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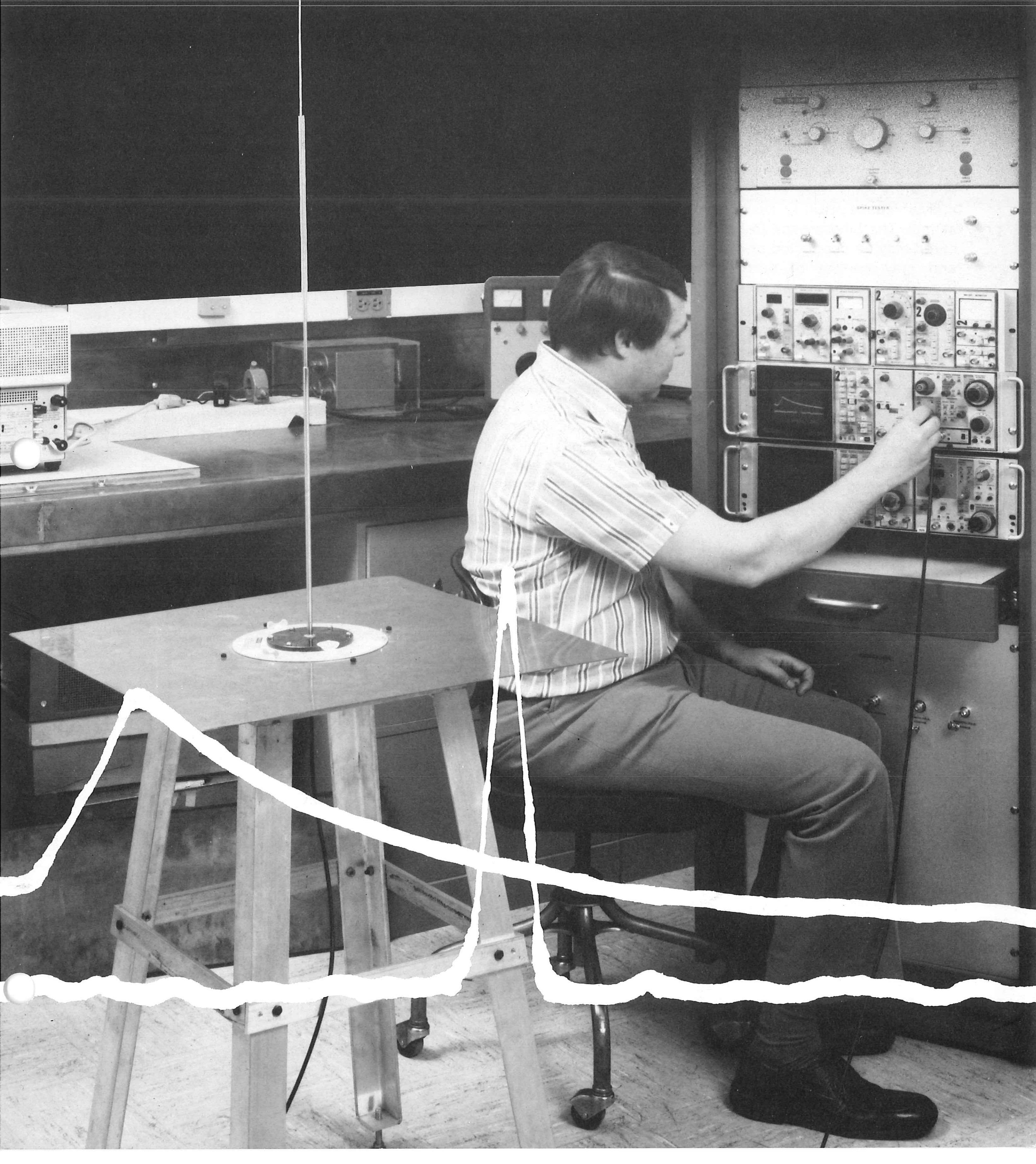
EMI APPLICATIONS USING THE SPECTRUM ANALYZER



EMI APPLICATIONS USING THE SPECTRUM ANALYZER

By Morris Engelson

Radio frequency interference (rfi), electromagnetic interference (emi), electromagnetic compatibility (emc), and spectrum signature are all related terms. They deal with the tendencies of electronic equipment to interfere with each other. Two distinct types of interference tests are made on a given instrument: tests to identify and measure undesired emissions, and tests of the instruments' susceptibility to external stimuli. The interference to be measured may be conducted or radiated and may consist of narrowband, broadband, transient or other types of signal.

