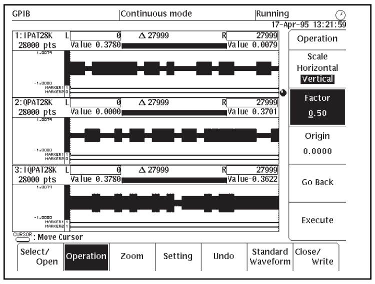
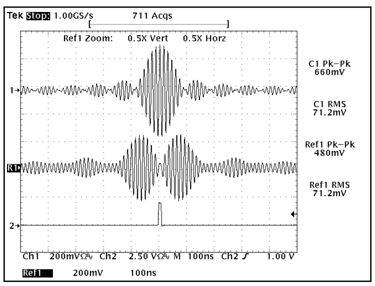
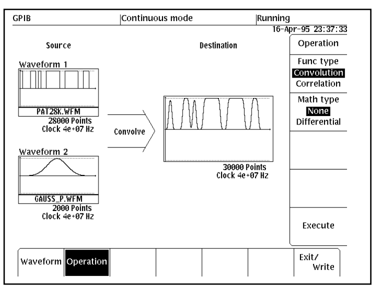
Tektronix

Signals and Measurements for Wireless Communications Testing







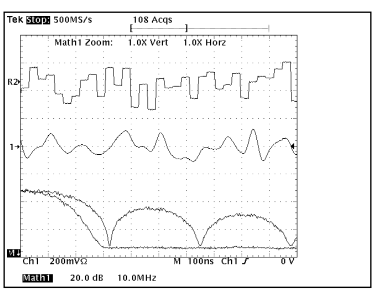


Table of Contents

Note: Each signal and waveform screen in this application note originates from one of three types of instruments: an arbitrary waveform generator, a digital storage oscilloscope, or a spectrum analyzer. Each illustration is annotated with a symbol indicating its origin:

A AWG

O Oscilloscope (DSO)

S Spectrum Analyzer

Signals and Measurements for Wireless Communications Testing

Introduction

One of the most challenging tasks in designing wireless communications products is the development of a rational approach to characterizing and testing components, assemblies, and sub-systems. Baseband modulation and RF signal characteristics are becoming increasingly complex as standards and common sense force more efficient use of the finite electromagnetic spectrum. In addition, manufacturers must often make equipment that is capable of switching between different modes with differing signal characteristics. As before, realistic test signals are needed to simulate nominal and worst case conditions. Yet traditional signal generators with limited modulation capabilities are inadequate and it is not always feasible to have a test department develop customized systems.

Test equipment has historically allowed two approaches. If a standard has reached a threshold of maturity, then you could obtain a generator/analyzer that addresses that standard—from a traditional FM broadcast to a digital PCS system. Or you could concoct a combination of signal, RF, and pattern generators to simulate the desired test signal. The former approach is excellent for production and field service applications but lacks flexibility for development applications. The latter approach often turns into an expensive kluge providing both inconsistent performance and limited flexibility.

More recently, test equipment manufacturers have filled the gap between the two approaches with the arbitrary waveform generator (AWG). The AWG is the signal generator equivalent to the computer spreadsheet; you can create limitless “what-if” waveforms to more thoroughly evaluate or test new concepts, prototype circuits, or production sub-assemblies. Like a spreadsheet, the power of the AWG comes from the ability to define and re-define a signal’s value as a function of time. But a blank spreadsheet is of little use—how do you get the first waveform to appear at the BNC connector? The most straightforward method is the record-playback technique. A live signal is recorded into the memory of a digital oscilloscope, and the record is transferred to the AWG for playback. This method is expedient but has limited flexibility. Creating and editing a customized signal is a more powerful technique and is the focus of this note: once created, re-creating a complex signal at a later date is as simple as retrieving it from memory—rather than re-cabling and re-configuring an assortment of interconnected generators.

Ironically, the flexibility of an AWG can make it difficult to select a model that fits a given application. For example, you will not find a specification that explicitly defines an AWG’s ability to generate a particular modulation type. In general, an AWG’s ability to generate a specific signal must be demonstrated by example.

In this paper, we begin with examples of basic AM-FM analog signals and introduce variations such as multiple carriers and multiple modulation signals (e.g., FM stereo). Then we demonstrate that digital modulation generation is a straightforward extension of basic analog modulation.

Throughout this application tutorial, we have used the Tektronix AWG 2021 Arbitrary Waveform Generator as the signal source, and the Tektronix TDS 744A oscilloscope to capture and analyze signals. The AWG 2021 provides the signal capabilities, modulation features, and bandwidth essential to effective wireless communications testing. The TDS 744A is an ideal complement to the AWG 2021 and is unique in its ability to capture signal minutiae.

Certain test setups described in this book may require external RF generators to provide carrier signals, which are then modulated by the baseband signal from the AWG 2021. There are many appropriate RF signal sources available today, including products from Tektronix, Rohde & Schwarz, and others. For more information about RF sources, contact your local Tektronix representative.

Analog Carriers and Modulation

1 Basic Sine Wave Amplitude Modulation (AM)

The best introduction to the AWG is to parallel the procedure of generating a carrier with a conventional signal generator. With a signal generator, one simply enters the carrier frequency and the output amplitude, such as 1000 kHz at 0 dBm. With an AWG, one creates a sequence of points to represent the waveform:

$A \sin \omega_c t$

where A is the peak amplitude and ω_c is the frequency. Since a 0 dBm sinusoid has a peak amplitude of 0.316 V (0.224 Vrms), the carrier is:

$0.316 \sin (2\pi\ 1000e3\ t)$ Volts.

For a continuous sinusoid this equation applies for all time, but the signal can also be defined as a single cycle sinusoid with a period of 1 µs that repeats every 1 µs. The unique or arbitrary part of the signal is a 1 µs series of points defined by the above equation. If amplitude modulation is enabled on a signal generator, one enters the tone modulation frequency and depth, such as 1000 Hz at 50%.

Similarly, with an AWG, one adds the modulation to the waveform description:

$(1 + k \sin(\omega_m t))\ A \sin \omega_c t$,

where k is the modulation depth between 0 and 1, and ω_m is the sinusoidal modulation frequency. Thus, our example waveform becomes:

**$(1 + 0.5 \sin(2\pi\ 1000\ t))$
$\times\ 0.316 \sin (2\pi\ 1000e3\ t)$ Volts.**

This waveform description can be entered in the AWG's equation editor to describe our modulated carrier (Figure 1). The unique or arbitrary part of the continuous waveform is now 1 ms, so one defines a time range of 0 to 1 ms. For convenience, define several constants, k0, k1, and k2, so that the modulation parameters are easily altered. Finally, a record length of 20,000 points is selected, keeping in mind the basic AWG relationship:

**Record length (points)
= Waveform period (seconds)
x Sample rate (points/sec).**

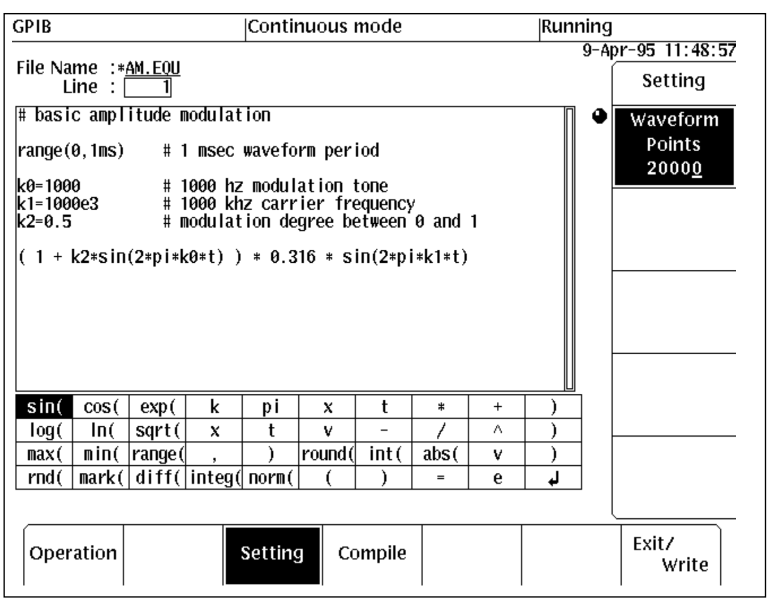


Figure 1. The AWG's equation editor permits direct entry of the mathematical representation of the modulated carrier. Constants k0, k1, and k2 are used to simplify alterations to modulation parameters. The user can directly specify the record length — 20,000 points in this case.

A record length must be selected that has an adequate number of points to reconstruct the desired waveform. The waveform period is 1 ms and there are 1000 carrier cycles in this period. A record length of 20,000 points would allocate 20 points per cycle, which adequately over-samples the ideal waveform. Any sampling system must sample at least twice as fast as the analog bandwidth of the underlying signal (i.e., 1000 kHz). A sample rate of 20 MHz meets this criterion and would require a record length of 20,000 points. In general, to obtain reasonable results the sample rate should be at least 3 times the analog bandwidth of the underlying signal.

The AWG equation compiler converts the waveform definition to a 1 ms series of 20,000 points (Figure 2). The AWG can repetitively generate this series to create the AM carrier in Figure 3. The TDS 744A scope captures the resulting waveform. To aid in scope triggering, the AWG was programmed to generate a marker signal once per period on a separate output.

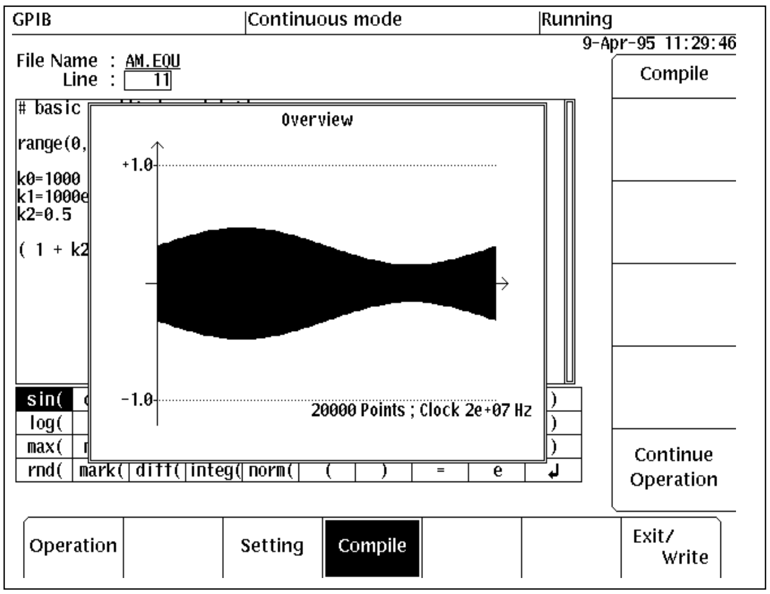


Figure 2. The AWG's compiler converts the modulation equation into a series of points that will become the output record. The graphical display provides an oscilloscope-like overview of the record.

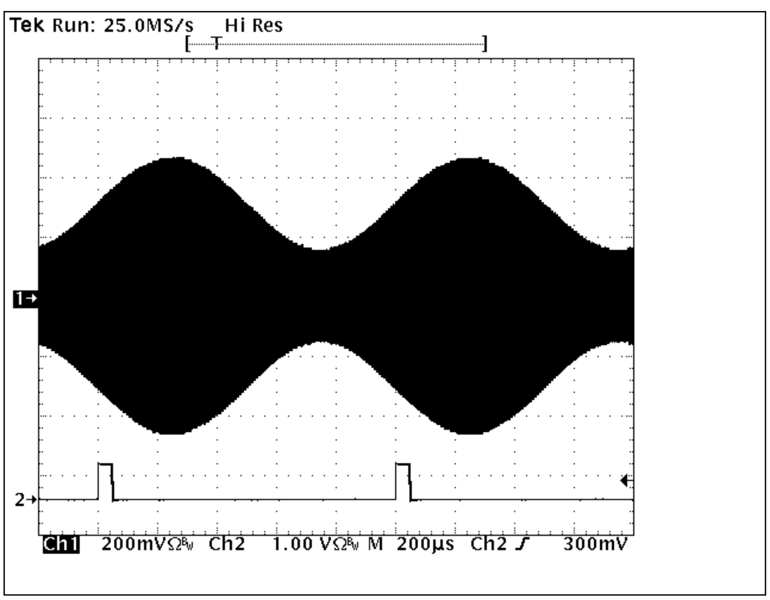


Figure 3. This is a TDS 744A oscilloscope display of the modulated waveform; two complete AWG records are shown in this two millisecond display. The scope is triggered on one of the two marker outputs from the AWG. The marker output was programmed to generate a pulse once per record.

AM with Adjacent Carriers

A simple addition to the AM signal demonstrates the flexibility of equation-based waveform descriptions. A common task in evaluating receiver performance is to evaluate the effect of adjacent carriers. For the basic AM signal, one can easily add modulated carriers 10 kHz above and below the original signal (Figure 4). One simply adds two copies of the basic AM equation to the original equation. The modulation frequency of the adjacent carriers was changed to 3 kHz for later identification, and the carrier frequencies were altered accordingly. In this case, the amplitudes are not explicitly selected, and the AWG's normalization function (last line) is used to automatically scale the peak values encountered in the equation to ensure that there is no clipping within the AWG when the signals are added together. The output level can be set as needed using the AWG's setup menu (Figure 5). In this case the signal amplitude is set to 1 V peak-to-peak. The setup menu summarizes key waveform parameters such as the 20 MHz sampling rate and 20,000 point record length. The resulting spectrum of the three modulated carriers is shown in Figure 6 (on the following page).

