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Some Topics Concerning Feed Arms of Reflector IRAs

Carl E. Baum
Air Force Research Laboratory
Directed Energy Directorate

In designing a reflector impulse radiating antenna (IRA) one needs to make a choice of the ratio of focal length to reflector radius or diameter. This strongly impacts the shape and length of the feed arms forming a conical transmission line from the source capex or focal point) to the terminations at the reflector. This paper considers the impact of this choice on the radiated waveform and other aspects of the design. This leads to an intermediate value of the ratio as optimal in typical cases.

1. Introduction

In designing a reflector impulse radiating antenna (IRA) there are many factors to be considered as discussed in a number of summary papers [8–12]. One of the fundamental parameters to be chosen is the ratio of the focal distance F to the radius a or the diameter D of the paraboloidal reflector. This ratio affects various aspects of the antenna performance involving the prepulse (before the approximate impulse) and the post pulse (following the impulse) including the feed blockage and reflector rim diffraction. Small F/a leads to a large prepulse, but large values lead to significant post pulse increase.

This F/a ratio impacts various geometric features of the reflector IRA as well. As one increases this ratio above 0.5, there is little effective size increase until this ratio exceeds 1. Making the feed-arm length equal to F (to minimize reflections back into the source at the conical-transmission-line apex) restricts the regions available for the transmission-line terminations (including for high-voltage insulation), also limiting F/a.

Combining the various design considerations leads to an intermediate value of roughly around 1 for F/a for some typical applications. Subsequent sections go into the details of the various considerations and the tradeoffs involved.

2. Some Basics

First, let us summarize some basic performance characteristics of a reflector IRA. Figure 2.1 shows the basic geometry of a two-arm reflector IRA. The two feed arms form a conical transmission line (with spherical TEM wave) of characteristic impedance

$$Z_c = f_g \; Z_0 \; , \; f_g \equiv \text{dimensionless geometric factor}$$

$$Z_0 = \left[\frac{\mu_0}{\varepsilon_0}\right]^{\frac{1}{2}} \equiv \text{wave impedance of free space} \tag{2.1}$$

For such a two-arm feed, Z_c is conveniently chosen as 400 Ω, giving reasonable angular width $(\beta_2 - \beta_1)$ to the coplanar triangular feed plates (about 15° in the example considered in [5]).

A fundamental parameter in the IRA design and performance is the ratio of the focal distance F to the diameter D or radius a of the reflector. For this we define

$$f_d \equiv \frac{F}{D} \; , \; f_a \equiv \frac{F}{a}$$

$$f_d = \frac{1}{2} f_a \tag{2.2}$$

Then a line from the conical apex (reflector focal point) to the edge (a circle of radius a) of the paraboloidal reflector makes an angle β_0 with respect to the reflector axis of revolution (the z axis) with [5]

$$\cot(\beta_0) = f_a - \frac{1}{4f_a} \tag{2.3}$$

This gives the effective electrical center (not geometrical center) of the conical plates. The edges of the conical plates, defined by β_1 and β_2 can be found via elliptic integrals [5]. We also have

$$\sin(\beta_0) = \csc^{-1}(\beta_0) = \left[1 + \cot^2(\beta_0)\right]^{-\frac{1}{2}}$$

