BISTATIC SCATTERER AND ANTENNA IMAGING

Steve Inge (in-j)

Broadcast Communications Ltd.

P.O. Box 98, Wellington, New Zealand

ABSTRACT: Two computing techniques to create an image of the radiating centres on an antenna or scatterer using Fourier optics is presented.

Steve Inge died on October 24, 2002 at the age of 61 after this article was submitted for publication. The reviewers accepted this article subject to revisions. Since that is not possible, this article is published as submitted.

The late Ian McEnnis, Chief Antenna Engineer at Broadcast Communications Limited in New Zealand, and one of Steve's colleagues, notified us of his death and had the following remembrances of Steve, which we print below.

Steve had been with our organization for 42 years. His immense intellect enabled him to become a "guru" in any area he focused on. Most of BCL's in house engineering software has been developed by Steve. BCLIPPS (BCL's Interactive Planning and Propagation Software) was Steve's crowning. It has formed the basis of our coverage work for the past 10 years and has enabled us to be a leader in this area. Steve was the engineer who solved the most difficult of problems and he was the one his colleagues turned to when they were having difficulty. His mathematical ability was awesome and once he got his teeth into a problem he would not let it go until he had it sorted. There is nothing Steve liked more than to share his knowledge with others. Having said all that, in the end Steve was just a "good bloke" who will be sorely missed by many.

Introduction

Bistatic k-space (BSKS) imaging from antenna currents was introduced by John Shaeffer et al (Ref 1). It is a technique to graphically show the active radiating centers on a conducting body. The currents on the body are found using either a computer program or measurements, for a particular excitation. The excitation may be a plane wave being scattered by the body, or sources on the body for an antenna. This paper describes two simple approaches to imaging a radiator.

Brief Overview

The radiation emanating from any antenna (or scatterer) may be visualised by simple operations upon the antenna currents. First choose the far field direction from which to look at the antenna. Create a plane surface at the antenna, normal to the look direction. Project all of the antenna currents onto this surface, adjusting the phase as necessary, to maintain the same phases and polarisation in the far field. Filter the current image on the surface by removing all spatial frequencies above one cycle per wavelength. Display the current intensity as brightness in a 2D graphic image, which will show which parts of the antenna are "glowing" when viewed from this direction. This is repeated for both polarisations, which may be combined into a single total radiation image if desired.

Imaging theory

How does it work? By flattening the currents on to a surface we create a two dimensional current plane. If we now take the Fourier transform (FT) of this current surface, we create a new description of the currents. The FT creates a set of sinusoidal waves equivalent to the original currents. Since the currents occupied a finite area on the surface, the FT range is infinite. Each point on the FT surface represents a particular uniform linear phase advance, and thus represents a plane wave propagating in a single direction. This is known as a plane wave spectrum of the radiation. The Fx, Fy positions on the spectrum are the direction cosines of the plane wave direction. The z component of the radiation is $Fz = \sqrt{1-(Fx^2+Fy^2)}$ The centre of the plane (0,0) is constant phase, which creates a wavefront propagating toward the look direction. When $Fx^2+Fy^2=1$, the wave direction is normal to the look direction. All points on this unit circle correspond to a phase advance of one cycle per wavelength. The spectrum outside this circle gives direction cosines > 1, indicating imaginary angles. This energy does not radiate, but represents evanescent waves which eventually return to the antenna as reactive energy. (Ref.3)

The antenna image is created by projecting the currents onto a normal plane, and removing spatial frequencies greater than one cycle per wavelength. The latter process may be achieved by setting the FT spectrum to zero at all points outside the one cycle per wavelength circle and inverse FT, or equivalently by convolving the current surface with the $J_1(\pi\rho)/(\pi\rho)$ point spread function (PSF), where $J_1()$ is the Bessel function of the first kind and order one, and rho is the radius. This point spread function is known from optics as the Airy disk.

The image is a view of the far field antenna radiation toward the look direction. For scatterers, the look direction may be the same as the incident illumination, which is the monostatic (single antenna) radar case. Similarly, when the look direction is different to the illumination direction, we have the bistatic (separate antennas) radar case.