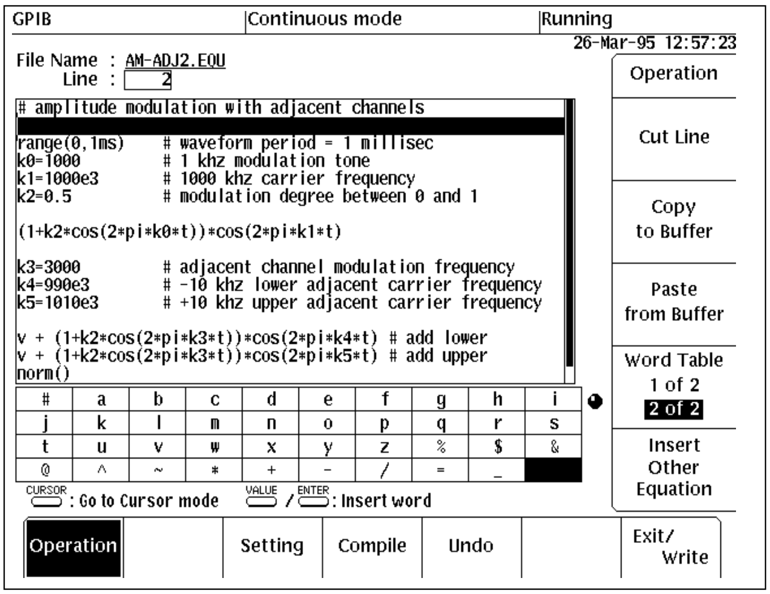


Figure 4. Two additional carriers are added 10 kHz above and below the original carrier. The "v" term in the equation is a place holder with the current value of the equation. This allows adding additional terms on separate lines in the equation editor. The cosine operator was used in this example. We can still use the 1 millisecond period since exactly 3 periods of the 3 kHz adjacent channel modulation tones occur in 1 millisecond.

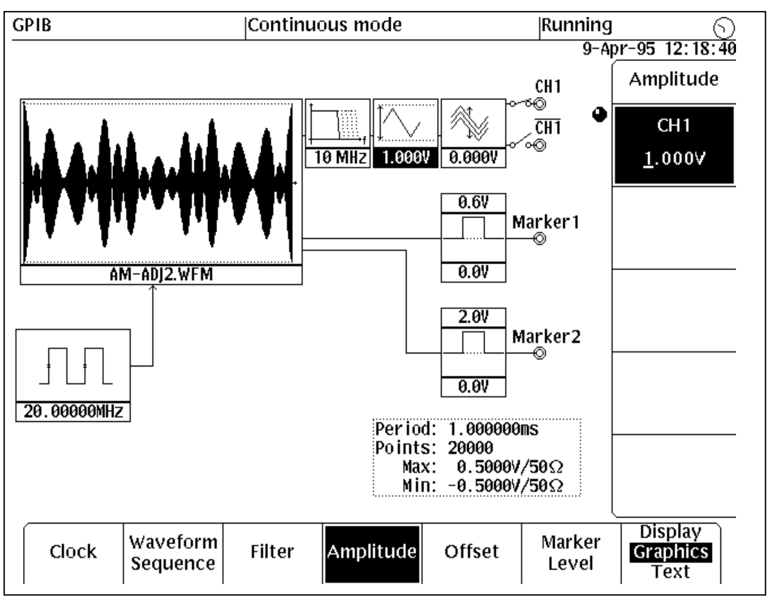


Figure 5. The AWG's setup menu allows direct entry of the peak-to-peak waveform amplitude. The record of the 3-carrier signal is graphically displayed.

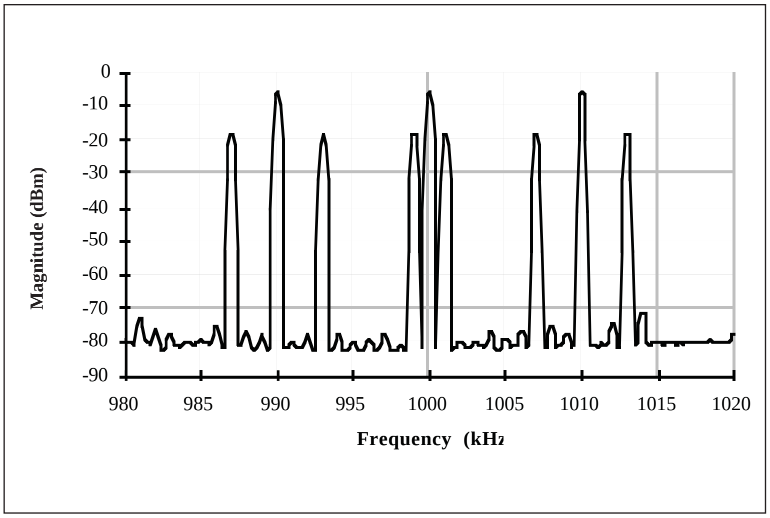


Figure 6. Spectrum analyzer plot of the 3 carriers. There are 3 kHz AM on the adjacent carriers and 1 kHz AM on the original carrier. Note the low level of close-in spurious components.

The logical extension of adjacent carrier testing is multi-tone testing. In addition to simulating multiple carriers in a multi-channel system, multi-tones can quickly test filter response when a scalar or network analyzer is not available, or they can identify intermodulation products resulting from saturation or non-linearities in supposedly linear component stages. Traditionally, multi-tone testing requires assembling as many signal generators as desired tones. And while the generators can be phase-locked to a common reference, the phase relationship between the independent signals is not absolute.

When creating a multi-tone using an AWG, the relationship between carrier phase is implicit in the multi-tone equation. Figure 7 shows the AWG equation editor specifying 11 tones centered at 70 MHz in 1 MHz steps (from 65 MHz through 75 MHz). In this case, the 1 MHz steps suggest a waveform period of 1 µs such that the record repeats at a 1 MHz rate. Thus, the 65 MHz tone is generated by 65 complete cycles in the 1 µs record. The 66 MHz tone is generated by 66 complete cycles in the record and so on. Thus, when the record repeats, *all the tones are continuous in phase*. A spectrum analyzer plot of the multi-tone signal is shown in Figure 8.

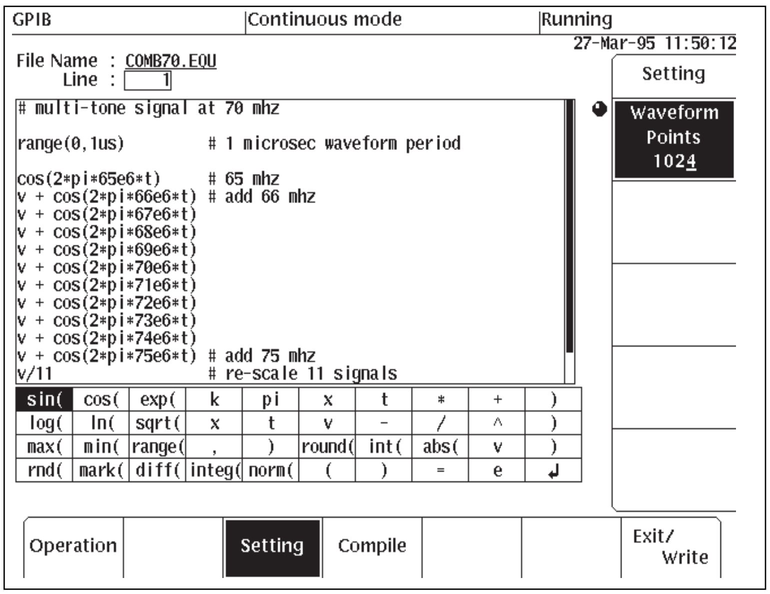


Figure 7. Eleven tones are added together. The record length of 1024 points and a waveform period of 1 µs requires a sample rate of 1.024 GHz. All the tones are in-phase such that the maximum value of the multi-tone occurs at t=0 (the beginning of the record) when all the cosine terms have a value of 1.

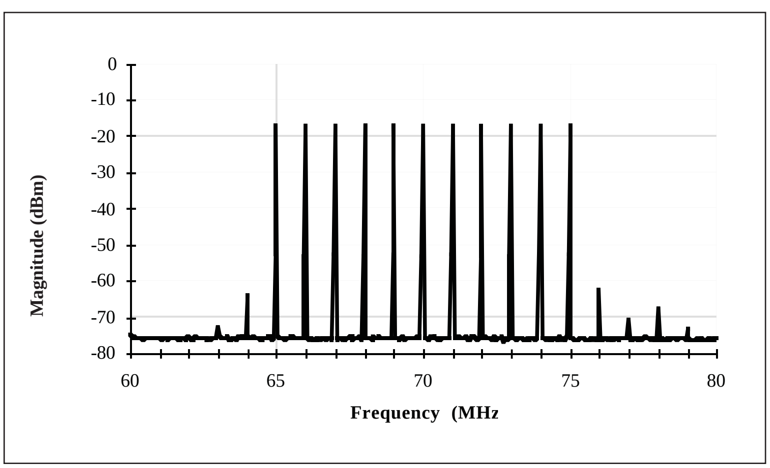


Figure 8. Spectrum analyzer plot of the 11 carriers. The tone levels were flat to better than 0.25 dB.

The 11 tone equation was then modified so that the last 5 tones (71 through 75 MHz) are inverted. The two different multi-tone results are shown in Figure 9. The scope shows that the rms levels of the two signals are identical, but the peak-to-peak values are different. All eleven tones in the original signal added in-phase at t=0. This was not the case with the second signal where 5 of the carriers were inverted at t=0. Thus, the crest factor (peak-to-rms ratio) of the two signals changed from 4.6 (original) to 3.4 (modified). This difference can have dramatic results when using multi-tones to test for saturation in transmitter or receiver stages. While both signals have the same power level, the peak levels are quite different.

Absolute control of phase relationships means that the AWG can ensure repeatable worst case testing, which is not possible with a non-coherent collection of signal generators. The AWG's marker output can simplify in-circuit performance characterization since a scope can be triggered at the exact instant of the test signal's peak value.

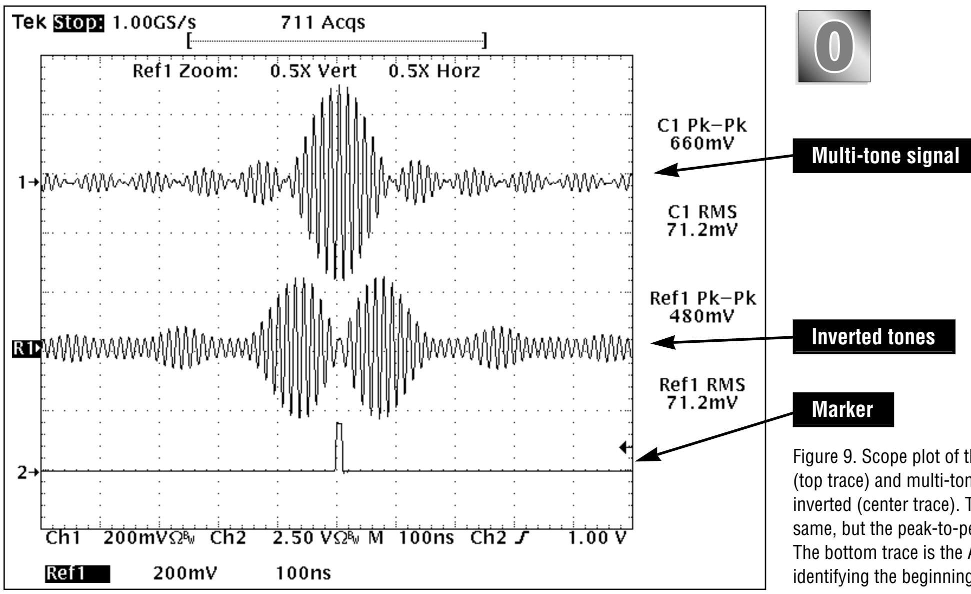


Figure 9. Scope plot of the original multi-tone (top trace) and multi-tone signal with five tones inverted (center trace). The rms levels are the same, but the peak-to-peak amplitudes differ. The bottom trace is the AWG marker output identifying the beginning of the record.

Frequency modulation introduces control of the phase argument, Φ, in the basic carrier equation:

A sin (ω_ct + Φ).

FM is implemented by varying Φ in direct proportion to the integral of the modulating signal. Thus, for a modulating signal m(t), the FM signal can be written:

A sin (ω_ct + k ∫ m(x) dx)

where k sets the peak frequency deviation. For the special case of a modulating tone cos (ω_mt), the phase argument becomes:

k/ω_m sin (ω_mt),

where k is the peak frequency deviation and k/ω_m is the FM modulation index.

The FM equation is entered directly into the AWG's equation editor (Figure 10). The modulation tone is 1000 Hz, so the unique or arbitrary portion of the signal repeats every 1 ms. Choosing a common FM IF carrier frequency of 10.7 MHz, note that the carrier frequency is a multiple of the modulating frequency. This means that the carrier signal will be phase continuous when the 1 ms record repeats.

Figure 11 shows a spectrum analyzer plot of the modulated signal. The peak deviation of 5.52 kHz was selected because a modulation index of 5.52 causes the carrier component in the modulated signal to vanish. This is confirmed by noting that the 0th order Bessel function for a modulation index of 5.52, J_0(5.52), is zero.

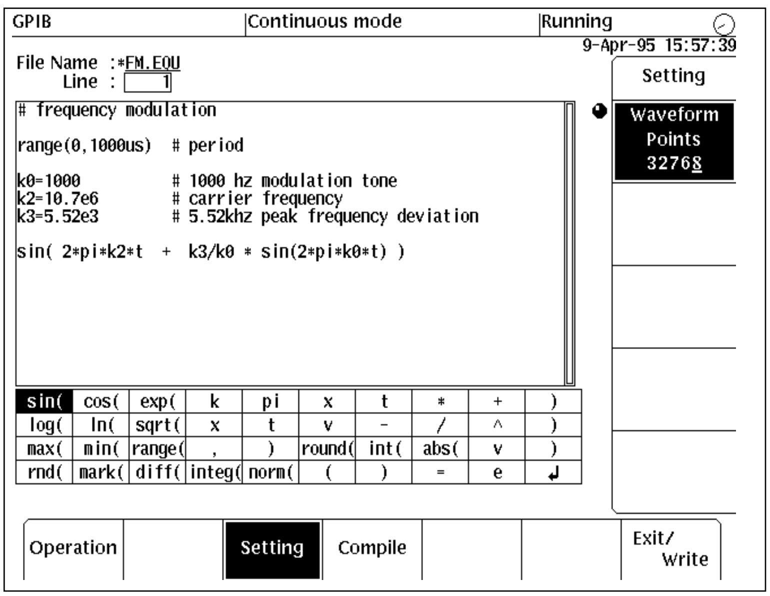


Figure 10. AWG equation for FM single-tone modulation. The peak deviation is 5.52 kHz with a modulating tone of 1000 Hz. The carrier frequency is 10.7 MHz. A 1 ms period is used with a 32,768 point record length; this sets the AWG sampling rate to 32.768 MHz.

