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J. J. G. McCue

The Evaporation Duct and Its Implications for Low-Altitude Propagation at Kwajalein

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FOR THE COMMANDER

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LINCOLN LABORATORY

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J. J. G. McCUE

Group 32

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ABSTRACT

The principal intent is to provide a basis for understanding the influence of the evaporation duct, a low region of strong refraction existing nearly all the time on the open sea, with varying thickness. There is a survey of the literature, followed by application of published data to the task of estimating the effect of the evaporation duct on the performance of the radars at Kwajalein when the target height is only a few meters. It is concluded that this duct has negligible effect at VHF, UHF, and L band, that at times it causes a large extension of the coverage of the S-band radar, and that it very importantly extends the range of the C-band radar on targets at heights such as 5 meters. Attention is given to the effects of the duct on signal velocity, pulse compression, and polarization ratio. There is also a discussion of the effect of the atmosphere over tropical ocean on the location of the radio horizon for frequencies that are too low to be influenced by the evaporation duct.

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I. INTRODUCTION

At the Kiernan Re-entry Measurement Site (KREMS) at Kwajalein Atoll, there is interest in the ability of the sensors to score RV impacts, i.e., to locate the impacts precisely, in space and in time. A matter calling for attention has been the meteorology of the propagation that enables sensors to observe targets below the optical horizon, which is basic to an understanding of the potential for observing impacts in the different target locations. In addressing itself to that subject, this report will discuss questions which are relevant also to the establishment of communication links on the atoll.

On 4 March 1976, a metal sphere with radius 0.15 m was dropped from a Caribou aircraft and tracked by ALCOR to splash at a range of 25 km. The RCS of the sphere was $\pi r^2 = -11.3$ dBsm; any variation in the apparent RCS can confidently be ascribed to a difference between the actual two-way path loss and the path loss that would obtain were the sphere at the same range in free space. In the absence of an atmosphere, the apparent RCS would diminish as the sphere neared the earth's surface; for a while after the sphere had dropped below the horizon, diffraction over the bulge of the earth could keep the echo at a discernible, though dwindling, level. Adding an atmosphere would introduce refraction, which is often taken into account by assigning to the earth a radius 4/3 as large as the geometric radius. That is called "using a 4/3 earth."

The actual behavior of the echo from the sphere is delineated in Figure 1, along with the curve predicted by using diffraction theory on a 4/3 earth. The agreement is not at all good. When the target altitude is 5 m, the echo is stronger than when the target is at 50 m; at 5 m, the discrepancy between measurement and uncritically applied theory is 45 dB. The altitude at which the sphere would be just at ALCOR's horizon on a 4/3 earth is 7 m.

The total failure of the 4/3-earth model to account for the sphere-drop data is to be ascribed to ducting. Section II will sketch the fundamentals of ducting, including its relation to humidity, whose gradient over the sea creates what is called an evaporation duct. Section III is a guide to the literature of the evaporation duct; it also extracts those findings that are most applicable to the question of assessing the influence of the evaporation duct on observing low targets at KREMS. There follow two sections, one for ALCOR and the second for TRADEX and ALTAIR, applying the available body of knowledge to predict the effect of the duct on these radars. Such prediction must be statistical, because the duct is a meteorological phenomenon, and though it is almost always present, its properties and influence are variable. The final section summarizes the conclusions.

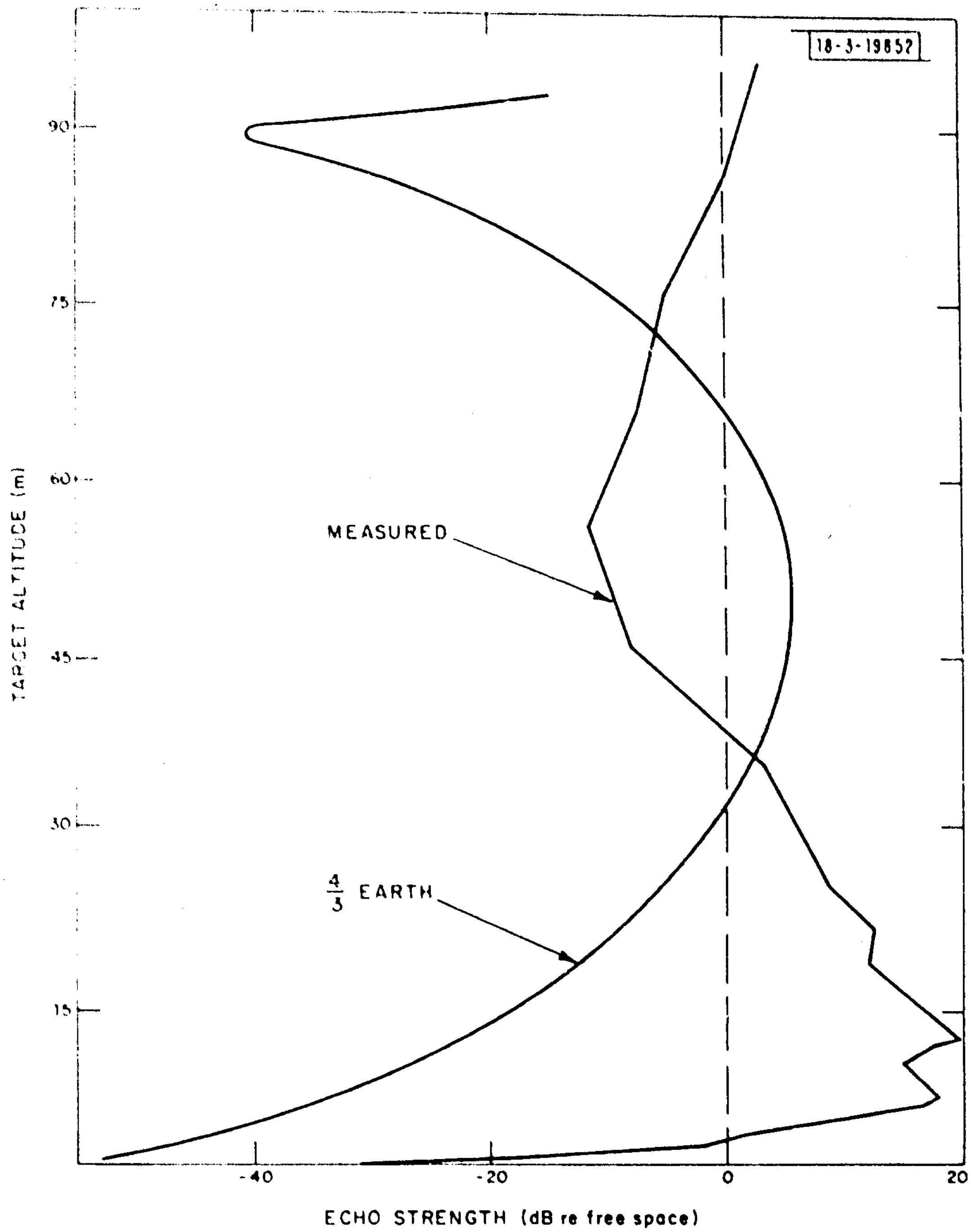

Fig. 1. Measured and calculated returns at ALCOR from a sphere dropped over the sea; range 24.7 km, altitude of ALCOR antenna 11 m. ALCOR data furnished by L. Thurman and M. Rockowitz, Lincoln Laboratory.

II. REFRACTION AND DUCTING

Refraction is a change in direction of the wave normal during propagation through an inhomogeneous medium. Because the water molecule in its ground state has an electric dipole moment, refraction of radio waves in the atmosphere is strongly dependent on the distribution of humidity. For waves of the frequencies used at KREMS, the refractive index n of air is -- practically speaking -- real, and at low altitudes it exceeds unity by about 3 parts in 10^4. A much-used measure of the index is the "refractive modulus" or "refractivity" N such that $N = (n-1)\ 10^6$. The dependence of N on temperature T, atmospheric pressure P and partial pressure e of the water vapor is

$$N = 77.6\ \frac{P}{T} + 3.73 \times 10^5\ \frac{e}{T^2}$$

where T is in kelvins and P and e are in millibars [1]. At sea level, N is generally in the range 300 to 400.

In a dry atmosphere, with e=0, the equation for N shows that it would be proportional to the density of the atmosphere, and therefore would nearly always "lapse," i.e., diminish, as one goes up from sea level, because the usual lapse of temperature only incompletely offsets the gravitational effect. If there is a temperature inversion, i.e., if temperature increases with height, the lapse rate of density, and hence of refractivity, is enhanced.

It follows from Snell's law that in a medium of slowly changing refractivity, the curvature of a horizontal ray is equal in magnitude to the vertical gradient of the index. Consequently, if the lapse rate of the index equals the reciprocal of the earth's radius, a horizontal ray will maintain its height, and a believer in a flat earth will see the ray as undergoing no bending. All that is needed for converting to a flat-earth frame of reference is to modify the lapse rate of the index by introducing a fictitious component whose lapse rate is the negative of the earth's curvature. The resulting "modified index" μ is

$$\mu = n + \frac{h}{a}$$

where h is height above the earth and a is the earth's radius. Related to it, and more convenient numerically, is the "modified refractivity" $M = (\mu-1)\ 10^6$, whose relation to the refractivity is

$$M = N + \frac{h}{a}\ 10^6$$

In dry air with no temperature inversion, M increases with height, and on the flat-earth model, a horizontal ray refracts upward. However, if there is humidity that lapses rapidly, M can diminish with height, over some range of h. The lapsing of M means that a ray is deflected downward, if we picture the earth as flat. If we recognize the earth as round, a lapsing M means that the ray curves downward faster than the earth does. On either basis, the ray (a normal to a wave front) is directed toward the earth instead of escaping into space. The region of lapsing M is called a "duct," if its height in wavelengths is large (~100 or more), propagation in the duct is much like that in a waveguide, except that there can be appreciable escape of energy through the boundary of the duct.

In this report, the region of decreasing M will have its base at zero height. Such a region is called a "ground based duct"; if the duct is only a few meters or tens of meters high and is caused by a lapse of humidity over water or wet terrain, it is an "evaporation duct." In what follows, it will develop that over tropical seas uninterrupted by land masses, the evaporation duct is practically always present in some degree, is very commonly high enough to trap X band, and is very seldom high enough to trap L band.

Above water or land, it is possible for temperature and humidity gradients to form a duct hundreds of meters high. Such high ducts, usually caused by advection (mass movement of air) can trap radiation with decimeter or meter wavelengths, but they occur only sporadically.

