Marconi
Instruments
MEASURETEST

ISSN 0542-6723

Instrument application notes from Marconi Instruments Limited No.55

Modulation Analysis with 2382 100 Hz – 400 MHz Spectrum Analyzer

by S.J. Gledhill, B.Sc. C. Eng. MIEE

Introduction

An accurate, high resolution spectrum analyzer can not only make modulation measurements, it can also reveal additional information about modulated signals.

Amplitude modulation, single sideband modulation and frequency modulation measurements are described and examples of typical spectrum analyzer displays are given. Modulation depth can be determined to as low as 0·02%, harmonic distortion can be assessed and measured. Using the zero span mode the demodulated signal can be viewed.

Single sideband measurements that can be made with a spectrum analyzer include modulation distortion, carrier suppression, sideband breakthrough and spurious signal identification.

Frequency modulation analysis is very important since the Bessel null method may be used to calibrate modulation meters and other equipment to a very high degree of accuracy. An FM demodulation mode in the 2382 spectrum analyzer is used to view and measure demodulated signals.

Amplitude Modulation

Amplitude modulation is best understood theoretically by considering an amplitude modulated wave to consist of two separate signals, the r.f. carrier and the modulation signal.

Let the carrier frequency be f_c, then the waveform can be represented by:

$v_c = V_c \sin \omega_c t$, where $\omega_c = 2\pi f_c$

Let the modulating signal frequency be f_m then it can be represented by:

$v_m = V_m \sin\omega_m t$, where $\omega_m = 2\pi f_m$

The modulated carrier is thus

$$v_c = (V_c + V_m \sin \omega_m t) \sin \omega_c t$$

The ratio V_m/V_c is the modulation depth, m, then $V_m = m\, V_c$

Thus $v_c = V_c \sin \omega_c t + m\, V_c \sin \omega_m t \sin \omega_c t$

Now $\sin \omega_c t \sin \omega_m t = \frac{1}{2} [\cos (\omega_c - \omega_m)t - \cos (\omega_c + \omega_m)t]$

$$\text{Hence } v_c = V_c \sin \omega_c t + \frac{(mV_c)}{2} \cos (\omega_c - \omega_m)\, t - \frac{(mV_c)}{2} \cos (\omega_c + \omega_m)t$$

From this equation it can be seen that there are three components of an amplitude modulated signal. The first term is the carrier frequency which is of constant amplitude and frequency. The second term is the lower sideband and the third term is the upper sideband.

The two sidebands have an amplitude proportional to the modulation index m and they are separated from the carrier by frequency fc. For 100% modulation, half of the power is in the sidebands so each sideband amplitude will be 6 dB less than that of the carrier. For lower modulation depths the sideband amplitudes are reduced. Figure 1 shows the theoretical spectrum of a carrier amplitude modulated by a single frequency sinewave.

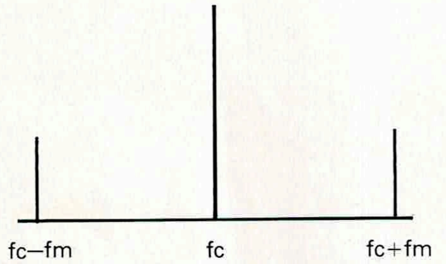

Figure 1. Theoretical spectrum of a carrier amplitude modulated by a single frequency sinewave.

Figure 2 shows a display from the 2382 Spectrum Analyzer using the GPIB direct plot facility. An 88 MHz carrier is modulated with a 1·75 kHz sinewave, one marker is placed on the carrier and the other on the upper sideband. The delta marker facility shows that the modulation frequency is 1·750 kHz and that the sideband is 12·00 dB less than the carrier amplitude. The modulation depth can be simply determined, the sidebands are 6dB lower in amplitude than would be the case for 100% modulation therefore the modulation depth is 50% (6 dB expressed as a voltage ratio).

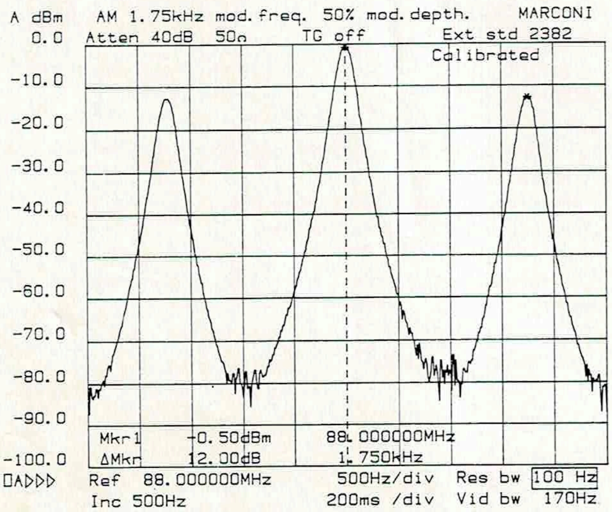

Figure 2. Amplitude modulation. 1·75 kHz modulation frequency, 50% modulation depth.

