FAST, WIDEBAND SEARCH FOR SPURIOUS RESPONSES

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ABSTRACT

A technique to quickly search frequencies in a signal path to find and measure low level spurs is described. It couples a wideband tuned receiver with a tuned digital, parallel, filter-bank analyzer to greatly reduce spur testing times. The receiver is step-tuned across the region of frequencies to be searched; and at each step, the filter bank is step tuned across the IF output. An example system is described; and elements of search time and sensitivity are discussed.

INTRODUCTION

Testing for low-level spurious responses over a wide region of frequency is time consuming. Such testing is done repeatedly during the design of electronic signal generating or signal monitoring equipment, and is done again during manufacturing and maintenance. Reducing spur test times is worthwhile in itself, and is a means to quicker and better designs, quality control, and maintenance.

Traditionally, a region is tested for spurs by sweeping a narrowband, tuned receiver from the lowest to the highest frequency. The receiver bandwidth is narrow to allow accurate measurement of spur amplitude to a specified low level. A low-level test over a wide frequency region requires a long test time because the sweep has to be slow enough to allow time for the receiver to fully respond at each frequency; a time equal to a multiple of the reciprocal bandwidth. A search for –100 dBm spurs over a 100 MHz region with 1 kHz-bandwidth receiver, for example, takes 1000 s.

The digital filter bank analyzes an entire span of frequencies simultaneously, rather than by sweeping, and thus has an inherent speed advantage. Its frequency span is divided into side-by-side, stationary resolution bands that are slightly overlapped. The filter bank acquires signal data in a relatively short span of time and performs parallel computation of signal amplitudes in all of its resolution bands from that data. In this regard, the filter bank is similar to a conventional FFT analyzer, of which it is an outgrowth. With modern digital signal processing (DSP) hardware, a filter bank can be implemented to span 1 MHz, and more, with resolution as narrow as 0.00125 of the span (1.25 kHz for a 1 MHz span), and to produce a signal spectrum within 10 ms.[1]

Operating alone, however, even a modern filter bank is not well suited to most requirements for wideband spur testing, because its tuning range and maximum span are limited to several megahertz. But, use of a tunable filter bank to analyze the IF output of a wideband tuned receiver results in a system that is well suited to wideband spur testing. The receiver has the necessary tuning range, the filter bank has the resolution; and together, they cover wide bands. In addition, the system is especially fast, because the wideband IF of the receiver is analyzed at high speed in the filter bank. An example system has been implemented that can complete a test for –100 dBm spurs over a 100 MHz region with 1.25 kHz resolution in roughly 50 s. This represents a 20-times reduction in test time relative to that possible by sweeping a narrowband tuned receiver. The technique and example system are described below.

TECHNIQUE AND SYSTEM CONCEPTS

A high-speed spur test and measurement system is diagrammed in Figure 1. As shown, a signal path from the equipment under test is connected to the receiver. This path is to be tested for the presence of spurious responses above a specified low level of amplitude.

Spurious responses are unwanted, stationary, CW signals that are generated within the equipment independently of signal inputs. Through careful design, manufacture and maintenance, spurs are kept to a low level, usually very near the noise floor. In preparation for the test, input signals are removed from the equipment. Of course, the test system should be free of spurs.

Prior to the test, the search region and the acceptable spur level specifications are incorporated into the test program, which resides in the host computer. The search region normally coincides with the operating frequency range of the equipment under test, or some portion of that range. In the course of the test, the receiver is step-tuned across the search region under control of the test program and through control lines such as the GPIB.

The IF output of the receiver is connected to the digital filter bank, which performs high speed spectral analysis. This connection is made through a down converter, if one is necessary, to translate the IF to the frequency range of the filter bank. The filter bank instrument accepts analog signal data and digitizes it prior to analysis of frequency.

The receiver is tuned in steps equal in size to the IF bandwidth, so that the receiver serially covers the search region in contiguous IF bandwidths. Division of the search region into IF bandwidths is illustrated in Figure 2.

For highest search speed, the frequency span of the filter bank would be made equal to the IF bandwidth. The sensitivity of the system, however, must be adequate to detect and measure spurs above the specified level. That sensitivity depends on the filter bank resolution. Since the span of the filter bank is a multiple of its resolution, it may be limited to a fraction of the IF bandwidth by the maximum acceptable

