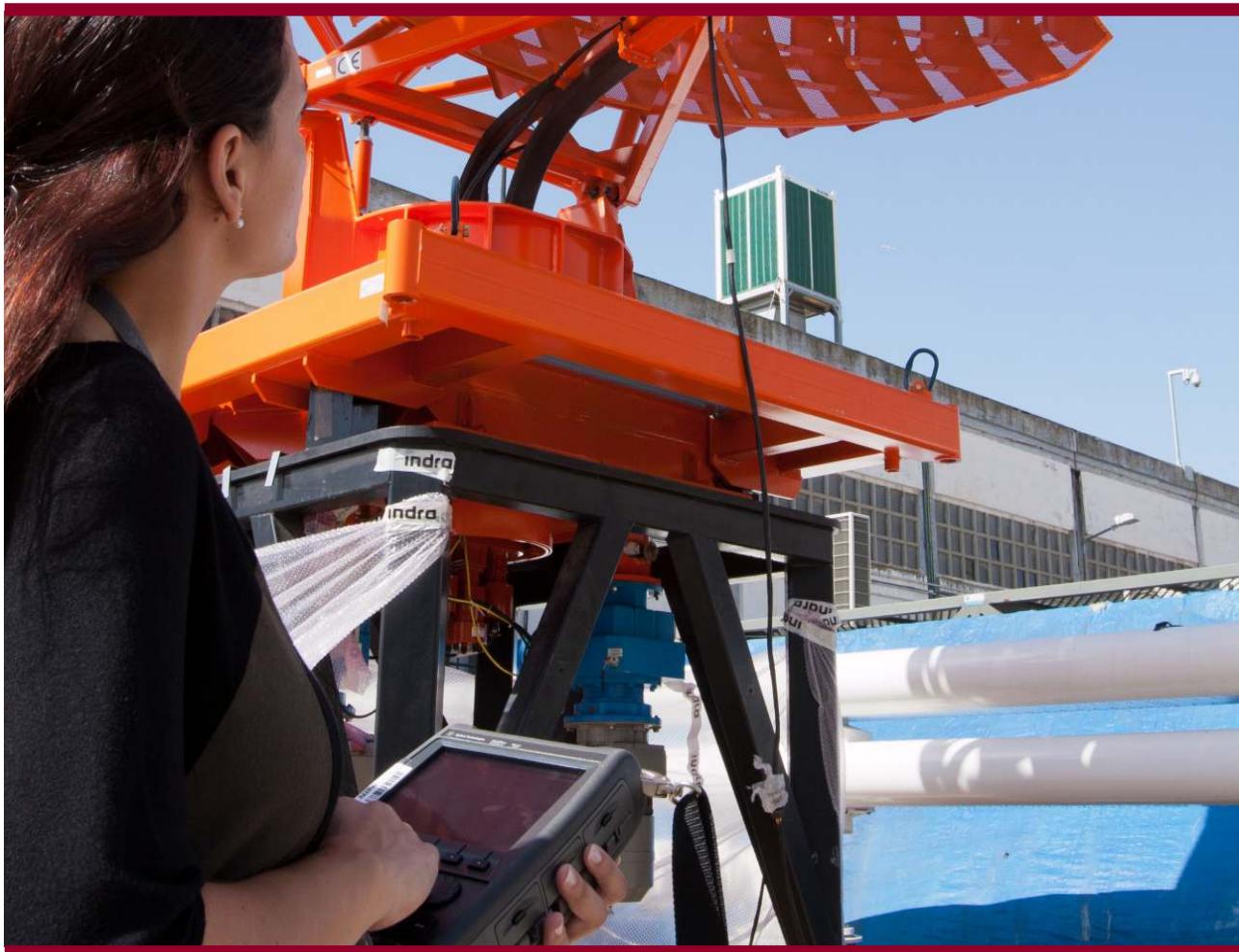




Techniques for Precision Validation of Radar System Performance in the Field

Using FieldFox handheld analyzers

Application Note



This application note provides an overview of field testing radar systems and Line Replaceable Units (LRU) using high-performance FieldFox combination analyzers having multiple measurement modes including a peak power analyzer, vector network analyzer, spectrum analyzer and vector voltmeter. This application note will show several measurement examples of pulsed and secondary radar signals and also reviews the basics of monopulse radar.

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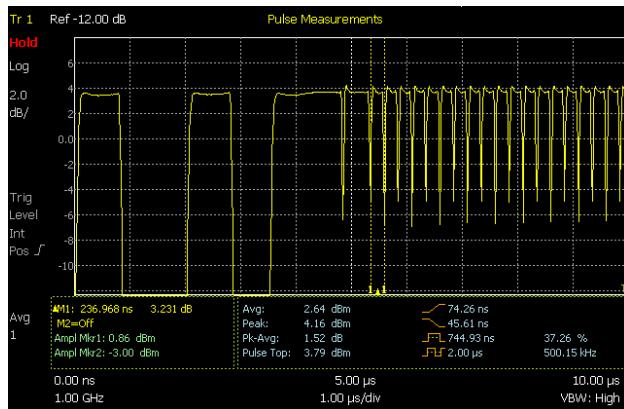
Introduction

Modern radar systems are typically classified as ground-based, airborne, ship-based or space borne. Radars have numerous applications including civilian air-traffic control, meteorology, traffic enforcement and military air defense. Key aspects of any radar system include frequency of operation, waveform characteristics and antenna type. Unmodulated continuous wave (CW) radars can measure target velocity and angular position. Range information is typically extracted using some form of modulation such as a pulsed waveform. These types of "primary" radars work by transmitting a waveform that is reflected off the target's surface and then these echoes are measured at the radar's receiver. There are other types of secondary or "beacon radars" creating a two-way data link between a ground station and an aircraft. Secondary radar originated from the Identification Friend or Foe (IFF) radar system developed during World War II and complements the limitations of the primary radar. Modern beacon systems, such as the Air Traffic Control Radar Beacon System (ATCRBS), separate the interrogation and reply frequencies resulting in stronger received signal levels at the ground station and improved weather-related performance.

