100-MHz oscilloscope displays innovations in digital storage

Overcoming some of the drawbacks of earlier digital storage oscilloscopes, unit samples at rates closer to theoretical maximum and coins new specification

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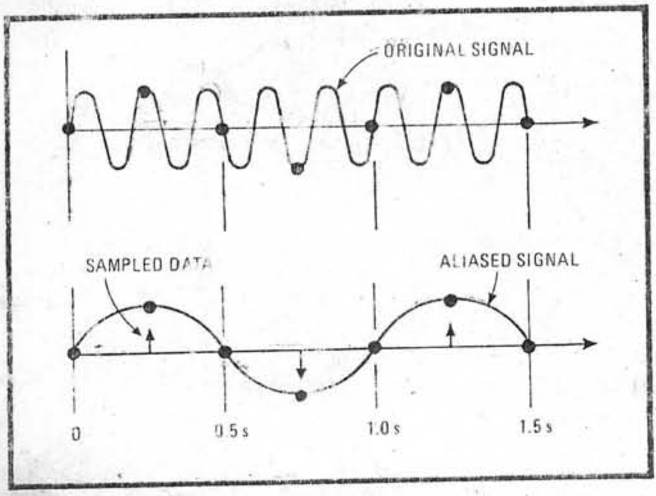
☐ Digital storage oscilloscopes are finding quick acceptance among those who understand their advantages. And recent innovations incorporated in the model 468 portable oscilloscope have overcome some of the problems of earlier digital scopes, such as jitter and envelope error, while at the same time boosting the useful storage bandwidth of the instruments.

An important advantage of the digital storage scope is ease of operation. Waveform storage is usually controlled by a single switch or push button, a system much easier to use than, for example, variable-persistence storage with a cathode-ray tube, where several interactive potentiometers control the storage of a signal.

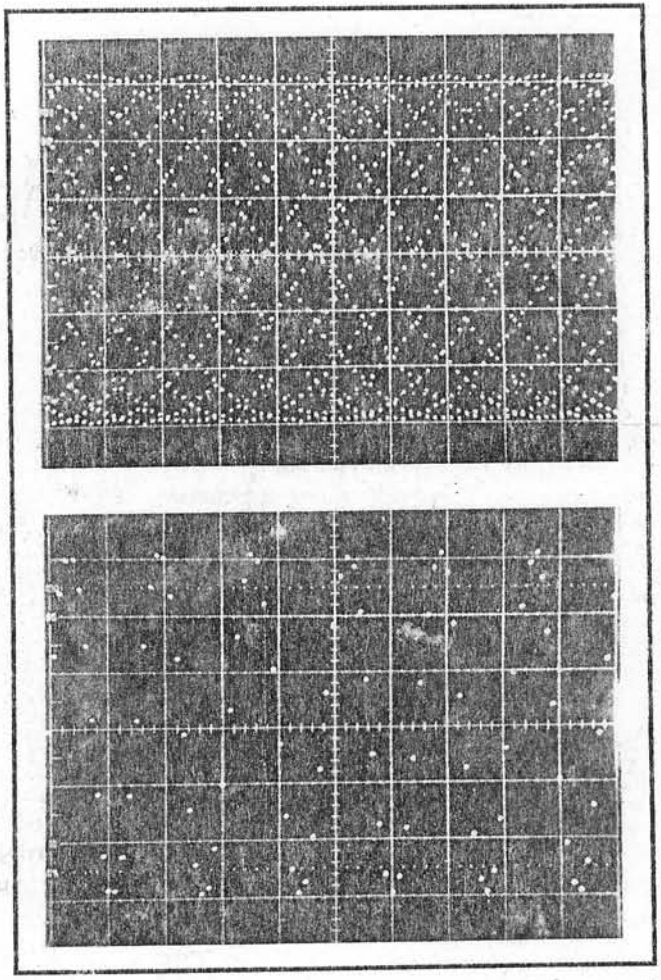
Another advantage is evident after a waveform has been acquired. Digital storage scopes have bright, crisp displays with better contrast than CRT storage scopes. The information in memory can be displayed on the screen using a constant refresh rate. Thus the display quality can be as good as that offered in nonstorage modes. Storage time is essentially unlimited and no fading or blooming will occur, no matter how long the waveform is stored or displayed.

With their ability to store multiple waveforms, digital storage scopes can be used like split-screen bistable storage scopes. What's more, some of them allow captured waveforms to be expanded and repositioned. Thus two waveforms can be overlaid for comparison, with fine enough trace quality to make this feature quite useful.