Table 1 shows modulation depth for a range of carrier/sideband amplitude differences.

Carrier/sideband amplitude difference (dB)	Modulation depth (%) (m)
6	100
7.9	80
10.4	60
12	50
16.5	30
26	10
46	1
60	0.2
80	0.02

Table 1. Modulation depths for a range of carrier/sideband amplitude differences.

Figure 3 shows the relationship between modulation depth and carrier/sideband amplitude difference plotted graphically, this graph may be used to quickly determine modulation depth.

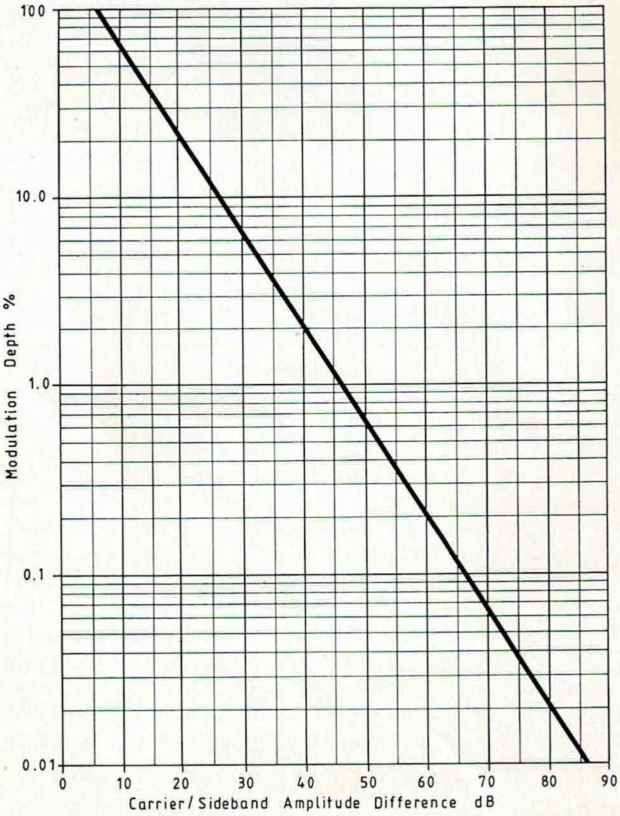

Figure 3. Carrier/Sideband amplitude difference plotted against modulation depth.

Modulation depths as low as 0·02% can be determined with the 2382 as shown in figure 4. It is significant to realize that such a low level of modulation would not be discernible with an oscilloscope and that even lower levels could be measured especially because with the 3Hz filter in the 2382 very low signals can be resolved.

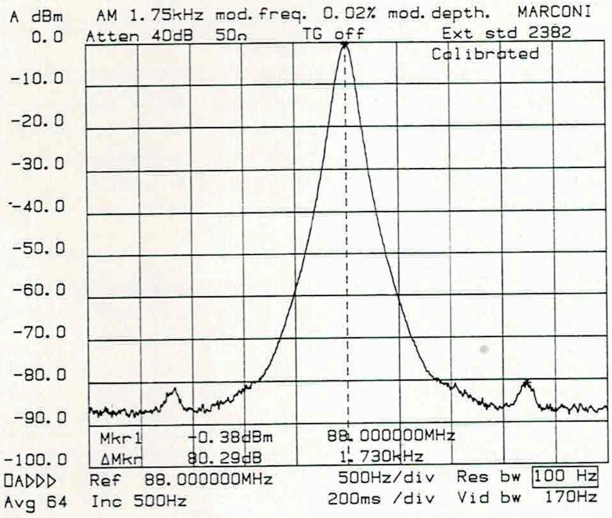

Figure 4. Low level amplitude modulation depth of 0·02%

Harmonic distortion can also be measured, figure 5 shows the spectrum with 80% modulation depth. Harmonics of the modulation frequency give additional symmetrical sidebands, the 2nd harmonic products at 3·50 kHz are approximately 30 dB down. The 3rd, 4th and 5th harmonics can also be measured and thus the total harmonic distortion can be calculated.

