# Direction Finding Antennas

## Accuracy, Sensitivity and Calibration

cyntony corporation

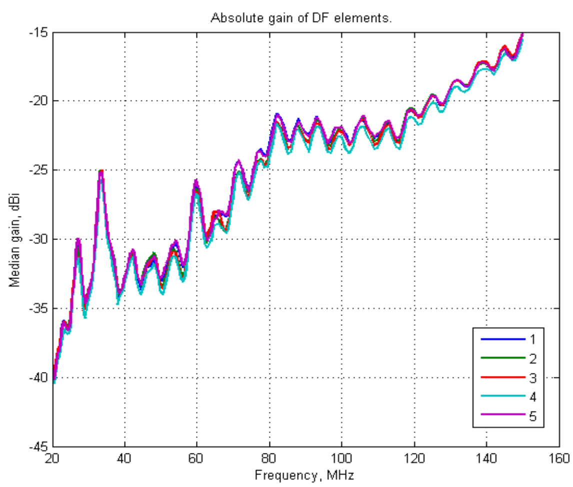
An explainer for electronic warfare and spectrum authority program managers, engineers and practitioners by direction finding experts at Alaris Antennas and RF product curator Cyntony Corporation

# Contents

# Why Should You Care?

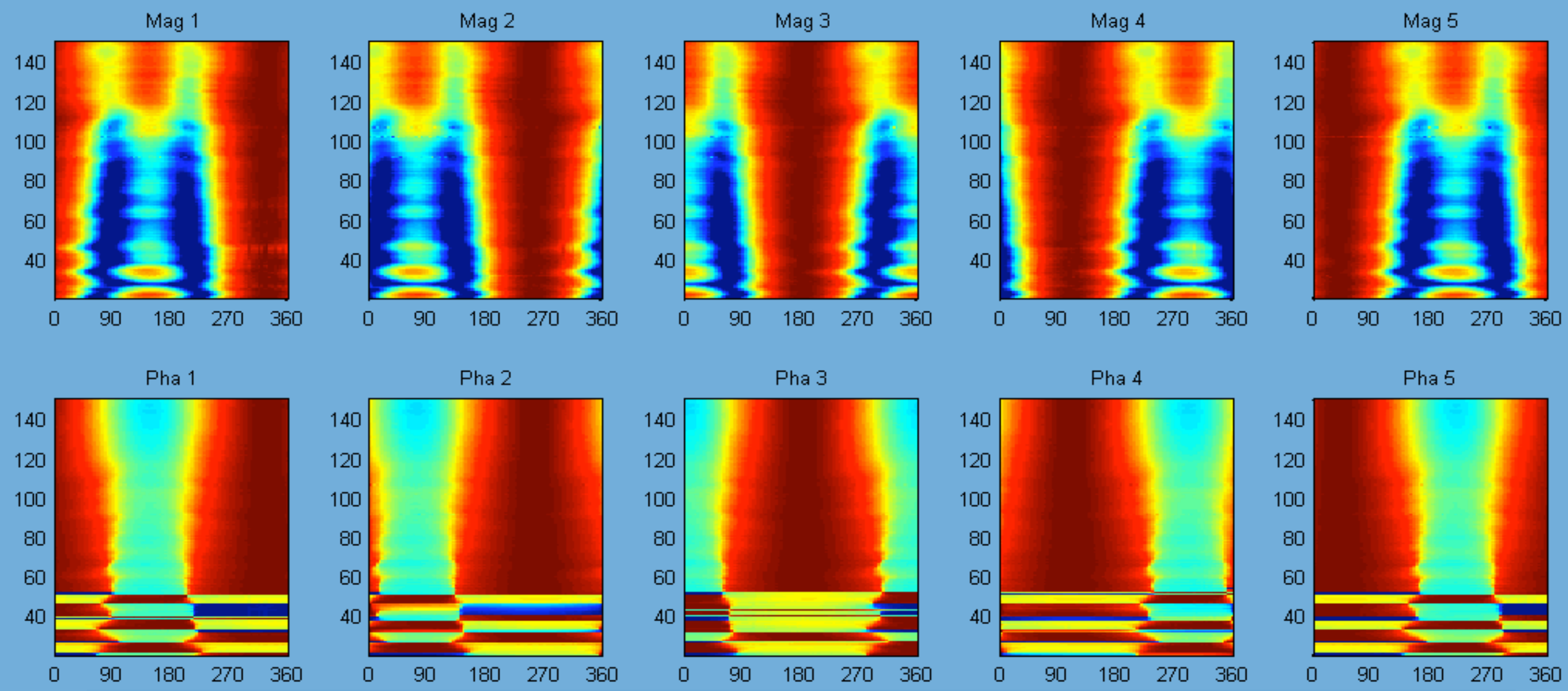
There are better ways of scientifically characterizing direction finder performance than a simple accuracy number. This white paper explains the right approach to assessing performance, assisting engineers' and managers' comprehension and interpretation of direction finding antenna specifications.