Additionally, internal or external waveform processing is possible with digital scopes. Features such as signal averaging to remove random noise or cursors for digitally controlled time and voltage measurements are available. If more extensive processing is needed, data can be



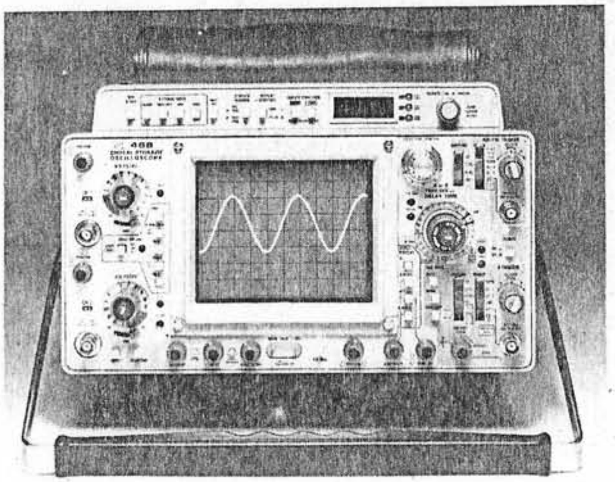
1. Aliasing electronically. The 5-MHz signal shown above was sampled at a rate of once per cycle, far above the Nyquist limit. Connecting the sample points with only the knowledge that the original signal was a sine wave gives the aliased 1-MHz signal below.



2. Aliasing by eye. Even though samples were taken at a rate well below the Nyquist limit, the display above looks like many untriggered sine waves because the eye tends to join points closest in space. The expanded display below shows the signal's true shape.

King Kong in a digital world

Building on the strength of its 100-MHz 465 oscilloscope, often referred to as the "King Kong of oscilloscopes" because of its towering market position, Tektronix has raised the 468 digital storage oscilloscope. At first glance the new scope even looks identical to the 465B44, the 465B oscilloscope introduced at NCC last spring [*Electronics*, May 24, 1979, p. 281] with the optional DM44 digital multimeter "penthouse" added.



In nonstorage mode, the 468 is the functional equivalent of the 465B; it displays dual traces up to 100 MHz at 5 mV per division, has a 2-ns-per-division sweep rate with X10 sweep magnifier, and provides trigger viewing, a variety of triggering modes, and an alternate sweep mode. In adding storage capabilities, Tektronix designers revised operation of the DMM, making it a digital storage pod.

The 468's pod is autoranging, so the range-selection push buttons of the DM44 have been replaced with keys to select store or nonstore operation, storage mode, and reference storage. The resistance, temperature, and period (1/time) functions of the earlier penthouse have also been eliminated to make room for buttons, which select pre- or post-trigger view and sine or pulse interpolators.

With the pod, bright-spot cursors select time- or voltage-measurement points. The cursors are placed on the waveform using the cursor position knob on the pod. The knob also selects the number of sweeps to be averaged if that storage mode is selected. With all these changes, the user can call into play the 468's full storage/display capabilities. **-Richard W. Comerford**

transmitted over interfaces such as GPIB or RS-232.

Digital scopes have also had their limitations. Perhaps the major one is the limit on storage bandwidth that has resulted from the relatively low speed and high cost of analog-to-digital converters and memory. Whereas a-d technology is advancing continually, digital storage scopes have a long way to go before competing with the fastest CRT storage scopes. Whereas the latter instruments can hold nonrepeating signals with frequencies of up to 400 megahertz (2,500-centimeter/microsecond beam writing speeds) with variable-persistence storage and 100 MHz (350 cm/μs) with bistable storage, digital storage had been limited to nonrepeating waveforms of about 1 MHz before the 468.

The storage bandwidth limitations of digital storage scopes have their roots in both sampling theory and display technique. Disregard for these limits results in different forms of aliasing—the signal displayed does not provide a good representation of the actual signal acquired. Aliasing can occur either because of the way in which the signal is sampled or because of the way the human eye perceives it.

Recovering signals

Sampling theory states that to be recovered completely a signal must be sampled more than twice per cycle. Another way to describe the limitation is by the so-called Nyquist frequency, which is equal to one half the digitizing rate. No signal at or above the Nyquist frequency can be recovered. Note that the Nyquist frequency rate is an asymptotic limit—exactly two samples per cycle will not do.

If a signal is sampled two or fewer times per cycle, a phenomenon called aliasing can occur, in which the reconstructed signal turns out to be a lower-frequency version, or alias, of the actual signal. Figure 1 shows a 5-MHz signal digitized at 4 MHz and the resulting display, an aliased image that appears to be a 1-MHz sine wave. Aliasing can only be prevented one way—by sampling a signal more than two times per cycle of the highest frequency it contains.