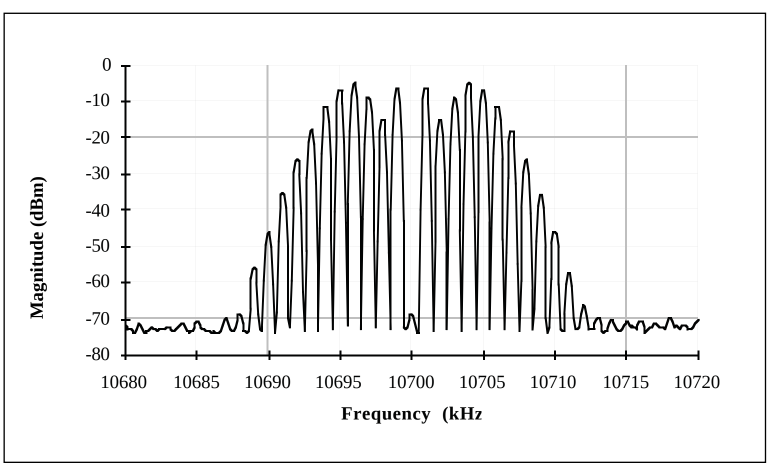


Figure 11. Spectrum analyzer plot of the FM signal. The carrier component vanishes for a modulation index of 5.52. The carrier would also vanish for indices of 2.40, 8.65, and 11.79. This is a simple way to verify that the peak deviation of an FM signal has been set properly.

While basic single-tone FM is a built-in function of virtually all conventional signal generators, dual-tone FM modulation clearly contrasts the flexibility of the AWG approach. Dual-tone modulation tests can be used to measure intermodulation products in a noise reduction *compandor* (compressor-expander) in FM receivers such as cordless phones. Standard dual-tone compandor test frequencies are 900 Hz and 1020 Hz and a typical minimum requirement is that intermodulation products should be 26 dB below the per tone levels. This test used to be performed at audio frequencies since compandors work in the audio band. But highly integrated receivers may not offer direct access to the compandor circuit, so the dual-tone signal must be injected as a modulated IF signal.

The apparently odd combination of tone frequencies means that the AWG waveform parameters must be carefully selected. The first step is to recognize that 900 Hz and 1020 Hz are both integer multiples of 60 Hz. Thus a waveform period of 16.666 ms will exactly fit an integer number of cycles for each tone (15 and 17 respectively). The next step is to ensure that the carrier frequency itself is phase continuous in a 16.666 ms record. If one wants to inject at an IF frequency of 455 kHz, one must consider that 455 kHz is not an integer multiple of 60 Hz. However, with a carrier of 454.98 kHz, exactly 7583 cycles of the carrier frequency fit in the 16.666 ms period. The 20 Hz error, less than 50 ppm, is irrelevant for all practical purposes.

Figure 12 shows the waveform definition in the AWG's equation editor. We take advantage of an equation compiler function which allows the parameter "x" to represent a dummy variable that takes on values between 0 and 1 in direct proportion to the location within the 16.666 ms record. For example, the 17 cycles of the 1020 Hz tone can be expressed as sin(2π 17 x). This takes the time variable "t" out of the equation and is particularly useful for fitting exact numbers of cycles within an AWG record. First, the two tones are added to make the modulating signal. Next the modulating signal is integrated using the AWG's integration function. The integrated signal must be scaled by the time between each point since the integrator integrates point-to-point without regard to sample rate (which can be changed). With a record length of 32768 points, the 16.666 ms period leads to a sample rate of 1.966 MHz. Finally, the integrated modulating signal is inserted into the phase argument of the basic carrier equation with a peak deviation of 3 kHz per tone.

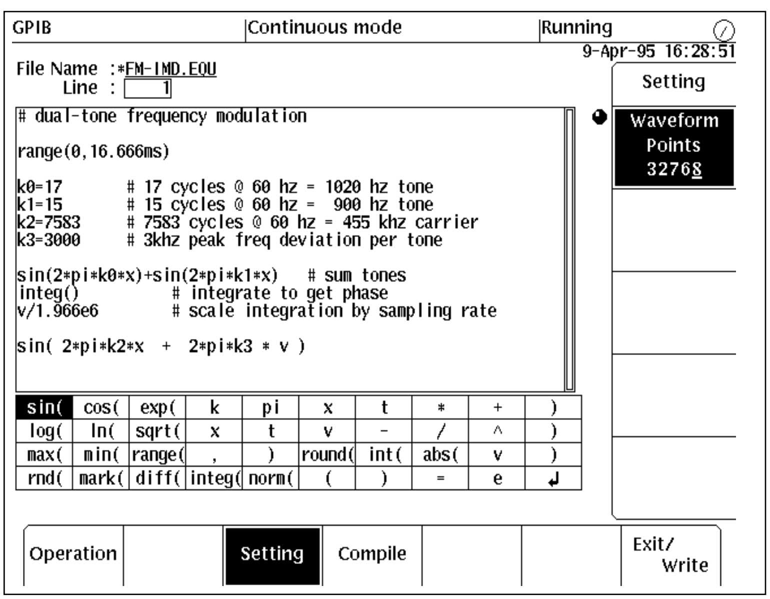


Figure 12. Description of a dual-tone FM signal. The modulating tones are 900 Hz and 1020 Hz on a 455 kHz carrier. The record length is 32,768 points, the waveform period is 16.666 ms, and the sample rate is 1.966 MHz. This FM signal is used to test the intermodulation distortion performance of a syllabic expander in an FM receiver.

Figure 13 shows the demodulated output from an FM receiver with the expander disabled and enabled. The top two traces show the unexpanded two-tone signal and its spectrum as calculated by the TDS 744A FFT function. The lower two traces show the same signals with the expander enabled. The intermodulation products are now significant, with the first order products about 35 dB below the fundamental tones.

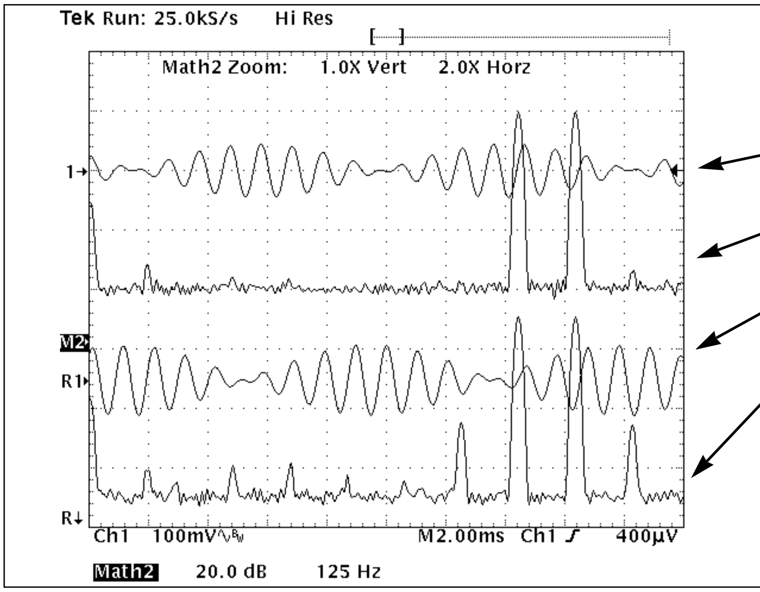


Figure 13. The TDS 744A shows the intermodulation performance with expanders disabled and enabled. There is no distortion with the expander disabled. The first order intermodulation products are about 35 dB below the fundamental tones with expanders enabled.

A final example of conventional analog modulation combines most of the above techniques to simulate the stereo modulation used in broadcast FM. The modulating signal consists of three components, 1) the composite audio which is the sum of the left and right (L+R) channels, 2) the stereo pilot signal which is a 19 kHz tone, and 3) the difference (L-R) signal which amplitude modulates a 38 kHz carrier. These three components are summed together and modulate the carrier using conventional FM. Figure 14 shows the waveform definition in the AWG's equation editor. This example uses a 5 ms waveform period, a 32768 point record, and a sampling rate of 6.5536 MHz. The carrier will be 455 kHz, which can be mixed externally to an appropriate IF frequency.

The left channel signal is an 800 Hz tone and the right channel signal is a 1000 Hz tone. The composite audio signal (L+R) is made by summing the two tones. The 19 kHz pilot tone is then summed at half the amplitude of the audio tones. The (L-R) signal amplitude modulates a 38 kHz carrier which is phase-locked (implicit in the equation definition) to the 19 kHz pilot. Unlike the previous AM example, suppressed carrier modulation is used, where the carrier is suppressed if there is no modulating signal (the "1" term is absent from the modulation product term). The three terms are integrated to implement FM modulation; the integration output is scaled by the sampling rate as described earlier. Finally, the integrator output is inserted into the phase term of the sinusoidal carrier with a peak deviation of 10 kHz per audio tone.

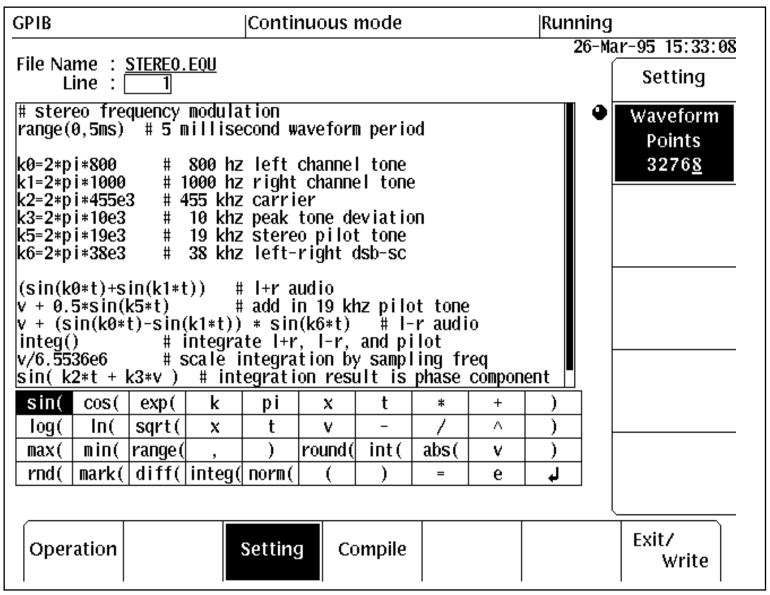


Figure 14. Definition of the stereo FM signal. The waveform period was 5 ms. All the modulating components have an integer number of cycles within the record (i.e., they are multiples of 200 Hz) so the signal is phase continuous.

The resulting 455 kHz signal is mixed up to the broadcast band and inserted into a stereo receiver. The stereo indicator is turned on, and the resulting left and right output signals are captured on the TDS 744A scope (Figure 15). The upper two traces are the right channel (1000 Hz) signal and spectrum. The lower two traces are from the left channel (800 Hz). The stereo encoding was successful with the receiver separating the two tones by over 35 dB. The 38 kHz sub-carrier in FM broadcast is not unique. Higher sub-carriers are commonly used to encode specialized audio channels or pager data to take advantage of the coverage of commercial FM transmitters.

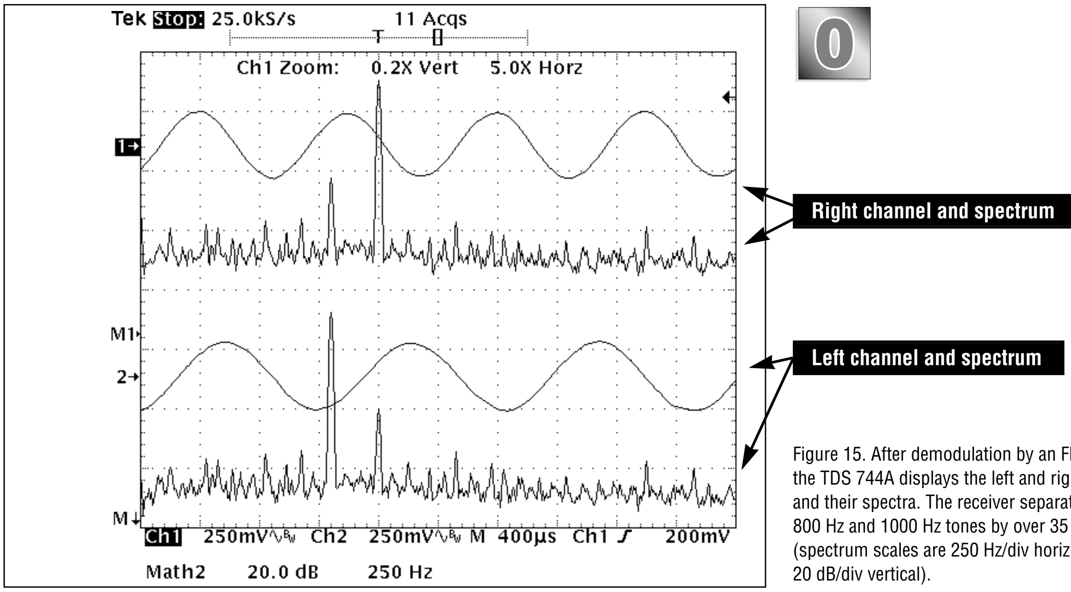


Figure 15. After demodulation by an FM receiver, the TDS 744A displays the left and right channels and their spectra. The receiver separated the 800 Hz and 1000 Hz tones by over 35 dB (spectrum scales are 250 Hz/div horizontal and 20 dB/div vertical).

Although the removal of noise is a common design goal, a noise source can be an extremely useful test stimulus or signal impairment. The AWG 2041 provides a built-in noise function, but its characteristics are quite different than traditional sources such as noise diodes. An AWG[1] noise waveform is actually a calculated series of pseudo-random numbers. There are two key properties of the AWG noise function. First, the AWG noise signal is actually a series of voltages that changes once per clock period. This has definite implications for the spectral characteristics of the signal. The second property arises because an AWG noise waveform is simply another pre-calculated record that must eventually repeat to obtain a continuous signal.

