Understanding Radar Signals Using Real-Time Spectrum Analyzers

PRIMER

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Contents

Measuring Methods

The transient nature of radar pulses combined with modern pulse compression schemes often demand carefully designed test setups. The most fundamental pulse measurements are timing-related. Pulse width and period are the fundamental parameters, which correspond to repetition rate and duty cycle. Pulse shaping is often used to contain the transmitted spectrum, which requires additional measurements to characterize. The pulse shape includes the rise time, fall time, and other unintended aberrations of the signal. The aberrations include overshoot, undershoot, ringing, and droop. An important measurement challenge is to measure the transient splatter and spectral re-growth when the pulse shaping is not as intended.

Timing variation from one pulse to the next is another important timing measurement. There may be intentional or unintentional variations degrading expected system performance and it's important to be able to measurement these changes over many pulses.

Radar signals may also contain modulations within each pulse. Pulse modulations can be simple (e.g. BPSK or QPSK) or very complex (M-ary QAM or hopping). There are several common ways to measure modulations within a pulse.

Amplitude, phase, and frequency versus time are all single parameter measurements. They operate on a sample-by-sample basis. An amplitude measurement plots the magnitude envelope detection. The magnitude is calculated for each sample by squaring both In-phase (I) and Quadrature (Q) values for each sample in sequence, summing them and then taking the square root of the sum.

AMPLITUDE–VS–TIME

The lower right pane of Figure 1 shows a frequency versus time plot of a pulse modulated with a seven-step random frequency hop. The upper right pane shows the amplitude versus time plot for the same pulse. Observe how the higher amplitude pulses are also lower in frequency. Likewise, the lower amplitude pulses are higher in frequency. This radar transmitter has an amplitude roll-off and the output decreases with increasing frequency.

Because the pulses are moving randomly across the transmitter slope, the amplitude changes show up more dramatically than if it had been a linear chirp. In this case, the transmitter frequency response error can potentially cause the receiver to incorrectly determine target attributes.

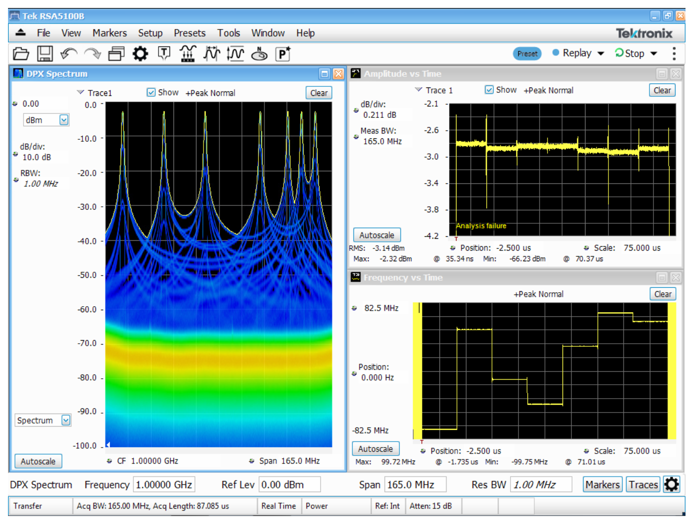

FIGURE 1. Seven hop random frequency hopped pulse.

PHASE–VS–TIME

Digital baseband data usually contains both In-phase (I) and Quadrature (Q) values and the phase at each individual sample can be calculated. The phase is the arctangent of Q/I for the simple phase versus time plot. The phase reference is most often the beginning of the acquisition record. Using this reference, the phase is plotted versus sample number (expressed in time).

In Figure 2, the right side of the display shows the frequency versus time plot and the left side shows the phase versus time plot for the same acquisition. The signal is a single pulse with Barker coded phase modulation. The phase plot shows thirteen phase segments within the pulse. For this particular coding, the phase values remain the same between the first five segments, between segments six and seven, and again between segments eight and nine, giving the appearance that those segments are wider than the last four.

The frequency plot shows very large frequency glitches because the phase modulation has two issues. First, the segments are not inherently phase-continuous. This does not impact the phase plot, but causes a large instantaneous frequency modulation at the instant of phase change. The discontinuity is a very brief wideband spectrum "splatter" that may exceed the allowed spectrum mask for a short time, may cause interference to equipment operating on nearby frequencies, and/or may create a recognizable "signature" for a particular radar.

Secondly, there is apparently little or no bandwidth limiting filter on the transmitter. This exacerbates the phase discontinuities. If the bandwidth were filtered and limited, the frequency plot would be closer to flat.

For the phase versus time plot, it is important to realize that since the phase reference is the beginning of the acquisition record, if the record starts within a pulse (triggered), then the phase may be similar from one acquisition to another. But if the beginning of the record is random (un-triggered), then the phase reference point will likely be in the inter-pulse noise. This will result in large random variations in the phase reference from one acquisition to the next.

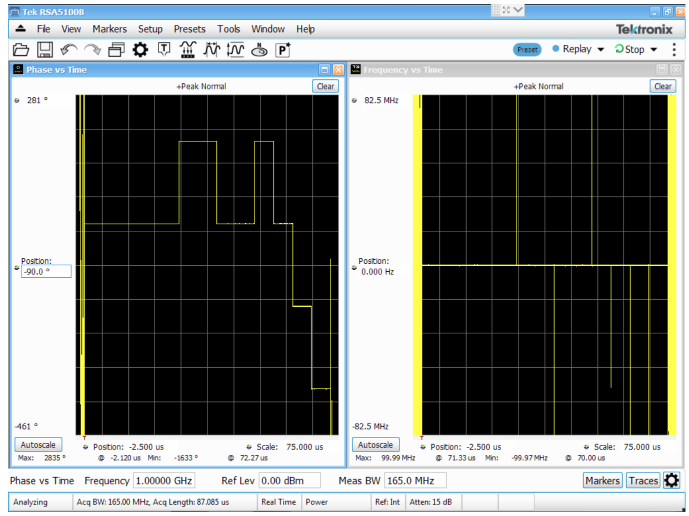

FIGURE 2. Barker coded pulse with Freq. vs Time on the right and Phase vs Time on the left.

FREQUENCY–VS–TIME

Frequency versus time measures the instantaneous frequency of a signal over a time of interest. Like a FM detector, it will measure the combination of all signals within its detection bandwidth, so the capture bandwidth of the instrument must be set, or another means must be employed to exclude undesirable frequencies (This is also true for a Phase versus Time measurement).

Frequency is simply the change in phase over time. In one cycle per second there are 360 degrees of phase rotation. The frequency at any two samples is measured by first measuring the phase at each sample and then dividing the phase change between the samples by the time between samples (as in "f = Δ Ø / Δt") from the IQ sample pairs.

DIGITAL MODULATION

Analysis of digitally modulated signals is more complex. Ideally, a modulation measurement will show the amplitude, the phase, or both plotted against the transmitted "symbols" (the data words transmitted). This requires matching the modulation type, symbol rate, and the measurement / reference filter parameters. Additional modulation measurements include constellation diagrams, error plots, signal quality, and a demodulated symbol table.

Pulses can have higher order modulations such as QAM, OFDM, and even direct sequence spreading (see Figure 3). These can spread the pulse spectrum, giving it less chance of discovery, and allow pulse compression in the receiver. They can even allow transmission of data contained within the radar pulses.

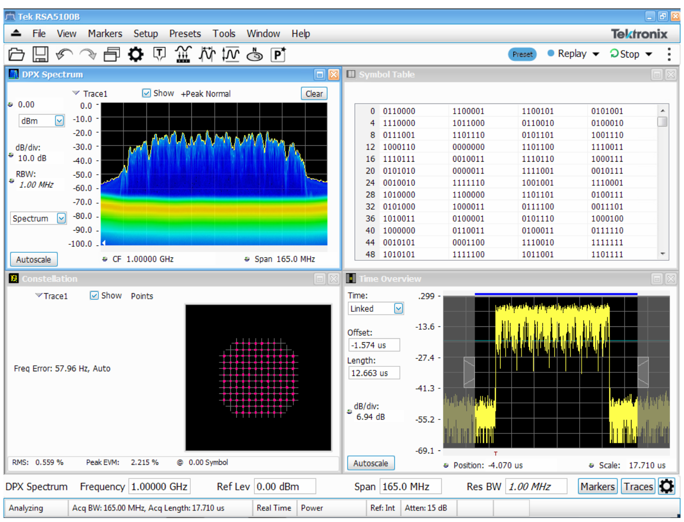

FIGURE 3. Demodulating QAM within a pulse.