Antenna specifications and datasheets contain a lot of jargon, acronyms, units of measure; and far too often: obfuscation, omissions and errors. A single 'accuracy' number on a product brochure is often an attempt to conform to end-user visions of how direction finding (DF) works by providing a spec that can satisfy an end-user query. Like many specifications, the term 'accuracy' is vague and fairly arbitrary, allowing suppliers to manipulate the data to get almost any number desired.




DF Accuracy, DF sensitivity and DF calibration concepts are presented below so that system integrators can successfully employ their RF electronics and signal processing techniques for correlative radio direction finding using the trustworthy information and DF antenna equipment from Alaris Antennas (AA). Unlike many DF manufacturers, Alaris does not sell the whole DF system – only the antenna. Cyntony distributes these antennas and relies on the strong electromagnetic analysis capabilities of the AA team to predict how a DF antenna will work in a 'generic' DF system deployment.

By making use of sophisticated models of DF systems, many of which are tailored to match real customer systems, numerical analysis can predict how the DF antenna system will work for specific system implementations. Alaris has good results in this respect, where predicted sensitivities generally tie up very well with Alaris DF antennas integrated into customer systems. It is important to note that when comparing AA specifications to a vendor such as Rohde&Schwarz (R&S), who specify their whole system, AA specifies the antenna assembly as hooked to a model of a realistic DF processor system. Furthermore, a DF processor system itself can impact performance greatly, so its implementation is key for overall performance of the direction finding system.




We've noticed that when end users, vendors and system houses talk about accuracy, they often like to talk about accuracy for a given signal to noise ratio (SNR) at the receiver when the antenna is measured in lab conditions, or, 'as calibrated'. In many cases, the SNR itself is not explicitly stated, but often implied to be a nominal value like 20dB. This is probably because when demonstrating a system to a prospective end user, the SNR is a readily available quantity to show the client, provided nicely from the receiver system and plotted on a screen in the control room. The client may then mistakenly believe that the system performs really well or really badly given the SNR reported, but this is only a small part of the story…

## Considering DF Accuracy

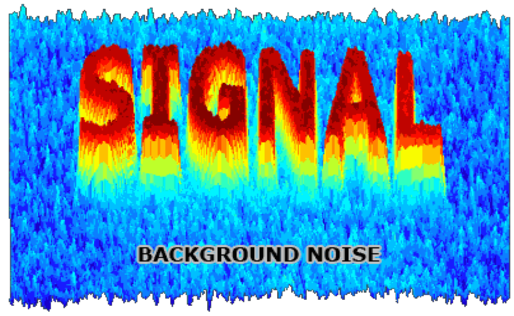
The accuracy of a DF system is generally defined as the root-mean-square (RMS) of the angle of arrival (AoA) estimate error. The accuracy can be specified as a function of frequency by taking the RMS estimation error over a set of azimuth test points at the frequency in question. This allows a plot of the accuracy as a curve, but it is more often than not also expressed as a single number. How vendors come to that number is not always clear: sometimes by considering the max RMS error in the band of operation, sometimes the RMS-of-the-RMS, sometimes as a typical or average value.

What influences the accuracy? Well, the strength of the incoming wave (field strength) carrying the signal is a big factor. If the field strength is weak, then we cannot expect the accuracy to be very good as the internal noise in the DF system will swamp the signal received by the antenna, making for difficult direction finding.