Susceptibility tests require various signal sources to generate the interfering signal. Emission tests involve measurement instruments such as field intensity meters (fim), and/or spectrum analyzers (sa). This paper is concerned with the use of the spectrum analyzer as an emi characterization tool and in particular with the TEKTRONIX 7L5 Spectrum Analyzer, which has several unique capabilities in this area.

"Spectrum analysis" rather than "emi" will be emphasized. This is not a treatise on the art of emi reduction or on how to comply with various military or commercial specifications. The intent is to show how spectrum analyzers in general, and the 7L5 in particular, can be used in achieving emi reduction objectives.*

I. Spectrum Analyzer Characteristics

The two most critical spectrum analyzer characteristics in emi measurement are impulse bandwidth and wideband overload. Let us consider each in turn.

Impulse Bandwidth

There are many ways to determine a spectrum analyzer's impulse bandwidth[1] (B_i). The 6 dB down bandwidth (B_6) may be used as a simple approximation for synchronously tuned stages. For rectangular-shaped nonsynchronous filters the relationship $B_i \simeq 0.75B_6$ should be used. The resolution bandwidth (B_R) of TEKTRONIX Spectrum Analyzers is specified at the 6 dB down points. Hence, for the 7L5, $B_i \simeq B_R$ at 3 kHz or less resolution (synchronously tuned stages) and $B_i \simeq 0.75\ B_R$ at the 10 kHz and 30 kHz resolution setting (nonsynchronous filter).**

For high-accuracy applications it is useful to measure the actual impulse bandwidths of the individual instrument. This may be done by driving the 7L5 with a train of very narrow pulses (impulses). The impulse bandwidth is then computed from

$$B_i = (V_p/V_{av})\ f_p;$$

where V_p is the peak output voltage, V_{av} is the average output voltage, and f_p is the pulse repetition frequency. The restrictions are that $5\ f_p \leq B_i$, and that the pulse width be less than about one tenth the inverse of B_i, V_p and V_{av} may be most easily measured using the peak and average measurement functions of the 7L5.

Overload Characteristics

Wideband overload limitation is a major problem in using spectrum analyzers for emi measurements. The difficulty arises because the front end of the spectrum analyzer is subjected to considerably greater signal levels than the level actually displayed. The ratio of input voltage to displayed voltage is equal to the ratio of input bandwidth to the impulse bandwidth used in the measurement. The input bandwidth for the 7L5 is 5 MHz and the measurement impulse bandwidth varies from about 20 kHz (at 30 kHz resolution setting) to about 10 Hz (at 10 Hz resolution setting). Therefore the ratio of input voltage to displayed voltage will vary from 250 (48 dB) to 5×10^5 (114 dB). Unless the front-end can handle exceptionally large signal levels, the instrument may be overloaded before a usable signal level is displayed. Front-end overload for most spectrum analyzers, including the 7L5 with L3 front-end, is a marginal −10 dBm (97 dBμV into 50 Ω).

The L3 provides 1 MΩ as well as 50 Ω and 600 Ω input impedance. It is a convenient unit for circuit probing, but marginal for high-level wideband impulse noise characterization.

The 7L5 with the 50 Ω L1 front-end has a +10 dBm (+117 dBμV) input overload point representing a 20 dB improvement over the L3. This permits a display level of +10 − 48 = −38 dBm (69 dBμV) at the widest resolution setting, and −54 dBm (53 dBμV) at a more convenient 3

Those interested in the emi properties of transmitters may refer to TEKTRONIX publication AX-3266 entitled AM Broadcast Measurements Using The Spectrum Analyzer.

***Reference 1 erroneously indicates that the 10 kHz and 30 kHz positions have a wider impulse bandwidth.*

[1]Noise Measurements Using The Spectrum Analyzer—Part Two: Impulse Noise. Tektronix 12/75 No. AX-3259.

kHz resolution setting. The 7L5/L1 internal noise levels are −95 dBm and −105 dBm respectively,* providing a measurement dynamic range of 56 dB and 51 dB. Even the narrowest (10 Hz) bandwidth yields usable measurement dynamic range of about 20 dB.

Impulse bandwidths, impulse noise input limits, dynamic range, and other measurement parameters for the 7L5 are tabulated in the appendix.