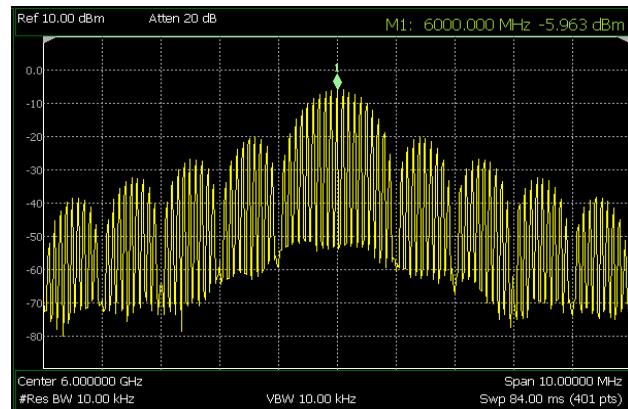
For example, figure 1a shows a field measurement of a beacon interrogation waveform captured using a peak power sensor and FieldFox analyzer. The waveform includes coded-pulse pairs for requesting aircraft identity and altitude. This time domain measurement display shows the pulse profile as a function of time and includes a table for peak power, average power, pulse width and rise and fall times. Figure 1b shows the measured spectrum of a radar transmitter using a rectangular pulsed waveform. This frequency domain measurement can be used to determine the center frequency of the RF carrier as well as the absolute amplitude of individual frequency components.

When maintaining and troubleshooting radar systems and components in the field, it is often necessary to measure both the time domain and frequency domain performance over a variety of test conditions. While traditional methods for measuring time and frequency performance of radar systems included 3-4 different benchtop instruments, modern "all-in-one" or combination analyzers provide the most convenient and economical solution to field testing. This application note provides an overview of field testing radar systems

and Line Replaceable Units (LRU) using high-performance FieldFox combination analyzers having multiple measurement modes including a peak power analyzer, vector network analyzer, spectrum analyzer and vector voltmeter. This application note will show several measurement examples of pulsed and secondary radar signals and also reviews the basics of monopulse radar starting in the next section.



(a) Beacon waveform in time



(b) Spectrum of a radar pulse

Figure 1. (1a) Time domain measurement of a beacon interrogation waveform and (1b) frequency domain measurement of a pulsed radar signal

Monopulse radar basics

One of the most widely used radar techniques for deriving the angular information of a target is the monopulse system. The monopulse technique can estimate these angles with higher accuracy than comparable systems while using a single (mono) pulse measurement in time. Figure 2 shows a simplified block diagram of a monopulse radar with capability for determining target angle in either elevation or azimuth. The transmitter creates a pulsed waveform that is applied to a duplexing network, such as a circulator or switch, which directs the high power signal to the antenna. If the antenna is mechanically rotated, the connection between the transmitter and the antenna is managed through a rotary joint. The transmit signal is applied to the "sum" (sigma) port of the antenna assembly which ideally creates a thin beamwidth pattern that is perpendicular to the antenna plane. This beam direction is often called the boresight of the antenna. This transmitted signal illuminates the target which returns a reflected signal. The receive antenna simultaneously creates two overlapping patterns referred to as the "sum" (sigma) and "difference" (delta) patterns. As shown in the figure, the sum pattern maintains a peak in the boresight direction and the difference pattern contains a null in the boresight direction. In this figure, the antenna pattern sidelobes are omitted for simplicity.

The received signals from the sum and difference antenna ports are downconverted and measured by the radar's signal processing subsystem for target detection. It is very important that amplitude and phase tracking is tightly controlled between the sum and difference channels otherwise errors in angle calculations will occur. A low-noise stable local oscillator, or STALO, provides the signal source for the downconversion.

One issue with this basic monopulse system occurs at short ranges when the antenna sidelobes may receive signals high enough to exceed the detection threshold and incorrectly report a target. The next section reviews a technique for suppressing any large amplitude signals that may enter through the sidelobes of the antenna pattern.

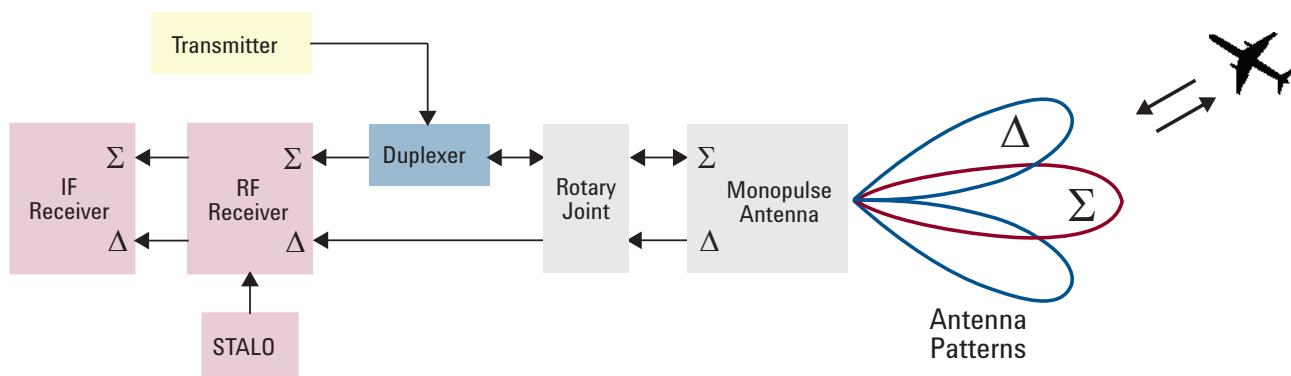


Figure 2. Simplified block diagram of a monopulse radar system

Monopulse radar with sidelobe suppression

When there is a possibility that false detections can result from energy entering the sidelobes in the monopulse antenna pattern, a secondary "omnidirectional" antenna may be added to the system to improve the overall detection performance. Figure 3 shows the addition of a secondary receiver which includes the omnidirectional antenna with pattern labeled with an "omega" symbol. The antenna gain of the omnidirectional antenna is lower than the peak gain of the sum pattern and this gain difference will be useful when determining if a target is within the boresight of the antenna. Figure 3 includes a representation of the sidelobes in the sum pattern. In the signal processor, the outputs from the sum, difference and omega channels are compared and those signals having higher power

level in the omega channel relative to the sum channel are assumed to be signals coming from the antenna's sidelobe. The total receiver gain of the omega channel can also be adjusted and also used to cancel the undesired energy received from the sidelobe. The technique of adding the secondary (omega) channel to improve the performance of a monopulse radar system is called Sidelobe Suppression (SLS). The secondary channel in figure 3 also shows a second transmitter connected to the omnidirectional antenna through a separate duplexer. This auxiliary transmitter is important to beacon systems when attempting to identify the location of an aircraft relative to the ground station. The next section shows an application for using this auxiliary transmitter in air traffic control radar.

