All-Digital IF Gives New Spectrum Analyzers FFT Speed and Swept Dynamic Range

This month's cover introduces the Agilent E4440A, offering technological innovations that enhance measurement speed and accuracy

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The PSA Performance Spectrum Analyzer Series is introduced this month with the first model, the Agilent E4440A. This series of spectrum analyzers covers frequencies from 3 Hz up to 26.5 GHz with its all-digital IF enabling 160 resolution bandwidth settings. Additional technical improvements include phase noise optimization, sensitive detectors and accurate step attenuators that provide 0.35 dB amplitude accuracy up to 3 GHz and 113 dB usable dynamic range. The Agilent E4440A is priced at $48,000.

The most significant technological advance included in the PSA Series is the all-digital IF which will be discussed in this article. In many ways, the IF is the heart of a spectrum analyzer, providing the least expensive and most accurate location for most signal processing functions. Those functions include resolution bandwidth (RBW) filtering, video bandwidth (VBW) filtering and detector types that govern the translation of continuous spectrum information into display points. To better understand the contributions of an all-digital IF, we will first review the traditional analog IF.

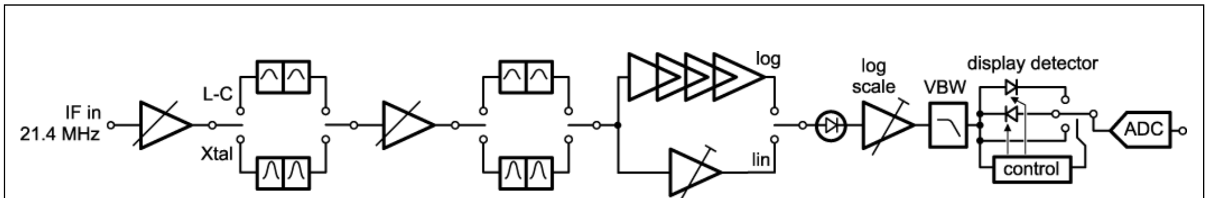
A review of analog IF technology

Figure 1 shows the block diagram of IFs that date back to the first digital-display spectrum analyzers of the 1970s. We will discuss the problems associated with analog IFs.

The first stage provides much-needed gain variability. But it also affects the noise/distortion tradeoff in the spectrum analyzer. With the gain set high, the effect of the noise of succeeding stages is minimized. However, the third-order intermodulation in the first filter stage is exacerbated by higher gains in the first stage. So, the first gain stage is set to trade off distortions versus noise.

Next in the block diagram are filter poles, which are switchable between L-C resonators and crystal filters. As explained in the previous paragraph, the first filter stage has significant noise and distortion effects. However, after just one pole of filtering, intermodulation distortions become irrelevant because there is only one signal in the passband at a time. When distortion is irrelevant, signal levels can be kept high to minimize noise. But if the signal levels are too high, signals can compress in the IF, leading to amplitude errors. In spectrum analysis, these errors are specified as the log scale fidelity.

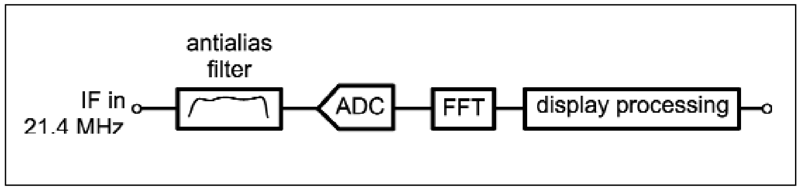
The filter bandwidth range covers many decades, controlled by PIN diodes. The parameters of these diodes have significant setting-dependent uncertainties and temperature instabilities. Therefore, RBW filters have gain uncer-



▲ **Figure 1. An analog IF spectrum analyzer has step gains, L-C and crystal filters, log amps and detectors.**

tainties, as well as width and centering errors.

The gain stage between the filter poles allows a wide range of input signals to drive the succeeding log stages to their maximum calibrated level. Inaccuracies in the calibration of the gain lead to reference level errors. The specification of the uncertainty of reference level from this source is called "IF Gain Uncertainty."