II. Measuring to a specification

Measurement technique varies depending on whether the emi is radiated or conducted, whether it is broadband or narrowband, and whether a qualitative (meets/does not meet spec) or quantitative analysis is required. The variations are too numerous to be covered in a single general procedure. Instead, a few specific examples will be presented to illustrate the process.

Radiated Measurements

Figure 1 shows the radiated interference limits, to 5 MHz, specified in MIL-STD-826. The measurement units are in dB above one microvolt per meter (DBUE) electric field strength for narrowband emissions and dB above one microvolt per meter per megahertz of impulse bandwidth (DBUE/MHz) for broadband emissions. The 7L5 Spectrum Analyzer indicates amplitude in three basic units: volts/div in the linear vertical mode, dBm (dB above one milliwatt) and dBV (dB above one volt) in the logarithmic vertical mode. The measurement unit most easily convertible to dBμV is dBV, the conversion equation being

$$\text{dB}\mu\text{V} = \text{dBV} + 120.$$

These are peak noise levels and are 10 dB above the usually specified averaged noise levels.

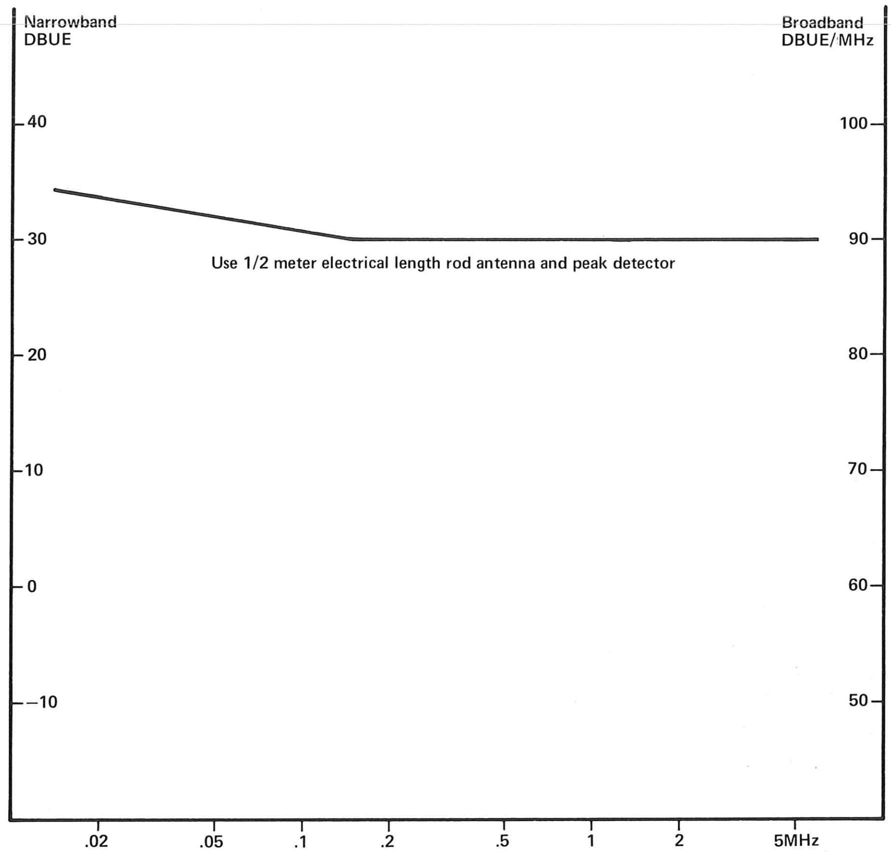


Figure 1. Radiated interference limits per MIL-STD-826.

Two calibration factors must be used: the antenna factor (F_A) which converts volts to volts per meter, and the bandwidth factor (F_B) which converts the measurement impulse bandwidth to the specified normalization bandwidth of 1 MHz.

The usually specified rod antenna has an electrical length of one half meter. Hence an electrical field strength of 1 μV/m will produce an output of ½ μV. The antenna factor is thus 0.5, or $F_A = 6$ dB. This means that in terms of display voltage the narrowband limit at 14 kHz (fig 1) is 34.5 DBUE − 6 UV/UE = 28.5 dBμV. At higher frequencies it is

$$30\ \text{DBUE} - 6\ \text{UV/UE} = 24\ \text{dB}\mu\text{V}.$$

Converting to the dBV scale, the limits become −91.5 dBV (28.5 dBμV − 120) and −96 dBV (+24 dBμV −120). It may be noted from table 2 (Appendix) that all 7L5 bandwidth positions have sufficient sensitivity to make this measurment. An illustration follows.