SHORT FRAME (SINGLE PULSE)

Measurements made of a single pulse (sometimes called short frame measurements) depend on the intended use of the pulse. The applied modulation will determine the needed measurements. For simple single-frequency (CW) pulses the measurements may include power (or voltage), timing, shape, RF carrier frequency and RF spectrum occupancy.

LONG FRAME (MULTIPLE PULSES)

Measurement of a single pulse is not usually sufficient to assure transmitter performance. Many pulses can be measured, and any differences can be used to diagnose problems that may otherwise be difficult to find. A table of measurement results helps to manually see if there is a difference in a measurement result. Often, FFT analysis of the results make it possible to determine the root cause of any variations (see Figure 4).

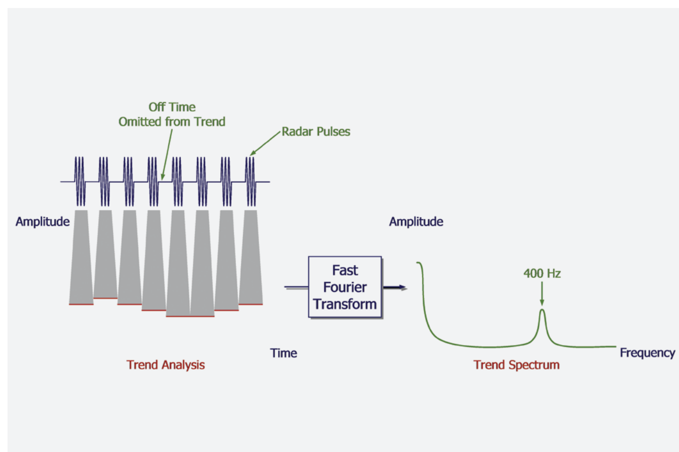

FIGURE 4. The process of performing an FFT on measurement results.

CENTER FREQUENCY OFFSET

Measurements on hopping radar signals, measuring signals over-the-air, and even measuring signals in the presence of adjacent channel interference have typically represented a challenge for measurement systems. Traditionally, either modulation hopping was required to be turned off, or you were challenged to capture a pulse sequence at the center frequency to be able to analyze the radar signal.

The flexibility to measure signals that are not captured in the center of the analysis bandwidth can be extremely important in the analysis of the true hopping behavior of a radar. Figure 5 shows a frequency hopped pulse signal. By de-selecting the measurement frequency lock to the center frequency, a sliding measurement window appears so the user can easily select the frequency of the interest over the acquired spectrum.

The flexibility of selecting a measurement window that is not at the center frequency is an invaluable method for over-the-air measurements and testing for problems with hopping radars that only manifest themselves during hopping conditions (such as frequency settling and timing issues).

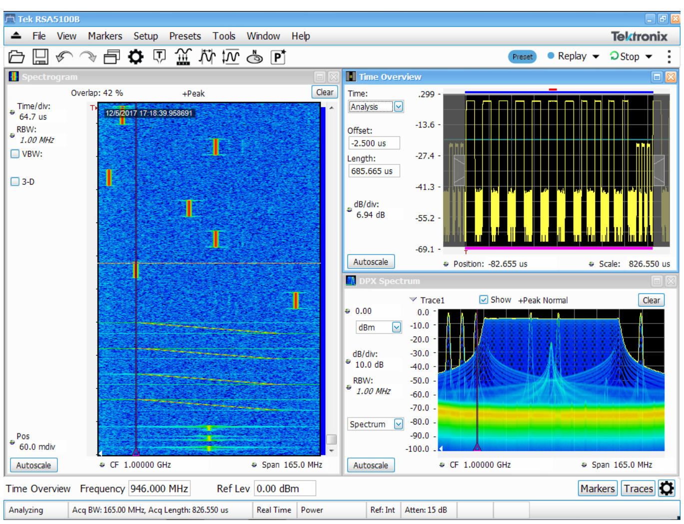

FIGURE 5. Pulse analysis is only performed on the set of pulses in the selected measurement window.

Choosing Measurement Parameters

There are several parameters that the user must set correctly before measurements are attempted. These affect the processing of pulsed signals, and are dependent on the character of the signal and on the desired interaction of the instrument with the incoming pulses.

MEASUREMENT FILTER TYPE

A crucial parameter when measuring a pulse signal is the measurement filter type and bandwidth. All measurement devices are inherently bandwidth limited. Once the signal is digitized (using either a spectrum analyzer or an oscilloscope) further digital processing can reduce and shape the measurement bandwidth. Narrower bandwidth filters will reduce the noise within the measurement bandwidth and therefore reduce the uncertainty of some measurement parameters. This is only useful in cases where the incoming pulse to be measured does not contain spectral components wider than the applied filter (either fast rise/fall edges, or wide frequency/phase modulations). Rise time measurement uncertainty is increased with the use of narrow filters.

If a pulse signal passes through a band limiting filter, there will be some signal distortion. A filter will add its own contribution to the pulse rise time. Any pulse with a sharp rise or fall time will have spectral components widely spaced from the carrier. The more of these frequencies removed by a filter, the more distortion (overshoot and ringing) can be introduced into the pulse signal. Filters also have phase and amplitude variations that introduce distortions even if the filter is wide enough to otherwise pass the pulse without problems.

PULSE DETECTION THRESHOLD AND MINIMUM OFF TIME

A typical pulse detection algorithm requires a set threshold amplitude. In some cases, there may be variations in the noise floor and it is desired that the measurements not be attempted on the noise. In an off-the-air situation it may be desirable to only measure the highest amplitude pulses from a nearby transmitter. The pulse measurements will search the acquired record and find the pulse top first. Then it will decide if any pulses exist that cross a user-specified threshold (see Figure 6).

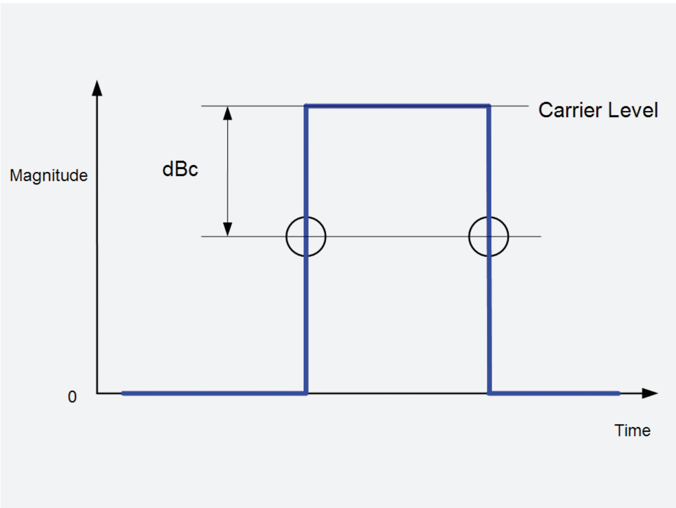

FIGURE 6. Pulse detection threshold.

Some pulses may not have flat tops. A pulse may also have intentional amplitude variations across the top including a reduction in amplitude that may cause a pulse detector to incorrectly find two separate pulses. In this case, it can be helpful to specify a minimum off time. This allows for a pulse with an amplitude dip below the threshold, but of a duration shorter than the minimum off time to be properly detected.

NUMBER OF PULSES TO MEASURE

The user needs to determine the number of pulses required for detailed statistics on the trends of pulse parameters. If the measurement does not need all the available pulses, then entering a smaller number in the can vastly reduce the time needed to process the data and get the pulse measurement results.

DROOP COMPENSATION AND RISE/FALL DEFINITIONS

Rise time and fall time measurements have two different definitions. Many measurements use 10% to 90% of full amplitude as the definition of the transition time, but in some cases the definition is 20% to 80%.

Even with this flexibility, it is often not good enough. How the top of a pulse is measured can greatly affect the definition of transition time. If the top of the pulse is flat, then there is no problem (see Figure 7). But if the top of the pulse is tilted or has droop then there is a potential problem (see Figure 8). If the pulse droops down, by 20% over the duration of the pulse and if the upper transition point is 90% of the highest part of the top, then the rise time will be correctly calculated. However, the fall-time will be quite incorrect as the falling 90% point will be in the middle of the pulse due to the droop.

