

An FM Spectrum Analyser

By Dr Stewart Bryant, G3YSX*



The finished FM Spectrum Analyser.

THE MOVE TO 12.5kHz FM channel spacing on the 144MHz amateur band brings with it a pressing need within amateur radio circles for a simple method to check and set the deviation of an FM transmitter. This article describes a simple but accurate method of measuring the deviation of an FM transmitter by using a multi-media PC as a narrow-band spectrum analyser. Calibration is solely reliant on the accuracy of the clock crystal in the PC sound card, and thus the system can be regarded as self-calibrating. In practice it is thus possible to set the deviation of an FM transmitter to better than 5% without any external calibration.

THE RIGHT APPROACH

THE CORRECT SETTING of the deviation of an FM transmitter is important for both technical and social reasons. The bandwidth occupied by the signal is directly related to the deviation. The larger the deviation of the signal, the larger the bandwidth. The bandwidth of an FM signal is also directly dependent on the bandwidth of the audio modulation. The greater the bandwidth of an FM signal, the fewer users that can be supported in a given band. Radio users therefore accept constraints on bandwidth in order to achieve a suitably high spectral efficiency. If a user operates with a higher than agreed deviation (or maximum modulation frequency) their signal will spread over adjacent channels, causing interference to other users.

It is also important for communications efficiency that the transmitter and receiver operate with commonly agreed deviation and maximum modulation frequency. If either is too high, the transmission sidebands will fall outside the receive passband, causing severe distortion of the received signal. If the deviation is too low, the output of the FM discriminator will be weak causing 'thin' audio. If the receiver IF filter is too narrow, this will have the same effect of signal quality as over deviation. If the receiver IF filter is too wide additional noise is received, degrading the received signal and reducing range.

It is therefore important that the deviation of an FM transmitter and the receiver bandwidth be correctly matched, and set to operate within the agreed channel widths. There is no deviation formally specified for amateur radio transmissions, but the commercial specification for 12.5kHz spacing is 2.5kHz. This article assumes the use of the same standard for amateur use, but it will be obvious to the reader how to set the transmitter for any other preferred deviation. This article is also written in terms of the need to set deviation of a 144 MHz transmitter, but the system is applicable to other amateur bands, for example setting the deviation of an HF transmitter when operating on 10m FM.

AMATEUR MEASUREMENT

THE MEASUREMENT of FM deviation is a subject area that has received little attention in amateur radio literature. In the absence of a

to the user by voice announcement. This service is not yet normally found on British repeaters.

Direct reading of deviation is normally achieved with a deviation meter. FM deviation meters are occasionally available on the second hand market. The MFJ224 2M FM analyser has the capability of measuring FM deviation as one of its functions. However, there remains the problem of how the amateur would verify the calibration of either of these instruments.

A *RadCom* article describing the construction of a deviation meter was published by G3BIK [2], but needed a calibrated FM signal generator as a fundamental reference. An approach that I initially prototyped was a variant of G3BIK's design that used a DC coupled precision rectifier to measure the control voltage of the phase-locked loop FM demodulator. The use of DC coupling allowed the calibration of the deviation meter, by recording the change in meter reading as the carrier was tuned away from the centre

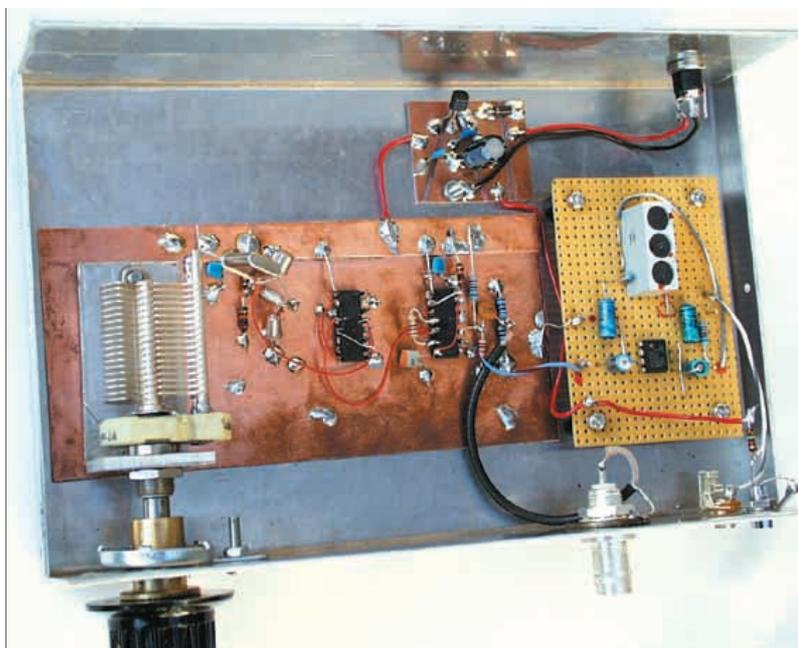
frequency position. This promising approach was eventually abandoned in favour of the carrier null method, which was a much simpler design that had the overwhelming advantage of being self-calibrating.