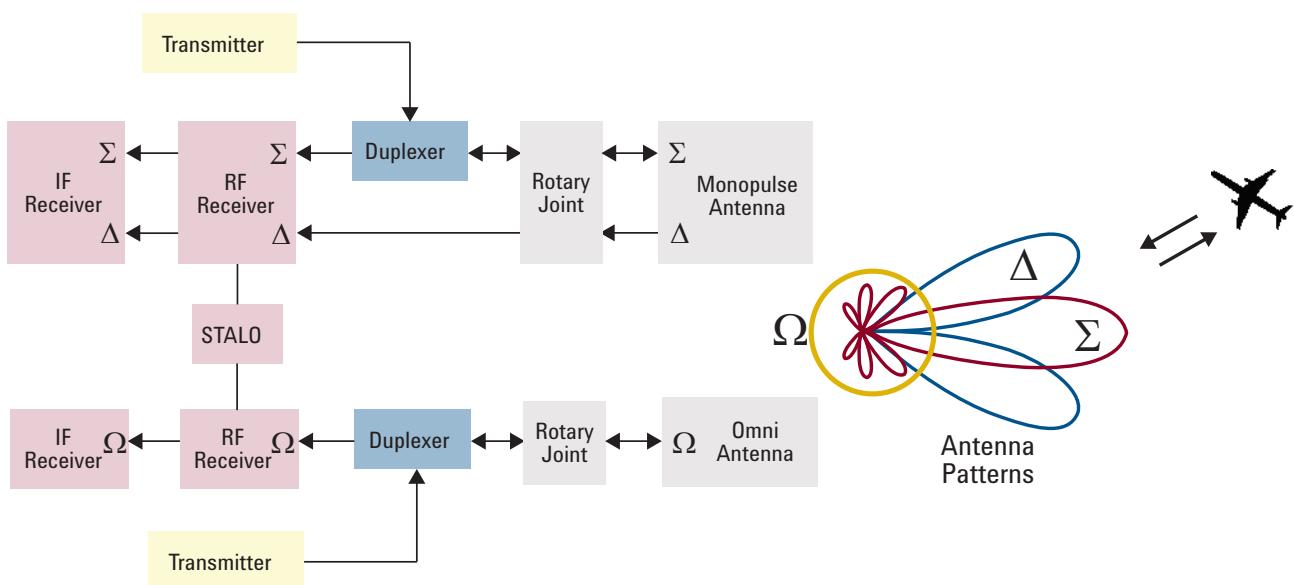


Figure 3. Simplified block diagram of a monopulse radar system with sidelobe suppression (SLS)

Application of sidelobe suppression to Radar Beacon System

A typical Air Traffic Control Radar Beacon System (ATCRBS) is based on the similar block diagram to the monopulse system previously discussed in figure 3. The beacon system is a two-way “data link” between a ground station and a transponder that is installed onboard the aircraft. The data link begins when the ground station transmits an interrogation signal requesting the aircraft’s identification or altitude. The aircraft transponder replies with the requested data. The ground station-to-transponder transmissions occur at a carrier frequency of 1030 MHz. The transponder-to-ground station replies are transmitted at a carrier frequency of 1090 MHz. Data is encoded onto the RF carriers in the form of pulsed sequences [1]. Figure 4 shows the transmitted and received data sequences for the ground station-to-transponder link. The pulse pairs, P1 and P3, are transmitted at specific time intervals denoting whether aircraft identification or altitude information is requested. For example, identification requests (Mode A) use a relative spacing between P1 and P3 of 8 microseconds. Altitude requests use

a 21 microsecond spacing (Mode C). The P1/P3 pulse sequence is transmitted by the high-gain sum (Σ) antenna.

To avoid undesired replies from aircraft transponders receiving energy from a sidelobe of the sum antenna, the ground station transmits a secondary pulse, shown in figure 4 as the P2 pulse. This secondary pulse is transmitted through the omnidirectional (Ω) antenna. The timing relationship places the P2 pulse between P1 and P3. As all the pulses are transmitted on the same 1030 MHz carrier, the aircraft transponder will receive these waveforms as a single time sequence which can be used to compare the relative pulse amplitudes. If the aircraft is located near the boresight of the antenna system, the received P1 amplitude will exceed the P2 amplitude, as the antenna gain of the sum beam is much higher than the gain of the omnidirectional antenna. Under these conditions, the aircraft transponder will reply to the ground station. Figure 4 shows the received pulse sequence when the aircraft is positioned

at the boresight of the antenna system (position #1). When the aircraft is located off boresight, shown as position #2 in figure 4, the received P1 amplitude no longer exceeds P2 and the aircraft transponder will not reply to any ground station requests. As the antenna system is mechanically rotated in azimuth, the aircraft at location #2 will eventually enter the main beam and properly reply to ground station interrogations.

During installation, periodic maintenance and troubleshooting of this or any radar system, it is often required to field test and tune the numerous functional blocks, also known as Line Replaceable Units (LRU), that make up the radar. Because of the unique amplitude and phase relationships between the various channels in a monopulse system, testing LRUs often requires coordinating and comparing waveforms in the time and frequency domains. The next section of this application note will review the various domains and measurements required to test the operation of the LRUs in the field.