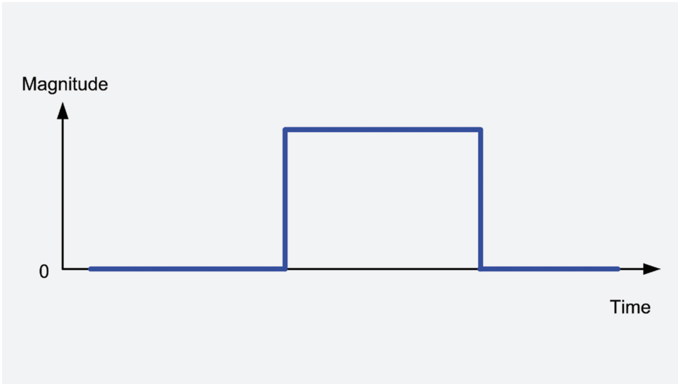

FIGURE 7. An idealized pulse representation.

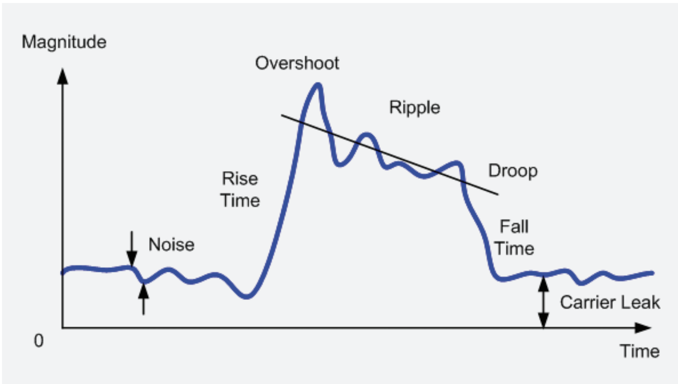

FIGURE 8. A real-world pulse can have many distortions.

Finding the Pulse

Before any parameters can be measured, a measurement system must first identify that a pulse exists and further locate some critical features of the pulse. Once the pulse is detected, the timing, amplitude, and frequency measurements can be determined.

USING THE THRESHOLD SETTING

Spectrum analyzers and other RF receivers often have dynamic range exceeding 100 dB, which gives visibility of very low-level signals, and low-level noise. The threshold setting prevents the detection algorithm from seeing the noise as pulses, as well as any overshoot, undershoot, and other pulse distortions. The threshold is usually specified in dBc relative to the pulse-top carrier amplitude. For a pulse to be detected, there must be an increase in the digitized power level passing through the threshold level. A corresponding decrease in signal power back through the threshold must also occur.

The actual detection of pulses is complicated by the extremes and variations in some of the parameters, which are encountered in modern pulsed radars. The duty cycle may be very small, which leaves the pulse detector looking at only noise for most of the pulse interval. The pulse timing may also vary from pulse to pulse, or the frequency of each pulse may hop in an unpredictable sequence. Even the amplitude may vary between pulses.

Other pulse detection difficulties arise if the pulses exhibit real-world characteristics such as ringing, droop, carrier leakage, unequal rise and fall times, or amplitude variations such as a dip in the middle of a pulse.

The greatest difficulty is a poor signal-to-noise ratio (SNR). Particularly as a pulse width gets narrower, the rise time gets faster. Similarly, as a frequency chirp gets wider, the bandwidth of the measuring system must can capture wider instantaneous bandwidth. Of course, as the bandwidth increases, the overall measured noise increases and the possibility of measuring unintended spurious signals grows.

FINDING THE PULSE CARRIER AMPLITUDE

The basic tradeoff in any pulse amplitude algorithm is between the reliability of the detection versus the speed of the algorithm. Even though the pulse measurements are generally an offline process (they only operate on data already stored in memory), the user still wants measurements to be fast.

A common carrier-level detection algorithm uses envelope detection. With this method, a simple CW pulse is represented by a voltage waveform of a baseband pulse that modulates an RF carrier. The actual mechanism is to take the square root of the sum of the squares of the (I) and (Q) values at each digital sample of the IF signal. In Figure 9, the blue trace illustrates an RF pulse. There are 16 complete cycles of the RF contained in this pulse. The pink trace is the complex envelope of the pulse.

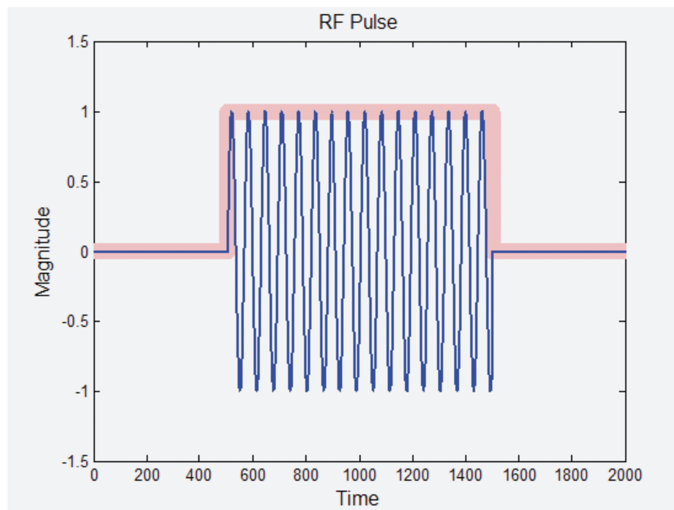

FIGURE 9. Pulse envelope detection as observed on an oscilloscope.

Modern pulse analysis methods speed up the process of characterizing transmitter designs by taking advantage of the increased computing power of modern test and measurement instruments, with their ability to quickly crunch through multiple algorithms. For example, one method applies four separate algorithms to perform pulse detection: Magnitude Histogram, Local Statistics, Moving Average, and Least Squares Carrier Fit. Each of these algorithms is loaded into the DSP engine of the instrument one at a time, with the simplest and fastest performed first. If a pulse is found at any time, the process ends. This method ensures that a pulse is detected and its amplitude is measured as quickly and accurately as possible.

LOCATING THE PULSE CARDINAL POINTS

Once it has been determined that a pulse does exist, a model of the pulse will be constructed with four "cardinal points" and four lines. These points and lines are the fundamentals from which all the measurements are referenced (see Figure 10).

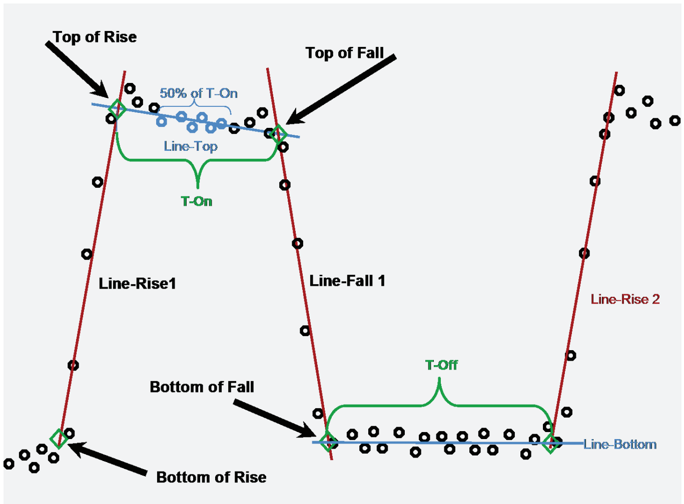

FIGURE 10. Cardinal points and rise/fall time lines.

Estimating the Carrier Frequency and Phase

All pulse frequency and phase measurements are made with respect to the carrier frequency of the pulse. The carrier frequency is normally specified by the user if the frequency is known. Some instruments can automatically estimate the carrier frequency, though automatic frequency detection is often unreliable. If the carrier were on constantly, there would be little difficulty determining the frequency. But for pulses, the carrier is typically on for short periods of time. These periods are often discontinuous, which makes pulse frequency estimation particularly difficult.

CONSTANT PHASE

In the case of a CW pulse, with a single carrier frequency and a constant pulse to pulse phase, the pulse frequency is calculated by the difference in frequency between the pulse carrier and the currently selected center frequency of the analyzer. If the pulse carrier frequency is the same as the center frequency, the phase of the signal within each pulse will be the same as the other pulses. This is the trivial case and results in no frequency offset.