CARRIER NULL METHOD

THIS METHOD of FM deviation measurement is the standard professional method of setting the deviation of an FM transmitter. It is described in principle in both the amateur [3] and professional [4, 11] technical press. The carrier null method is based on the observation that if an FM transmitter is modulated with a pure

sine wave, then as the deviation is increased from zero, the amplitude of the carrier goes through a series of nulls. The first null occurs when the deviation ratio = 2.405, where:

$$\text{Deviation Ratio} = \frac{\text{Peak Deviation (Hz)}}{\text{Modulation Frequency (Hz)}}$$



The internal view of the FM Spectrum Analyser, showing its construction.

readily available measurement method, the current advice of the VHF Committee is to take the empirical approach of adjusting the deviation until the signal sounds right when received on a receiver equipped with a 12.5kHz filter [1].

In the United States, it is common for repeaters to incorporate a facility to measure the deviation of a received signal and, on request, to report this

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From this we can calculate that when a transmitter with a peak deviation of 2.5kHz is modulated with a 1.040kHz sine wave at an amplitude equal to the maximum peak audio amplitude, the carrier amplitude will be zero. To correctly set the deviation of an FM transmitter to 2.5kHz, a 1.040kHz sine wave of appropriate amplitude is therefore injected into the microphone socket, and the deviation increased from zero until the carrier amplitude goes to zero. **Fig 1** shows the changing spectrum of an FM transmitter as the deviation ratio is increased from 2.2, through 2.4 to 2.6. Note how sharply the carrier disappears when the deviation is changed by $\pm 10\%$. This demonstrates the sensitivity of the carrier null method.

By starting with a high audio modulation frequency, and reducing it until the carrier is observed to null, and then applying the equation above, we can measure the deviation of a transmitter. A description of the basis of the carrier null method is provided in [3].

In professional measurements, a spectrum analyser capable of resolving the components of an FM transmission is assumed to be available. Such resolution is beyond the capability of the simple spectrum analysers described in amateur literature. Some writers have suggested monitoring the amplitude of the carrier with a narrowband CW receiver. If a suitable receiver is available, this is a simple and practical approach. Most amateur VHF receivers however use a 2.5kHz SSB filter for CW reception. Because of the complex spectral structure of the FM signal, this measurement is much easier to accomplish if an audio CW filter is added. When using the carrier null method to set transmit deviation to 12.5kHz, the FM sidebands spacing is approximately 1kHz. Thus, if an 800Hz beat is used, there will also be an audible tone at approximately 1.8kHz, and possibly some filter leakage at approximately 2.8kHz and 200Hz (folded back from the other side of the carrier).

This article describes an alternative method

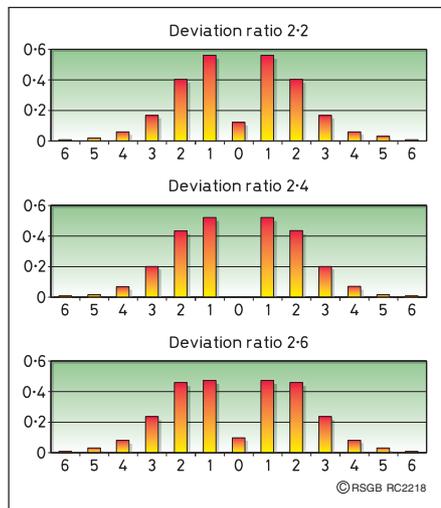


Fig 1: The FM spectrum at deviation ratios of 2.2, 2.4 and 2.6.

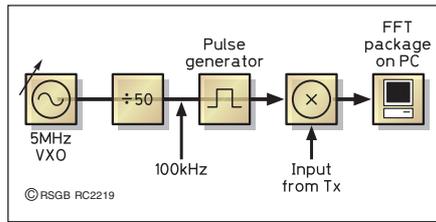


Fig 2: The FM Spectrum Analyser system block diagram.

of observing the transmitter carrier null. A simple, wideband monitoring receiver is used to convert the transmitter output to an audio IF. The spectral components of the transmission can then be viewed by using a PC with a sound card, in conjunction with a Fast Fourier Transform (FFT) package to analyse the IF signal in detail.