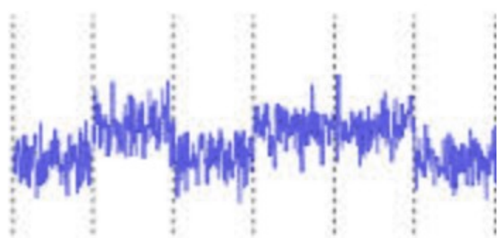
> “You’d be amazed how many systems are terrible when having to work with ‘real’ incoming waves, rather than the ideal waves they were calibrated with”
>
> *Dr. Chris Vale, CTO, Alaris Antennas*

Even if the field strength is large, other factors can degrade accuracy by introducing what is often referred to as bias error. At Alaris, this accuracy is stated as Large Signal Accuracy (LSA). We will talk about the factors that influence LSA a little later. LSA, and hence accuracy as well, can be made to look good by testing the antenna in ‘favorable’ conditions: such as with a carefully chosen test field with pure polarization, or by using azimuth test points that are aligned with the characterization table (also known as manifold) data points. In correlative systems, the problem of bias error is neatly handled in marketing literature with a catch-all like “measured in laboratory conditions”, or “as calibrated.” In effect, this removes bias error from the accuracy assessment, but does not help when it comes to explaining disappointing performance that may arise in client demonstrations and practical deployments.

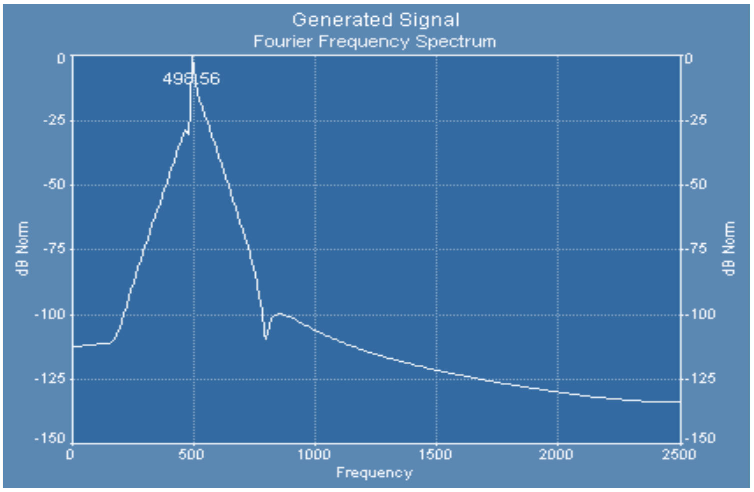
Finally, to simplify matters for confused buyers that may struggle with a curve plotted over frequency, spec sheets often contain only one value for accuracy. Now, when a DF array is electrically small (has a small aperture) even with a high SNR, the accuracy can be quite low, so providing a single ‘typical’ number can hide weaknesses at low frequencies.




**First, looking at the accuracy for a given SNR completely discounts the antenna element gain** because the SNR is determined after the antenna elements have done their job of converting the incoming field to an electrical signal. This is good for vendors who are marketing systems of many ‘small’ or active antenna elements, as the terrible gain of the elements or noise contributed by the active matching circuitry is ignored by the specification. Antennas that have good element gain, or in other words, can convert incoming waves to electrical signals more efficiently and with less added noise, don’t get recognized by this specification.



**Second, bias error is often fully ignored with such an approach,** as the antenna is not stressed with practical disturbances (other than noise) that may introduce other inaccuracies. In badly designed DF arrays bias error can be high when the antenna is stressed under the right conditions, but you would never see it until some thorough practical tests are performed and analyzed.




**What is Large Signal Accuracy?**
*Large Signal Accuracy (LSA) is a special case where we consider the incoming field strength to be very high, such that the SNR is very high (e.g. > 100dB). LSA is more a theoretical ideal than a practically measurable value. In ideal circumstances, with an ideally characterized correlative DF system and perfectly polarized incoming test field direct from the horizon, the large signal accuracy should be perfect (i.e. zero RMS error). In practice, of course, none of these things are perfect so one seldom measures perfect accuracy even in strong signal conditions and even in a carefully setup measurement environment.*

Large signal accuracy is a useful quantity to try to determine, as it provides an idea of the 'best-one-could-hope for' performance of a practical system; and one can measure or simulate it under various conditions. For example, during the design phase, one could simulate a condition where the antenna is exposed to slant polarized waves, rather than the vertical polarized waves with which it was characterized; or one could compare the impact of characterization table resolution of say, 4° or 8° on the system accuracy. Thus, LSA is never perfect in practice because of shortcomings in design, implementation and operation