Figure 11 shows the result if the frequency is not exactly at the instrument center frequency. Each pulse is measured for phase. Since the IF signal has been digitized and processed into sample pairs with In-phase (I) and Quadrature (Q) values, the carrier phase at any sample pair within a pulse can be calculated by taking the inverse tangent of the Q sample value divided by the corresponding I sample value.

This is done in the middle of each pulse to avoid errors that could be introduced by overshoot or ringing at the beginning and end of the pulse. The first pulse in the record determines the reference phase. There will be a different phase found from one pulse to the next. Plotting the phase of each pulse versus the time, a straight line will be found if the frequency is indeed constant. The slope of the line is the change in phase versus time. The formula for the delta frequency is the change in phase divided by 2π times the change in time. This determines the frequency offset between the measured pulses and the instrument center frequency.

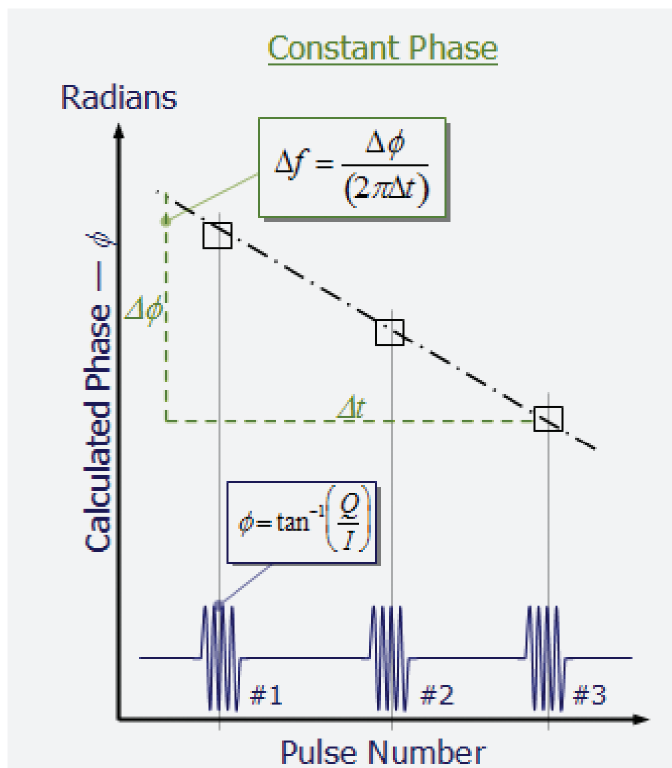

FIGURE 11. The calculations for a constant frequency offset with constant phase.

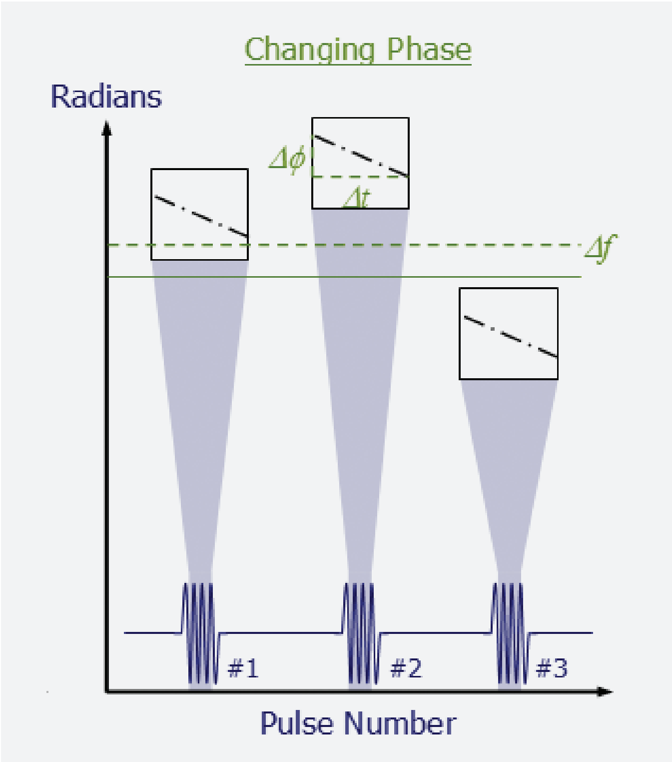

FIGURE 12. Frequency estimation method for varying pulse-to-pulse carrier phase.

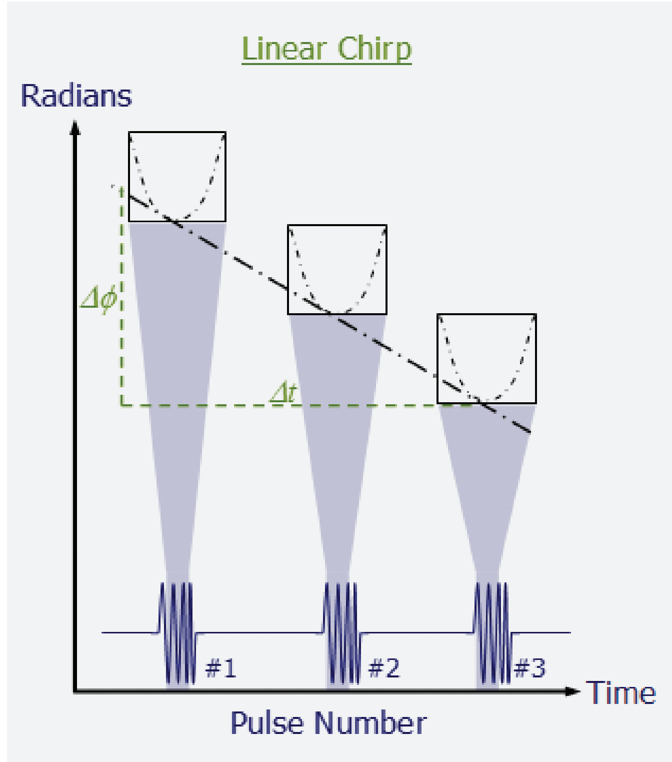

FIGURE 13. The calculations for frequency offset when each pulse is a LFM chirp.

CHANGING PHASE

Figure 12 shows the situation where the frequency is not exactly at the instrument center frequency and the phase of each pulse is different from the others. In this case, there is no clear phase relationship from one pulse to the next. A complete frequency measurement must be made for each pulse using the change in phase versus time across the pulse. All the different frequency measurements are averaged together. This not only finds the average frequency error, but it also averages out the errors that are inherent in frequency measurements over short time intervals. This method is more calculation-intensive than the others and should not be used unless it is required.

LINEAR FM (LFM) CHIRP

For a LFM chirp, it is a bit more complicated. Neither the frequency nor the phase is constant across each pulse and, if there is a frequency offset, the phase will vary from pulse to pulse. The phase is measured and plotted across the time of each pulse. Since the pulses are LFM chirps, the phase of each pulse will have a parabolic shape. Once the pulses have all been measured for phase, a tangent line is fitted to all the phase parabolas (see Figure 13).

Timing Measurements

Once the cardinal points have been located (see Figure 10), the timing measurements can be calculated. All timing measurements are made with reference to these points.

RISE AND FALL TIME

The rise and fall time of a pulse depends on the rise and fall times of all the RF components the pulse passes through. All passive elements, linear active elements and many non-linear active elements will degrade the rise and fall time of the pulses passing through them. Band-limiting filters will degrade the rise and fall time of pulses.

Rise time measures the amplitude transition time from bottom to top and fall time measures the amplitude transition time from top to bottom. Best-fit lines are found as part of the pulse and cardinal point location process. While one approximation would be to simply measure the time between the lower and upper points at each transition, this would be inaccurate. The measured time should be based on two points that lie on the actual pulse and at specified amplitudes. Amplitudes are normally specified as either the 10 and 90 percent levels or 20 and 80 percent levels of the full pulse amplitude.

PULSE WIDTH

The measurement points for pulse width are commonly defined as the 50% points of the rising and falling edges of the pulse. The user specifies whether the 50% points are measured in voltage or power. Once these points have been located, the width is simply the time between them. These points may be actual samples, or they may be interpolated between samples in the case of sparse sampling.