SYSTEM ARCHITECTURE

THE APPROACH USED in the FM Spectrum Analyser is to use a sampling mixer [5, 6] to heterodyne the RF signal to an audio IF, and then to analyse the IF spectrum with an audio spectrum analyser. The audio spectrum analyser is an FFT package [7] run on a PC with a suitable input sampler such as a SoundBlaster®. The FFT package is capable of providing sufficient frequency resolution to clearly distinguish the carrier from the first modulation sideband, whilst still allowing a sufficiently wideband display that spectral aliasing is not an overwhelming problem. Many suitable audio FFT packages are available [8], although the user should select one that supports a 'scope display of the spectrum and not a waterfall display.

A block diagram of the FM Spectrum Analyser is shown in **Fig 2**. The system consists of a 5MHz VXO which is divided by 50 to produce a 100kHz square wave. This is used to drive a pulse generator, which produces a 100kHz frequency comb. The signal from the transmitter under test and the comb are mixed, and a 15kHz low pass filter filters the resultant mixing products. This removes signals that would produce aliases in the FFT. The resulting audio signal is fed to the PC sound card.

As G4COL explained, it is necessary to have a stable oscillator whose harmonics can be tuned across the frequency of interest. The short-term frequency stability and freedom from microphony are vital in the design of this system. I therefore elected to use a VXO, rather than a VFO. The choice of the VXO frequency is not critical, although 5MHz is quite convenient. The VXO is divided by 50 to give a 100kHz square wave, which is then used to drive a pulse generator which in turn has a spectral output that consists of a 100kHz frequency comb, extending beyond 433MHz. To obtain complete coverage at 145MHz the VXO must be pulled by 3.5kHz. This was achieved on the prototype. On lower frequency amateur bands it was not possible to pull the crystal sufficiently to obtain

complete coverage. On these bands it was necessary to tune the transmitter to a region covered by the instrument. This is not a problem with a synthesised transmitter. If a lower frequency comb had been used (say 50kHz) it would not have been necessary to pull the oscillator as far, but it would have placed tighter design constraints on the anti-aliasing filter.

CIRCUIT

THE OSCILLATOR, divider, pulse generator and mixer circuit is shown in **Fig 3(a)**. The oscillator and divider chain are similar to that used by G4COL [6], except for the omission of one divide by two stage to give a PRF of approximately 100kHz. Although the oscillator circuit proved reliable in the author's prototypes, the output level of this circuit is critically depend-

COMPONENTS

Resistors (all 0.6W)

R1	10k
R2	10k
R3	2k2
R4	10k
R5	150R
R6	100R
R7	100R
R8	3k3
R9	2k2
R10	3k3
R11	3k3
R12	1k5

Semiconductors

D1	1N4001
D2	LED
IC1	74HCT390
IC2	74F00 (Available from RS Components)
IC3	TL082
IC4	78L05
TR1	BC109

Capacitors (unless specified, all fixed capacitors 50V working)

C1	150pF variable
C2	390pF
C3	390pF
C4	10nF
C5	56pF
C6	100nF
C7	10nF
C8	10nF
C9	10µF, 63V
C10	10µF, 63V
C11	10µF, 63V
C12	47µF, 63V
C13	10nF
C14	10nF

Miscellaneous

FL1	Toko A258BLV5085 (Available from Maplin)
X1	5.000MHz (Available from Maplin)

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ent on crystal activity and other component parameters. If this proves to be a problem, or if a more conservative design approach is preferred, then an amplifier-limiter stage may be inserted between the oscillator and the first stage of the 74HCT390 divider. This alternative arrangement is also shown in Fig 3(b). The first stage of the limiter uses one of the inverters from a CD4049UB hex inverter with a 10k resistor connected between the input and output. This creates a high gain amplifier, with the input biased to 2.5V. This high gain stage is AC coupled to the emitter of the oscillator transistor. This amplifier stage is followed by a further buffer stage, to hard limit the signal to the counter. All unused inverters have their inputs grounded to set them at a defined logic voltage, and hence minimise dissipation. This limiter will

function with oscillator levels below 100mV peak-to-peak.

The design of the pulse generator is a compromise between practical simplicity and rigorous design. I adopted the same pulse generator used by G4COL [5, 6], on the basis that it was better characterised (and more stable) than most of the discrete designs, and orders of magnitude simpler than a fully synchronous logic design. Because the system was to be used at 146MHz, the higher performance TTL FAST logic family was needed. The use of a high-speed logic device in this circuit position is critical to the operation of the system. This type of pulse generator relies on an artificially generated race hazard between the inputs of NAND gate IC2(a). To ensure that the differential delay is sufficient to switch the NAND gate, the delay is extended by reducing

the rise time of the voltage from the inverter connected NAND stage IC2(d). This is achieved by feeding the gate through a 150Ω resistor and connecting a 56pF capacitor in parallel with the second input of IC2(c). This delay could also be extended by adding one or more pairs of inverters in this logic path, however the delay though an inverter is not accurately characterised, nor is it adjustable. The setting of this delay is a compromise between providing sufficient delay for the NAND gate to switch, and yet providing a short enough pulse to correctly sample the input. Since both the output drive voltage and the input switching threshold for the 74F00 varies from device to device, some adjustment of the 56pF capacitor may be required.