$$= \left[f_a + \frac{1}{4f_a}\right]$$

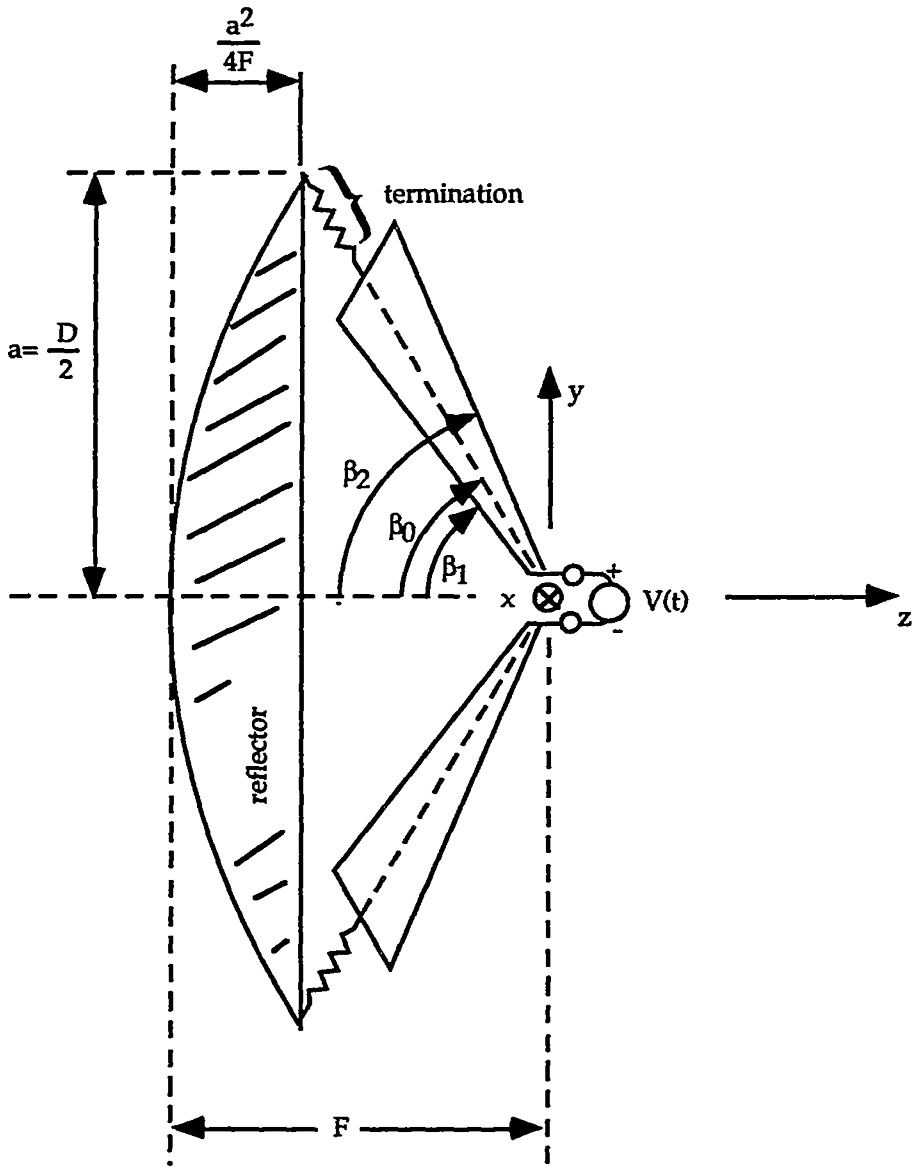

Fig. 2.1 Reflector IRA with Two Feed Arms

$$
\begin{aligned}
\cos(\beta_0) &= \left[f_a - \frac{1}{4f_a} \right] \left[f_a + \frac{1}{4f_a} \right]^{-1} \\
\cot\left(\frac{\beta_0}{2}\right) &= \frac{1 + \cos(\beta_0)}{\sin(\beta_0)} = 2\, f_a \\
\sin\left(\frac{\beta_0}{2}\right) &= \left[\frac{1 - \cos(\beta_0)}{2} \right]^{\frac{1}{2}} = \frac{1}{2}\, f_a^{-\frac{1}{2}} \left[f + \frac{1}{4f_a} \right]^{-\frac{1}{2}} \\
\cos\left(\frac{\beta_0}{2}\right) &= \left[\frac{1 + \cos(\beta_0)}{2} \right]^{\frac{1}{2}} = f_a^{\frac{1}{2}} \left[f + \frac{1}{4f_a} \right]^{-\frac{1}{2}}
\end{aligned}
\tag{2.4}
$$

The electric field on the z axis launched toward the reflector is larger than that launched in the opposite direction (toward the far-field observer) by a ratio

$$
\eta_{fb} = \cot\left(\frac{\beta_1}{2}\right) \cot\left(\frac{\beta_2}{2}\right) \equiv \text{front-to-back ratio} \tag{2.5}
$$

