MEASUREMENT OF ANTENNA PERFORMANCE FOR ACTIVE ARRAY ANTENNAS WITH SPHERICAL NEAR-FIELD SCANNING

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Abstract

Here we address some of the issues faced by antenna engineers when testing active antennas. We review some features of phased arrays and report on how MI Technologies has dealt with the issue of measuring the effective isotropic radiated power (EIRP) and antenna patterns by use of the spherical near-field scanning technique. We take as an example the test methodology of the SAMPSON radar antenna.

1. Introduction

Active antennas are antennas that have active elements as an integral part of the radiating structure and are differentiated from conventional passive antennas by the absence of a port at which the active component(s) can be separated form the radiating structure. Active antennas can in general be either purely transmitting antennas or purely receiving antennas or in fact antennas with both modes available by use of switching control circuitry. This then makes the classical antenna parameters, gain and effective area, not applicable in characterizing the antenna because of the lack of an available transmission line port at which a test instrument can be connected. Instead the active antenna must be characterized purely by the strength of the radiation that is emits or by its sensitivity to the radiation to which it responds.

With modern integrated circuit technology, such active antennas can be formed into arrays of active modules, termed transmit/receive (T/R) modules with their performance under the control of a central antenna control computer. When outfitted with common timing signals distributed to each module individually, a set of active modules can be operated as phased arrays -- both in the transmit and the receive modes -- with dynamic performance agility able to rapidly adapt to changing external conditions. An outstanding example of such an antenna is the SAMPSON radar antenna, which we describe in Section 4.

First, however, we briefly review the classic antenna quantities and lay the groundwork for understanding how near-field scanning has come to be applied to the measurement of active antennas in Section 2. Then in Section 3 we summarize some descriptive information about digital beamforming (DBF) to enable the reader to appreciate the functioning of the SAMPSON antenna. In Section 6 we describe the test system at a high level sufficient for the reader to appreciate how the testing is carried out.

2. Antenna Parameters

2.1. Antenna Patterns

Classic antenna patterns are measured on a far-field range sufficient in length to make the recorded amplitude and phase quantities independent of distance and functions only of angle, polarization state and frequency. Typically, for each frequency, there will be two phasor quantities, one for each polarization state, that are recorded for each of two spherical coordinate angles (e.g. θ and φ) which define direction about the antenna. These data sets comprise a set of antenna patterns -- one for each frequency of interest. In the case of a sophisticated radar antenna, there may be hundreds of beam states, hundreds of frequencies, numerous ports and both transmit and receive modes for which measurements must be made.

Spherical near-field (SNF) scanning is a modern method of making antenna patterns that permits the far-field criterion on range length to be circumvented. [1] SNF scanning enables measurements to be made indoors under controlled laboratory conditions. One records the same two phasor quantities per frequency as in the far-field case, but he must control and determine the near-field range length very accurately. To obtain the far-field pattern, taking one data set, that corresponds to a single frequency, at a time, he performs a (NFFF) to far-field transform, resulting in the desired far-field pattern. This is repeated for each beam, frequency and port for the test scenario that is associated with the antenna.

A schematic view of the test chamber layout for the SAMPSON antenna is shown in Fig. 1. The spherical near-field scanning is accomplished by motion in two axes. The rotator of the SAMPSON antenna is employed for the azimuthal φ - axis motion and vertically-oriented semi-circular arch is employed for the θ-axis motion. A carriage on the arch carries an open-ended waveguide probe over a 135 degree range of angles.

The SAMPSON antennas are covered by a spherical radome and mounted on a mechanical rotator just as when mounted on a ship's mast when in service. The test chamber contains a planar scanner for initial alignment of the modules.