The mixer is the fourth element of the 74F00 NAND gate pack. The use of a NAND gate for this function may at first seem unusual. The most common type of RF mixers use a linear signal path, hard switched by the local oscillator such that the output is either proportional to the input signal or zero. Because this system is designed to measure the characteristics of an FM signal, we can assume that the input signal is constant amplitude. It is also normal practice to follow the mixer in an FM receiver with a limiter. Since there a high level signal available when testing a transmitter, a simple logic gate fulfils the input limiting, mixing and output limiting function in one stage. To improve the sensitivity of the mixer, the RF input is biased to +2V, the logic high threshold for this logic family. A pair of 100Ω resistors in parallel with the input present a 50Ω input impedance to the transmitter and its external attenuators. The mixer has a relatively low dynamic range (15mW to 50mW), so a simple external variable attenuator is used to bring the signal into the required range. This attenuator is described in the Appendix.

The mixer is followed by the buffer-filter-buffer arrangement shown in Fig 3(c). A TL082 voltage follower provides a high impedance load to the mixer. The 15kHz LPF filter block requires a 3k3 input and output load to function correctly. Feeding its input through a 3k3 resistor sets the input impedance of the filter. The output impedance is achieved by a 3k3 resistor in parallel with the input of a second voltage follower. This output buffer provides a low impedance output, to drive the audio input of the PC via a 2m length of screened cable. By AC coupling the voltage follower configuration, the filter buffers are able to operate from a single nominal 12VDC power supply with series diode protection. A 78L05