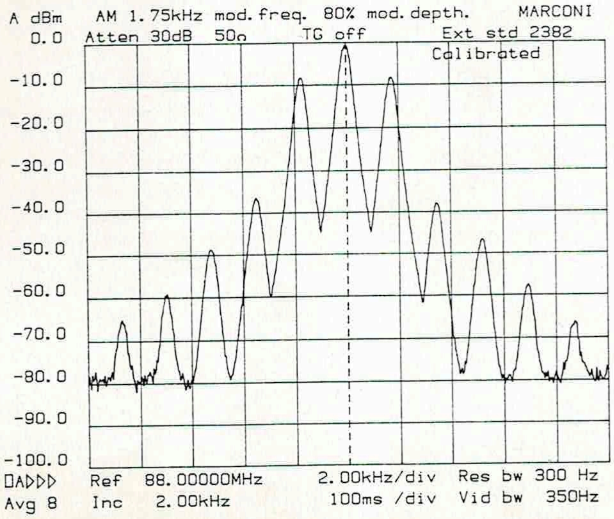

Figure 5. Harmonic distortion products of a.m. sidebands.

Zero span mode is invaluable when analysing and measuring amplitude modulation. The instrument is turned into a fixed tuned receiver and the display shows the demodulated waveform. For a valid display the resolution bandwidth should be at least twice the modulation frequency. A linear (volts/division) vertical scale is generally used in zero span since a logarithmic vertical scale is unfamiliar. Figure 6 shows the same signal analyzed in figure 2 displayed on zero span mode, the horizontal scale is 200 μs/division so the modulation rate can also be measured from this display. A notable feature of the 2382 is that the timebase is very accurate since it is locked to the crystal reference standard.

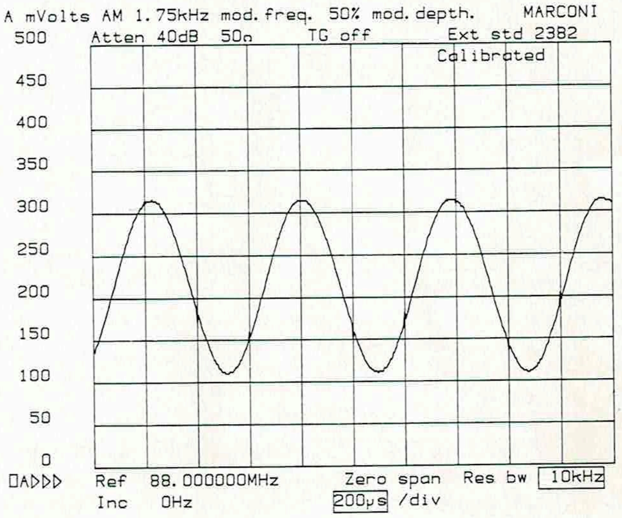

Figure 6. Zero Span mode used to display demodulated a.m.

Off-Air Measurements

AM broadcast transmitters can be analyzed using the 2382. Figure 7 makes use of the MAX HOLD facility to show spectrum occupancy. Many successive sweeps are stored so that any over-modulation causing an excessively wide bandwidth can be monitored.

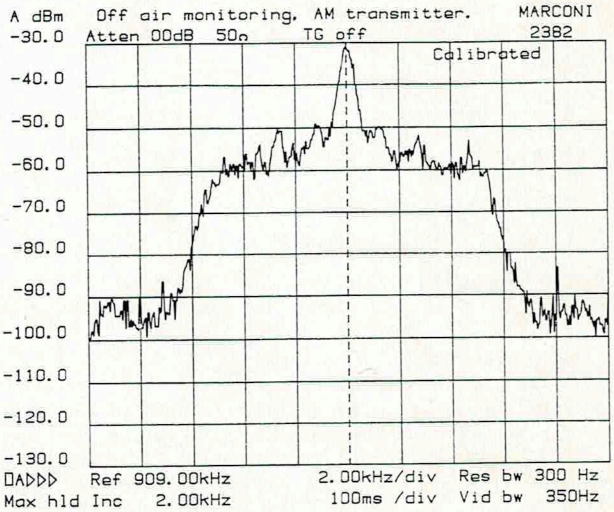

Figure 7. Max Hold mode used to measure a.m. spectrum occupancy.

