Measure Electromagnetic Fields with the Vector Field Analyzer

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Introducing the Vector Field Analyzer

Most of us in the microwave / wireless business are familiar with the common RF measurement devices:

- ***A microwave power meter (PM) indicates total microwave signal power over its sensor's frequency range. The power meter is a "broad brush" – there's plenty of room for unanticipated signals outside the intended measurement frequency to affect the measurements.***

- ***A spectrum analyzer (SA) is more selective, showing signal amplitude versus frequency over a chosen frequency range. The spectrum analyzer's tuned receiver can separate and independently measure multiple signal components.***

- ***A scalar network analyzer (SNA) adds capability. This instrument provides a signal that can sweep over a chosen frequency range, and at the same time displays two or more received signal amplitudes over frequency, often in ratio form for convenience. A synchronized combination of signal stimulus and measurement response allows measurement of transmission and reflection parameters (VSWR and transmission loss) of microwave devices.***

- ***A vector network analyzer (VNA) adds another refinement. Like the SNA, it includes a stimulus signal source and a synchronized multi-channel receiver. However, the receiver channels in the VNA are coherent: the amplitudes and the relative phase between two received signals can be accurately measured. The VNA can display scalar transmission and reflection parameters, as well as full S-parameters (complex transmission and reflection coefficients).***

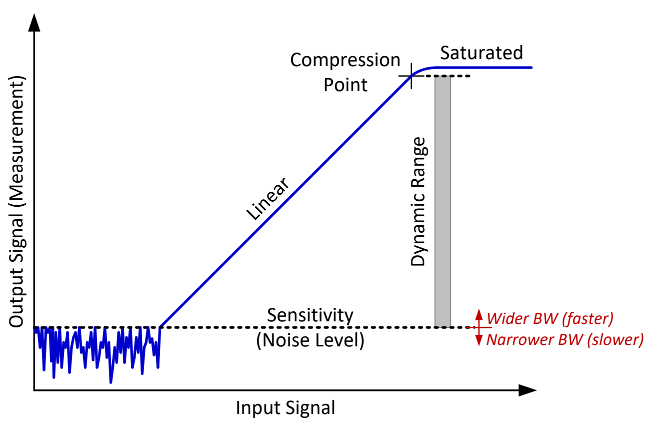
As wireless technology has evolved, the industry has integrated more "domains of control" to make useful measurements. The power meter can be triggered to measure at will; time is a controlled parameter. The spectrum analyzer integrates both time and frequency control. The SNA incorporates time and frequency control for both source and receiver, but also includes the added dimension of multiple measurement channels. Finally, the VNA includes all these as well as the ability to make coherent (amplitude/phase) measurements. There is one common factor among these measurement devices: They all center on measurement of microwave signals at ports, fixed connection points on the test article.

In keeping with the evolution of wireless technology, AMETEK NSI-MI has recently introduced a new instrument type, the Vector Field Analyzer (VFA). Like the other instruments, the VFA can measure signals at fixed ports, but its unique strength is its ability to make accurate electromagnetic (EM) field measurements. The VFA seamlessly blends multi-channel vector (amplitude/phase) electrical measurements with wide-band agile frequency control, 10-nanosecond precise timing, and convenient integration of complex device control schemes within the measurement flow. More importantly, the VFA precisely coordinates electrical measurements with spatial (position) measurements for complete understanding of three-dimensional EM fields.

Wireless systems and devices depend on antennas to transfer information, and antenna performance is important to the system's overall performance. Measuring antenna performance adds a new dimension to test requirements: we now need to measure an electric field "in the air" at known spatial positions relative to the device under test. This is a serious complication – we've added the requirement that we accurately know and control the relative positions of a field-measuring antenna or probe and the device itself. We live in a three-dimensional world, so antenna field measurements are normally needed at many locations over a volume. We also live in a broadband, multi-channel world where modern wireless devices have dozens, hundreds, or even thousands of states to be tested: frequencies, polarizations, and beam steering settings. Finally, we live in a fast-paced world, where the demands of business compel us to do all that testing more accurately, and in less time, than ever before.