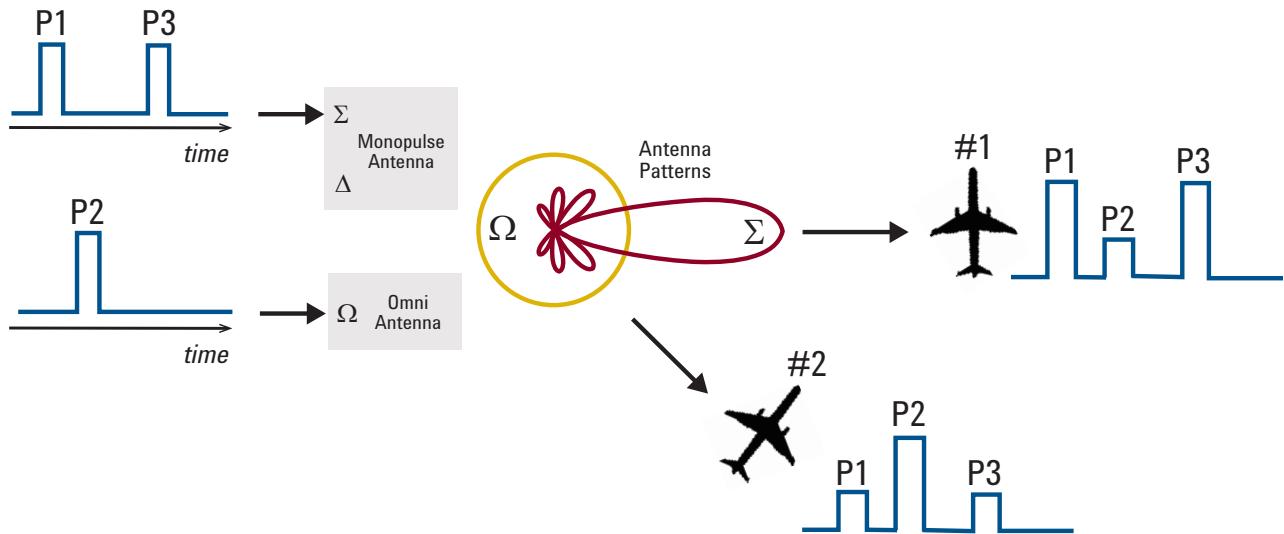


Figure 4. Block diagram of an Air Traffic Control Radar Beacon System (ATCRBS) showing transmit pulsed waveforms and the respective received waveforms at the aircraft transponder

Time and frequency domain measurements

When field testing LRUs of any radar system, there is typically a set of basic measurements that must be made in both the time and frequency domains. Time and frequency measurements result in absolute and relative type measurements. For example, figure 5a shows a time domain measurement of the peak power of a pulsed radar signal. This measurement was made using a peak power sensor connected to a peak power meter. A marker is used to measure the peak amplitude at a specific point within the pulse. Absolute measurements may also be made in the frequency domain using a variety of instrument types including a spectrum analyzer, vector network analyzer (VNA) and vector voltmeter (VVM). For example, figure 5b shows the measured spectrum, the pulsed radar signal and a marker is used to measure the amplitude at a specific frequency. LRUs that contain their own signal source are typically measured using a spectrum analyzer. VNAs and VVMs are typically used to measure the amplitude and phase of transmission paths which may include cables, filters and amplifiers.

Relative time domain measurements are also made using a peak power sensor and peak power meter. Figure 5c shows the relative measurements between two points in time. This type of measurement is useful for characterizing timing features such as pulse width, rise time, fall time and pulse repetition interval (PRI) to name a few. Relative frequency domain measurements can be performed using a spectrum analyzer, VNA and VWM. Figure 5d shows the relative amplitude (insertion loss) between two different coaxial cables. Along with relative amplitude, the relative phase between multiple channels, is an important measurement in monopulse radar systems and will be discussed later in this application note. It is worth noting that all the measurements shown in figure 5 were captured using a single FieldFox analyzer with multi-function capability. When making measurements in the field and/or challenging test environments, selecting the appropriate instrument types is critical to successful and accurate results.