The device under test is set up according to the specified physical configuration. The antenna output is connected to the 7L5 input and a frequency scan is effected. Figure 2 shows a full frequency scan from essentially zero hertz to 5 MHz. The crt readout indicates a full screen reference level of −60 dBV with 10 dB/div vertical scale. Center frequency at dot position is 2.5 MHz with a horizontal span of 500 kHz/div. Resolution bandwidth is 30 kHz. Several narrowband signals are on screen. All are more than 40 dB below −60 dBV for an amplitude level less than −100 dBV. These signals meet the derived specification limit of −96 dBV.

One thing not clear from figure 2 is what is happening at the low-frequency end. Clearly a resolution setting of 30 kHz is too wide for observing signals at 14 kHz. The low-end spectrum is shown in figure 3. Here the center dot frequency has been reduced to 50 kHz with a horizontal span of 10 kHz/div. Also, the resolution has been reduced to 3 kHz. We observe that the zero hertz marker at the extreme left-hand edge masks about the first 5 kHz. Beyond that, there is a broadband signal centered at about 32 kHz with a peak level of about −95 dBV. No narrowband signals are present.

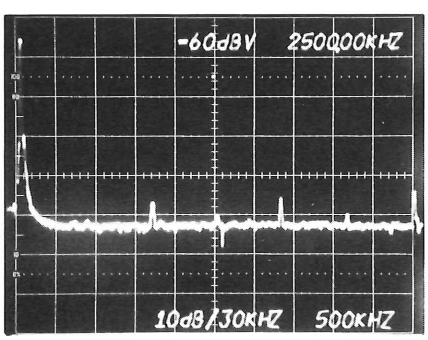


Figure 2. Five megahertz scan for radiated interference.

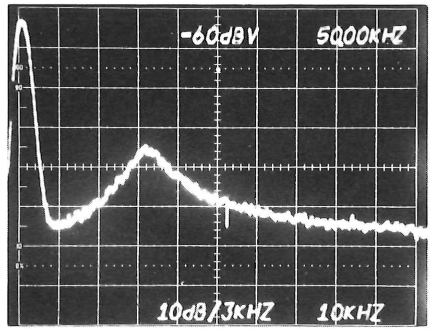


Figure 3. One hundred kilohertz scan for radiated interference.

Broadband measurements require use of the bandwidth factor, F_B, the ratio of the specification bandwidth (1 MHz for MIL-STD-826) to the measurement impulse bandwidth. At 30 kHz resolution, the impulse bandwidth is about 20 kHz and

$$F_B = \frac{1000}{20} = 50 \text{ (34 dB)}.$$

Using 3 kHz resolution, the impulse bandwidth is approximately 3 kHz and $F_B = 333$ (50 dB).

We can now determine the specification limits in terms of 7L5 Spectrum Analyzer measurement units of dBV. At 14 kHz the broadband limit is 94.5 DBUE/MHz. The antenna factor is $F_A = 6$ dB, the bandwidth factor at 30 kHz resolution is $F_B = 34$ dB and conversion from microvolts to volts is 120 dB. Therefore, the derived limit at 14 kHz is

$$94.5 - 6 - 34 - 120 = -65.5 \text{ dBV}.$$

At 150 kHz the specification decreases to −70 dBV. Using the 3 kHz resolution position the limits are −81.5 dBV and −86 dBV. Clearly, at −95 dBV the broadband noise shown in figure 3 is within specified limits.

If a qualitative analysis is also desired, the cause of the observed emi may be determined using the examination techniques discussed in section III.

Conducted Measurement

Conducted emi measurements can be made using a standard interconnecting filter such as a line stabilization network (LSN), by means of a current probe, or through direct connection to the cables to be tested. The current probe is presently the preferred MIL spec method.