All these factors contribute to the need for equipment better suited to the measurement of fields in well-defined spaces as opposed to signals at fixed connection points. Electromagnetic field measurement includes both electrical and mechanical considerations, and we'll address a few of them here. While we're centering on the VFA, these issues apply to EM field measurements made with any measurement device.

Electrical Considerations



The idealized figure here illustrates the concept of linearity. Most electrical components or systems are designed to faithfully reproduce some input signal: doubling the strength of the input doubles the strength of the output, or reducing the input signal by ten percent reduces the output signal by ten percent. This is especially important in making measurements, as we often compare an unknown test reading with the reading from a very well-known standard for accurate results. That comparison only works well if the measurement system is linear. We'll explore this figure from lowest to highest signal levels, and make some useful observations along the way.

Sensitivity (Noise Floor)

To measure electromagnetic fields, an antenna (or field probe) is connected to a measurement receiver with a flexible RF cable. This allows us to move the probe and sample the field at various locations. But there's a limit to how small a signal (or how weak a field) can be measured. This is determined in part by the probe antenna's characteristics, but more directly by the receiver. Every receiver has a minimum detectable signal level, or noise floor, below which any signals are masked. In general, a receiver designed for field measurements should have a low noise floor, as the signals to be measured are often quite weak. In situations where the measured signal is too strong, it's easy to add a microwave attenuator between the probe antenna and the receiver. On the other hand, adding an amplifier to boost the sensitivity of an insensitive receiver takes more care and money.

There's another way to improve a receiver's sensitivity: take more time with the measurements. Almost every instrument from power meter to VFA has a control for bandwidth, or integration time. The two are reciprocal: selecting a narrower bandwidth requires more time for each measurement, and results in a lower noise floor, extending the dynamic range of the instrument. On the other hand, a wide bandwidth requires less measurement time (a big "win," especially with lots of testing to be done) but also raises the noise floor and reduces the instrument's dynamic range. In selecting a receiver for field measurements, it's helpful to compare sensitivities at a specific bandwidth or measurement speed that fits your application. A bandwidth of 10 kHz is usually appropriate for these comparisons.

Linear Region

Any measurement receiver must be operated in its linear region to make accurate measurements. Within this area from noise floor to compression point, signals can be accurately measured and compared. For a measurement receiver, great care is taken to assure that the response is indeed linear over the full span between the noise floor and the compression point, as component imperfections can each add their own shape to the overall curve.

It's well known that the accuracy and repeatability of electronic measurements improves as the signal level increases above the noise floor within the linear range. The impact of the noise floor on the uncertainty of a measurement is given by this equation:

$$U_{dB} \approx -20\,\log_{10}[1 - 10^{(-SNR_{dB}/20)}]$$

where

SNR_{dB} is the Signal to Noise Ratio in decibels

A signal that is 20 dB over the noise floor can be measured with an uncertainty of about 1 dB, and increasing the SNR to 40 dB reduces that uncertainty to less than 0.1 dB. It's clear that a lower noise level at any bandwidth is better for measurement accuracy.

Compression Point

The 1-dB compression point is often used to describe an amplifier's performance at the upper end of its operating power range. This point is defined as the output power level where the amplifier's gain has decreased by 1 dB as the input signal is gradually increased. A similar concept is used to describe the performance of a measurement receiver at the upper end of its range. Because we're concerned about very accurate measurements, we use a more stringent 0.1 dB compression point to mark the upper end of the linear region. It is defined as the point where the displayed signal amplitude (or field strength) deviates by 0.1 dB from the "straight line" linear range of the system. A higher compression point means that we can accurately measure higher signal levels. Compression point and sensitivity are both expressed as RF or microwave signal levels at the receiver's input.

In general, the sensitivity and compression point for a modern receiver are complex functions of the components and the receiver design. Some receivers allow for more nuanced adjustments, such as IF Gain, Preamp, or Attenuator settings, to better optimize the receiver to a specific test situation. By better adapting available dynamic range to measured signal levels, receivers like the Vector Field Analyzer can acquire the fastest measurements for a given accuracy, or the most accurate measurements for a given speed.

