A 3-Axis Antenna Array for Polarimetric Spectrum Surveys

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***Abstract*—Complete and accurate characterization of the radio environment is necessary for effective management of an increasingly congested radio spectrum. Unfortunately most antenna systems commonly used to perform spectrum surveys only respond strongly to signals with one polarization and from a limited number of directions. This paper describes an easily constructed antenna array that can detect signals from a very broad range of directions, determine the total RF power at a given location regardless of polarization, and provide information about the polarization and arrival direction of signals.**

I. INTRODUCTION

As communication systems become ever more complex, the need for comprehensive spectrum surveys becomes more imperative. It's important to understand what signals are present in the radio environment in order to maximize the performance of a diverse collection of communication systems while simultaneously working to minimize the propensity for these systems to interfere with each other. At first glance this seems simple enough, set up an antenna and measure the power received at any given frequency. However, few things in life are that simple, and this is no exception. Radio transmissions can be differentiated by more than just frequency, and a comprehensive survey needs to take these differences into account. For example, radio signals can be separated from each other by:

- Frequency
- Time of transmission
- Propagation direction
- Polarization
- Modulation (AM, FM, FSK, etc.)
- Geography
- Power

If one performs a spectrum survey using a vertical whip antenna and a spectrum analyzer, the survey is limited to:

- The frequency range determined by the antenna response, receiver response, and sweep setting of the instrument.
- The time the instrument is taking data. (The type of sweep will also affect the time characteristics of the data since a frequency sweep doesn't see all frequencies simultaneously.)
- Vertically polarized signals.
- The geographical range of the measurement location.
- Power detected during the frequency sweep.

There is no implicit determination of directionality since the whip antenna is omni-directional, nor is there any implicit mechanism for modulation detection. Clearly there are choices and tradeoffs to be made depending on the types of signals that one wishes to study.

It is interesting to note that in the 1980s researchers at the National Bureau of Standards (now the National Institute for Standards and Technology - NIST) experimented with a resonant dipole array in an attempt to remove the limitations of polarization and direction of arrival inherent in simple antenna designs [1] [2]. However, at the time the NIST researchers were limited to the use of a single-channel receiver that was switched between these antenna elements. Consequently the relative phase information between the dipoles in the array were lost.

Today the prevalence of relatively inexpensive three-channel digitizing receivers begs us to take another look at the concept of using a 3-axis, crossed dipole antenna for spectrum surveys. Such a system makes it possible to perform a survey not limited to a specific signal polarization or direction of arrival. It also means that, unlike a traditional polarization-specific survey, we can determine the total RF energy incident at a given location and time.

II. THE 3-AXIS ANTENNA

The 3-axis antenna makes use of three dipole elements oriented as shown in Fig. 1. In this arrangement, each dipole element will respond most strongly to linearly polarized signals that match the antenna element axis, and which are incident at right angles to the plane in which the antenna resides. By connecting the three antenna elements to a synchronous, three-channel measurement system such as a digitizing oscilloscope as shown in Fig. 2, time synchronous data proportional to the three-dimensional vector field components E_x, E_y, and E_z can be collected.

A. DETERMINING TOTAL INCIDENT POWER

The total RF power incident on the antenna array can be computed as:

