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Disruption of Satellite-to-Ground Station Communication Links by Nuclear Fireballs

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DISRUPTION OF SATELLITE-TO-GROUND
STATION COMMUNICATION LINKS BY NUCLEAR FIREBALLS

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ABSTRACT

Diffraction around nuclear fireballs near the line of sight for satellite-to-ground communication links is calculated numerically. The geometry allows assumption of geometric optics and plane-wave signals. The fireball is modeled as an opaque disk normal to the line of sight. The effect of disk shape and edge taper is considered.

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SUMMARY

This report considers the effect of nuclear fireballs which intercept line-of-sight (LOS) communication links, such as used between satellites and ground stations. In such cases, geometric optics apply and the diffraction pattern around the fireball was calculated numerically. The fireball is modeled as an opaque disk that is (1) circular with sharp edges, (2) circular with tapered edges, or (3) elliptical with sharp edges. The main results are:

1. Highly symmetric (circular) apertures with sharp edges produce a Fresnel zone pattern with an on-axis bright spot surrounded by bright rings. The on-axis phase shift varies as the square of the aperture radius, and there is a 180-degree phase difference between adjacent bright rings.
2. Small amounts of asymmetry or nonsharp edges destroy the Fresnel pattern and result in a deep shadow with large phase effects. Results are very sensitive to shape and edge parameters.
3. Since nuclear fireballs are not perfectly circular and do not have sharp edges, they will cast a deep shadow essentially the same size as the fireball. Communications will be disrupted any time the fireball intercepts the LOS. Accurate predictions of attenuation or phase shift are not possible because of the randomness of the fireball geometry.

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DISRUPTION OF SATELLITE-TO-GROUND STATION COMMUNICATION LINKS BY NUCLEAR FIREBALLS

Introduction

The effect of low-altitude nuclear bursts on communications is generally negligible unless the resulting fireball is directly in the communication path. Even then, signals tend to diffract around the fireball and link disruption does not necessarily occur. This paper considers such diffraction for satellite-to-ground station links, though the results may apply to other links.

The diffraction calculations for such links are greatly simplified because geometric optics apply. This requires that (1) fireball dimensions be much larger than the wavelength, (2) the distance from either antenna to the fireball be much greater than the fireball dimensions, and (3) the angle between the LOS and a line from either antenna to the fireball center be small, i.e., the fireball must be near the LOS.¹ Also, satellite altitudes yield large satellite-fireball separations so that the down-link signal can be assumed to be a plane wave at the fireball. Finally, only the down-link need be considered because of reciprocity.

The fireball is modeled as an opaque disk on or near the LOS. Three cases are considered: (1) circular disk with sharp edges, (2) circular disk with tapered edges, and (3) elliptical disk with sharp edges.

Diffraction Calculations

Case 1: Circular Disk with Sharp Edges

This case has been previously solved in series form, but the number of terms required is prohibitive in this application. Consequently, the results obtained herein used numeric integration instead. Figure 1 shows the system geometry. The receiver (ground station) is at point P and the disk (fireball) is parallel to the wave front. For mathematical convenience, the disk is considered fixed and P is moved to explore field strength in the shadow region, though in reality the opposite is true. Symmetry dictates that field strength depend only on the radius r_1 of P from the origin of the $X' - Y'$ plane.

Figure 1. Geometry

Geometric optics implies that Hygens secondary wavelet theory can be applied.^{1,2} Each secondary wavelet is a new source, and its contribution to the field strength at P is found by applying the appropriate Green's function. Total field strength is obtained by integrating the Green's function over the appropriate area. The integration is simplified by using Babinet's principle. This allows solution of the complementary problem, i.e., the integration is performed over the area of the disk and the result, after normalization, is subtracted from one, the normalized unperturbed field strength.

The Green's function for the area dA is

$$d\psi = \frac{1}{4\pi R} \exp(ikR) dA ,$$

where $k = 2\pi/\lambda$ is the wavenumber and R is the distance from P to dA, or

$$R = (r_0^2 + r_1^2 + r^2 - 2r r_1 \cos \theta)^{1/2} \quad (1)$$

and where the terms in this expression are defined in Figure 1. Integrating gives the complementary solution as

$$\psi = -\frac{1}{4\pi} \int_0^a \int_0^{2\pi} \frac{r \exp(ikR)}{R} d\phi dr , \quad (2)$$

where a is the disk radius. The normalization factor is found to be $i\lambda/4\pi \exp(ikr_0)$ by putting P at the origin ($r_1 = 0$) and allowing a to increase without bound. The normalized solution is then:

$$\psi_P = 1 - \frac{i}{\lambda} \int_0^a \int_0^{2\pi} \frac{r \exp[ik(R - r_0)]}{R} d\theta dr \quad (3)$$

This can be solved in closed form for $r_1 = 0$ and yields the familiar result of an "on-axis" bright spot:

$$\begin{aligned} \psi_P &= \exp \left\{ -ik \left[\left(r_0^2 + a^2 \right)^{1/2} - r_0 \right] \right\} \\ &\cong \exp \left\{ -ik \frac{a^2}{2 r_0} \right\}, \quad a \ll r_0 \end{aligned} \quad (4)$$

Note that the normalized bright-spot magnitude is unity for all a , but that the phase is proportional to a^2 . If a is an integral number (n) of Fresnel zones, then, from Figure 2,

$$a^2 = \left(r_0 + n \frac{\lambda}{2} \right)^2 - r_0^2$$

and

$$\psi_P = \exp \left\{ -in\pi \right\} = \begin{cases} +1, & n \text{ even} \\ -1, & n \text{ odd} \end{cases}$$

which is, again, a familiar result.