## Factors that degrade LSA in correlative DF systems

1. Interpolation error (in freq. and azimuth) when using low resolution characterization tables
2. Differences of the incoming waves than were present during calibration, arising from:
   a. Signals incident from off-horizon
   b. Signals incident with different/impure polarization
   c. Multipath incident signals
3. Differences in the system that was calibrated and as practically deployed, arising from:
   a. Misalignment of the array with respect to the reference direction
   b. Electromagnetic differences in the mounting structures used for calibration versus deployment that subtly change the way the antenna works
   c. Surrounding scattering objects that were not present when the system was calibrated (e.g. lightning rods) that, in effect, change the antenna system
   d. Differences in the RF chain leading down to the receivers from the antennas, arising from, e.g., temperature variation in cabling.

In the case of factors 1 and 2a-c, a well-designed antenna with large apertures, such as the Alaris Antennas DF-A0038, paired with a high-resolution characterization table, or manifold, will contribute very little to the error. However, factors 3a-d can have significant impact on large signal accuracy, and mitigating against them relies on good system design and implementation.

**Is Large Signal Accuracy a useful measure of DF performance?**

*LSA is an extremely useful measure of a DF system's performance when provided for various conditions that stress the operation of the antenna. This is because it is important to know if the system will fail to operate acceptably when practical signals and circumstances are brought to bear without having the added confusion of a finite SNR to confuse performance estimation. Demonstration and marketing related material are often carefully controlled to keep these non-ideal conditions at bay.*

*Sadly, the LSA of most DF systems are seldom quoted for non-ideal conditions such as the ones listed above. Instead the escape clause "ideal lab conditions", or "as calibrated" is exploited. During a shoot-out between competing products, few clients are kind enough to provide such a forgiving scenario, and one has to then hope that the antenna design has been good enough to reject the disturbances, without ever knowing for sure that it has even been considered.*

*LSA cannot be truly measured as there will always be a finite SNR in any measurement setup. Alaris normally makes use of Vector Network Analyzer (VNA) based measurements that can provide high SNRs (generally accomplishing between 30-40dB SNR), which are often large enough to let the error contribution due to noise be dominated by the other factors that we wish to investigate, and provide a good upper bound of the LSA error in various conditions.*

*Alaris Antennas can, and often does, measure the system accuracy under strong signal conditions with cross-polarized incoming waves, as well as waves incident from extreme elevation angles. We can share this data with clients where it is already available or measure or simulate it for serious requests. A key objective is to make users aware of this issue, if not already, and hopefully stimulate users to ask the right questions at the beginning of the system design.*

## Our Definition of Accuracy

**Correlative DF Accuracy**

For a correlative type system (often referred to as an interferometer although nowadays seldom used as a pure interferometer), Alaris generally defines DF accuracy as the typical accuracy that is obtained in the frequency band of a system with an SNR of about 20-40dB (i.e. high) and characterized using a representative outdoor measurement facility. Sometimes, we may measure and quote accuracy for a lower SNR if it has been requested by a specific client to satisfy an end-user specification interpretation.

It is normal to make use of a 4° azimuth step in the characterization table $\varphi$={0; 4; 8;... 356}, and take a verification dataset at $\varphi$={2; 6; 10;... 358} or $\varphi$={0; 15; 30;... 345} to determine the accuracy. This ensures that the antenna has smooth enough patterns to be used with a reasonably sized characterization table that models interpolation error as well. A Matlab model of a correlative DF can be integrated with VNA-generated antenna measurement data to determine these quantities.

**Watson-Watt DF Accuracy**

In systems that utilize a non-correlative DF algorithm, such as the 'classic' arctan( ) Watson Watt estimation method, even under ideal SNR>100dB conditions, i.e. LSA conditions, the accuracy will not be perfect as the DF relies on the pattern to conform to a certain ideal shape. Alaris products described as 'Watson-Watt' antenna systems define the accuracy as the maximum RMS error that is obtained in the band with high SNR (typically around 30dB) when the antenna is measured in a representative outdoor setup such as found in a purpose-built ground reflection range and the AoA estimate is accomplished using the Watson Watt method.