Imaging process

1. Given the locations and currents of wire segments, from a NEC (Ref 4) analysis for example, calculate the contribution to far field (Efar) for each segment, in a chosen (theta, phi) radiation direction. The two polarisations are treated separately. The contribution from a single segment is

$$\Delta E_p = j30kI\exp(jk\hat{\mathrm{R}}\bullet\vec{\mathrm{S}})\left\{(\hat{\mathrm{R}}\bullet\Delta\vec{\mathrm{L}})\hat{\mathrm{R}}\text{-}\Delta\vec{\mathrm{L}}\right\}\bullet\hat{\mathrm{p}} \quad (1)$$

where $\hat{\mathrm{p}}$ is the chosen polarisation unit vector, *I* is the current, $\Delta\vec{\mathrm{L}}$ is the segment length vector, $\hat{\mathrm{R}}$ is the far field direction unit vector, $\vec{\mathrm{S}}$ is the coordinate vector of the segment centre and *k* is the wave number $2\pi/\lambda$. Note that the *1/r* distance factor is omitted, making the units in volts. This is the same operation as calculating the far field radiation pattern, without summing the voltages. The code can be extracted from a suitable antenna program far field radiation pattern routine.

2. Each segment is replaced with an isotropic source in the same location, with the magnitude and phase of the Efar contribution to the chosen polarisation. By placing this light source at each point, we create an image, viewable from any direction. At this point all the detail can be seen, so that wires with

rapidly varying phase from a particular viewpoint are visible. This does not agree with radiation reality.

3. Filter the image to remove spatial frequencies above one cycle per wavelength. This physical limit is due solely to the wave nature of light. Note that even the tiniest point source appears as a circular blob, surrounded by faint rings, known as the Airy disk. The Airy disk has the form of $J_1(u)/(u)$, where J_1 is the Bessel function of the first kind and order 1. The resolution limit is the Raleigh criterion of 0.61 wavelength, which is where the maximum of one Airy disk overlaps with the first minimum of another.

   Starting with the Efar elements, we Fast Fourier Transform (FFT) the (1D, 2D, or 3D) space, remove all spatial frequencies above one cycle per wavelength, and inverse FFT. The wanted spatial frequencies are found in the line, circle or sphere sectors in the corners of the transformed matrix, the remainder are set to zero.

4. Now the image appears as it would in our “microwave microscope”. Note that optical microscopes have the same limit to magnification, where a point is reached where more magnification just gives more blur. Hence the move to higher frequencies and electron microscopes. These images may be named radio wave photographs, since they show the luminosity of each part of the antenna or scatterer.

Example Consider a long wire with a sinusoidal standing or traveling wave current pattern. If we view the currents from broadside, we can see the alternating pattern. However if we apply the blur filter, we find that at all internal points along the wire, the cyclic currents integrate to zero. Only at the ends is the last current pattern not cancelled by its neighbour, so we see a bright spot centred on each wire end. This illustrates the maxim "radiation is due to the acceleration of charge". See the first example below.

