Sensor and Simulation Notes

Note 546

25 October 2009

Peak Power Gain in Time Domain of Impulse Radiating Antennas (IRAs)

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Abstract

Gain and beam width of antennas vary with frequency and are well defined in the frequency domain. Standardized definitions of these performance parameters do not yet exist in the time domain for pulsed antennas. In this note, we have attempted to define a peak power gain of a reflector type of an IRA along its optical axis. In doing so, well established expressions of the radiated far fields have been used. This peak power gain is valid at one instant of time, when the electric field on axis reaches its peak value in the far field.

1. Introduction

The modern version of the IRA was conceived in 1989 [1] and the prototype IRA was successfully built in 1994 and its varied aspects have been reported in many papers [2 to 9] and also recently in a reference book [10]. A photograph of this prototype IRA is shown in Figure 1.

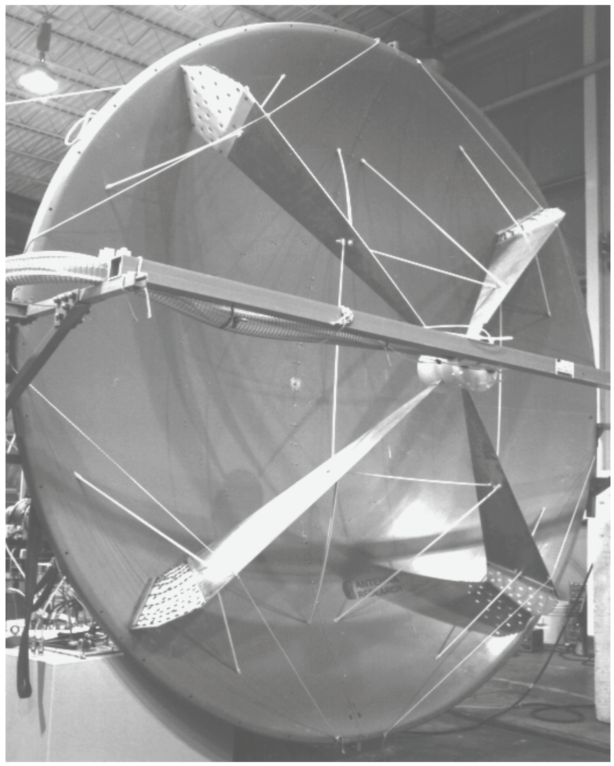

Figure 1. Prototype IRA [2] Circa 1994

The geometry and the performance parameters of the prototype IRA are summarized in Table 1. In this Table 1, we have separately listed the geometry of the reflector, the pulser parameters and the measured far field quantities. Having outlined the salient features of the prototype IRA, we now proceed to look into its peak power gain along the boresight direction.

(a) Antenna Details

Parameter	Value
Reflector diameter D	3.66.m
Focal length F	1.22m
F/D	0.33
Number of arms	4
Arm configuration	90 deg
Impedance Z_{in}	200 Ohms
Geometrical factor $f_g = Z_{in}/Z_0$	0.53
Polarization	Linear/Vertical

(b) Pulser Details

Parameter	Value
Peak voltage V_P	~ $\pm$ 60 kV ~ 120 kV
Peak rate of rise $\left(\frac{dV}{dt}\right)_P$	~ 1.2 x 10^{15} V/s
Maximum rate of rise $t_{mr} = \frac{V_P}{\left(\frac{dV}{dt}\right)_P}$	~ 100 ps
Pulse repetition freq PRF	~200 Hz
Pulse decay time t_d	~ 20 ns
Duty cycle $\tau = t_d\, PRF$	~ 4 X 10^{-6}
Peak power $P_{in} = \frac{V_P^2}{Z_{in}}$	~ 72 MW
Average power	~ 72 MW x 4 x 10^{-6} ~ 288 Watts

(c) Far Field Quantities

Parameter	Value
Range r	304 m
$E_P(r)$	4.2 kV/m
$V_{far} = r\, E_p(r)$	1,277 kV
$r\, E_p(r) / V_p$	~ 10
Bandwidth	~ 40 MHz to 4 GHz
Band ratio	~ 100
Impulse FWHM	~ 100 ps
Prepulse duration	2F/c = 8 ns
H-plane beamwidth	1.8 degrees