**Accuracy – Summary**

Accuracy is not a fundamental property of a DF system, or antenna, as a lot of marketing literature would have people believe. It depends on the SNR it is tested with, as well as the degree to which the antenna is stressed with non-ideal conditions – i.e. how it is measured.

There is a tendency to oversimplify accuracy by defining it for a specific SNR and measured under ideal conditions. This gives a seriously distorted view of the system's true capabilities or weaknesses.

Alaris favors the use of the 'Large Signal Accuracy' to define the accuracy of a DF system, where the accuracy is shown when the antenna is subjected to extreme conditions or disturbances that may be encountered in real deployments – it can give a feeling for the 'best-one-can-hope-for' performance in practice. To account for how the system works with weak signals, as we shall see, we believe that sensitivity is a better way of describing the system performance, rather than accuracy for a specified SNR.

That said, to conform to the norms currently extant, Alaris quotes accuracy based on tests in a practical setup using a moderate to high SNR and a quasi-interleaved set of azimuth test points and characterization table data points.

Large signal accuracy is a useful quantity to try to determine as it provides an idea of the 'best-one-could-hope for' performance of a practical system and one can measure or simulate it under various conditions. For example, during the design phase one could simulate a condition where the antenna is exposed to slant polarized waves, rather than the vertical polarized waves with which it was no doubt characterized, or one could compare the impact of characterization table resolution of 4° or 8° on the system accuracy. Thus LSA is never perfect in practice because of shortcomings in design, implementation and operation

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# DF Sensitivity

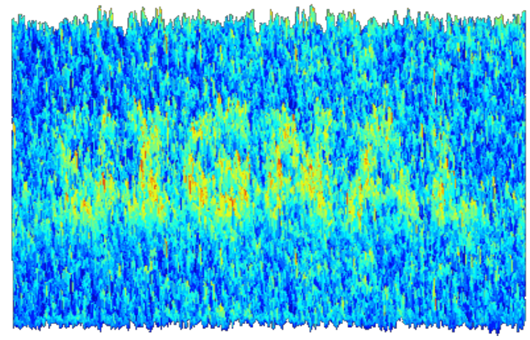
In a general sense, not just for DF, sensitivity is a measure of the weakest discernable signals that a receiving system can detect and process. A good measure of the incoming signal strength is a measure of the field strength that arrives at the antenna.

Furthermore, in the case of DF, the mission is to estimate the AoA of an incoming signal with a certain reliable accuracy, so the sensitivity of the DF system is therefore a measure of the incident field strength at the antenna that guarantees a specified RMS AoA estimation error whilst ensuring a wild bearing probability below some nominal value, e.g. 1%.

The benefit of a sensitivity spec is that it accounts for the gain of the individual antenna elements, the aperture size, as well as the suitability of the antenna patterns to work with a DF processing scheme. It also provides an idea of the typical range of the system or the extent to which it can pick up weak signals.

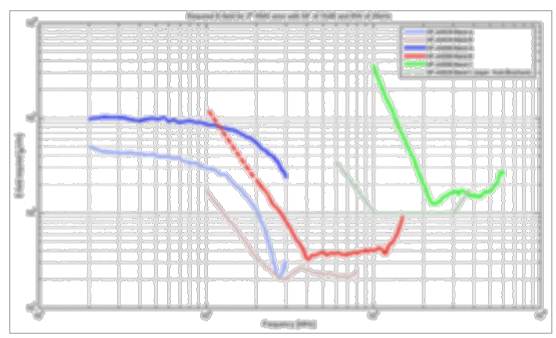
A problem with sensitivity specification alone is that many systems make use of averaging to improve estimates (and thereby AoA accuracy), and many publications do not provide enough information to determine the amount of averaging employed in the stated sensitivity specification. This can make it difficult to compare DF sensitivity as quoted by different suppliers. With averaging, it is of course possible to produce any sensitivity one desires. Alaris Antennas has recently started standardizing DF sensitivity calculations by applying a noise figure of 6dB in the receiver with a 1Hz system bandwidth and no averaging. Sensitivity data normalized to these parameters will eventually appear in all documents and can also be obtained on request for older products that may still use fairly arbitrary choices based on then customer-specific parameters.