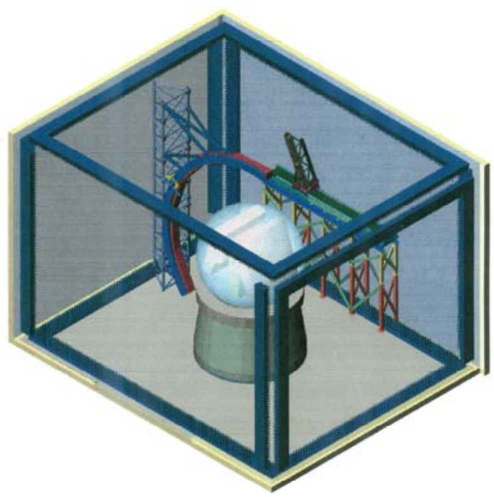

Fig.1. Schematic - Layout of the SAMPSON Radar Antenna Test Chamber

2.2. Gain and Directivity

One method of making gain measurements on a far-field range is to employ the Friis transmission equation and utilize an antenna of known gain to receive the radiated wave from the unknown test antenna that is taken to be transmitting. Knowing the wavelength of the radiation and the range length, one can compute the gain of the unknown test antenna. This technique is useful only on ranges of modest length because of the necessity of making a transfer measurement of the ratio of the received power to the input power.

With a spherical near-field range and for conventional antennas this same approach to gain measurement can be used. Assuming that one knows the gain of the probe antenna, the frequency of the radiation and the near-field range length, one can employ the SNF transmission equation and a measurement of the range insertion loss to find the normalization constant for the near-field scanning data set. After the spherical NFFF transform, the gain of the unknown test antenna is obtained from the radiation intensity computed by the transform.

2.3. EIRP Measured in the Far Field

Consider an antenna transmitting a wave into the far field region where strength of its field is to be measured. Classically, the quantity of interest with the antenna in transmit mode would be the radiation intensity, Φ, expressed in units of power per steradian. Recall that gain is defined as the ratio of the radiation intensity to the isotropic level $P_0/4\pi R^2$ where R is the distance of the measuring antenna away from the transmitting antenna, and P_0 is the power accepted by the transmitting antenna. The transmitting antenna illuminates the measuring antenna with a radiation power density S. The power received by the reciprocal measuring antenna, whose gain and therefore whose effective area is known, is the product of the effective area A_{eff}^{Meas} and the area power density S.

$$P^{Rcv} = A_{eff}^{Meas} S \tag{1}$$

The area power density S of the transmitted wave from the test antenna and the radiation intensity Φ of the transmitted wave are related by and

$$S = \Phi / R^2 \tag{2}$$

A useful way of expressing the EIRP is as 4πΦ. Thus we can write the EIRP as

$$EIRP \equiv 4\pi\, \Phi = 4\pi R^2 P^{Rcv} / A_{eff} \tag{3}$$

Once the received power is measured, the quantities on the right side are known for the far-field range. Thus we measure the far-field EIRP from knowledge of the range geometry, the known calibrated measuring antenna and a measurement of

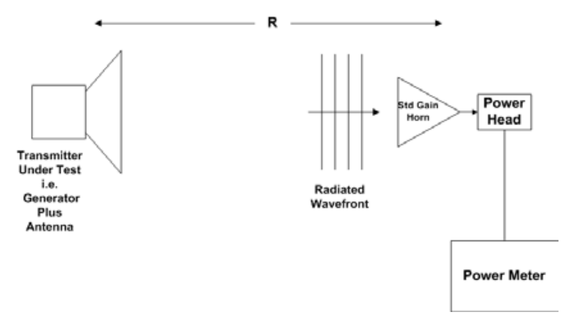

Fig.2. Schematic – Far-Field Measurement of EIRP

received power.

2.4. EIRP Measured in the Near Field

To measure EIRP for the transmitting antenna using spherical near-field scanning we can expect to follow the same approach – i.e. to calculate it from a knowledge of the range geometry, a calibrated probe antenna and a measurement of received power at the port of the probe.

MI Technologies employs a SNF Transform package designated SNIFTD furnished by TICRA. [2] This software implements the SNF transform algorithm developed in the 1980's by workers at the US National Bureau of Standards (now renamed the US National Institute of Standards and Technology) and at the Technical University of Denmark. It is based upon a scattering matrix representation of a general antenna and employs Fourier digital signal processing techniques to accomplish the NFFF transform.

The spherical near-field (SNF) transform computes the Normalized Far-Field voltage response of an elemental Hertzian dipole as a function of φ and θ -- i.e. as a function of position on the radiation sphere.

