THE SCREENING EFFECT OF OBSTACLES WITH A STRAIGHT EDGE

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SUMMARY

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The fundamentals of the mathematical treatment of a special diffraction problem are outlined and numerical values are presented. It was not the purpose to repeat mathematical hardware and be complete, but rather to draw attention to various assumptions and approximations. It is not the illusion given, that diffraction belongs to the "classical" solved problems.

Author

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PROBLEM

A sensitive receiving antenna should be positioned in such a way that it is the least possible affected by noise, in particular, man-made noise. Increasing the distance from the noise sources is the most obvious remedy, but there is always a distance where no further increase is possible. In this case the influence of the noise can be diminished by screening, either by a mountain range or an artificial screen.

In the following the diffraction pattern behind a screen is discussed and numerical values are given. Then a method is outlined to deal with the diffraction pattern of two screens.

DIFFRACTION PATTERN OF A HALF PLANE

First, solutions of this problem are discussed and then it is shown that these can be applied to the shielding effect of a mountain.

The Classical Treatment

The solution of diffraction problems as a boundary problem is very difficult and only successful for special cases.

However, a treatment of the diffraction problem on the basis of Huygens' principle is simpler, but not exact. Huygen states that every point of a wave may be considered to be a source of secondary spherical waves. The mathematical formulation of this principle is due to Kirchhoff,[1] (p. 378) by means of Green's theorem. This theory is scalar. That means that only a scalar quantity, U, is considered. U is called light disturbance and has no dimension. U is proportional to the field strength, or — more essential — U^2 is proportional to the intensity. Further, U has to satisfy the wave equation. For monochromatic radiation U is usually split into a time and space dependent factor.

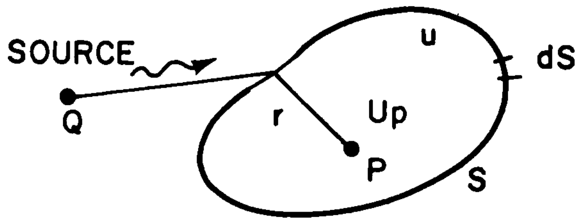
$$U = u_{(x,y,z)} \cdot \exp j \omega t$$

When one is interested only in the intensity, the knowledge of u is sufficient.

The celebrated formula of Kirchhoff[1] expresses the disturbance u_p at a point P as the integral of the light disturbance over the boundary of a region containing P:

$$u_p = (1/4\pi) \oint_s \left[\frac{(\exp - jkr) \,\mathrm{grad}\, u}{r} - u \,\mathrm{grad}\, \frac{\exp(-jkr)}{r} \right] dS \qquad (1)$$

$$k = 2\pi/\text{wavelength } \lambda$$



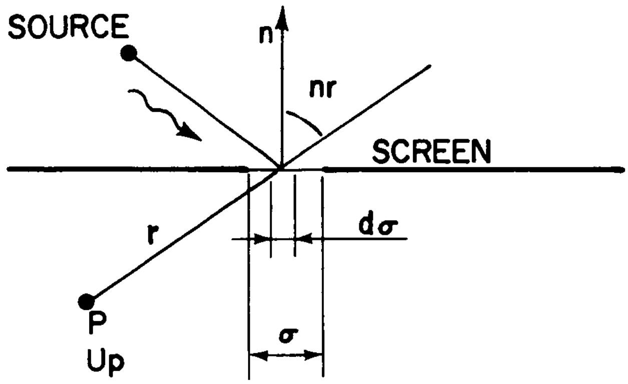
A basic remark is necessary before applying formula (1): This formula would give the exact result if we knew the boundary condition. Such knowledge would already be a solution of the boundary problem where we have the more basic conditions for the horizontal and vertical components of electric and magnetic field strength. Kirchhoff made the assumption that the disturbance in the free aperture is that which would exist if the screen were not present and that u and grad u are zero on the screen itself. This is the reason why no property of the material of the screen does enter into the solution. Also polarization cannot be attacked by this theory, because we deal only with the scalar disturbance u (proportional to the field strength) and for this reason nothing is said about the orientation of the field strength.

The two mentioned assumptions of Kirchhoff are physically justified for sufficiently small wavelengths. It is experimentally stated that shorter wavelengths cause less diffraction. So the assumption that u equals zero is nearly fulfilled. The field in the aperture is affected by the presence of the screen, but certainly the most within the order of magnitude of the wavelength from the edge of the aperture. So Kirchhoff's assumption in the aperture fits better for small wavelengths.

Simplified Huygens' principle: From Kirchhoff's formula (1) a simple mathematical expression for Huygens' principle can be derived. This is only valid for plane screens and under the assumption: $r >> $ wavelength λ

$$u_p = (1/j\lambda) \int_\sigma \frac{\exp jkr}{r} \cos(n, r) \cdot u \cdot d\sigma \tag{2}$$

reference 2, page 201



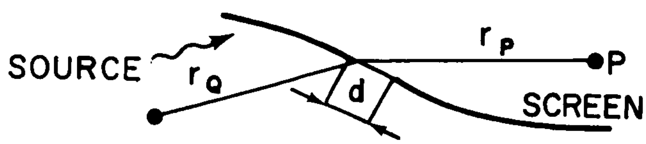
$(u \exp jkr)/r$ is a spherical wave with the excitation u. $\cos(n,r) \cdot d\sigma$ is the projected area of $d\sigma$ viewed from P. The factor $j\lambda$ is not easily explained, but it makes the dimension of the right and left sides equal (no dimension).

This simplified principle is sufficient to solve numerous diffraction problems in a surprisingly good way.

On the basis of the mathematical treatment, a classification of the diffraction is done.

Frauenhofer Diffraction

A mathematical condition for this type of diffraction is that the dimension of the diffraction opening is small, compared with the distance r_p as well as the distance r_Q. This condition must be fulfilled because a mathematical expression is expanded.



If r_Q and r_p approach infinity, all terms of the series expansion higher than that of the first degree vanish and in this particular case one speaks of Frauenhofer diffraction.

Fresnel Diffraction

When the condition $r_Q \to \infty$ and $r_p \to \infty$ is not fulfilled, one speaks of Fresnel diffraction. For the mathematical treatment the condition, r_Q, $r_p >> d$ (dimension of the diffraction opening) should be valid, because the same mathematical expression as mentioned in Frauenhofer Diffraction is expanded, to the term of second degree only. By a proper choice of the coordinate system the term of first degree vanishes. By all this a not too complicated mathematical treatment is possible. It is also obvious that the achieved solutions are more or less perfect approximations.

The diffraction pattern of a half plane (or diffraction of the straight edge) is derived from the diffraction pattern of a rectangular diffraction opening as a limiting case. The conditions r_Q, $r_p >> d$ are not fulfilled anymore, but nevertheless a solution is obtained. Omitting any justification of the various limiting processes which seem to exclude each other, it is surprising that the obtained solution is in good agreement with the rigorous solution obtained by Sommerfeld.

Rigorous Solution

Sommerfeld (reference 2, p. 247) solved this problem as a boundary problem. The solution has to satisfy the Maxwell equations everywhere and it has to satisfy the boundary condition (E_{tan}, H_{tan} continuity, etc.) on every surface. Further, the solution has to correspond to a given type of excitation (e.g., point source). The assumed screen is a half plane, infinitely thin, but nevertheless opaque and conducting. This is unrealistic and the assumptions arbitrary, but the solution is correct in the mathematical sense. The solution has two advantages. First, it takes into account polarization, second, it is valid for the whole space.