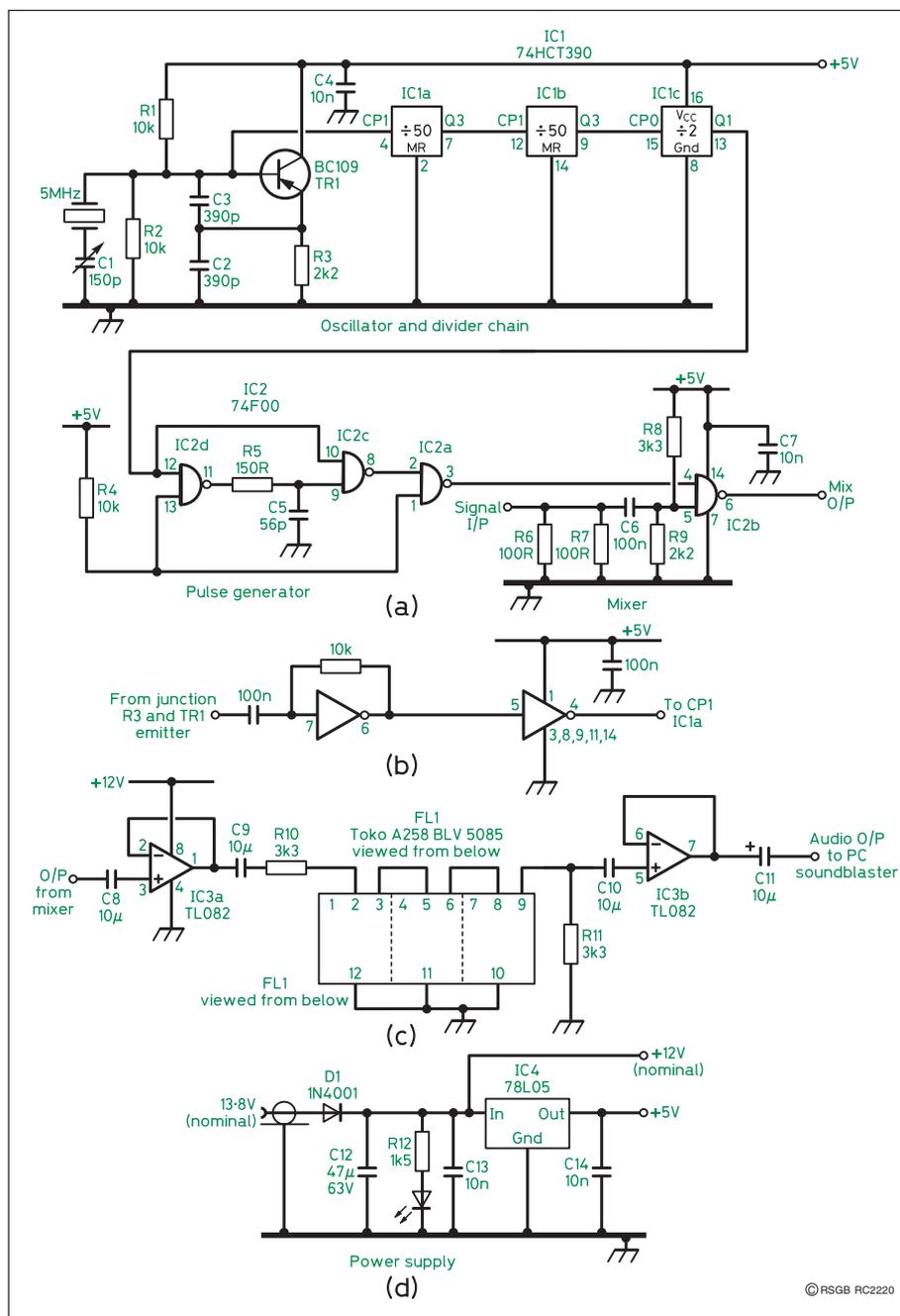


Fig 3: Circuit diagram of the FM Spectrum Analyser.

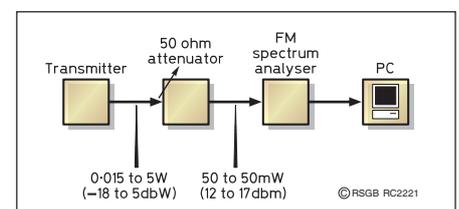


Fig 4: System configuration used for measurements.

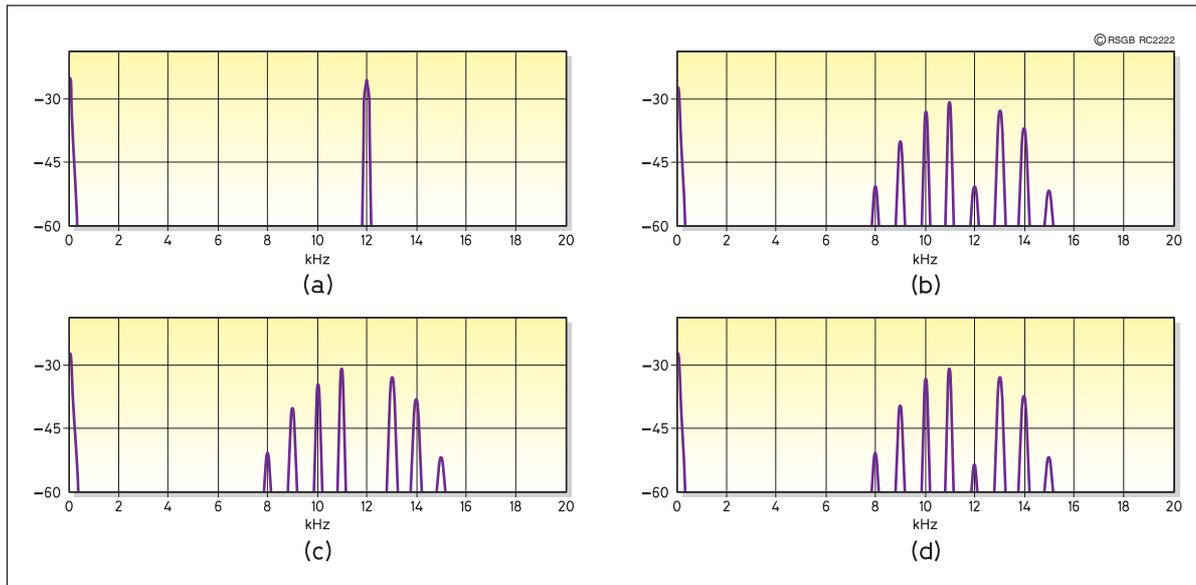


Fig 5: Spectrogram display of unmodulated 145MHz carrier, and carrier modulated with 1kHz sine wave at 2.3kHz, 2.4kHz and 2.5kHz deviation.

voltage regulator - Fig 3(d) - provides 5V for the oscillator and TTL logic. The total power consumption is about 30mA.

The software audio FFT package used in the author's system was 'Spectrogram' by RS Horne [7]. This was used in 'scope mode, and was run on a 233MHz Pentium laptop running Windows95 using the built-in sound input system. The Spectrogram software is a highly capable package that will run under Windows95 or Windows NT V4.0 and needs 16MB of RAM. Its use is free in non-commercial applications. Many members of the UK low frequency amateur radio community have successfully used the spectrogram program. I have not tested the FM spectrum analyser on any other audio FFT packages, but would not anticipate any difficulties, provided the system also supported the use of 16 bit sampling at 44kHz.