The theta- and phi- components of the electric field of the test antenna, E_θ and E_ϕ, are related to the Hertzian dipole voltage response w^e, sampled at two values of the polarization angle χ -- 0 degrees (0 radians) and 90 degrees (π/2 radians):

$$w^e(A;0,\theta,\phi) = \frac{\sqrt{6\pi\eta}}{2k} E_\theta(A,\theta,\phi) \quad (4a)$$

$$w^e(A;\frac{\pi}{2},\theta,\phi) = \frac{\sqrt{6\pi\eta}}{2k} E_\phi(A,\theta,\phi) \quad (4b)$$

where

A = radius of the measurement sphere
η = admittance of free space
k = 2π/λ
λ= wavelength of the radiation

The units of the voltage quantities w, and later v, and of the spherical modal expansion coefficients are $[\text{watts}]^{1/2}$ See Hansen [1], (3.45 and 3.46) p. 77.

The *normalized far field* of the test antenna W^e is defined as the voltage response of an electric dipole probe to a transmitting test antenna normalized by the factors kA and e^{ikA}, and extrapolated to the far field - kA→∞.

See Hansen [1], (3.50) p. 78. The units of w^e are $[\text{watts}]^{1/2}$ See Hansen [1], p.27, paragraph 2. Because the quantity kA is dimensionless, the units of W^e are also $[\text{watts}]^{½}$.

The far-field output of the TICRA software is related to the normalized far-field defined by Hansen by the relation

$$W^{TICRA} = \frac{2\sqrt{2}}{\sqrt{3}} W^e \quad (5)$$

This is because the TICRA software utilizes a very useful – but fictitious -- dipole probe that is a Hertzian dipole with a gain of 4 –i.e. 6dB, whereas Hansen's dipole is a simple Hertzian dipole with a gain of 3/2 or 1.76 dB. The TICRA 6 dB dipole has a value of the probe receiving $R_{s\mu n}$ characteristic [2] of 1.15 (i.e. 2/√3) whereas the Hertzian dipole has a value of $R_{s\mu n}$ of 0.707 (i.e. 1/√2).

In the context of SNF theory, one can write an expression for the EIRP of an antenna identical in form to the usual classical EM expression:

$$4\pi\,\Phi_{SNF} = \frac{\eta}{2}[\,|E_\theta|^2 + |E_\varphi|^2\,]R^2 \quad (6)$$

where R is a far-field distance -- i.e. R = A, as A→∞. With substitutions from the SNF equations above, one finds the simple result that the EIRP is given by

$$4\pi\,\Phi_{SNF} = \frac{1}{2}\left|W^{TICRA}\right|^2 \quad (7)$$

where again Hansen's impedance convention applies.

This SNF result is premised upon the assumption that the input to the SNF transform is expressed in absolute voltage units, not the relative antenna measurement receiver readings expressed in dB. To correct for the arbitrary units of the receiver a normalization of the relative receiver data must be made. The calibration factor derives from a receiver calibration using a power meter with the SNF probe located in a region of strong near-field energy, desirably at the values of θ and ϕ where the near-field peak is found.

$$\text{Calibration Factor} = \{P^{NFcopol}(\theta_{NFpk},\varphi_{NFpk}) \,/\, [\tfrac{1}{2}\left|\mathbf{w}_p^{NFcopol}(\theta_{NFpk},\varphi_{NFpk})\right|^2] \quad (8)$$

Here $w_p^{NFCopol}$ is the near-field response of the probe. This factor has the effect of "dividing out" the arbitrary receiver units and "multiplying in" the units in which the power meter quotes its reading. Since the SNF transform is linear, the calibration factor can be applied either before or after the transform is taken. Note that this equation is linear power units such as mW, not in dBm. The EIRP can be expressed in logarithmic units such as dBW, once the calibration factor is applied. [3].