The graph in figure 4 shows composite narrowband emissions limits as specified by MIL-STD-461. The limits are given in units of dB above one microampere (dBμa). The measurement transducer is a current probe, which is simply a single winding transformer with the line under test as the single turn primary. Current probe calibration factors are expressed as a transfer impedance. These probes may be built for the desired application, but many commercial units are available, including some from Tektronix. Many current probes come with instrumentation amplifiers to compensate for frequency roll-off and turns ratio, and have an associated calibration factor of one microvolt per microamp into 50 Ω. Thus their dBμa specification translates directly into dBμV measurements. As before, we subtract 120 to go from dBμV to dBV. Therefore the derived specification for this type of probe ranges from 0 dBV below 400 Hz to −100 dBV above 2 MHz.

Figure 5 shows the results of a conducted emi measurement using the 7L5 Spectrum Analyzer with a unity calibration factor current probe. The large signal at 250 kHz does not meet the specification. The other signals at 750 kHz and 1.25 MHz are at best marginal. What can be done about this?

Figure 6 shows a more detailed analysis of the large interfering signal. Amplitude level is −75 dBV (larger trace) while the derived specification at 250 kHz is

$$24 - 120 = -86 \text{ dBV}.$$

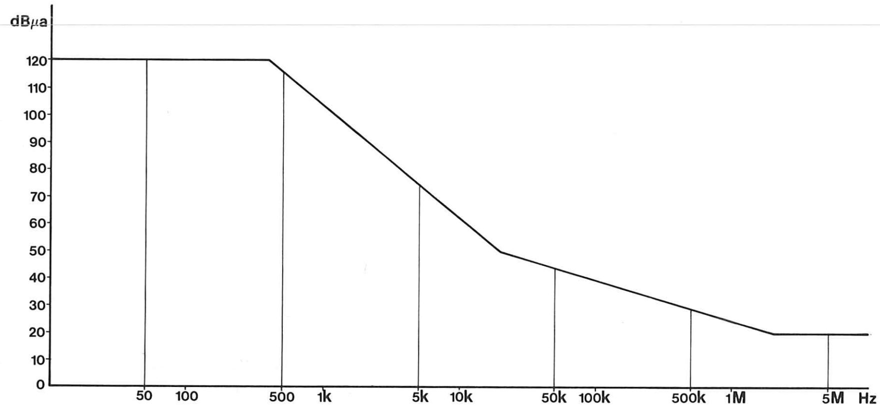


Figure 4. Narrowband conducted interference limits per MIL-STD-461.

We are at least 10 dB over the specification. The exact signal frequency is identified as 250 kHz by aligning the signal display with the frequency dot at center screen. In this particular case, the interfering signal was generated by a local oscillator in the equipment under test. The addition of a feedthrough filter on the appropriate power leads reduced the interference by almost 40 dB (smaller trace). At −113 dBV, the interference level is now well within specification.

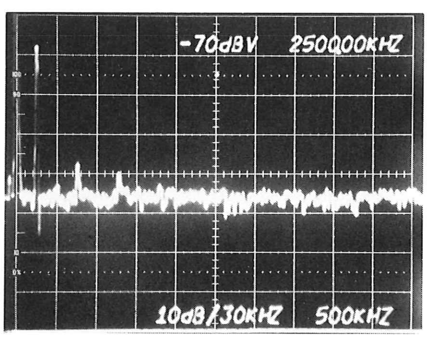


Figure 5. Five megahertz scan for conducted interference.

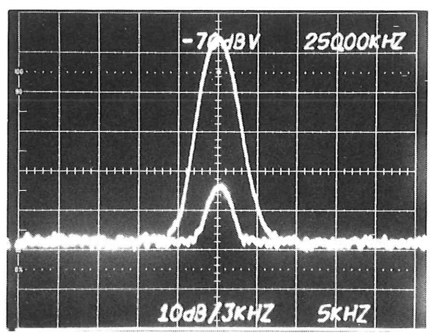


Figure 6. Detailed analysis of interfering signal found in figure 5.

III. Taking a Closer Look

The 7L5 Spectrum Analyzer has unique capabilities which are particularly useful when hunting for emi.

Frequency Accuracy & Averaging

The instrument uses a synthesized local oscillator which tunes in steps of 250 Hz. This permits precise frequency identification which aids in determining the source of interference, as illustrated previously in relation to figure 6.