MEASUREMENT PROCESS

THE SYSTEM configuration used for making measurements is shown in Fig 4. The transmitter is coupled to the FM Spectrum Analyser through a variable attenuator. The attenuator is set for maximum attenuation (minimum signal). The VXO is tuned until a suitable harmonic is heard on the receiver. The transmitter is set for low power and keyed. It is not modulated at this stage, and ideally the microphone should not be active. The attenuation is reduced (RF signal increased) until the carrier is seen at a comfortable level on the PC FFT display. The user will normally see the carrier offset from zero beat and a cluster of harmonics of the beat with decreasing amplitude. The VXO tuning control is then adjusted until the carrier is seen at about a 12kHz offset from the zero beat.

An audio sine wave of 1.04kHz (for the 2.5kHz deviation needed for operation with 12.5kHz channel spacing [9]) is injected into the microphone socket. The audio level of this modulating signal is increased until the onset of limiting, and then increased by a further 10 to 20dB.

This process is required to ensure that the maximum possible deviation of the transmitter is being measured. Maximum deviation will correspond to maximum spectral width on the FFT display. With the modulating tone still applied, the transmitter deviation is reduced to zero, and then steadily increased until the carrier goes to zero. Care needs to be taken that the second null (at 5.7kHz deviation) is not set. Care also needs to be taken not to confuse the carrier with the first sideband or with a spurious signal arising from leakage through the anti-aliasing filter.

If setting up a transmitter for 25kHz spacing, the required deviation is 5kHz, the audio sine wave is 2.08kHz, and the second (spurious) null occurs with a deviation of 11.5kHz.

The accuracy of the measurement is completely dependent on the accuracy of the frequency of the audio signal injected into the microphone socket. In the absence of a suitably calibrated audio source, or an audio frequency meter, the frequency of the audio signal can be measured using the FFT package on the PC, which can also be used to check the purity of the modulating waveform.

CONSTRUCTION

THE CONSTRUCTION of the FM Spectrum Analyser can be seen in the photo on page 15. The RF section is constructed dead-bug style, on copper clad board. Although this technique is not as aesthetically pleasing as a PCB or strip-board approach, the solid ground-plane, short lead lengths and low parasitic capacitance makes it ideally suitable for one-off RF designs. The number of wires needed is relatively small, so construction is not particularly onerous. Tuning is concentrated at the low capacitance end of the variable capacitor range, so a 6:1 reduction drive is needed. The VXO tuning capacitor was mounted on a sturdy bracket, to prevent elasticity in the mounting from causing backlash in the tuning. In other regards the construction of the VXO was remarkably uncritical, with no hint of

microphony.

To provide a low impedance 5V distribution rail, a narrow strip of printed circuit material was glued to the ground plane.

The filter stage is constructed on a small piece of strip-board. This is less critical than the RF stage, but care needs to be taken to ensure that the stray capacitance on the input is mini-

mised. Note that the data sheet on the Toko 15kHz LPF shows pin-out viewed from the bottom of the package, rather than the conventional top view.

For many years I was put off home construction because of the difficulty of achieving a professional appearance of the finished project. The approach used in this project was to use a computer package to produce the artwork for the front and back panel. This artwork is then printed using a laser printer, and glued to the panel metalwork using a transparent spray-on adhesive. When the adhesive is dry, the panel is then covered with a layer of the transparent plastic film sold for covering books. Provided care is taken to avoid stretching or tearing the plastic surface when mounting components on the panel, the result is a durable and attractive finish. A copy of the panel artwork with suitable drilling marks inscribed may be tacked over the panels and used as a template to ensure the correct hole alignment with the final panel artwork. The finished result is shown in the photo.

At the time of writing, the new cost of components and enclosure is less than £20 + the cost of the variable capacitor. The 74F00 is available from RS Components and from Electronics Services.

RESULTS

OPERATION OF THE system was initially verified by monitoring the output of an FM signal generator. A carrier at 145MHz was input to the FM Spectrum Analyser. The VXO was tuned a harmonic was offset from the carrier by 12kHz. The resulting FFT display is shown in Fig 5(a). The horizontal axis is calibrated in units of kHz, and the vertical axis is calibrated in relative dB. The 12kHz beat is clearly visible. The peak at 0Hz is a mixture of the DC component and any residual 50Hz pickup. It was found that the cleanest display was obtained with an input signal level of +8dBm. Above this level a number of low level spurs were visible. The

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source of these spurs has not yet been identified.

The signal generator was frequency modulated with a 1kHz tone. From the equation on page 16 we would expect the carrier amplitude to go to zero when the deviation is 2.4kHz. This is clearly demonstrated in **Fig 5(b)**, **5(c)** and **5(d)**, which show the measured spectrum at deviations of 2.3kHz, 2.4kHz and 2.5kHz respectively.

To demonstrate the full operation of the system, a Yaesu FT-736R was connected to the FM Spectrum Analyser through the variable attenuator. At minimum output power and with no audio modulation the carrier was set for a 12kHz beat with the VXO harmonic. This is shown in **Fig 6(a)**. The 11kHz at -50dB is a spurious signal from within the PC. The source of the spurs at 4kHz and 8kHz have not yet been identified.