This is manipulated as

$$
\begin{aligned}
\tan\left(\frac{\beta_0}{2}\right) &= m^{-\frac{1}{4}} \tan\left(\frac{\beta_1}{2}\right) = m^{\frac{1}{4}} \tan\left(\frac{\beta_2}{2}\right) \\
\eta_{fb} &= \cot^2\left(\frac{\beta_0}{2}\right) = 1 + \csc^2\left(\frac{\beta_0}{2}\right) \\
&= 2\, f_a
\end{aligned}
\tag{2.6}
$$

Since we are interested in a small prepulse (the "back" radiation) we woud like a large η_{fb} and hence a small β_0, a point to which we shall return.

A fundamental aspect of IRA design is the approximate impulse (delta function) produced in the far field due to a step function excitation [1] defined by

$$
V(t) \equiv V_0 \; u(t) \tag{2.7}
$$

The far field on axis due to this excitation is

$$
\vec{E}_f(\vec{r},t) \; \frac{V_0}{r} \, \frac{1}{2\pi c f_g} \, \vec{h}_a \; \delta_a\left(t - \frac{2F + r}{c}\right)
$$

$$c = [\mu_0 \varepsilon_0]^{-\frac{1}{2}} \equiv \text{speed of light in vacuo}$$

$$\vec{h}_a \equiv \text{an effective height} \tag{2.8}$$

$$\delta_a \equiv \text{approximate delta function (tending to true delta function as } r \to \infty)$$

Referring to fig. 2.1, the symmetry of the problem has

$$\vec{h}_a = h_a \vec{1}_y \tag{2.9}$$

and calculations [3, 5] have shown that (for thin feed arms)

$$h_a = a = \frac{D}{2} \tag{2.10}$$

While the configuration in fig. 2.1 is convenient for analysis, the reader should note that this is typically modified to a symmetrical 4-arm configuration (conical plates, two each on perpendicular planes intersecting on the z axis [2]). In this case there are two conical transmission lines, each with fields not interacting with the other conductors due to the symmetry. In this case, Z_c is reduced (conveniently) to 200 Ω. With f_g reduced in half, but the fields from the two biconical feeds adding vectorially to raise the far field by a factor of $\sqrt{2}$, the effective height becomes

$$h_a = \frac{a}{\sqrt{2}} = \frac{D}{2\sqrt{2}} \tag{2.11}$$

to be used in (2.8) with the new f_g (thereby increasing the far field).

Another configuration of interest is the half reflector IRA discussed in [7]. In this case the ground plane (say on the x, z plane) is truncated near the antenna so that we can take the antenna aperture plane just beyond the truncation. The antenna aperture (positive y) is now radiating both above and below the ground plane. As a result, the aperture integral is halved for $V(t)/2$ between feed arms and ground plane, these two factors cancelling. Furthermore, Z_c is further reduced to 100 Ω, halving f_g again. The effective height then becomes

$$h_a = \frac{a}{2\sqrt{2}} = \frac{D}{4\sqrt{2}} \tag{2.12}$$

for use in (2.7) with the new f_g and $V(t)$ now on the two arms with respect to the ground plane.

3. Prepulse

The prepulse is the spherical TEM wave propagating from the transmission-line apex along the positive z axis to the observer. This is treated in detail in [5]. It lasts for a time $2F/c$, and is opposite in sign to the impulse which immediately follows it. As shown in [5] the prepulse and impulse portions have equal and opposite time integrals to a good approximation (typically much better than 1%) for typical values of f_d. Making these time integrals (areas) exactly equal and opposite makes the far field including both prepulse and impulse take the simple form

$$\vec{E}_f(\vec{r},t) = \frac{V_0}{r}\frac{1}{2\pi c f_g}\vec{h}_a\left[t_p^{-1}\left[-u\left(t-\frac{r}{c}\right)+u\left(t-t_p-\frac{r}{c}\right)\right]+\delta_a\left(t-t_p-\frac{r}{c}\right)\right]$$
$$t_p = 2\frac{F}{c} \equiv \text{prepulse width} \tag{3.1}$$

where δ_a is the approximate delta function [1]. When applied to a more general $V(t)$ and δ_a is regarded as a true δ function, this becomes

$$\vec{E}_f(\vec{r},t) = \frac{1}{r}\frac{1}{2\pi c f_g}\vec{h}_a\left[t_p^{-1}\left[-V\left(t-\frac{r}{c}\right)+V\left(t-t_p-\frac{r}{c}\right)\right]+\frac{d}{dt}V\left(t-t_p-\frac{r}{c}\right)\right] \tag{3.2}$$