▲ **Figure 2. An FFT-based IF digitizes the signal and computes the spectrum to be displayed.**

The next stages are the log/lin amps. In the common successive-compression topology of a logarithmic amplifier, the envelope of the IF signal is compressed in an approximation of logarithmic response. The errors in the approximation are the biggest cause of log fidelity errors. The envelope detector creates a baseband (video) signal from the envelope of the logarithmically or linearly amplified signal.

A gain (and offset) stage after the detector is used to change the log scale factor, expressed in dB/division units. But great strides in economical high-resolution analog-to-digital converters (ADCs) at the end of the IF chain allow digital implementation of this function in modern spectrum analyzers.

The video bandwidth filter is useful for smoothing noise and noise-like detected signals. The display-detector hardware allows the digitization of display points according to rules. One such rule, for the peak detector, is to measure the peak response across the time interval corresponding to a display point. Imperfect input/output isolation in the analog hardware can cause display errors in high span-to-RBW settings, such as full spans. Peak detectors also have a "blind time" during reset between display points. They also have droop between peaks and a voltage-dependent blind spot near the held voltage. All these errors create large uncertainties in measuring very narrow pulsed-RF signals.

Other rules for A/D conversion include the rarely-used negative peak and the simple sample rule. Some analyzers show noise-like signals as alternating between positive and negative peaks to help the user tell the difference between noise-like and CW-like signals.

Swept spectrum and FFT analysis

In traditional swept spectrum analysis, a sweeping LO is mixed with the signal to be measured. If the sweep rate is slow enough, the mixing product sweeps through the IF center frequency, sweeping out the shape of the RBW filter. The displayed spectrum becomes the convolution of the input spectrum with that RBW shape.

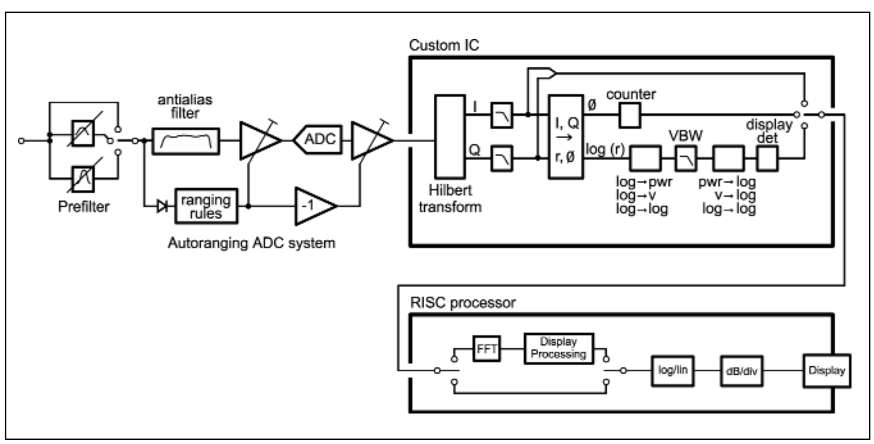
Figure 2 shows the block diagram of an FFT-based IF. In FFT analysis, the entire IF signal is digitized, instead of just converting the envelope of a signal with an ADC. FFTs offer a major advantage over swept processing. In an FFT, analysis in many bandwidths is effectively performed in parallel. In many narrow-RBW cases the FFT will analyze spectra better than two orders of magnitude faster than the serial processing of a swept IF.

Unfortunately, FFT processing requires exceptional ADC performance. An ADC takes a near-instantaneous sample of the IF signal and converts it to one of thousands of coded states. Such processing requires very wide bandwidths. Even with technological improvements, this extended bandwidth requirement will continue to make ADCs noise-prone well into the future. Despite avoiding almost all of the inaccuracies of the swept analog IF, the passband flatness of the antialias filter, even after alignment, causes amplitude uncertainty versus input frequency not seen in analog IFs.

The all-digital IF

FFT spectrum analysis is decades old. The combination of FFT (for narrow RBWs) and swept analysis (wider RBWs) in RF analyzers has existed for over 10 years. The ADC is constantly moving closer to the input port in all kinds of signal processing as the result of improvements in the converters and other digital hardware. The all-digital IF of the Agilent PSA series is the latest reflection of this trend, bringing a wealth of advantages to the user. We will first look at the block diagram of the all-digital IF in the PSA in Figure 3.