With the FT-736R then set in the normal (wide) FM mode and a 1.73kHz audio tone applied to the microphone socket, the amplitude of the modulating signal was increased until maximum deviation was observed. At this point the VOGAD circuit was limiting the deviation to the maximum permitted level. This is shown in **Fig 6(b)**. The carrier at 12kHz is diminished, and the sideband at 1.73kHz spacing clearly visible. As the modulation frequency is increased in units of 100Hz we see the carrier go to zero amplitude when the modulating frequency is 1.93kHz. This corresponds to a peak

deviation of 4.64kHz, which is consistent with the manufacturer's specified frequency deviation of 5kHz.

Observant readers will note from **Fig 6(b)** through **Fig 6(f)** that there are a number of spurs that change frequency at a rate of approximately 10 times the change in modulation frequency. The source of these spurs has not yet been positively identified.

ACKNOWLEDGEMENTS

I WOULD LIKE to acknowledge the assistance of G3GRO, G3VJM, G3VLH, and G3WPH in developing these ideas and preparing this article for publication.

APPENDIX - A VARIABLE ATTENUATOR

A RELATIVELY simple outboard variable attenuator (**Fig 7**) was constructed to allow the RF output of the transmitter under test to be reduced to the level needed to drive the FM Spectrum Analyser. Because of the relatively low dynamic range of the mixer used, a continuously variable attenuator is desirable. Because the attenuator is being used as a sampler, accurate calibration is not required. The attenuator used an external 25W 50Ω dummy load connected to a PL259 T-piece, with a 1kΩ linear modular conductive plastic variable resistor between the input and the output. This was chosen for its 1 watt power

handling capability. The output was assumed to be terminated externally with a 50Ω load, normally provided by the FM Spectrum Analyser. This rather crude design has a known 2:1 SWR at minimum attenuation, but approaches 1:1 at maximum attenuation. In view of the simplicity of the approach and the fact that SWR was satisfactory at high power (where it is most critical), this design limitation was accepted. The variable resistor has a power dissipation of 1W, limiting the maximum power handling capability of the attenuator to 20W. The attenuator was built into a Maplin 100mm x 70mm x 40mm aluminium box, with the PL259 input socket at one end, the BNC output connector at the other end, and the variable resistor in the middle. No attempt was made internally to reduce the effects of wiring inductance, other than to use shortest wire lengths possible.

The attenuation was measured using a signal generator with a built-in precision attenuator and a diode detector [10], connected to a DVM. The variable attenuator was set to maximum attenuation, and the reading on the DVM noted. The attenuation was measured by changing the variable attenuator setting, and then compensating for this by increasing the output of the signal generator until the same reading was observed on the DVM. This allowed the attenuation to be measured without reference to the character-