Saturation

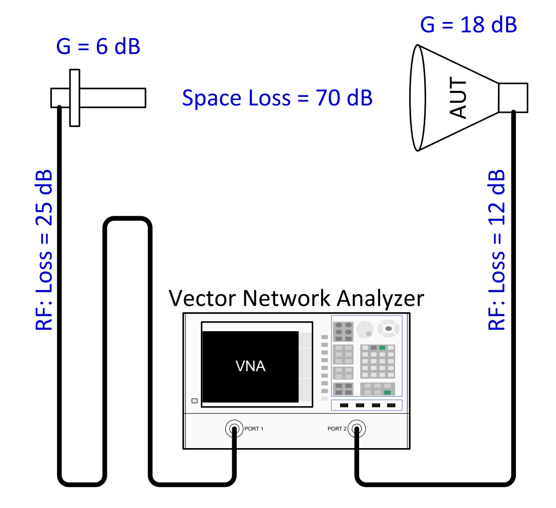
The area above the compression point is not useful for measurements, as any receiver will produce unreliable readings when overloaded. To measure higher signal levels, an attenuator may be added at the front end of the receiver. Adding a 10 ¬dB attenuator will raise the compression point by 10 dB, but will raise the noise floor by 10 dB as well. This in turn may prompt a bandwidth reduction to restore the original noise floor as discussed earlier. Making fast, accurate electromagnetic field measurements depends on carefully adjusting test and receiver parameters to optimize the measurement.

Dynamic Range

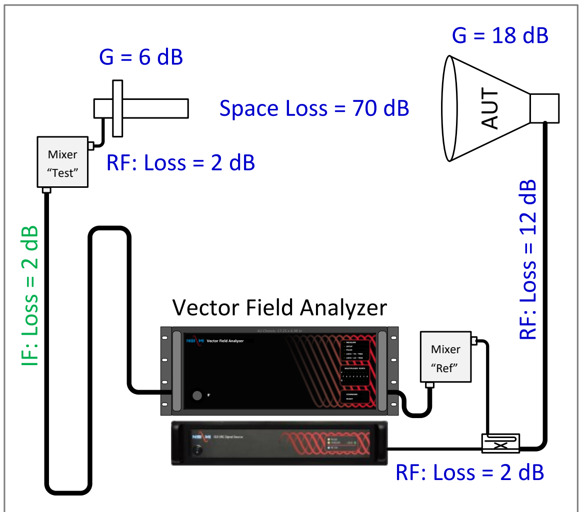
Dynamic range is simply the full extent of the linear range for a measurement system. Dynamic range can be expanded or contracted by selecting bandwidth (affecting sensitivity), but can only be "shifted" up or down by adjusting front-end attenuation (the attenuator affects sensitivity and compression point). For practical electromagnetic field measurements, there is another method that can improve sensitivity and speed. Consider these two test setups, designed to test an example antenna under test (AUT):

In our example, the VNA and VFA systems have the same output power, and are used for the same test, using equal cable lengths to accommodate the locations and motion of the antennas. Parameters given for antennas, cables, and instruments are all typical values. Long cables normally connect the antennas to the receiver to accommodate the mechanical systems used to move those antennas. Because their electrical characteristics change when abruptly flexed, the cables are often routed through cable handlers or tracks to allow smooth, repeatable cable motion at the cost of increased length.