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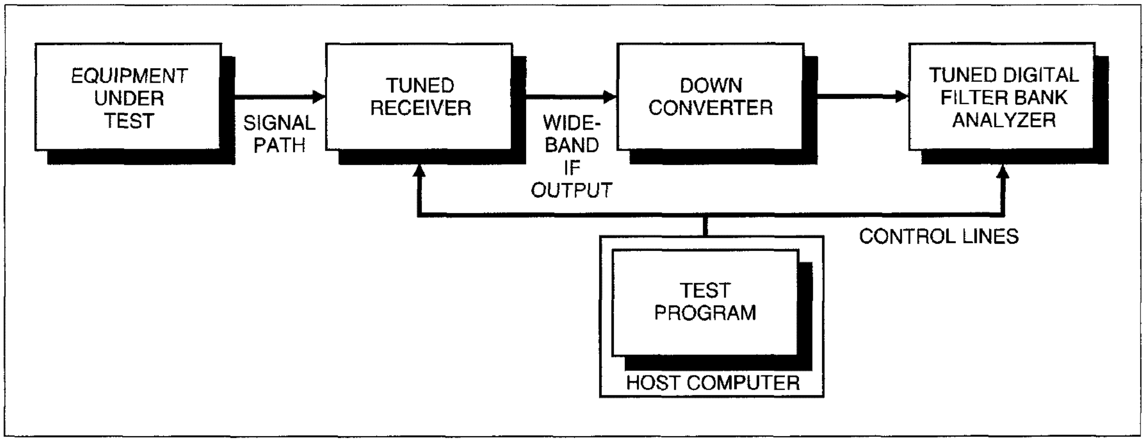

Figure 1. High-Speed Spur Test and Measurement System.

spur level. In that case, the filter bank can be made to cover the IF bandwidth in steps, similar to the stepping process described above for the receiver. For the test system to accept a variety of spur level specifications, and to cover the IF bandwidth of the receiver, the filter bank must have variable resolution and be tunable.

A tunable digital filter bank with selectable frequency spans has incorporated in it a digital down converter that follows the signal digitizer and precedes the actual filter bank circuits. The digital down converter performs tuned bandpass filtering operations on the data within the overall tuning range of the instrument, which can be as much as several megahertz.

The filter bank is tuned in steps across the IF bandwidth of the receiver to cover it in contiguous, smaller spans. Use of these smaller spans to meet sensitivity requirements along with step tuning to cover the IF bandwidth has relatively minor impact on speed, because the required digital processes of tuning, data acquisition, and frequency analysis all can be done quickly.

By combining the processes of step tuning the receiver and step tuning the filter bank in a nested loop, these two instruments can search a wide region as Figure 2 illustrates. The region is divided into contiguous bands equal to the IF bandwidth of the receiver, and the IF bandwidth is subdivided into contiguous search spans of width equal to the span of the filter bank. To set up the quickest test that meets the spur level requirement, the filter bank span selected is the widest available that has narrow enough resolution to yield the necessary sensitivity.

The nested tuning loop has two levels, in which the first tunes the receiver and the second tunes the filter bank. Pseudo code for such a loop is presented in Figure 3.

The center frequency of the receiver is initially tuned to the lowest frequency of the search region plus one-half the IF bandwidth. Thereafter, the loop tunes the receiver in increments equal to the full IF bandwidth, and is exited after the highest frequency of the region has been reached. Then, the test program stores the file on disk and the test operator can then display the results.

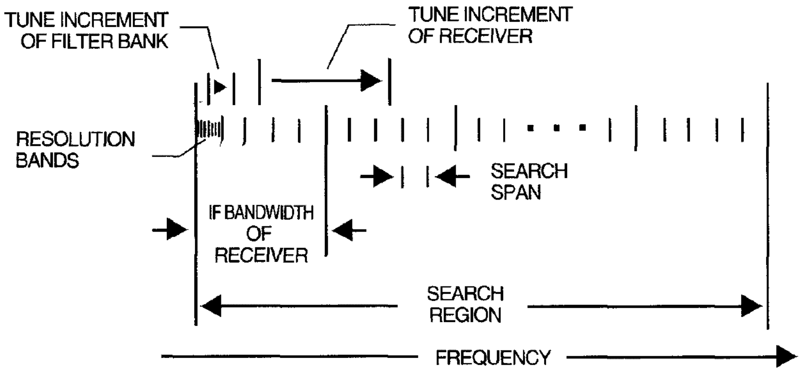

Figure 2. Subdivision of Frequency Search Region.

```
initialize center frequency of receiver
do */ tuning loop, first level /*
{
    initialize center frequency of filter bank
    do */ tuning loop, second level /*
    {
        acquire spectrum of search span
        initialize pointer to lowest frequency
        do */ spur test loop/*
        {
            if(spur found)
            {
                save amplitude and frequency
            }
            increment pointer to next resolution band
        } until pointer has reached end of search span
        incrementally tune the filter bank
    } until filter bank has reached end of IF band
    incrementally tune the receiver
} until receiver has reached end of search region
save the spur data in disk file
```

Figure 3. Pseudo Code for Tuning and Spur Measurement

After the receiver has been tuned each time, the second level of the tuning loop step tunes the filter bank across the IF bandwidth. At initiation of that level, the center frequency of the filter bank is set to the lowest frequency of the IF band plus one-half its span, in order to align it with the first search span. The loop then tunes the filter bank in increments equal to the full span to align it with each succeeding search span. The second level of the loop is exited after the highest frequency of the IF band has been reached.