Another useful feature is digital averaging. The signal is digitally sampled and an average value is computed and displayed. In this way noise may be reduced without disturbing narrowband cw signals. Figure 7 illustrates this function. The signal is the same as in figure 6, except that the peak/average cursor has been moved up from the baseline to about two-thirds of screen height. At levels above the cursor, the signal is peak detected; below the cursor it is averaged. Baseline noise is reduced about 10 dB compared to the peak display of figure 6. The signal levels remain unchanged. This capability is useful for hunting narrowband signals among broadband noise. Figure 8 shows an averaged version of figure 3. The interfering noise level is sufficiently reduced to assure us that there are no narrowband signals above −100 dBV. Reducing the measurement bandwidth is another convenient method of pulling narrowband signals out of noise.

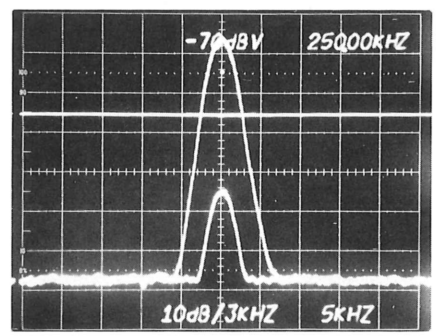


Figure 7. Illustration of noise reduction by averaging the display of figure 6.

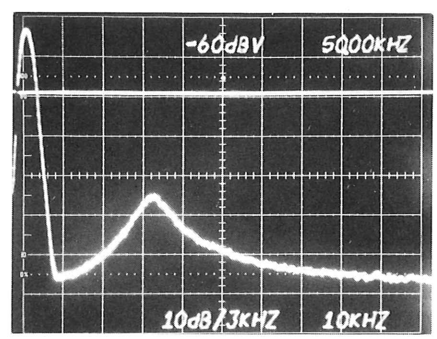


Figure 8. Display averaging applied to the signal of figure 3.

Split Storage

A particularly useful function is the split storage display capability. The displayed spectrum may be stored in memory indefinitely at the push of a button. A second trace in real time may be displayed simultaneously with the stored signal, permitting a direct comparison between the original and the current input. This mode is very helpful in hunting for an experimental fix. The two traces in figures 6 and 7 were generated in this manner. Here the large interfering signal is the original stored display while the smaller signal shows the improvement after bypassing the power supply leads.

Amplitude Accuracy

Accurate amplitude measurement is useful when dealing with interference whose amplitude is marginal with respect to the specified limit. Figure 9 illustrates an accurate measurement of the first interference signal of figure 2. The vertical display is 2 dB/div and the reference level has been adjusted so that the signal is almost full screen. Signal amplitude is −107.5 dBV at a frequency of 1698.75 kHz. Half a dB repeatability is something of an overkill; the smallest movement of the antenna or personnel within the screen room can change readings by several dB. Nevertheless, the capability is there for those few times when it is needed.

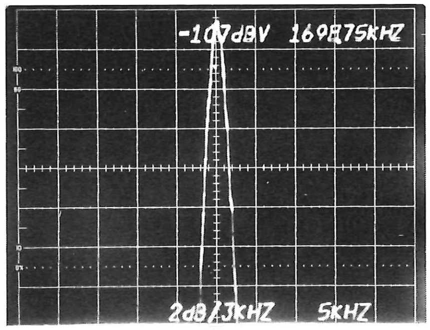


Figure 9. Accurate signal frequency and amplitude measurement.

Random Interference

Hunting for randomly intermittent interference can be a frustrating exercise. Here the 7L5's MAX HOLD function may help. With MAX HOLD activated, the instrument will display and hold in memory the maximum signal level intercepted at any particular frequency. The MAX HOLD display will slowly build up as more and more interfering transients are intercepted until a clearly defined signal emerges. Figures 10, 11 and 12 illustrate a random interference hunting sequence. Figure 10 shows what seem to be a couple of interference spikes, but we cannot be sure. After five minutes there is no doubt that the signal is as shown in figure 11. A ten-minute wait yields the fully-defined display of figure 12, showing an interfering signal at about 25 kHz and −108 dBV.

High Impedance Probing

It is often necessary to probe the various circuits and power supplies during design in order to minimize emi. This requires a high-impedance measuring instrument which will not load down the circuits. The 7L5 with L3 input module provides a 1 MΩ input impedance as well as 50 Ω and

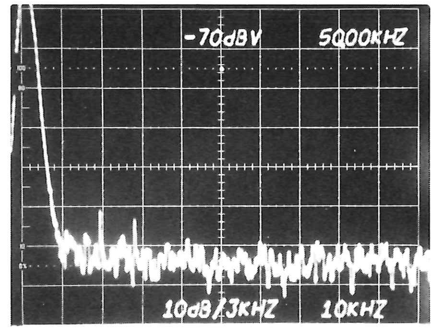


Figure 10. Random intermittant interference spectrum after a few spectrum analyzer scans.