Sommerfeld generalized the above-mentioned solution for a "black" screen. But essentially this is not free of arbitrariness (reference 2, p. 265). No particular work has been done on this problem, but the applied method is ingenious. An infinitive sheeted Riemann surface is used. The cut S of the top sheet represents the screen. Every energy falling on S disappears in the infinitive number of sheets.

The Black, or Reflecting, Screen

The following is copied from reference 2, pages 205 and 246:

F. Black or Reflecting Screen

In the theory of diffraction it is customary to speak of a black screen. However, in actual diffraction experiments one finds that the physical nature of the screen in general does not affect the results noticeably. Thus a piece of tin foil into which a narrow slit has been scratched yields the same diffraction pattern regardless of whether the foil has been left reflecting or whether it has been blackened. Therefore we need only describe the screen as opaque in order to specify that in spite of arbitrary thinness it shall transmit no light. In the Maxwell theory such a screen would have to be defined as a material possessing an infinite conductivity. Such a screen would not be black but would be perfectly reflecting; its reflecting power would be $r = 1$. On the other hand, black, that is completely non-reflecting material, cannot even be defined in the Maxwell theory; blackening is not a property of the material but is a property of the surface. We shall take this into account in Sec. 38 where we shall try to describe the property "black" mathematically. Our presentation of Huygens' principle shows that this property is not essential to the theory of diffraction. Only very refined experiments can reveal the nature of the material of which the diffracting screen is composed.

The material composition of the screen, of course, affects the light field only in the immediate vicinity of the edge of the opening, that is, only within a distance of a few wavelengths from the edge. If the opening is fairly large, this edge zone is negligible compared to the rest of the aperture. This explains why the crude assumptions (4 a, b) or (6 a, b), which can of course be valid only outside the edge zone, have been so eminently successful. Deviations from Huygens' principle are to be expected with the usual methods of observation only for extremely small openings which are of the order of magnitude of a wavelength in size (or for experimental arrangements which correspond to such small openings in accordance with the similarity law of Sec. 35 E).

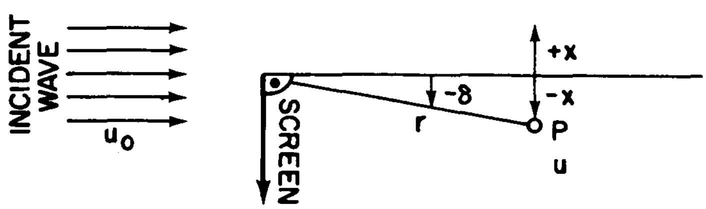
We have assumed the diffraction screen to be infinitely thin and at the same time opaque. Therefore these results cannot be realized experimentally. Under a microscope even the edge of a razor looks more like a parabolic cylinder than like a sharp half-plane. However, it is very remarkable that the patterns on precise diffraction photographs (see for instance, Arkadiew loc. cit. p. 220) exhibit almost no dependence on the material and shape of the diffraction edge. Even a bent glass plate whose radius of curvature is several meters and which may or may not be blackened yields essentially the same diffraction fringes as the edge of a razor. In each case the pattern is that shown in Fig. 75.

One remark about the black screen should be added. Why cannot it be defined within the Maxwell theory? The condition is, that all incident energy has to be absorbed. One could try to achieve this by establishing the condition, that on the surface a current is flowing in such a way, that it neutralizes the field there, and so no reflection is possible (etc.). But such a condition assumes already that the exact boundary values are known and this is not true. This is exactly what should be evaluated.

Solutions

Fresnel Diffraction — A parallel wave is normal incident on half plane.

$$F(w) = \int_0^w \exp\left(j \frac{\pi}{2} r^2\right) dt \cdots \text{Fresnel integral}$$

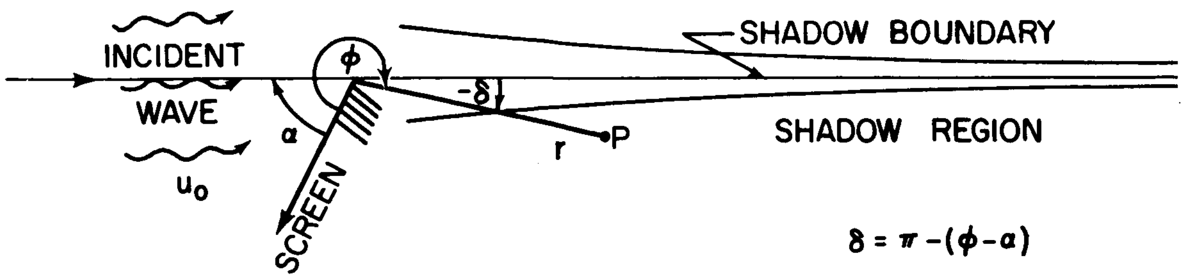


The solution is: $|u/u_0| = |F_{(\infty)} + F_{(w)}|/\sqrt{2}$ (3)

$$w = \frac{x}{\sqrt{\lambda r/2}} = \sqrt{kr/2}\,\sin\delta \qquad k = 2\pi/\lambda \qquad \lambda = \text{wavelength}$$

$|u/u_0|$ is the ratio of the field strength in P to the field strength of the incident wave.

The Sommerfeld Solution — A monochromatic, linearly polarized wave is incident on the front surface at an angle α. The screen is infinitive thin, opaque and conducting. The figure below shows the meaning of the symbols.



The solution is: (reference 2, p. 247)

$$|u/u_0| = \left| \int_{-\infty}^{\rho_1} \exp\left(j\frac{\pi}{2}\tau^2\right) d\tau \mp \int_{-\infty}^{\rho_2} \exp\left(j\frac{\pi}{2}\tau^2\right) d\tau \right| \frac{1}{\sqrt{2}} \tag{4}$$

$$\rho_1 = 2\sqrt{\frac{kr}{\pi}} \cos\frac{\phi - \alpha}{2} \qquad \rho_2 = 2\sqrt{\frac{kr}{\pi}} \cos\frac{\phi + \alpha}{2}$$

$$k = 2\pi/\text{wavelength } \lambda, \qquad -180° \leq \alpha \leq +180°$$

$|u/u_0|$ is the ratio of the field strength in P to the field strength of the incident wave.

The upper sign in (4), (5), corresponds to the case where the electrical field strength oscillates parallel to the edge of the screen, the lower sign in (4) corresponds to the case where the electrical field strength oscillates perpendicular to the screen edge.

The formula (4) can be discussed for various regions of the diffraction pattern and simpler expressions result.

Shadow Region — With the assumption $r >> \lambda$ and for large values of ρ_1 and ρ_2, formula (4) can be written as follows:

$$|u/u_0| = \frac{1}{2\cdot(2\pi k r)^{1/2}} \left| \frac{1}{\cos\frac{\phi-\alpha}{2}} \mp \frac{1}{\cos\frac{\phi+\alpha}{2}} \right| \tag{5}$$

This formula is not valid for the shadow boundary because ρ_1 becomes zero.

The field strength decreases as $1/\sqrt{r}$ or the intensity decreases as $1/r$. This is the same behavior as a cylindric wave emitted from the edge.

Shadow Boundary — Introducing the angle δ defined in the figure above, S_1 becomes:

$$\rho_1 = 2\sqrt{kr/\pi}\,\sin\left\{\frac{\delta}{2}\right\} \qquad \rho_2 = 2\sqrt{kr/\pi}\,\sin\left\{\frac{\delta}{2} - \alpha\right\}$$

If $|\rho_1|$ is small ($<<1$), the second term of formula (4) can be neglected, because ρ_2 is much more negative (α and $180-\alpha$ must be reasonably larger than δ). Formula (4) then becomes:

$$|u/u_0| = |F_{(\infty)} + F_{(\rho_1)}|/\sqrt{2} \tag{6}$$

$$F_{(\delta)} = \int_0^{\rho} \exp\left(j\frac{\pi}{2}\tau^2\right) d\tau \cdots \text{Fresnel integral}$$

The condition that ρ_1 is small can be fulfilled always, also for large kr, provided that δ is small enough. This is exactly the condition for the shadow boundary.