Taper windows

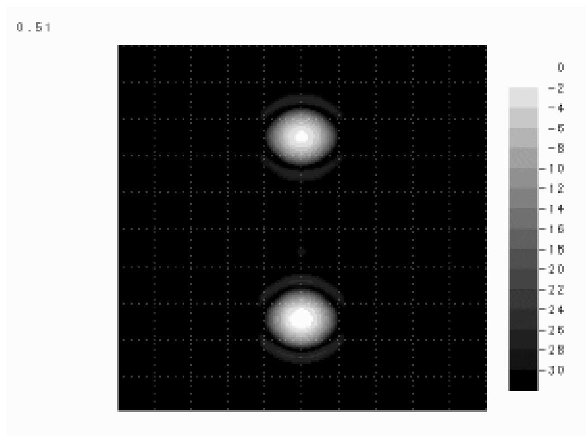
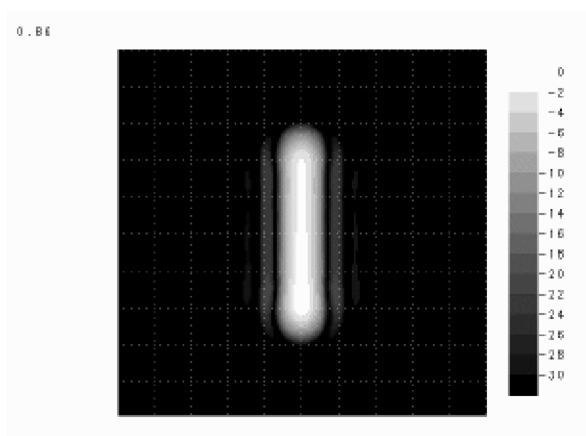
Tapering of the spatial window illumination reduces both resolution and sidelobe levels. The taper function used is $(1-\rho^2)^p$ where rho is the fraction of the window radius, and *p* is the taper exponent. In 2D, the resulting blur function form is $J_{p+1}(u)/u^{p+1}$ giving both reduced resolution and sidelobe levels as *p* increases. *p* = 0 for uniform illumination, *p* = 1 for parabolic taper, etc.

Example radio wave photographs

The grey scale is in decibels. The number at top left of each image is the maximum "brightness" across the image. The look direction for all the images is from the zenith, θ = 0, φ = 1°. The small φ offset is to ensure that the polarisation is properly defined. All these images used NEC-2 to calculate the current distributions. Unless specified, horizontal (Ephi) polarisation is used. The faint grid lines are spaced one wavelength apart. A multidimensional mixed radix FFT is used (Ref 5), with each image as 200x200 pixels. In the largest image spaces the pixel size is λ/20.

Table 1. Window Taper Performance

Taper Exponent p	0	1	2	3	4	5	6	7
Relative beam width	1	1.10	1.21	1.34	1.47	1.62	1.78	1.94
Sidelobe level dB.	-17	-24	-30	-36	-41	-46	-50	-54

Long wire, end fed This image is taken from broadside to a 5 wavelength wire, fed near the bottom end. The broadside radiation pattern is formed by the interference of the radiation from the two end points. (Image size 10 λ square)	
Long wire, end fed, radiation in main lobe. This image shows the radiation in the direction of the main lobe, from all along the wire. The contribution decreases from the feed point toward the far end. (Image size 10 λ square)	

<table>
<tr>
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Long wire, centre fed, broadside radiation.
This is the same 5 wavelength wire, but centre fed. The current discontinuity causes radiation from the feed point as well as the end points. (Image size = 10λ square)
</td>
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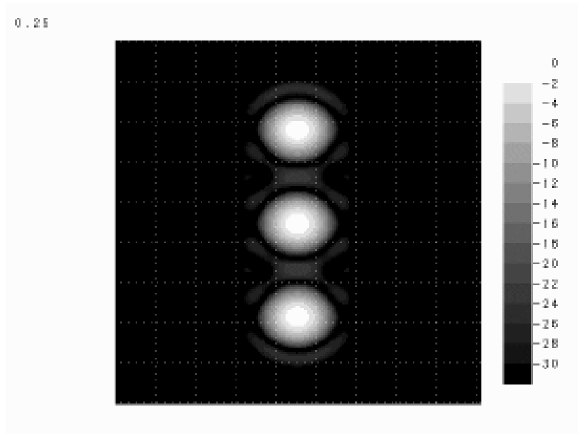

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Loop, radiation towards far right.
This is a 3 x 3 λ square loop antenna, in the horizontal plane. The radiation from the feed point, and from the four corners is visible. (Image size 6 λ)
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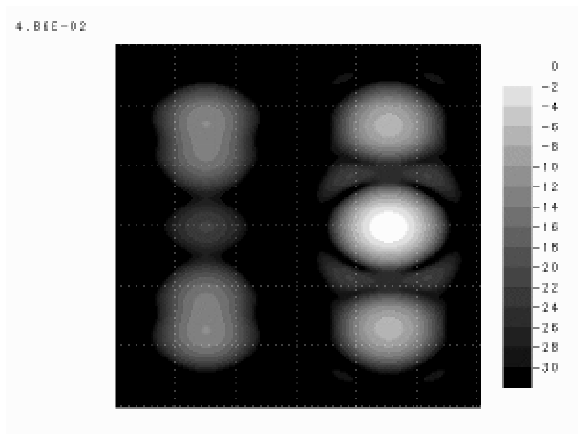