The third level "do" loop shown in Figure 3 is executed for each search span. In that loop, the filter bank acquires data, performs frequency analysis, and tests the signal amplitudes in each of its resolution bands against the maximum acceptable spur level. For every spur found, the amplitude and frequency are saved in a data file.

The time required to test the region depends heavily upon the number of times, N_{rec}, that the receiver is tuned plus the number of times, N_{fb}, that the filter bank is tuned. These numbers are calculated as follows:

$$N_{rec} = B_{sr} / B_{if}, \text{ and} \qquad (1)$$

$$N_{fb} = B_{sr} / B_{ss} \qquad (2)$$

where B_{sr} is the bandwidth of the search region,
B_{if} is the IF bandwidth of the receiver,
B_{ss} is the bandwidth of the search span, and

where if either N_{rec} or N_{fb} is a non-integer, its fractional part is to be rounded up to unity.

The time associated with each tuning step is the total system time to send and execute all associated commands and process the responses. For the receiver, it is the time, T_{rec}, required for the host computer to issue the tuning command; the receiver to accept the command, to tune and settle at the new frequency, and to respond by indicating that it is ready for new data. For the filter bank, it is the time, N_{fb}, required to send the tuning command; for the filter bank to tune, acquire new data, perform the frequency analysis, and to provide the data to the host computer for testing. The time required for the host computer to test the data for spurs is included in the time T_{fb} also. The total time, T_t, associated with tuning, therefore, is:

$$T_t = N_{rec} * T_{rec} + N_{fb} * T_{fb} \qquad (3)$$

As stated above, the sensitivity of the system must be adequate to detect and measure spurs above the specified level. Adequate sensitivity for reliable detection and measurement of spurs requires that the system noise floor be a minimum of 3 dB below the specified maximum acceptable spur level. For accurate measurement of amplitude, a margin of 10 dB is advisable. After the test operator enters the specified spur level and a margin value, the test program calculates and sets the appropriate filter bank span.

The system noise floor depends on the resolution of the filter bank. To gain system sensitivity, the resolution is made narrower. In a tuned filter bank, the width of the resolution bands is proportional to its span; therefore, to have the necessary sensitivity, a sufficiently narrow span is selected. Two other factors affect sensitivity. One is the noise floor of the receiver IF output (expressed in dBm/Hz); and the other is the noise equivalent bandwidth of the filter bank. The noise floor is a system parameter and not subject to change by the test program. The noise equivalent bandwidth of the filter bank, on the other hand, is proportional to the resolution; and therefore, to span, which the test program can change.

A derivation of the expression below is used to determine the required noise equivalent bandwidth, B_n of the filter bank, and from that the required span. (This expression scales the noise floor of the receiver by the noise equivalent bandwidth of the filter bank to calculate the system noise):

$$n_s = n_r + 10 * \log(B_n) \qquad (4)$$

where n_s is the system noise floor in (dBm),
n_r is the noise floor of the receiver in (dBm/Hz),
B_n is the noise equivalent bandwidth of the filter bank in Hz.

To support accurate amplitude measurement, the filter bank should have excellent filter characteristics. The filter should be flat across the passband to enable accurate amplitude measurement; it should have steep transition bands to exhibit narrow resolution for sensitivity and precise frequency measurement; and it should have high attenuation in the rejection bands to support sensitivity. Modern DSP design and components make such filter characteristics possible.

For the sweep method of spur testing, the analog, swept-spectrum analyzer is often used as a tuned receiver. It has a wide tuning range, narrow resolution filters, and is adequately sensitive and accurate for all but the lowest level spurs.[2] Typically, the analyzer is set to wide span, narrow resolution, and slow sweep rate: wide, to cover the frequencies of interest; narrow, for sensitivity and frequency precision; and slow, for amplitude accuracy. For the most exacting tests, the more sensitive, more accurate, but slower, narrowband tuned receiver is used.

For the high-speed, filter bank method of spur testing an analog swept-spectrum analyzer with a wideband IF output and operated in the non-sweep (Zero Span) mode may be used, or a sensitive, wideband, tuned receiver may be used. In the example system described below, a swept analog spectrum analyzer is used.

SYSTEM EXAMPLE

An example high-speed spur search system consisting of the Tektronix 2756P Spectrum Analyzer, RF160 Down Converter, and 3052 DSP System[3] is pictured in Figure 4. From top to bottom are: 1) the display monitor; 2) the main chassis of the 3052 with the operator keyboard, storage peripherals, and connectors visible; 3) the RF160 Down Converter; 4) the 2756P Spectrum Analyzer. The 3052 has the tunable filter bank. It also has a VMEbus monoboard