Formally, formula (6) agrees with formula (3), but the arguments are different:

$$w = \sqrt{kr/\pi}\,\sin\delta \qquad \rho_1 = \sqrt{kr/\pi}\;2\sin\delta/2$$

For small δ this is only a difference of the third order since

$$\sin \delta \sim \delta - \frac{\delta^3}{6}$$

$$\delta << 1$$

$$2 \sin \delta/2 \sim \delta - \frac{\delta^3}{24}$$

So the Sommerfeld solution and the Fresnel solution are surprisingly well in the shadow boundary.

A conclusion, important from the practical point of view, can be drawn from (6) and (3). Only the angle δ appears in the solution. For this reason the diffraction pattern of the shadow boundary does not depend on the position of the screen (angle α). Also the solution does not depend on polarization.

Since (6) and (3) are approximations, all this is not true in the very exact sense.

Numerical Solutions

Figures 1 and 2 are calculated on the basis of the Sommerfeld solution (5). The wave (2000 Mc) is incident from the left. The position of the screen (angle α) is different in Figures 1 and 2, but the diffracting edge is at the same position (0,0). The attenuation is calculated for certain points (black dots) for horizontal and vertical polarization and expressed in decibels. The diffracting edge acts like the emitting region of a cylindrical wave; this wave interferes with the incident wave in the region ($\delta > 0$) and causes intensity minima and maxima; along the line $\delta = +3°$ the rough position of this extrema are indicated by (1.MIN, etc.). Keeping r constant and increasing δ, we pass through a first maxima, a first minimum (noted as 1.MIN in Figures 1 and 2), a second maxima, a second minima (2.MIN), etc.

For a comparison the results (Figure 3), obtained by formula (6) are presented in the same manner as Figures 1 and 2.

This solution is only valid for the shadow boundary while formula (5) (Figures 1 and 2) is valid for the shadow region with exception of the shadow boundary. Polarization and the position of the screen do not enter in this solution.

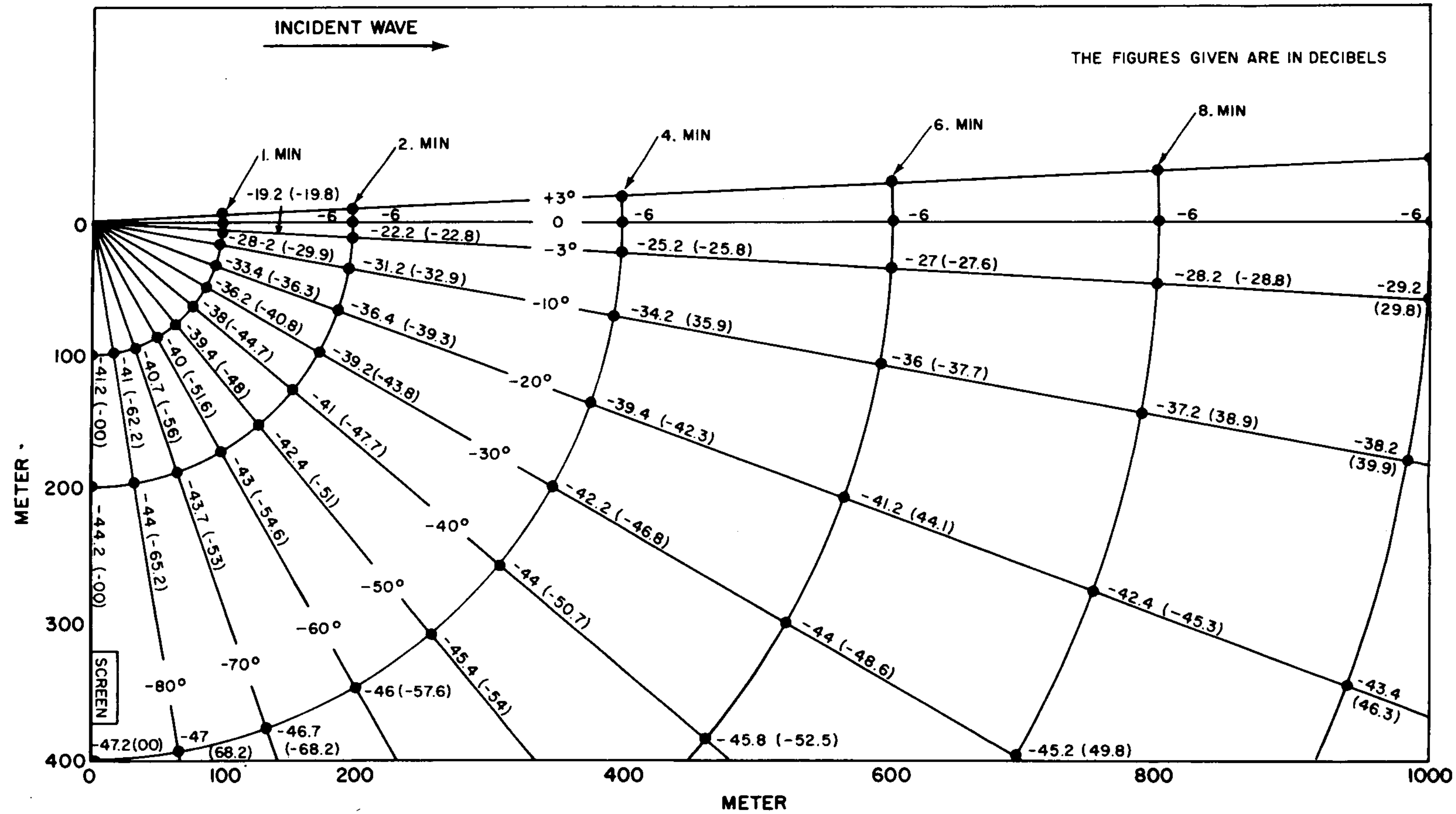


Figure 1—Diffraction Pattern Behind a Halfplane (2000 Mc)