As with the problem of bias error not being fully accounted for in accuracy specifications, one would have to specifically investigate how the sensitivity degrades under practical stressors like cross polarization or off-horizon incidence, before one can plot the sensitivity under these conditions.



**Sensitivity is the number to look at when comparing DFs – especially from the same vendor.** DF Sensitivity is dependent on many factors, the most important are:

1. Design and behavior of the DF antenna array, including both antenna gain and any interactions with surrounding structures that may affect the large signal accuracy
2. RF electronics losses and noise introduced in the RF chain
3. Performance and configuration of the receivers (bandwidth, noise figure, etc.)
4. DF processing system estimation methodology, averaging time, correlation algorithm, etc.

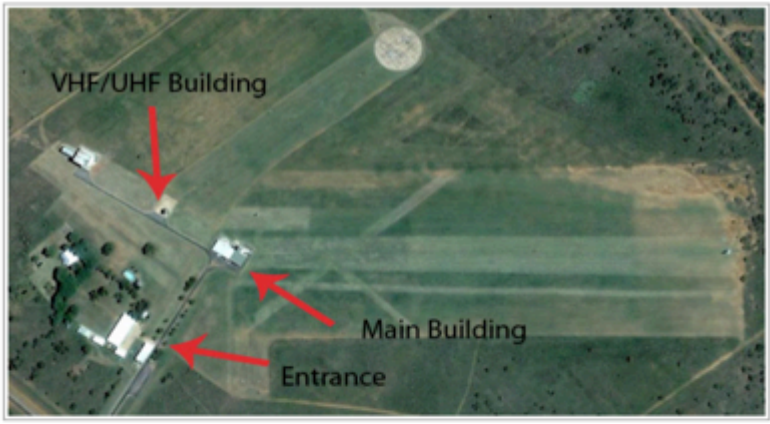


**An illuminating aspect of this approach to sensitivity specification is that it can be expressed in a graph versus frequency**. One can see how the required incident field strength for a given array has a sweet spot in the chosen frequency band bounded by the low end, as the antenna becomes electrically too small, and the high end, where wild bearings begin to dominate. Sensitivity can be plotted for various possible desired RMS accuracy values to get a feeling for the accuracy degradation vs field strength.

GEROTEK TEST FACILITIES

The South African National Antenna Test Range

General Facilities




The National Antenna Test Range covers an area of 30 acres (24Ha) and is fully security fenced, with access control and 24 hour CCTV surveillance.

The main building contains stores, workshops and offices along with a full kitchen and bathroom facilities. The VHF/UHF building contains offices and stores. Both buildings are fully air-conditioned.

Prime power for the range is provided by the substation next to the entrance gates which is fed into a high capacity UPS system. A diesel generator serves as back-up supply for the entire facility.

A Cherry Picker is available for hire for clients needing to mount larger antennae on the positioner, this vehicle is only to be operated by individuals licensed to do so.

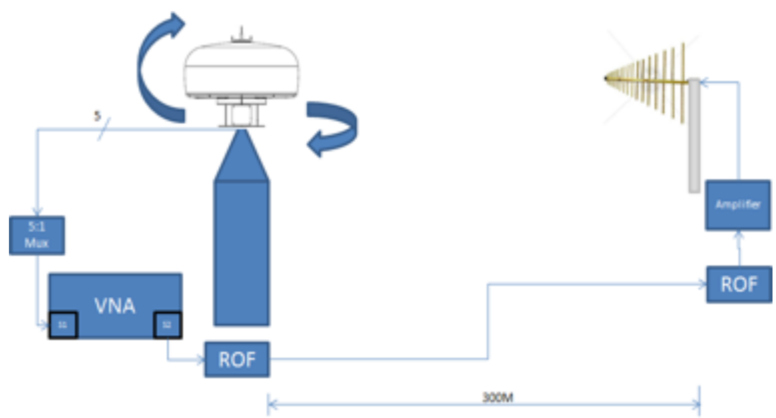
**Alaris Antennas utilizes the South African National Antenna Test Range is situated at Paardefontein, 45 km north of Pretoria, South Africa. It is the only open air, far field reflective antenna test range in the country, allowing precision testing of antennas that cannot be tested in indoor anechoic chambers due to their dimensions, weight and/or frequencies. This extremely versatile range can test frequencies from 300 kHz - 18 GHz and possesses automated motion control automation to assist the acquisition of precision RF data for the purposes of characterization of DF antenna systems.**

