Electromagnetic Wave Propagation

EDITED BY

M. DESIRANT J. L. MICHIELS

ELECTROMAGNETIC WAVE PROPAGATION

International Conference Sponsored by the Postal and Telecommunications Group of the Brussels Universal Exhibition

EDITED BY

M. DESIRANT
Société Belge de Physique
Loverval
Belgium

J. L. MICHIELS
Laboratoire de Recherches
Physiques, A.C.E.C.,
Charleroi Belgium

1960

ACADEMIC PRESS
LONDON AND NEW YORK

ACADEMIC PRESS INC. (LONDON) LTD.
17 OLD QUEEN STREET
LONDON, S.W.1.

U.S. Edition Published by
ACADEMIC PRESS INC.
111 FIFTH AVENUE
NEW YORK 3, NEW YORK

Library of Congress Catalog Card Number: 59-12033

PRINTED IN GREAT BRITAIN AT
THE UNIVERSITY PRESS
ABERDEEN

FOREWORD

In planning the 1958 Brussels International Exhibition, the organizers envisaged from the outset that one of its most important aspects would be to review scientific progress and its contribution to the welfare of mankind.

Pursuing this idea, Group 38, the Postal and Telecommunications Group of the Exhibition, which included eminent representatives of the Universities, Government Departments and Industry, under the able and energetic chairmanship of Mr. L. Ros, Inspector General of the "Régie des Télégraphes et Téléphones," came to the conclusion that the organization of suitably chosen International Scientific Conferences lying within the field of interest of the Group was one of the most appropriate means of furthering this end.

The papers presented at one such conference form the contents of the present volume. The choice of subject, we feel, needs no particular justification. The importance of a wider and deeper knowledge of electromagnetic wave propagation for the continued progress of modern telecommunication needs no emphasis. Moreover, research on this subject has been particularly active in recent years and has led to advances of major interest. An outstanding illustration of this is the investigation of ionospheric and tropospheric scatter and its application to beyond-the-horizon communication.

The response of the scientists and engineers working in the field to the invitation to participate was most gratifying and in itself an indication of the opportunity of holding the Conference. Some fifty papers were presented by authors from eleven different countries. There was thus every opportunity of a fruitful comparison of the work carried out in different parts of the world.

It is a pleasure to mention our indebtedness to the Minister of Economic Affairs for a stbstantial contribution toward the cost of the Conference and to the Belgian Physical Society for secretarial and other assistance in its organization.

We must also extend our special thanks to the Academic Press Inc. for undetaking the arduous task of publishing the Proceedings of the Conference. In order to avoid unnecessary delay in publication, no attempt has been made to standardize notations and so on, the papers having been prepared according to the customs prevailing in the country of origin.

J. L. MICHIELS
M. DESIRANT

CONTRIBUTORS

L. A. AMES, *Electronic Research Directorate, Air Force Cambridge Research Center, Bedford, Massachusetts.* (pp. 215, and 603)

L. J. ANDERSON, *Smyth Research Associates, San Diego, California.* (p. 209)

E. J. BAGHDADY, *Massachusetts Institute of Technology, Cambridge, Massachusetts.* (p. 183)

B. R. BEAN, *National Bureau of Standards, Boulder, Colorado.* (p. 163)

B. BECKMANN, *Fernmeldetechnisches Zentralamt, Darmstadt, Germany.* (p. 157)

P. BECKMANN, *Institute of Radio Engineering and Electronics, Czechoslovak Academy of Sciences, Prague, Czechoslovakia.* (p. 445)

R. BELLMAN, *The RAND Corporation, Santa Monica, California.* (p. 243)

Å. BLOMQUIST, *Research Institute of National Defence, Stockholm, Sweden.* (p. 127)