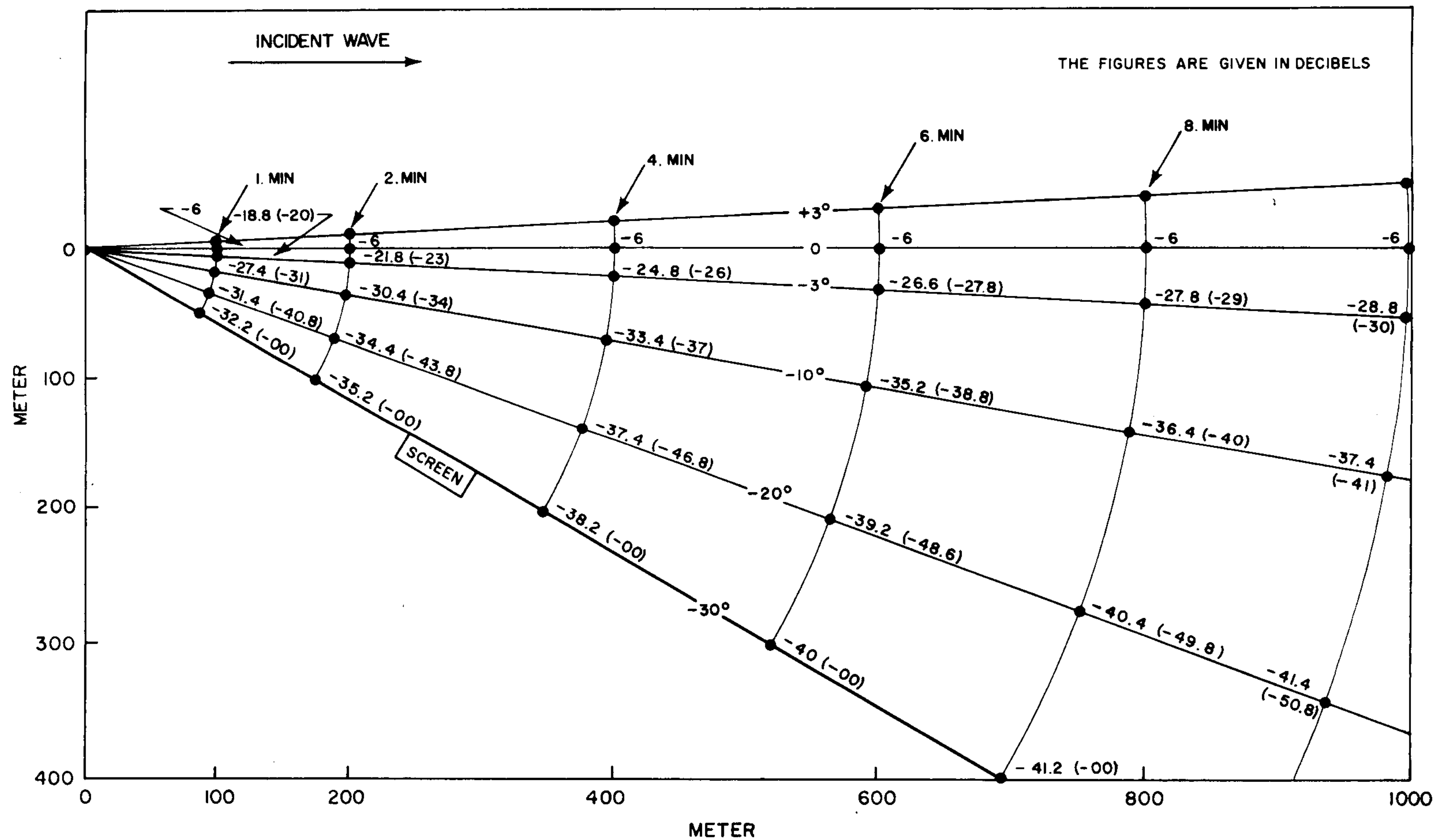


Figure 2–Diffraction Pattern Behind a Halfplane (2000 Mc)

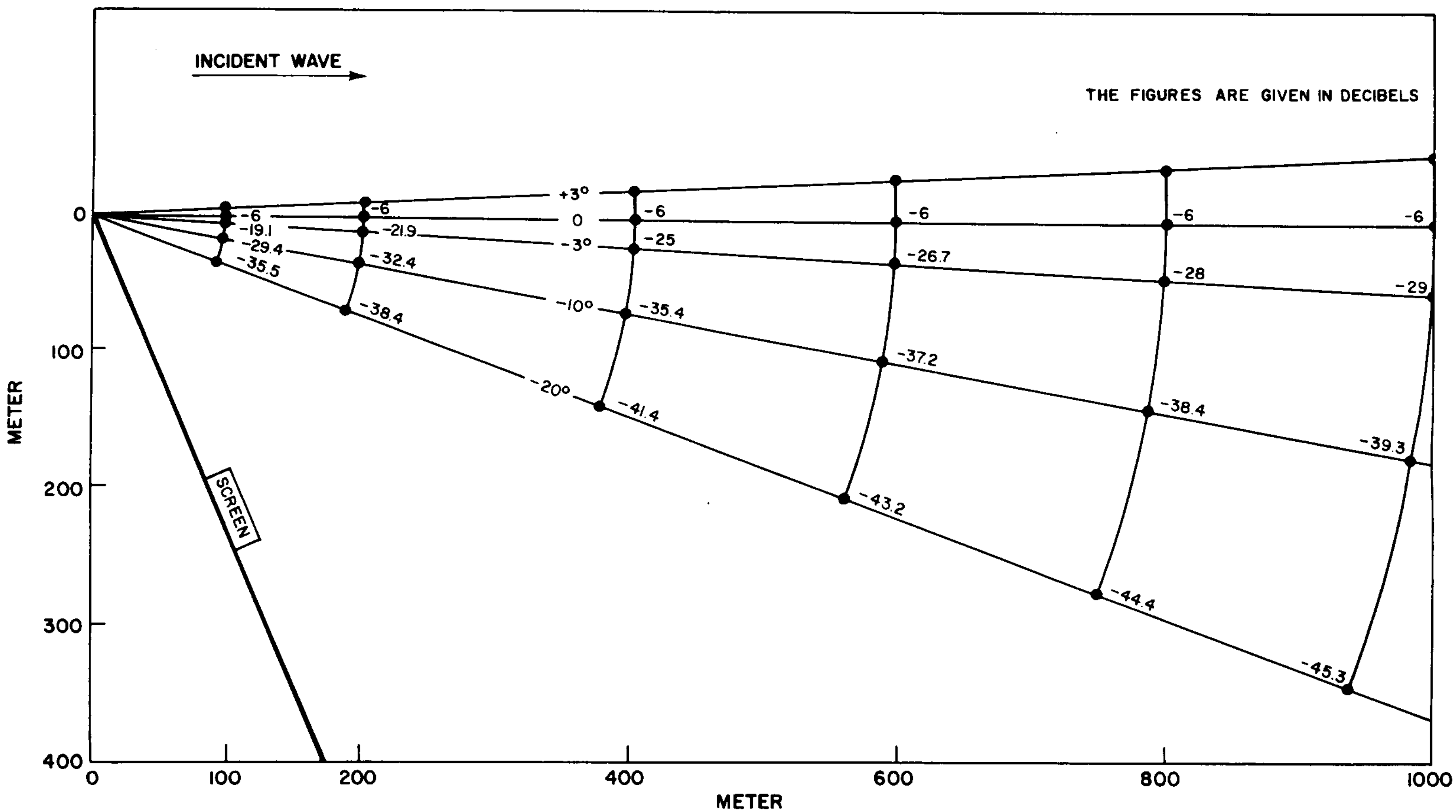


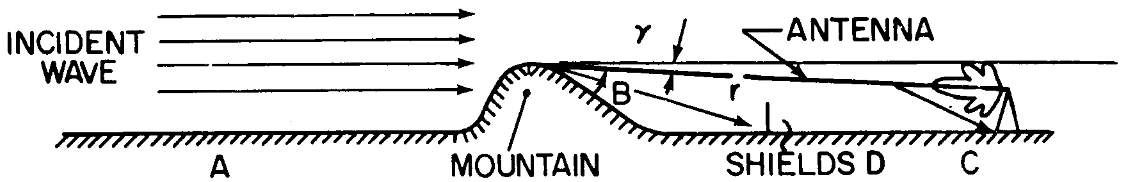
Figure 3–Diffraction Pattern Behind a Halfplane (2000 Mc)

Comparison of Figures 1 and 2 with Figure 3 shows that the two solutions fit together very well and overlap in a surprisingly good manner.

Figures 4, 5, 6 and 7 give the same type of graphical representation of the diffraction pattern as Figure 3, but for various frequencies, (1000, 300, 100, 30 Mc). The intensity in the geometrical shadow increases with decreasing frequency.

Application of the Obtained Solution

With some approximations, the obtained solution can be applied to the problem outlined in PROBLEM. Let us consider manmade noise as a plane wave with constant amplitude propagating parallel to the surface of the earth.