Zero span mode is also invaluable for off-air monitoring, figure 8 shows a typical example. 2382 has a built in loudspeaker which is accessed with the AUDIO key so that the demodulated signal can be heard as well as seen.

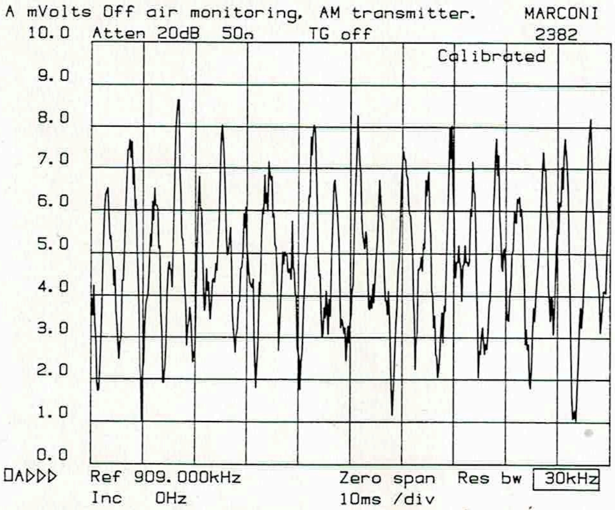

Figure 8. Zero Span used to demodulate an a.m. broadcast transmitter.

Single Sideband Modulation

Single sideband (SSB) modulation is similar to amplitude modulation but only one sideband is transmitted and the carrier is suppressed. The advantage of this method of modulation is that spectrum occupancy is reduced and transmitted power is less.

Many measurements need to be made on SSB transmitters, two key ones will be examined. Further detailed information is given in Measuretest number 54 "Using the Marconi 2382 400 MHz Spectrum Analyzer for SSB and CW Transmitter Testing".

Figure 9 shows the spectrum from an SSB transmitter with a 1 kHz test tone applied to the upper sideband.

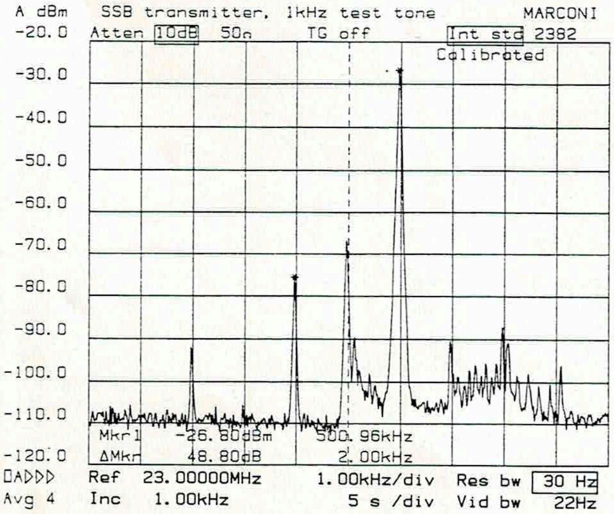

Figure 9. SSB transmitter. 1 kHz test tone applied to upper sideband.

Four important aspects can be analyzed from figure 9.

- Harmonic distortion. As well as the 1 kHz test tone in the upper sideband there are additional distortion products at 2 kHz and 3 kHz.
- Carrier suppression. The carrier is not completely suppressed, the amplitude is approximately −67dBm.
- Lower sideband breakthrough. Unwanted breakthrough into the lower sideband can be quantified, there are significant components at 1 kHz and 3 kHz.
- Spurious signals. Unwanted signals and noise are also present in the upper sideband.

Figure 10 shows an even more important measurement, the intermodulation performance. Two audio test tones at 1 kHz and 2 kHz are fed into the input of the transmitter. Intermodulation, caused by non-linerity throughout the transmitter, has caused intermodulation products to be generated.

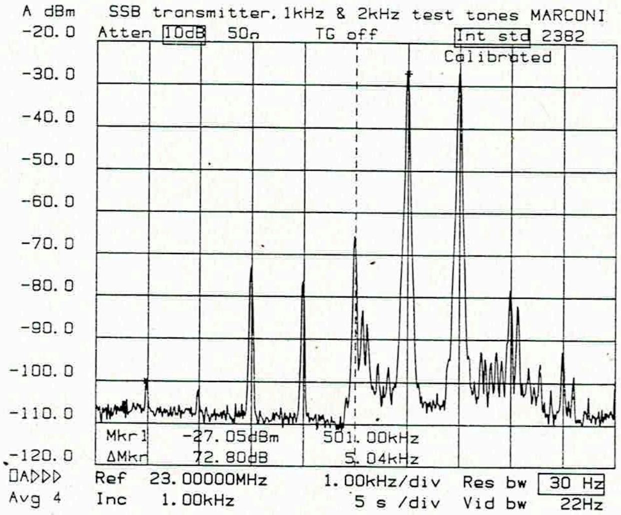

Figure 10. SSB transmitter. 1 kHz and 2 kHz test tones to measure intermodulation.