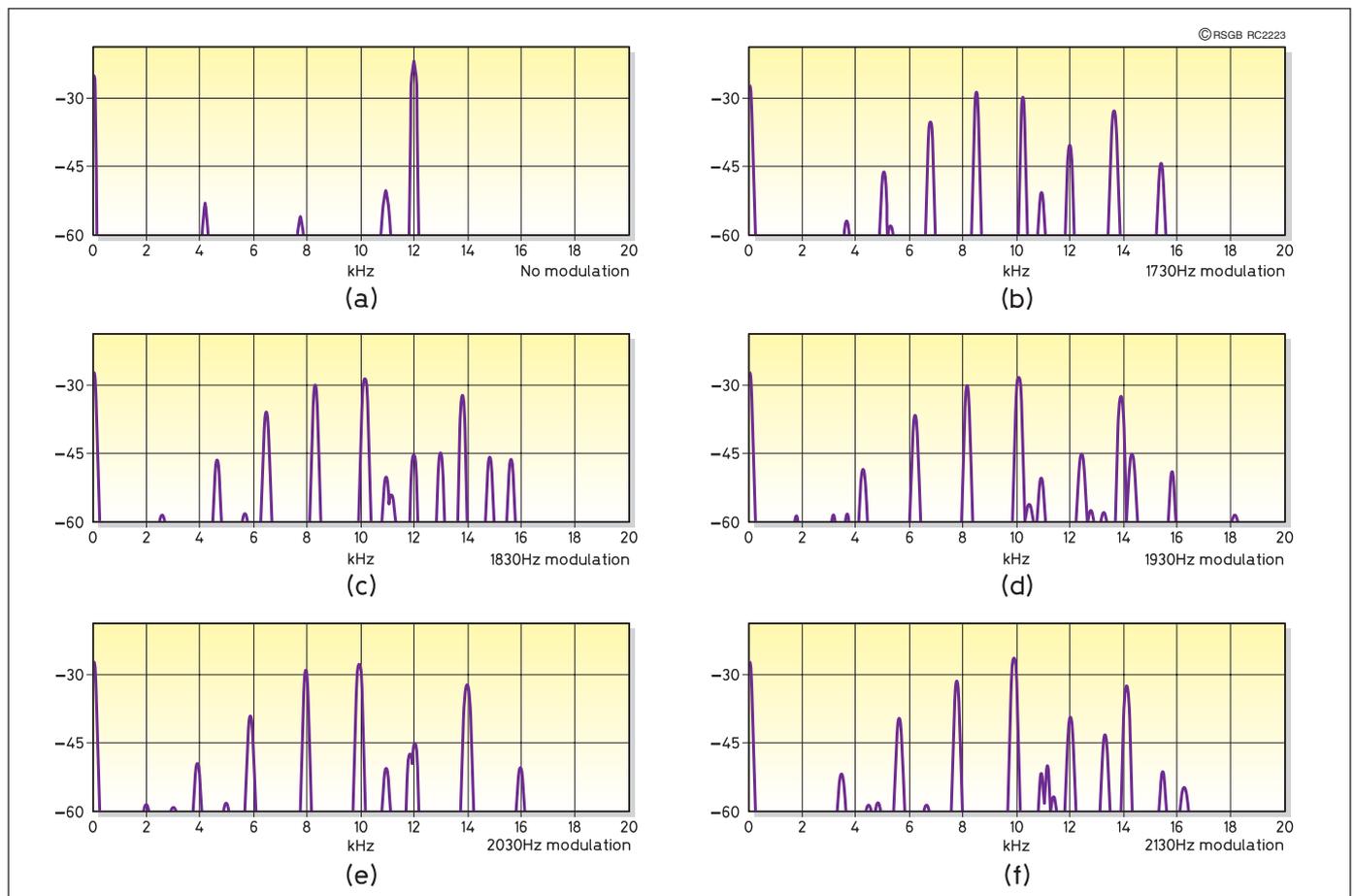


Fig 6: Measurements of the output of a Yaesu FT-736R transceiver.

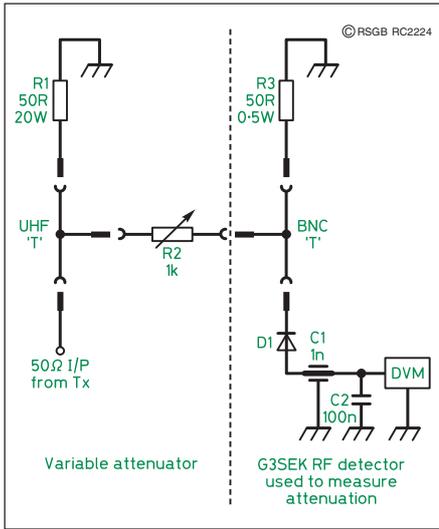


Fig 7: The variable attenuator design.

istics of the diode detector. The attenuation at 145MHz and 10MHz is shown in Fig 8(a). The reduced attenuation at VHF is thought to be due to capacitive coupling within the variable resistor. The 23dB attenuation achieved at 145MHz limits the power handling of the FM Spectrum Analyser to 5W, unless an additional 6dB 50Ω attenuator is connected between the output of the variable attenuator and input of the analyser.

A scan of the attenuator input SWR vs fre-

quency at various attenuation settings was made using an MFJ259 antenna analyser is shown in Fig 8(b). This showed that at low frequencies the SWR is close to the expected 2:1, but as the frequency increases to 150MHz this reduces to 1.3:1. This is presumably due to the inductance of the attenuator, reducing the effect of the 50Ω output load. The high power 50Ω load on the input had an SWR of 1:1 up to 120MHz, and the 50Ω load used in the diode detector was flat beyond 160MHz.

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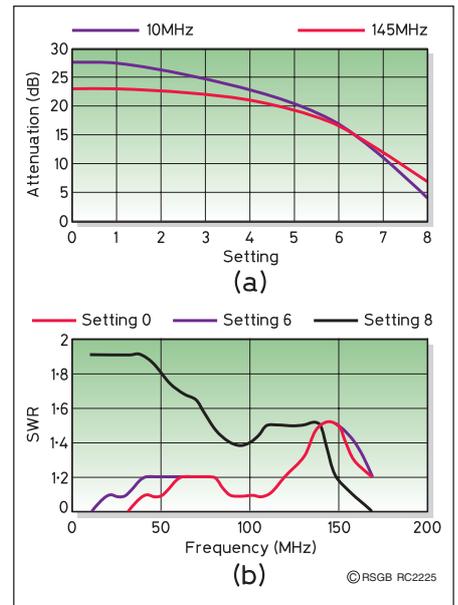


Fig 8: Variable attenuator measured results.

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