H. BREMMER, *Philips' Research Laboratories, N.V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands.* (p. 253)

F. CARASSA, *Laboratorio Centrale Radio della Fabbrica Italiana Magneti Marelli, Milano, Italy.* (p. 471)

G. CARLSON, *Research Institute of National Defence, Stockholm, Sweden.* (p. 459)

F. du CASTEL, *Centre National d'Etudes des Télécommunications, Issy-les-Moulineaux (Seine), France.* (pp. 591 and 671)

A. M. CONDA, *National Bureau of Standards, Boulder, Colorado.* (pp. 103 and 661).

P. W. COUCH, *Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.* (p. 479)

E. DEWAN, *Electronics Research Directorate, Air Force Cambridge Research Center, Bedford, Massachusetts.* (p. 575)

W. DIEMINGER, *Max-Planck-Institut für Aeronomie, Lindau (Harz), Germany.* (p. 699)

P. R. DROUILHET, *Jr., Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.* (p. 149)

W. J. FAY, *Smyth Research Associates, San Diego, California.* (p. 317)

B. FRIEDMAN, *University of California, Berkeley, California.* (p. 261)

M. W. GOUGH, *Research Division, Marconi's Wireless Telegraph Co., Great Baddow, Essex.* (p. 557)

J. S. GREENHOW, *University of Manchester, Jodrell Bank Experimental Station, Cheshire.* (p. 493)

S. GRUBER, *Air Force Cambridge Research Center, Bedford, Massachusetts.* (p. 299)

O. HACHENBERG, *Heinrich-Hertz-Institut der Deutschen Akademie der Wissenschaften, Berlin, Germany.* (p. 143)

E. HARNISCHMACHER, *Ionosphären Institut Breisach im Fernmeldetechnischen Zentralamt der Deutschen Bundespost, Breisach (Rhein), Germany.* (p. 527)

J. L. HERITAGE, *Smyth Research Associates, San Diego, California.* (p. 317)

G. A. ISTED, *Research Division, Marconi's Wireless Telegraph Co., Great Baddow, Essex.* (pp. 515 and 541)

C. JAUQUET, *Laboratoire de Recherches Physiques, Ateliers de Constructions Electriques de Charleroi, Charleroi, Belgium.* (p. 271)

R. KALABA, *The RAND Corporation, Santa Monica, California.* (p. 243)

T. J. KEARY, *U.S. Navy Electronics Laboratory, San Diego, California.* (p. 277)

J. M. KELSO, *Space Technology Laboratories, Los Angeles, California.* (p. 291)

U. KÜHN, *Betriebslaboratorium für Rundfunk und Fernsehen, Berlin-Adlershof, Germany.* (p. 615)

A. W. LADD, *Communications Division, Hughes Aircraft Company, Los Angeles, California.* (p. 357)

E. A. LAUTER, *Observatorium für Ionosphärenforschung, Kühlungsborn, Germany.* (p. 505)

E. A. LEWIS, *Electronics Research Directorate, Air Force Cambridge Research Center, Bedford, Massachusetts.* (p. 335)

F. A. LOSEE, *Communications Division, Hughes Aircraft Company, Los Angeles, California.* (p. 357)

S. G. LUTZ, *Communications Division, Hughes Aircraft Company, Los Angeles, California.* (p. 357)

C. L. MACKEY, *Rome Air Development Center, Griffiss Air Force Base, Rome, New York.* (p. 685)

F. MARIANI, *Istituto di Fisica dell' Università and Istituto Nazionale di Geofisica, Roma, Italy.* (p. 451)

H. S. MARSH, *Air Force Cambridge Research Center, Bedford, Massachusetts.* (p. 719)

E. J. MARTIN, *Electronics Research Directorate, Air Force Cambridge Research Center, Bedford, Massachusetts.* (pp. 215 and 603)

P. MISME, *Centre National d'Etudes des Télécommunications, Issy-les-Moulineaux (Seine), France.* (pp. 591 and 671)

H.-G. MÖLLER, *Max-Planck-Institut für Aeronomie, Lindau (Harz), Germany.* (p. 699)