The modified index is an artifice for masking the curvature of the earth by using a fictitious refraction. It is always a valid device. A complementary scheme, applicable under some conditions, masks the refraction by assigning to the earth a fictitious curvature. The combined effect of ray curvature and earth curvature is given by the left side of the following equation; the right side is the same, except that it pretends there is no refraction, so that the whole effect is assigned to a fictitious earth whose radius is a':

$$\frac{dn}{dh} + \frac{1}{a} = 0 + \frac{1}{a'}$$

The substitution is of no value unless a single value of a' is applicable to the whole situation, i.e., unless dn/dh has the same value over the whole region in which the wave in question is propagating. Empirically, it has been found that over land in the temperate zones, much of the time, dn/dh near the ground is about $-(4a)^{-1}$, so that the criterion stated by the equation above is fulfilled by choosing for a', the "effective earth radius," the value (4/3)a. By pretending that the earth is 4/3 larger than its true size, one can calculate the distance to a horizon by treating the rays as straight lines; furthermore, diffraction beyond the horizon can be calculated without any other allowance for refraction.

The "4/3 earth" is well known among radio and radar engineers. Less familiar are its limitations. One is that it is based on having refractivity that lapses linearly, and at the same rate over the whole path. Of course, the vertical gradient of the index need not be strictly constant in order for the fictitious-earth model to provide engineering approximations that are useful. An important sort of case is one where dn/dh varies strongly in some interval such as $0 < h < 10$ m, possibly in such a way as to form a duct, but then settles down to a constant value $(4a)^{-1}$ for the next kilometer. For 3-cm radiation from a high-gain antenna 5 m off the ground, the 4/3-earth model is not applicable to the case. A wavelength of 3 m, would, so to speak, sense the atmosphere in a much coarser way. If radiated from an antenna 20 m off the ground, it would be little affected by the changing gradient in the lowest 10 m, and a 4/3-earth calculation of path loss would be approximately correct.

Another limitation of the 4/3 earth is that 4/3 is not the appropriate multiplier unless the lapse rate of the index of refraction is $(4a)^{-1}$. In the arctic, the lapse rate is rarely that large, and in the tropics -- especially over the sea -- it is seldom that small.

Transmission over the Caribbean, predominately by tropospheric scatter, was studied by Gray [6], using 0.80 and

and 1.0 GHz on paths 135 t0 920 km in length; in order to make the loss as a function of distance agree with the function found for 0.9 GHz on paths over land in temperate climates, he had to assume that over the Caribbean, the angles of intersection of his antenna beams were governed by an earth factor of 12/5, or 2.4.

Conclusions in harmony with that of Gray were reached by Misme [29] as a result of experimerts on refraction of a radar beam, of unspecified frequency, on a path from the French mainland to Corsica, a distance of about 70 km. He gives cumulative distributions of the earth factor for this path during four seasons. His medians are: winter 1.4, spring 2.7, summer 2.6, autumn 1.9. For the whole year, the median was 2.1, and 4/3 was exceeded 83 percent of the time. For July, the monthly median exceeded 5.0. Very large values like 5 or 10, which indicate ducting, are put forward by Misme as measures of a fictitious constant gradient which, if present, would result in the observed transmission loss. However, if the lapse rate of n (and consequently those of N, μ, and M) is markedly inconstant over the volume that is important to the propagation -- as is true for example, in a duct high enough to trap the radiation -- then the modified-earth model has no real usefulness. Over a specific path, one can observe the transmission loss and calculate from that an earth-radius that would apply over that path if the model were valid, but if the model is not applicable, that value of earth-radius will not correctly foretell the loss over a longer or a shorter path, and it is likely to give a wrong value for the loss at a different frequency, even over the same path.

The fictitious-earth model will be useful in estimating the probable performance of ALTAIR and L-band TRADEX against low targets. Diffraction calculations will use Fock's formulation [2] of the theory; Section IV comments on the choice of an earth-radius factor. For these radars, the evaporation duct can be ignored, because it is seldom high enough to have an appreciable effect. For S-band TRADEX, the effect of the evaporation duct will often be noticeable; for ALCOR, it will be usually important, and often spectacular. Assessment of the effect on ALCOR is undertaken in Section IV. It has to rest on a piecing together of data from several sources. At the outset of the study, it became apparent that a review of the literature on the evaporation duct would be of value. It is presented in Section III as an introduction to the properties of the evaporation duct, and also as a data base from which conclusions can be drawn in later sections, or in other contexts. It is hoped that this survey and the associated bibliography will be useful generally to engineers concerned with the propagation of microwaves over water, but on a first reading, readers interested primarily in effects at Kwajalein are encouraged to skim Section III lightly, absorbing the picture only qualitatively.

III. SURVEY OF LITERATURE ON THE EVAPORATION DUCT

One of the most pertinent of the reported researches was made in 1945, using antennas on a tower 18 m from the water's edge at Antigua, in the West Indies, and on a naval patrol vessel (173 ft, 350 tons) [3]. Unlike most other reported experiments, this one included use of antennas at heights down to 2 m. The time of year was February to April. A clear-cut conclusion was reached that at 3-cm wavelength, the best transmission was achieved with the lowest antennas, though at 9 cm, the reverse was usually true. Thus, there was firm indication of a thin duct in the lowest few meters of the atmosphere -- a duct thick enough to trap X band, but too thin to trap S band strongly. On a run said to be "rather typical of the average," lowering the antennas from 46 and 54 ft to 16 and 16 ft raised the X-band signal by 40 dB when the range was 80 nautical miles (148 km). With the low antennas, the signal level at 80 n mi was the same as if the propagation were through free space. At this distance over land, X-band signals would propagate chiefly by tropospheric scatter, the free-space loss would be exceeded by about 50 dB, and the change in antenna height would have no effect. On a 4/3 earth, the loss between the high antennas would exceed the free-space loss by 83 dB, which would increase by 40 dB for the low antennas.

The experimenters moved the receiver back from the shore; they concluded that the duct was destroyed 1/4 to 1/2 mile inland, but that it reformed on the other side "completely" at the smallest distance they could test, which (because of shoals) was 2 miles. Their principal experimentation was done on the windward side of the island, and the reforming occurred on the lee side.

One must appreciate that the ducting considered here is not at all an anomaly. It is caused by a sufficiently negative derivative of humidity with respect to height, in the first meter or few meters above the ocean. At Kwajalein, its absence would be an anomaly. The ducting that is observed at greater heights, and has been called "anomalous propagation," may arise from a humidity gradient or from a density gradient, or from a combination of these. The "evaporation duct," as it is called, is less conspicuous, partly because it affects only a limited range of frequencies, but in the ocean in the trade-wind latitudes, this duct is present almost all the time, though with varying height and strength.*

Pekeris [4] correlated the experimental data of [3] with a mode theory of ducting. His paper remains one of the best

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*The "strength" of an evaporation duct is the difference between the surface and minimum values of the modified index. The "height" of the duct is the altitude of that minimum. Fock [Chapter 17 of Reference 2] has shown that the second derivative of the index, evaluated at the minimum of the index, is also important.

introductions to that now widely adopted type of calculation.

Pidgeon [5] reported an experiment using transmitters on a boat and receivers on the Virginia coast; it resembled that of Katzin et al. [3], but was so slender in scope as to be of very limited value. The shore antenna was 9 m above sea level, at an unspecified distance from the water's edge. Data were collected on five days in May 1969, at S,C,X, and K_a bands, at ranges up to five times the horizon distance on a 4/3 earth. It appears that there was ducting on some days and not on others. The most noteworthy aspect of the tests was that ducting seemed strongest with calm wind and sea, whereas Katzin et al. correlated strong ducting with strong wind.

Some IT and T work [6] at 800 to 1000 MHz, between various sites in the Caribbean area, is of considerable interest, even though the frequency was relatively low and the antenna heights, when specified, were much higher than ALCOR's. That author found that for overland paths, an earth-radius factor of 3/2 or 5/3 is better than 4/3, but that his data on overwater paths are fitted by using 12/5. His work is interesting for us because it is indicative of a persistent large humidity gradient in the first few tens of meters over sea at about the same latitude as Kwajalein.

The most conspicuous center for study of the evaporation duct has been the Geophysical Institute at the University of Hamburg, which has produced an extensive and valuable series of studies of the duct in the Bight of Heligoland [7-16]. Two sketchy summaries, illustrated with assorted curves from prior publications, are to be found in proceedings of conferences [17,18]. An endlessly cited paper [19] was never published. The Hamburg work, continuing over many years, found an "almost permanently existing" [13] duct close to the water. Many thousand observations (1950-54) made on a weather ship in the North Atlantic, 1100 n mi east of Yarmouth, N.S., showed a duct height of at least 10 m 50 percent of the time in summer and 79 percent of the time in winter [7]*. A duct height of 10 m is sufficient to make a very large difference (as compared with so-called "normal" propagation, characterized by the 4/3 ear... in the propagation loss between the ALCOR antenna and an RV ... a comparable height and at a range of 25 or 30 km.

An important aspect of the Hamburg group's work was its finding that duct height and strength can be assessed from a small number of meteorological observations, namely the water temperature at the surface and, at some chosen height such as 4 or 10 m, the wind velocity, the air temperature, and the humidity [8,12,20]. Over open sea, height of the evaporation duct is fairly uniform over a radius of 50 km or more [11,11a].

*H. Booker (Quarterly Journal of the Royal Meteorological Society 74, 277-207 (1948)) on the basis of experience with propagation over the English Channel and the Mediterranean, speaks of a positive correlation between ducting and fine weather. However, Brocks [7], in the text and also in the legend of a graph, states that the evaporation duct at the cited weather ship was found less frequently in summer than in winter. For Katzin et al. [3], low path loss was associated with high wind.

Jeske [12,13], using an overwater path from Heligoland to the German Coast, made extensive observations on propagation loss in its relation to duct thickness, as estimated by the method just mentioned. With a transmitting antenna at 29 m and a receiving antenna at 33 m, he found at 7 GHz that the propagation loss over a 77-km path diminished by 50 to 60 dB as the duct height increased from 2 m to 17 m. The increase in dB was about linear with duct height. When the duct was at the "critical height" of the Booker-Walkinshaw mode theory of ducting [21], the propagation loss was only about 5 dB more than if the antennas had been at the same separation in free space. With that duct height, lowering the transmitting antenna to 6 m made no appreciable change in the transmission loss. The same was true when the duct height was less than 2 m; then, propagation over the tropospheric scatter path may dominate. With intermediate duct heights, the path loss was as much as 15 dB more when the transmitting antenna was in the low position. The observed path loss was nearly always greater than the loss calculated from the Booker-Walkinshaw Theory; Jeske ascribes the discrepancy to turbulence within the duct and to roughness of its lower boundary, the water.