REPETITION INTERVAL/DUTY CYCLE

The aforementioned measurements can be performed within a single pulse. Other pulse measurements, however, require multiple pulses. Pulse measurements such as the Pulse Repetition Interval (PRI), Pulse Repetition Rate (PRR) and duty cycle can only be made if there is a second pulse that follows the one being measured. These three measurements use the time between the rising edge of the first pulse and the rising edge of the next pulse. The PRI is the measurement between the 50% points of the rising edge of the first pulse and the next pulse. The PRR is the inverse of PRI expressed as a frequency. The duty cycle is the pulse width divided by the PRI, and may be expressed as a ratio or a percentage.

PEAK AMPLITUDE

The Peak Amplitude measures the highest RMS voltage (local average power) of the pulse top. This represents the overdrive capability needed if this pulse is to be fed into a power amplifier. If a pulse has significant overshoot, the Peak Amplitude will be the highest of the overshoot peaks (Figure 14).

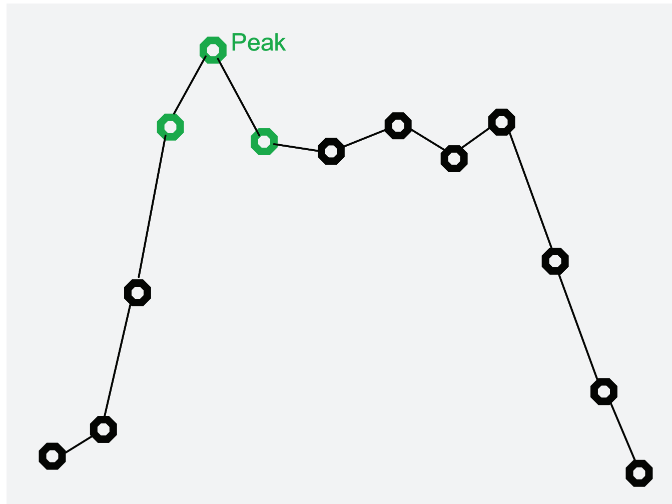

FIGURE 14. The Pulse peak is the highest amplitude sample.

AVERAGE ON POWER

Average ON Power is the integrated power (RMS) present only during the pulse "ON" time. This measurement is gated off during the time in between pulses, so no matter how much noise or other power may be incoming during the off time, it does not contribute to the measurement. The units of this measurement are often available as voltage, power, and dBm.

AVERAGE TRANSMIT POWER

The difference between Average ON Power and Average Transmit Power is that for the transmitter measurement ALL power is measured between the rising edge of a pulse and the rising edge of the subsequent one. This represents all power emanating from the radar transmitter integrated over time.

DROOP

The ideal pulse usually has constant power throughout its duration. But there are two conditions where this might not be the case. The first is sometimes found in high power transmitters (such as klystron amplifiers) if the amplifier is unable to maintain full power output during a long pulse. The result is a pulse that "droops" as the power falls off.

The droop measurement examines the set of samples making up the top of the pulse. The first 25% of samples across the top and the last 25% of samples are excluded from consideration because these are the most likely places to have overshoot distortions.

A typical droop measurement is the difference between the start and end of the pulse top expressed as a percentage of average pulse voltage amplitude (Figure 15).

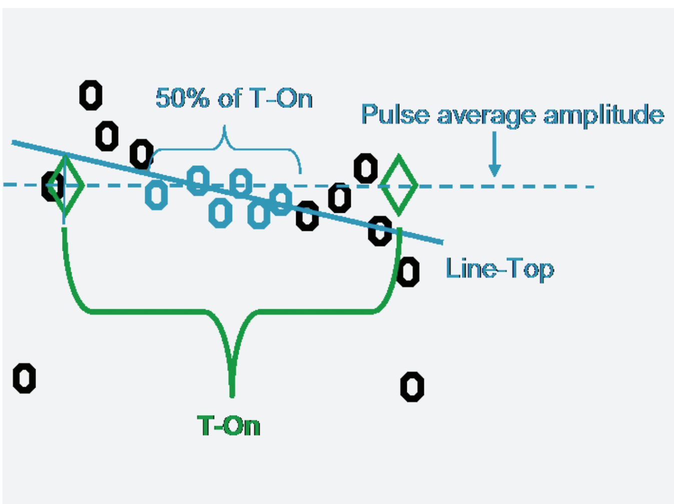

FIGURE 15. Pulse-top droop calculation.

PULSE TOP RIPPLE

Once the droop has been found, ripple can be measured. The ripple is defined as the difference between the peak positive and negative excursions from the best-fit line (which was already found to be the droop). This ripple is expressed in percent of the pulse-top voltage (see Figure 16).

This measurement does not differentiate between coherent ripple (such as a sinewave impressed on the pulse top) and random variations in the pulse top. All variations are considered to be ripple.

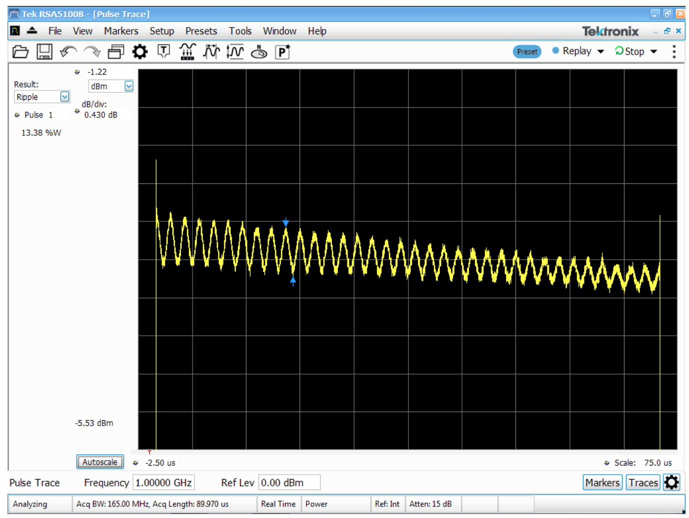

FIGURE 16. The pulse ripple measurement.

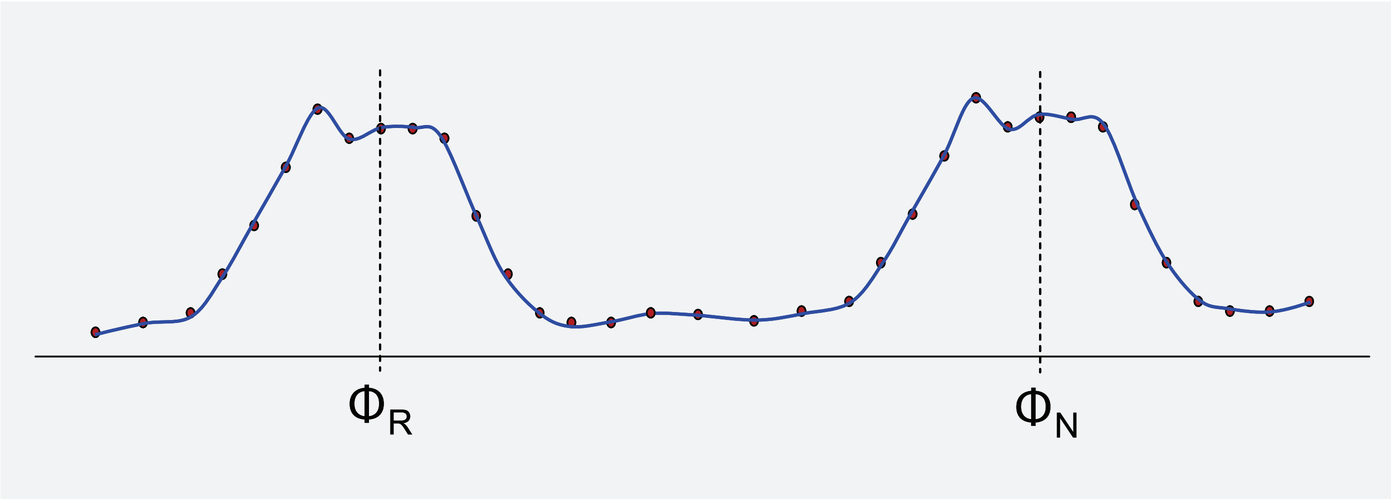

FIGURE 17. Measurement points for pulse-to-pulse measurements.

