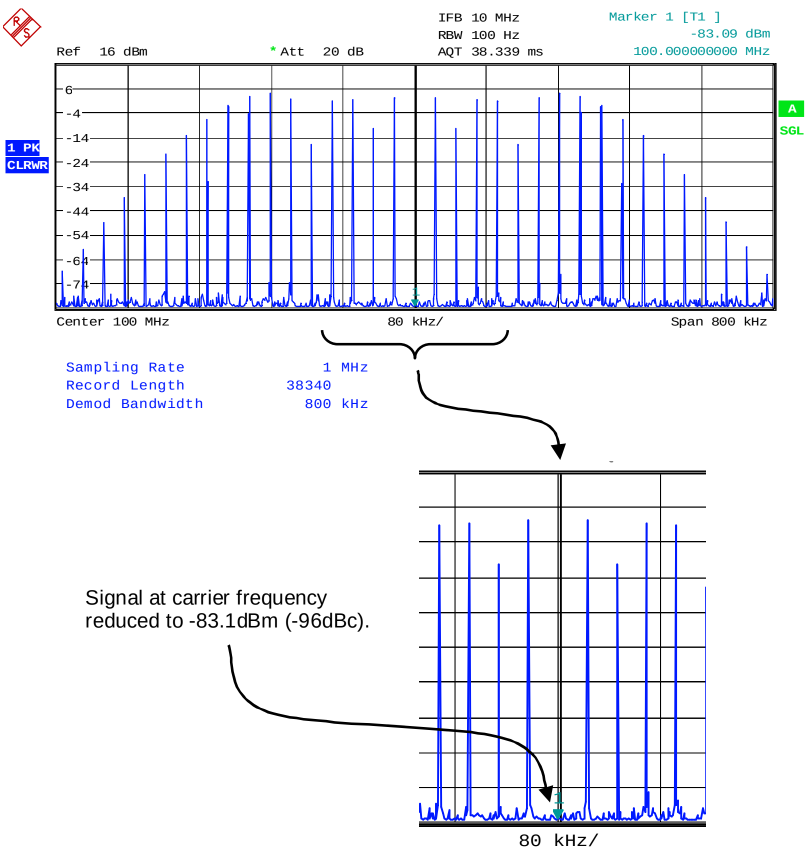

Figure 11. RF spectrum of 3rd carrier null with 9640A set to 200 kHz deviation at 23.113 kHz.

The depth of carrier null achieved contributes to the uncertainty in the deviation value[3, 4], as shown in Table 4. Distortion of the modulating signal or non-linearity in the modulating process results in a change of the value of modulation index at which carrier null occurs[3, 4]. With no distortion of the modulating signal the carrier term becomes zero when $J_o(\beta)$ passes through zero, but when the modulating is signal distorted there are some residual components of the carrier. The amount of null shift depends on the phase of the distortion, and worst case values for 0.1 % (-60 dBc) distortion appear in Table 5. Incidental AM also contributes to the uncertainty[3], but at a negligible level in this example.

Carrier Null	% Deviation Error			
	-70 dB	-65 dB	-60 dB	-55 dB
1	-0.025	-0.045	-0.080	-0.142
2	0.017	0.030	0.053	0.095
3	-0.014	-0.024	-0.043	-0.076

Table 4. Deviation error (%) for null depth

Carrier Null	% Null shift due to 0.1% distortion	
	3rd Harmonic	2nd Harmonic
1	0.015	-0.001
2	-0.025	-0.001
3	-0.030	-0.002

Table 5. Null shift deviation error (%) due to 0.1% distortion (worst case).

To produce the RF spectrum shown in Figure 11 the 9640A FM rate was set to 23.113 kHz and its deviation was set to 200.00 kHz. To obtain the deepest null a feature of the 9640A's user interface specifically designed for calibration applications was used – the ability to introduce a % change in the output quantity (in this case FM deviation) to directly read the UUT error. The % error control was adjusted to achieve carrier null into the analyser noise floor (96dB below the unmodulated carrier level), requiring the introduction of a 0.01 % error. Figure 12 shows a screenshot of the 9640A under these conditions. This corresponds to the actual deviation being in error from the nominal 200 kHz setting by 0.01 %, i.e. deviation frequency 200.02 kHz. The null depth of -96 dBc is remarkably deep, and its effect of the deviation error is negligible.

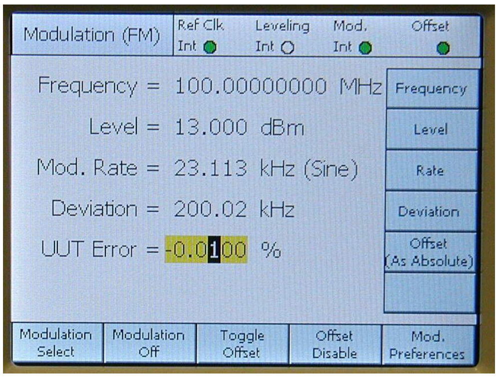

Figure 12. Use of 9640A % Error control to adjust FM deviation for deepest carrier null.