Separately reported [10] work, using essentially the same path and antenna heights ("about 30 m") gives the statistical distribution of field strengths during September to November, 1957.

At 6.8 GHz, the level calculated from diffraction over a 4/3 earth was exceeded by 45 dB, or more, during 30 percent of the time.* At 2.3 GHZ, the 45-dB enhancement over the 4/3-earth level occurred only 8 percent of the time. For an "observed" (i.e., calculated from the four meteorological parameters cited above) duct height of 10 m, Jeske and Brocks observed [13] an enhancement of 30 to 50 dB at 6.8 GHz, but only 20 to 30 dB at 2.3 MHz; for a duct height of 15 m, the respective enhancements were 40 to 65 and 20 to 40 dB. The duct thickness was measured at the middle of the path; the dB values refer to hourly medians of the field strength. Note that for these data, the antenna heights exceeded the duct height.

Another extensive program has been that of Richter and Hitney at the Naval Electronics Laboratory Center, San Diego [22]. Of particular relevance to our problem are measurements of basic transmission loss (path loss) on a 34-km overwater path between the islands of Naxos and Mykonos (latitude 37° N) in the eastern Mediterranean. Each measurement period lasted two weeks, and there was one during each of the four seasons of

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*Here the 4/3-earth result has value as a fiducial level, but in the absence of ducting, tropospheric scatter would frequenctly reduce the loss to less than the 4/3-earth amount; at 6.8 GHz the median difference would be on the order of 10 dB, and the same would be true at 2.3 GHz.

1972. At 9.6 GHz, the transmitting antenna was 4.5 m above mean sea level. Receiving antenna heights were 19, 9.6 and 4.9 m above mean sea level. For the low antenna, the eyeball-average transmission loss was less than the (4/3)-earth value by 35 dB in February, by 50 dB in April, 60 dB in August, and 30 dB in November.

During the February fortnight, the signal levels at the high and low antennas were about the same, namely 0 to 20 dB below the value calculated for transmission through free space. In April, field strengths at these two antennas were approximately equal, though higher at the low antenna when the ducting was strongest. For 80 percent of the time, the path loss to the high antenna was less than the free-space value.

In August, the signal at the high antenna averaged at about the free-space value, and that at the low antenna exceeded the free-space value more than 90 percent of the time. The larger signal at smaller elevation is an indication that the duct height is large enough (~ 10 m) so that the lowest guided mode is completely trapped. During this fortnight, the signal level at the low antenna averaged 60 dB more than the value calculated from diffraction on a 4/3 earth. In November, the signal at the high (19 m) antenna approximated the free space value about a third of the time, and was lower the rest of the time. When that one was low, the signal at the low antenna was lower; in fact, for about eight hours out of the two weeks, the signal at the low antenna dipped below the 4/3-earth value. Except for a few minutes in February, this was the only time in 53 total days of observation that the propagation was not above the 4/3-earth value, which therefore was exceeded 99.6 percent of the time the experiment was running.*

Richter and Hitney [22] did a similar but less extensive experiment over a 27-km path from Key West to another key, for two weeks in May 1972. They describe the ducting as "very persistent," and found the observed path losses to be "well correlated" with path losses calculated on the basis of meteorological measurements. From long-term meteorological data, the authors concluded that the ducting during the rest of the year is likely to be similar to what they observed in May. For the reason given above, it is significant that 60 percent of the time, the signal was stronger at the lower antenna; this is an indication of strong trapping, from which it can be inferred that the propagation loss was not much different from a free-space loss. It is to be expected that this experiment at 9.6 GHz near Key West should find strong trapping more frequent than did the Hamburg group, using lower frequencies at higher altitude;

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*On this short (34-km) path, tropospheric scatter can be ignored; a calculated median value for the tropo-scatter signal is 30 dB weaker than the signal over a 4/3 earth.

it seems [20,24] to be generally true that evaporation ducts of an assigned height occur more often in the tropics than they do in the temperate zones.

There have been a few observations on the effect of the evaporation duct at frequencies above 10 GHz [5,22,23]. The results of Pigeon [5] at K_a band were inconclusive. Richter and Hitney [22] tested at 18 and 37.4 GHz during the November phase of their experiment over the Mediterranean. At 18 GHz, the signal level exceeded the free-space level about 40 percent of the time, against about 25 percent for 9.6 GHz during the same hours. This result is suggestive of an evaporation duct that was frequently less than about 10 m high [21]. At 37.4 GHz, this signal during those two weeks never reached the free-space level (even after a correction for absorption in the atmosphere), but most of the time it was 50 to 60 dB higher than the 4/3-earth value. The authors conclude [22] that "the evaporation ducting effect appears to have a broad maximum in the 10-20 GHz frequency range."

Hitney has developed a mathematical model for calculating the effects of evaporation ducting, using mode theory as developed by Budden [25] and numerical values derived from the work of the Hamburg group. It includes provision for roughness of the water. He presents [26] results calculated for 1,3,9.6,18, and 37.4 GHz using a 35-km path and a transmitter height of 4.9 m; this geometry replicates that of the Mediterranean experiment. The calculations yielded a propagation loss as a function of height of receiving antenna, with duct height as a parameter. The summary that follows is selective, concerning itself with situations that have a close relevance to conditions at KREMS. The cited calculations assumed smooth water.

When the duct height is 23 m, for 1.0 GHz the path loss at all heights less than 30 m is 10 to 12 dB less than it would be for a 4/3 earth; at low (7 to 1 m) target heights, the duct just about doubles the range at which a given target can be detected. Figure 2 shows that for 3.0 GHz, that same duct, which is a rather high one, reduces the loss to that in free space as long as the receiver or target height is at least 15 m. At 1 m, the ducting reduces the path loss by 40 dB. Again with the same duct, but for 9.6 GHz, the signal enhancement by the duct (Fig. 3) is only 5 dB at a height of 30 m, but it grows to 70 dB as the height drops to 3 m; the signal is then 15 dB above its free-space value, and at 1 m it is 10 dB above free-space and 75 dB above the 4/3-earth value. Note that these are one-way losses. The polarization is horizontal. A more frequently encountered duct height might be 6 m. This height would give a scarcely noticeable enhancement for 1.0 GHz, about 3 dB for 3.0 GHz, and for 9.6 GHz about 15 dB for heights of 3 to 1 m.

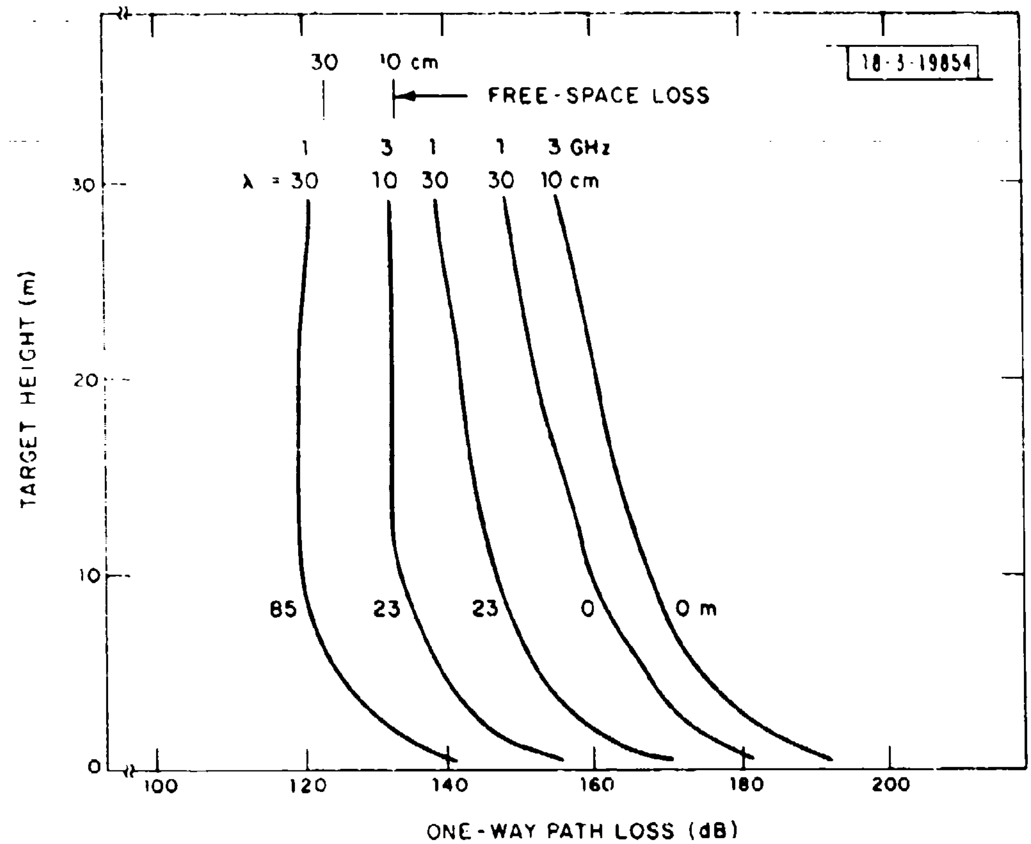

Fig. 2. Calculated path loss for 10-cm and 30-cm radiation as a function of target height, when the radiator is 4.9m above the sea and the range is 35 km. The parameter is the height of the evaporation duct; ticks denote the path loss through 35 km of free space. The calculations for zero duct height are for the ground wave on a 4/3 earth. Calculations by H. V. Hitney, graph redrawn from Figs. 7 and 8 of [26].