Calculating Noise
The AWG provides a built-in function to calculate the noise waveform of a specified record length. In Figure 16, the AWG creates a 32768 point noise waveform. Digital random number generators typically produce uniformly distributed values, but circuit noise is better modeled with a Gaussian distribution. In practice, the AWG actually calculates a noise value by averaging 12 consecutive random numbers. Thus, by the central-limit theorem, the noise values will more closely approximate a Gaussian distribution than the underlying uniform distribution.

The top trace in Figure 17 shows the resulting noise output. The key feature relating to the clock is that the waveform appears to be a staircase function. The sharp edges can be removed by

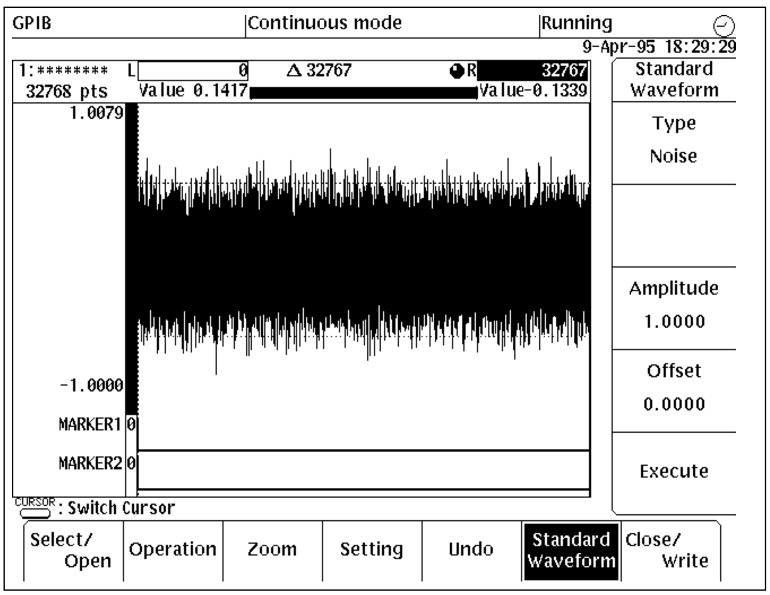


Figure 16. The noise waveform is a built-in function in the AWG. In this case, the 32768 point record length specifies a pseudo-random series of values. The values are approximately Gaussian in distribution with a crest factor of about 3 to 1.

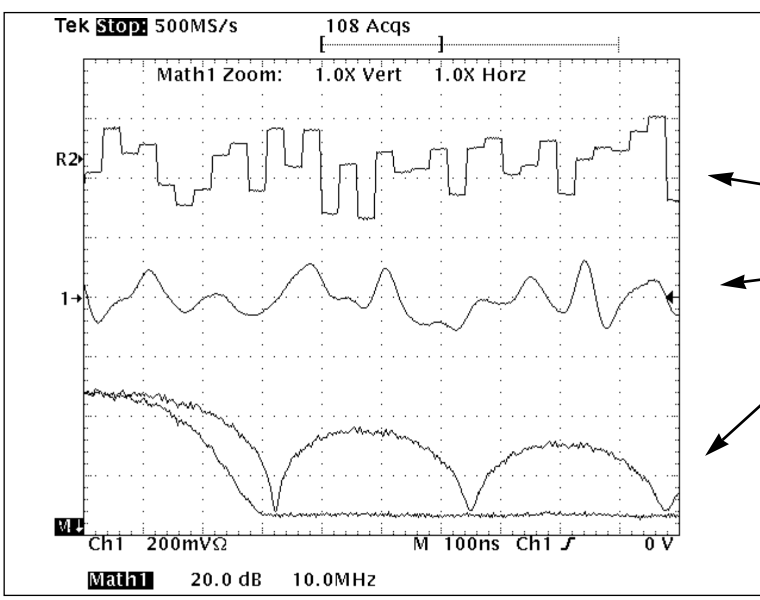
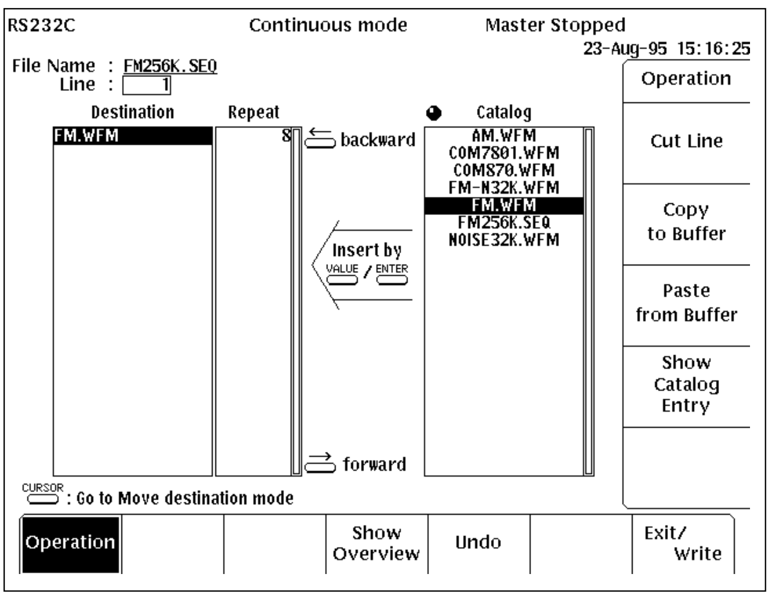


Figure 17. Upper waveform is a pseudo-random sequence with a 32.768 MHz clock. The second waveform is the same signal filtered by the AWG's 10 MHz Bessel low-pass filter. The lower two traces are the calculated FFT spectra. The horizontal scale of the spectra is 10 MHz per division.

[1]AWG refers to Arbitrary Waveform Generator as opposed to Additive White Gaussian, an unfortunate coincidence in this context.

the AWG's 10 MHz low-pass filter (middle trace). The TDS 744A FFT spectra for the two signals are overlaid below the time domain waveforms. The salient characteristic of the unfiltered noise spectrum is that it rolls off with a (sin x)/x function with the first null at the 32.768 MHz clock frequency and subsequent nulls at multiples of the clock rate. If the goal is to add this noise waveform to the 10.7 MHz FM carrier, then noise density is required only in the vicinity of 10.7 MHz. The filtered noise signal is a suitable bandwidth-limited source. Thus, when using the AWG noise function, one consideration is to account for the clock rate dependent roll-off.

Maximizing "Randomness"
The second property to consider when using the AWG noise waveform is to observe that the noise waveform itself is a pre-calculated series of points that will repeat at each period of the record length. The period of the 32K point noise waveform at a 32.768 MHz sample rate is 1 ms and the exact noise waveform repeats at a rate of 1 kHz. This periodicity translates into the resulting noise spectrum. The ideal noise waveform would exhibit no periodicity (i.e., no repetition). While this is not an option with pre-calculated AWG waveforms, the effect of the periodicity can be reduced by increasing the period of the noise waveform relative to the corresponding signal waveform. Figure 18 shows how the AWG's sequence editor converts the 32K point FM waveform into a 256K point waveform which is simply 8 concatenated copies of the same waveform. Thus, if the same clock waveform of 32.768 MHz is used, the resulting signal waveform is identical. However, if a 256K noise waveform is generated, then the period of the noise waveform is increased by a factor of 8.



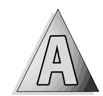


Figure 18. The 32K point FM waveform can be converted to a 256K point waveform by simply sequencing or concatenating 8 copies of the original 32K waveform. This expansion means that a 256K noise waveform can be added to the FM waveform instead of a 32K noise waveform.

The AWG's graphical waveform editor provides a variety of mathematical operators for existing waveforms. Waveforms can be combined with other waveforms, or a waveform can be squared, scaled, differentiated, integrated, etc.

Combining the Noise with the Carrier

The signal and noise waveforms are summed using the AWG's waveform editor (Figure 19). The spectra of the 32K point waveform and the 256K point waveform are overlaid in Figure 20. Recall that the period of the 32K point waveform is 1 ms. You can see that the noise "floor" of the spectrum of the 32K point waveform is a series of discrete components spaced 1 kHz apart. Thus, even though the objective is to define signal waveforms with the minimum number of record points, noise waveforms should be created with the maximum number of record points! The two objectives are resolved by creating a longer version (to match the noise record length) of the signal waveform by sequencing multiple copies of itself.

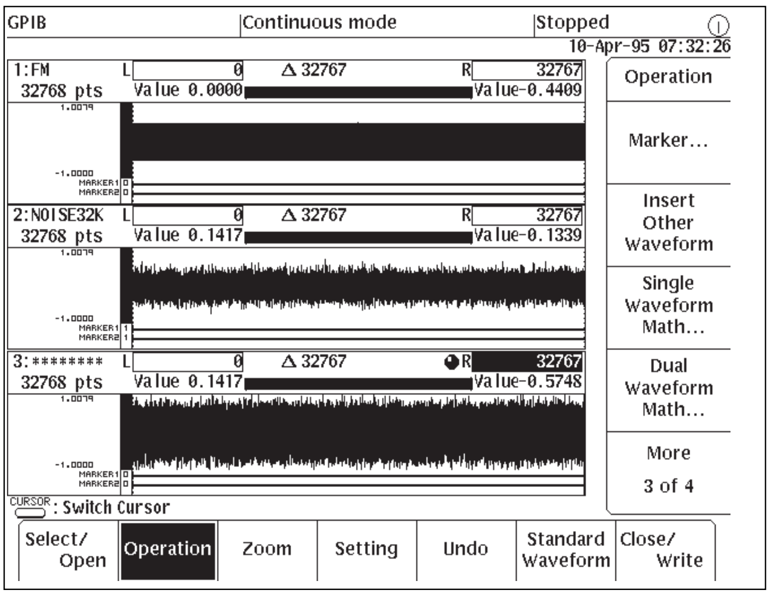


Figure 19. The 32K point FM waveform is added to the 32K point noise waveform.

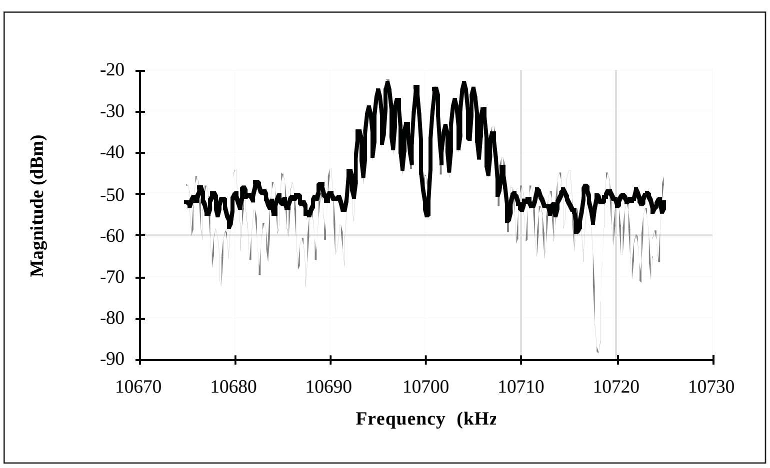
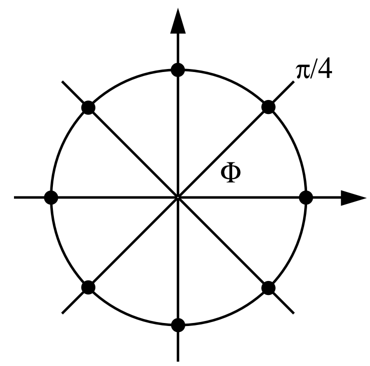


Figure 20. Spectrum analyzer plots of the 32K point FM carrier plus noise (lighter) and the 256K point FM carrier plus noise. Longer noise waveforms repeat less often so the noise density characteristics will be flatter.

Digital Modulation

8 Digital Phase Modulation — PSK

The modulating signals in the foregoing examples have been sinusoidal or continuous waveforms. A simple step to digital modulation is made with a slight variation to sinusoidal modulation. Figure 21 shows one cycle of a sinewave that has been quantized into steps between –0.5 and +0.5. The equation defining these steps is shown in Figure 22. The second line simply quantizes a cosine wave by rounding and scaling the continuous waveform to the nearest eighth. This quantized modulating pattern is then directly inserted in the phase argument of a cosine carrier. Thus, the phase argument takes on values between $-\pi$ to $+\pi$ in $\pi/4$ steps. If the polar graphical representation of the signal is used, a family of eight points of equal magnitude is defined, spaced around the circle in $\pi/4$



or 45° phase increments.

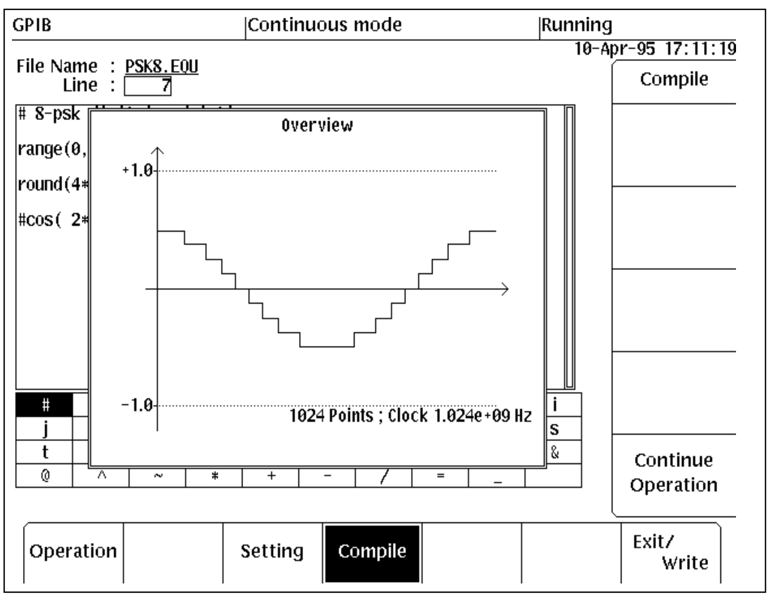


Figure 21. The sinusoidal modulating pattern is quantized into discrete steps. The steps are equally spaced in amplitude and will shift the phase of the carrier in $\pi/4$ or 45° increments.