## Characterization and Calibration

The collection of all array steering vectors as a function of AoA, polarization and frequency is referred to as the characterization table or array manifold. Characterization of the manifold, also sometimes (confusingly) referred to as antenna calibration, can be done either by using an antenna measurement approach or by calibrating with full systems that include receivers. In both cases, the measurements can be done at an outdoor test facility (such as the Paardefontein South African National Antenna Test Range outdoor ground reflection facility) or an indoor facility such as an anechoic chamber of sufficient size, which are generally only suitable for smaller antenna arrays operating above a few hundred MHz.

Sometimes it can even be possible to generate a manifold by simulation, although this is normally only done when a practical characterization exercise is not possible or very expensive.

The outdoor facility used by Alaris is attractive to many international customers because transmission of fairly high levels of RF power over a wide frequency band is possible, as the procedures describe below.




**Measurement Setup**
*When characterizing at the outdoor ground reflection range, a source antenna and power amplifier is deployed 100-500m from the antenna under test (AUT) and linked to the control room using an RF-over-Fiber (ROF) link. A PC-controlled vector network analyzer is used in conjunction with a commutating switch located at the antenna output and an antenna positioner (rotator) to perform the calibration. The VNA transmitting port is connected to the source antenna via the ROF and the receive port is connected to the output of the commutating switch. With the AUT mounted on a rotating positioner, the transmission coefficient (S21) is gathered for each antenna element, or channel, by switching between the antenna outputs with the commutating switch. This is done for each azimuth point in the characterization table.*

During characterization, it can be helpful to use source setups that provide cross-polarized waves, and with the waves originating from different elevation angles, to see how the antenna characterization table performs under stress.

Measured S21 data can be processed into a table that provides the vector current or voltage at the antenna outputs for a 1 V/m incoming wave incident on the antenna. Combining system specific processing as required by the DF processing method makes the manifold. The verification data can also be processed to provide accuracy, LSA, and sensitivity projections.

## Characterization involving the full DF system

For full DF system characterization, system integrators hook up all the system specific receivers and commutation switches, if needed, to the antenna outputs and with the source transmitting via programmable signal generator and with sufficient power via a power amplifier to ensure a high SNR, to gather the aperture outputs directly from the receivers. Normally some averaging is employed to further improve the SNR of the manifold data. The process usually takes longer than the network analyzer approach above, but has the benefit of including the 'real' DF system in the measurements.

Confusingly also named 'calibration', but quite a different exercise, in all cases it is important to calibrate out the RF chain leading down from the antenna and its band selection switch to the receivers, as it changes over time and with positioner rotation, cable flexing and temperature. It is helpful to use the internal calibration source feature built into Alaris Antennas DF band switches for this purpose. This activity is done both during characterization of the manifold and during actual use. Alaris tends to make supplemental use of a fixed reference antenna co-located with the DF antenna for this purpose when doing characterization using the antenna measurement approach.

It is important to note the following when characterizing and calibrating a DF antenna system:

- ✧ Illuminate the AUT with a high E-field (high SNR) and pure vertical polarization.
- ✧ Assure a large quiet zone and that the field is flat for AUT illumination.
- ✧ Make use of a vector network analyzer (VNA) to measure the relative phase and amplitude of the received signal between elements.
- ✧ Use a fast commutating switch to route between port 2 and the DF elements for each band as well as any reference antennas connected. Commutation has to be done fast enough to ensure that the field phase stays constant between measurements.
- ✧ Provide Port 1 of the VNA a signal to the amplifier in the far-field via RF over optical transducers
- ✧ Measurements the relative amplitude and phase between elements and log by a PC that communicates with the VNA.
- ✧ Log relative phase and amplitude per element, per azimuth step and per frequency point with the axis of the antenna parallel to the field (hence zero elevation).

*The material presented herein is primarily the edited comments on DF system accuracy and calibration written by Dr. Chris Vale, CTO and Head of Engineering of Alaris Antennas, and published by permission in 2015. About the editor: David A Moschella is founder of Cyntony Corporation, authorized distributor in North America for Alaris Antennas. Mr. Moschella possesses wide experience in physical science based technology and business, running a variety of ventures in antennas, measurement, automation and software.*

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