E. L. NEUFELD, *University of Manchester, Jodrell Bank Experimental Station, Cheshire.* (p. 493)

K. A. NORTON, *National Bureau of Standards, Boulder, Colorado.* (p. 375)

A. OMHOLT, *The Auroral Observatory, Tromsö, and The Institute of Theoretical Astrophysics, University of Oslo, Norway.* (p. 75)

K. W. OTTEN, *Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.* (pp. 63 and 149)

G. B. PARRENT, *Jr., Air Force Cambridge Research Center, Bedford, Massachusetts.* (p. 55)

L. PENNINCKX, *Régie des Télégraphes et des Téléphones, Bruxelles, Belgium.* (p. 49)

P. QUARTA, *Laboratorio Centrale Radio della Fabbrica Italiana Magneti Marelli, Milano, Italy.* (p. 471)

I. RANZI, *Centro Radioelettrico Sperimentale "G. Marconi", Roma, Italy.* (p. 29)

K. RAWER, *Ionosphären Institut Breisach im Fernmeldetechnischen Zentralamt der Deutschen Bundespost, Breisach (Rhein), Germany.* (p. 647)

R. Rawhouser, *Wright Air Development Center, Wright-Patterson Air Force Base, Dayton, Ohio.* (p. 227)

G. C. Rider, *Research Division, Marconi's Wireless Telegraph Co., Great Baddow, Essex.* (p. 631)

T. F. Rogers, *Electronic Research Directorate, Air Force Cambridge Research Center, Bedford, Massachusetts.* (pp. 215 and 603)

G. Rose, *Max-Planck-Institut für Aeronomie, Lindau (Harz), Germany.* (p. 699)

R. Schünemann, *Heinrich-Hertz-Institut der Deutschen Akademie der Wissenschaften, Berlin, Germany.* (p. 15)

P. Springer, *Aerial Reconnaissance Laboratory, Wright Air Development Center, Dayton, Ohio.* (p. 227)

K. Toman, *Geophysics Research Directorate, Boston, Massachusetts.* (p. 1)

L. G. Trolese, *Smyth Research Associates, San Diego, California.* (p. 209)

J. Voge, *Centre National d'Etudes des Télécommunications, Issy-les-Moulineaux (Seine), France.* (pp. 591 and 671)

K. Vogt, *Fernmeldetechnisches Zentralamt, Darmstadt, Germany.* (p. 157)

H. Volland, *Heinrich-Hertz-Institut der Deutschen Akademie der Wissenschaften, Berlin, Germany.* (p. 143)

J. R. Wait, *National Bureau of Standards, Boulder, Colorado.* (pp. 87, 103 and 661)

A. T. Waterman, *Jr., Stanford Electronics Laboratories, Stanford University, Stanford, California.* (p. 111)

S. Weisbrod, *Smyth Research Associates, San Diego, California.* (pp. 209 and 317)

H. J. Wirth, *U.S. Navy Electronics Laboratory, San Diego, California.* (p. 277)

E. Wolf, *The Physical Laboratories, University of Manchester, Lancashire.* (p. 119)

M. S. Wong, *Electronics Research Directorate, Air Force Cambridge Research Center, Bedford, Massachusetts.* (p. 37)

CONTENTS

Ray-geometry Considerations for Highly Elevated Antennas

K. TOMAN

Geophysics Research Directorate, Boston, Mass.

A minimum property of the circle * and a maximum property of two concentric circles is stated. Based on these properties geometrical conditions are described as they apply to a spherical earth and ionosphere for highly elevated antennas. Under simplifying assumptions the ray paths are obtained and intersected radially at great angular distances from the antenna. For given parameters and because of the requirement that each point along the radial orbit corresponds to only one ray path it is found that optimum conditions exist for the largest possible range of positive and negative elevation angles. The importance of the minimum property regarding the MUF-concept is pointed out.