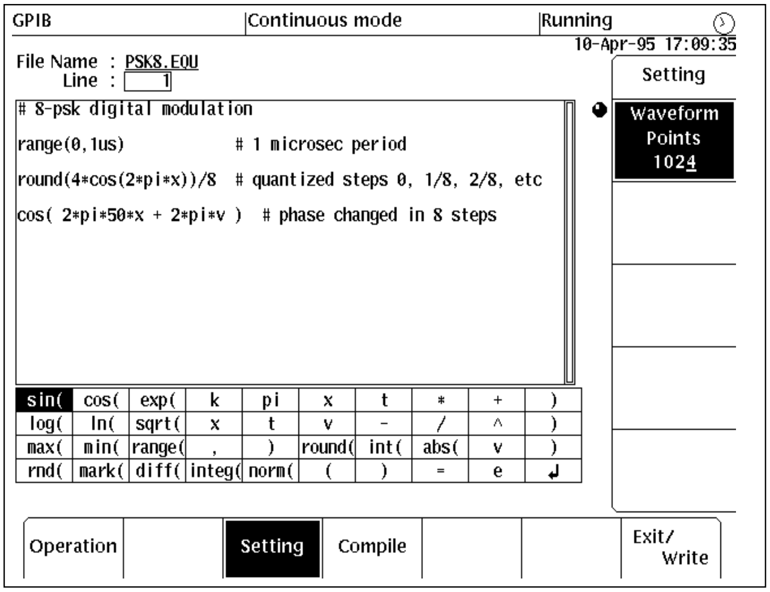


Figure 22. The equation defining the quantized 1 MHz modulating pattern and its subsequent insertion into the phase argument of the 50 MHz carrier. The modulating pattern shown in Figure 21 is the result of the rounding definition.

The record length of 1024 points and a waveform period of 1 µs requires a sampling rate of 1.024 GHz. The resulting carrier frequency is 50 MHz. Since each level represents one of eight states or symbols, 3-bits of data can be transmitted per symbol. Of course, no data *per se* is associated with this particular modulating pattern since a sinusoid was quantized without regard to the symbol or baud rate.

Figure 23 shows the resulting AWG output. The top trace is the marker output generating a scope trigger pulse once per record. The second trace is the phase modulated waveform. The third trace is the carrier waveform without the phase modulation. That is, the phase argument was removed from the final equation line on the AWG in Figure 22, leaving just the expression cos (2*pi*50*x). This waveform was captured separately by the TDS 744A but is synchronized to the same trigger

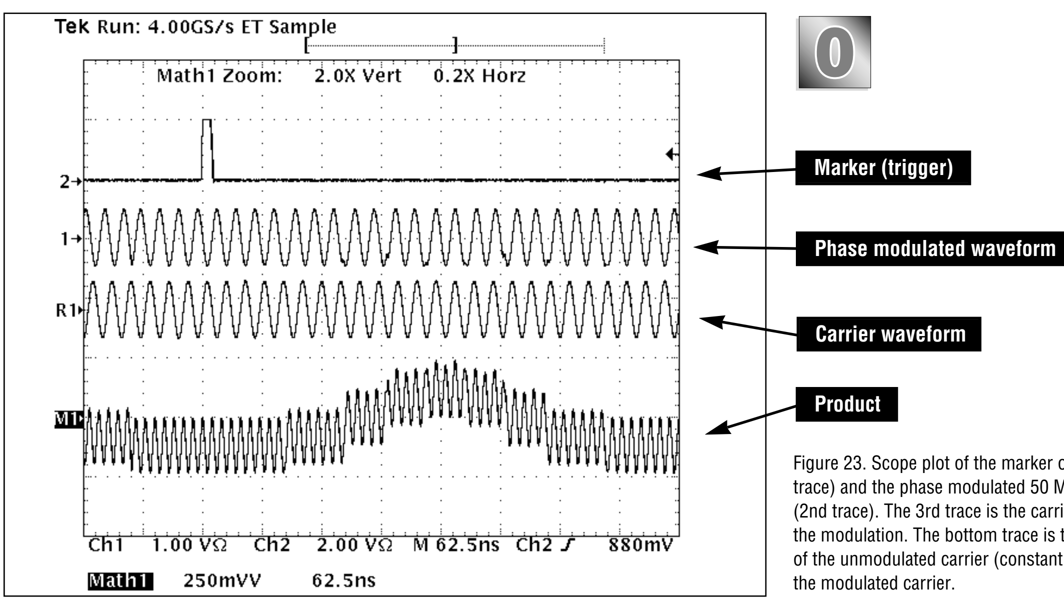


Figure 23. Scope plot of the marker output (top trace) and the phase modulated 50 MHz carrier (2nd trace). The 3rd trace is the carrier without the modulation. The bottom trace is the product of the unmodulated carrier (constant Φ=0) and the modulated carrier.

Before continuing with examples of digital modulation, it is important to establish a method of creating arbitrary test data patterns. Figure 24 shows direct entry of a 28-bit binary pattern. In this case, the 0 or 1 value of each data bit is repeated for 1000 points in the record, which requires a record length of 28,000 points. A binary data pattern requires only one bit of the AWG's dynamic range. Multi-level digital encoding can be used by altering more than one bit at each record point. In addition to direct data entry, the AWG can automatically generate pseudo-random data streams. Figure 25 shows the setup for a length = 9 linear feedback shift register that repeats only after 511 data bits. As with direct entry, the number of record points per data bit can be specified. In this case, each bit repeats for 32 data points, requiring a record length of 16,352 points.

In some applications, the data pattern itself is the desired output signal for the AWG. For example, the data pattern can be the baseband modulation signal to an external RF generator or modulator. However, the following examples use the simple 28-bit, 28,000 point record as the baseband signal in demonstrating several digital modulation techniques.

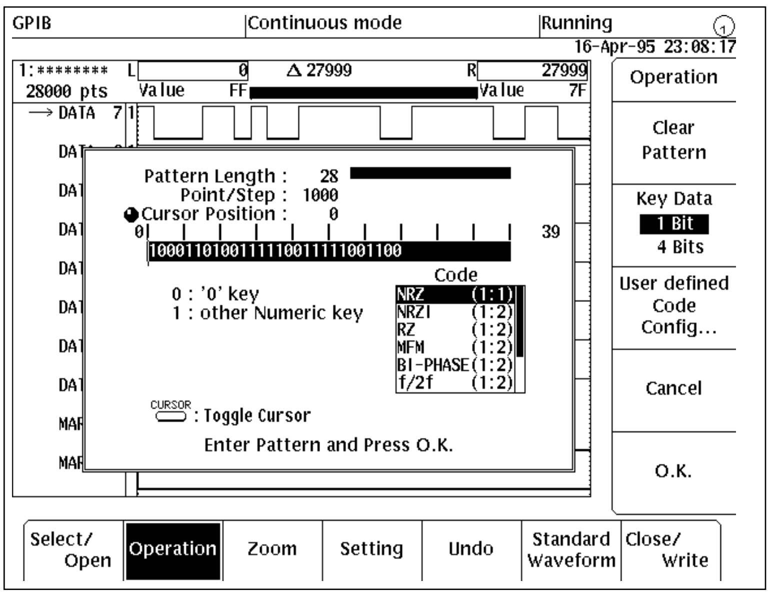


Figure 24. A binary or hex (4-bit) data pattern can be directly entered from the keypad. The AWG directly translates a variety of encoding formats such as NRZ, RZ, and NRZI. The number of record points that each bit interval occupies can be specified.

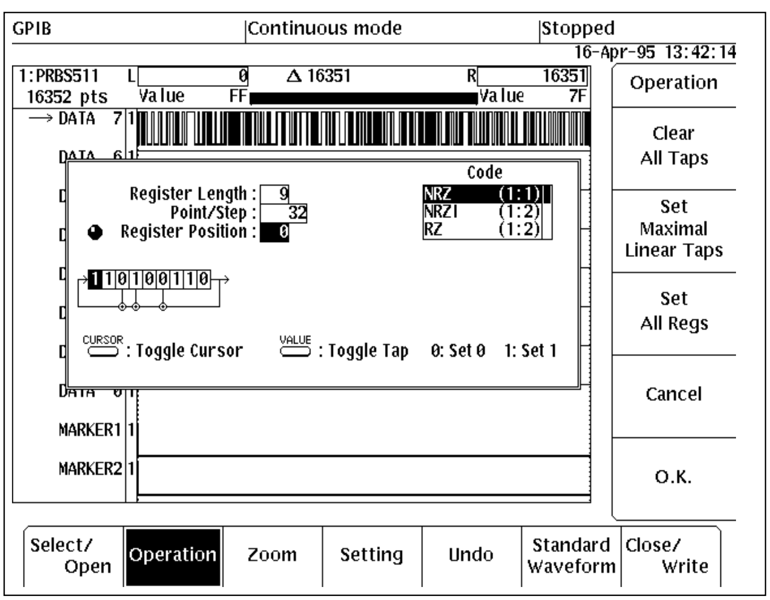


Figure 25. The pseudo-random generator supports register lengths from 2 to 32 bits. The binary output stream from the generator can be assigned to a specific bit in the output range or to one of the marker bits.

10 Digital AM — OOK and BPSK

The simplest example of digital modulation is to turn the carrier on or off, depending on the state of the modulation data. On-off keying (OOK) can be directly implemented by multiplying a carrier by the 1 or 0 value of the data pattern. This example uses a 10.7 MHz carrier created in a 28,000 point record to match the record length of the data pattern. The AWG sampling rate is 40 MHz so the record period is 700 µs. Since each of the 28 data values occupies 1000 record points, the data rate is 40 kbaud. Figure 26 shows how the AWG's dual waveform math capability multiplies the data pattern (top display) and the 10.7 MHz carrier (middle) to produce the modulated carrier (bottom). Since 10.7 MHz is a popular receiver IF frequency, these signals can be directly injected at the appropriate receiver point to characterize demodulator performance. The AWG's sequencing and triggering capabilities are particularly useful in OOK remote-control device simulations. The AWG can generate single or occasional bursts with varying parameters such as carrier frequency offset or data rate. The burst itself can be amplitude modulated with another waveform to simulate the power ramping found in many battery-powered transmitters.

If the data pattern is simply shifted vertically so that it takes on bipolar values of –1 and +1, instead of 0 and 1, then the modulation inverts the sign of the carrier. Since inverting the sign is equivalent to shifting the phase argument of the carrier by π, this implements two-state or binary phase-shift keying (BPSK). Figure 27 illustrates the same AWG setup except that the modulating pattern is offset using the shift and scale functions. The resulting BPSK has a constant envelope since the magnitude of the multiplier is always 1.

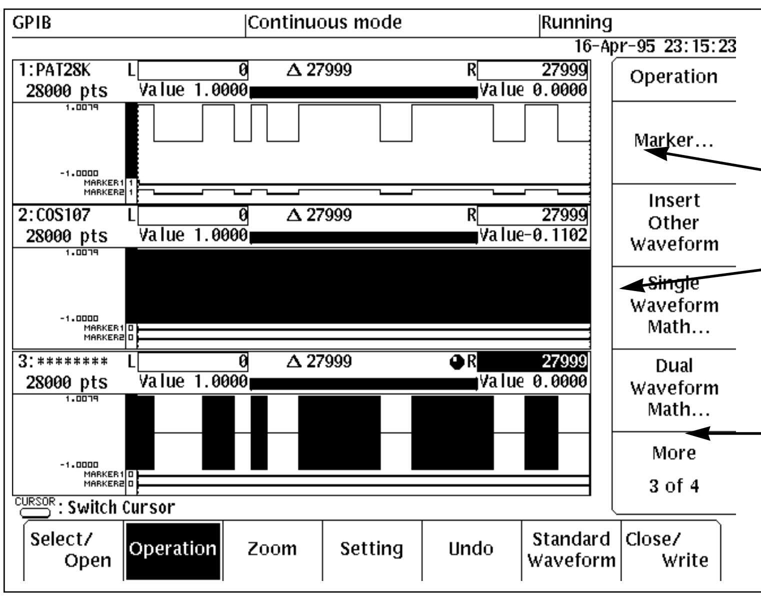


Figure 26. **OOK:** The "1" and "0" values of the data pattern turn the carrier on and off. The carrier frequency is 10.7 MHz. The data rate is 40 kbaud.

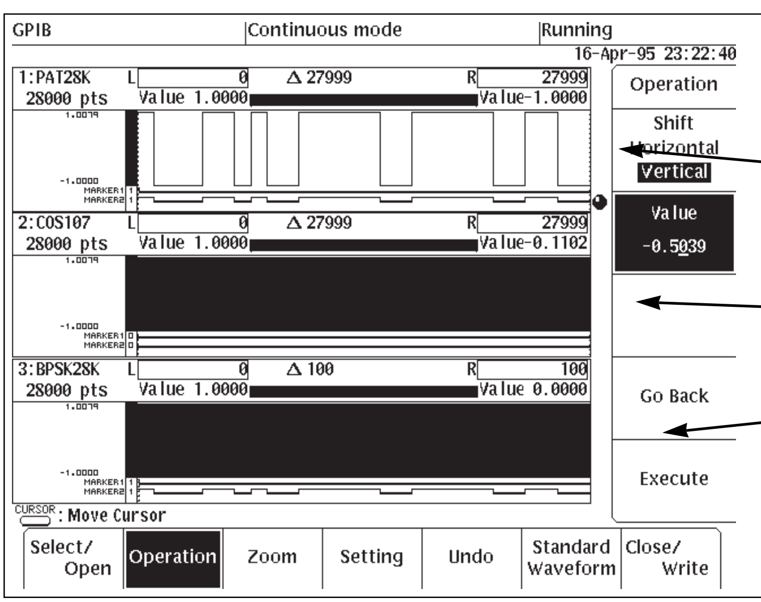


Figure 27. **BPSK:** The 28-bit data pattern is shifted and scaled to generate a bipolar pattern. This implements BPSK modulation when multiplied by the carrier. The BPSK waveform has a constant envelope.