$$P_{total} = C_x|V_x|^2 + C_y|V_y|^2 + C_z|V_z|^2 \tag{1}$$

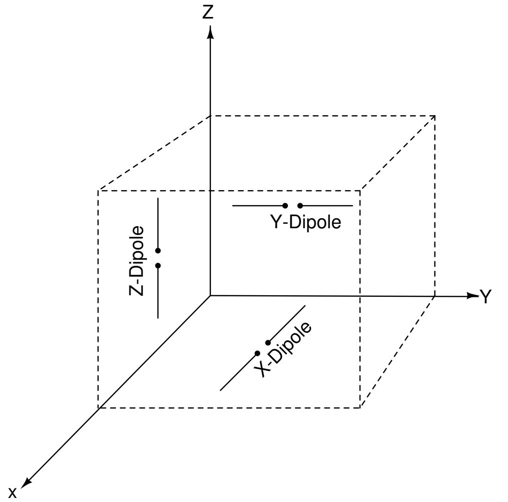

Fig. 1. Dipole antennas relative to a 3D reference cube

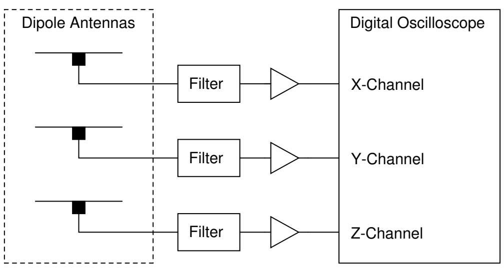

Fig. 2. Schematic diagram of the 3-channel measurement system

where:

- P_{total} is the total RF power incident on the antenna array,
- C_x, C_y, and C_z are calibration coefficients for each antenna element respectively, and
- V_x, V_y, and V_z are the measured antenna voltages.

B. DETERMINING DIRECTION OF ARRIVAL

If one is looking for a specific signal, then the maximum response of the antenna array to this signal will be along the average of the axis through the antenna where the total power magnitude of the signal is the greatest. Simply converting from Cartesian to spherical coordinates gives the magnitude of the signal as:

$$E_{total} = \sqrt{(A_x V_x)^2 + (A_y V_y)^2 + (AzV_z)^2}. \quad (2)$$

The elevation angle from the zenith is:

$$\theta = \arccos\left(\frac{A_z V_z}{E_{total}}\right), \quad (3)$$

and the azimuthal angle is:

$$\phi = \arctan\left(\frac{A_y V_y}{A_x V_x}\right). \quad (4)$$

In this case,

- E_{total} is the combined electric field,
- V_x, V_y, and V_z are the measured antenna voltages,
- A_x, A_y, and A_z are the dipole antenna factors.

There are two limitations to using this antenna for direction finding, but both can be resolved. First, there will be a 180 degree discrepancy for linearly polarized signals, since the response from the array will be identical for sources located on opposite sides of the axis of arrival. For circular or elliptically polarized signals, it may be possible to resolve the ambiguity if one knows in advance whether the signal incident on the array has left or right handed rotation. Second, if a linearly polarized signal is located in a position where it is cross polarized to two of the axes, the antenna will behave fundamentally as a single dipole antenna. The element aligned with the wave receives essentially all of the signal. This creates a 360 degree discrepancy around the receiving dipole. The good news is that if this condition occurs, rotating the antenna would resolve that issue.

C. DETECTING POLARIZATION

Since the output from the antenna system consists of the time synchronous voltages V_x, V_y, and V_z, simply plotting these in three dimensions will trace out the E-field rotation that is proportional to these voltages. If the resulting graph shows the voltages tracing a line in three dimensional space, the wave is linearly polarized. If the graph is a circle or ellipse, the signal of interest is either circularly or elliptically polarized. The axis of arrival will also be the normal through the center of the resulting trace. This works fine for visual analysis of simple signals, but if one wishes to facilitate automated processing of the signal there are a at least five possible representations that could be pursued:

1) Polarization ellipse [3, pp 32–36]
2) Poincaré sphere [3, pp 36–38]
3) Complex vector [3, pp 38–43]
4) Stokes parameters [3, pp 43–46]
5) Polarization ratio [3, pp 46–53]

Each of these representations are derived relative to a two dimensional reference plane with the x and y axes oriented so the propagation of the wave is normal to this plane. For the 3-axis antenna that is not generally the case, so we either need to generalize the mathematics to three dimensions or use the axis of arrival information determined in the previous section to define a reference coordinate system ($\hat{x}$,$\hat{y}$) with the wave incident along the $\hat{z}$ axis. This is a topic beyond the scope of this paper.

III. A PROTOTYPE 3-AXIS ANTENNA

To test the ideas presented above, a prototype 3-axis antenna array was constructed (see Fig. 3) and tested in an anechoic chamber as shown in Fig. 4.