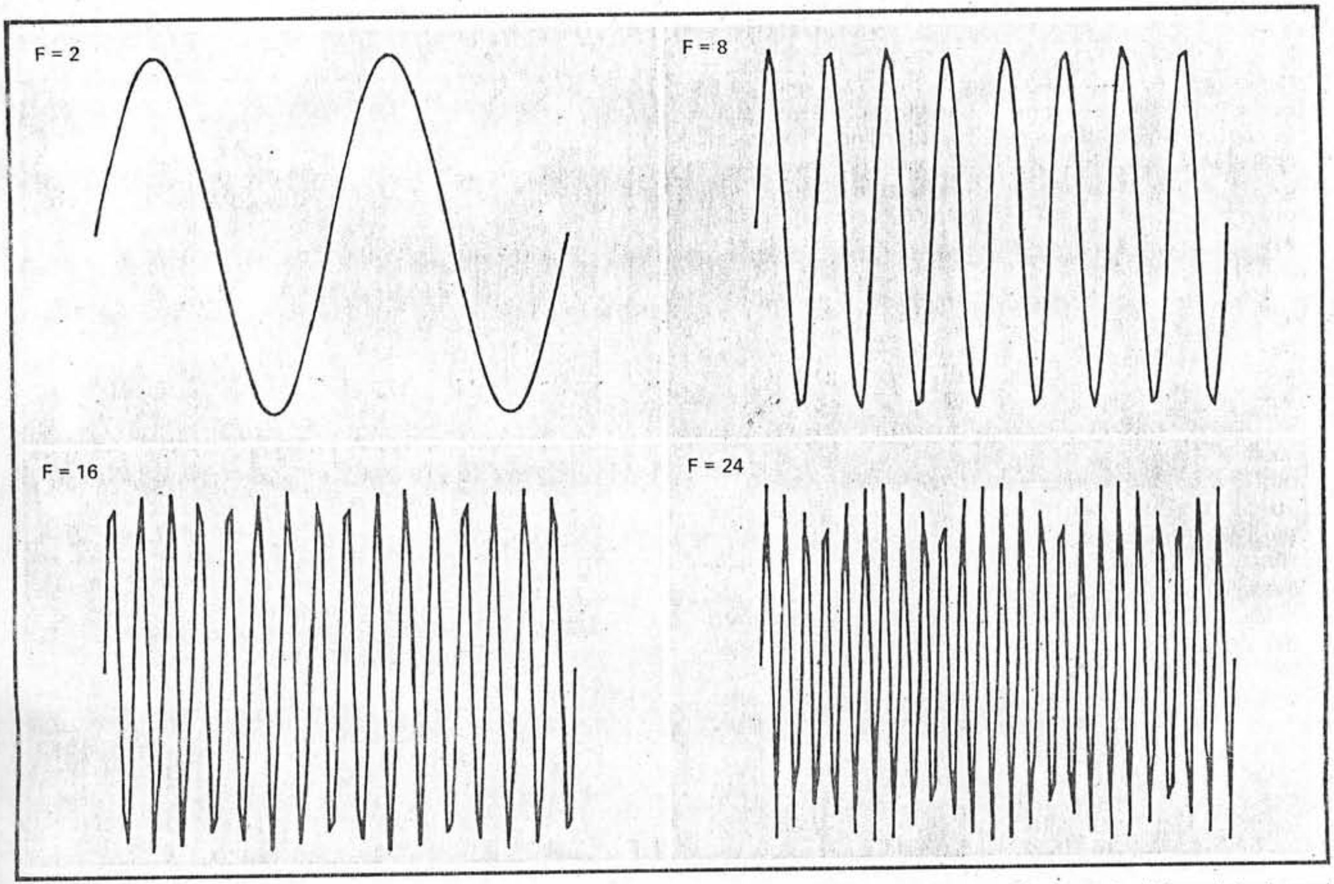
The storage bandwidth limitations of digital storage scopes are also determined by the way a stored signal is displayed. With the dot display used in some digital storage scopes, another type of aliasing—perceptual aliasing—can take place with signals that are well below the Nyquist frequency. Perceptual aliasing—seeing the wrong signal despite theoretically adequate sampling—is a result of the eye's tendency to join the closest points in space to make an image, although these may not be the closest points in time. Figure 2 illustrates this. Joining the sample points eliminates perceptual aliasing, a solution incorporated in several digital storage scopes.

Phantom carrier

Whether the dots are joined or not, another type of perceptual error can occur in which the displayed signal seems to be amplitude-modulated—that is, it appears as a carrier wave inside an envelope. This envelope error is a function of the number of samples per period, or sample density—when the digitizing rate is too low, samples will not always be taken at, or very close to, the peaks of the waveform. Figure 3 shows the envelope error increasing as the number of samples per cycle, or sample density, decreases with a fixed digitizing rate.

A third type of problem that is display-related and greatly annoys users is horizontal jitter.