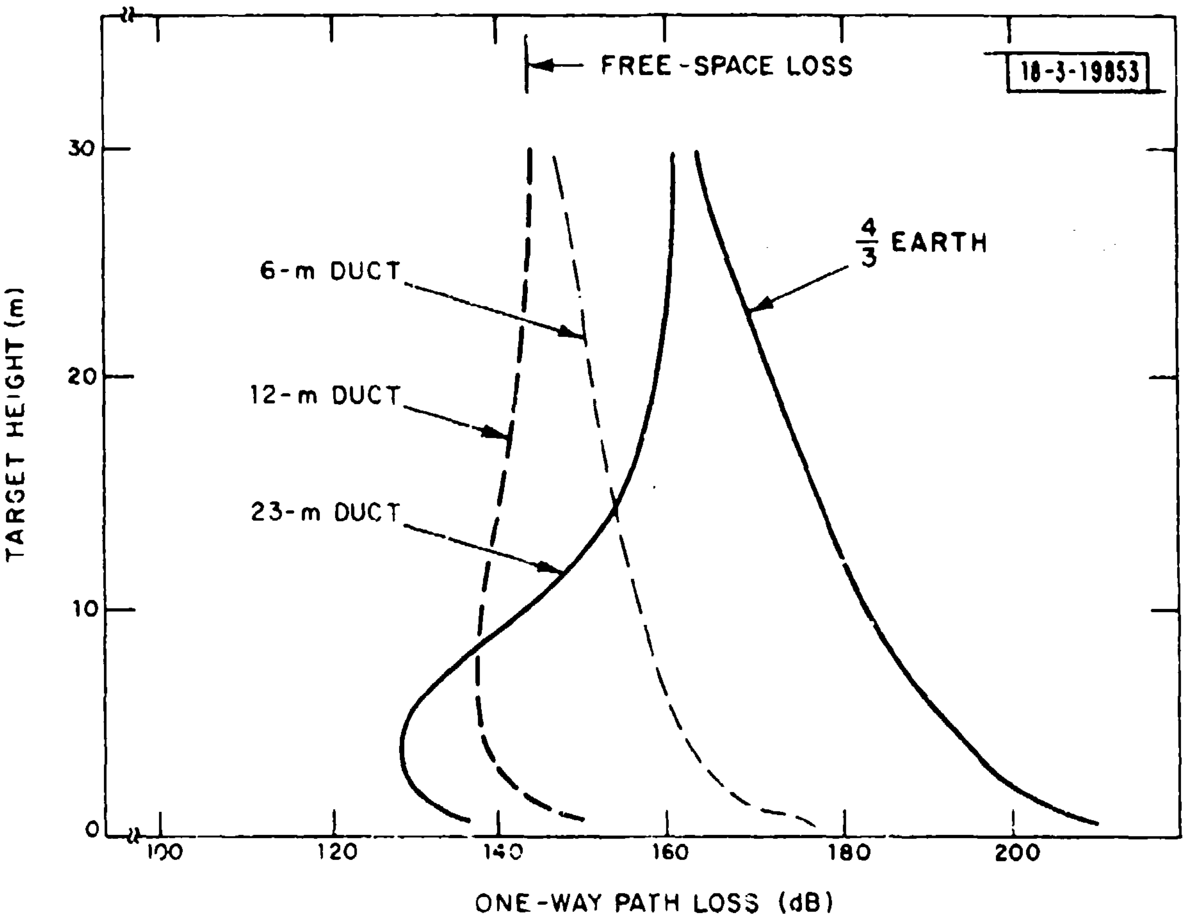

Fig. 3. Like Fig. 2, but for λ = 3.1 cm. Calculations by H. V. Hitney, graph redrawn from Fig. 9 of [26].

Hitney has communicated to us a distribution of duct heights in latitudes 30° - 40° N off the West Coast (Marsden square 120), calculated from more than 16,000 sets of meteorological observations made at the surface in all seasons. The duct height exceeded 6 m 82 percent of the time and 24 m 20 percent of the time. Similarly, 453 sets of observations made from vessels in the Aegean Sea show heights exceeding 6 m 91 percent of the time, and 24 m 35 percent of the time. The cumulative distributions are plotted as Figs. 4 and 5; note that over a considerable range, they are lognormal.

It is important to know how the duct height needed for trapping depends on wavelength.* Even for the first mode, which is all that we need to be concerned about, because it has the smallest loss, there is not a simple relation between wavelength and the duct height needed for full trapping. However, here we do not require elegance or generality. We can settle, at present, for a way of applying the data in the literature, taken at various wavelengths, to the radars at Kwajalein, which use other wavelengths. Since only a small part of the spectrum is strongly influenced by the evaporation duct, we

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*Logically, it would be preferable to use frequency, but our theory is not refined enough to be influenced by the changes in wavelength caused by the meteorology.

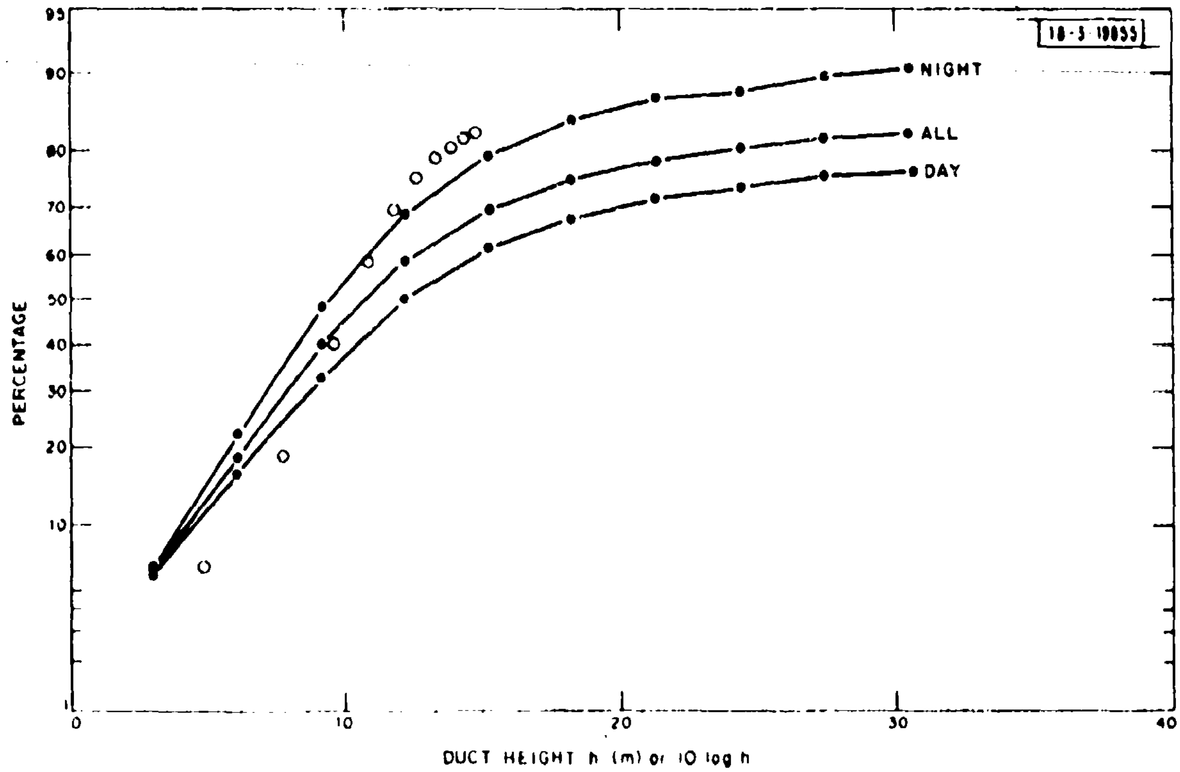

Fig. 4. Cumulative distributions of duct heights and their logarithms, calculated by H. V. Hitney from meteorological readings off southern California and Lower California. For the circles, the abscissa is 10 times the logarithm of the height; if the distribution were lognormal, the circles would lie on a straight line. Data from H. V. Hitney, by private communication.

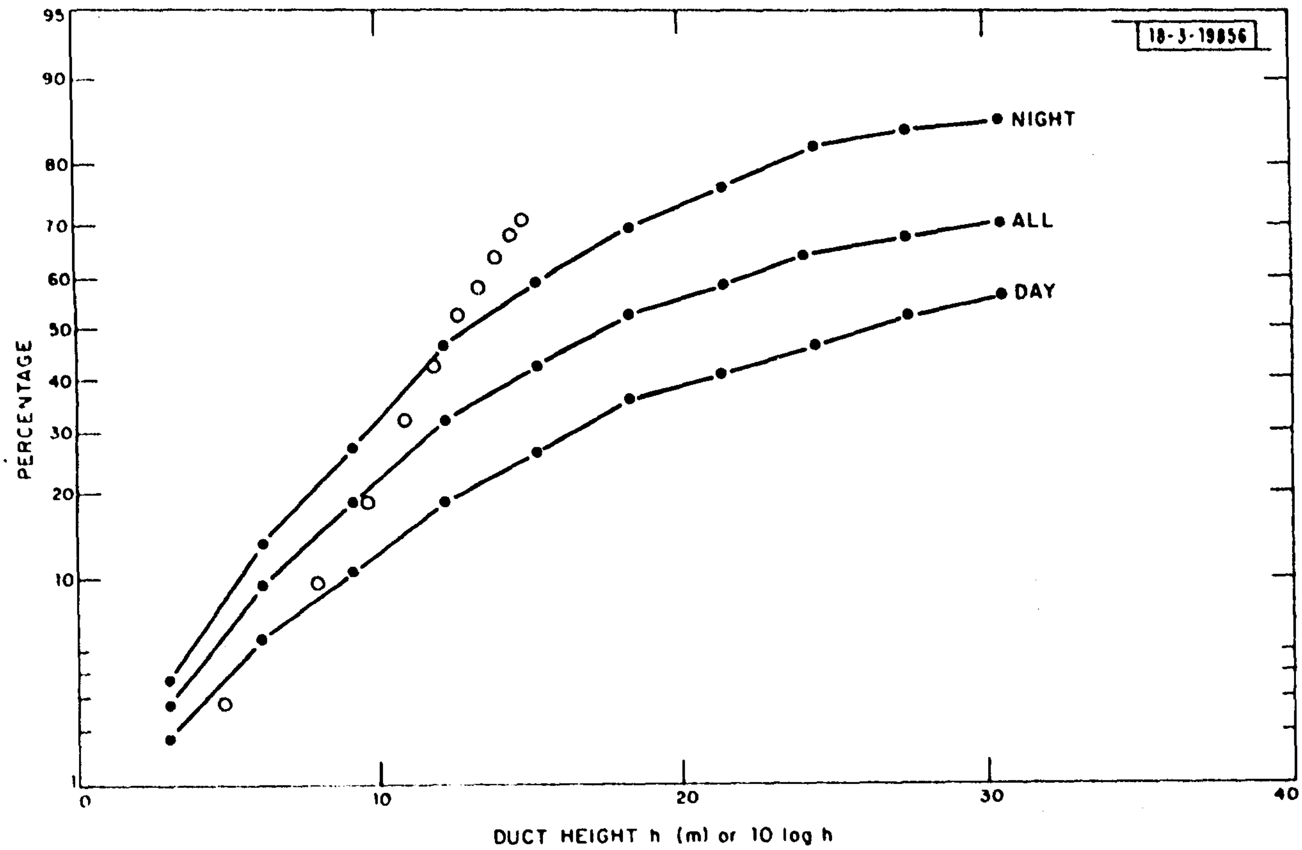

Fig. 5. Like Fig. 4, except that the meteorological readings were made by ships at various places in the Aegean Sea. Data from H. V. Hitney, by private communication.

are concerned with only a narrow range of wavelengths, and we can seek empirically a power law.