This is an approximation. First the intensity of the noise varies essentially. This means that also lower frequency components must be present in the detection equipment. Lower frequencies show a stronger diffraction. If the intensity of the incident and diffracted wave are determined by the same equipment and $|u/u_0|$ is determined, then this value is larger than the theoretical value for an incident wave, with constant amplitude and being strictly monochromatic.

Second, the incident wave cannot be a plane wave because of the earth, designated by A in the figure above.

Disregarding these differences, the diffraction pattern is the same as shown before, if the angle between the slope B of the mountain and r ($\gamma < 10°$) is not too small, (e.g., not smaller than $\approx 20°$).

The earth (part C on the figure above) has essentially a reflecting effect since γ is small. The reflected wave superposes with the diffracted. However, the antenna under consideration has a pronounced directivity in the forward direction, so that the radiation can only be picked up by the less sensitive side loops. This influence could be further diminished by suitable shields D on C.

Further a mountain is opaque for UHF waves (300-3000 Mc).

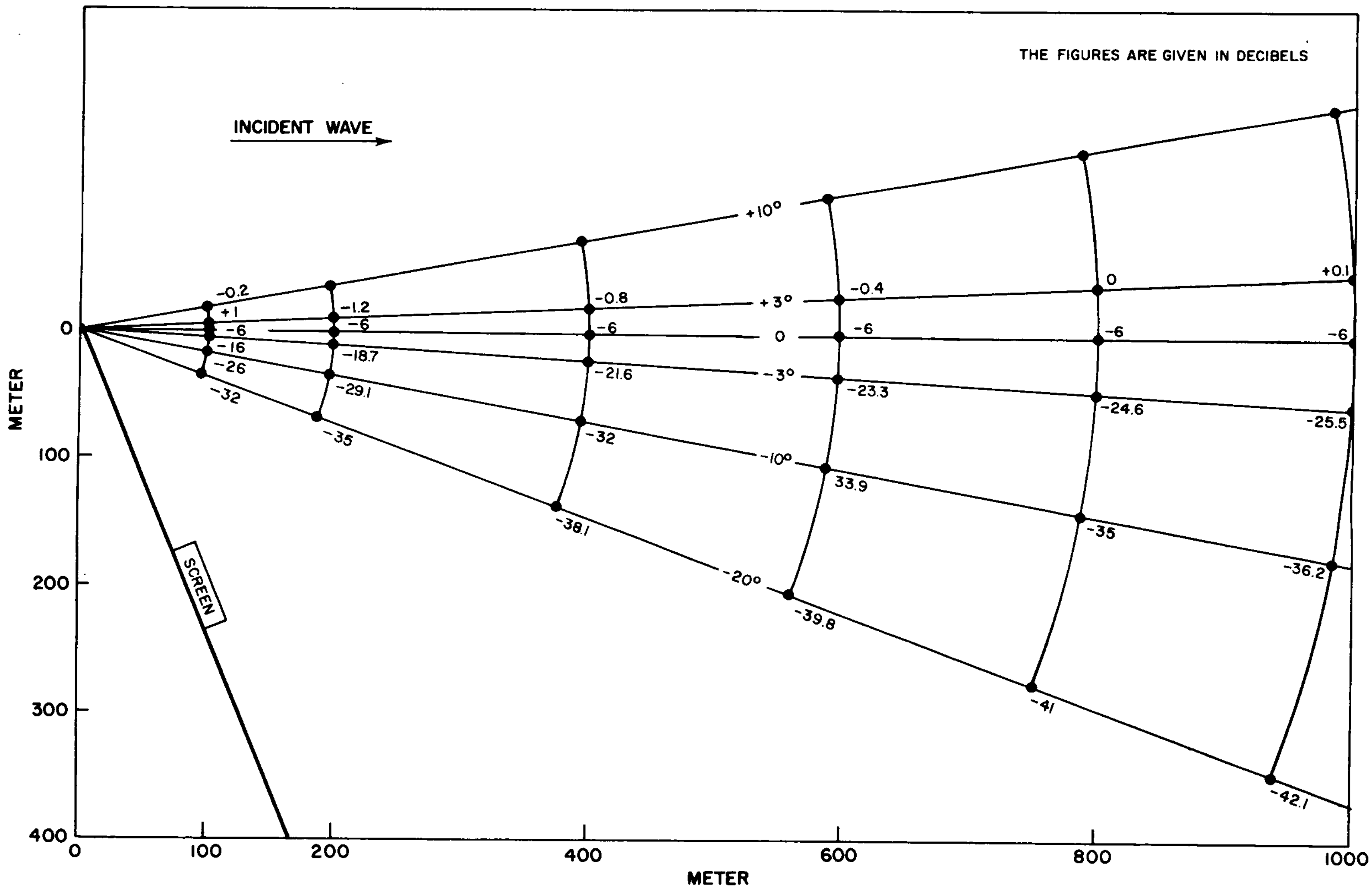


Figure 4–Diffraction Pattern Behind a Halfplane (1000 Mc)