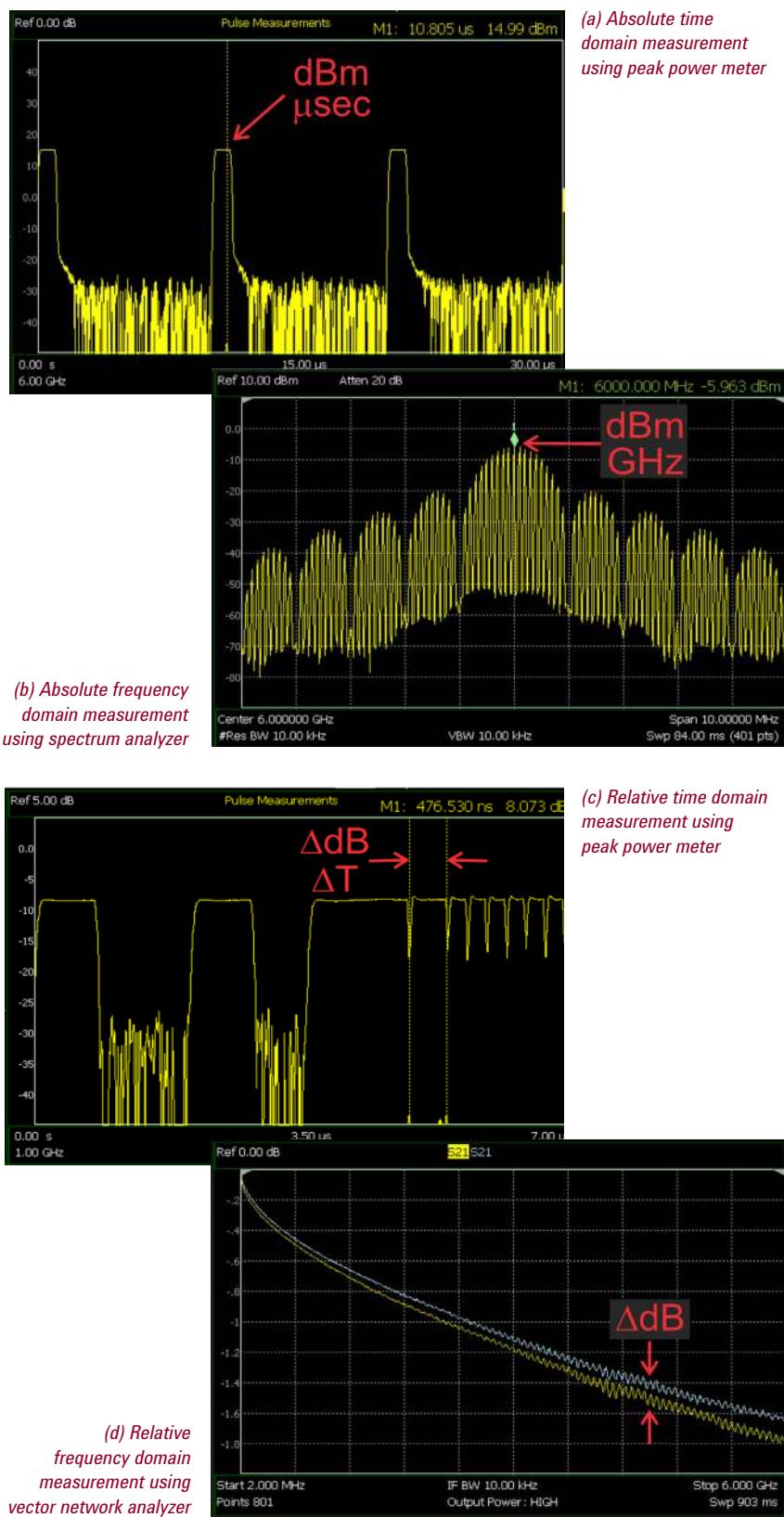


Figure 5. Time and frequency domain measurements of radar signals and radar components

Instrumentation for field testing

With the numerous measurement combinations required to fully characterize LRUs in a radar system, it is important to compare the choices between benchtop and modern handheld analyzers when installing, maintaining and troubleshooting radar systems in the field. For example, to characterize a commercial aviation radar system, the instrument list includes a peak power sensor and meter, spectrum analyzer, VNA and VVM. As most benchtop equipment was designed for indoor laboratory environments, the test site must have the adequate weather protection to guarantee the safety of the equipment against harsh weather conditions. For the highest measurement accuracy, the equipment typically requires a minimum of 30 minutes of warm-up time.

Another option for field testing would be to replace the multiple benchtop instruments with a single "all-in-one" FieldFox analyzer. FieldFox was specifically designed for field testing having a fully sealed enclosure that is compliant with US MIL-PRF-28800F Class 2 requirements to ensure durability in harsh environments. FieldFox includes a peak power meter, spectrum analyzer, VNA and VVM all in a six pound instrument. At the test site, FieldFox includes a unique feature, named InstAlign, that allows the spectrum analyzer mode to make accurate measurements immediately at turn on and also automatically corrects the measurements for any temperature changes over a range of -10°C to +55°C.

When using FieldFox as a substitution for benchtop instruments, it is important to note that technology breakthroughs have enabled high-performance measurement capabilities in the handheld analyzer that are comparable to benchtop instruments. It has been shown that measurements using FieldFox correlate well to benchtop instruments often within hundredths of a dB. Agilent provides a very informative application note that details the correlation between handheld and benchtop instruments [2].

Measurement examples

The remainder of this application note will detail several examples for characterizing and troubleshooting LRUs using a variety of test modes available on the FieldFox analyzer.

Basic power measurement of a radar transmitter operating at 40 GHz

Figure 6 shows the measured power of an unmodulated radar pulse as a function of time. The pulsed waveform has a measured pulse width of 994 nanoseconds and a PRI of 10 microseconds. The measurement was made with an Agilent U2022XA 40 GHz USB peak and average power sensor connected to a 26.5 GHz FieldFox. One benefit to using an external power sensor is that it allows a lower frequency analyzer to capture peak and average power measurements across the rated frequency range of the sensor. FieldFox can be configured to display the pulsed waveform as a function of time, as shown in figure 6, or it can be configured to display the peak or average power as a numeric

value only. When configured to display the pulse timing, an Auto-Analysis feature rapidly displays the basic pulse parameters such as peak power, average power, rise time, fall time, pulse width, duty cycle, PRI and pulse repetition frequency (PRF).

When using FieldFox connected to an external USB power sensor, such as the U2021XA or U2022XA sensors, the accuracy of the measurement is directly related to the

accuracy of the power sensor. There are many factors that enter into an uncertainty calculation for a power sensor and Agilent provides a spreadsheet to calculate the uncertainty limits [3]. For example, the measurement uncertainty in an average power measurement using the U2022XA 40 GHz peak power sensor with a 0 dBm input signal level is +/- 0.18 dB at 1 GHz and +/- 0.25/-0.27 dB at 40 GHz.

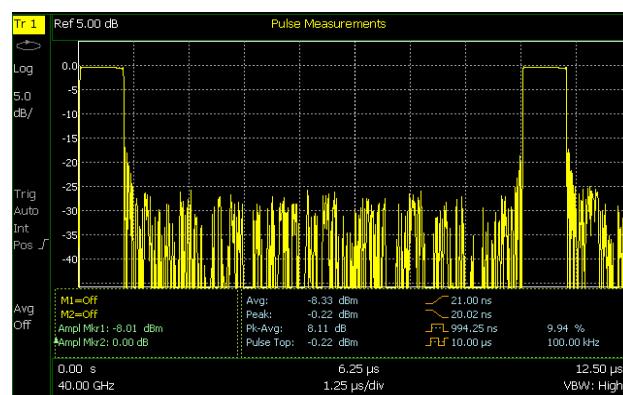


Figure 6. Peak power measurement of a 40 GHz radar transmitter

Measurement examples

Measurement of pulse timing in commercial air traffic control radar

As previously discussed, air traffic control radars communicate with sidelobe suppression by using two separate transmitters having one transmitter connected to a high gain antenna and the other connected to an omnidirectional antenna. The sidelobe suppression control pulse is transmitted through the omnidirectional antenna as the single P2 pulse. There is a two microsecond delay between the P1 and P2 pulses. This relative timing measurement requires two separate peak power measurements.