The modulating data alters the carrier frequency in frequency-shift keying (FSK). A digital modulation index of 0.5 is used in this example; that is, the frequency shift will be ½ the 40 kbaud data rate or 20 kHz. If the carrier remains centered at 10.7 MHz, this results in the two data frequencies of 10.710 MHz and 10.690 MHz. Figure 28 shows one way to implement binary FSK to take advantage of the AWG's mathematical precision. First, a second 28-bit data pattern is generated which is the 1's complement of the original pattern. Then two 28,000 point carriers are generated at 10.690 MHz and 10.710 MHz. Note that the carriers are phase continuous since exactly 7483 and 7497 cycles, respectively, of the carriers fit in the 700 µs record. The upper waveform is the 10.690 MHz carrier multiplied by the original data pattern, and the middle waveform is the 10.710 MHz carrier multiplied by the complemented pattern. If the two waveforms are added (bottom trace), then the carrier shifts between the two frequencies exactly at the data transitions. The spectra of the two unmodulated carriers and the modulated FSK signal are shown in Figure 29.

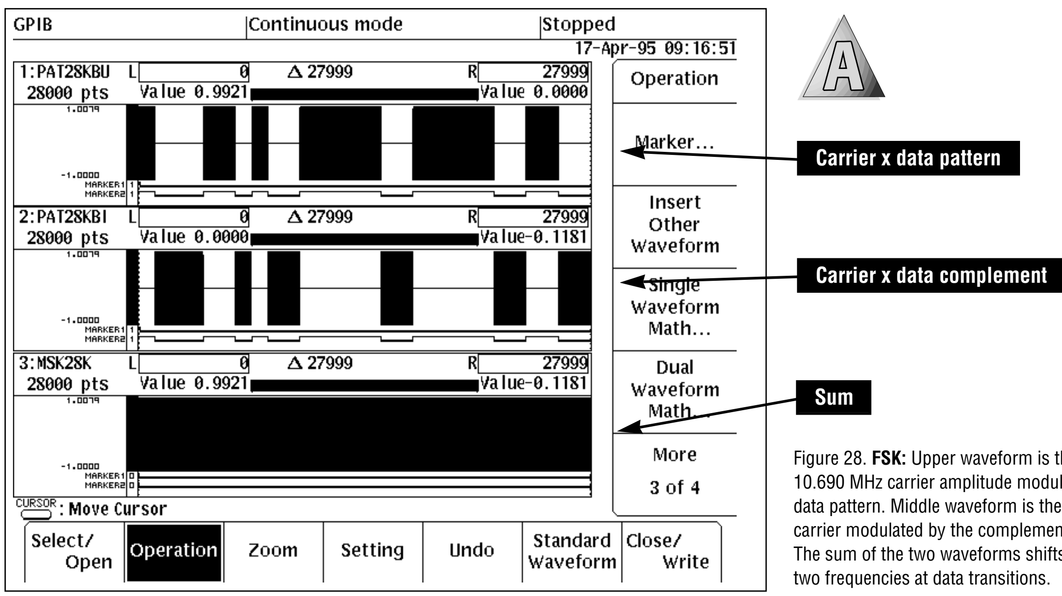


Figure 28. **FSK:** Upper waveform is the 10.690 MHz carrier amplitude modulated by the data pattern. Middle waveform is the 10.710 MHz carrier modulated by the complemented pattern. The sum of the two waveforms shifts between the two frequencies at data transitions.

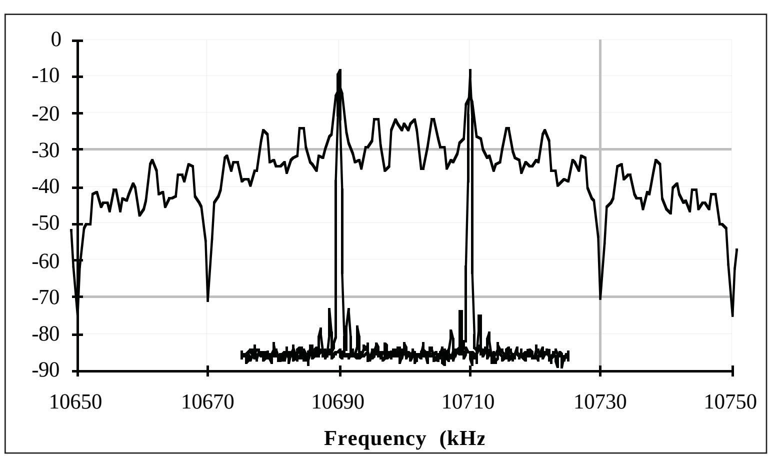


Figure 29. Spectrum analyzer plots of the two unmodulated carriers, at 10.690 MHz and 10.710 MHz, and an overlay of the FSK signal with the 28-bit modulation.

As previously mentioned, the AWG's two binary marker output signals can be modulated with a data pattern. Figure 30 shows how this can be used as a tool for testing or troubleshooting digital receivers. One marker output is programmed to generate a trigger pulse at the beginning of each 700 µs record (top trace). The second marker is programmed with the 28-bit data pattern (second trace). The two marker signals are generated in real time with the AWG's main signal output. The third trace is the FSK modulated signal with no indication of modulation since it is a constant envelope waveform. However, a coherent copy (using a marker pulse at the same record point) of the 10.710 MHz unmodulated carrier is captured and saved in the TDS 744A reference memory. The lower trace is the real-time product of the FSK signal and the coherent reference carrier. When the data is 0, the FSK signal is at 10.710 MHz and the coherent demodulation yields a positive-only component. When the data is 1 (e.g, between the cursors), the frequencies are not equal and a constant frequency difference during the interval generates a beat component at 20 kHz. Note that the time between peaks, or the period of the beat product, is 50 µs or 20 kHz.

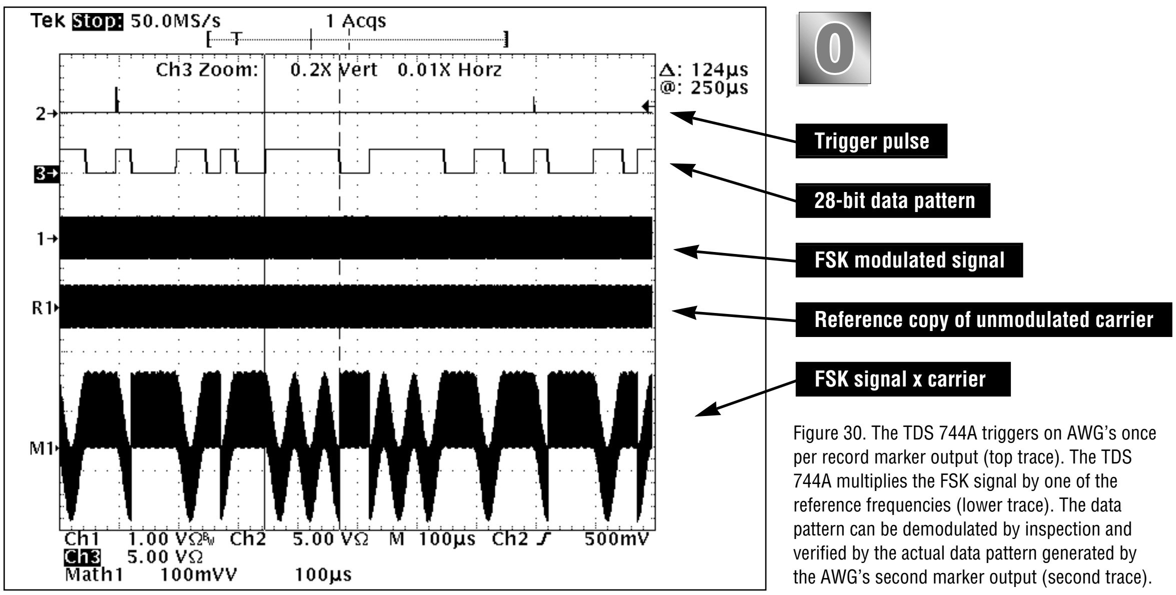
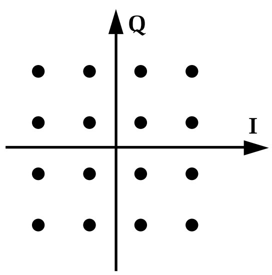


Figure 30. The TDS 744A triggers on AWG's once per record marker output (top trace). The TDS 744A multiplies the FSK signal by one of the reference frequencies (lower trace). The data pattern can be demodulated by inspection and verified by the actual data pattern generated by the AWG's second marker output (second trace).

Multi-level data modulation splits the amplitude, frequency, or phase of the carrier into more than two discrete states. 8-PSK previously demonstrated direct control of the phase Φ in the equation **$A \cos(\omega_C t + \Phi)$**; A was constant. The eight symbols were equally spaced points around the polar axes. Alternatively, the I-Q mapping can be used by noting the relationship:

$$A \cos(\omega_C t + \Phi) = A \cos \Phi \cos(\omega_C t) - A \sin \Phi \sin(\omega_C t)$$

That is, any symbol location can be expressed as a vector sum of an in-phase (I) component and an orthogonal quadrature component (Q). Thus, if we select 16 equally spaced points to send 4 bits of information per symbol, then we can easily transmit the symbols by amplitude modulation of two carriers.



For example, the I component could be –¾, –¼, ¼, or ¾ times $\cos(\omega_C t)$. The Q component would be one of the same multipliers applied to $\sin(\omega_C t)$. Figure 31 illustrates a 28-symbol pattern, each with one of these four multipliers. Each quadrature component carries 2 bits of information. Figure 32, on the following page, illustrates the creation of the quadrature amplitude modulated carrier using the AWG's waveform editor. The top waveform is the I pattern modulating the 10.7 MHz cosine carrier. A separate 28-symbol Q pattern was created and modulates the 10.7 MHz sine carrier in the middle waveform. The two waveforms are combined in the third pattern.

Signal impairments are easily generated with this approach. The cosine or sine carrier (before modulation) can be altered relative to each other in phase or amplitude to simulate errors in the modulated signal. For example, the cosine carrier could be altered from $\cos(\omega_C t)$ to $\cos(\omega_C t+\delta)$ where δ is a small offset to move the two carriers out of quadrature. Or the levels of the baseband data pattern can be altered in the waveform editor to corrupt the uniform spacing of the 16 symbols. To accomplish quadrature modulation at appropriate frequencies, it may be necessary to couple the AWG with a specialized dual-input RF signal generator designed to handle I and Q information. Figure 33 depicts the interconnection of the two instruments, as well as the other elements of the test setup.

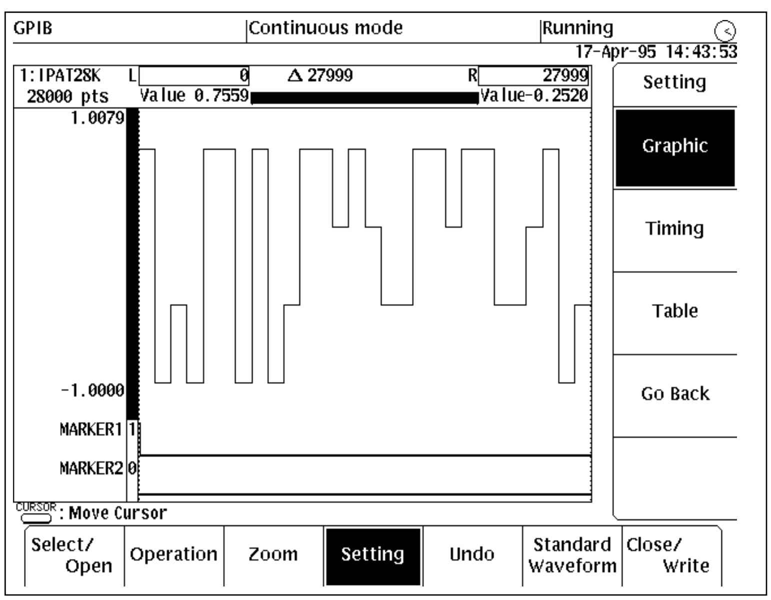


Figure 31. The AWG's waveform editor was used to generate this 28-symbol data pattern which has four potential uniformly spaced levels per symbol.

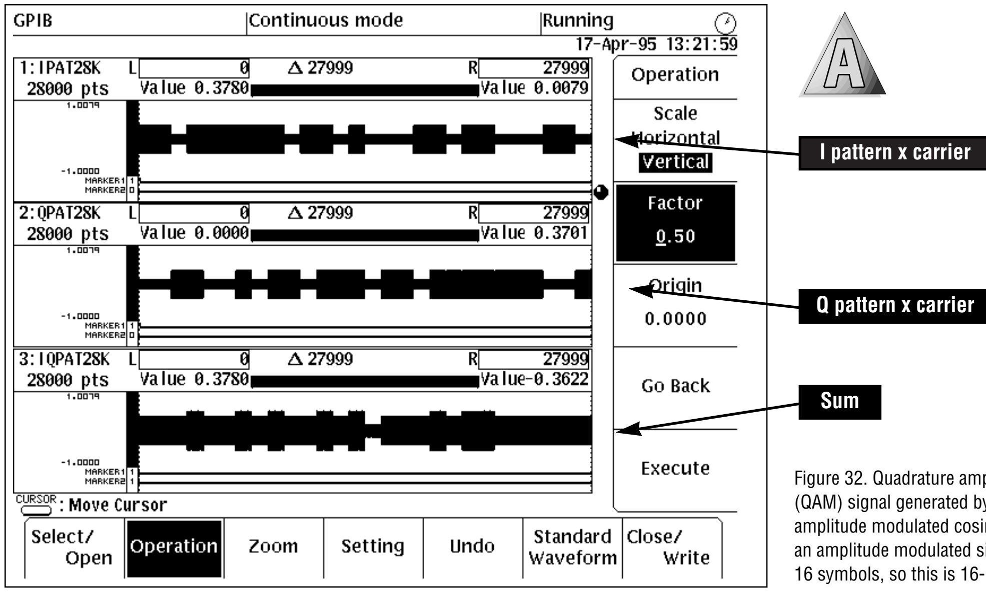


Figure 32. Quadrature amplitude modulated (QAM) signal generated by combining an amplitude modulated cosine carrier (upper) and an amplitude modulated sine carrier. There are 16 symbols, so this is 16-QAM.