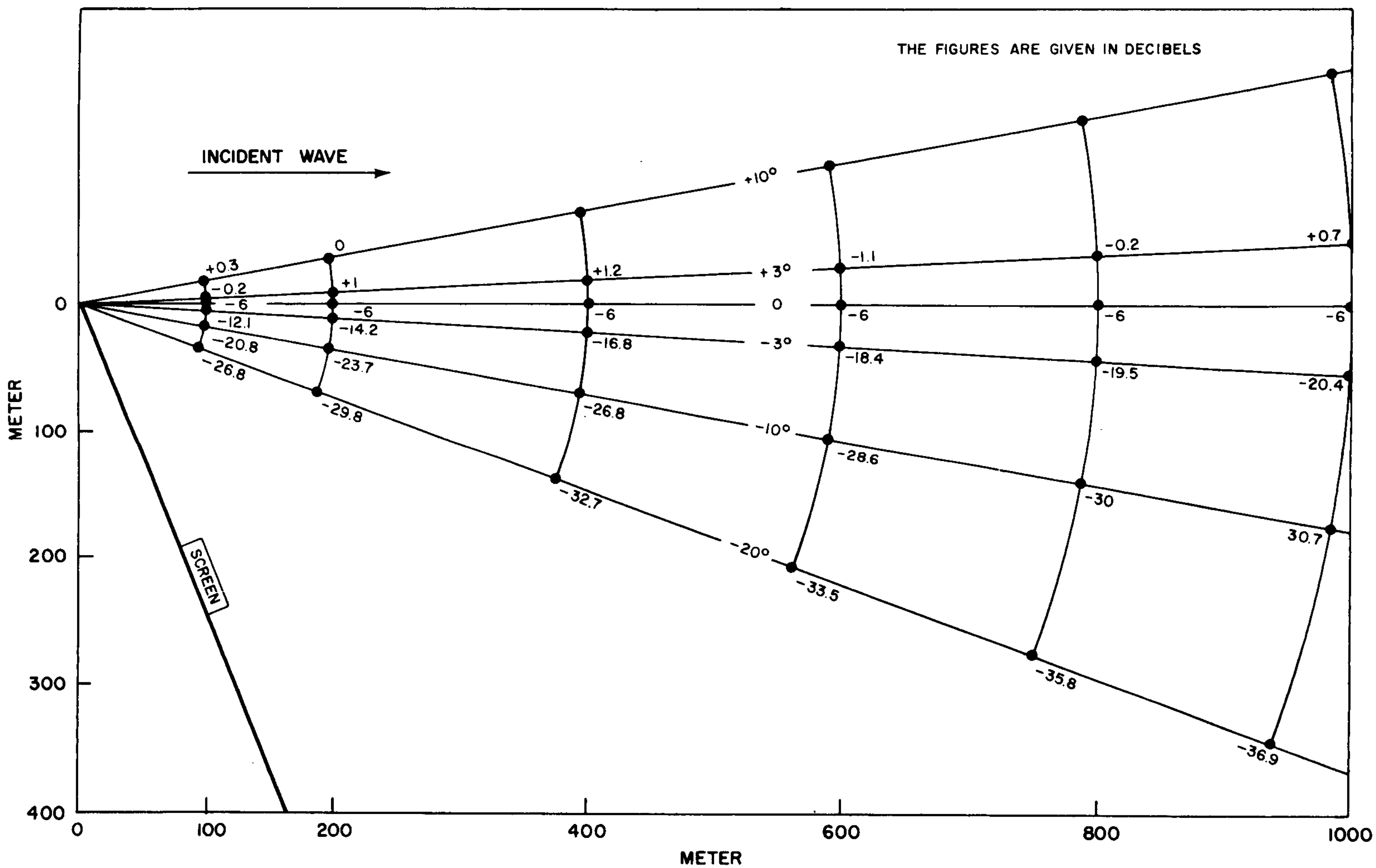


Figure 5–Diffraction Pattern Behind a Halfplane (300 Mc)

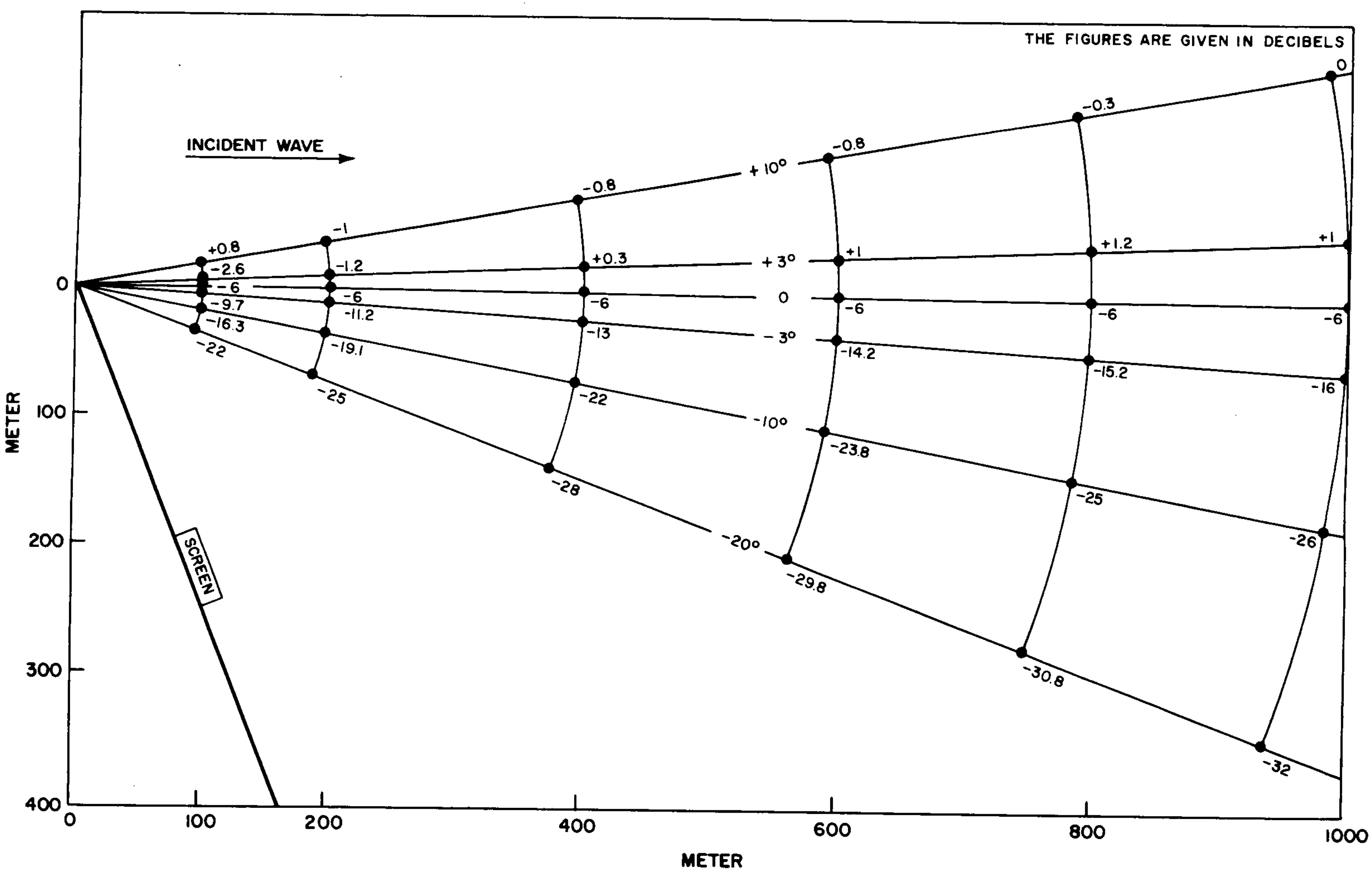


Figure 6–Diffraction Pattern Behind a Halfplane (100 Mc)