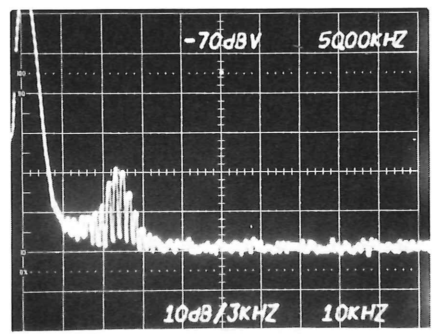


Figure 11. The same interfering signal as shown in figure 10 after 5 minutes build up with MAX HOLD function activated.

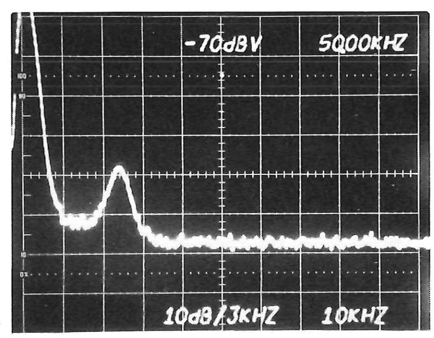


Figure 12. The same interfering signal as shown in figure 10 after 10 minutes build up with MAX HOLD function activated.

600 Ω. Figure 13 shows a direct measurement of line voltage using the 1 MΩ mode of the 7L5/L3 with a 100X probe. Full-screen reference level is +6 dBV with the 60 Hz fundamental at about +1 dBV giving 112 volts into the 100X probe. Harmonic and noise levels are easily observed. Even harmonics are almost nonexistent while odd harmonics are over 35 dB down.

Figure 14 is a full 5 MHz scan showing that harmonics extend to well above 5 MHz. Amplitude level is −95 dBV after the probe, or −55 dBV into the probe.

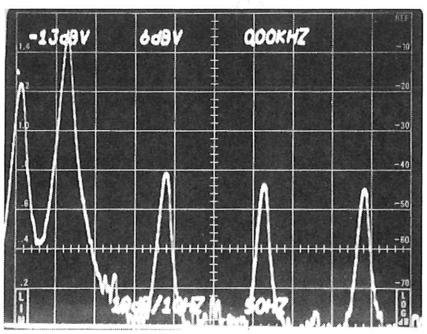


Figure 13. Line voltage measurement using 1 MΩ input impedance.

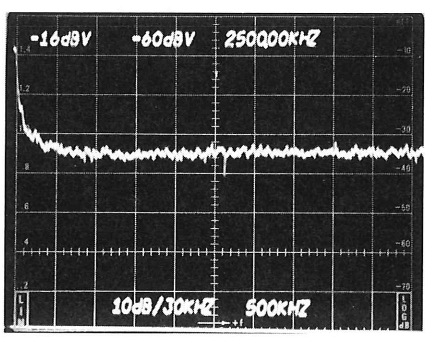


Figure 14. Line frequency harmonic content to 5 MHz.

The Tracking Generator

In addition to finding the level or source of emi, the spectrum analyzer can be used in evaluating a fix. The split memory feature has already been discussed in this connection. Another useful feature is the tracking generator (tg), a signal source whose output frequency tracks in synchronism with the spectrum analyzer input. A detailed description and applications will be found in Tektronix publication AX-3281 entitled, "The Tracking Generator/Spectrum Analyzer System."

The main emi application of tracking generators is in evaluating the transmission and rejection properties of emi suppression components, such as feedthroughs and line filters. This is illustrated in figures 15 and 16 which were generated with a 7L5 Option 25 (7L5 with tracking generator). The Option 25 Tracking Generator has 50 Ω, 75 Ω, and 600 Ω output impedance capabilities for use with various components and front-end L modules. Figures 15 and 16 were taken at a 50 Ω impedance level using the L1 module.

Figure 15 shows the transmission characteristics of an 8500 pF feedthrough capacitor. The horizontal line across the top of the crt is the tracking generator signal going directly into the spectrum analyzer. Both the tg output and sa input levels are set at 0 dBm. The second trace shows the characteristic of the capacitor. The response is down 10 dB at 2 MHz.