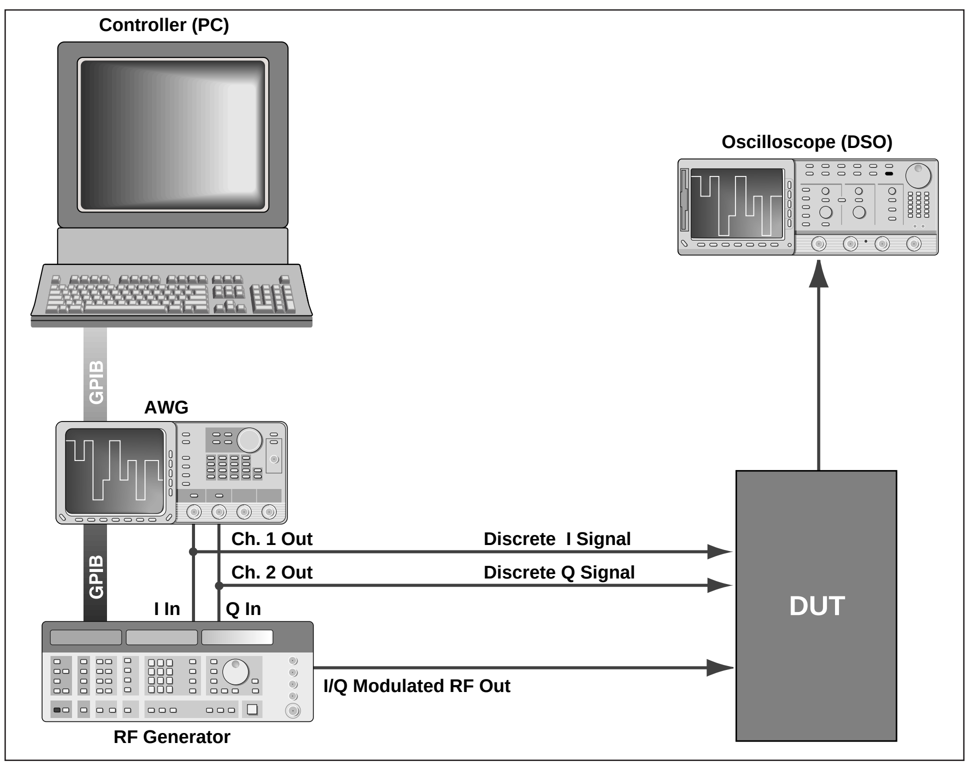


Figure 33. This block diagram shows the setup for quadrature modulation. For more information about suitable RF sources, contact your local Tektronix representative.

One effect of the edge transitions in digital modulation patterns is a wider than desired occupied spectrum of the transmitted signal. The solution is to filter the baseband digital signal before it modulates the carrier. The two most common filter types for this application are Gaussian and Nyquist filters. Application of the Gaussian filter is illustrated here, though the process for applying any filter type is the same. The baseband modulating pattern is filtered by convolving it with the impulse response of the desired filter in the time-domain. The AWG directly performs the convolution function. Figure 34 shows the convolution setup. The upper left waveform is the 28,000 point data pattern, while the lower left waveform is the 2000 point Gaussian impulse response. The result of the convolution process is shown at the right.

The impulse response of the Gaussian filter is defined by:

$h(t) = \exp\{-t^2/2s^2\}$,
where $s = PW_{50}/(2\sqrt{(2\ln(2))})$.

PW_{50} is the half-width for the pulse and is approximately equal to 0.31/B, where B is the filter bandwidth in Hz. Figure 35 shows the implementation in the AWG's equation editor. The key parameter to select is the half-width. This example uses a BT parameter of 0.5, where B is the filter bandwidth and T is the data period (25 µs). This means the bandwidth must be 20 kHz and the PW_{50} = 15.5 µs. By trial and error it is determined that a 50 µs total pulse interval defines the total response so that both tails drop to zero within the interval. For the sample rate of 40 MHz, this requires a record length of 2000 points.

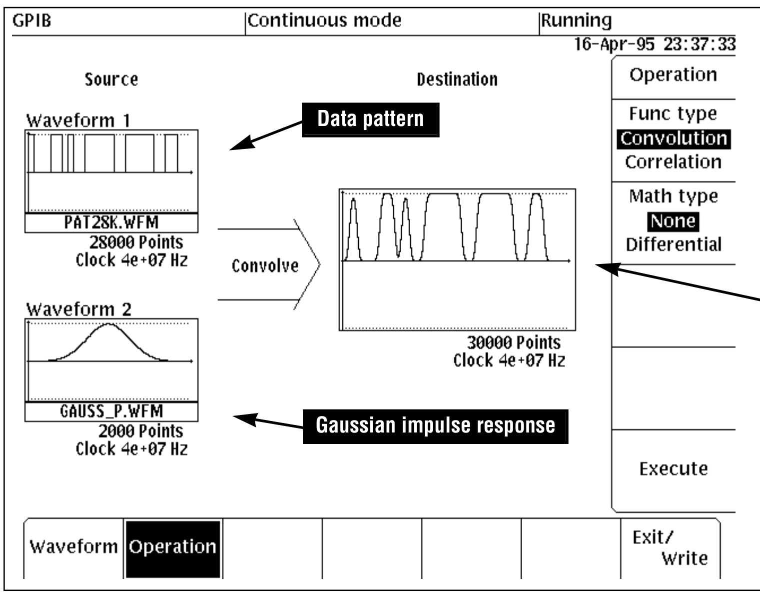


Figure 34. The data pattern (upper left) is convolved with the Gaussian impulse response (lower left). The result is the filtered data pattern. The convolution of the two waveforms produces a new waveform that is 30,000 points long. This is the sum of the two individual waveform lengths and is a by-product of the convolution process.

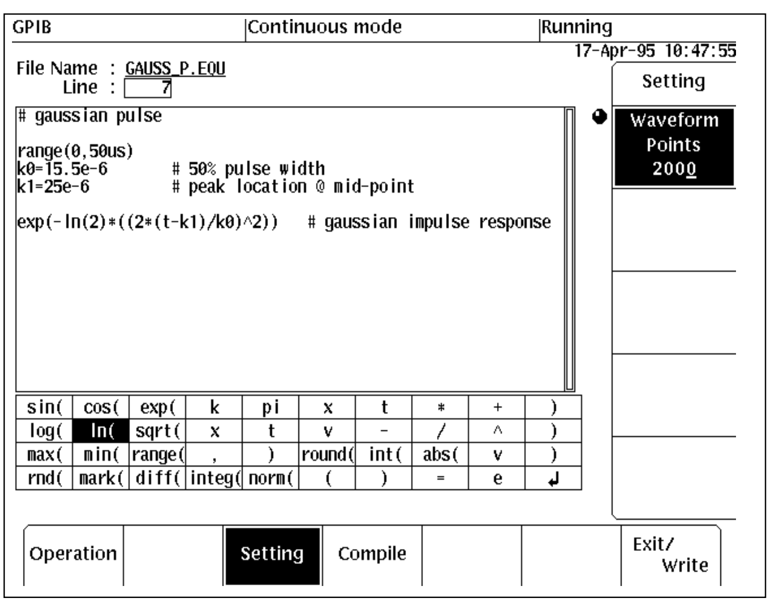


Figure 35. The Gaussian impulse response is defined by the pulse half-width, which is approximately equal to 0.31/B, where B is the –3 dB filter bandwidth. The constant k1 offsets the peak of the impulse response to the center of the record.

The convolution result is 30,000 points long. Note that the impulse response is 2000 points long, which is longer than the 1000 points per data bit. This means that each data bit affects more than the 1000 points that it immediately occupies. Hence, a possible anomaly must be accounted for in the convolution process. The AWG assumes that the data before and after the data pattern is 0. It does not “know” that the data pattern is to repeat over and over. However, a continuous signal is being created by adjoining copies of the same waveform record. What is to be done with the extra 2000 points? In the example, a data pattern was selected in which the last two bits are 00. This means that the last two bits (2000 points) do not contribute to the convolved response, and it matches the convolution assumption that the data before the first bit in the pattern is 0. Thus, the 2000 points can be simply removed from the 30,000 point record, and the 28,000 point record will not have any discontinuities when concatenated.

Of course this was a selected example. The general solution to insuring that a convolved pattern can be concatenated is to add extra bits to the ends of the pattern before convolution. The extra bits simply duplicate the bits that would be there for a repeating pattern. In other words, add the first few bits of the data pattern to the end of the pattern. The number of bits to add depends on the length of the impulse response.

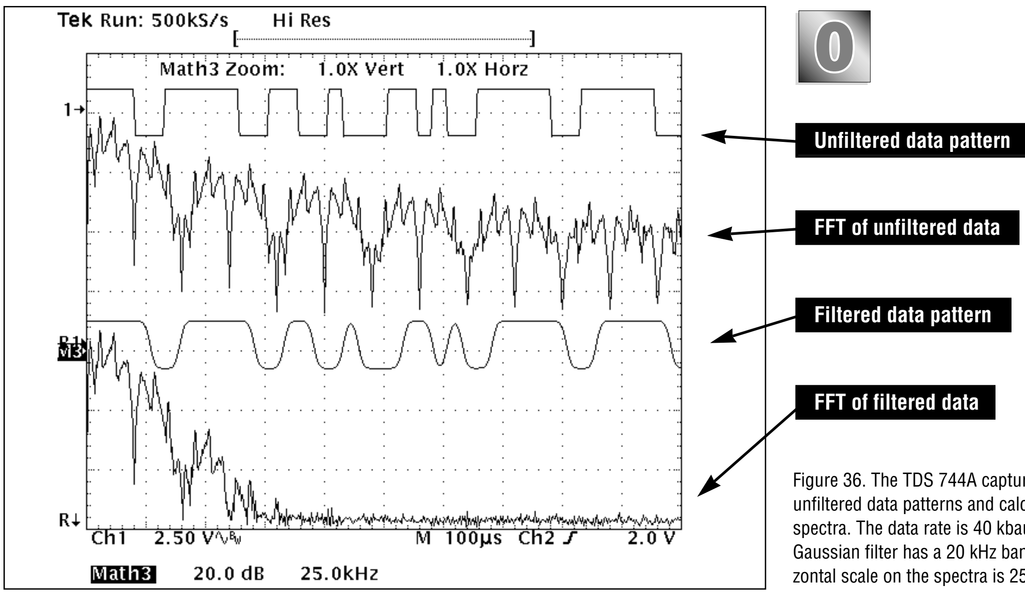


Figure 36. The TDS 744A captures the filtered and unfiltered data patterns and calculates their FFT spectra. The data rate is 40 kbaud, and the Gaussian filter has a 20 kHz bandwidth. The horizontal scale on the spectra is 25 kHz per division.

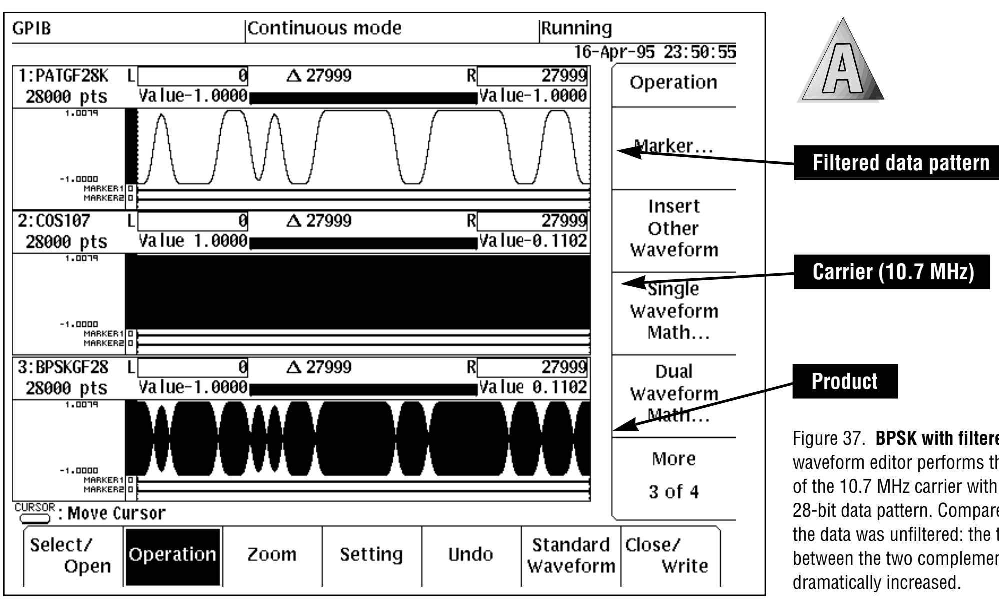


Figure 37. **BPSK with filtered data:** The AWG waveform editor performs the BPSK modulation of the 10.7 MHz carrier with the Gaussian filtered 28-bit data pattern. Compare to Figure 27 where the data was unfiltered: the transition time between the two complementary phases has been dramatically increased.

Figure 36 compares the original and filtered data patterns. The upper two traces are the unfiltered data pattern and its spectrum. The lower two traces are the filtered data pattern and its spectrum. Note how the spectrum of the filtered version rolls off more quickly. The spectrum of a modulated carrier shows the same results. Figure 37 shows the filtered baseband pattern modulating (BPSK) the 10.7 MHz carrier, as in Figure 27. Figure 38 shows the difference in their spectra.

The convolution operator can be applied to multi-level patterns. Figure 39 shows Gaussian filtered I and Q baseband patterns for the 16-QAM signal in Figure 32. (The unfiltered I pattern is shown in Figure 31.) The falling edge of the data clock output defines the center of the symbol period. Using the marker output as a data clock provides a convenient reference when characterizing the performance of symbol timing recovery circuits. Careful attention was given to wrapping data at the ends of the data patterns so that the convolution result would be continuous across the seams.