Now let us compare the impulsive part of the waveform to the prepulse part. For this purpose let the waveform be taken as a step of amplitude V_0 with a short, but nonzero, risetime (short compared to t_p). Assuming a constant polarization on boresight to scalarize the problem the prepulse amplitude is

$$E_f^{(p)} = -\frac{1}{r}\frac{1}{2\pi c f_g}h_a\frac{V_0}{t_p} \tag{3.3}$$

The peak amplitude associated with the impulsive (derivative) part is

$$E_f^{(i)} = \frac{1}{r}\frac{1}{2\pi c f_g}h_a\frac{V_0}{t_i}$$
$$t_i^{-1} \equiv \frac{1}{V_0}\left[\sup_t \frac{dV(t)}{dt}\right] \equiv \text{maximum rate of rise} \tag{3.4}$$
$$t_i \equiv \text{effective rise time}$$

Then define a ratio

$$\eta_{ip} \equiv -\frac{E_f^{(i)}}{E_f^{(p)}} = \left|\frac{E_f^{(i)}}{E_f^{(p)}}\right| = \frac{t_p}{t_i} \tag{3.5}$$

as a figure of merit comparing the impulsive part to the prepulse. Noting that t_p is closely related to the low-frequency content of the radiated pulse, and t_i to the high-frequency part, then η_{ip} is closely related to the band-ratio of the radiated pulse [11, 12].

This ratio depends on both the pulser for t_i and the antenna for t_p. Larger η_{ip} is achieved by a faster rising pulser and a larger antenna (implied by larger F from t_p). So this is not a function of only the antenna. Such an antenna in reception (for an incoming δ-function plane wave by reciprocity [4]) will, in general, have a high-frequency limitation based on imperfections in the antenna design. An effective t_i can then be estimated based on high-frequency losses due to imperfections in the antenna dimensions (reflector surface accuracy), the connections to the cables at the conical apex (and elsewhere), and the cable losses. Thus one can define an η_{ip} which is a function of only antenna parameters if one looks in reception, or in transmission with a step-function pulse, the rise time of which is small compared to the effective t_i of the antenna.

To increase η_{ip} one can decrease t_i and/or increase t_p. Consider increasing t_p. This is accomplished by increasing F, and in principle arbitrarily large values can be obtained. However, the antenna size is then becoming impractically large. If one has $F >> a$, then one can obtain a better antenna performance by increasing a and hence h_a (Section 2) and hence the amplitude of the impulsive part of the waveform. For a given antenna size (say determined by the diameter of the minimum circumscribing sphere), a large f_a indicates that a should be increased to better fill the so-defined antenna volume. Said another way, f_a should be no larger than a number of order 1 (except possibly for special applications).

For the case of a half reflector IRA with truncated ground plane, the prepulse diffracts at the truncation, giving a different shape to this part of the waveform, depending on the observer location and detailed shape and location of the truncation. This is in general not just a simple factor of 2 as it is for the impulsive part (Section 2).