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Loop, radiation toward bottom of page.
In this direction there is radiation only from the corners. (Image size 6λ)
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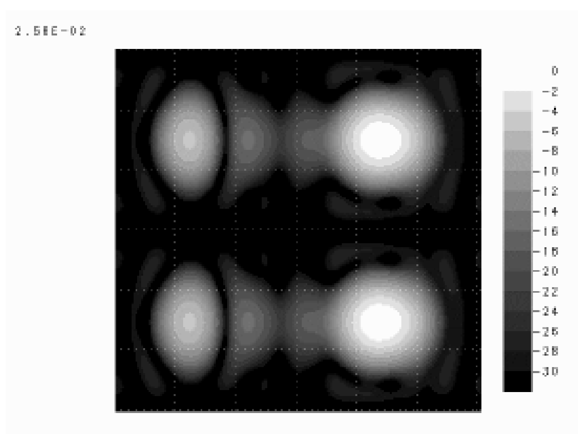

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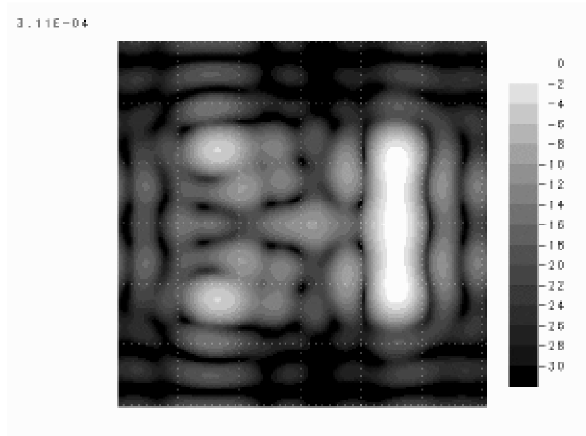
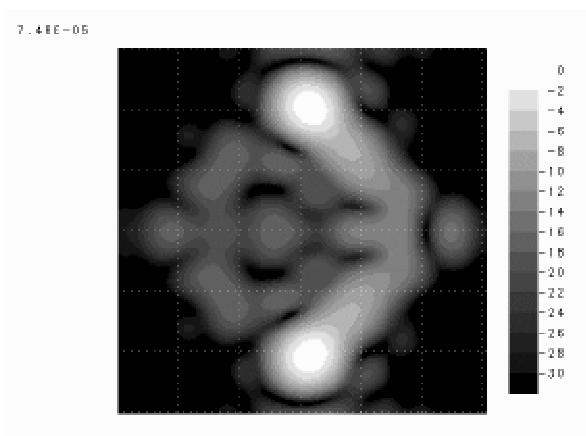
Square plate, edge normal to illumination.