3. Active Antennas and Beamforming

Phased array antennas work on the principle of combining the received or transmitted signal of a number of antennas in order to simulate a larger aperture with the possibility of steering the main beam and changing the overall beamwidth. Beamforming is another way of describing this technique. Beamforming is the combination of radio signals from a set of small non-directional antennas to simulate a large directional antenna. The simulated antenna can be pointed electronically, although the antenna does not physically move. In communications, beamforming is used to point an antenna at the signal source to reduce interference and improve communication quality. In direction finding applications, beamforming can be used to steer an antenna to determine the direction of the signal source. By varying the signal phases of the elements in a linear array, its main beam can be steered. The simplest way of controlling signal phase is to systematically vary the cable lengths to the elements. Cables delay the signal and so shift the phase. However, this does not allow the antenna to be dynamically steered. In an electronically steered array, programmable electronic phase shifters are used at each element in the array. The antenna is steered by programming the required phase shift value for each element. In beamforming, both the amplitude and phase of each antenna element are controlled. Combined amplitude and phase control can be used to adjust side lobe levels and steer nulls better than can be achieved by phase control alone. A beamformer for a radio transmitter applies the complex weight to the transmit signal (shifts the phase and sets the amplitude) for each element of the antenna array.

In digital beamforming, the operations of phase shifting and amplitude scaling for each antenna element, and summation for receiving, are done digitally. Either general-purpose digital signal processors (DSP's) or dedicated beamforming chips are used. The rest of this discussion focuses on beamforming receivers. Digital processing requires that the signal from each antenna element is digitized using an A/D converter. Since radio signals above shortwave frequencies (>30 MHz) are too high to be directly digitized at a reasonable cost, digital beamforming receivers use analog "*RF translators*" to shift the signal frequency down before the A/D converters. The complex weights w_k for the antenna elements are carefully chosen to give the desired peaks and nulls in the radiation pattern of the antenna array. In a simple case, the weights may be chosen to give one central beam in some direction, as in a direction-finding application. The weights could then be slowly changed to steer the beam until maximum signal strength occurs and the direction to the signal source is found. In beamforming for communications, the weights are chosen to give a radiation pattern that maximizes the quality of the received signal. Usually, a peak in the pattern is pointed to the signal source and nulls are created in the directions of interfering sources and signal reflections. *Adaptive Beamforming* is the process of altering the complex weights on-the-fly to maximize the quality of the communication channel.

4. The SAMPSON Radar

BAE Systems was commissioned to build several units for the new Royal Navy Type 45 Destroyer depicted in Figure 3. SAMPSON is described by BAE Systems as being "vastly more powerful than existing systems," able to handle multiple threats simultaneously, and "immune" to jamming. The ability of the computer-based management system to shape and point the radar beam instantaneously in any direction, coupled with its ability to change or adapt the radar characteristics in real time in response to current and future threats in an environment of heavy jamming and land and sea clutter, enables SAMPSON to perform a number of tasks simultaneously. As an example, the radar may employ a wide variety of different waveforms, each optimized for certain search angles and/or environmental conditions (for instance using moving target indication waveforms in the lower regions of the search volume). A SAMPSON test site has been constructed for testing of the radar. Please see Fig.4.

SAMPSON employs two arrays, mounted back-to-back on a rotating (up to 60rpm) antenna structure (Figure 2), with a total of 5,200 elements. In fact, the radar has approximately 650 T/R modules of four channels each, per face of the antenna, equalling 2,600 elements per face. It is one of the first radars in the world to use digital adaptive beamforming,

Fig. 3. Royal Navy Type 45 Destroyer

Fig. 4. SAMPSON at BAE Systems Insyte (Cowes - UK)

which makes it virtually immune from all forms of electronic jamming. Its modular design reduces the through-life costs, whilst significantly increasing availability.

5. RF Testing of an Array Antenna Whose Beam is Formed Digitally

MI Technologies was chosen by BAE Systems in 2002 as a supplier of the test facility in which the SAMPSON phased array is aligned and tested. The facility consists of an anechoic chamber and control room to support spherical and planar near-field scanning. The chamber was outfitted with a circular arch scanner, which, together with the mechanical rotator of a radar, forms the scanning motion of the probe antenna relative to the antenna. The test system supplied was based on the MI Technologies MI-3000 Automated Microwave Measurement System that was designed to enable near-field scanning measurements. In addition, the chamber was outfitted with a planar near-field scanner for acquiring phase/amplitude data over a plane by which the antenna would be aligned, including compensation for the effects of the radome. Rather than employ the planar scanner to produce far-field patterns, the spherical near-field method was chosen to afford more nearly complete solid angular coverage. A simplified block diagram of a generic MI-3000–based spherical near-field measurement system is shown in Fig. 5. An ordinary antenna test would be configured in this manner.