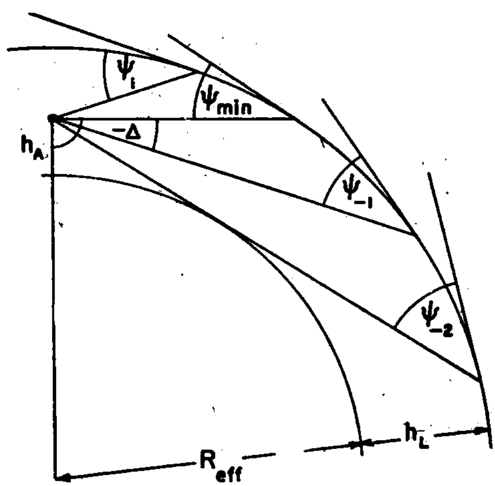

FIG. 1. A minimum property of the circle.

I. THE MINIMUM PROPERTY OF THE CIRCLE [4]

Without including the geometrical proof which was reported elsewhere [5] the general formulation of the minimum property is as follows: If one chooses an arbitrary point P inside of a circle other than its center, a normal s upon the diameter, both through P, intersects the circle with ψ, which is the angle between the normal and the tangent to the circle at the intersection point. Rotating s on P in either sense increases ψ. For the conditions stated above ψ must be a minimum. This is illustrated in Fig. 1. R_{eff} is the symbol for the modified earth

* The minimum property was reported at the Spring URSI-meeting, 23–26 April 1958 in Washington, D.C.

radius. h_A represents the height above ground of an antenna. h_L is the height of the reflecting layer. The normal upon the radius through the point at h_A intersects the circle with ψ_{min}. If positive and negative deviations from the right angle are of equal magnitude the angles of intersection ψ_1 and ψ_{-1} are equal.

The minimum property is of importance as it pertains to the reflection of radio waves from an ionospheric layer. For frequencies above about 30 kc/s the reflection coefficient of the ionosphere depends upon the angle of incidence at the layer. Consequently, the minimum property of the angle ψ corresponds to a maximum property for the reflection coefficient.

For increasingly negative elevation angles, which become feasible for highly elevated antennas, ψ increases and the reflection coefficient decreases until the bulge of the earth obstructs the radio beam. This is obtained when the beam is tangential to the earth. Accounting for uniform refraction the actual radius of the earth is modified by a factor of 1·25. This factor has been adopted by the National Bureau of Standards for ionospheric radio propagation [1].

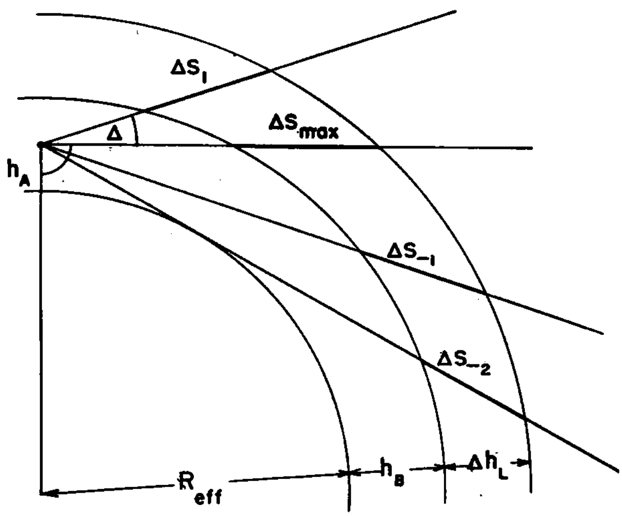

FIG. 2. A maximum property of two concentric circles.

II. The Maximum Property of two Concentric Circles

The geometrical proof was reported elsewhere [6]. The general formulation of the maximum property is as follows: If one chooses an arbitrary point P inside of two concentric circles a normal s upon the diameter, both through P, forms two secants. The difference in length between the secants of both circles diminishes if s is rotated on P in either sense. For the conditions stated above this difference is a maximum. This is illustrated in Fig. 2. h_B represents the height of the bottom of a layer of thickness Δh_L. The normal upon the radius through the point at h_A intersects both circles and forms a segment Δs_{max}. If positive and negative deviations from the right angle are of equal magnitude the segments Δs_1 and Δs_{-1} are equal.