There are two aspects to be analyzed.

- Upper sideband. Intermodulation products at 3 kHz and 4 kHz indicate that the transmitter will occupy excessive bandwidth since out of band intermodulation products are generated as well as other spurious signals.
- Lower sideband. Intermodulation products falling in the lower sideband are seen especially at 1kHz and 2kHz. This is a problem because they will affect the quality of information transmitted in a lower sideband if independent sideband (ISB) transmission is used. If ISB is not used then the intermodulation products will again cause excessive bandwidth occupancy.

Frequency Modulation

An r.f. carrier of frequency f_c, frequency modulated by a single sinusoidal tone of frequency f_m with modulation index m can be expressed in the form:

$$v_c = V_c \sin(\omega_c t - m \cos\omega_m t)$$

$$\text{where modulation index } m = \frac{\text{Frequency Deviation}}{\text{Modulation Frequency}}$$

The equation can be further expanded:

$$\begin{aligned} v_c = V_c\, [&J_0(m) \sin \omega_c t \\ &- J_1(m)\, [\cos(\omega_c + \omega_m)t + \cos(\omega_c - \omega_m)t] \\ &- J_2(m)\, [\sin(\omega_c + 2\omega_m)t + \sin(\omega_c - 2\omega_m)t] \\ &- J_3(m)\, [\sin\ldots \end{aligned}$$

This reveals that an f.m. spectrum theoretically has an infinite number of sidebands which are symmetrical about the carrier and separated by the modulation frequency. An f.m. spectrum is thus more complex than an a.m. spectrum. Sideband and carrier amplitudes are determined by the unmodulated carrier amplitude and the Bessel functions J_0, J_1, J_2, . . . etc. and the modulation index. In practice there is a finite number of sidebands since the amplitudes of the higher frequency ones rapidly reduce to zero and have negligible amplitude. The bandwidth of an f.m. signal can be determined by using Carson's rule. This states that the bandwidth is twice the sum of the maximum frequency deviation and the modulating frequency. Figure 11 shows a typical spectrum of an f.m. signal.

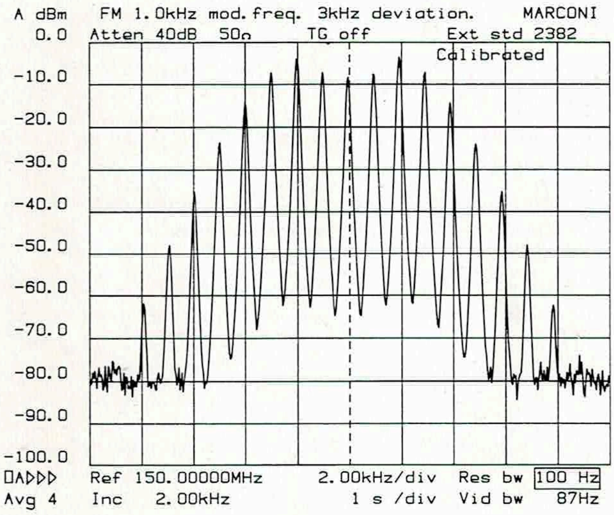

Figure 11. Typical f.m. spectrum. 1 kHz modulation frequency, 3 kHz deviation.

The carrier amplitude is not constant, it varies according to the modulation index (peak deviation/modulation frequency) and may become zero. Sideband amplitudes also become zero at specific values of modulation index. Modulation indices at which the carrier or sidebands have zero amplitude can be calculated. Table 2 gives some examples of the zeros, or Bessel nulls as they are more commonly called.