4. Termination of the Feed Arms

Each feed arm is terminated to the reflector rim via a resistive load matched to an appropriate portion of the characteristic impedance of the conical feed system. In terms of the typical impedances previously discussed, such terminations are each 200 Ω. There is then a space between the end of each feed arm of some length d_T and the reflector rim (with distance measured for convenience along the line from the apex to the reflector rim with angle β_0). How large should d_T be? Equivalently, what length d_f should the feed arm be from apex to the termination? The sum of these two is just

$$\begin{aligned} d_T + d_f &= a\csc(\beta_0) = a\left[f_a + \frac{1}{4f_a}\right] \\ &= F + \frac{a^2}{4F} = F\left[1 + \frac{1}{4f_a^2}\right] \end{aligned} \qquad (4.1)$$

Consider fig. 4.1. Here the paraboloid is described by

$$\begin{aligned} \Psi^2 &= 4F[z + F] \\ \Psi &= \left[x^2 + y^2\right]^{\frac{1}{2}} \equiv \text{cylindrical radius (from } z \text{ axis)} \end{aligned} \qquad (4.2)$$

where the origin ($\vec{r} = \vec{0}$) is taken as the focal point. The vertex (intersection with the z axis) is at $z = -F$. At the vertex the curvature is given by

$$\left.\frac{d^2 z}{d\Psi^2}\right|_{z=0} = \frac{1}{2F} \qquad (4.3)$$

so that 2F is the radius of curvature. If we place a sphere of radius 2F with center on the z axis at z = F, this defines a spherical reflector which approximates the paraboloidal reflector for small a. It is described by

$$\Psi^{-2} + [z - F]^2 = 4F^2 \qquad (4.4)$$

This sphere is everywhere to the right of the paraboloid except at the vertex z = -F.