The maximum property is of importance as it pertains to the absorption of a radio wave passing through an ionospheric layer of finite thickness. The absorption depends on the absorption coefficient integrated over the length of the ray path in the absorbing medium [2]. In the following analysis only the geometrical behavior of ray paths is described. Moreover it is assumed that ray paths are not refracted inside the absorbing layer. This assumption conflicts less with actual physical conditions the higher the frequency of the radio wave.

III. The Earth Geometry

The above mentioned geometrical properties are generally valid. Applied to a spherical earth and ionosphere and selecting specific values for various parameters the following geometrical conditions were obtained. As shown in Fig. 3

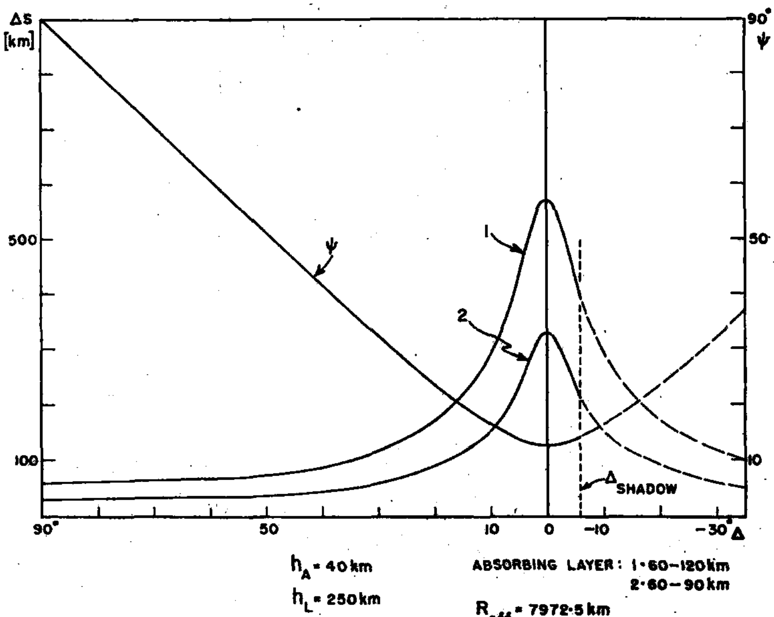

Fig. 3. Reflection angle ψ and absorption path length Δs as a function of the elevation angle Δ.

a radio source is assumed to be at a height $h_A = 40$ km above the surface of the earth. The effective earth radius is 7972·5 km. The elevation angle Δ of a linear ray is progressively moved from 90° to about $-35°$. The behavior of the absorption path length Δs as a function of Δ for two absorbing layers, one extending from 60–120 km (1) and the other from 60–90 km (2), reveals a sharp maximum at $\Delta = 0$. Δs is a minimum for $\Delta = 90°$. In either case the ratio of $\Delta s_{max}/\Delta s_{min}$

is approximately equal to 10. The beam, originating at h_A, grazes the earth for a negative elevation angle marked Δ_{shadow}. In this case $\Delta_{shadow} = -5{\cdot}7°$. For a reflecting layer height of $h_L = 250$ km, ψ is displayed as a function of Δ. ψ is a minimum for $\Delta \equiv 0$. Like the distribution of Δs, the ψ-distribution is symmetrical with respect to $\Delta = 0$. As pointed out before, this property holds for any point inside of the circle; thus it is true for any antenna height below the absorbing layer. It can also be seen that for elevated antennas these optimum properties for ψ and Δs are within the observation range until the bulge of the earth commences its obstruction at Δ_{shadow}.