This allowed us to illuminate the 3-axis antenna system with horizontally polarized, slant polarized, and vertically polarized waves while simultaneously rotating the antenna to a number of orientations. The goal was to test the antenna's response to these waves when incident from varying directions. A plot of the measured voltages V_x, V_y, and V_z for these test signals

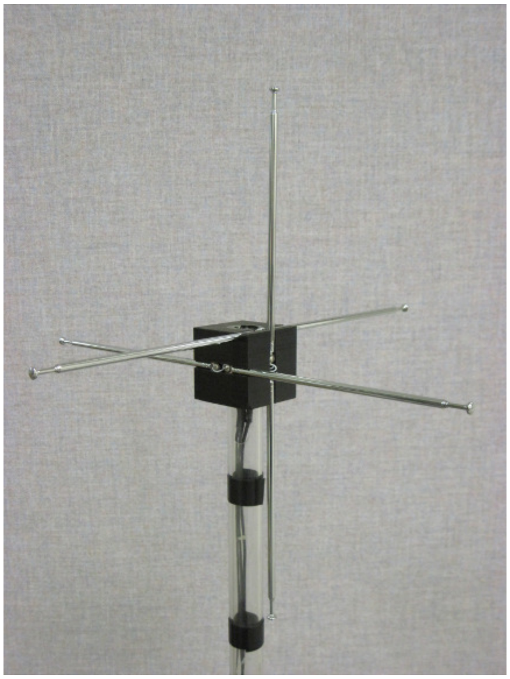

Fig. 3. Picture of the 3-axis antenna

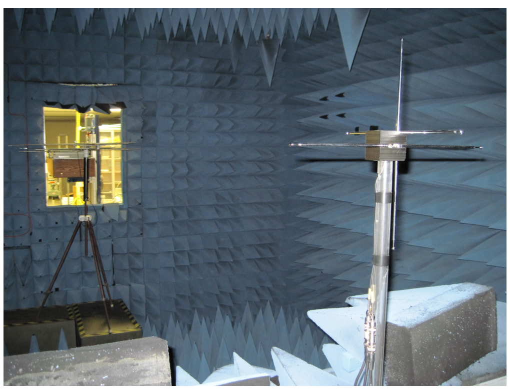

Fig. 4. Picture of the anechoic chamber test setup

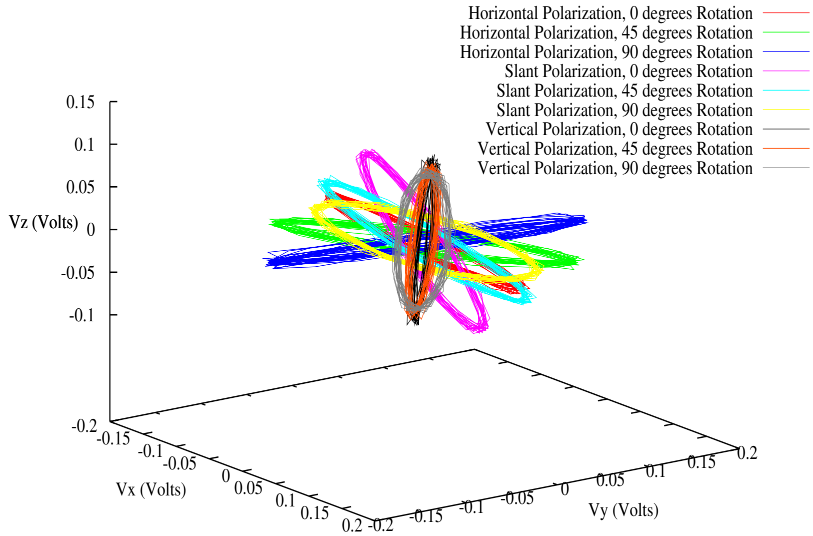

Fig. 5. Plot of the X, Y, and Z antenna element voltages

with the 3-axis antenna rotated 0 degrees (axis of arrival parallel to the Y-axis), 45 degrees (axis of arrival between the X and Y-axes), and 90 degrees (axis of arrival parallel to the X-axis) can be seen in Fig. 5.