The measurement begins with the power sensor connected to the primary transmitter generating the P1 pulse. The power sensor is triggered using a TTL control signal delivered from the radar system. The P1 measurement is stored to the memory of the FieldFox. The power sensor is then moved to the auxiliary transmitter for the P2 measurement. The same TTL signal is required to properly trigger the power sensor for this second measurement. Markers are used to measure the timing offset between the P1 pulse, which is stored in memory, and the P2 active measurement. Figure 7 shows the measurement of this relative timing offset between P1 and P2. The data sheet for the U2021XA and U2022XA power sensors shows a trigger latency of 50 nanoseconds. The trigger latency is specified as the time when the power sensor begins to record the measurement from the time the trigger is seen by the sensor. As the measurements shown in figure 7 are a relative measurement using the same power sensor and TTL trigger, the accuracy in the measured offset time between P1 and P2 will be much lower than 50 nanoseconds. It should be noted that the peak power sensor in triggered mode is capable of 20,000 measurements per second.

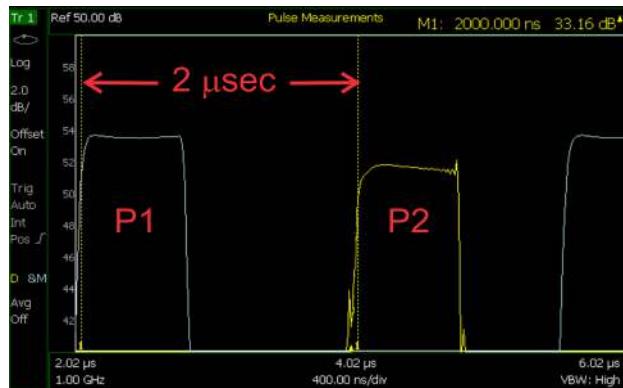


Figure 7. Measurement of ATCRBS transmitter P1/P2 timing offset

Measurement of amplitude and phase characteristics of a rotary joint

Rotary joints provide RF continuity to a continuously rotating antenna system. During periodic maintenance of a radar system, it is important to verify that rotational variations in the amplitude and phase through the rotary joint will not affect the system performance. Figure 8 shows a typical configuration for measuring the rotational variation of a multi-channel rotary joint. In this configuration the FieldFox is connected to one side of the rotary joint. On the other side, the antenna ports are disconnected and a short jumper cable connects two channels of the rotary joint in series. It is important that the jumper cable be high quality with good amplitude and phase

stability. In this figure, the testing begins with the sum (sigma) and omni (omega) channels connected together. The FieldFox, configured in the network analyzer (NA) mode, measures the transmission characteristics through this series connection. The rotary joint can be manually turned in order to observe the amplitude and phase responses as a function of rotation angle. If one of the channels is faulty, the measurement will fail the test. Measurements of the difference (delta) channel can be made by moving the test cable connections from the sum channel over to the difference channel, as shown by the dotted lines in figure 8.

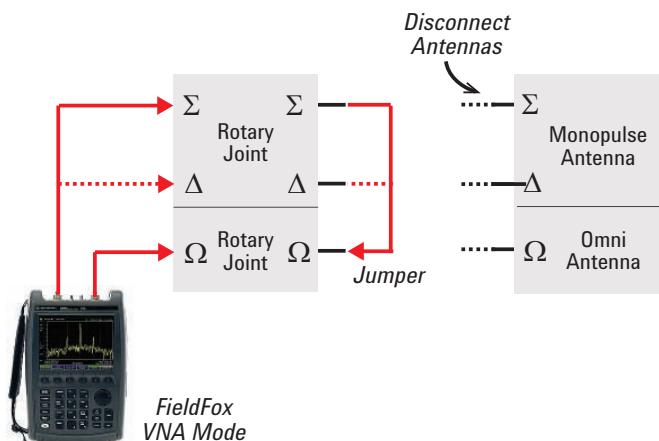


Figure 8. Configuration for measuring transmission characteristics of a rotary joint

Measurement examples

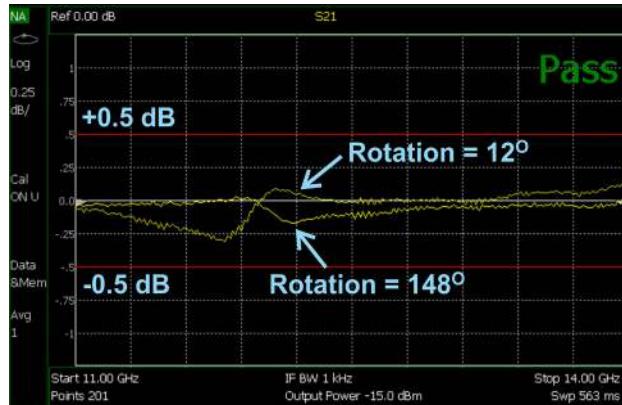
Measurement of amplitude and phase characteristics of a rotary joint *continued*

Figure 9 shows S21 measurements of a single-channel coaxial rotary joint over the frequency range of 11 GHz to 14 GHz. The rotary joint was initially lined up at the 0-degree position and this measurement was used to normalize the display of the FieldFox. Ideally, the amplitude and phase measurements will not vary as the rotary joint is physically turned around 360-degrees. This particular rotary joint is specified at 0.5 dB variation in amplitude and 3.5 degree variation in phase. As shown in figure 9, FieldFox was configured with limit lines to quickly identify when the S21 measurements exceed the specs as the device is rotated. For this example, FieldFox was also configured with a Pass/Fail indicator that will highlight the portion of the frequency response that exceeds the limits. Figure 9a shows the S21 Log Mag response at two rotation angles, namely 12-degrees and 148-degrees of rotation. These angles were chosen as having the worst case performance. For this amplitude measurement, the 0.5 dB specification was not exceeded. Figure 9b shows the phase responses at the two worse case positions. In one case, the phase exceeded the specification when the

