Measurement of Time-Evolving Electronically Steerable Radiation Patterns at Fast Timescales by a Sampling Technique

Justin Henrie and Matthew Tang

Naval Air Warfare Center Weapons Division, Point Mugu, California, 93042, USA

Abstract — Modern electrically steerable antennas have the ability to evolve their far-field radiation pattern on nanosecond timescales. The transient radiation that occurs during this evolution cannot be captured by conventional radiation pattern measurements, which take at least several minutes to complete. We present a temporal and spatial sampling method of measuring the rapid temporal evolution of an electronically steerable antenna’s near- and far-field radiation pattern, which allows for time-domain measurement of the radiation pattern of an antenna at relevantly short timescales and over an arbitrarily large solid angle. An experimental validation of the method is reported, in which an azimuth-plane measurement of a phased-array antenna captures the transient far-field radiation pattern as the antenna switches its main-beam scanning angle with 7-nanosecond time resolution.

Index Terms — Electromagnetic transients, beam steering, phased arrays.

I. INTRODUCTION

One of the principal characteristics of phased antenna arrays and other electronically steerable antennas (ESAs) is their ability to dramatically change their far-field radiation characteristics on short timescales. Because of this, ESAs are a popular choice for radar systems as they give the radar the ability to rapidly raster its transmit and receive beams through a search area, allowing for faster update rates and increased temporal and spatial resolution.

Measurement of the time-evolution of the radiation pattern of an ESA during “beamsteering” events is desirable for a number of reasons. Although extremely rapid, beamsteering operations are not instantaneous; but are characterized by a transient period that is difficult to measure by conventional methods. For a given ESA system, the amount of time between the dissolution of one aperture mode and the establishment of steady state operation in the next is an important parameter that limits, for example, the number of targets that a radar system may track simultaneously. Additionally, the behavior of the radiation pattern during this transient period can be of critical importance to various characteristics of the system such as co-site interference, stealthy operation, and fratricide reduction. The measurement of time-changing radiation patterns during ESA transients may also be valuable to obtaining a system-level understanding of the interaction of an ESA antenna and its power amplifier and beamformer networks as such interactions are difficult to model because of their complexity.

II. DESCRIPTION OF THE TRANSIENT RADIATION MEASUREMENT METHOD

This transient radiation measurement technique is similar to the well-known method of high-speed sampling oscilloscopes [1], which sample a repeating signal at a period other than the signal’s, resulting in the amalgamated measurement of a
single period of the measurement, effectively sampled at a much higher sampling rate than that achievable by the sampling oscilloscope’s analog-to-digital converter (ADC). The measurement of a fast-transient radiation pattern over an arbitrary solid angle follows a similar strategy. By serially sampling a repeatable transient radiation pattern at multiple angular sampling points, we can completely characterize an ESA’s radiation pattern evolution over an arbitrarily large solid angle.

The process is depicted in Fig. 1, which shows a cartoon of the measurement process, as well as a basic block diagram of the experimental setup used for this study. The equipment used in the measurement is similar to that used in conventional radiation pattern measurements, except that here the conventional swept-frequency receiver is replaced with a high-speed digitizing receiver of some kind, such as a wide-bandwidth oscilloscope or digitizing spectrum analyzer. The measurement of a fast-transient radiation pattern over an arbitrary solid angle follows a similar strategy. By serially sampling a repeatable transient radiation pattern at multiple angular sampling points, we can completely characterize an ESA’s radiation pattern evolution over an arbitrarily large solid angle.

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This pulse train was also used as a trigger signal for the digital receiver used in the measurement (Tektronix RSA 6114A), so that the disparate measurements could be time-correlated later to visualize the time-evolution of the radiation pattern over the entire angular measurement domain. The RSA is a heterodyne digitizing receiver, which downconverts an interval of the spectrum (up to 110 MHz bandwidth) to baseband before digitizing it. As the incoming radiation was a CW tone at 5 GHz, which is broadened during switching events by the rapid transient of the RF switch, as well as other transients induced by switching between different ports of the beamformer. We configured the RSA to digitize a 110-MHz region of spectrum, centered at 5 GHz. This resulted in a time-domain sampling of the resolution of 6.67 ns (somewhat higher than the Nyquist minimum to allow for filter rolloff compensation).

As stated before, the receiver captured one angular “slice” of the transient radiation pattern per angular measurement point. For this experiment, we recorded 2 milliseconds (about 66 beamsteering events) of RF at each angular measurement point. Two examples of these single-angle, time-domain measurements are shown in Fig. 2. These are plots of the magnitude of the received RF radiation versus time, at two different angular measurement points. For clarity, only 200 microseconds of the measurement is shown; however the recorded signal is periodic across the entire 2 millisecond measurement.

Measuring multiple switching events at each angle is important, because many switching events must be compared to establish that the repeatability (or time-invariance) of the beamsteering mechanism. Repeatability of the beamsteering mechanism is important for reliable operation of the phased array system in general, but is particularly important when attempting to measure transient radiation patterns with this technique because angular measurements must necessarily be obtained at different times. Thus, accurate reconstruction of a single radiation transient from all measurements assumes that all elements of the ESA are time-invariant. For this example study this was found to be the case—all 66 beamsteering transients taken within each 2 millisecond measurement were identical to within the measurement uncertainty of the measurement system.