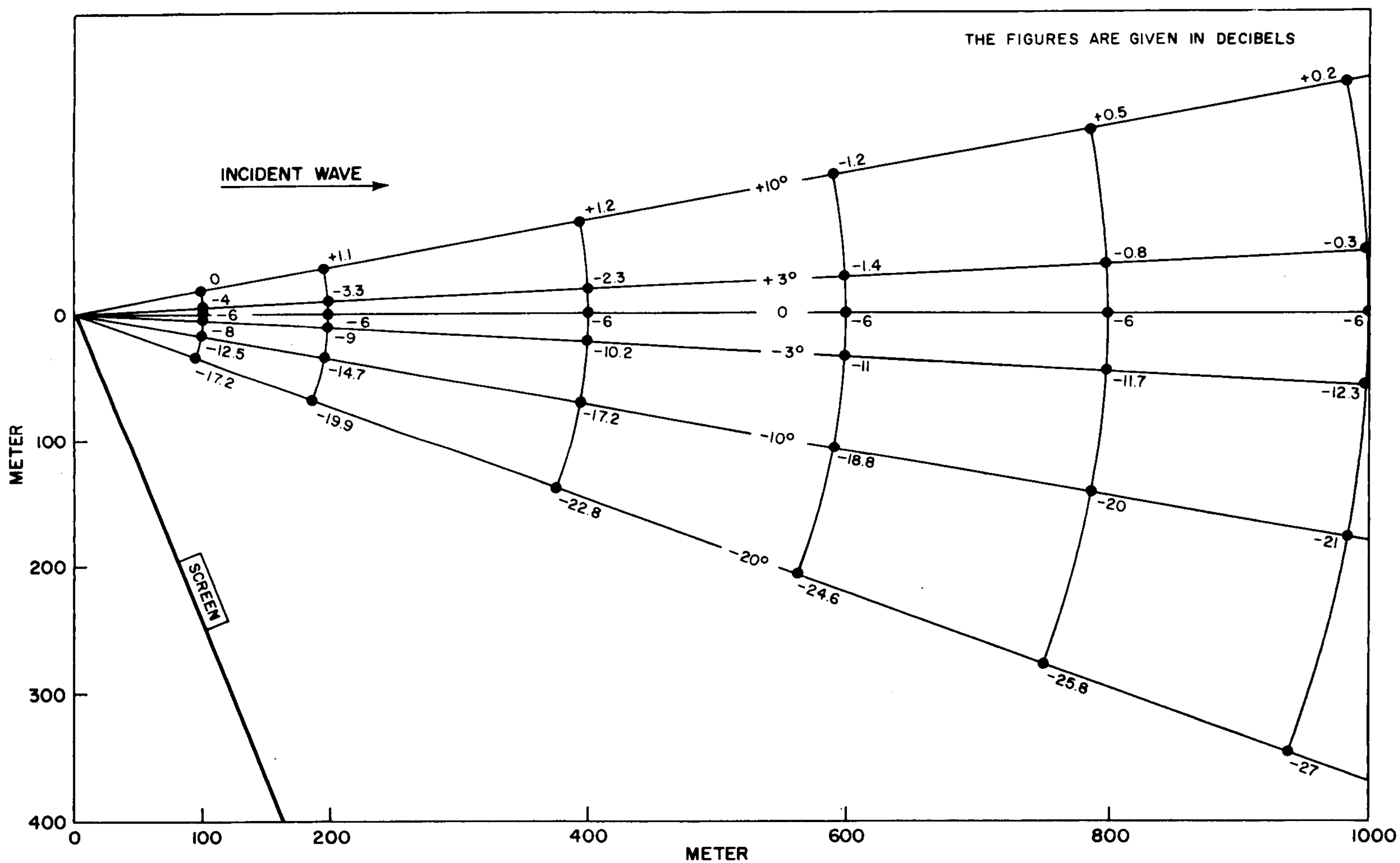
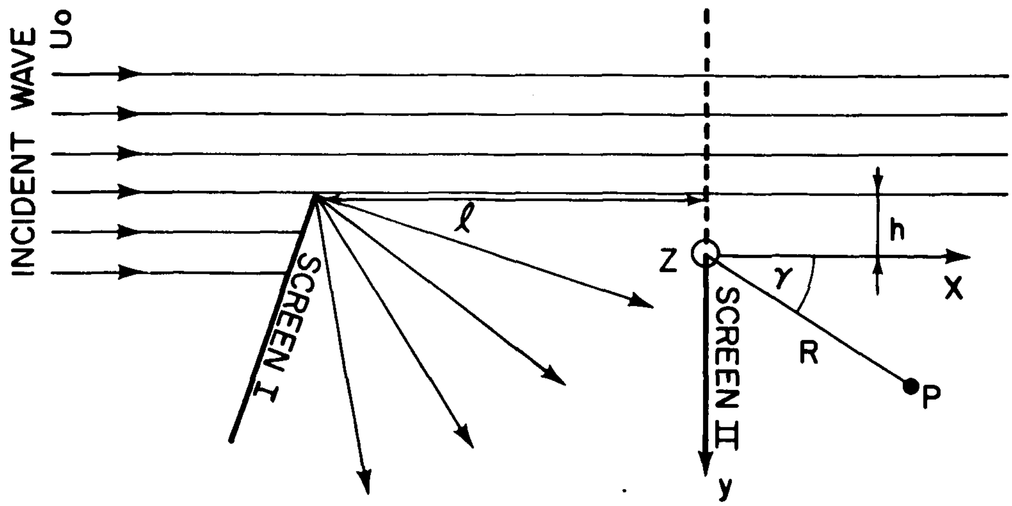


Figure 7—Diffraction Pattern Behind a Halfplane (30 Mc)

TWO SCREENS

The question arises in how far the diffracted wave can be shielded by a second shield as it is shown in the figure below:



By means of Babinet's principle, Huygens' principle and applying (4), a solution of this problem can be written down. The derivation is given in Appendix I.

$$\left|\frac{u_{P\,II}}{u_0}\right| = \left|\frac{u_{P\,I}}{u_0} + \frac{2jR\cos\gamma}{\lambda}\int_{\bar{y}=0}^{\infty}\frac{u_s}{u_0}\int_{\bar{z}=0}^{\infty}\frac{\exp jkR(1+\bar{y}^2+\bar{z}^2-2\bar{y}R\sin\gamma)^{1/2}}{1+\bar{y}^2+\bar{z}^2-2\bar{y}\sin\gamma}\,d\bar{y}\,d\bar{z}\right| \quad (7)$$

$r \gg \lambda \quad \bar{y} = y/R \quad \bar{z} = z/R$

$\frac{u_{P\,II}}{u_0}$ Means the ratio of the field strength at the point P to the field strength of the incident wave.

$\frac{u_{P\,I}}{u_0}$ Means the ratio of the field strength at the point P if screen II is absent, to the field strength of the incident wave.

$\frac{u_s}{u_0}$ Means the ratio of the field strength on screen II to the field strength of the incident wave (screen II has to be thought not to be present).

The integration could not be carried out, but numerical approximations are possible (Appendix I, 4).

Inspection of the integral reveals that integrand consists of a sine and cosine with rapidly decreasing amplitude. The oscillations of this sine and cosine are very rapid because of the large value of kR (for 2000 Mc and 50 meters: kR = 1800).

In order to draw conclusions the formula should be evaluated numerically. It seems to be not too difficult to write an appropriate computer program for this purpose. A special case is interesting, e.g., if the edges of the two screens fall together, this would be a better representation of a mountain. If the two screens fall together, the diffraction pattern of one screen should result.

APPENDIX
Derivation of Formula (7)

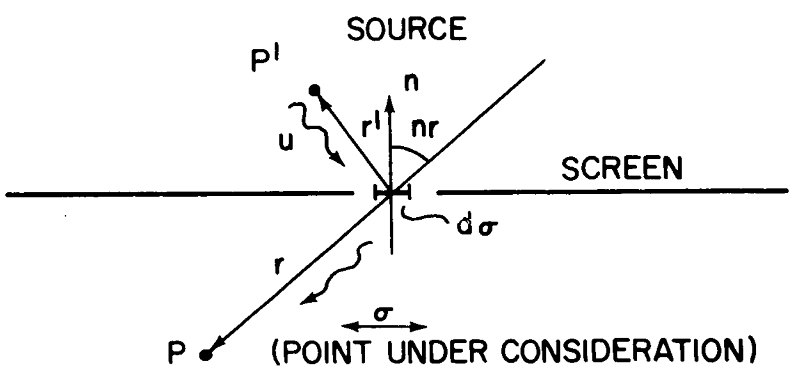
HUYGENS' PRINCIPLE

1. When the dimensions of the diffracting aperture become small compared to the wave length or even only a few times longer, Huygens' principle becomes meaningless. This is so, because then the boundary conditions play the dominant role.

2. Huygens' principle is an approximation (but a very successful one). This is so, because this principle does not take into account the vectorial character of the electromagnetic wave and so the boundary conditions cannot be defined exactly. For the same reason polarization effects — as a consequence of boundary conditions — cannot be evaluated with this principle. Huygens' principle operates with the quantities, designated by u or v, representing scalar solutions of the wave equations.

3. Simplified formulation of Huygens' principle: (Sommerfeld, Lectures on Theoretical Physics, Vol. IV, Academic Press 1954, p. 199).