Order of Null	Modulation Index			
	Carrier	1st Pair Sidebands	2nd Pair Sidebands	3rd Pair Sidebands
1	2·4048	3·832	5·136	6.380
2	5·5201	7·016	8·417	9·761
3	8·6531	10·173	11·620	13·015
4	11.7915	13·324	14·796	16·223
5	14.9309	16·471	17·960	19·409

Table 2. Carrier and sideband Bessel nulls for a range of conditions

Such a table has limited practical use, what is more valuable is a table which shows how to set up accurately known deviations. Suppose for example that one wishes to generate an f.m. deviation of 10 kHz. We know that if the carrier amplitude drops to zero for the first time then the modulation index is 2·4048, so the desired modulation frequency can be calculated as follows:

$$\text{Since Modulation Index} = \frac{\text{FM Deviation}}{\text{Modulation Frequency}}$$

$$\text{Then Modulation Frequency} = \frac{\text{FM Deviation}}{\text{Modulation Index}}$$

$$= \frac{10 \text{ kHz}}{2{\cdot}4048}$$

$$= 4{\cdot}158 \text{ kHz}$$

More practical values are given in table 3, this gives the modulation frequencies which need to be set to generate known deviations using both first and second carrier nulls.

The great advantage of this method is that as long as distortion is low, the accuracy depends on setting the modulation frequency correctly and this can be determined very accurately with a frequency counter.

Carrier- first null mod. index (2·4048)		Carrier- second null mod. index (5·5201)	
Freq. Dev. in kHz	Mod. Freq. in Hz	Freq. Dev. in kHz	Mod. Freq. in Hz
1	416	5	906
2	832	7.5	1359
3	1247	10	1812
4	1663	12.5	2264
5	2079	15	2717
6	2495	20	3623
7	2911	25	4529
7.5	3119	30	5435
8	3327	35	6340
9	3742	40	7246
10	4158	45	8152
12.5	5198	50	9058
15	6238	55	9963
20	8317	60	10869
25	10396	65	11775
30	12475	70	12681
35	14554	75	13587

Table 3. Modulation frequencies required to generate standard f.m. deviation values using the Bessel null method

Figures 12 and 13 show two examples of carrier nulls, figure 12 is the first carrier null, deviation is 2·4 kHz, modulation frequency is 1 kHz and the modulation index is 2·4. Figure 13 shows the first 1st sideband pair null with a modulation index of 3·83. It will be noted that the amplitudes of the sidebands are not completely zero since an exact null has not been achieved.

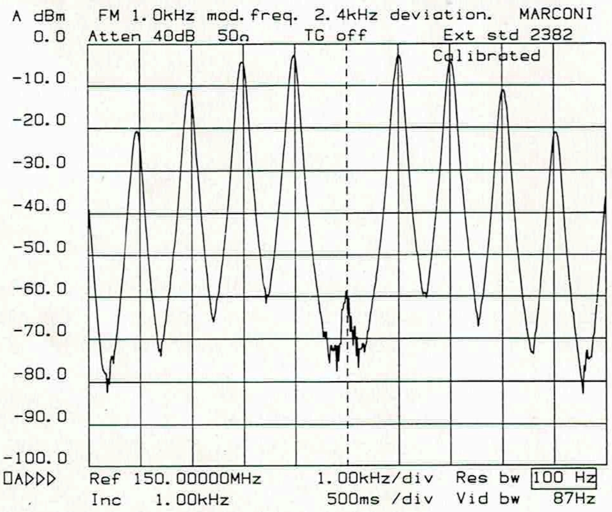

Figure 12. First carrier Bessel null. 1·0 kHz modulation frequency, 2·4 kHz deviation.

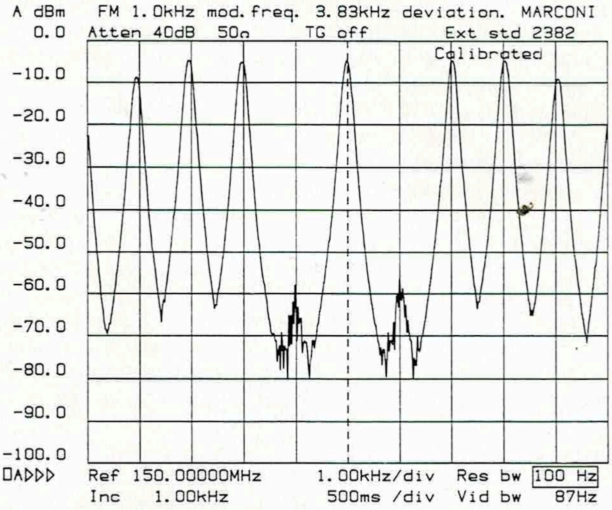

Figure 13. First 1st sideband pair null. 1·0 kHz modulation frequency. 3·83 kHz deviation.