The displayed 200 microsecond time interval of the measurement shown in Fig. 2 comprises several RF switching events, which can clearly be seen as the rapid transitions from low to high received signal levels. The samples shown in Fig. 2 (a) and (b) are at -23° and +40° from boresight respectively, corresponding to the center of the main lobes generated by the two ports of the Butler matrix beamformer that were switched between in this experiment. While not taken simultaneously, these two measurements are time-synchronized by triggering the RSA capture with the voltage pulse used to actuate the RF switch, thus both measurements start with time \( t=0 \) and can be treated as being roughly synchronous. The switching of the RF received sensitivity between these two angles can be seen by comparing the two plots—when (a) records a high receive signal, (b) records a low signal level, and vice versa.

Comparing the transition times of the two plots, we can see that using the pulse train to trigger the capture of the RF data provides a reasonably good synchronization of measurements—the transitions occur at nearly the same times in both measurements. With 6.67 nanosecond sample spacing, there is also ample temporal resolution in the measurement to resolve the transient periods between steady-state beam states. In the next Section, we will present how the combination of these measured single-angle transients yields a visualization of the wide-angle time evolution of the entire radiation pattern.

### IV. TIME-SYNCHRONIZATION OF MEASUREMENT DATA

Once time-domain measurements of the beamsteering transient have been made, they can be arranged in whatever manner is best conducive to studying the time-evolution of the radiation pattern. One intuitive way to visualize the data is to simply animate a standard radiation 2- or 3D radiation plot. This can be done most readily, but is not conducive to reporting in a printed medium such as this paper. For the single-axis “az-cut” measurements performed in our experiment, the time-evolving radiation pattern can also be displayed using a surface plot, with time and angle being the

![Fig. 3. Plot of all of the time-correlated single-angle measurements together results in a visualization of the time evolution of the radiation pattern.](image)
two horizontal axes, and RF intensity being the vertical or colored axis, as shown in Fig. 3, where a the roughly 700 ns region around one of the abrupt switching events shown in Fig. 2 is displayed for all the angular sampling points simultaneously. In this plot, the horizontal axis tracks time (in nanoseconds) and the vertical indicates the angle in degrees at which each sample was taken relative to boresight. Thus the rows of this surface plot are of the same type displayed in Fig. 2 (zoomed-in on the first switching transition of each), while the columns are “plane cut” antenna radiation pattern plots, which are common in the literature [4]. The result is a visualization of the time-evolution of the radiation pattern, read from left to right.

Ideally, utilizing the same signal to actuate the beamsteering as well as trigger the probe that is capturing the data would provide perfect time-correlation of the disparate single-angle measurements. However, because of limitations in the timing accuracies of the systems involved, timing uncertainties of the captured waveforms occur and may in fact be significant with respect to the length of the transient event. For example, in our experiment the transient region was approximately 100 ns, and an RSA6000 series spectrum analyzer has an external triggering uncertainty of +/- 12 ns for the acquisition bandwidth used (110 MHz) [5]. These timing uncertainties manifest themselves as right- or left-hand shifts on the time axis, and can be seen in Fig. 3 as the jagged regions in the switching transition region between 300 and 400 ns. We expect a vertical cut of the graph in Fig. 2a near the transition to yield a typical power pattern with smooth lobes; instead, we find sharp jagged lobes because the transition times of the probe measurements do not line up. We can be assured that these artifacts are due to timing uncertainty and not to some real radiation transient during beamswitching, because they correspond to antenna directivities that are much greater than can be obtained with an antenna of the size used in this experiment.

To obtain more reasonable power patterns, we reason that because of the abovementioned limit on the directivity of the antenna, adjacent angular sample points must experience beamswitching transitions closely enough in time so that this directivity limit is not violated. Capitalizing on this distinctive feature, we time-shift the measured power waveforms so that the transitions of adjacent angular measurement points more nearly coincide.

Consider two sets of measured power waveforms, \( m_1(t) \) and \( m_2(t) \), where each is a horizontal cut of the graph in Fig. 3. When the transition event happens, the magnitudes of their derivatives experience a rapid maximum or “spike”. So to line up the transition event, we choose \( k \) to minimize the following cost function:

\[
J = \left( \frac{\partial}{\partial t} m_1(t) - \frac{\partial}{\partial t} m_2(t-k) \right)^2
\]

With a knowledge of the statistical distribution of the timing jitters, we can regularize the cost function in (1) with an additional term \( f(k) \). For example, if we know the jitters to be normally distributed, we can choose \( f(k) = k^2 \). The resulting regularized cost function (with parameter \( \alpha \)) is then given by:

\[
J_{REG} = J + \alpha f(k)
\]

By minimizing the above cost function, we can line up the transition events of angularly adjacent waveforms while controlling for the magnitudes of the time-shifts so that they are not too large with respect to a reference waveform (usually the starting waveform in the analysis). The resultant jitter-corrected plot is shown in Fig. 4, which shows the evolution of the ESA’s radiation pattern with time.

**REFERENCES**