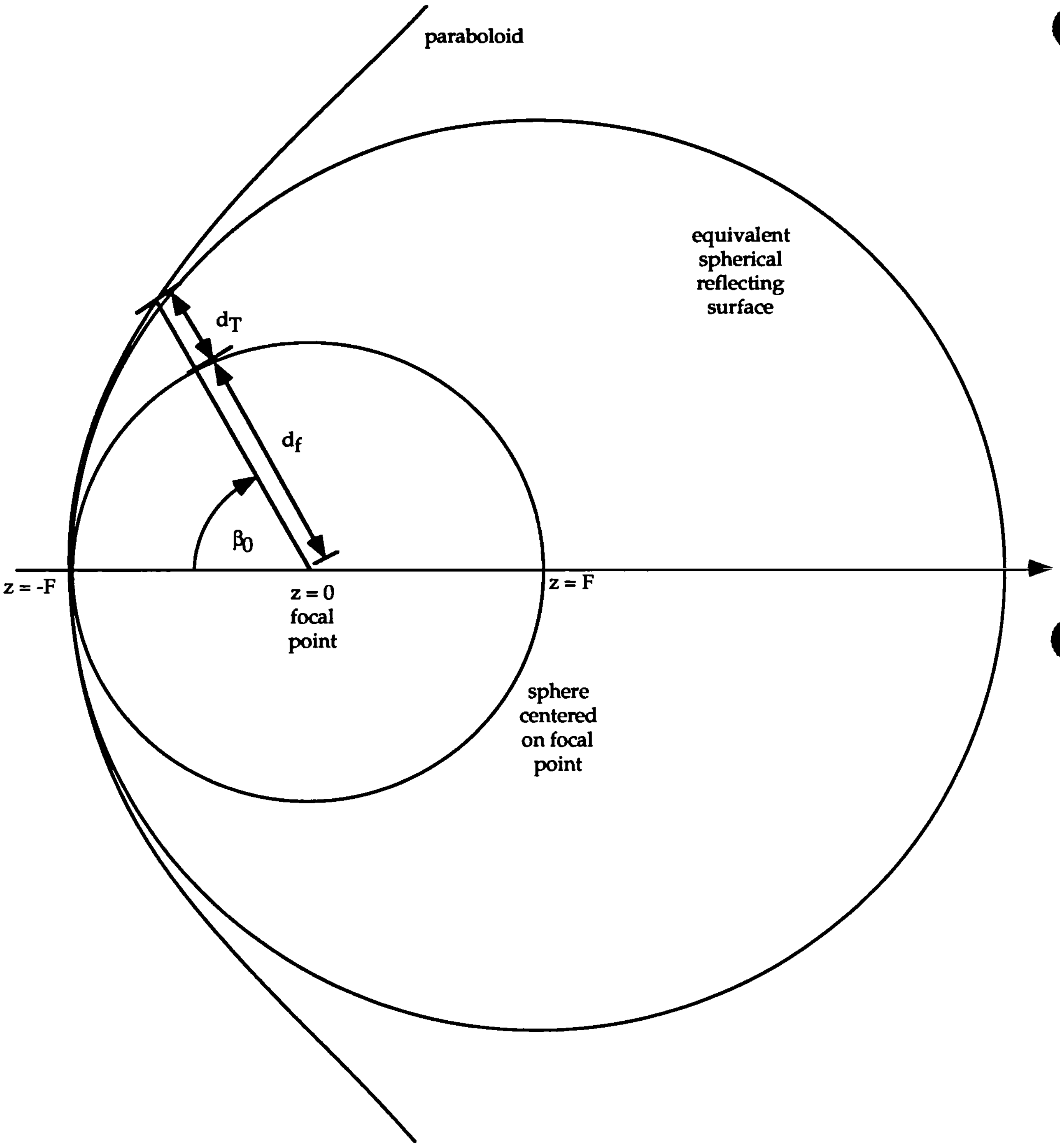

Fig. 4.1 Reflector IRA with Two Feed Arms.

A spherical TEM wave is launched from the focal point, reflects from the paraboloid as a TEM plane wave (negative) and is first seen at the apex of the conical transmission line (focal point) exactly a time t_p later. This is seen as a negative reflection and is the first possible effect of the reflector at the apex. The same wave launched from the apex reflects (with positive sign due to the termination as an impedance increase relative to metal) after a time d_f/c, returning to the apex after a time $2d_f/c$. By choosing $d_f \geq F$, this perturbation returns to the apex at a time no sooner than that from the reflector. If we choose

$$d_f = F \tag{4.5}$$

then two signals of opposite sign arrive simultaneously at the apex, allowing one some compensation of the two effects.

With this choise we see in fig. 4.1, that the ideal conical feed arm is contained in a sphere of radius F, centered at the focal point, and tangent to the paraboloid at the vertex. The termination region of length d_T (along the line defined by β_0) is where resistors and perhaps other structures to compensate for various non-ideal conditions, are placed. Now we have from (4.1) and (4.4)

$$d_T = \frac{a^2}{4F} = \frac{a}{4f_a} \quad , \quad \frac{d_T}{d_f + d_T} = \left[1 + 4f_a^2\right]^{-1} \tag{4.6}$$

For the extreme case of $f_a = 0.5$ ($\beta_0 = 90°$, $\eta_{fb} = 1$) we have $d_T = a = d_f$ so that fully half the distance from apex to reflector rim is termination. For more reasonable (larger) values of f_a the termination region reduces to a more reasonable fraction of the total.

On the other hand f_a should not be so large that d_T is too small to accommodate the termination. This includes various items including resistors, spacing for high-voltage insulation, and possible spacing for reduction of capacitance.

Note that the termination region of length d_T, since it has items of higher impedance than metal, contributes less to the blockage (discussed in Section 6) than would the metal conical plates extended into this region.

In the case of a half reflector IRA (Section 2) with ground plane truncated near the antenna, there is a reflection (positive) of the prepulse spherical TEM wave from the ground plane truncation (edge, perhaps rounded). This also induces a signal at the apex of the conical transmission line (focal point). One can also adjust the time that this arrives at the focal point and the waveform induced there. This signal can be combined with the two discussed above (from reflector and termination) in order to improve the overall performance.