With digital storage, the trigger point is a reference for stopping signal sampling. Since that point occurs asynchronously with respect to the sampling clock there



3. Pseudomodulation. A perceived envelope, seen most noticeably at bottom right of figure, results even when a vector interpolator is used to correct sample points because those points do not occur frequently enough to capture values at or near the signal's maxima or minima. For each of the above displays (showing 2, 8, 16, and 24 cycles), 64 samples are taken regardless of the number of cycles.

is a ±½ sample interval uncertainty each time a waveform is acquired. When the same waveform is acquired many times, the resultant display can look much the same as a jittery analog display. Jitter becomes very noticeable in expanded waveforms or waveforms with low sample density, where ±½ sample interval can be a significant fraction of the screen or a waveform cycle.

Recognizing these disadvantages that have plagued other digital storage scopes as well as the advantages digital storage offers in a general-purpose oscilloscope, Tektronix developed its 468, which combines 10-MHz useful digital storage with all the nonstorage capabilities of the industry-standard, 100-MHz 465B (see "King Kong in a digital world," opposite page). Key to overcoming the disadvantages was the development of a very fast digitizer in combination with stored-signal–processing capabilities that permit the user to select a display scheme that is appropriate to the particular measurements he is making.

The heart of the 468 acquisition system is a 25-megasample-per-second a-d converter. Inside this very high-speed converter are 255 strobed comparators with decoding logic to convert the outputs of the comparators into an 8-bit data word. The digitizing rate varies from 10 samples per second at a 5-second-per-division sweep speed to a maximum of 25 million samples per second at sweep speeds of 2 microseconds per division and faster. Until now, this maximum digitizing rate has been specified by digital storage scope manufacturers to suggest the storage bandwidth of digital storage oscilloscopes.

Although this specification indicates the Nyquist frequency, it does little to allow a potential user to compare them with CRT storage scopes. This is because the fastest signal that can usefully be digitized and displayed depends not only on the digitizing rate but also on the display technique. This combination is embodied in the concept of useful storage bandwidth (USB) (see "About the new scope specs," p. 164).

Reducing samples

For sine waves, approximately 25 samples per cycle are necessary for a dot display to give an accurate representation of the signal. Were it to provide such a display, the 468's useful storage bandwidth with this type of display would be 1 MHz. Joining the dots with vectors improves this ratio to only 10 samples per cycle, so the USB is therefore 2.5 MHz. But by internally processing a stored signal using its sine interpolator, the 468 requires only 2.5 samples per cycle to display sinusoidal signals accurately and thus achieves a useful storage bandwidth of 10 MHz.

The use of this proprietary sine interpolator prevents envelope errors from occurring during sine-wave measurement; it looks at the relative location of each sampled point before interpolating intermediate points between the last two sample points. Several factors in the

About the new scope spec

Sampling theory states that more than two samples per cycle of a sine wave are needed to characterize the signal. But despite this mathematical acceptability, ergonomically speaking, a signal shown with little more than two dots per cycle is impossible to understand. Increasing the number of samples per cycle begins to show the shape of a sine wave, and at approximately 25 samples per cycle the display is unmistakably that.

When vectors are used to connect the slightly more than two samples per cycle of a sine wave, the display is again meaningless. As the number of samples increases, however, the sine-wave image starts to appear. Now approximately 10 samples per cycle alone are needed to define it.

Since mathematically the signal can be defined with little more than two samples per cycles, it should be possible to represent the signal to a user with fewer than 10 samples per cycle. If the digitized information is passed through an interpolator—in this case, a digital low-pass filter—the original signal can be recreated from fewer samples.

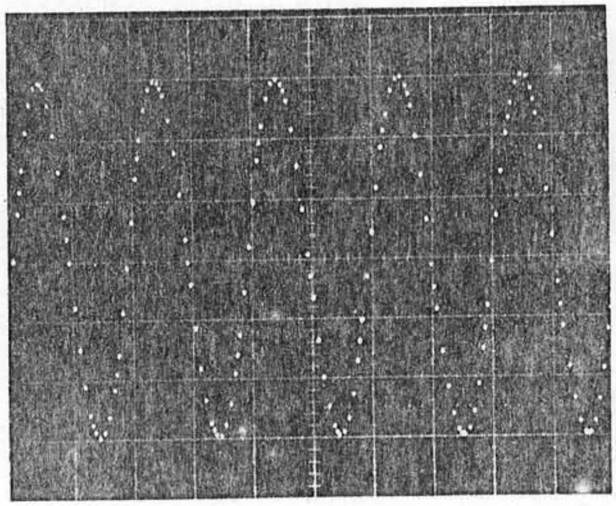
With the sine interpolator in the 468, only 2.5 samples per cycle of a digitized sine wave are needed to display that waveform. This is a sample reduction factor of 10 over a simple dot display and a factor of 4 over a simple vectored display. The accompanying screen photos demonstrate the result of digital interpolation.