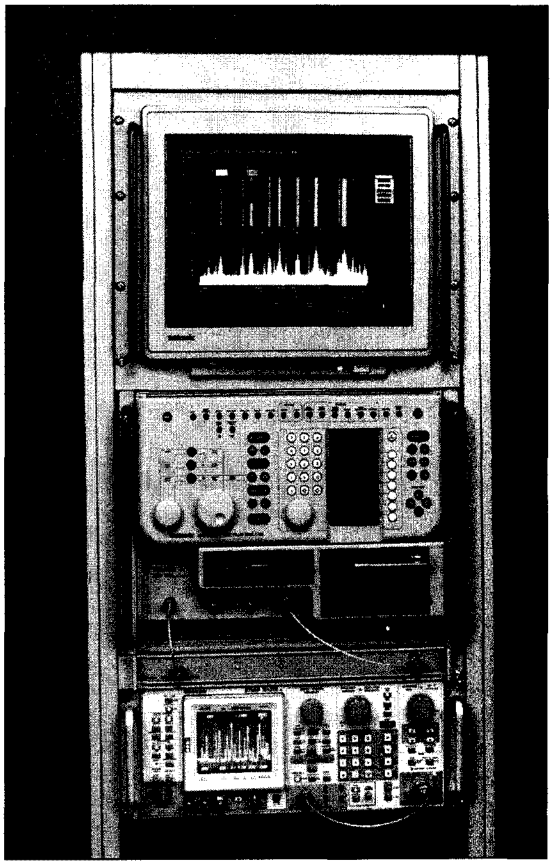

Figure 4. High-Speed Spur Search System consisting of a 3052 DSP System, 2756P Spectrum Analyzer, and RF160 Down Converter.

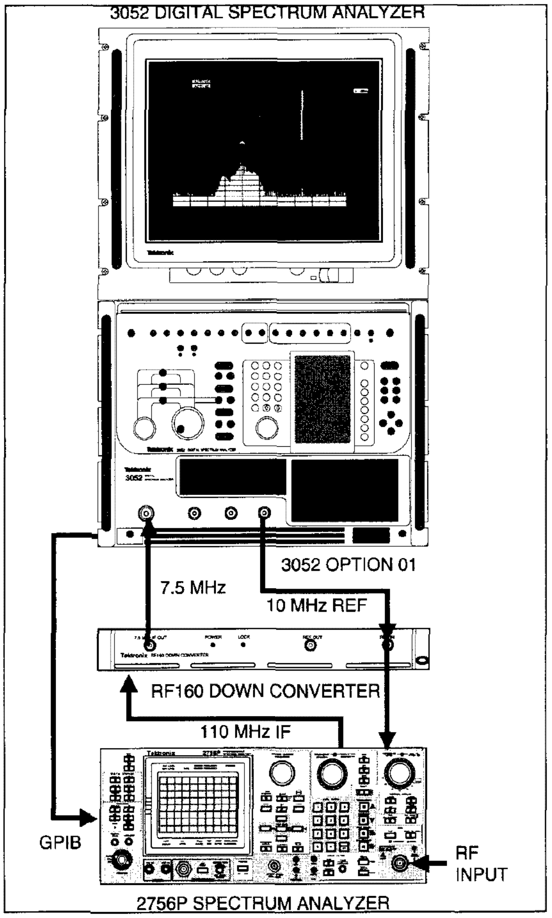

Figure 5. System Connections.

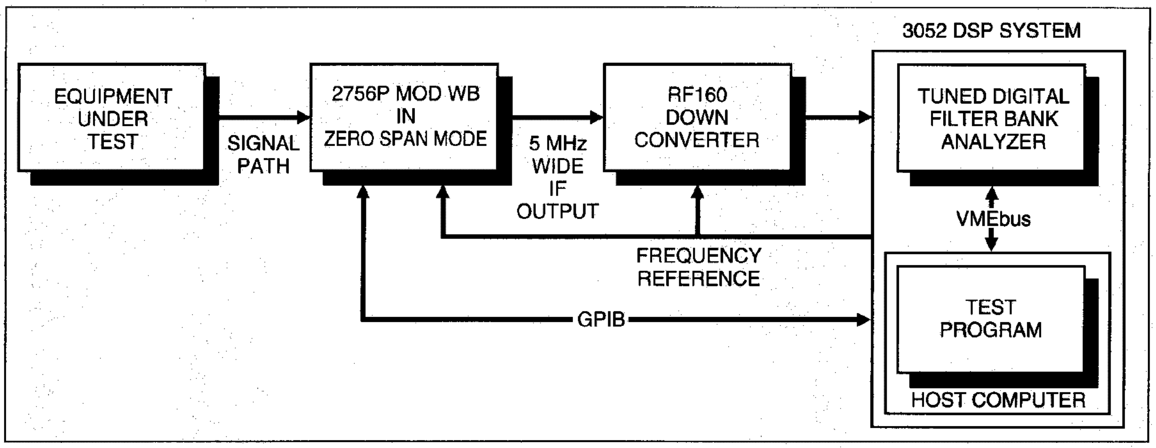

Figure 6. System Block Diagram.

microcomputer, which is the system host computer; and a VMEbus/GPIB interface board. The 2756P has a tune range of 10 kHz to 21 GHz for coaxial input. The test program is compiled C.

Figure 5 shows the routing of the signal path, GPIB, and the 10 MHz frequency reference signal. The reference is generated in the 3052 and used to phase-lock all local oscillators.