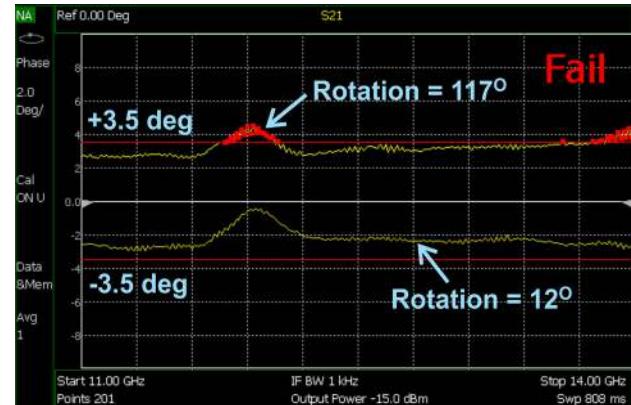
device was positioned at 117-degrees. As this rotary joint did not pass the manufacturer's operational specification, it would need to be repaired or replaced.

In some test environments, it may be difficult to control and observe the FieldFox display while simultaneously operating some part of the radar system. For example, in the monopulse configuration shown in figure 8, it is desirable to observe the S21 variation while the rotary joint is turned through 360 degrees of rotation. Unfortunately, the FieldFox connection into the radar system may be physically located in a different area from where the rotary joint may be manually rotated. In general, this type of measurement would require two operators positioned at different locations or long cable runs would be required to bring the FieldFox to the user.

Fortunately, FieldFox includes remote operation through an app that runs on an Apple® iOS device. In this way, FieldFox would be connected to the equipment while a single operator can wirelessly control and observe live measurements from a remote location. The iOS interface can show the same instrument panel as the FieldFox allowing the instrument to be directly controlled from the iOS device [4].



(a) S21 Log Mag



(b) S21 Phase

Figure 9. Measured S21 of a single-channel coaxial rotary joint showing (a) Log Mag response and (b) Phase response

Measurement examples

Phase alignment of a STALO

When measuring the phase difference between the sum and difference channels using the downconverted signals from a monopulse receiver, it is not possible to use a standard network analyzer as there is a carrier frequency difference between receiver input (RF) and the receiver output (IF). To overcome this difficulty, FieldFox is configured in vector voltmeter (VVM) mode and set to measure the ratio of signals at the downconverted IF carrier frequency. The VVM is configured in an "A/B" measurement where port 1 is the "A" measurement and port 2 is the "B". For this measurement, the internal source of FieldFox is not required and should be turned off.

In one possible measurement configuration, shown in figure 10, the omega channel IF receiver output is connected to port 2 of FieldFox. This "B" measurement will be used as the reference. The receiver output of the sum channel is initially connected to port 1 of FieldFox and will be used as the test, or "A" measurement. As this phase measurement only requires the relative phase difference between the sum and difference channels, this sum channel measurement is used to "zero" the vector voltmeter. Port 1 of FieldFox is then moved over to the difference channel of the receiver system, as shown with the dotted line in figure 10. The relative amplitude and phase difference between the sum and difference channels will be displayed on the meter. For this example,

the relative amplitude is -0.03 dB and the relative phase is 79.04 degrees. Many radar systems have phase adjustments along the STALO transmission path in order to re-balance the system as part of the routine maintenance.

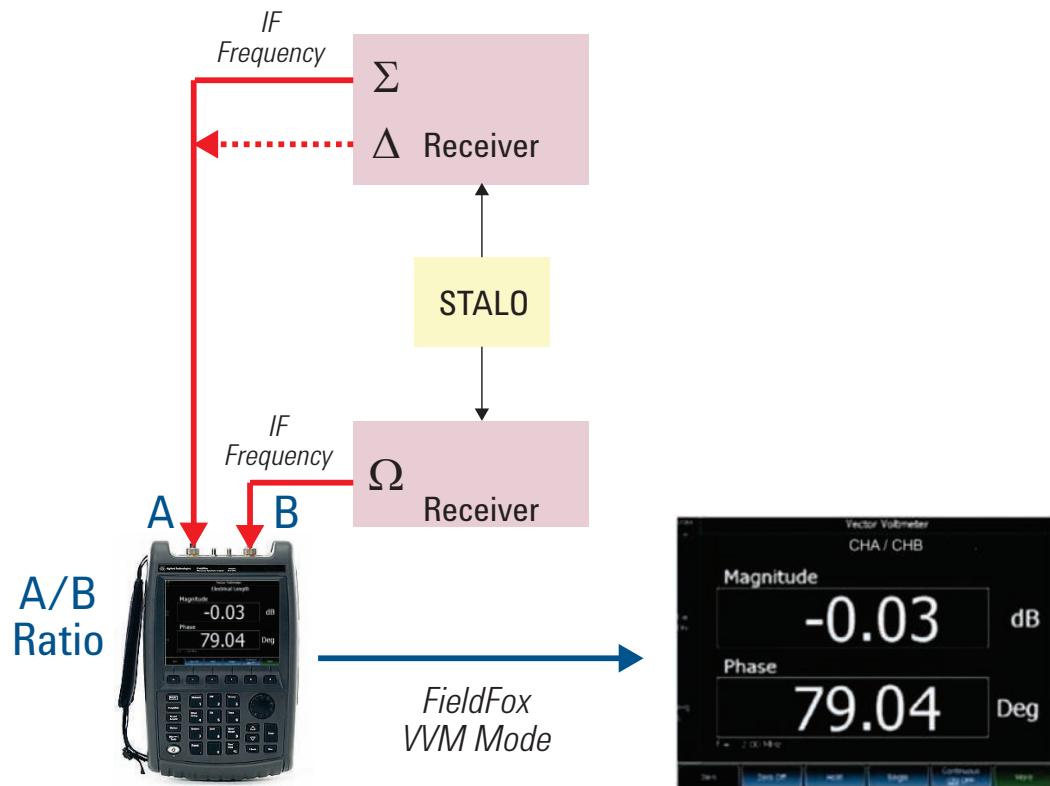


Figure 10. Configuration for measuring STALO phase alignment using downconverted receiver outputs