Figure 3a of [12] shows transmission loss of the first mode as a function of duct height, on the basis of the Booker-Walkinshaw theory [21], for several wavelengths 1.8 to 53 cm. The path length is 77 km; the transmitting antenna and the field point are 30 m above the sea. Full ducting in the first mode is indicated by a minimum in the loss.

In Figure 6, Jeske's heights for full ducting are plotted against wavelength.* It is seen that they are well fitted by the curve $z_d = 250\ \lambda^{0.90}$, where z_d is duct height for full trapping of the first mode, λ is wavelength, and both quantities are expressed in meters. To test the extent to which the $\lambda^{0.90}$ relation is valid for other heights and ranges, we can try relating it to Figs. 2 and 3, where the range is only 35 km and the transmitter height is 5 m. From those figures, one can estimate the height of a duct such that the loss to a field point 10 m high is equal to the loss over 35 km of free space. Jeske's curves [12,Fig. 3a] show that full trapping, with his geometry, gives a loss nearly equal to that

*Jeske's curves are reproduced in a larger size in R. Spellauge, Elektromagnetische Streckmessungen im Radiosicht - und Überhorizontbereich über See, Lehrstuhl für Topographie und Kartographie an der Technischen Universität Hannover, Hannover 1972. Figure 6 uses data scaled from these enlarged curves.

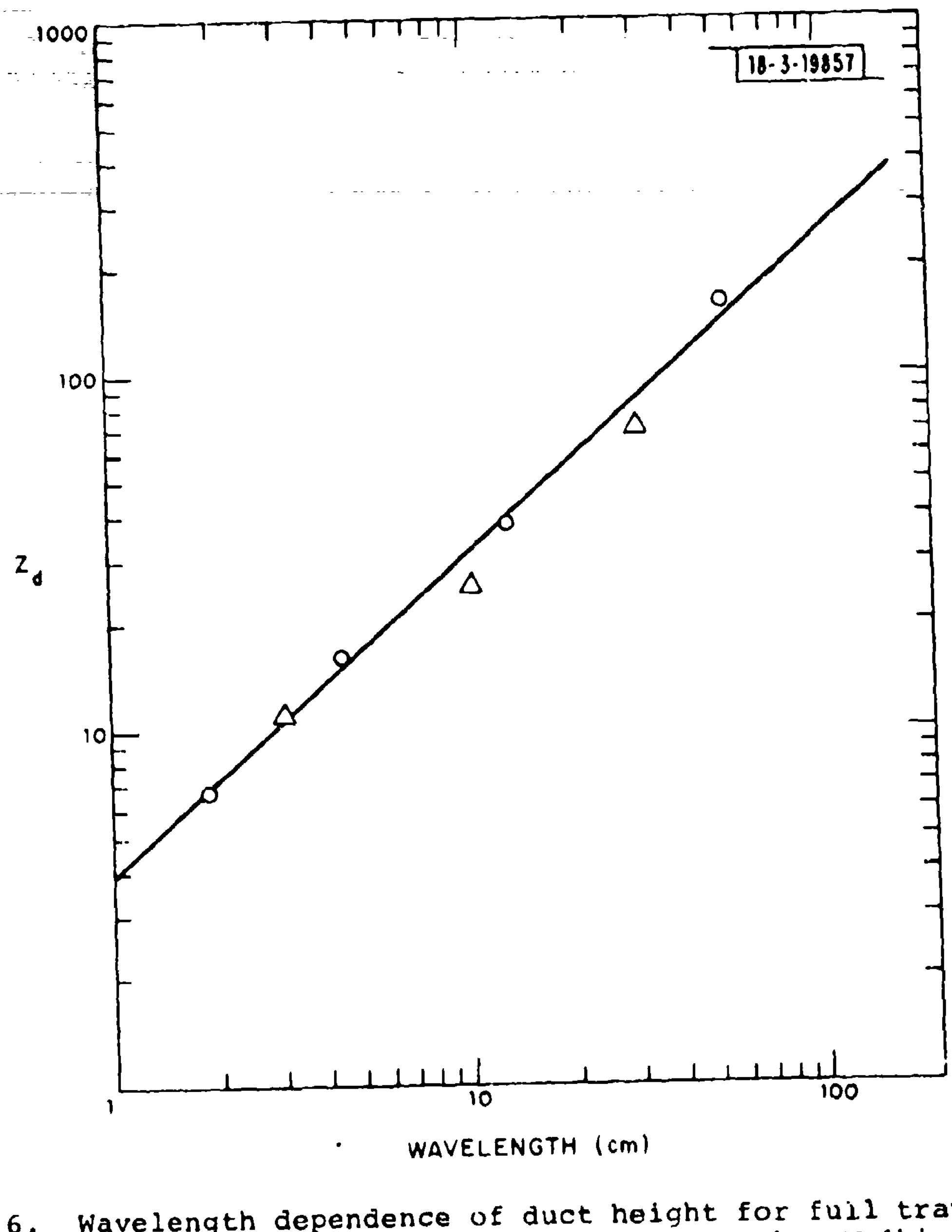

Fig. 6. Wavelength dependence of duct height for full trapping. Circles, calculations by Jeske [12] based on Booker-Walkinshaw theory [21]; triangles, estimates from Hitney calculations, Figs.2 and 3, of duct heights for transmission loss equal to that of free space. Line, $z_d = 250\ \lambda^{0.90}$. The ranges and antenna heights, different for the two sets of points, are specified in the text.

through free space, when λ is in the range 4 to 10 cm; when $\lambda >$ 10 cm, the free-space loss is reached with ducts somewhat too low to give full trapping. The triangles in Fig. 6 are points read from Figs. 2 and 3. Despite the differences in geometry and some differences in the assumed shape of the humidity profile, the points taken from Hitney's calculations conform sufficiently well to the 250 $\lambda^{0.90}$ curve so that we can use that relation to make allowance for the influence of wavelength, with confidence that the wavelength dependence is not very sensitive to range or antenna height.

Another important consideration is the comparison of path losses calculated from meteorological data with path losses actually measured. An extensive study of this question by Jeske [12] is summarized by Jeske and Brocks [13]. The situation is not clean-cut: when the duct is low, the ducted signal may be overridden by a signal arriving over a tropo-scatter path; furthermore, advection may bring in a high duct ("anomalous propagation") that is not evident from the observations made near the surface to find the height of the evaporation duct. To some extent, these complications can be detected, when present, by their effect on the rate and depth of the fluctuations in signal level. Even when they are absent, the received field is not steady; Jeske and Brocks use as data points the hourly median of the logarithm of the level. When plotted against duct height, and in the seeming absence of large contributions by other propagation models, the hourly median levels at 6.8 GHz show a spread on the order of ± 10 dB, and even the higher points are below the curve based on Booker-Walkinshaw theory and a simulated refractivity profile cho .. ` be analytically manageable. As an explanation, Jeske anc . .s note that the theory does not take into account any scattering by inhomogeneities in the duct, or any effect of roughness at the bottom and top of the duct. The spread in signal level with given duct height is not surprising, because the ducts provided by Nature surely do not all have the same refractivity profile, even when they have the same height; use of a single parameter to characterize a phenomenon as complex as an evaporation duct can succeed in a limited way at best*. However, practically all of the observed signal medians at 6.8 GHz fall below the level given by the theory. Such is to be expected if roughness of the duct boundaries is diminishing the signal, but roughness seems not to be the whole story, because

*As was mentioned earlier, the important parameters of a smooth, homogeneous evaporation duct are its height, its strength, and curvature of the refractivity profile at the top of the duct. The various mode-theory calculations have used one-parameter refractivity profiles; choosing the duct height fixes implicitly the strength and the curvature. An interesting plot by Jeske [27] demonstrates that the transmission loss is only weakly correlated with the change in refractivity between air just above the water and the air 6 m higher; that ΔN is not a useful parameter for assessing the effect of the duct.

at 2.3 GHz, where the boundaries were smoother relative to the wavelength, the agreement between the data and the theory was no better [13]. At any rate, the observed signal medians at 6.8 GHz, with duct heights of 10 to 15 m, are 10 to 20 dB below the values given by the theory. This shortcoming may arise at least in part from the function used to describe the shape of the duct, given the duct height. The function (Booker and Walkinshaw's "fifth-root profile" [21]) was chosen for mathematical tractability as well as for probable resemblance to the real duct profile.

The work of Richter and Hitney [22,26,28] also provides a comparison of calculated and observed signal levels. During the November 1972 experiment over the Naxos-Mykonos path, meteorological observations specifically for the determination of duct height were made hourly during the fortnight, and the calculated heights are reported in Fig. 149 of [28]. Figures 99 and 100 of the same report give continuous records of the measured path loss, one for antennas at 10 and 5 m above the water, and the other for antennas both at 5 m. The present author has combined the two kinds of data* to produce Figs. 7 and 8.

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* In place of Fig 149 of [28], the author has used duct-height data calculated by an improved program and supplied by J. V. Hitney (private communication).