Figure 6, an adaptation of Figure 1, shows the block diagram of the system. The Mod WB of the 2756P is a custom modification that provides a 5 MHz wide IF output. The 3052 architecture is based upon the VMEbus, and the host computer in it controls the tuned filter bank over that bus. The 2756P is controlled over the GPIB.

Figure 7, an adaptation of Figure 2, includes some settings used to produce the spur test result shown in Figure 8. As Figure 7 shows, the search region is 198 MHz wide and is divided into widths of 5 MHz, the same width as the IF output of the 2756P. These 5 MHz bands are subdivided into search spans of 1 MHz, which is equal to the span setting of the 3052; i.e., of the filter bank in the 3052. The 3052 has 800 resolution bands across its span, each of 1.25 kHz width (and equivalent noise bandwidth of 1.93 kHz) for the 1 MHz span.

The 2756P is step tuned across the search region in increments of 5 MHz. While it dwells at each tune position, the 3052 is step tuned across the 5 MHz IF band in 1 MHz increments. To cover the search region, therefore, the 2756P is tuned 40 times (see Equation 1), and the 3052 is tuned 198 times (see Equation 2).

Figure 8 shows a display of the test results. The region tested starts at 102 MHz and stops at 300 MHz, and the test was made with the settings shown in Figure 7. Forty spurs were found, and the test was completed in less than 120 s. That time includes storing the test data on disk. The maximum acceptable spur level specified for the region was –105 dBm. One can see that the noise floor of the system is more than 10 dB below the specified level; and therefore, that sensitivity is sufficient for accurate spur amplitude measurement.

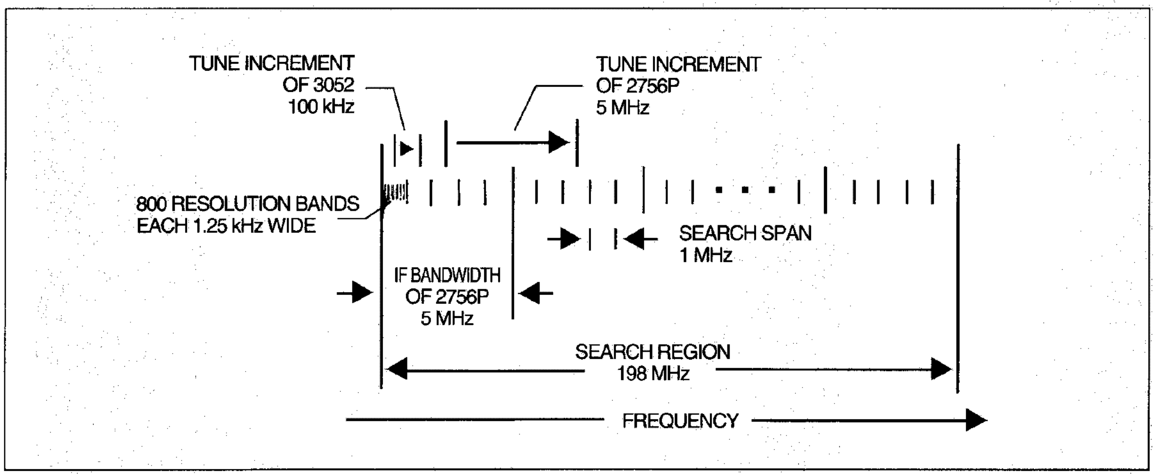

Figure 7. Example Search Region and its subdivision.

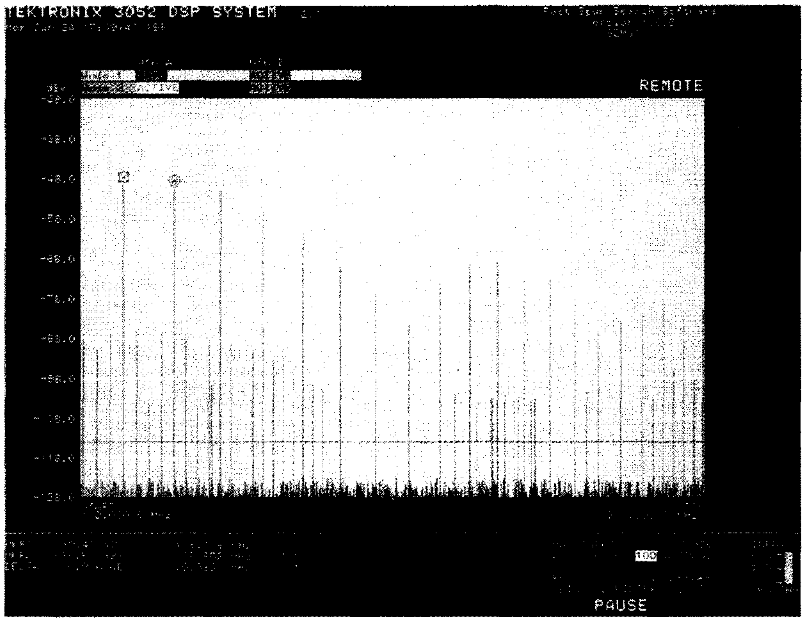

Figure 8. Display of Spurs Found.