Somewhat different results are obtained when the antenna touches the bottom of the absorbing layer. This is illustrated in Fig. 4. The absorbing layer extends

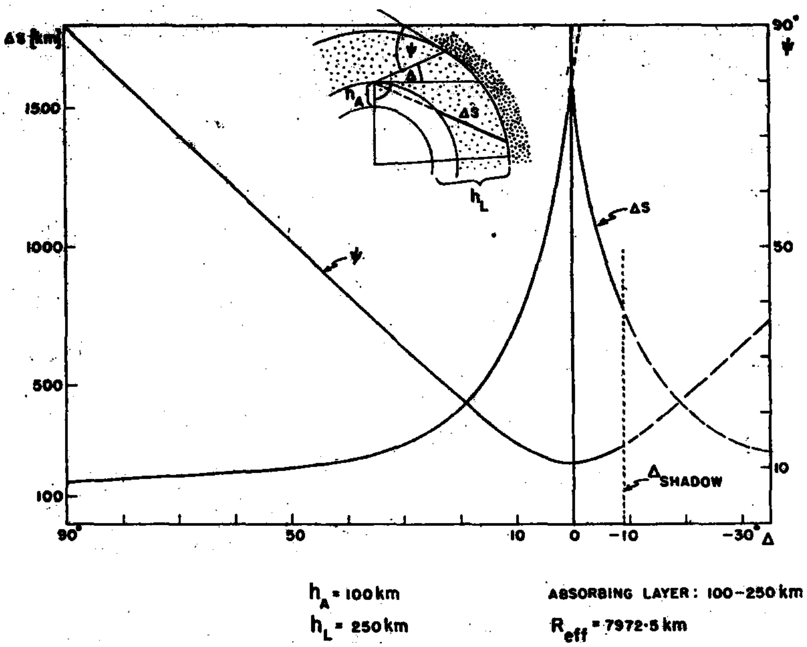

FIG. 4. Reflection angle Ψ and absorption path length Δs as a function of the elevation angle Δ.

from 100–250 km. The reflection takes place at 250 km. Again, the maximum of Δs is obtained at $\Delta = 0$. Although the general shape of the curve is different from the one in Fig. 3, Δs is still symmetrical relative to $\Delta = 0$. The same is true for ψ as a function of Δ. In this example the shadow angle is about 9°.

Fig. 5 displays the dynamics of Δs relative to Δ for values of h_A which increase from below to above the absorbing layer. The layer extends from 60–120 km. For an antenna height of 40 km Δs is a continuous function of Δ as was also shown in curve 1 of Fig. 3. For an antenna height of 60 km Δs has the shape similar to the display of Fig. 4. In both cases Δs_{max} is obtained for zero elevation angle Δ. For an antenna height of 90 km, which places the ray source inside the absorbing region, the maximum of Δs does no longer occur at $\Delta = 0$. The Δs-distribution also ceases to be symmetrical. As the antenna height is progressively increased the maximum of Δs increases while advancing towards more negative values of Δ. Once h_A lies above the absorbing region, Δs_{max} remains constant, although the maximum moves to the right as the antenna height continues to rise. The dotted line represents the locus of the shadow angles for the selected antenna heights.