Errors may be introduced and it is therefore necessary to take precautions to minimise them. A full analysis of errors and uncertainties is given in Measuretest number 50 "Modulation Measurements for 2305 Modulation Meter". The factors that effect the accuracy of the Bessel null method are summarised.

Depth of the carrier disappearance: A disappearance of greater than 60 dB is necessary to reduce the uncertainty to less than 0·1%.

Modulation Distortion: Distortion products, especially 3rd harmonic, shifts the carrier null and introduces errors because the value of the modulation index at which the carrier is zero is changed.

Spurious a.m.: Also produces errors or shifts in the position of the zero.

Modulation frequency accuracy: Contributes a negligible error and can usually be ignored.

Setting a null precisely takes time since it is necessary to wait for a new sweep before the effect of an adjustment can be seen. The METER mode on the 2382 greatly assists in setting a null, the mode allows one to stop the instrument from sweeping and to just view the amplitude of a selected frequency component. In this way the level of the carrier or any sideband can be continuously read in real time so that adjustment is much faster. Figure 14 shows the meter mode being used to set a carrier null.

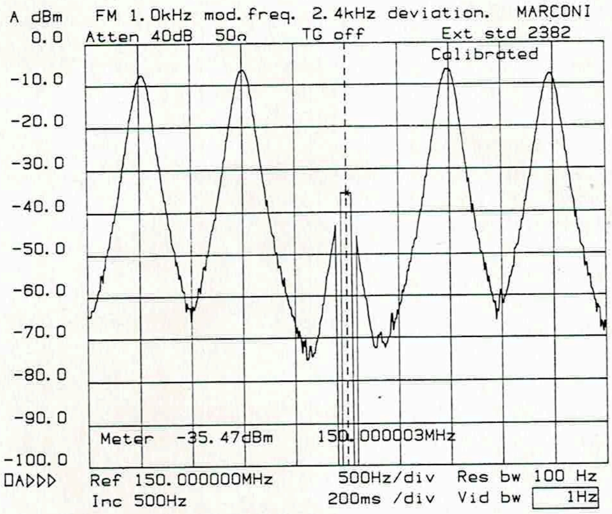

Figure 14. Meter mode used to speed up the setting of an f.m. carrier null.

If there is not a Bessel null condition it is very difficult to interpret a spectrum analyzer display. Various techniques have been evolved but they are either time-consuming or very inaccurate. There is one exception however, narrow deviations may be measured directly with a spectrum analyzer. When the modulation index is less than 1 only two sidebands are significant. The ratio of sideband to carrier level is equal to half of the modulation index.

$$\text{Sideband to carrier voltage ratio} = \frac{\text{FM Deviation}}{2 \times \text{Modulation Frequency}}$$

The 2382 has an FM DEMOD mode to measure FM directly. The demodulated FM signal is displayed on a graticule which is vertically calibrated in f.m. deviation, the horizontal scale is calibrated in time as for zero span. Figure 15 shows an example, the vertical scale is 1 kHz/division.

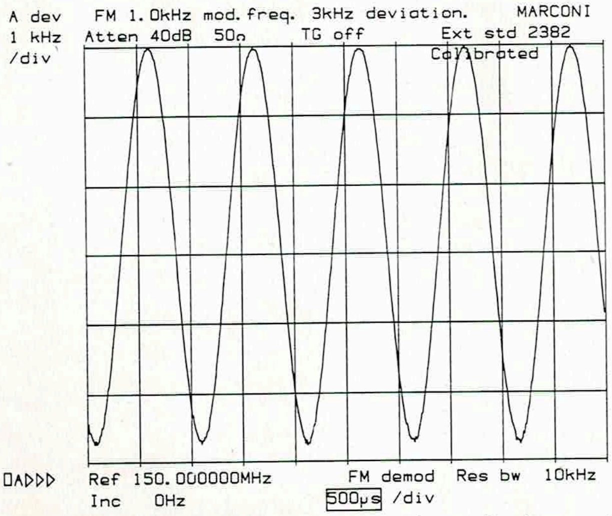

Figure 15. FM DEMOD mode used to display and measure demodulated f.m.

The demodulated signal covers 5·75 graticule lines, the peak-to-peak deviation is therefore 5·75 kHz and the mean deviation is 2·875 kHz.

Accuracy of this method is ±20% which is not as good as a modulation meter but it is an extra measurement that spectrum analyzers have traditionally not made. Other advantages include the fact that f.m. can be measured on lower level carriers and that deviations down to a few Hz can be seen and measured to assist in pinpointing carrier f.m. noise.