The examples show how the Signal to Noise Ratio (SNR) and the uncertainty due to noise for a measurement can be estimated, using our baseline 10 kHz IF bandwidth (0.1 ms integration time). The big difference in SNR and uncertainty shown here results from the VFA's remote mixers, which allow



Component	G / Pwr	Units
VNA Output	15	dBm
AUT RF Cable	-12	dB
AUT Gain	18	dBi
Space Loss	-70	dB
Probe Gain	6	dBi
Probe RF Cable	-25	dB
VNA Input	-68	dBm
VNA Noise Floor (10 kHz)	-90	dBm
Meas. SNR	22	dB
Uncertainty from Noise	**0.719**	**dB**



Component	G / Pwr	Units
Source Output	15	dBm
Cable/Coupler Loss	-2	dB
AUT RF Cable	-12	dB
AUT Gain	18	dBi
Space Loss	-70	dB
Probe Gain	6	dBi
Probe RF Cable	-2	dB
Probe IF Cable	-2	dB
VFA Input	-49	dBm
VFA Noise Floor (10 kHz)	-110	dBm
Meas. SNR	61	dB
Uncertainty from Noise	**0.008**	**dB**

us to eliminate almost all the probe cable's loss. The compact remote mixer mounts at the probe, and converts the test frequency down to a much lower intermediate frequency (IF) where cable loss is greatly reduced. The VFA is designed around remote mixers, and offers this advantage in multiple, broad frequency ranges. It can also be configured with internal mixers for simpler, smaller measurement tasks where cable lengths are not so critical.

Instead of comparing these two systems based on a fixed IF bandwidth, we may now compare them by requiring each to meet a specific uncertainty level. For our example, we will specify that both systems must meet 0.05 dB uncertainty, or SNR = 45 dB from the uncertainty equation above.

Initially, the VNA system on the left shows an uncertainty of about 0.7 dB (SNR = 22 dB). To improve sensitivity (and SNR) by 23 dB we need to increase integration time by a factor of about 200. We take the original 0.1 ms (from the 10 kHz bandwidth) and multiply by 200 to get 20 ms (BW = 50 Hz).

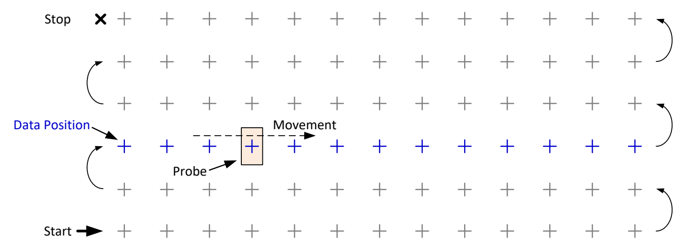
Meanwhile, the VFA system on the right initially shows an uncertainty of 0.008 dB (SNR = 61 dB). In this case, we can reduce the sensitivity by 16 dB by decreasing integration time by a factor of 40. The needed integration time for the VFA system is thus only about 2.5 microseconds (BW = 400 kHz). Measurements on the remote-mixer VFA system can be completed about eight thousand times faster than with the internal-mixer VNA system, with equally low uncertainty. Overall test time is a complex function of mechanical capabilities, test plan complexity, setup times, and measurement times, so you'll likely never see a time reduction factor of eight thousand. However, real-world reduction factors of 10 to 100 are commonplace. It's easy to see the value in reducing an 8-hour test to 10 minutes!

Mechanical Considerations

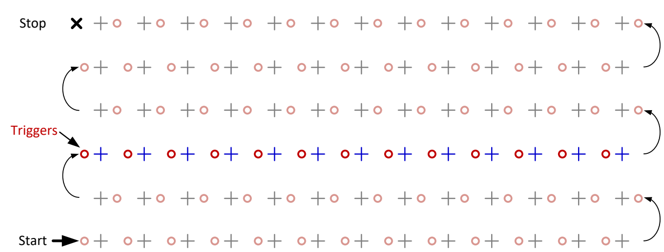
To measure an electromagnetic field at more than one location, it's common to use a mechanical positioner to move a probe antenna with respect to the antenna under test. In automated test systems, antenna motion is provided by electric motors, either steppers or servos, to assure accurate, controllable positioning. To take measurements at many points – typical for EM field measurements – it's too time-consuming to move an antenna to the first position, wait for it to stop, make a few measurements, then continue to the next position. To improve test speed, positioners are designed to follow a useful trajectory, one in which successive data points can be quickly captured "on the fly" as the antenna moves, eliminating as much as possible any motion (and time) spent while not taking data. Those "useful trajectories" include straight lines, rotations about various axes, and smoothly curved paths, depending on the nature of the field or the antenna under test (AUT) to be measured. The subject of antenna positioning is too broad for this discussion, but rest assured that modern positioning equipment can be configured to accurately follow a particular trajectory and provide trigger signals at defined points of interest. From the measurement perspective, we wish to use those trigger signals to make the required measurements as efficiently as possible.