Frequency and Phase Measurements

CARRIER FREQUENCY

For CW pulses, a frequency measurement can be made using the marker on a spectrum display, However, this method may have limitations due to the PRF lines and the ability to locate the center depending on space interpolation and signal repeatability.

In this section we look at methods to find the carrier frequency within pulses in preparation for the automated measurement of all the phase and frequency parameters.

PULSE–TO–PULSE MEASUREMENTS

pulse-to-pulse measurements compare the phase or frequency of the pulse carrier at a certain point on each pulse relative to the same measurement made on the first pulse in the digital acquisition (Figure 17).

PULSE–TO–PULSE CARRIER PHASE DIFFERENCE

The measurement is made using the same I/Q processing as other phase measurements. However, the accuracy of this measurement is subject to four major influences that need to be considered: SNR, phase noise, estimation of the pulse rising edge, and overshoot present on the pulse as measured.

SNR EFFECTS ON PULSE–TO–PULSE PHASE

If the SNR is less than perfect, the added noise will cause the phase measurements to have uncertainty (see Figure 18). The variability is the gray circle, and the resultant angular measurement uncertainty is shown as the angle that encompasses the circle.

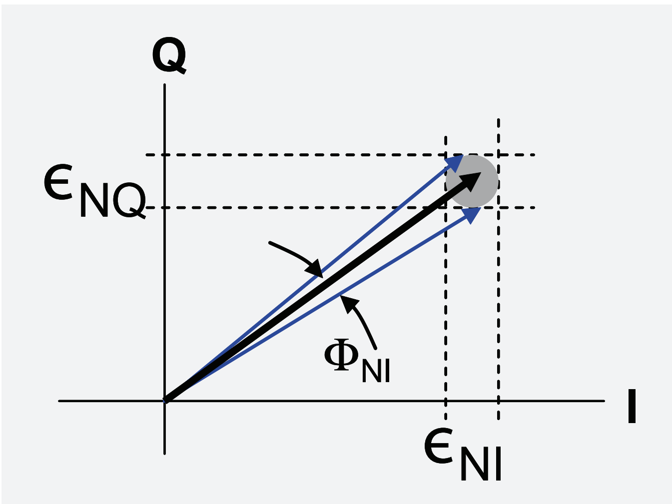

FIGURE 18. The S/N effect.

The formula for the SNR error, expressed as a ratio of powers (not in dB), is:

$$\Phi_{SNRerror} = 2\sqrt{\int_{1/2\pi\tau}^{BW} \frac{1}{SNR}\, df}$$

Where:

t = Time between measured pulse and reference pulse
BW = Measurement Bandwidth.

PHASE NOISE EFFECTS ON PULSE–TO–PULSE PHASE

Phase noise adds an uncertainty term directly to the measurement of phase. The added phase noise is heavily impacted by the length of time between the reference pulse and the measured pulse. The longer the time, the greater the uncertainty. This is a result of the longer integration time which includes the phase noise at lower offsets (see Figure 19). The phase noise at the lower offset frequencies rises significantly.

The formula for the Phase Noise error is:

$$\Phi_{PNerror} = 2\sqrt{\int_{1/2\pi\tau}^{BW} S_{\phi}^{2}(f)\, df}$$

Where:

t = Time between the measured pulse and the reference pulse
BW = Measurement Bandwidth.

For example, if the time between the reference pulse and the measured pulse is 1 millisecond, there will be 0.22 degrees of error. If that time were to increase to 100 ms, the error contribution rises to 4 degrees at a measurement frequency of 10 GHz.

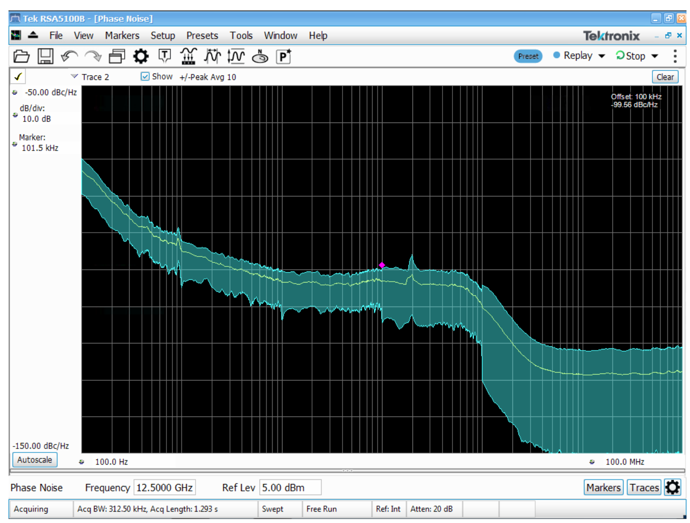

FIGURE 19. Example phase noise plot.

PULSE LEADING EDGE EFFECTS ON PULSE–TO–PULSE PHASE

Uncertainty in determining the shape and location of the rising edge of both pulses creates another source of error. The user defines the point at which the phase measurement is made on each pulse, which leads to a time delay from the center of the rising edge. If there is an error in determining the exact location of the rising edge, then there will be a time error in the location of the measurement position. This time error directly causes a phase error in the measurement.

Poor SNR adds vertical noise to all samples in the pulse, and this noise can cause timing errors. SNR-induced timing error has a greater effect on pulses with slow rise and fall times because a given magnitude of vertical noise causes larger relative disturbances in gradual slopes than it does for steep slopes. These disturbances introduce errors into the algorithms used to detect the 50 percent point in the pulse edges, which propagate onto any measurements using those points. If there is a frequency offset of the pulse carrier frequency, there will be increased phase error due to the leading edge uncertainty. This is because a frequency error translates to a constantly changing phase and the time uncertainty error walks up and down this changing phase.

OVERSHOOT EFFECTS ON PULSE–TO–PULSE PHASE

When a pulse passes through a band-limiting filter, the filter does two things. First, the further-out sidebands that are due to the rate of rise of the transition time will be filtered out. This adds some overshoot. Changes in group delay near the filter edges also contribute to overshoot.

Both analog and digital filters exhibit these effects. Digital filters also can exhibit a "Gibbs effect", which is a result of the digital sampling of the signal.

A crude simplification of the filtering effect is that a good Gaussian filter (to at least 12 dB down) will likely introduce up to 5% overshoot. Band-limited RF converters with sharper filters can introduce overshoot that is 30 to 50 percent of the pulse amplitude.

Figure 20 shows the decaying ringing that starts at the overshoot and decays as it progresses toward the center of the pulse top. If the measurement point is picked somewhere within the ringing, then with very small changes in the pulse width, pulse position, or other parameters, the measurement point will move up and down the ringing. This causes highly variable phase readings.

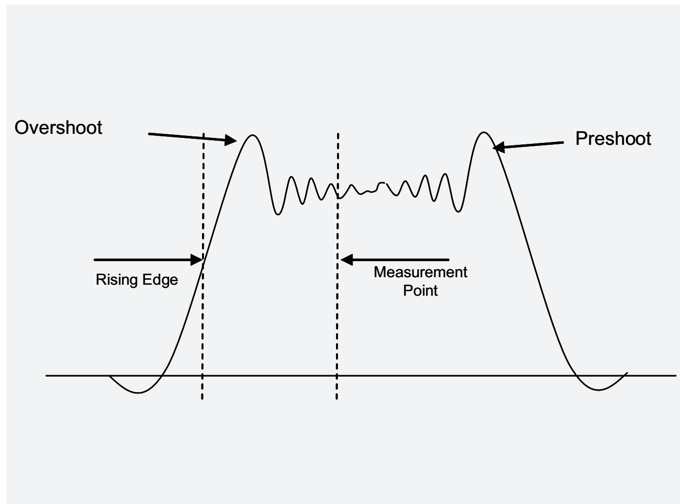

FIGURE 20. Overshoot usually occurs due to the filtering of a pulse.

PULSE–TO–PULSE CARRIER FREQUENCY DIFFERENCE

The pulse-to-pulse frequency measurement is just like the corresponding phase measurement, except the effect of the error is far less pronounced. Frequency measurements are a relative phase-change measurement made locally on the pulse, from which the frequency is calculated. This measured pulse frequency is compared to the reference pulse frequency which was found locally within the first pulse. Because frequency is a local absolute measurement and is not dependent on phase differences across multiple pulses, it does not suffer from increased uncertainty when the time between pulses is large.