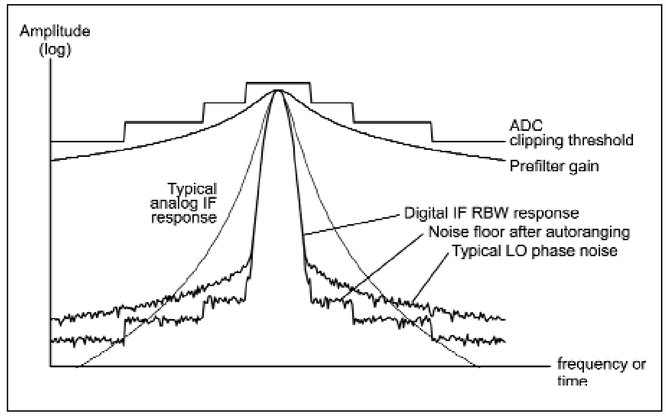
The all-digital IF is called all-digital because all 160 of



▲ **Figure 3. Block diagram of the all-digital IF, with analog, custom ASIC and processor.**

its RBWs are digitally implemented. However, it does have analog circuits, starting with an L-C or crystal-based single pole pair. This pole, like the first one in the analog IF, prevents succeeding stages from contributing third-order distortion, as well as enabling dynamic range extension via autoranging.

The output of the single-pole prefilter is routed to the auto-range detector and the antialias filter. As in the FFT-based IF, the filter is required to prevent aliasing, the folding of out-of-band signals into the ADC sampling process. This filter has many poles, and thus has substantial group delay. Even a very fast rising RF burst, downconverted to the IF, will experience a delay through the alias filter of more than three cycles of the ADC clock (30 MHz).



▲ **Figure 4. Autoranging keeps the ADC noise close to the carrier and lower than LO noise or RBW filter response.**

The delay allows plenty of time for an impending large signal to be recognized before it overloads the ADC. The autorange detector and its rules-based logic will turn down the gain in front of the ADC before a big signal hits it, preventing clipping. If the signal envelope remains small for a long time, the autoranging circuit pumps up the gain, reducing the input-referred noise. The digital gain after the ADC is also changed to compensate for the analog gain in front of it.

The result is a "floating point" ADC with very wide dynamic range when autoranging is enabled (which it is in swept mode). Figure 4 illustrates the sweeping behavior. The single-pole prefilter allows the gain to be turned up high when the analyzer is tuned far from the carrier. As the carrier gets closer, the gain falls and the quantization (ADC) noise rises. The noise level will depend on the signal level frequency separation from the carrier, so it looks like a step-shaped phase noise.

Phase noise is different from this autoranging noise. Phase noise cannot be avoided in a spectrum analyzer. Auto-ranging noise, however, can be re-duced at most frequency offsets from the carrier by reducing the prefilter width, since the prefilter width is usually 2.5 times the RBW, reducing the RBW reduces the autoranging noise. Also, in those rare circumstances where the autoranging noise is high enough to be visible above the phase noise, it is only visible because of the excellent shape factor of the digital RBW filter. The "shape factor" is the ratio of the filter width at its –60-dB response level to its width at –3 dB. A typical analog IF filter has an 11:1 shape factor, with analog uncertainties. The digital filter has a consistent shape factor of 4.1:1. [For more information, see the sidebar "Autoranging ADC and Three Kinds of Dynamic Range" on the next page.]

Custom signal processing IC

Turning back to the block diagram of the digital IF, after the ADC gain has been set with analog gain and corrected with digital gain, a custom IC begins processing the samples. First, it splits the 30 MHz IF samples into I and Q pairs at half the rate (15 Mpairs/s). The I and Q pairs are given a high-frequency boost with a single-stage digital filter that has gain and phase approximately opposite to that of the single-pole analog prefilter.

Next, I and Q signals are low-pass filtered with a linear-phase filter with nearly ideal Gaussian response. Gaussian filters have always been used for swept spectrum analysis, because of their optimum compromise between frequency domain performance (shape factor) and time-domain performance (response to rapid sweeps).

With the signal bandwidth now reduced, the I/Q pairs may be decimated and sent to the processor for FFT processing or demodulation. Although FFTs can be performed to cover a segment of frequency span up to the 10 MHz bandwidth of the antialias filter, even a narrower FFT span such as 1 kHz, with a narrow RBW such as 1 Hz, would require FFTs with 20 million data points. With decimation for narrower spans, excessively long FFTs are not required, which speeds computations.