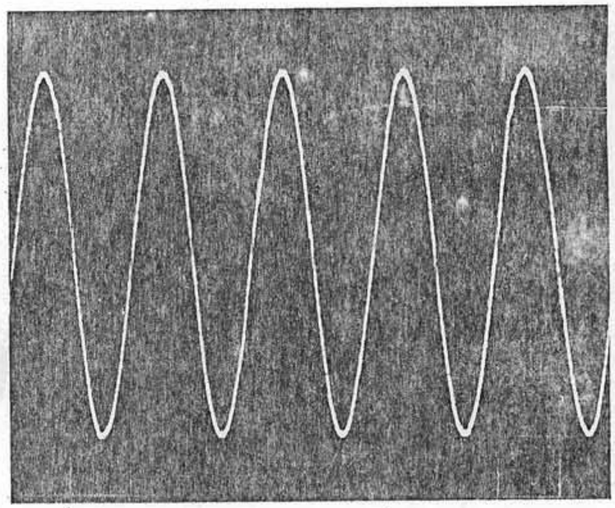
With this background, the useful storage bandwidth of digital storage oscilloscope can now be defined with the following equation:

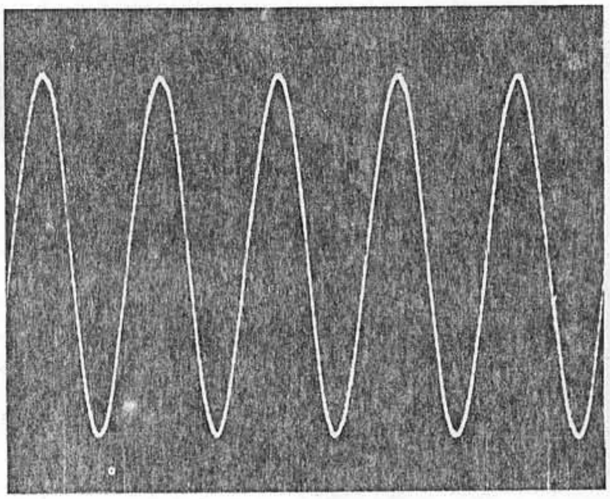
$$\mathrm{USB}_{(\mathrm{MHz})} = \text{digitizing rate}_{(\mathrm{MHz})}/K$$

where K is 25 for dot displays, 10 for vector displays, and 2.5 for a sine interpolator like that used in the 468.

1 MHz


DOT INTERPOLATION


VECTOR INTERPOLATION


SINE INTERPOLATION

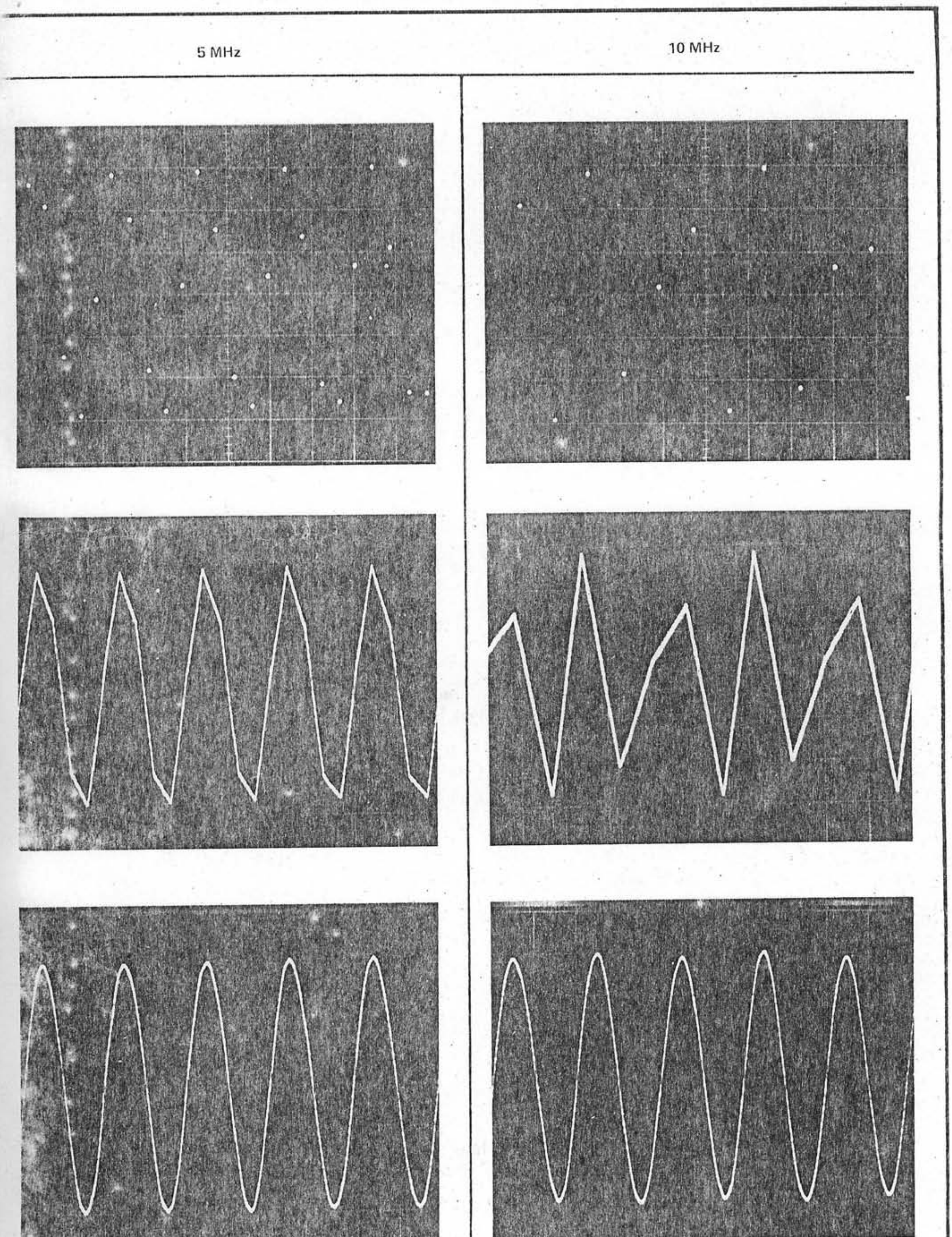
design of the interpolator are balanced against each other, the most important being processing time, amplitude response as the signal approaches cutoff frequency, and impulse response. Basically, the sine interpolator can be considered an approximation of an ideal brick-wall filter, which drops all frequency components above the usable storage bandwidth.