Cable trimming using network analyzer time domain mode

As the phase relationship between the sum and delta channels is very important for monopulse operation, coaxial cables and related transmission lines are typically phased matched by the radar system manufacturer. It is possible that a cable could become damaged and a field replacement would be required. The replacement must be amplitude and phase matched to the other cables already installed in the system. The first step in the process is to cut a section of the new cable that is slightly longer than the original cable or a test standard. The replacement cable should be of the same type and have the same electrical properties as the original cable. The replacement will then be iteratively trimmed and measured until it achieves the desired performance. If a test standard is available, phase measurements of the replacement can be compared to the measurements of the standard. If a test standard is not available, it is most likely that the cable length is specified in terms of measured electrical length reported as distance or time. If the cable is specified in electrical length, then a time domain approach may be required.

There are two ways to measure the phase length or electrical length of a coaxial cable, either through a transmission measurement or a reflection measurement. FieldFox can measure transmission and reflection using the VNA or VM modes. As the replacement cable will be physically trimmed from one end, there is typically only one connector initially attached to the cable, thus a reflection measurement will be required. Once the replacement is properly trimmed, the second connector is permanently attached to the cable.

When using FieldFox in VM mode, it is expected that a test or master cable is available to use as a measurement reference.

VVM mode on FieldFox includes a "1-port cable trimming" feature that aides the operator during the trimming operation. The FieldFox User's Guide [5] will provide additional information regarding this procedure. When using the VNA mode, FieldFox can be configured to display the phase or the time domain response. The time domain measurement on FieldFox is not a direct measurement but a calculation, or "transform", based on the measured frequency response of the device under test. For those interested in learning more about the details of time domain measurements using a VNA, Agilent provides an application note specific to the FieldFox [6]. As an example, figure 11 shows the time domain response of a coaxial cable with one end connected to port 1 of the analyzer and the other end of the cable left disconnected. As this display is a time response, the x-axis is time and the y-axis is amplitude. The large peak in the plot is the time to the open discontinuity. The exact location of the open ended cable can be measured using a trace marker. Knowing the target value for the desired electrical length of the cable, the cable can be trimmed until the electrical length is within a specified tolerance. The trace marker in FieldFox will also display the physical length to the end of

the cable. For example, the marker shown in Figure 11 also displays the length of this cable as 3 meters. It is important to note that the electrical length and physical length are related by the speed of light and the velocity factor of the coaxial cable [6]. The cable manufacturer's datasheet should list velocity factor (VF) for the cable and this number should be entered into FieldFox. With the proper VF entered, the displayed distance measurement will accurately represent the physical length to the cable end. The VF is also needed if the cable length is reported in "degrees". In this case, the electrical length in degrees is calculated by the following equation.

$$\text{Cable length (degrees)} = (\frac{1}{2})(t)(360)(f)$$

Where t is the measured electrical length in nanoseconds and f is the frequency in GHz. As this cable trimming procedure relies on a reflection measurement from the open ended cable, the displayed electrical length represents the two-way travel time. Dividing this value in half provides the one-way cable length in degrees.

Once the replacement cable is properly trimmed to the required specification, the second connector can be permanently affixed and a new cable can be installed in the radar system.

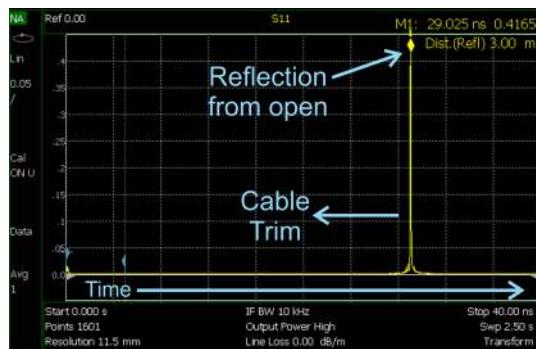


Figure 11 Measured time domain response from an open-ended cable using FieldFox VNA mode

Conclusion

Modern radar systems are used in a multitude of applications; from traffic enforcement to weather prediction. In order to assure highest uptime for these systems, routine maintenance and occasional troubleshooting and repair must be done quickly, accurately, and in any weather condition. Breakthrough technologies have transformed the way these systems can be tested in the field while providing higher performance, improved accuracy and capability. It was shown that a single FieldFox handheld analyzer can replace four benchtop instru-

ments including a peak power analyzer, vector network analyzer, spectrum analyzer and vector voltmeter. This application note reviewed several measurement modes available in FieldFox with specific examples to monopulse radar testing. Measurement examples included time and frequency domain testing of radar transmitter and receiver components.

References

- [1] Orlando, V.A., "The Mode S Radar Beacon System," *The Lincoln Laboratory Journal*, Volume 2, Number 3, 1989
- [2] Agilent Application Note, *Correlating Microwave Measurements between Handheld and Benchtop Analyzers*, part number 5991-0422EN
- [3] Agilent U2020 X-Series *USB Sensor Uncertainty Calculator* or <http://www.home.agilent.com> and search for "USB sensor uncertainty calculator"
- [4] Agilent FieldFox N9916A-030 *Remote Control Capability*
- [5] Agilent FieldFox Analyzers User's Guide, part number N9927-90001
- [6] Agilent Application Note, *Techniques for Time Domain Measurements Using FieldFox Handheld Analyzers*, part number 5991-0420EN

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Related literature	Number
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FieldFox Microwave Spectrum Analyzers, Technical Overview	5990-9782EN
FieldFox Microwave Vector Network Analyzers, Technical Overview	5990-9781EN
FieldFox Handheld Analyzers, Data Sheet	5990-9783EN
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FieldFox N9912A RF Analyzer, Technical Overview	5989-8618EN
FieldFox N9912A RF Analyzer, Data Sheet	N9912-90006
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