The frequency axis (horizontal) in Figure 8 covers offset from the start frequency and is logarithmic. Two markers on the display can be moved higher and lower in frequency to read out the amplitude and frequency of each spur. The marker readouts are at the lower right of the display in rows labeled MKR1 and MKR2 for Markers 1 and 2; and DELTA, the differences between the marker readouts. Marker 2 is the square marker that is positioned on top of the first tall spur near the right-hand edge of the display. Marker 1 is the circular marker on the second tall spur. The MKR1 readout values are –39.42 dBm and 119.916 MHz; and for MKR2, they are -38.52 dBm and 109.852 MHz. The DELTA readout (MKR2 minus MKR1), shows that the second tall spur is 0.906 dB down from the first, and 10.063 kHz higher. A tabular display of spur data is also available to the operator, but is not shown.

Toward the right-hand side of the readout area of the display is the indication "100 AVERAGE," with "100" highlighted. This indicates that 100 samples of spectral data were averaged for use in the spur amplitude measurements. Averaging improves sensitivity and adds little time to the test. This averaging time is included in the 120 s test time stated above. The spectral data averaging process and another process that screens each search span for the presence of spurs are described below. The screening process greatly speeds up the test, because, if no spurs are found to be in a given search span, further steps to locate and measure spurs are omitted, and the 3052 immediately tunes to the next search span.

DSP TOOLS FOR SPUR TESTING

As alluded to above, digital signal processing tools apply powerfully to speed up wideband spur search testing. Numerous DSP tools are embodied in the 3052 DSP System, and key ones are emphasized below.

The filter bank covers wide spans with high resolution, and has fast tuning and analysis capability with which to analyze the 5 MHz IF output of the 2756P. The tuning is done digitally in the digital down converter that precedes the filter bank. Digital tuning is inherently fast in relation to analog tuning because the digital, local oscillators in the down converter change frequency virtually instantaneously; and for wide spans, the interruption to data processing caused by each tuning step is short.

The frequency-response shape of the resolution filters is important in realizing the sensitivity, amplitude accuracy, and frequency precision needed to detect and measure low-level spurs. Figure 9 represents the filter bank, and Figure 10 shows the filter shape. The filter passband is flat; the transition bands, steep; and the rejection of the stop bands, high.

Each spectrum that is output from the filter bank is screened for the presence of spurs by a process called "Spectral Event Detection." A spectrum is comprised of the array of signal

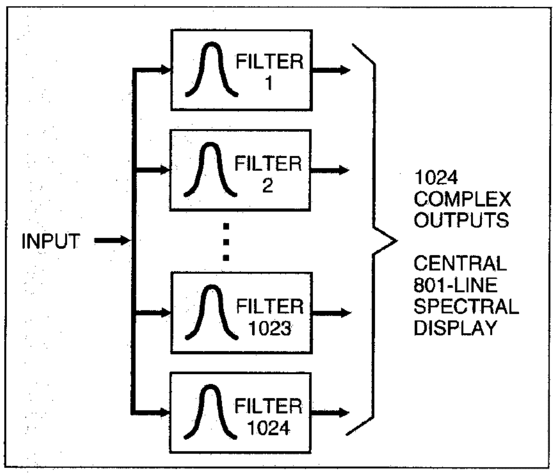

Figure 9. Parallel Filter Bank.

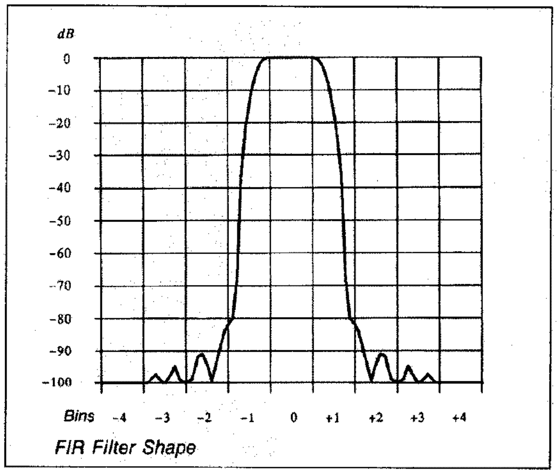

Figure 10. Standard Filter.

data words that is simultaneously output from the filters in the bank. The power values of these outputs in dBm are each compared to a limit, which is set by the test program to be equal to the specified maximum acceptable spur level. When the test program starts, it down loads this limit to a RAM that is positioned near the output of the filter bank; and thereafter, every power value output from each filter is compared to that limit. In the event that no spurs in the current spectrum exceed that limit, the test program breaks to the next iteration of the filter bank tuning loop. In the event that one, or more, spurs is present, the test program is then presented a spectrum that is an average of many of the spectrums containing the spur(s).