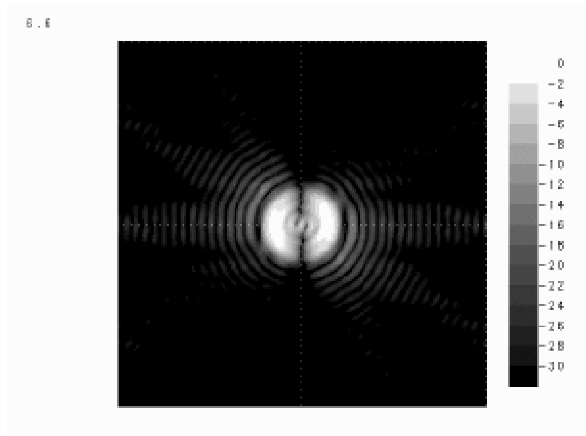
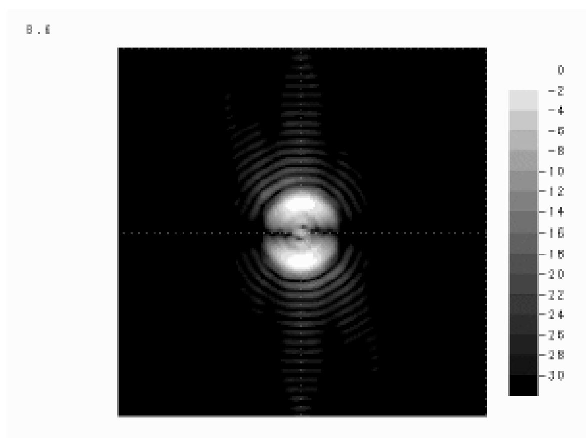
This is a 3λ square PEC plate in the horizontal plane. (Actually modelled as a grid of wires at λ/10 spacing). The image shows the radar cross section when illuminated with a plane wave from the right. The bright line shows where the wave E field is shorted out by the conducting plate. Also there is some radiation from the trailing corners. Note the number of spurious image points, even beyond the plate, due to the untapered 1 cycle per λ filter. (Image size 6λ)



Square plate, illuminated diagonally.

This shows the radar cross section when the same 3λ square plate is illuminated by a plane wave arriving diagonally from the right. The main contribution to the radar echo comes from the outer corners. (Image size 6λ)



Archimedian spiral, Etheta polarisation Because the image filtering process is separated from the radiation integral, it is possible to make near field images, as well as far field. This image is a near field image of an horizontal Archimedian spiral antenna viewed from above. This is a near field view of the image formed from the far field radiation. The spiral diameter overall is half a wavelength. Resolution 0.1λ/cycle. The faint outer rings are filtering artefacts. (Image size 2λ)	
Archimedian spiral, Ephi polarisation The same antenna, but Ephi. Together these two images show the circular polarised radiation coming from the spiral turns where the turn circumference equals one wavelength. (Image size 2λ)	

Radio Camera

An alternative imaging process is to emulate a camera. In this process a plane is created in the far field of the antenna/scatterer, and the E field is calculated at many points on the plane (usually in a rectangular grid). This array of complex field values is a numerical hologram. A reference wave is not needed, as the phase is recorded in the complex E field value. This numerical hologram may be reconstructed using a camera lens, or equivalently by taking the FT of the 2D complex field values. The image is formed at one focal length behind the camera lens. The radiation integral has already removed the evanescent energy, so it is not necessary to filter the image any further. Note that the point spread function may be larger than the theoretical Airy disk, since the finite lens aperture (or grid size) can only worsen the resolution. In microscopy this reduction is known as the "numerical aperture". Using NEC for example, we can evaluate the far field over a rectangular grid of points on a plane normal to the look angle. The difference from the previous imaging process is that the plane is in the far field. The antenna/scatterer should be rotated (with a GM card) so that the desired look angle is moved to the x axis. The near field command (NE) is used to create a planar grid of field values in the YZ plane. There are still two polarisations required. After gathering the output values into a suitable matrix form, the FT image may be formed using Matlab or Mathematica etc.

Acknowledgement

I wish to thank John Shaeffer and Edmund Miller for introducing the concept of imaging at their ACES short course, and also for the many conversations since that helped further my understanding of the subject.

Conclusion

Two practical radiator imaging techniques have been described. These are thought to be new, but similarities to near field measuring techniques and holography suggests that they have simply been rediscovered. However, it is timely to bring imaging to the attention of CEMists as a useful tool in understanding radiation. The author has used the first technique to examine currents induced in a support tower, which caused an unwanted null in the radiation pattern. Viewing the currents only confused the situation, since most of the currents did not radiate in the null direction.

References

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4. "Numerical Electromagnetic Code (NEC) – Method of Moments", Naval Electronic Systems Command Technical Document 116, Part III Users Guide, GJ Burke and AJ Poggio, 1977.

5. Subroutine FFT, multivariate complex Fourier transform, computed in place using mixed-radix fast Fourier transform algorithm. R. C. Singleton, Stanford Research Institute, Sept. 1968.