TABLE 1. Geometry and performance parameters of the prototype IRA

2. Peak Power Gain of G_P of IRAs

To start with, we observe that the far field starts [10] at a range r given by

$$r \geq \frac{D^2}{2 c\, t_{mr}} \tag{1}$$

which turns out to be $r \geq 216$ m for the prototype IRA. The measured observation point of 304 m is certainly in the far field of the IRA, at the shortest wavelength of the transient energy provided to the IRA. In the far field, the impulse amplitude is given by [10]

$$E(r,t) = \frac{h_a}{2\pi\, c\, r\, f_g} \left(\frac{dV(t)}{dt} \right) \quad \text{(V/m)} \tag{2}$$

where h_a is the effective height of the aperture [11,12].

Focusing on the impulsive portion and denoting the peak quantities by a subscript P, we have

$$E_P(r) = \frac{h_a}{2\pi c\, r\, f_g} \left(\frac{dV(t)}{dt} \right)_P \text{(V/m)} \tag{3}$$

Let us now use the definition of the maximum rate of rise t_{mr} as

$$t_{mr} = \left(\frac{V_P}{\dot{V}_P} \right) = \left(\frac{V_P}{(dV/dt)_P} \right) \qquad \text{(s)} \tag{4}$$

Using (4) in (3), we have

$$E_P(r) = \frac{h_a}{2\pi\, c\, f_g\, r} \left(\frac{V_P}{t_{mr}} \right) \qquad \text{(V/m)} \tag{5}$$

The peak power density on the optical axis is then given by

$$p_P(r) = \frac{E_P^2(r)}{Z_0} = \frac{1}{Z_0} \left(\frac{h_a\, V_P}{2\pi c\; t_{mr}\, f_g\, r} \right)^2 \; \text{(W/m}^2\text{)} \tag{6}$$

We recognize the peak input power into the IRA is given by

$$P_{in} = \left(\frac{V_P^2}{Z_{in}} \right) = \left(\frac{V_P^2}{Z_0 \, f_g} \right) \quad \text{(W)} \tag{7}$$

Recasting (6) in terms of P_{in} , we have

$$p_P(r) = \frac{1}{f_g} \left(\frac{h_a}{2\pi r \, c \, t_{mr}} \right)^2 P_{in} \quad \text{(W/m}^2\text{)} \tag{8}$$

We are now ready to define a dimensionless power gain G_P as

$$G_P = \frac{4\pi r^2 \, p_P(r)}{P_{in}} = \frac{1}{\pi \, f_g} \left(\frac{h_a}{c \, t_{mr}} \right)^2 \quad \text{(dimensionless)} \tag{9}$$

G_P is the numerical gain and one can also write the peak gain in dB as

$$G_P \, (dB) = 10 \, \ell og_{10} \, (G_P) = 10 \; \ell og_{10} \left[\frac{1}{\pi \, f_g} \left(\frac{h_a}{c \, t_{mr}} \right)^2 \right] \quad \text{(dB)} \tag{10}$$

For example, typically the IRAs have been built in the 4-arm full IRA (400 Ohms) and 2 – arm half IRA (100 Ohm) configurations. Other possibilities are possible with other impedances.

2 – arm full IRA with an impedance of 400 Ohms

4 – arm full IRA with an impedance of 200 Ohms

2 - arm half IRA with an impedance of 100 Ohms

1- arm half IRA with an impedance of 200 Ohms

We recognize that the IRA can be configured in many ways resulting in various combinations of (h_a and f_g) values, as listed in Table 2.

#	Type of IRA	Peak Applied Voltage (Volts)	Geometrical factor f_g (typical)	Effective height h_a (m)	$V_{far} = r\,E_P$ (Volts)
1	2-Arm Full IRA	V_P ($\pm V_P/2$) differential	(400 / Z_0) = f_g =1.061	$\frac{D}{2}$	$\frac{D}{4\pi c\, f_g}\left(\frac{V_P}{t_{mr}}\right) = V_{far1}$
2	4-Arm Full IRA 90 deg	V_P ($\pm V_P/2$) differential	(200 / Z_0) = 0.531 $f_{g1/2} = f_g/2$	$\frac{D}{2\sqrt{2}}$	$V_{far2} = \sqrt{2}\, V_{far1}$
3	2-Arm Half IRA	V_P (single-ended)	(100 / Z_0) = 0.265 $f_{g14} = f_g/4$	$\frac{D}{4\sqrt{2}}$	$V_{far3} = \sqrt{2}\, V_{far1}$
4	1-Arm Half IRA	V_P (single-ended)	(200 / Z_0) = 0.531 $f_{g1/2} = f_g/2$	$\frac{D}{4}$	$V_{far4} = V_{far1}$

TABLE 2. Effective heights and impedances of various IRA configurations

We can now apply the above tabulated results to two examples of the prototype IRA [10] and JOLT [13] in the next section.