5. Initial Signal Induced at Apex Due to Wave from Reflector

The initial spherical TEM wave incident on the reflector at the vertex for the two-arm feed (fig. 2.1) is [5] (for step excitation)

$$\begin{aligned} E_y &= -\frac{V_0}{F}\,\frac{1}{4\,\mathrm{K}(m)\,\tan\left(\frac{\beta_1}{2}\right)} \\ m &= \frac{\tan^2\left(\frac{\beta_1}{2}\right)}{\tan^2\left(\frac{\beta_2}{2}\right)} = 1 - m_1 \\ f_g &= \frac{\mathrm{K}(m)}{\mathrm{K}(m_1)} \end{aligned} \tag{5.1}$$

where for 400 Ω we have from elliptic-function tables

$$\begin{aligned} f_g &\simeq 1.061 \\ m &\simeq 0.5645 \\ \mathrm{K}(m) &\simeq 1.913 \end{aligned} \tag{5.2}$$

This wave reflects from the vertex and comes back from the reflector with sign reversal as a TEM plane wave (inhomogeneous). The field incident at the apex is just $-E_y$ above at time t_p. While the plane wave is nonuniform the symmetry of the problem has first spatial derivatives with respect to x and y zero on the z axis. The above field will then give a good early-time estimate of the signal received at the apex.

Knowing the antenna (feed) transmission in the $-z$ direction we can find the reception of a plane wave propagating in the +z direction by reciprocity [4]. The radiated far field (noting that fortunately the field on conical antennas has $1/r$ variation even close to the antenna in this special case) has the form

$$\begin{aligned} \tilde{\vec{E}}_f(\vec{r},s) &= \frac{e^{-\gamma r}}{r}\,\tilde{\vec{F}}_V(\vec{1}_r,s)\tilde{V}(s) \\ \sim &\equiv \text{Laplace transform (two-sided)} \\ s &\equiv \text{Laplace-transform variable or complex frequency} \\ \gamma = \frac{s}{c} &\equiv \text{propagation constant} \end{aligned} \tag{5.3}$$

With $\vec{1}_r$ as $-\vec{1}_z$ and the single (y) polarization F_V is scalar and frequency independent as

$$F_V = -\frac{1}{4\,K(m)\,\tan\left(\frac{\beta_1}{2}\right)} \tag{5.4}$$

In reception we have the short-circuit current

$$\tilde{I}_{s.c.} \equiv \vec{\tilde{h}}_I(\vec{1}_i, s) \cdot \vec{\tilde{E}}^{(inc)}(s) \tag{5.5}$$

with the convention of positive current for power *into the antenna port*. The antenna reciprocity condition has

$$\vec{\tilde{F}}_V(\vec{1}_r, s) = \frac{s\mu_0}{4\pi}\,\vec{\tilde{h}}_I(-\vec{1}_r, s) \tag{5.6}$$

With the single polarization and $\vec{1}_r$ as $\vec{1}_z$ this scalarizes as

$$\tilde{h}_I(s) = \frac{4\pi}{\mu_0}\,\frac{1}{s}\,F_V \tag{5.7}$$

which is a time-integral operation.

The temporal incident field at the apex is a step (arriving at $t = t_p$) of amplitude

$$E_y^{(inc)} = \frac{V_0}{F}\,\frac{1}{4\,K(m)\,\tan\left(\frac{\beta_1}{2}\right)} = -\frac{V_0}{F}\,F_V \tag{5.8}$$

The short-circuit current is then

$$\begin{aligned} \tilde{I}_{s.c.} &= \tilde{h}_I(s)\,\tilde{E}_y^{(inc)}(s) \\ I_{s.c.} &= -\frac{4\pi}{\mu_0}\,\frac{1}{F}\,F_V^2\,V_0\left[t - t_p\right]\,u\left(t - t_p\right) \end{aligned} \tag{5.9}$$

Viewed as an input admittance (looking from the antenna port *into the antenna*) the current convention is reversed [4]. This current increase is then an increase in admittance (decrease in impedance) corresponding to a negative reflection from the reflector (short circuit).