For swept analysis, the filtered I/Q pairs are detected (converted to magnitude/phase pairs). For traditional swept analysis, the magnitude signal is video-bandwidth (VBW) filtered and samples are taken through the display detector circuit. The log/lin display selection and dB/division scaling occur in the processor, so that a trace may be displayed on any scale without remeasuring.

Additional video processing features

The VBW filter normally smooths the log of the magnitude of the signal, but it has many additional features. It can convert the log-magnitude to a voltage envelope before filtering, and convert it back for consistent behavior before display detection. Filtering the magnitude on a linear voltage scale is desirable for observing pulsed-RF envelope shapes in zero span.

The log-magnitude signal can also be converted to a power (magnitude squared) signal before filtering, then converted back. Filtering the power allows the analyzer to give the same average response to signals with noise-like statistics, such as digital communications signals, as to CW signals with the same RMS voltage.

An increasingly common measurement need is total power in a frequency band. In such a measurement, the display points might represent the average power during the time the LO sweeps through that point. The VBW filter can be reconfigured into an accumulator to perform averaging on either a log, voltage or power scale.

The custom IC is also designed with some possible future instrument capabilities in mind. The VBW filter can also filter phase signals with wrapping, frequency demodulated signals and I/Q pairs. It can do QPD (quasi-peak detection) for EMC applications and gating for time-selective spectrum analysis of TDMA signals and rotating-media storage devices.

Frequency counting

Swept spectrum analyzers usually have a frequency counter. This counter counts the zero crossings in the IF signal and offsets that count by the known frequency offsets from LOs in the rest of the conversion chain. If the count is allowed to run for a second, a resolution of 1 Hz is achievable.

The frequency counter is less necessary in the PSA

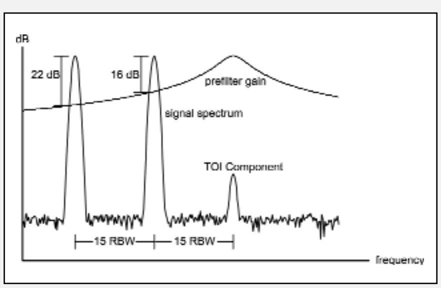
Autoranging and Three Kinds of Dynamic Range

The main text demonstrates the operation of the autoranged ADC in swept measurements. Let's see how it works in terms of three different measures of dynamic range: TOI (two-tone test signal)-to-noise range; amplitude detection range, demonstrated as carrier on/off ratio; and compression-to-noise dynamic range.

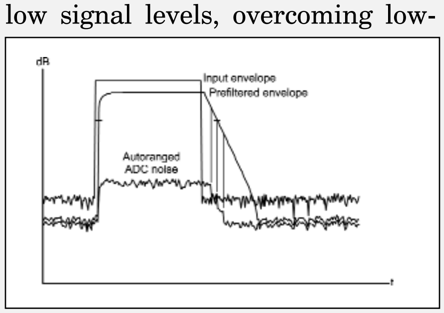
The TOI-to-noise dynamic range of the all-digital IF is enhanced by the prefilter, because the prefilter attenuates the two tones that would intermodulate when the analyzer is tuned to the location of the intermodulation product. This is shown in Figure A. Furthermore, ADC distortions tend to remain roughly constant with drive level (unlike most circuit elements), so increasing the drive level with autoranging when tuned to the TOI product reduces the input-referred distortion.

The amplitude detection range ("log scale fidelity") is enhanced with autoranging because the drive level to the ADC is increased for low signal levels, overcoming low-level nonlinearities in the ADC. Control of amplitude detection range with pulsed-RF signals is illustrated in Figure B.