The host computer via digital control of the RF subsystem and the mechanical positioning subsystem directs the scanning measurement. It sets the mechanical axes into motion in step-scan fashion moving the probe and the test

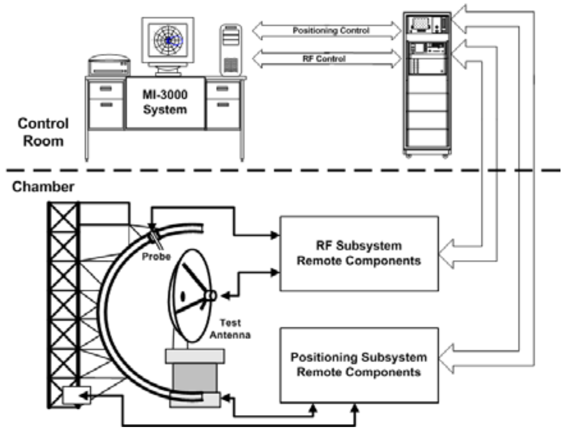

Fig.5. MI-3000 with Typical Spherical Near-Field Arch

antenna through the spherical angles θ and φ. At preselected near-field values of these angles the signal received at the port of the probe is measured and recorded in a file. This file is then processed via the SNF transform to obtain the far field.

The MI-3000 computer system includes a variety of interfaces to support mechanical scanning subsystems and RF subsystems of different types. For example, the MI-3000 System supports three third-party network analyzers as RF subsystems in addition to MI's proprietary Model 1797. This flexibility is at the heart of the MI-3000's ability to perform the control functions need to test the SAMPSON antenna.

To test the SAMPSON, the radar control computer must appear in the system block diagram to control the antenna and to control the rotary positioner. An additional interface is employed between the MI-3000 measurement computer and the radar control computer. When the SAMPSON radar antenna is transmitting the signal is generated within the radar and a sample of the CW signal is provided to the measurement receiver as a phase reference. Meanwhile, the azimuth motion is also controlled by the radar. The arch motion is controlled by an MI-4190 Position Controller. To measure EIRP in the near field, the power received by the probe is measured by manually installing a power meter head at the port of the co-polarized port of the probe antenna. One must utilize a calibrated pad attenuator to avoid damage and saturation of the sensor. A message on the measurement computer display prompts the operator to change over from the measurement receiver to the power meter. The response of the power meter is recorded through a computer interface to the power meter controller.

When the SAMPSON radar antenna is receiving, the individual modules act collectively to receive and digitize their signals and the radar software produces a composite near-field antenna response, which must be transferred to the host computer for recording. Meanwhile the transmitting probe uses a signal from the radar's internal signal generator whose frequency is controlled indirectly by the measurement computer.

A photograph of the arch at the time when the test facility was being commissioned is shown in Fig. 6. The antenna was a reflector antenna chosen for the evaluation and also measured with an outdoor cylindrical near-field antenna range.

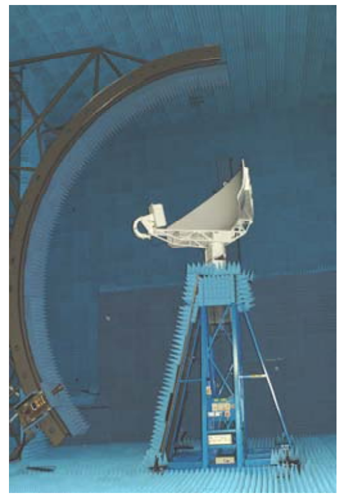

Fig.6. Photo of Arch with Reference Radar Antenna and Rotator for Evaluation of Test Facility

6. Conclusion

We have described the SAMPSON radar and it s antennas as it is implemented in a digital beamforming architecture. We have described the layout of a test facility that employs spherical near-field scanning to determine the far-field antenna patterns. We described in detail how spherical near-field scanning has been extended by the addition of a power measurement to determine the EIRP of the active SAMPSON antenna. We conclude that any active antenna can be tested for its pattern and EIRP provided that a reference signal from the internal generator is available and that digital control of the internal signal is available for setting of the CW frequency.

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