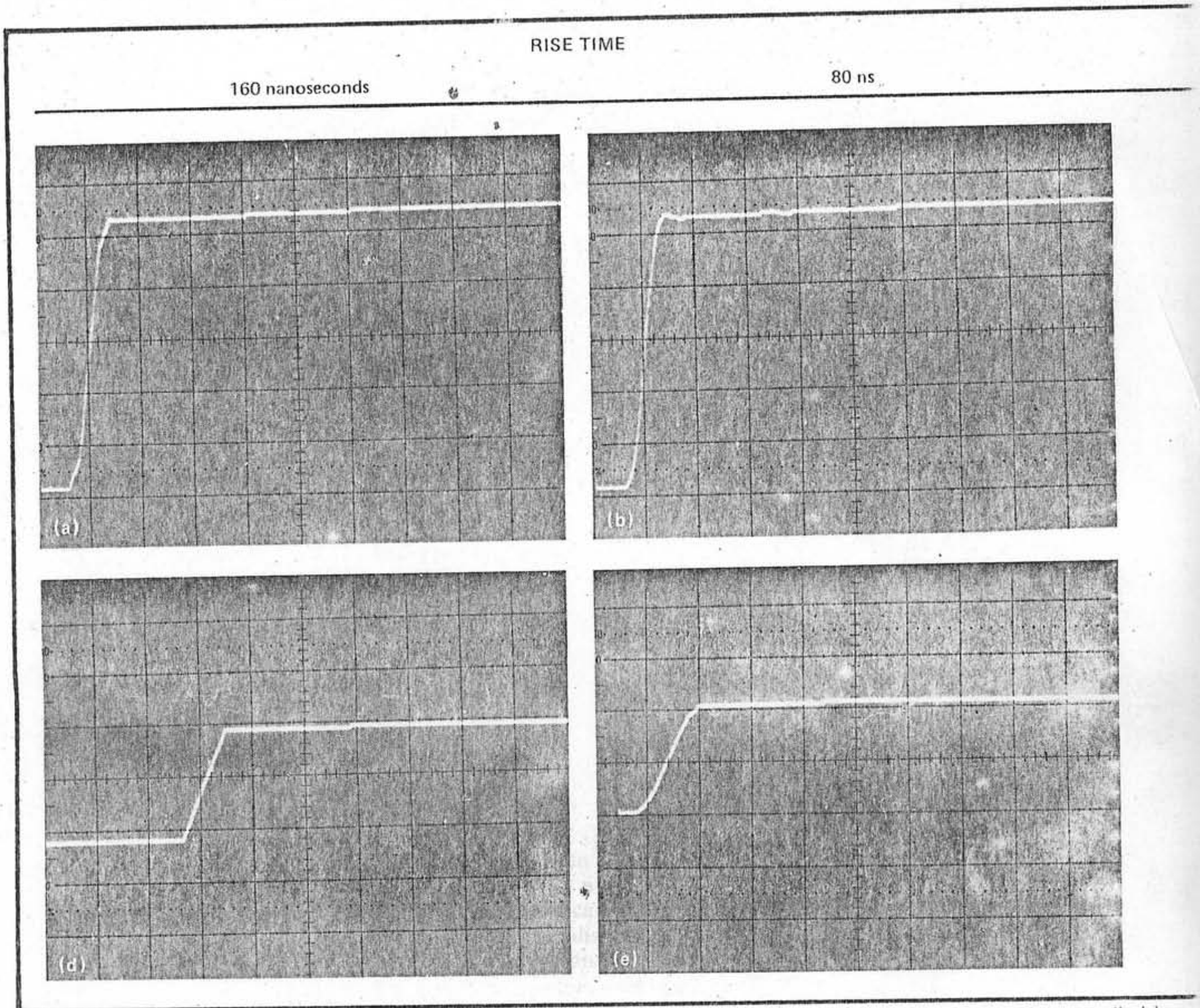
As such, the interpolator works wonders with sinusoidal signal samples, but its manipulation of pulses would be less than ideal. This is why a pulse interpolator like that in other digital scopes is also provided.