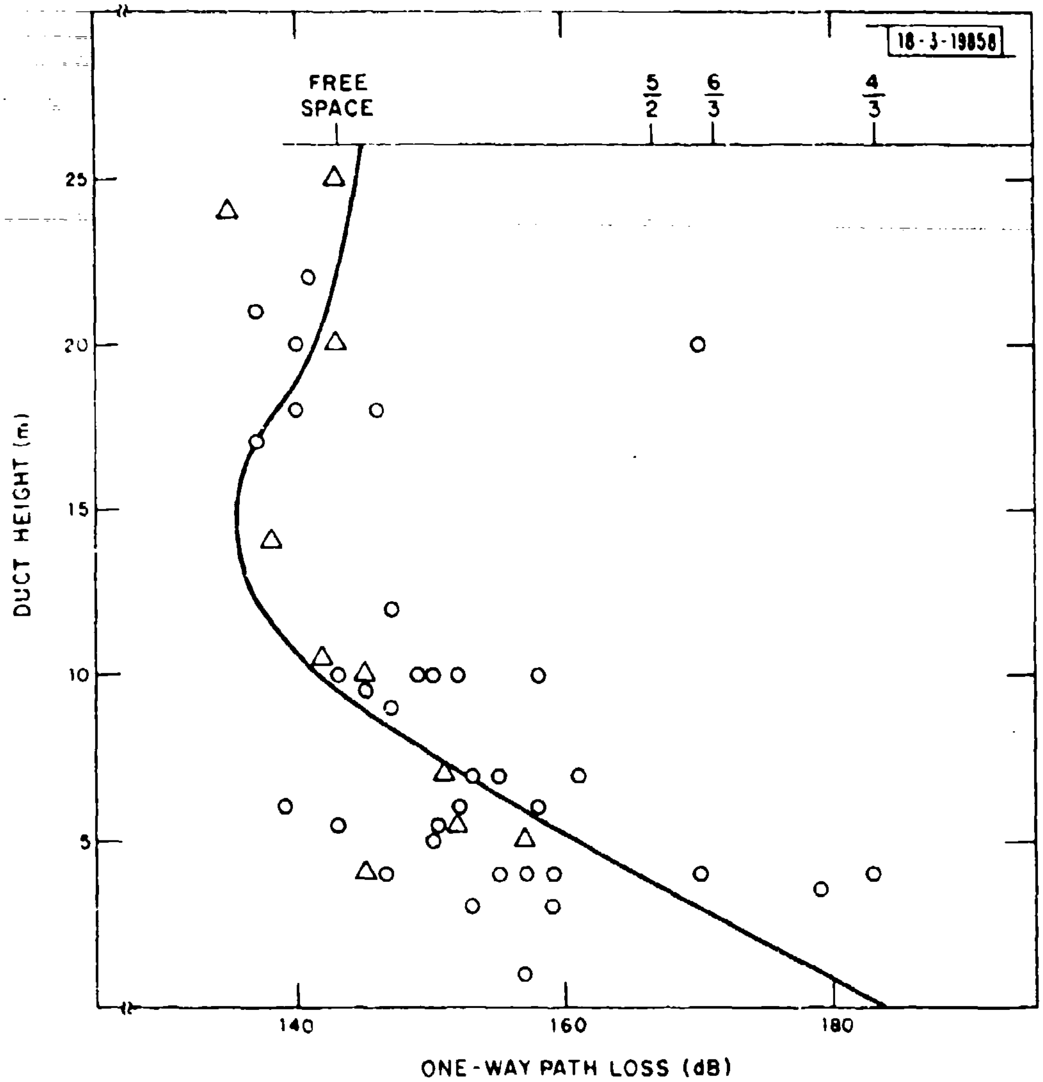

Fig. 7. Transmission loss for 9.6 GHz on a 35-km path, as a function of duct height, The transmitter is 10 m above the water, and the receiver height is 5 m. The curve, calculated from the mode theory, is redrawn from Fig. 14 of [26]. The circles are for pseudorandom times during the Naxos experiment by Richter and Hitney [28]; the points marked by triangles are similar except that the times are selected so that neither variable is changing rapidly. Pips show the amount of loss over a diffraction path using earth factors of 4/3, 6/3, and 5/2, another marks the free-space loss.

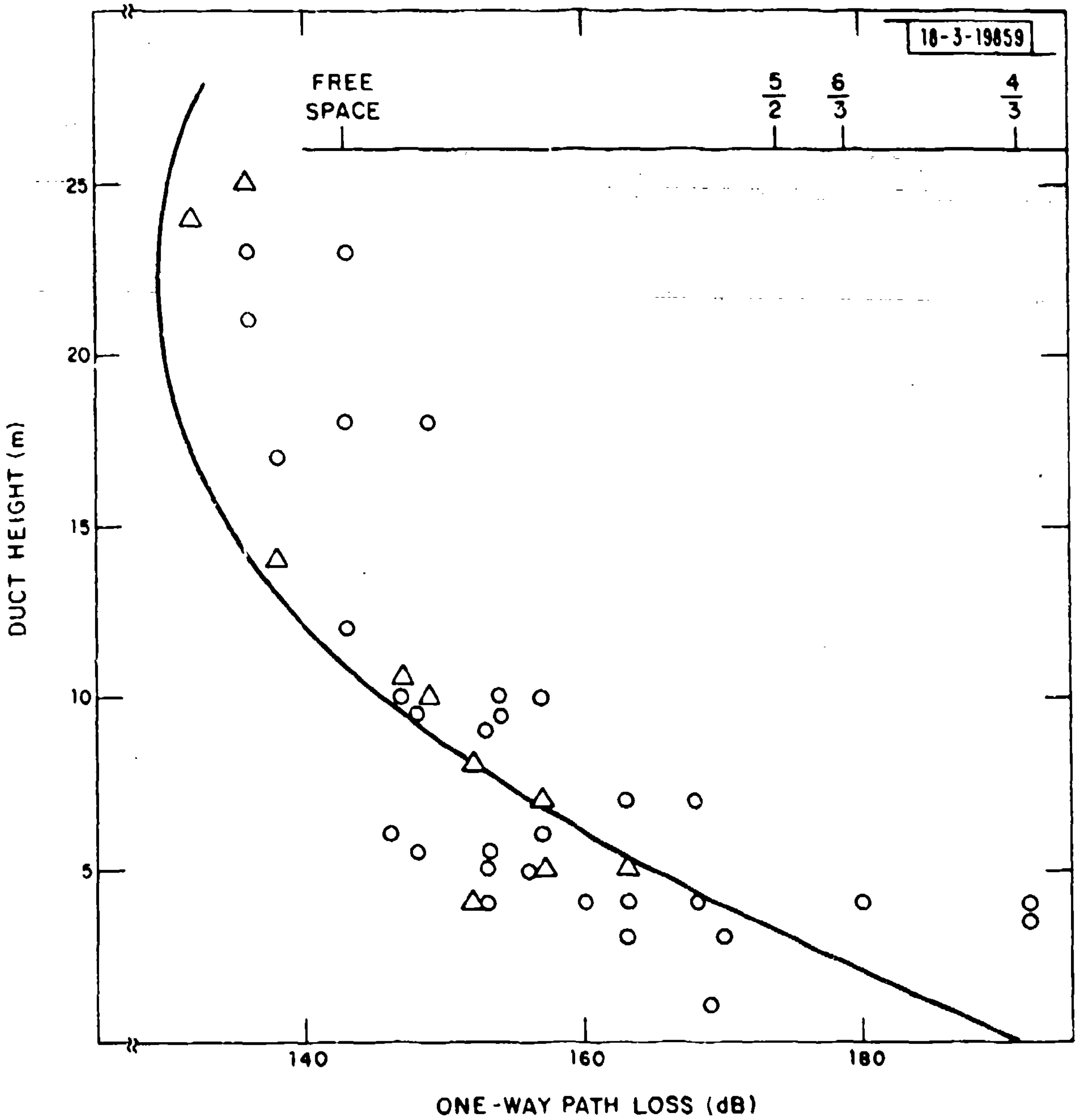

Fig. 8. Like Fig. 7, except that both stations were 5 m above the water. Path loss from Fig. 100 of [28], duct height as function of time supplied by H.V. Hitney (private communication).

The two-week time line of the continuous records was marked at times distributed randomly at intervals of about 4 to 12 hours, to spread the times over the two weeks while avoiding periodicity. For these times, the duct heights and path losses were paired and plotted as circles in Figs. 7 and 8. The curve in each figure shows Hitney's calculated path loss, redrawn from Fig. 14 of [26].

At many of the times, one of the variables was in rapid change; sometimes, both were. Since it seems improbable that a change in duct height would occur over the whole path at the same instant, the circles do not constitute a strong test of the relationship between the variables. In an attempt to improve on the test, ten other times were chosen, such that neither the duct height nor the path loss was changing rapidly. The results are plotted as triangles in Figs. 7 and 8; these points cluster closer to the calculated curves than the random samplings do. If instead of using 4/3 as the earth-radius factor the calculations had used 6/3, which is almost certainly a better choice for an overwater path in the tropics [6,29], agreement near the foot of the curve, where the duct height is zero, would be even better; the upper part of the curve would be essentially unaffected.

Because the effect of a low evaporation duct can be masked by other phenomena (including an advection duct and -- probably only rarely in Hitney's configuration -- tropospheric scatter) a good deal of spread in the measurements is to be expected when the duct is low. At duct heights larger than about 6 m (corresponding to about 10 m for ALCOR's wavelength), the measured transmission losses were usually greater than the calculated values, though on the whole the differences were smaller than in Jeske's work [13]. A distinction between the two sets of calculations is that Hitney used a "log-linear" profile of refractivity, which is thermodynamically realistic, whereas Jeske used Booker and Walkinshaw's "fifth root" profile, a convenient approximation.

Even Hitney's calculations appear in Figs. 7 and 8 to understate the path loss when the duct is higher than about 6 m, which would transform to about 10 m for C band. Possibly the larger errors at the lower station (Fig. 8) are associated with roughness of the lower boundary of the duct. Though it may be necessary to make an allowance for effects that the calculations do not take into account, it is clear that Hitney's method is in close touch with reality; it can be employed with confidence in assessing transmission loss in the duct at Kwajalein.

IV. IMPLICATIONS FOR ALCOR

The review in Section III establishes that in the North Sea there is at nearly all times an evaporation duct high enough to have a significant effect on transmission loss at 7 GHz, and that among the Greek islands, the evaporation duct is so strong that during a large part of the year, transmission of 9.6 GHz over a 35-km path at very low altitude is approximately as good as, or better than, transmission over the same distance through free space. The same was true at 9.4 GHz over a 150-km path off Antigua [3], at latitude 17° N. There seems to have been no similar transmission study of evaporation ducting over open sea at latitudes as low as that of Kwajalein (9° N), but one expects [20,24] the duct to manifest itself at least as strongly there as at higher latitudes.