Positioning Example

Consider a planar scan, where the field probe maps out a plane in space by moving along a line while making measurements, stepping in the orthogonal direction, and returning in the opposite direction to trace the next line of points. Viewed from the front of the probe, we cover a rectangular portion of space with a regular grid of measurements to define the measured field.



The motion controller is configured to produce a Trigger pulse ***before*** each point is reached, so that a complete set of measurements will be centered on the desired position. Because the direction of movement is reversed, the trigger positions differ between forward and reverse lines.



Now we'll zoom in, showing just a few grid points. Here we picture a simple test plan that makes three measurements at each Data Position, at frequencies F1, F2, and F3. Looking closer, you can see that the individual measurements are reversed in time, but not in space, between forward and reverse lines. This re-ordering makes sure that every measurement for a particular frequency, AUT state, or channel remains on a regular (not "zig-zagged") grid; the F1, F2, and F3 measurements on successive lines are vertically aligned. This re-ordering reduces the complexity and the residual errors involved in interpolating all the measurements back to the prescribed Data Positions (field locations) as shown by the "plus" markers.

You can also see that there is some space between the three Measurement "diamonds," corresponding to the time it takes to set up the test conditions for each measurement. The setup time is a function of the electronic equipment, while the setup distance is the product of setup time and movement velocity. The horizontal size of the Measurement diamonds represents both measurement time as discussed earlier and measurement distance. The probe is in constant motion, so decreasing setup and measurement times allows us to move faster, reducing the time it takes to scan the desired area. The ultimate "speed limit" depends on the density of Data Positions requested, and the total of all the setup and measurement times for the data set. Enough space (and time) must be available to fit all the requested setups and measurements between the triggers.

SYNCHRONIZATION

The example above shows one of many possible motion profiles that a field measurement system's electronics must interact with. Speed and accuracy requirements dictate that even the most complex test plans need to be repeatable and deterministic. This in turn requires tight integration among the receiver, sources, switches, and AUT hardware. The VFA incorporates an FPGA-based measurement controller that accepts position triggers from a positioning system and generates all the commands and events needed to control range and AUT equipment with 10-nanosecond precision. This timing engine is fully integrated with the receiver to assure the most accurate and efficient data collection.

Synchronization of external equipment, like sources, switches, and AUT controllers can be done using precise electronic triggers, available as TTL pulses or parallel words depending on the target device. A full complement of digital I/O ports assures that practically any device or instrument can be synchronized to the VFA's data acquisition process. The VFA also includes NSI-MI's Trigger Bus connections to quickly interface with our own positioner controllers, sources, and other equipment.

RECORDING

Integrating the measurement controller with the receiver offers another critical benefit for EM field measurements. Most antenna or probe positioning systems have multiple, interdependent motion axes. For precise knowledge of location, it's often required that the positions of multiple axes be measured and recorded (not just commanded) during data acquisition. Analysis software is then used after the acquisition to correct for positioning errors. The VFA's measurement controller is the same "engine" that drives the test plan, the external equipment, and the receiver. This makes it a simple matter to send triggers back to the positioner subsystem to record axis positions at the exact moment of acquisition to assure the most accurate field measurements possible.

WRAPPING IT UP

Modern wireless devices from cell phones to satellites have made a necessity of fast, accurate, and complex electromagnetic field measurements. As product complexity increases, test complexity increases as well, requiring improved speed and accuracy in electrical, time, and even spatial domains. The Vector Field Analyzer connects these domains, forming the heart of an acquisition system that can handle the demands of leading-edge product development and production testing.