Fourier analysis shows that a step consists of many harmonics all summed together. As the step time decreases, a system with a greater bandwidth is required to pass the signal without degrading its rise time. If a step that contains significant energy beyond the cutoff frequency is put into the sine interpolator, it will emerge with preshoot and overshoot. This preshoot and overshoot on a square wave are similar in appearance to the Gibbs phenomenon.

If the signal presented to the 468 sine interpolator has many samples on the rise time, the convolution of the impulse response of the filter and the input waveform will not produce any distortion. When there are less than three samples, the preshoot and overshoot will begin to manifest themselves.

When there is only one sample on the rise, the convo-


5 MHz
10 MHz



4. A matter of interpolation. Signals with rise times of 160, 80, and 6 ns are reconstructed using a sine interpolator (a, b, and c, respectively) and a pulse interpolator (d, e, and f). When fewer than three samples are taken during rise time as in c, the sine interpolator produces overshoot and undershoot in the reconstruction. For this reason, both interpolators are included in the 468.

lution of the input step and the impulse response of the filer yields the integral of the impulse response. This integration can be plainly seen in Fig. 4. As the number of samples on the rise decreases (Figs. 4b and 4c) the amount of preshoot and overshoot increases. Figures 4d, 4e, and 4f show the input waveforms processed by the pulse interpolator of the 468.

To provide the greatest possible measurement accuracy with all possible input signals, it was decided that the 468's users should be able to select the form of interpolation, hence the inclusion of the pulse interpolator.

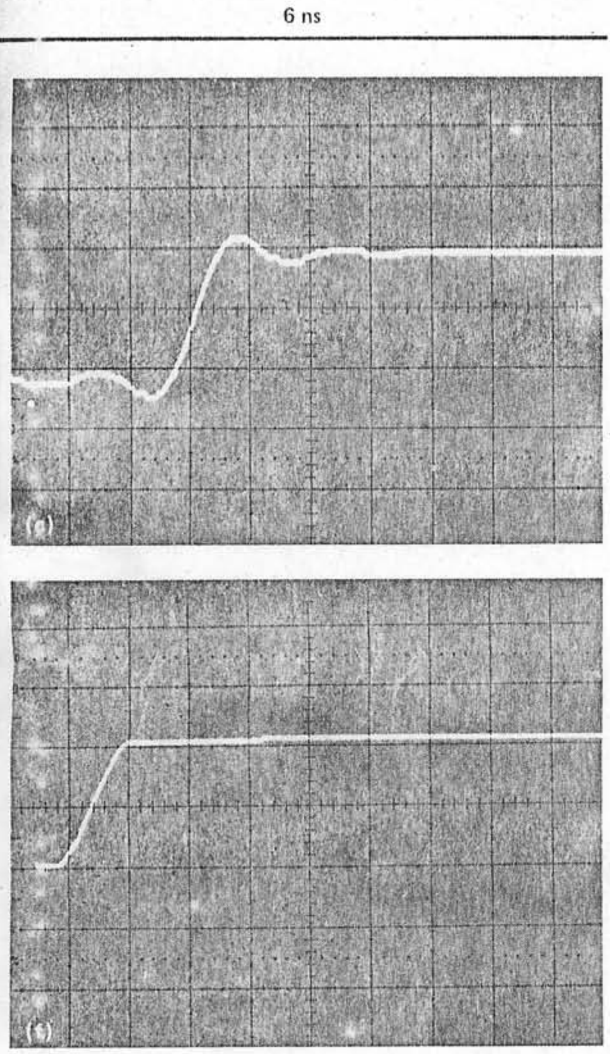
Judicious use of the 468's high sampling rate permits it to address other shortcomings digital storage scopes have had. The time resolution of digital scopes is not as great as that of CRT storage scopes: digital sampling is a discrete process, whereas CRT storage is continuous, making CRT-stored signals infinitely divisible. This has made certain measurements more difficult, if not impossible, with digital storage scopes.