Low Level Power Line Modulation

The 3 Hz filter in the 2382 is invaluable to measure low levels of modulation at power line frequencies (50 Hz or 60 Hz) caused by inadequate power supply smoothing. Figure 16 shows a rather noisy carrier with a 50 Hz component 49·80 dB down as measured by the markers. The excellent close in noise of the instrument allows for 50 Hz components to be determined at least 80 dB down to facilitate the design of clean carrier signals and oscillators.

It is important to interpret such a spectrum display carefully since the spectrum could be caused either by a.m. with a modulation depth of around 1% or by a small amount of spurious f.m. Further investigation is essential to fully resolve the causes of such a signal.

An oscilloscope or modulation meter may be needed to assist in identifying the type of modulation.

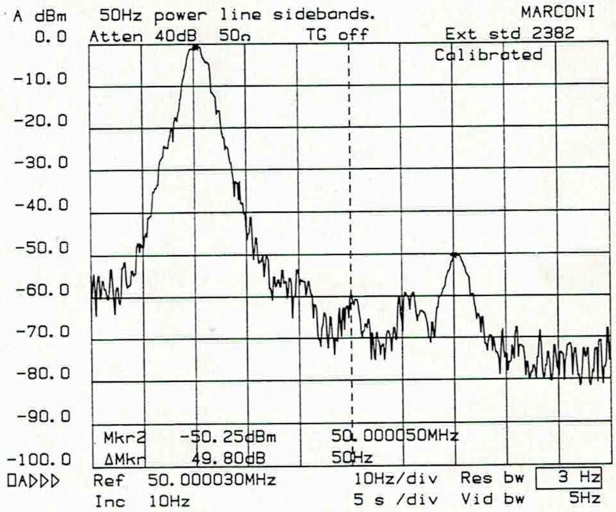

Figure 16. 50 Hz power line sideband resolved using 3Hz resolution bandwidth.

Marconi
Instruments

Asymmetrical Sidebands

Pure a.m. and f.m. signals will have symmetrical spectra thus if a spectrum display of modulation is asymmetrical this will indicate the presence of unwanted signals. An example is shown in figure 17, each sideband should be 26 dB down since modulation depth is 10% but incidental f.m. has caused asymmetry such that the fundamental modulation sidebands differ in amplitude by 10 dB.

Asymmetry is caused because upper and lower f.m. sideband pairs are 180 degrees out of phase. A spectrum analyzer does not display this phase difference but since the a.m. sideband pairs are in phase the incidental f.m. will increase or decrease sideband power depending on whether the f.m. and a.m. sidebands are in or out of phase.

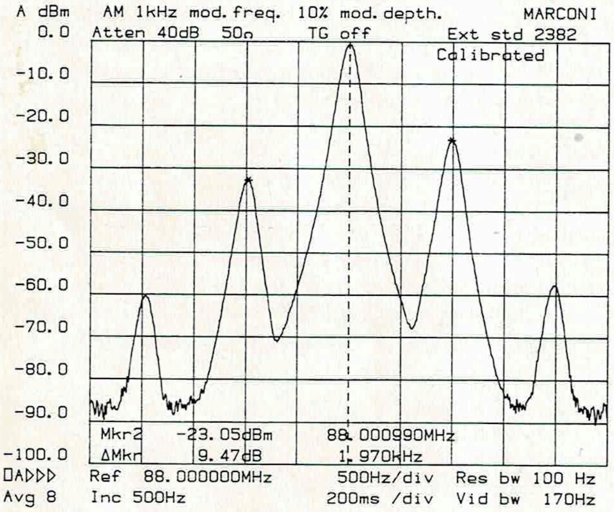

Figure 17. Asymmetrical sidebands indicating incidental f.m. on an a.m. signal.

References

A.D. Skinner
Modulation Measurements for 2305 Modulation Meter.
Measuretest No. 50 – Marconi Instruments.

A. McKenzie
Using the Marconi 2382 400 MHz Spectrum Analyzer for SSB and CW Transmitter Testing.
Measuretest No. 54 – Marconi Instruments.

H. Taub & D.L. Schilling
Principles of Communication Systems.
McGraw – Hill Inc. 1971.

E. Jahnke & F. Emde
"Tables of Functions". Dover Publications Inc., New York 1945.

Printed in the UK (R) 5/86