The meaning of the symbols is shown in the figure below:



$k = 2\pi/\lambda$

$|n| = 1$

$u_p \sim$ fieldstrength

Huygens' principle for a plane screen:

$$u_p = \frac{1}{\partial\lambda} \int_\sigma \frac{\exp jkr}{\tau} \cos(n, r) \cdot u \, d\sigma \qquad (1')$$

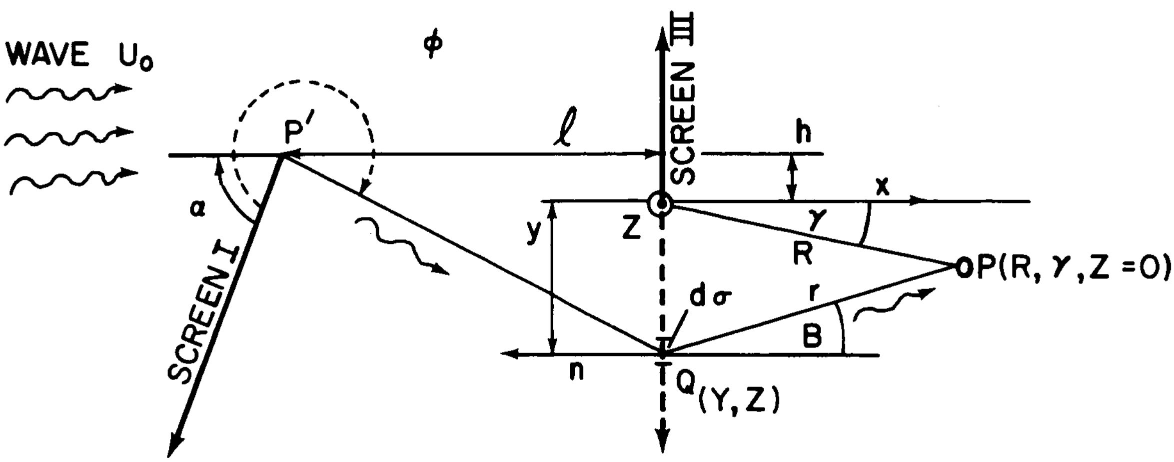
In words: A wave falling on the aperture σ, propagates as if every element $d\sigma$ emitted a spherical wave, the amplitude and phase of which are given by that of the incident wave u, the factor cos (nr) corresponds to Lambert's law of surface brightness.

Assumption: (1) Plane screen

(2) $kr \gg 1$

THE SHIELDING OF A DIFFRACTED WAVE (p. 5)

Let us first consider the following arrangement of screens for a reason which will be pointed out at the end. We can use (1') to evaluate the field on the right side of Screen III.



$$\cos(n, r) = \cos\beta = R(\cos\gamma)/r.$$

U_s/U_0 = the ratio of the field strength on the dotted line to the field strength of the incident wave (no screen III).

$$r = \left\{(y - R\sin\gamma)^2 + (R\cos\gamma)^2 + z^2\right\}^{1/2} = (R^2 + y^2 + z^2 - 2yR\sin\gamma)^{1/2}$$

Substituting these values above in (1') yields for screen III:

$$U_{P\,III}/U_0 = \frac{R\cos\gamma}{j\lambda} \int_{y=0}^{\infty} \int_{z=-\infty}^{\infty} \frac{\exp(jkr)}{r^2}\, U_s/U_0 \, dy\, dz \tag{2'}$$

$U_{P\,III}/U_0$ means the ratio of the field strength at the point P to the field strength of the incident wave (U_0).

U_s/U_0 is a function of y only.

Since the problem is cylindric, it is sufficient to evaluate $U_{P\,III}/U_0$ for one particular (x, y) plane. In our case this is the plane $Z = 0$.

But we are actually interested in the arrangement of screens as shown on page 18.

Screens II and III should represent complementary screens. Then we can apply Babinet's principle:

$$U_{P\,I}/U_0 = U_{P\,II}/U_0 + U_{P\,III}/U_0 .$$

We are interested only in the absolute value of $U_{P\,II}/U_0$:

$$\left|U_{p\,II}/U_0\right| = \left|U_{P\,I}/U_0 + \frac{2j\,R\cos\gamma}{\lambda} \int_{y=0}^{\infty} U_s/U_0 \int_{z=0}^{\infty} \frac{\exp\, jk(R^2+y^2+z^2-2yR\sin\gamma)^{1/2}}{R^2+y^2+z^2-2yR\sin\gamma}\, dy\, dz\right|$$

or

$$\left|U_{p\,II}/U_0\right| = \left|U_{PI}/U_0 + \frac{2j\,R\cos\gamma}{\lambda} \int_{y=0}^{\infty} U_s/U_0 \int_{z=0}^{\infty} \frac{\exp\, jkR\left(1+(y/R)^2+(z/R)^2-(2y/R)\cdot\sin\gamma\right)^{1/2}}{1+(y/R)^2+(z/R)^2-2(y/R)\sin\gamma}\, d\frac{y}{R}\, d\frac{z}{R}\right| \tag{3'}$$

Now substituting: $y/R = \bar{y}$ $z/R = \bar{z}$ yields formula 7 (p. 18). The advantage of the calculation of U_{pII}/U_0 via the complementary screen III consists in the following:

1. In the solution appears U_{PI}/U_0 and an additive term. This is convenient, since we want to compare our solution with U_{PI}/U_0.

REFERENCES

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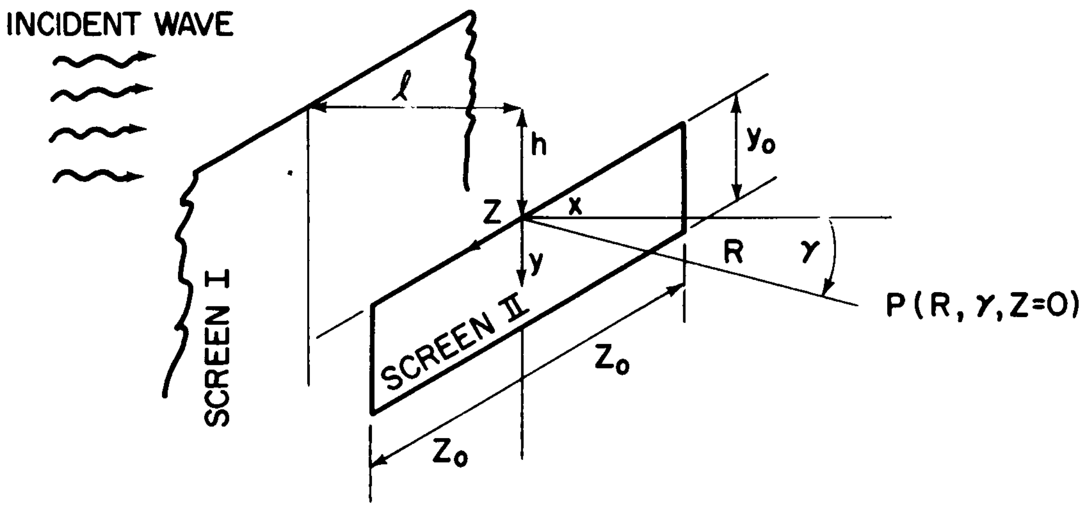
2. U_s/U_0 +) is essentially smaller than the values of U_s/U_0 along Screen III. U_s/U_0 decreases with increasing y and the convergency* is perhaps improved. Besides U_s/U_0 could be represented by a simpler analytical expression.

$$U_s/U_0 = \frac{1 + j}{4(\pi k r)^{1/2}} \left(1/\cos\left((\phi - \alpha)/2\right) \mp 1/\cos\left((\phi + \alpha)/2\right)\right)$$

-··· field strength parallel to edge.

3. One could try the approximation to substitute U_s/U_0 by the largest value U_s/U_0 and try to evaluate the integrals. Would we have integrated along Screen II and if we would do this, we would essentially get the known diffraction pattern of a half plane as screen.

4. If we are not able to carry out the integration in (3') until infinity, but only to our finite value of $y = y_0$, $z = z_0$, the physical interpretation of this is the following: instead of a half-plane as screen II we have then only a strip of screen as shown below:



This solution is perhaps more of interest from the practical point of view than this of a half-plane.

+) Along screen II   * Of integral (5)