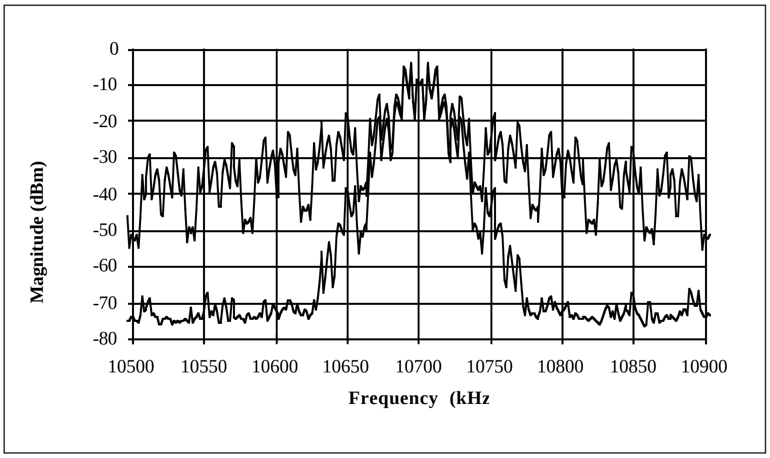


Figure 38. Spectrum analyzer plots of unfiltered (upper) and BT=0.5 Gaussian filtered (lower) BPSK carriers at 10.7 MHz. The data rate is 40 kbaud. Compare the roll-off to the baseband roll-off in Figure 35.

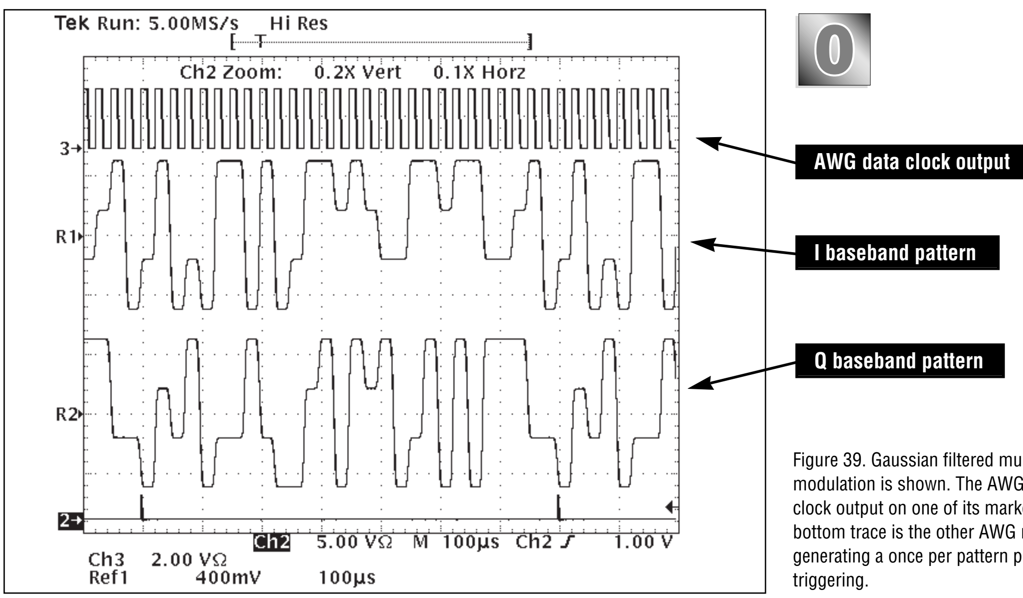


Figure 39. Gaussian filtered multi-level baseband modulation is shown. The AWG generated a data clock output on one of its marker outputs. The bottom trace is the other AWG marker output generating a once per pattern pulse for scope triggering.

Direct Sequence Spread Spectrum

The final example of digital modulation spreads the energy in a BPSK signal by amplitude modulating the carrier with a spreading pattern. In the same way that the baseband data pattern spreads the energy of an unmodulated carrier, a spreading pattern further spreads the energy of a modulated carrier. Pseudo-random sequences are generally used as the spreading pattern, with a bit rate or chipping rate that is much higher than the data bit rate. The 511-bit pseudo-random sequence generated in Figure 25 is used as the spreading sequence—the assumption being that a receiver would use the same sequence to de-spread the signal. Since the data pattern is 28 bits, one can directly implement a chipping rate to data rate ratio of 18.25 or (power reduction of 12.6 dB) by simply mapping the 511-bit sequence into 28,000 AWG record points.

Figure 40 shows how the AWG's waveform editor can horizontally interpolate a waveform into another record size. The spreading is implemented by using the AWG waveform editor to multiply the spreading sequence and the modulated BPSK carrier from Figure 37. The spectra of the original and spread signals are shown in Figure 41. The first null in the spread signal occurs at the chipping rate of 730 kHz, which is 18.25 times the 40 kHz data rate.

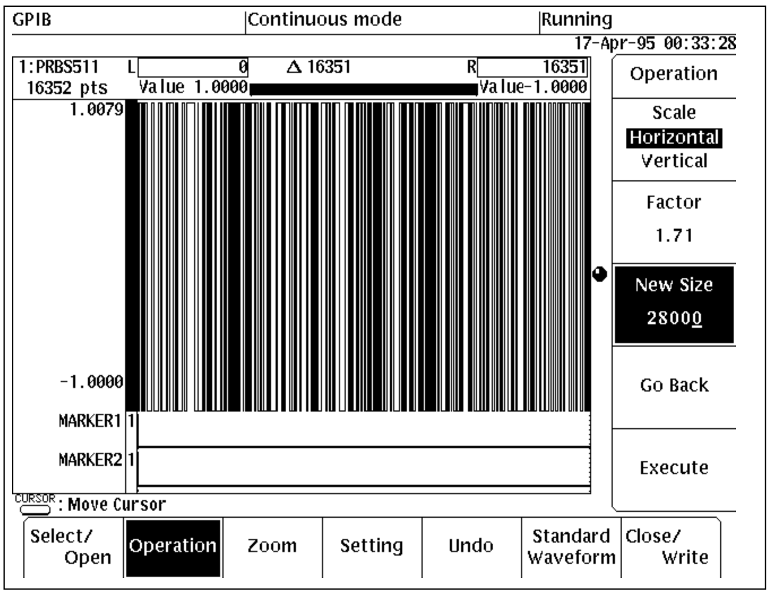


Figure 40. The AWG waveform editor performs horizontal scaling of the 511-bit spreading sequence. The original record length was 16,352 points. A "new" size of 28,000 points is entered, and the AWG expands and interpolates the waveform by a factor of 1.71.

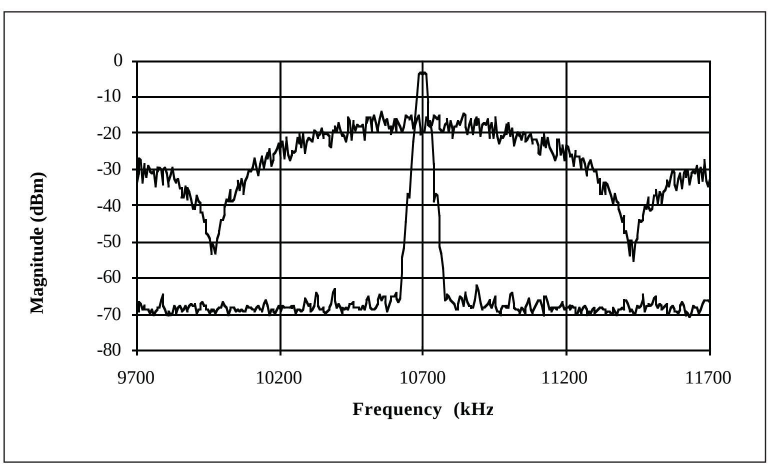


Figure 41. Spectrum analyzer plots of the BPSK carrier at 10.7 MHz before and after a 511-bit pseudo-random spreading sequence. The data rate is 40 kbaud and the chipping rate is 730 kHz. The original spectrum is the same as the filtered spectrum in Figure 38, but it is displayed here at a wider span.

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- AFG 2020 data sheet 11297
- Signals and Measurements for Disk Drive Design 11478
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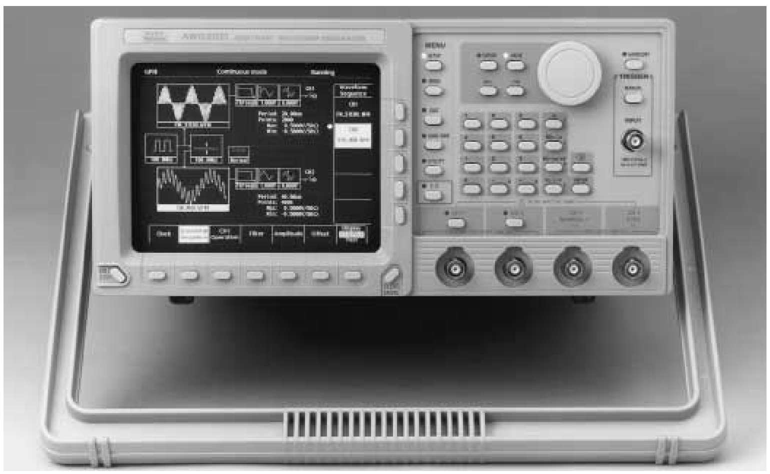
Tektronix AWG Arbitrary Waveform Generators give the most extensive capabilities for editing waveforms, with 8 or 12 bits of vertical resolution and waveform frequencies to 500 MHz. AWGs contain a high speed, high resolution digital to analog convertor with sophisticated triggering and mode settings, plus up to 4 megabytes of internal memory in which to create and edit waveforms.

You can import a waveform from a scope or disk, select one of the AWG's standard waveforms, or define your own from scratch. Using their powerful editing tools, you can edit the waveform right on the screen, then clock it out at rates up to 1 GS/s.

For computer-controlled production test applications demanding high throughput, the AWG 2021 is available in VXI format as the VX4792. This uncompromised signal source delivers the same bandwidth and accuracy as the AWG 2021, and its waveform record formats are identical to those of the benchtop unit. As such, the VX4792 allows easy movement of waveforms and instructions from the design lab to the production line.

Where the utmost signal purity is required, the AFG 2020 Arbitrary Function Generator offers direct digital synthesized waveforms with exceptionally low distortion and high frequency agility.



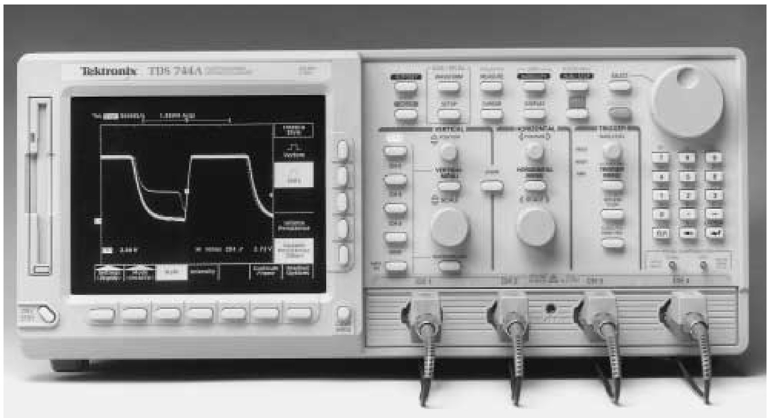
	AWG 2041	AWG 2021	AWG 2005
Clock Rate	1 GS/s	250 MS/s	20 MS/s
Max Output Waveform Frequency	500 MHz	125 MHz	10 MHz
Region Shift	Yes	Yes	Yes
Direct Waveform Transfer from DSOs	TDS, 2000 Series, 11000 Series, DSA, RTD 700 Series, and others	Same as AWG 2041	Same as AWG 2041
External Clock	Clock In & Out	Same as AWG 2041	Same as AWG 2041
Graphical Waveform Editing	Draws, Timing Table, Equation; FFT (Opt. 09), Digital Word/Pattern Generator (Opt. 03)	Same as AWG 2041; TTL Digital Word Generator (Opt. 03)	Same as AWG 2041; Digital Word/Pattern Generator option not available
Max P–P Amplitude into 50 Ω	2 V	5 V	10 V
Memory: Execution per Channel	1 MB; expandable to 4 MB (Opt. 01)	256 kB per channel	64 kB per channel
Memory: Non-Volatile	512 kB	512 kB	512 kB
External Modulation	AM	AM	AM
Output Channels	1 Analog & Complement; 8 ECL Digital (Opt. 03)	1 Analog; 2 Analog (Opt. 02); 12 ECL Digital (Opt. 03); 24 TTL Digital (both Opt. 02 and 04)	2 Analog; 4 Analog (Opt. 02); 24 TTL Digital (Opt. 04);
Predefined Waveforms	Synthesized, 10 MHz	Synthesized, 2.5 MHz	Synthesized, 2.5 MHz
Sweep	Sequencer and Equation Editor used to create sweep	Same as AWG 2041	Linear; Log; User-defined (Opt. 05)
Time Base Accuracy	1 ppm	50 ppm	5 ppm
Vertical Resolution	8 bits	12 bits	12 bits
Built-In Floppy Drive	Yes	Yes	Yes

TDS 744A Digitizing Oscilloscope

The TDS 744A represents the next generation of digitizing scope performance. This versatile general-purpose instrument introduces Tek's new InstaVu™ acquisition feature and sets a benchmark in waveform capture rate for DSOs. The TDS 744A can display more than 400,000 acquisitions per second—a rate 2,500 times faster than the most advanced DSOs available.

Other TDS 744A features include advanced triggering, graphical user interface, high-speed signal processing, complementary probing, and sophisticated documentation capability.

With its long record length and high bandwidth, the TDS 744A is an ideal complement to the 2000 Series AWGs for wireless communications testing.



	TDS 744A
Bandwidth	500 MHz
Input Channels	4
Sample Rate per Channel	
1 channel	2 GS/s
2 channels	1 GS/s
3 or 4 channels	500 MS/s
Vertical Resolution	8 bits; > 12 bits with Hi-Res; 11 bits with Averaging
Record Length	500 to 50,000 points per channel Max. 500,000 points (optional)
DC Gain Sensitivity	± 1.0%
Vertical Sensitivity	1 mV to 10 V/div; 50 Ω: 1 mV to 1 V/div
Automatic Measurements	25
Triggering System	Edge, Pulse (Width, 1 ns Glitch, Runt, and Slew Rate), Logic (Pattern, State, and Setup and Hold Time Violation), HDTV Video (optional)
Special Features	InstaVu, Dual Window Zoom, FFT, Differentiation, Integration, Color Monitor, 3½" Floppy Drive

For further information, contact Tektronix:

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