Figure 2. Fresnel Zone

A computer program was written to numerically integrate Equation (3) for various values of r_0 , r_1 , a , and λ . The results are given in Figures 3 through 6 for the parameter combinations in Table I.

TABLE I
Case 1 Parameter Combinations

Figure No.	r_0 (km)	a (km)	λ (m)
3	80	2	1
4	80	1	1
5	80	2	2
6	40	2	1

Figure 3. Circular, $r_0 = 80\text{km}$, $a = 2\text{km}$, $\lambda = 1\text{m}$

Figure 4. Circular, $r_0 = 80km$, $a = 1km$, $\lambda = 1m$

Figure 5. Circular, $r_0 = 80km$, $a = 2km$, $\lambda = 2m$

Figure 6. Circular, $r_0 = 40\text{km}$, $a = 2\text{km}$, $\lambda = 1\text{m}$

Several things can be noted from Figures 3 through 6. First, there is always a bright spot on axis with equally spaced bright rings of lower intensity around the bright spot. Second, the phase difference from the bright spot to the first ring and between adjacent rings is essentially 180 degrees. Finally, the ring spacing equals the width of the outer Fresnel zone, or

$$\Delta \approx \frac{\lambda r_0}{2a}$$

Case 2: Circular Disk with Tapered Edge

The above model in effect assumes infinite attenuation through the fireball, no attenuation outside it, and a sharp discontinuity at its edge. The first assumption is good at early times, but the last two are questionable. These assumptions were modified by tapering the attenuation near the edge. This was implemented by adding a weighting function $w(r)$ to Equation (3):

$$\psi_P = 1 - \frac{i}{\lambda} \int_0^a \int_0^{2\pi} w(r) \frac{r}{R} \exp[ik(R - r_0)] d\phi dr$$

Symmetry is preserved by making w a function of only r .

The weighting function used was

$$w(r) = \begin{cases} 1, & r \leq b \\ \frac{1}{2} \left(1 + \cos \frac{r-b}{a-b} \pi \right), & r > b \end{cases}$$

where $a - b$ is the width of the transition from infinite to zero attenuation. This function is plotted in Figure 7 along with the rectangular function that was, in effect, used in Case 1.

Figure 7. Nonuniform Field Modeling

The effect of the edge taper is illustrated in Figures 8 through 10. These figures are for the same parameters as Figure 3 except that $a - b$ corresponds to 1, 2, and 5 Fresnel zones ($b = 1980, 1960, 1900$ m). The Fresnel pattern previously obtained quickly degrades to a deep shadow. Thus, even small transition regions destroy the Fresnel pattern.

Figure 8. Edge Effect Circular, $b = 1980\text{m}$

Figure 9. Edge Effect Circular, $b = 1960\text{m}$

Figure 10. Edge Effect Circular. $b = 1900\text{m}$

Case 3: Elliptical Disk with Sharp Edges.

Fireballs are not truly spherical except possibly for low yields at low altitudes very shortly after detonation. Lack of symmetry was modeled using an elliptical disk, and was incorporated into the calculations by using the weighting function

$$W(r, \phi) = \begin{cases} 1, & r \leq R_e \\ 0, & r > R_e \end{cases}$$

where

$$R_e = b / (1 - e^2 \cos^2 \phi)^{1/2}$$

and where a and b are the semimajor and semiminor axes and e is the eccentricity, or

$$e^2 = 1 - (b/a)^2$$

These parameters are illustrated in Figure 11.

$$W(r, \phi) = \begin{cases} 1 & \text{inside ellipse} \\ 0 & \text{outside ellipse} \end{cases}$$

Figure 11. Noncircular Disk

Figures 12 and 13 are comparable to Figure 5 except that $b = 1980$ m and 1960 m, respectively ($a - b$ is 1 and 2 Fresnel zones). The bright spot is again attenuated, and the Fresnel pattern has broken up. *

* Since symmetry about the Z axis is destroyed, Figures 12 and 13 apply only to points along the Y' axis.

Figure 12. Elliptical Disk, $b = 1980\text{m}$

Figure 13. Elliptical Disk, $b = 1960\text{m}$

Conclusions

Although an on-axis bright spot always exists with a circular disk having sharp edges, any deviation from this ideal case quickly degrades the diffraction pattern. In particular, degrading the symmetry or the sharpness of the edges results in a deep shadow instead of the Fresnel pattern. Fireballs differ significantly from the spherical ideal so that the diffraction pattern cannot be relied on for communication links. In general, any time the fireball intersects the LOS, the link should be considered disrupted.

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