For example, suppose the one-time occurrence of the time difference between two 10-μs pulses about 7 seconds apart were to be measured. Using CRT storage, the time base could be set to one division/s and the scope triggered by the first pulse. The time between pulses could then be read from the screen-stored signal as the length of time from the start of the trace to the displayed second pulse.

Resolving the differences

Making this measurement with most digital storage scopes would be more difficult. First, a sample rate fast enough to guarantee capturing the pulses—say 5 microseconds per sample—would be needed, as well as a record length long enough to capture over 7 s of information. Assuming a 10-s record length and 5 μs per sample, 2 megabytes of memory would be needed in order to acquire the signal.

The 468 allows this type of measurement with its

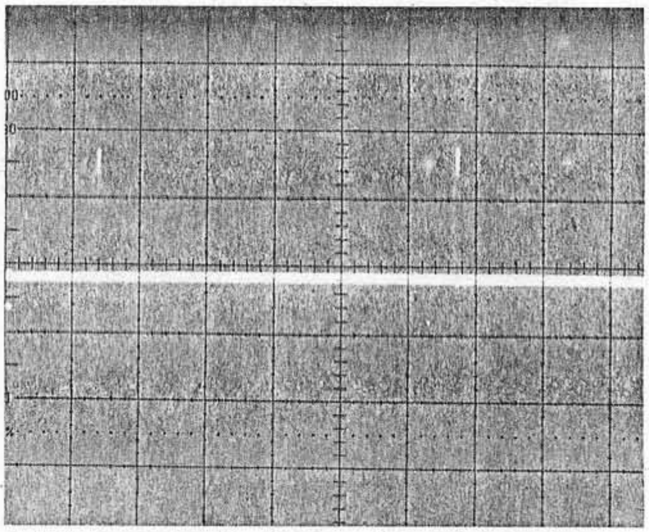


envelope mode, which effectively uses two sampling rates to capture the pulses and the time difference.

The overall sample rate is controlled by the time/division setting. Each horizontal division represents 50 samples; dividing the time/div setting by 50 gives the sample rate. For instance, if the time/div setting is 1 s/div, the sample interval is 1 s/50 samples, or 20 milliseconds/sample.

But the 468's high-speed a-d converter can go much faster. In this situation, it is beneficial to use the converter's full sampling capability to determine during which two 20-ms sample intervals the two 10-μs pulses occurred. The envelope mode runs the converter at a fast rate (in this case 200 nanoseconds/sample) and looks for the minimum and maximum values that occur in the window between sample storages. These values are recorded in memory, and the 468 display (Fig. 5) shows a 10-s record with the two 10-μs pulses easily and clearly displayed.

The envelope mode is also useful for catching glitches or indicating occasional dropped or extra pulses in a pulse train, when multiple sweeps are acquired and displayed. In this mode, the firmware routine that transfers information from the acquisition memory to the display memory also performs another minimum and maximum comparison. The new data is compared with that already in the display system, and only the minimum and maximum values for each sample window are retained. This enables the user to see how an input waveform is changing over a user-selectable number of sweeps—from 1 to 256, as well as continuously.



5. Judicious capture. To display two 10-μs pulses the scope must sample at 25 megasamples/s. Since retaining all samples for the 10-s interval shown would require massive memory, only the maximum and minimum of each 50 samples are stored in envelope mode.

The 468's unique envelope mode is also useful as an aliasing indicator. If aliasing is not occurring, the envelope mode display will look like the normal storage acquisition display. If a signal is being undersampled and aliasing is occurring, the envelope mode will indicate this with a solid band across the oscilloscope's CRT display.

The 468's display also incorporates jitter correction, solving a problem that has plagued all other commercial digital storage scopes. The jitter-correction circuit corrects for the ±½ the sample interval shifting of a waveform caused by the asynchronous relationship between trigger point and sample clock.

First, during acquisition the time between the trigger and the next sample clock is measured. A horizontal offset is then computed and the offset summed with the ramp displaying the digitized waveform. This results in a stable waveform on the CRT display, even when the waveform has been expanded. Though the technology needed to correct jitter is not too difficult to implement, other scope manufacturers seem not to have felt the need to include it.

These innovations address three shortcomings present in previous digital storage oscilloscopes. Display interpolation improves the useful storage bandwidth possible with a particular sample rate. The envelope mode detects aliasing and also catches glitches and other fast pulses. Jitter correction helps make the displays useful, even at low sample density. Such advances let digital oscillography achieve its full potential. ☐