During the averaging process, the 3052 remains tuned to the current search span, while the filter bank outputs spectrums at a high rate — 5000 spectrums per second for a 1 MHz span. Each filter in the bank outputs 5000 samples of signal power per second, which are time-averaged as they occur. In the example test, a block of 100 samples were averaged, which required 20 ms. The samples that are averages are of linear power (watts). The resultant average spectrum, is then converted from linear to log power (dBm), and that spectrum is searched for the spurs it contains.

A programmable signal finding marker is used by the test program to find and measure each spur. The test program sets an amplitude threshold above which the marker searches, and then moves from one above-limit spur to the next. The threshold, of course, is set to the specified spur level. Upon finding a spur, the frequency and amplitude of the signal at the marker location are queried by the test program.

BASIC DESIGN OF THE TEST PROGRAM

The test program is a user program in compiled C. Through an extensive library of commands, it controls the tunable filter bank and its associated DSP facilities, as well as the GPIB and the display.

The test program facilitates operator entry of test specifications from the keyboard. That information is stored in a setup file that can be recalled for execution or revision. At execution, the test program reads the setup file selected by the operator, and then executes the test according to the contents. The pseudo code presented in Figure 11 is an extension of that in Figure 3 to include use of the DSP facilities: Spectral Event Detection, spectral averaging, and the signal finding marker; and information the program would get from the setup file for the test resulting in Figure 8.

Associated with each command to tune the 2756P, but not represented in the pseudo code, are checks to determine if the 2756P has been tuned 500 MHz since the previous calibration query. If so, the test program accesses a calibration file created during system installation, and reads data for use in correcting amplitudes received from the 2756P IF output. The time required for these checks and reads is generally insignificant to the total.

PERFORMANCE IMPROVEMENTS AND TRADE-OFFS

Speed: Faster tuning wideband receivers in the high-speed, wideband spur test system, would result in an even faster system.

The main consumption of test time in the example involves tuning (see Equation 3). For purposes of estimating this time, T_t, 800 ms is a reasonable estimate for T_{rec}, the time associated with each tune-step of the 2756P; and 10 ms for T_{fb}, for each tune of the 3052. The estimated total time associated with tuning is therefore:

$$\begin{aligned} T_t &= 40 * 800\text{ ms} + 198 * 10\text{ ms} \\ &= 32\text{ s} + 2\text{ s} \\ &= 34\text{ s} \end{aligned} \tag{4}$$

One way to reduce the time would be to change to a similar receiver that has a 10 MHz IF bandwidth, instead of 5 MHz. That change would cut the number of receiver tune steps from 40 to 20, with the result that T_t would be cut to 18 s.

Still faster would be a fast tuning receiver. There are spectrum analyzers that have tuning times on the order of 50 ms.

```
tune the 2756P Spectrum Analyzer start at 102 MHz
do */ 2756P tuning loop /*
{
    tune the 3052 DSP System start at the bottom of the IF
    do */ 3052 tuning loop /*
    {
        arm Spectral Event Detection
        acquire spectrum of search span
        if(spectral event detected)
            move marker to start of averaged spectrum
            do */ spur measurement loop/*
            {
                move marker to next right signal
                save spur amplitude and frequency
                increment spur count
            } until the marker finds no further signals
        tune the 3052 higher by 1 MHz
    } until filter bank has reached top of the 5 MHz IF band
tune the 2756P higher by 5 MHz
} until 2756P has reached 200 MHz
save the spur data in disk file
```

Figure 11. Pseudo Code for Example System.

Putting that time into Equation 4, instead of 800 ms cuts T_t to 4 s. Also, there are high speed synthesizers that have tune times on the order of 1 ms, and substituting that time for 800 ms in Equation 4, cuts T_t to 2 s and leaves the time associated with tuning the 3052 predominant.

Sensitivity: Some improvement may be achieved through use of the narrowest spans available on the 3052, but the main reason for use of the 3052 is speed, and not sensitivity improvement. Normally, one would choose a filter-bank resolution to be the same as for the narrowband sweep method of spur testing. That choice maintains comparable sensitivity and increases speed substantially. Overly narrowing filter bank resolution to gain sensitivity quickly consumes the speed advantage. Moderately lower resolution, however, may result in usefully more sensitivity with yet a good speed improvement. But the usual way to increase sensitivity remains the best way: increase it at the front end of the system, at the receiver.

At 7.1 GHz the Tektronix 2782 Spectrum Analyzer is a 5 dB more sensitive receiver than the 2756P; and the margin widens at higher frequencies. Where appropriate to the test situation, low-noise amplification ahead of the spectrum analyzer is recommended for increased sensitivity. For some special test situations, a high sensitivity receiver would be good, and probably less expensive than a general purpose spectrum analyzer.