Ideally, we would expect to see straight line plots at varying angles depending on the polarization orientation of the illuminating antenna and the angle of incidence of the wave on the 3-axis antenna. Clearly what we actually measured shows tight ellipses rather than straight lines, but this deviation from ideal can be explained by non-ideal coupling between the antenna elements and measurement system noise.

Tests were also performed to verify that computing the total power detected by the array as described in (1) would be consistent regardless of the angle of incidence. The results of those tests indicated that the the total power detection was consistent to within approximately ± 0.9 dB. The details of this experiment can be found in [4].

IV. CONCLUSION

The push for more efficient spectrum use, shared spectrum, and ever higher bandwidths creates a need for comprehensive spectrum surveys. We truly need to understand the multidimensional aspect of the radio environment rather than just taking a narrow sampling of signals with specific characteristics. We need to build survey systems capable of detecting signals arriving from any direction, at any time, and with any polarization. The use of single antenna systems is problematic since this limits the scope of the survey to the polarization of the antenna used. Additionally, if multiple, mixed polarization antennas are employed on a single channel receiver at different times, the temporal distribution of these signals cannot be directly compared. Indeed, a number of researchers have considered the measurement complications for making comprehensive surveys of the multidimensional radio environment. However, these systems are often fairly complex and/or rely on MIMO type antenna arrays [5] [6].

The development of the 3-axis antenna described here was an attempt to design a simple, easy to build antenna array that could be used as a test antenna for spectrum survey work. The performance and characterization of the three dipole antenna elements is well understood and mounting these antennas coincident with each other in a crossed polar manner makes it possible, when using a suitable three-channel receiver, to obtain complete real-time data. This antenna arrangement makes it possible to preserve the time and phase dependence of the signals in three-dimensional space.

There are a few possible improvements that could be made on the prototype discussed so far. One improvement would be to modify the mounting support so that the support mast and cables are equidistant from each of the elements as shown in Figure 6. This would complicate the analysis by adding

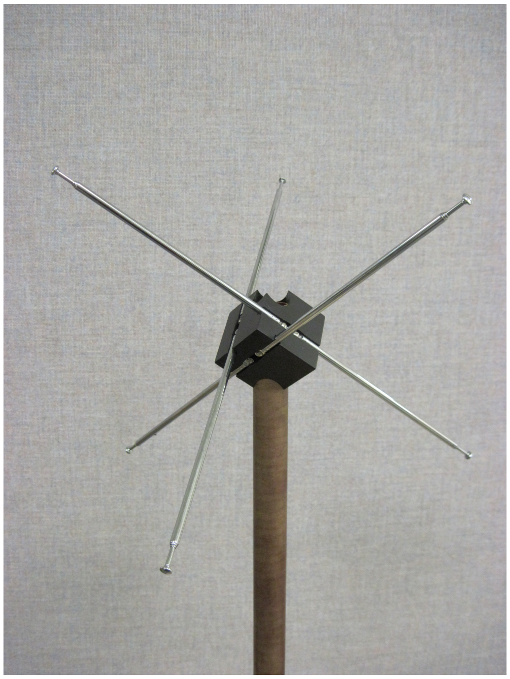

Fig. 6. Picture of a diagonally mounted antenna array

the need to perform coordinate system transformations to reference the measured data to the laboratory floor or the surface of the earth, but it would ensure that the mounting structure and cabling affects each antenna element equally.

Another area of concern is that dipole systems are fairly narrow banded. However, experiments done at NIST with resistively loaded dipoles may point to a way to overcome this limitation. Tests on a structure like this built at NIST showed that it performed well over a range from 10 MHz to 1 GHz, and that it might be possible to extend the useful range of this device up to 8 GHz [1]. In any case, the 3-axis antenna seems to make possible a true polarimetric, real-time, spectrum survey.

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