3. Illustrative Examples

Many IRAs have been built in the U. S., and western European nations and a list of these is available in [10]. We can consider 2 examples here, namely the prototype IRA and JOLT [10, 13]. First of all, we can find the V_{far} of the prototype IRA and JOLT to be

<u>Prototype IRA</u>

D = 3.66m, f_g = 1.062, V_P = 120 kV, t_{mr} = 100 ps

$$V_{far} = \frac{D\sqrt{2}}{4\pi c\, f_g}\left(\frac{V_P}{t_{mr}}\right) = 1{,}537 \text{ kV} \tag{11}$$

This is a somewhat higher than the observed value of 1,280 kV, perhaps because the wave launch is not as ideal as implied by the theoretical idealizations. The peak amplitude and t_{mr} of the voltage wave launched onto the reflector can only be indirectly measured by placing a ground plane B-dot sensor on the reflector. Inferred values from such a measurement are not always available.

JOLT

D = 3.048m, $f_g = 0.265$, $V_P = 890$ kV, $t_{mr} = 180$ ps

$$V_{far} = \frac{D}{4\sqrt{2}}\left(\frac{1}{2\pi c f_g}\right)\frac{V_P}{t_{mr}} = 5.4\,MV \qquad (12)$$

We do not precisely know the values of V_P and t_{mr}. These are estimates inferred from the measured far field parameters and appear to be reasonable numbers.

We can now estimate the peak gains of these two IRAs (see Table 3).

Parameter	**Prototype IRA [10]**	**JOLT [13]**
Type	Full IRA	Half IRA
Reflector diameter D	3.66.m	3.048m
Focal length F	1.22m	1.158m
F/D	0.33	0.375
Number of arms	4	2
Arm configuration	90 deg	90 deg
Impedance Z_{in}	200 Ohms	100 Ohms
Geometrical factor f_g	0.531	0.265
Polarization	Linear/Vertical	Linear/Vertical
Peak voltage V_P	~ ± 60 kV ~ 120 kV	890 kV
Peak rate of rise	~ 1.2 x 10^{15} V/s	5 x 10^{15} V/s
Maximum rate of rise	~ 100 ps	~ 180 ps
V_{far}	~ 1,280 kV	~ 5.4 MV
G_P *(Numerical) from equation (9)*	~ 2,230	~ 97
G_P *(dB)*	~ 33.4 dB	~ 19.9 dB

TABLE 3. Estimated peak power gains of the prototype IRA and JOLT

There appears to be yet another use for the peak gain as defined in (9), which is reproduced below.

$$G_P = \frac{1}{\pi f_g}\left(\frac{h_a}{c\,t_{mr}}\right)^2 \qquad (13)$$

We observe from the above equation that the peak gain is a function of the antenna size, antenna impedance and the risetime of the input pulse. If we have the same pulser feeding two different IRAs, one can define a relative gain between the antennas (keeping the same risetime) as follows

$$G_{P1} = \frac{1}{\pi f_{g1}} \left(\frac{h_{a1}}{c t_{mr}} \right)^2 \qquad G_{P2} = \frac{1}{\pi f_{g2}} \left(\frac{h_{a2}}{c t_{mr}} \right)^2 \tag{14}$$

and the relative gain for the same t_{mr}

$$G_{r_{2,1}} = \frac{G_{P1}}{G_{P2}} = \frac{f_{g2}}{f_{g1}} \left(\frac{h_{a1}}{h_{a2}} \right)^2 \tag{15}$$

This is a simple result that is useful in comparing the performance of two IRAs that are fed by the same input pulse. Furthermore, this relative gain holds good in both time and frequency domains.

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