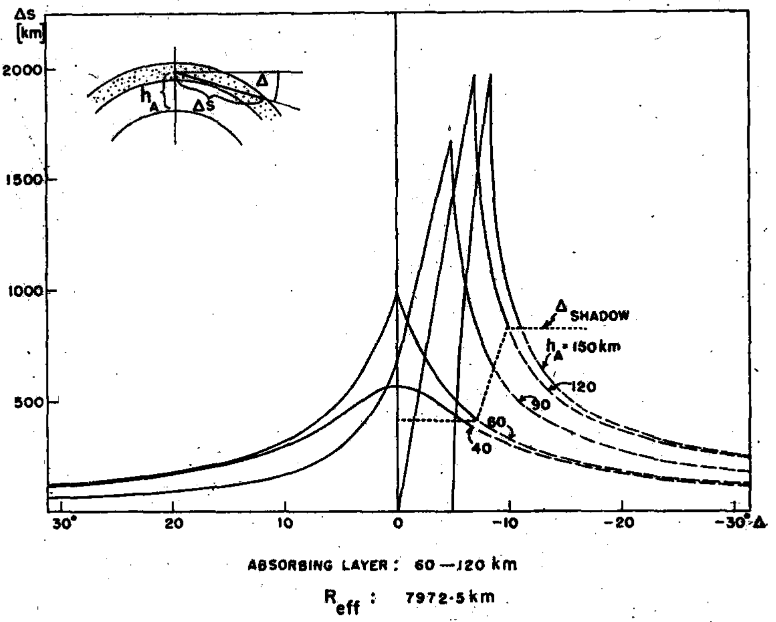

FIG. 5. Absorption path length Δs as a function of the elevation angle Δ for various antenna heights h_A.

It is now of interest to conceive an experiment in which the optimum properties of the circle are utilized for a radio transmission experiment. These optimum properties are perhaps observable if an orbiting satellite is monitored from a highly elevated receiver. In this case the satellite itself may be transmitting or it may act as a passive reflector. In either case the geometry is simple. A more complicated geometry exists when these optimum properties are to be observed by intersecting the ray paths along a radial orbit at great angular distances from the elevated source. This case will now be treated in more detail. Fig. 6 illustrates the spherical geometry involved. The ray path length from the source at h_A to the reflecting layer is x. The distance from the reflection point to the orbit is y. The shadow line of the direct ray is obtained when the ray is tangent to the earth (Δ_{shadow}). y_s is the length of the reflected ray where it intersects the shadow line. The latter is considered an upper limit for the radial orbits. It is convenient to also introduce a limiting condition when the reflected ray grazes the earth. This occurs for an elevation angle which is equal in magnitude to Δ_{shadow}. $K = \infty$ marks one point of infinite convergence factor.

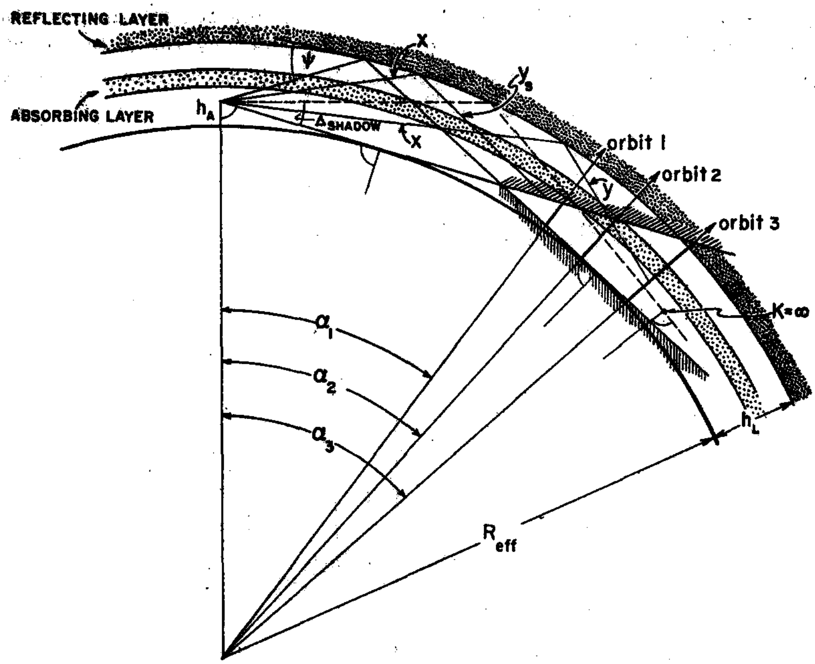

FIG. 6. Ray geometry for a spherical earth.