As with phase measurements, the bandwidth of the measurement directly impacts the uncertainty due to the increased noise power in the measurement bandwidth. For FM chirps, the uncertainty also increases as the measurement point approaches the edges of the measurement bandwidth filter.

Chirp Measurements

There are specialized measurements required for verification of the performance of frequency chirped pulses. For simple time-of-flight pulsed CW radar, the main concern are the timing parameters of the pulse. For chirped radar, transmit errors may cause subtle receiver errors. Parameters such as pulse timing, center frequency, chirp frequency width, and frequency errors across the chirp will cause problems when added to the radiated transmitter signal. Phase stability within and across pulses contribute to the fidelity of the entire radar system.

FREQUENCY DEVIATION

Frequency deviation is the chirp frequency width. The plot defaults to zero frequency in the middle of the vertical axis (see Figure 21), which is the carrier frequency. The extent of the frequency sweep is measured as positive and negative frequency deviation from the carrier. The actual measurement is performed using the standard sample-to-sample phase shift divided by sample period calculation. The frequency difference from the carrier is also calculated at each sample.

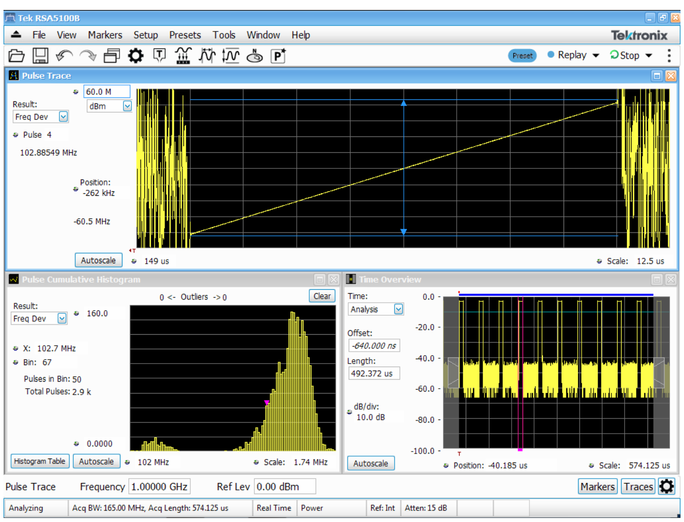

FIGURE 21. Frequency deviation of a linearly chirped pulse.

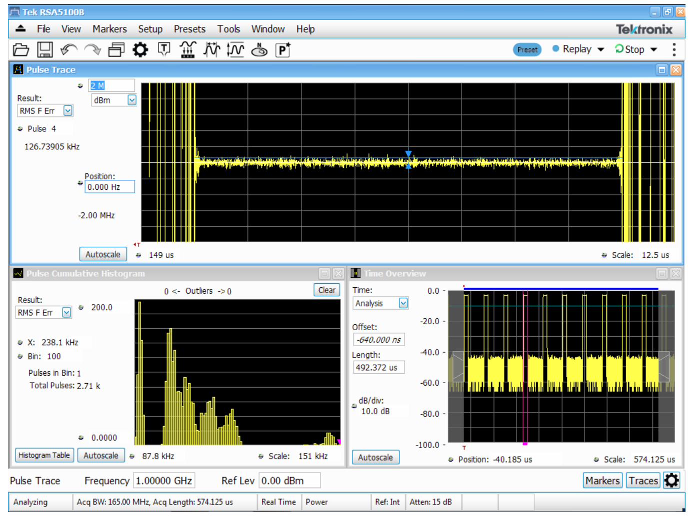

FIGURE 22. The frequency error versus an ideal model.

FREQUENCY LINEARITY

Once the frequency data has been built for the chirp, a best-fit straight line is calculated from the measured points. A linear FM model for the ideal chirp is subtracted point-by-point from the measured frequency plot (see Figure 22). There is a single numeric result available for each pulse. The calculation of this number is selectable as either the peak value or the RMS of all the values across the pulse measurement window.

PHASE DEVIATION

The term phase deviation is used because the phase change is similar to frequency deviation in FM modulation. The frequency term came from FM communications where the modulation is expressed as a change or deviation from the carrier frequency as the modulation is performed.

Phase calculation values are bounded by a limit of +/- 180 degrees, so the phase “wraps” around when the phase change between two samples would exceed this limit. Measuring absolute phase requires that the software "unwrap" the phase by adding or subtracting 360 degrees whenever the plot would have values that change from -180 to plus 180. The result is the complete non-minimum-phase change plot. There can be huge phase change numbers across a chirp, Figure 23 shows 44830 degrees across the chirp.

The RF pulse carrier frequency may be used as a reference against which the phase values are compared. When the phase is referenced to the carrier frequency (which is at the center of a linear FM chirp) the phase plot will be a parabola centered on the carrier. Each instantaneous phase value is calculated with respect to the center frequency, the phase deviation is the phase change across the pulse time and is plotted versus time.

If the chirp has increasing frequency with time, the parabola will have its "opening” facing up as in Figure 23. If the chirp is decreasing in frequency, the parabola will be upside down.

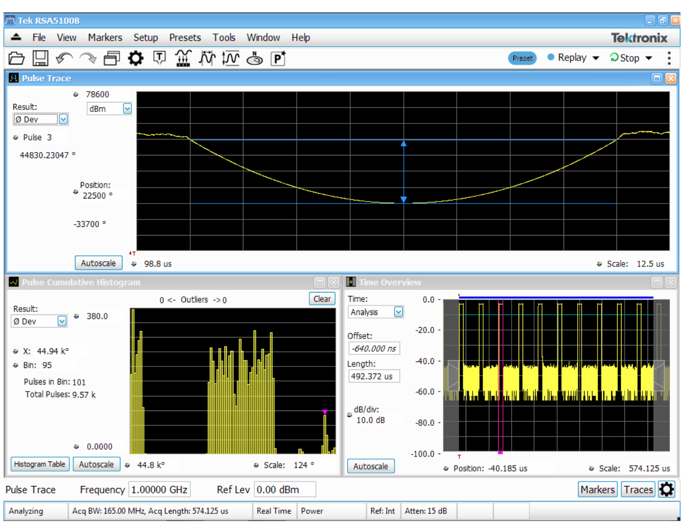

FIGURE 23. Phase deviation of a linear chirp.

PHASE LINEARITY

Phase linearity is the single most important characteristic of most frequency chirps. The most common reason for chirping a pulse is to compress the pulse in the radar receiver. When a pulse is compressed, all the frequency components are condensed in the time domain into one very short pulse. In this manner, the pulse return from each target will be very short, and a much longer transmitted pulse can now separately resolve targets which may be physically close.

When this pulse compression technique is used in a single target situation, the return signal from a perfectly linear chirp would result in a single impulse. If there were two closely-spaced targets, there will be two closely spaced impulses. However, if the transmitted pulse is not perfectly linear, the compressed return from a single target will have distortions in the impulse. Depending on the character of these distortions, they may produce side lobes on the impulse response which can obscure a smaller target. In extreme cases, this can produce false targets in the receiver. The most sensitive measure of these distortions is the phase linearity of the pulse.

To measure the phase error, the perfect reference phase deviation must first be determined. This reference can be calculated using the carrier frequency and frequency deviation values. For a linear frequency chirp with equal frequency deviation above and below the center frequency, the phase deviation is a parabola if the center frequency is the reference for phase calculations. The reference trajectory is then subtracted from the measured phase deviation, resulting in the phase linearity error across the pulse (see Figure 24).

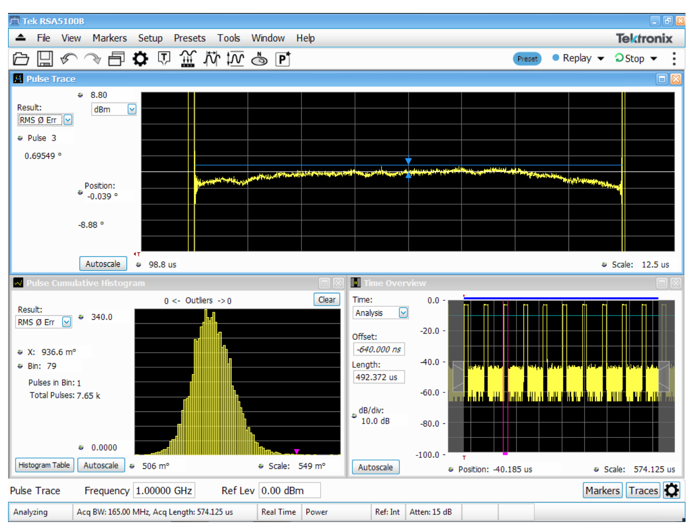

FIGURE 24. Phase error plot across a linear chirp.