Figure 16 shows the characteristics of the two line filters. One has a rejection of only 30 dB at 2 MHz, while the other one is down 55 dB. This is an easy way to determine how much improvement in conducted emi suppression a particular filter will give.

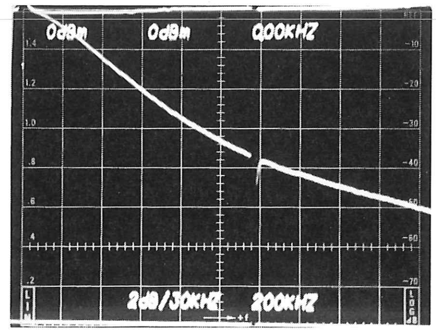


Figure 15. Transmission characteristic of 8500 pF feedthrough capacitor.

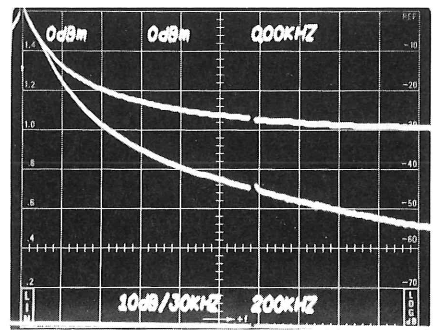


Figure 16. Transmission characteristics of two line filters.

Appendix

Some 7L5 Parameters Useful in Emi Measurement

Table 1

Approximate Impulse Bandwidth for 7L5 Spectrum Analyzer

Resolution Bandwidth	**30 kHz**	**10 kHz**	**3 kHz**	**1 kHz**	**300 Hz**	**100 Hz**	**30 Hz**	**10 Hz**
Approximate Impulse	**20 kHz**	**7.5 kHz**	**3 kHz**	**1 kHz**	**300 Hz**	**100 Hz**	**30 Hz**	**10 Hz**

Table 2

7L5 Input Level and Sensitivity

Resolution Bandwidth		**30 kHz**	**10 kHz**	**3 kHz**	**1 kHz**	**300 Hz**	**100 Hz**	**30 Hz**	**10 Hz**
Maximum Impulse (dBμV) Noise Input (50 Ω)	**L1**	**69**	**60**	**[53]**	**43**	**33**	**23**	**13**	**3**
	L3	**49**	**40**	**33**	**23**	**13**	**3**	**−7**	**−17**
Measurement Dynamic (dB) Range (50 Ω)	**L1**	**57**	**53**	**[51]**	**46**	**41**	**36**	**29**	**21**
	L3	**37**	**33**	**31**	**26**	**21**	**16**	**9**	**1**
Peak Detection (dBV) Sensitivity (50 Ω)	**L1**	**−108**	**−113**	**[−118]**	**−123**	**−128**	**−133**	**−136**	**−138**
	L3	**−108**	**−113**	**−118**	**−123**	**−128**	**−133**	**−136**	**−138**

[ ] See sample calculations

Sample Calculations

Sensitivity

For a 3 kHz resolution bandwidth, the impulse bandwidth (B_i) is also 3 kHz. At 3 kHz bandwidth, 7L5/L1 average noise level is specified as −115 dBm. Peak noise level is 10 dB greater than average or −105 dBm. (See instrument specifications.) To convert between dBV and dBm at various impedance levels the following formula applies:

dBV = [dBm(50 Ω) −13] = [dBm(75 Ω) − 11] = [dBm(600 Ω) − 2].

Hence −105 dBm @ 50 Ω = −105 − 13 = [−118 dBV].

Dynamic Range

Maximum impulse spectral level for 7L5/L1 front-end overload is +10 dBm. Front-end signal level is greater than the displayed signal level as the ratio of front-end bandwidth (5 MHz) to the display bandwidth (3 kHz). This factor is $5 \times 10^6 / 3 \times 10^3$ = 1667 → 20 log 1667 = 64 dB. Maximum display level is +10 −64 = −54 dBm. This is the same as −54 −13 = −67 dBV. To convert between dBV and dBμV we use dBμV = dBV + 120. Hence, maximum display level is 120 −67 = [53 dBμV]. Measurement dynamic range is the difference between the noise level (−118 dBV) and maximum display level (−67 dBV). Measurement dynamic range is 118 −67 = [51 dB].

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