The 9640A % error control was returned to zero, and the measurement demodulator was used to measure the FM deviation directly, with the demodulated FM frequency domain display shown in Figure 13. the measured deviation values is 200.037 kHz, corresponding to an error from nominal of 0.019 %. Second harmonic distortion of -75 dB (0.018 %) is present, but from Table 5 its effect on the Bessel null measurement can be seen to be negligible.

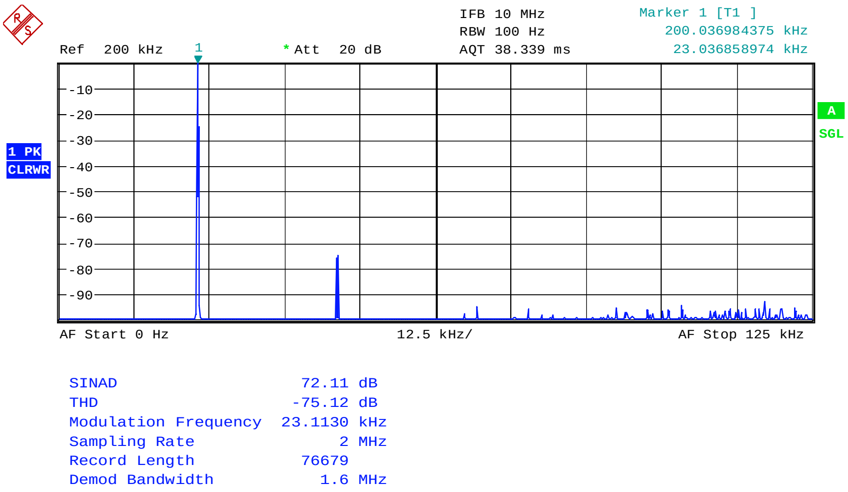

Figure 11. Demodulated FM frequency display with 9640A set to 200 kHz deviation at 23.113 kHz.

The agreement between the Bessel Null result and the measurement demodulator is extremely good, and the deviation error of the 9640A under these conditions is extremely small.

New Modulation Measurement Method Developments

A method for modulation measurement using in-phase and quadrature (IQ) referencing is under development at the UK National Physical Laboratory (UK NPL). In a collaboration with NPL staff working at the Fluke UK facility[5] the IQ referencing technique has been applied to amplitude modulation measurement, and encouraging preliminary results have been reported[6].

The IQ referencing technique employs three channels of an equivalent-time sampling oscilloscope with an appropriate architecture, compensating for measurement jitter contributions, correcting timebase linearity errors and recovering the modulation envelope of the signal. The underlying principle is that the jitter (time uncertainty) between the three sampling gates is much smaller than the jitter between the trigger and the sampling gates of the individual channels. Two of the channels can therefore be used to provide accurate time reference for the third channel, which samples the modulated carrier.

The sampling of the modulated carrier must support recovery of carrier phase and amplitude (certainly above Nyquist) and must capture several modulation cycles. This very long data record is captured by incrementing trigger delay to sequentially capture shorter record segments. The segments are then concatenated together using the IQ reference waveforms to achieve alignment.

When two sinusoidal RF signals nominally in quadrature with approximately equal amplitudes are measured on the sampling oscilloscope using the same trigger event a good estimate can be made of the exact point within the RF cycle, and hence sample time. Due to residual timing skew, gain, linearity and offset in the two channels, a parametric plot of these signals typically describes an ellipse that that is not centred on the origin. A series of transformations are used to map this ellipse to a unit circle so that the phase of the RF signal can be found, and corrections for the sampling times can be applied to correct for timebase errors.

An AM signal can be represented in terms of its components $\sin((\omega_c \pm n\omega_m)t)$, $\cos((\omega_c \pm n\omega_m)t)$, where ω_c is the angular frequency of the carrier signal and ω_m is the angular frequency of the modulating signal. All the modulation parameters can be determined directly using the corrected timebase values by solving for these terms simultaneously. Since these terms are orthogonal, their coefficients can be determined using a least squares fit.

Figure 12 shows a diagram of the system with a photograph in Figure 13 of the experimental setup to measure an AM signal generated by the 9640A source of 100 MHz +14 dBm modulated at 20 kHz at depths of 10 %, 50 % and 90 %. A second 9640A source is used to generate the unmodulated reference signal. An adjustable delay line is used to set the modulated and reference signals nominally to quadrature.

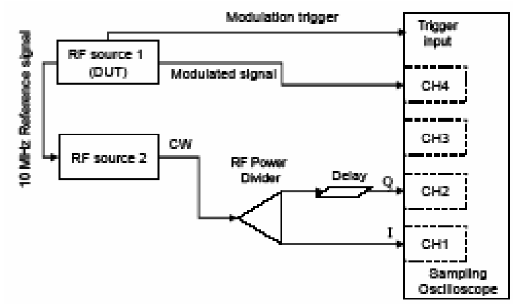

Figure 12. Modulation measurement system.