IMPULSE RESPONSE MEASUREMENTS

Impulse response (IPR) is typically a time-domain measurement of the input-to-output transfer response of a network. This measurement is usually performed on separate components such as amplifiers, filters, switches, etc. Figure 25 shows the amplitude and time differences of an impulse response. In this case, we are performing a time-domain measurement of a frequency-domain linear FM chirp pulse.

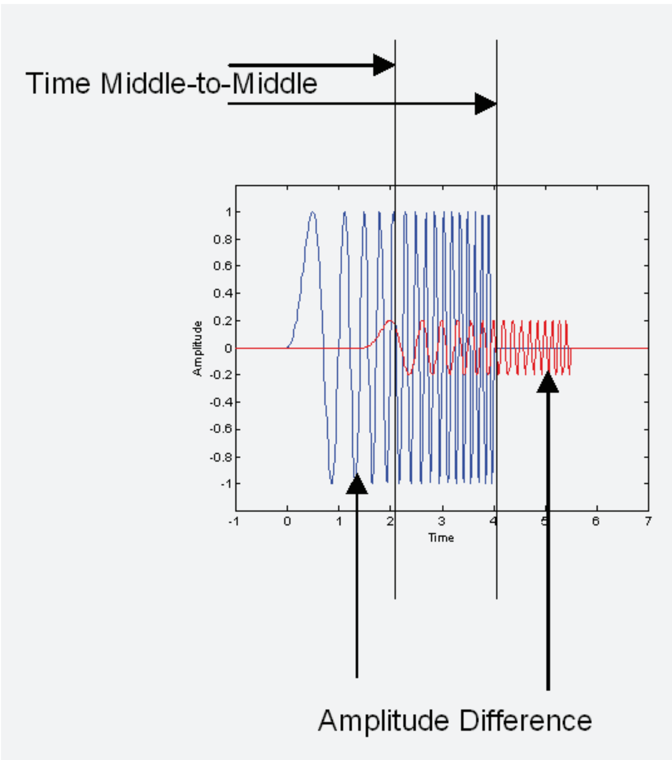

FIGURE 25. The impulse response measurement of a frequency chirp.

Any reflections or otherwise delayed copies of the main chirp will show up in the output plot as a sidelobe of the main lobe. Figure 26 shows an example of a mismatch error that can contribute to the impulse delay (reflections) and suppressed level of a response. The IPR measurement is sometimes referred to as a time sidelobe measurement.

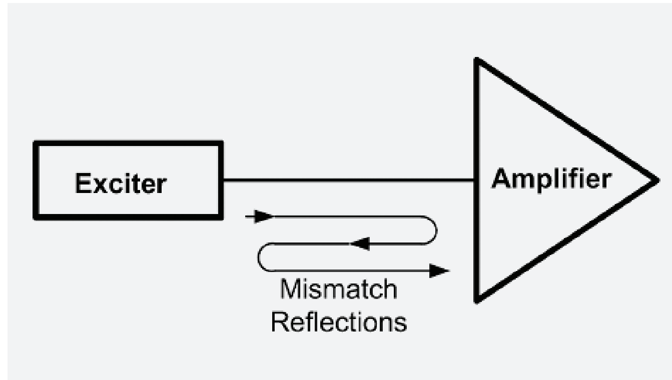

FIGURE 26. A major contributor to the response of the impulse are mismatch errors, which are sometimes referred to as “triple returns”.

The IPR method shows both time and amplitude simultaneously for signals that are copies of one another. Of the other available chirp measurements, none replace the detail or the insight of the IPR measurement method:

- **Frequency vs. Time** only work for single RF signals. If multiple signals are present, an FM discriminator will follow the higher amplitude signal, or produce noise.
- **Spectrogram** can see multiple signals at the same time, but it cannot compare two signals for errors if they are copies of one another. More importantly, the spectrogram is limited in time resolution. It can see no shorter time than one FFT frame of digitized samples of the signal.

Several chirp defects are best discovered using the impulse response. Both time reflections and incidental modulations can be discovered in this way. The frequency sidebands that result from undesired modulations present on a chirp pulse appear as a lower amplitude chirp on both sides of the main chirp pulse.

As the chirp changes frequency, the sidebands move along with the carrier and are indistinguishable from any other side lobe except that they appear on both sides of the main lobe.

The relationship between the impulse side lobe delay time and the frequency components of the chirp is given by the formula

$$\Delta T = F_m \left(T_d / F_d \right)$$

Where:

ΔT = the time difference between the time side lobes and the main lobe

F_m = the frequency of the incidental modulation

T_d = the duration time of the chirp

F_d = the frequency sweep width during the chirp.

Figure 27 shows the IPR amplitude response of a reflected pulse due to multipath interference. The IPR measurement method can be an important tool in assessing the overall quality of the chirp response.

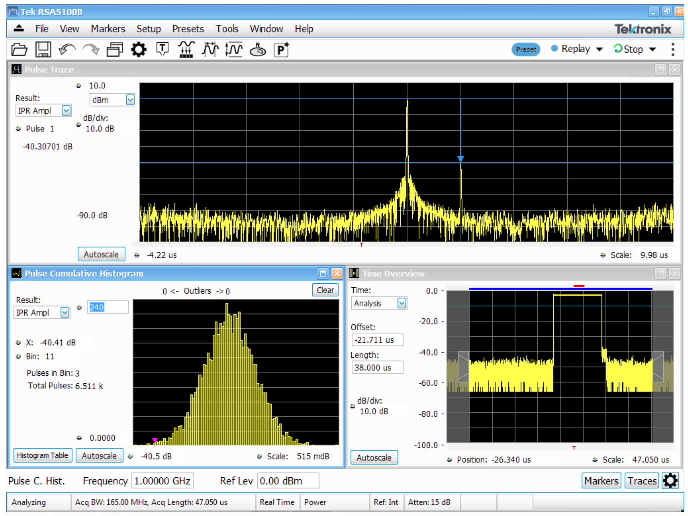

FIGURE 27. Reflection and intermodulation effects can be characterized using the IPR measurement method.

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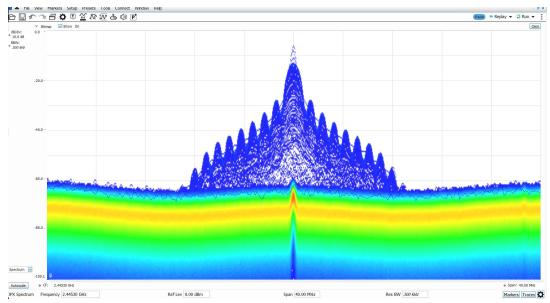

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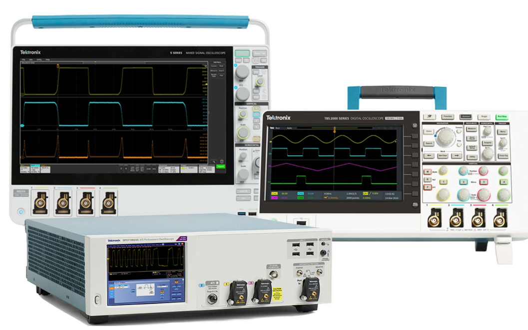

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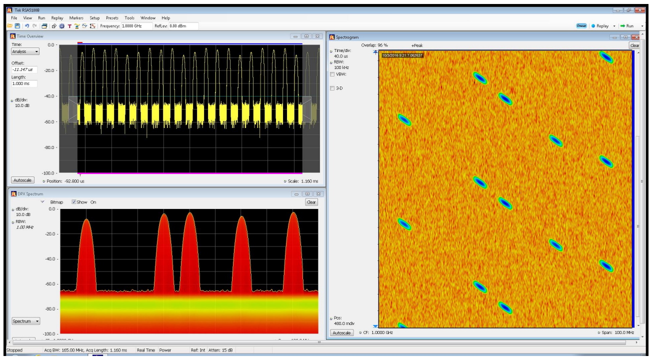

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