Speed versus Spur Level: Figure 12 shows graphs of test times versus spur level for a search region 200 MHz wide for the example filter-bank system described above. In the figure, this example system is identified as the 2756P/3052 System. Also plotted for comparison are the times for the 2756P used alone. These plots were produced by use of Equations 1, 2, and 3. For the 200 MHz search region, the 2756P tests for spurs above –70 dBm in a shorter time than does the 2756P/3052 System. Between –70 and –80 dBm, the two approaches are roughly comparable in speed. However, between –80 and –90 dBm, the 2756P/3052 System takes considerably less time to complete the test. Between, –90 and –100 dBm, the times required by the 2756P become impracticably long, while the 2756P/3052 maintains a short test time. Below –100 dBm, the test times required by the 2756P/3052 System begin to increase, but remains practical for spur levels as low as –120 dBm.

The 2756P alone and the 2756P/3052 System each has a minimum test-time limit; and no reduction of this time is possible for high level spurs. This time limitation is set by the maximum resolution bandwidth of each. The 2756P is faster because its maximum resolution bandwidth is 3 MHz, whereas the maximum in the 2756P/3052 System is narrower, 6.2 kHz. For lower spur levels, resolution narrower than the maximum is required; and at that point, test times for each must increase as a result.

For very low spurs, these test times increase dramatically, but they increase at different levels for the 2756P than for the 2756P/3052 System. The times increase because, for very low spur levels, the number of resolution bands across a given search span must be large; and the width of each resolution band, very narrow. This has a square-law affect on search time. When the spur level specification is reduced by a decade, the test time tends to increase by two decades. The increase is by two decades, because narrowing the resolution bandwidth one decade, has the compound result that the number of bands required to cover the search span is increased by one decade, and the response time for each band is also increased by one decade. It can be seen in

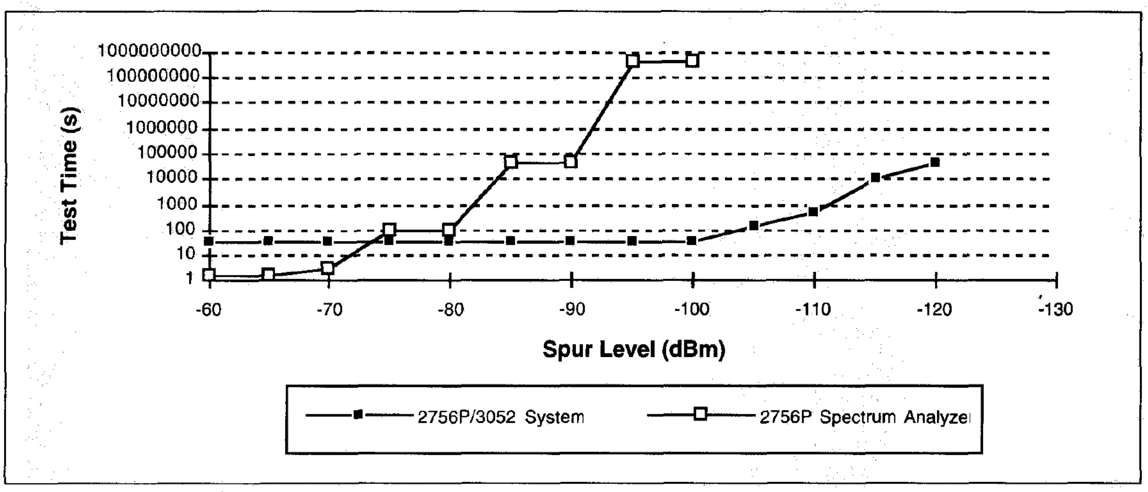

Figure 12. Test Time versus Spur Level for a 200 MHz Search Region.

Figure 12 that for the 2756P/3052 System, the dramatic increase in test time occurs at about a 30 dB lower spur level than for the 2756P. This difference in level results from the fact that the 2756P/3052 System can test as fast with a two-decade narrower filter than can the 2756P alone.

SUMMARY AND CONCLUSION

A high-speed, wideband, low-level spur test technique has been presented, its basic characteristics described and compared with those of traditional test methods; i.e., sweeping or stepping a narrowband receiver. The system consists of a wideband tunable receiver whose IF output is analyzed by a high speed, wideband, tunable filter bank analyzer. The example system presented employs a wideband Tektronix 2756P Spectrum Analyzer in Zero Span mode as a receiver and a Tektronix 3052 DSP System for IF analysis. Other DSP tools such as fast data averaging, Spectral Event Detection, and programmable signal finding markers are used to further shorten test times. The speed advantage is realized in wideband tests to spur levels of roughly –80 dBm and below. The main benefit is in extraordinarily shorter test times, especially in detecting and measuring low-level spurs. Further speed improvements are possible with fast tuning wideband receivers in front of the filter bank.

[1] J. Snell. "Fast, Real-Time, DFT Instrument Based on VMEbus," in IEEE AUTOTESTCON '89 Conference Record, 1989, pp. 49-54.

[2] M. Engelson, Modern Spectrum Analyzer Theory and Applications. Massachusetts: Artech House, 1984, ch. 1, pp. 5-6.

[3] Option 02 and 10 are required in the 3052 for this application.