The variation with f_a is contained in

$$\frac{1}{F} F_V^2 = \left[a\, f_a\, 16\, \mathrm{K}^2(m) \tan^2\!\left(\frac{\beta_1}{2}\right)\right]^{-1} \tag{5.10}$$

Using [5]

$$\tan\!\left(\frac{\beta_0}{2}\right) = m^{-\frac{1}{4}} \tan\!\left(\frac{\beta_1}{2}\right) = m^{\frac{1}{4}} \tan\!\left(\frac{\beta_2}{2}\right) \tag{5.11}$$

we have

$$\begin{aligned} \frac{1}{F} F_V^2 &= \frac{1}{a\, f_a\; 16\, m^{\frac{1}{2}}\; \mathrm{K}^2(m) \tan^2\!\left(\frac{\beta_0}{2}\right)} \\ &= \frac{f_a}{a} \left[4\, m^{\frac{1}{2}}\, \mathrm{K}^2(m) \right]^{-1} \end{aligned} \tag{5.12}$$

Thus increasing f_a (with constant Z_c and a) leads to larger negative short-circuit current at the apex in (5.9). This is another indicator that f_a should not be too large.

While the present result is derived for a two-arm configuration (fig. 2.1), it is easily generalized to the symmetrical four-arm case by multiplying the right-hand side of (5.9) by 2. This is just summing the currents from the two orthogonal conical transmission lines. For the half reflector IRA one merely replaces V_0 by $2\, V_0$.

6. Reflector Edge Diffraction and Feed Blockage

Estimates have been made of the post pulse (immediately following the far-field impulse) based on early-time diffraction calculations for the reflector edge and the conical-transmission-line feed structure (blockage) [6, 11]. Not considering the details of the derivations here, let us look at how f_a affects the results.

The feed blockage (negative compared to the impulse) is approximated at early times by diffraction at the β_1 edge which is proportional to $[t - t_\ell]^{-\frac{1}{2}}$ and to $\csc^{\frac{1}{2}}(\beta_1)$. As the full plate width ($\beta_2 - \beta_1$ in angle) becomes important this blends into a reciprocal logarithm of t times $\csc(\beta_0)$ with another $\sin(\beta_0)$ term in the logarithm which we can neglect for the present discussion. Approximating β_1 by β_0 we see from (2.4) that $\csc(\beta_0)$ is minimum at $\beta_0 = 90°$ with $f_a = 0.5$. However, decreasing β_0 and increasing f_a initially has little effect due to the zero derivative at $\beta_0 = 90°$. For example, if β_0 is decreased to 60° (giving $f_a \simeq .866$), then $\csc(\beta_0) \simeq 1.18$ which is only a modest increase in the blockage.

The diffraction from the reflector rim is a step function (at early times) which is proportional to

$$
\begin{aligned}
\frac{1-\sin\left(\frac{\beta_0}{2}\right)}{\cos\left(\frac{\beta_0}{2}\right)} &= \frac{1-\cos\left(\frac{\pi-\beta_0}{2}\right)}{\sin\left(\frac{\pi-\beta_0}{2}\right)} = \tan\left(\frac{\pi-\beta_0}{4}\right) \\
&= \frac{1 - \tan\left(\frac{\beta_0}{4}\right)}{1 + \tan\left(\frac{\beta_0}{4}\right)} \\
&= \left[1 + \frac{1}{4 f_a^2}\right]^{\frac{1}{2}} - \frac{1}{2 f_a}
\end{aligned}
\tag{6.1}
$$

This is a slowly varying function, ranging from $\simeq .414$ at $f_a = .5$ to 1 at fa = ∞. At our previous example of $\beta_0 = 60°$, this function is $\simeq .56$, only a modest increase from .5.

7. Concluding Remarks

There are then several factors affecting the optimal choice of f_a. One extreme of $f_a = .5$ (or $\beta_0 = 90°$) helps reduce the post pulse magnitude, but significantly increases the prepulse magnitude. On the other hand $f_a \to \infty$ (or $\beta_0 \to 0$) greatly reduces the prepulse magnitude, but increases the postpulse magnitude and increases the antenna size (for fixed a and hence impulsive part of the radiation) if f_a exceeds around unity. One cannot be precise in the choice of optimum f_a, particularly noting the various circumstances in which a reflector IRA may be employed. However, a general rule would give an f_a on the order of unity as desirable.

Commercial paraboloidal reflectors come with a variety of choices of f_a. These are generally in the range of .6 to 1 which is a reasonable range per the development in this paper. Note that a reflector's f_a can often be increased (depending on construction details) by cutting away material near the rim, thereby decreasing a for a given F.

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