Fig. 7 illustrates the total absorption path length Δs_{total} as a function of the elevation angle Δ. The absorbing layer extends from 60-120 km. The reflecting layer is at 250 km. The antenna height $h_A = 40$ km. The distribution displays a transition from $2\Delta s$ to Δs as the orbits intersect the ray paths inside the absorbing region. For example, for $\alpha = 24°$ the curve for $2\Delta s$ passes through the maximum at $\Delta \equiv 0$. For increasing values of $-\Delta$ the absorption path length diminishes uniformly. At $\Delta \doteq 2°$ intersection commences inside the absorbing region. For $\Delta \doteq 5°$ the radial orbit intersects the ray path above the absorbing region and the Δs-distribution takes over.

IV. THE CONVERGENCE FACTOR K

The convergence factor is a measure of the focusing effect. This effect is important in the vicinity of $\Delta = 0$. K is defined [3] as follows:

$$K = \left(1 - \frac{2xy}{r_0(x+y)\sin\psi}\right)^{-1}$$

where x, y, and ψ were already identified. r_0 is the radius of curvature of the smooth reflecting layer ($r_0 = R_{eff} + h_L$; Fig. 6). Advancing from the source at h_A (Fig. 6) along a ray path of elevation angle Δ, the convergence factor K remains identically equal to unity. After reflection at a distance x from the source K becomes greater than unity as y increases. Eventually it reaches infinity. This is the point where initially diverging rays intersect each other after reflection. A further increase of y leads to diminishing values of K of opposite sign.

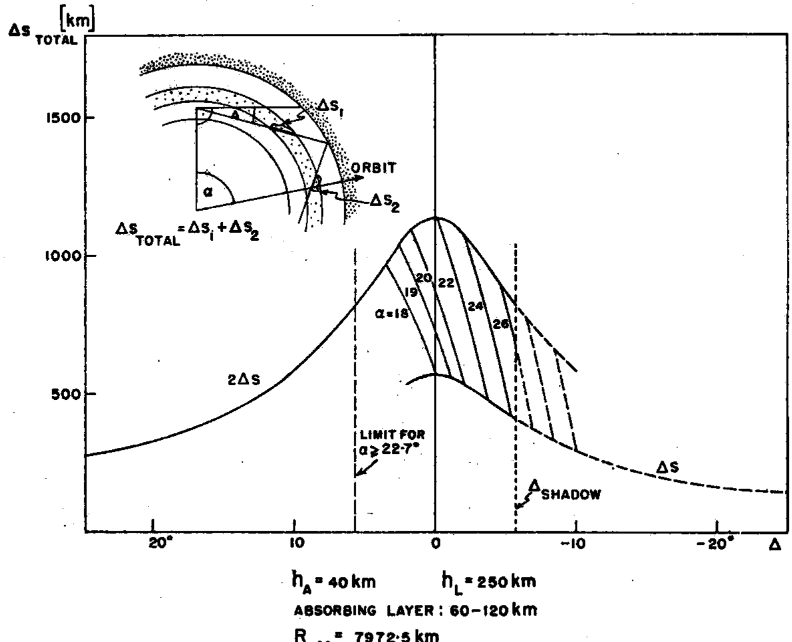

FIG. 7. Absorption path length Δs encountered for radial orbits at various angular distances α.

The behavior of $x + y$ as a function of Δ for K as a parameter is shown in Fig. 8. In this case the antenna height $h_A = 120$ km and the layer height $h_L = 250$ km. The curve for x ($K = 1$) represents the locus of the length of the ray paths between source and reflection point. $(x + y)_{shadow}$ is the distance from the source along the ray path to the interception with the shadow line (Δ_{shadow}). An observation point which is to remain below the line of sight must lie above the locus of $(x + y)_{shadow}$.

For $K = \infty$ the locus of $x + y$ as a function of Δ reaches a minimum for $\Delta \equiv 0$. Thus, $\Delta = 0$ represents an optimum condition not only with respect to ψ_{min} and Δs_{max} but also with respect to $K = \infty$. For values of $K \neq \infty$ this minimum is displaced from zero.

For simplicity it is desirable to restrict an intersecting orbit to positive values of K. Together with the requirement of remaining below the shadow line, i.e.