For this report, H. Hitney of NELC has graciously supplied a print-out of duct heights derived from meteorological data collected in Marsden square 59, a land-free area east of the Phillipines, bounded by latitudes 15 ± 5° N, longitudes 135 ± 5° E. The distribution of duct heights for night and day in each of four seasons is plotted in Figures 9 through 12. The original tabulation gave the percentage of duct heights that fell into 10 foot intervals between 0 and 100 ft (30.4 m). Each distribution involved at least 2400 calculated heights. The curves show the percentage of the calculated heights that

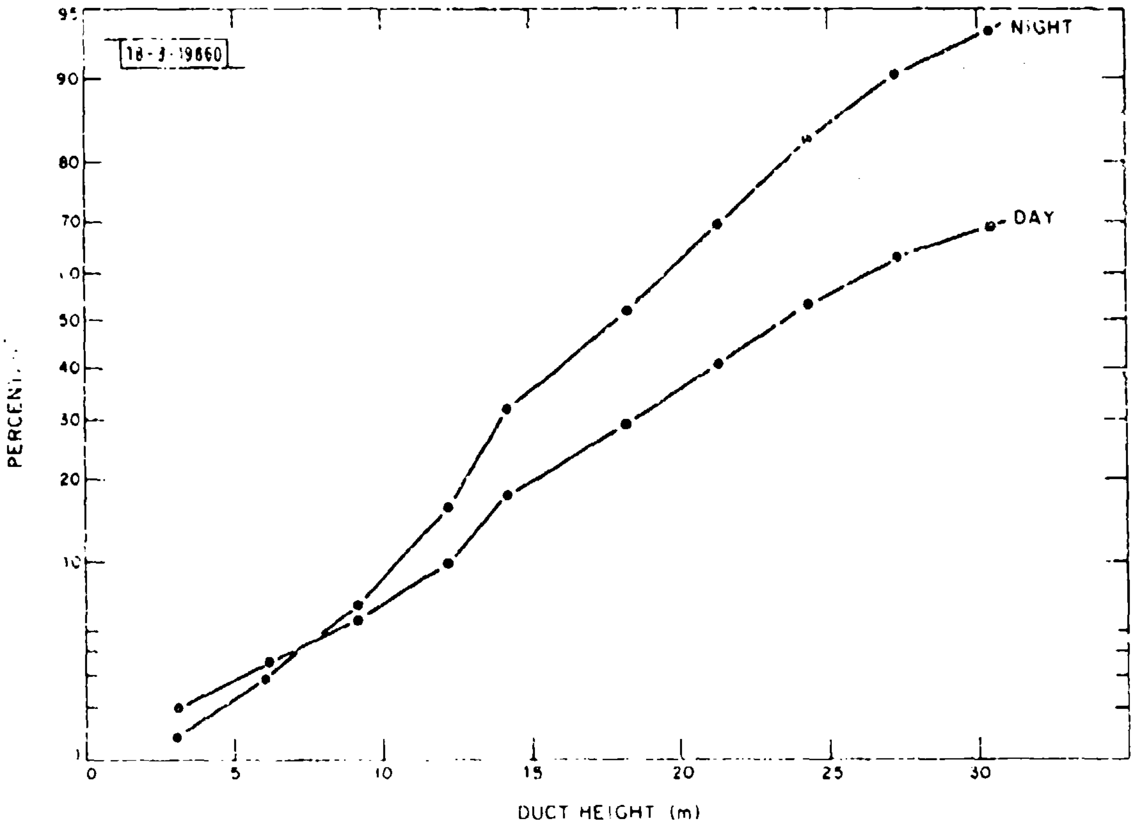

Fig. 9. Cumulative distribution of duct heights in Marsden Square 59, in the Phillipine Sea, winter months. Data furnished by H. V. Hitney.

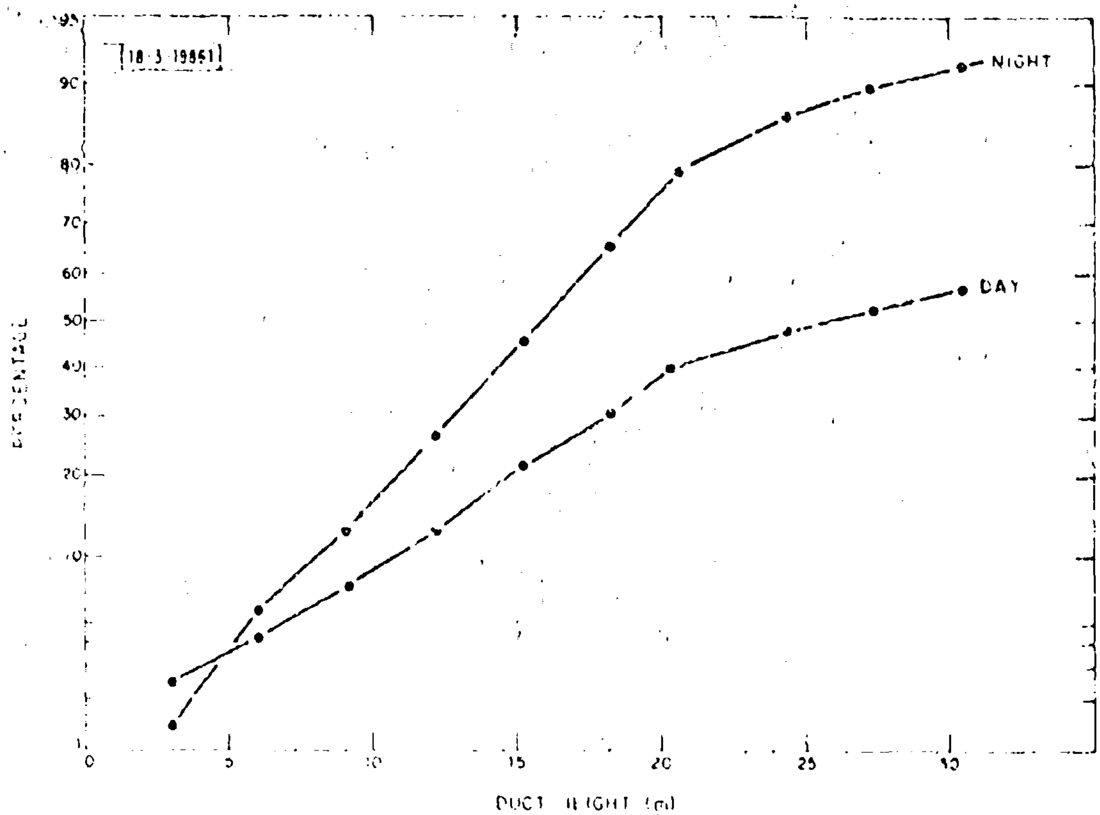

Fig. 10. Like Fig. 9, but for spring quarter.

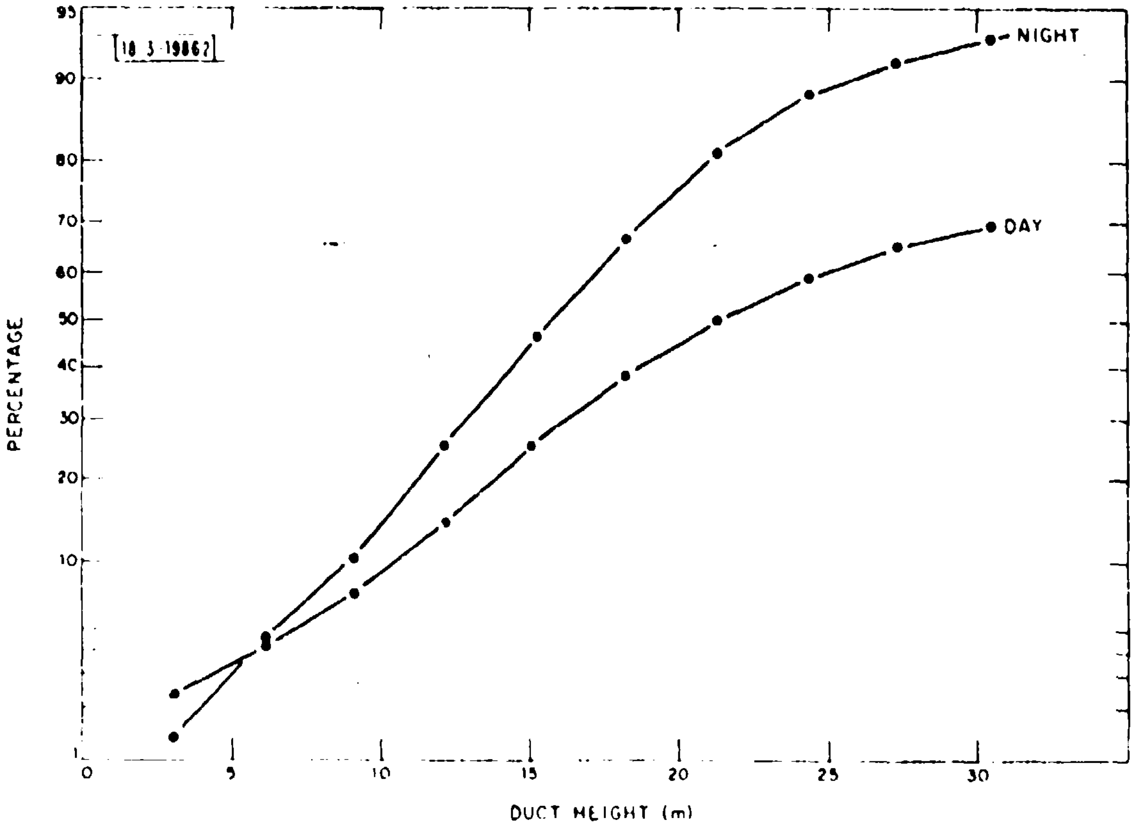

Fig. 11. Like Fig. 9, but for summer quarter.

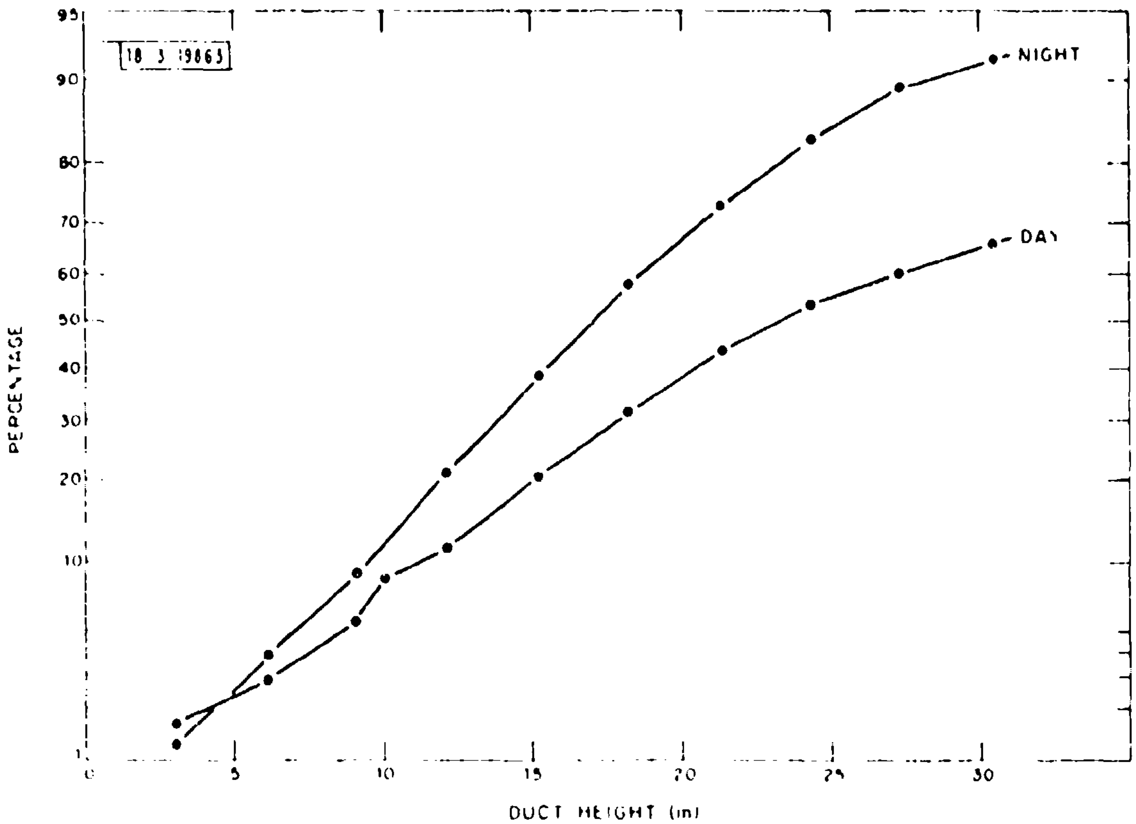

Fig. 12. Like Fig. 9, but for autumn quarter.

failed to exceed the abscissa. For example, on the winter days (Fig. 9), only 10 percent of the ducts were less than 12 m high; at night, the figure rose to 15 percent.