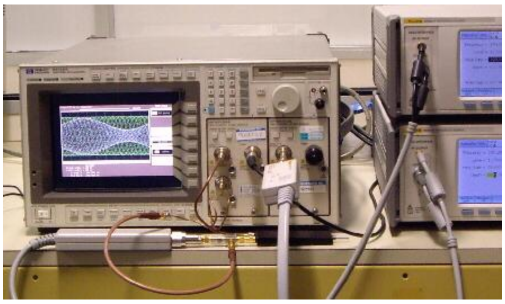

Figure 13. Experimental setup with the 50 GHz sampling oscilloscope and 9640A signal sources.

The AM depth may be determined by calculating the values of the carrier and sideband components as described above, and then using the ratio of carrier and sideband levels to calculate the modulation index m:

$m = \frac{V_{Lsb} + V_{Usb}}{V_c} \times 100\%$ where V_c is the amplitude at the carrier frequency, V_{Usb} and V_{Lsb} are the upper and lower sideband amplitudes. The AM depth may also be determined by recovering the modulation envelope, in this case by using the Hilbert transform to generate a $\pi/2$ phase shifted copy of the measured waveform. The AM envelope is recovered by combining the original signal with the Hilbert transform processed signal in quadrature.

Preliminary results are very encouraging, and indicate agreement of <1 % of nominal modulation depth was achieved, as shown in Table 6. Figure 14 shows the modulation components for a 50 % modulation depth, indicating low distortion AM modulation. The expected noise floor calculated from the vertical resolution of the sampling oscilloscope and the number of samples is shown on the plot. The expected dynamic range may be lower than achievable with the measurement demodulator. However, these results show a surprisingly good dynamic range of > 80 dB for one hundred 4096-point trace acquisitions.

Nominal Modulation (%)	Calculated Modulation (%)	
	Sideband Method	Envelope Method
10	9.9	9.9
50	49.5	49.5
90	89.2	89.2

Table 6. Comparison of modulation calculations.

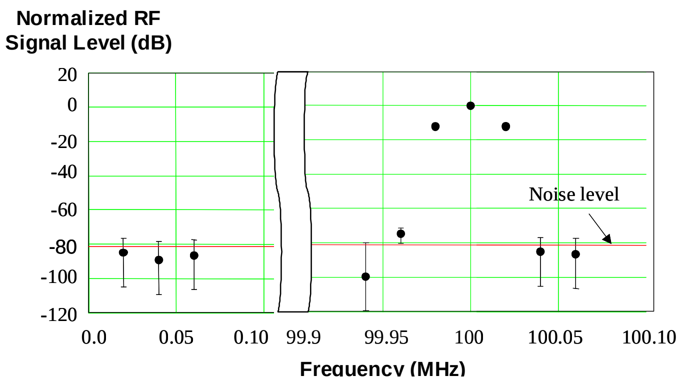

Figure 14. Signal components for 50% AM depth.

For certain combinations of carrier and modulation frequency, such as this example (100 MHz/20 kHz), the timebase jitter and nonlinearity will be less than the period of the carrier. This allows the carrier phase and timebase correction to be performed without the use of additional reference signals. Where system jitter exceeds carrier wavelength (e.g. at microwave carrier frequency) it should be possible to use modulation frequency, sampled on a fourth oscilloscope channel, as a long term timing reference.

A further enhancement to the system of Figs 12 and 15, is to extract un-modulated carrier from RF source 1 and thus replace RF source 2. This would eliminate jitter between the source clocks.

Sampling oscilloscope vertical nonlinearity generates baseband and intermodulation components. The intermodulation sidebands cannot easily be distinguished from any modulation distortion present on the signal. An additional two-tone intermodulation test with two unmodulated signals is required to identify intermodulation components. Details of the intermodulation tests and estimates of other impairments are reported in the references[6]. However, in this case their impact appears not to be significant.

There are several benefits to this approach. The nonlinearities within the system are explicit and quantifiable, and analysis of the data provides both the results and their uncertainties. Further work is required to compare determine the stability and repeatability of the results and compare this technique with the measurement demodulator.

Conclusions

Analysis of the inherent error sources within the spectrum analyzer and measurement demodulator suggest extremely accurate modulation measurements should be obtained, much better than the performance described by its manufacturer's specifications. In addition to tests with the 9640A discussed in this paper, further tests with the 9640A and other popular high performance modulation sources[7] have also given results consistent with this expectation.

The Bessel Null technique for FM deviation measurement offers a method for validating the FM deviation a performance of both the 9640A RF Reference Source itself and of the measurement demodulator technique. However, finding techniques or other laboratories capable of providing low uncertainty confirmation of the 9640A performance or the measurement demodulator results for other modulation characteristics has been much more difficult.

Some comfort can be taken from obtaining such close agreement between the 9640A and the measurement demodulator, and also from results obtained with other high performance modulation sources[7], but those results do not convey traceability in its usual definition. Some measurements are essentially ratiometric (such as deriving AM depth from the carrier to sideband amplitude ratio), but confirmation by an alternative technique is always good metrology practice.

A new modulation measurement technique using in-phase and quadrature referencing is also under development. Preliminary results indicate it has the potential to provide accurate measurement of amplitude modulation allowing the desired AM cross checks to be performed in the future, and establish traceability at lower levels of uncertainty than existing traditional techniques.

References

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