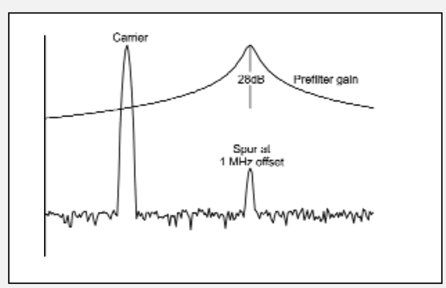
Compression-to-noise dynamic range is enhanced by the combination of prefiltering and autoranging. The prefiltering allows the IF to reduce the level of large carriers when tuned to other signals, as shown in Figure C. When tuned to those other signals, autoranging will then increase the drive level to the ADC, reducing the effective ADC noise. ■



▲ **Figure A. In swept TOI testing, when the analyzer is tuned to the TOI product, the interfering tones are attenuated 16 and 22 dB by the prefilter.**



▲ **Figure B. A pulsed-RF input signal is delayed by the prefilter, allowing the ADC ranging to follow. The effective ADC noise stays below visible levels (not to scale).**



▲ **Figure C. When the IF is tuned to a spurious component, it attenuates the carrier by so much that the ADC clipping-to-noise ratio does not affect the compression-to-noise.**

than in previous generation analyzers, because the frequency readout accuracy in an instrument with a fully digitally synthesized LO and all-digital RBWs is incredibly accurate (0.1 percent of span). Thus, the first reason a frequency counter was included was only for backwards compatibility with previous generation analyzers.

This frequency counter observes not just zero crossings but also the change in phase. Thus, it can resolve frequency to the tens of millihertz level in 0.1 s. It has no observable resolution limitations; its ability to resolve frequency changes is determined by the noisiness of the signal being counted.

More advantages

We have already discussed a number of features in the PSA Series: power/voltage/log video filtering, high-resolution frequency counting, log/lin switching of stored traces, excellent shape factors, an average-across-the-display-point detector mode, 160 RBWs, and of course, FFT or swept processing.

The filtering action of RBW filters causes errors in frequency and amplitude measurements in spectrum analysis that are a function of the sweep rate. For a fixed level of these errors, the all-digital IF's linear phase RBW filters allow faster sweep rates than do analog filters. But, even better, the digital implementation allows well-known compensations to frequency and amplitude readout, permitting sweep rates typically twice as fast as older analyzers, and excellent performance at even four times the sweep speed [3].

The digitally implemented logarithmic amplification is very accurate. Typical errors of the entire analyzer are much smaller than the measurement uncertainty with which the manufacturer proves the log fidelity. The log fidelity can be specified at ±0.07 dB for any level up to –20 dBm at the input mixer of the analyzer. The log fidelity at low levels is not limited by the range of the log amp as it would be in an analog IF; the range is only limited by noise around –155 dBm at the input mixer. Because of single-tone compression in upstream circuits at higher powers, the fidelity specification degrades to ±0.15 dB for signal levels up to –10 dBm at the input mixer. By comparison, analog log amps are usually specified with tolerances in the ±1 dB region.

Other IF-related accuracies are also exemplary. The IF prefilter is analog and must be aligned like an analog filter, so it is subject to alignment errors. But it is much better than most analog filters. With only one stage to manufacture, that stage can be economically made much more stable than the 4- and 5-stage filters of analog IF-based spectrum analyzers. As a result, the gain variations between RBW filters is held to ±0.03 dB specification, a decade better than its predecessor.

The accuracy of the IF bandwidth is determined by settability limitations in the digital part of the filtering and calibration uncertainties in the analog prefilter. Again, the prefilter is highly stable and contributes only 20 percent of the error that would exist with an RBW made of five such stages. As a result, most RBWs are within 2 percent of their stated bandwidth, compared to 10 to 20 percent specifications in analog-IF analyzers. The most important purpose of bandwidth accuracy is minimizing the inaccuracy of channel power and similar measurements. The noise bandwidth of the RBW filters is known to much better specifications than the 2 percent setting tolerance, and noise markers and channel-power measurements are corrected to a tolerance of ±0.5 percent. Therefore, bandwidth uncertainties contribute only ±0.022 dB to the amplitude error of noise density and channel-power measurements.

Of course, with no analog reference-level-dependent gain stages, there is no "IF Gain" error at all. The all-digital IF makes a quantum improvement in accuracy.

Aside from these technological improvements, the PSA Series also features highly flexible connectivity and data transfer using standard PC-based software.

Summary

The Agilent Technologies PSA series has an all-digital IF. This advances the state of spectrum analyzer technology in accuracy, flexibility and speed, without losing the dynamic range of analog IFs. ■

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or circle Reader Service #200

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