In autumn (Fig. 12), ducting was little different than in winter. The greatest difference came in summer (Fig. 11), when 14 percent of the daytime observations gave duct heights less than 12 m, and at night the figure rose to 25 percent.

The broad conclusion is that in a region not far from Kwajalein, the evaporation duct is more likely to be high at midday than at night, and that statistically autumn and winter provide more effective ducting than summer does. This dependence on season is strikingly different from that found on the Naxos-Mykonos link [22], where the propagation loss was on the whole lowest in summer and highest in winter and autumn. Recall that Brocks [7], over waters of the North Atlantic, found high ducts more often in winter than in summer.

We need a correlation between duct height and propagation loss at the wavelength of the ALCOR radar, 5.3 cm, over distances of interest for scoring. Figure 6 shows that for full trapping, the needed duct height is about 17 m. It would be an extravagance to demand a duct as high as that, because at the range that concerns us (c. 25 - 100 km) and for not-too-low stations within the duct, full trapping results in a path loss less than that through free space. It will be useful, though, to estimate the duct heights such that if Nature agreed with the calculations, the path loss between stations at 11 m (the height of ALCOR) and 5 m would be equal to that through free space. Figures 2 and 3 give path losses from a station at 5 m to one 35 km away and at a height given by the ordinate. Figure 2 shows that a 10-cm transmission from 11 m will be subjected to a loss equal to that of free space if the duct height is 23 m. From Fig. 3, one can estimate that for $\lambda = 3.1$ cm, the corresponding duct height is 11 m. These heights, 23 and 11 m, differ as $\lambda^{0.63}$; interpolating on that basis gives 15 m as the height which, in the given geometry, will result in a path loss equal to that of free space.*

Table I, derived from Figs. 9 to 12, shows the fraction of the time that the duct height in Marsden square 59, calculated from thousands of sets of meteorological measurements, exceeded 15 m. In daytime, the calculated loss between ALCOR and an RV at height 5 m and range 35 km is equal to that of free space about 80 percent of the time; at night, the percentage is in the neighborhood of 60. For longer ranges, free-space propagation spreads in three dimensions and fully ducted propagation spreads principally in only two. However, there is some

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*Proportionality to $\lambda^{0.63}$ here is not in conflict with the $\lambda^{0.90}$ relation inferred earlier in regard to duct height for full trapping. One difference is that the loss through free space is itself dependent on λ.

TABLE I

FRACTION OF THE TIME THAT THE DUCT HEIGHT IN MARSDEN SQUARE 59 (PHILLIPINE SEA), CALCULATED FROM METEOROLOGICAL DATA, EXCEEDED 15 M.

	Day	Night
Winter	80	65
Spring	79	56
Summer	75	55
Autumn	80	63

leakage at the boundaries of the duct. As a plausible working approximation, we can assume that in the 15-m duct, propagation loss and free-space loss are equal from 35 km out to 100 km or so, unless the duct height changes at some smaller range. In Section III, there was evidence that the duct height was often not constant over the 35-km path from Naxos to Mykonos. However, the sea there is much broken by islands, and Mykonos is only about 120 km from the Greek mainland. Moreover, the islands are higher than atolls; Mykonos rises to well over 300 m. The Bight of Heligoland more closely approximates the open ocean. There, Fengler [11a] found that the meteorological parameters from which duct height is calculated were closely correlated at stations 70 km apart. She had no findings for stations well offshore and farther apart than 70 km, such stations being not available. Given that Kwajalein is much farther from large land masses than is Heligoland, it is to be expected that the horizontal homogeneity of the marine boundary layer will be at least as extensive, i.e., that duct height near Kwajalein will be usually reasonably constant out to ranges on the order of 100 km. At high angles of elevation, such that the transmission path approximates free space, ALCOR has a single-hit signal-to-noise ratio (S/N) of 63 dB on a cross section of 0 dBsm at a range of 100 km [30]. The discussion in Section III indicates good agreement between Hitney's calculations of path loss and the path loss observed on the Naxos-Mykonos path, when the loss is equal to that through free space. The environment of Kwajalein seems at least as favorable for successful calculation of path loss. Assume the following:

a) Hitney's procedure for calculating path loss as a function of duct height gives correct results for a 35 km path at Kwajalein when the evaporation duct reduces the path loss to that of free space;

b) Duct-height statistics are the same at Kwajalein as in Marsden square 59;

c) Our interpolation to the ALCOR wavelength is valid;

d) At the least favorable aspect angle, the target cross section is -20 dBsm.

e) The needed single-hit S/N at ALCOR is 18 dB.

Then it follows from Table 1 that in nearly 80 percent of daytime hours, ALCOR on a target 5 m above the water at 100 km range will have S/N 25 dB above what is needed. Even if our calculations here have overestimated the S/N by 10 dB or so, as seems possible from Figs. 7 and 8, for a target at 5 m there is a 10-dB margin for scintillation caused by rapid fluctuation in the loss through a duct [12]. Such fluctuations should be mitigated by the circular polarization.

Seeing the target in the duct is not the whole problem; it has to be tracked while above the duct. Though the criterion may be unnecessarily strict, we can suppose that the target has to be detectable at all parts of the trajectory down to 5 m. A program under development at NELC will calculate losses on paths to points in and above the duct. As this report was being completed, Hitney used that program to calculate some coverage patterns for ALCOR and for TRADEX. Because of troubles with the program, the results are incomplete, but as far as they go, they are believed to be reliable. The available patterns are reproduced in the Appendix. Figure A-4 shows that when the duct height is 15 m, ALCOR can follow -20 dBsm continuously as it descends to 5 m at ranges up to 130 km. A 20 m duct permits continuous tracking at a range of 170 km, but at that range with higher ducts, the increased trapping diminishes the signal strength at heights of a few hundred meters; the range at which the target is continuously detectable shrinks. Above a 25 m duct, the range for continuous coverage is about 40 km.

Other calculations by Hitney indicate that the range is 50 km when the duct height is 10 m, so a 50 km range on -20 dBsm 5 m above the water is available when the duct height is between 10 and about 24 m; in Marsden square 59, this happens about 55 percent of the time, averaged over all hours and seasons. In the 45 percent when the duct height is between 12 and 22 m, the range with continuous tracking is over 100 km. The percentages for specific seasons can be estimated from Figs. 9 through 12. Figure 13 gives the cumulative distribution without regard

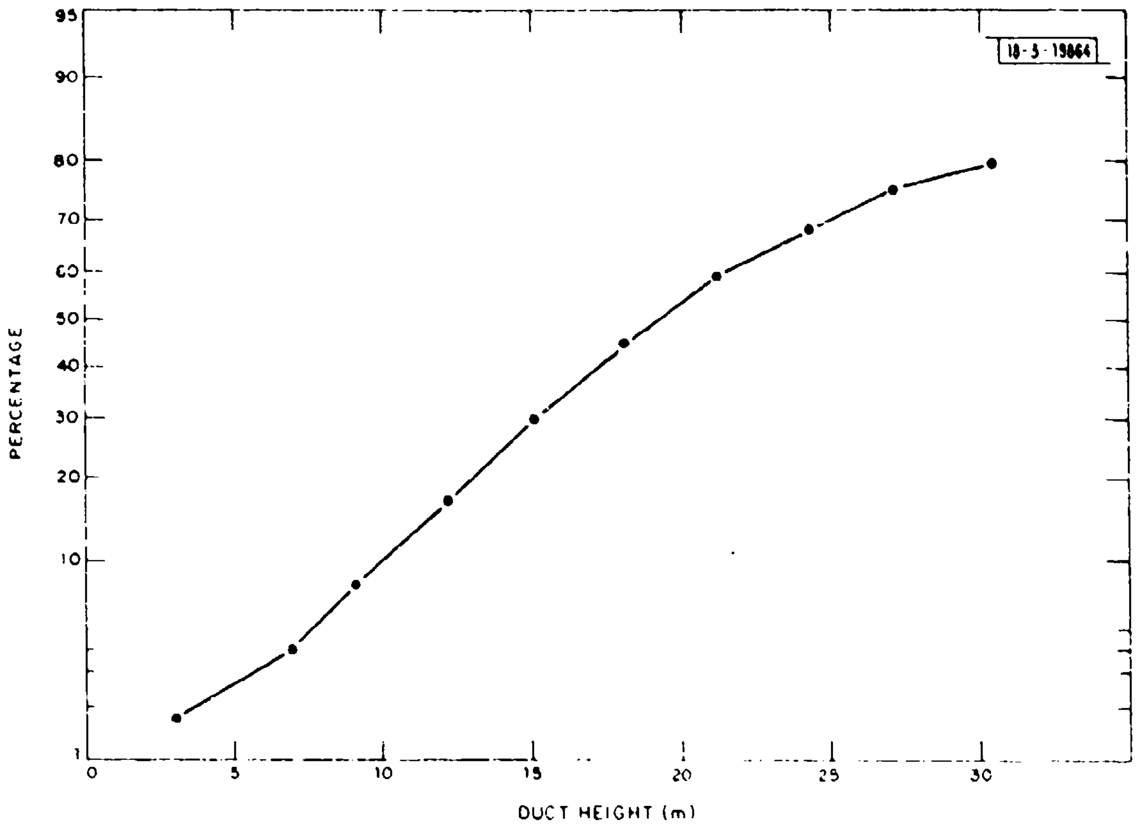

Fig. 13. Cumulative distribution of duct heights in Marsden Square 59, all hours, all months. This is a cumulation of all the data plotted in Figs. 9 through 12.

to time or season.

About 10 percent of all time, the duct height in Marsden square 59 is less than 10 m, implying a range of less than 50 km. To estimate how much less, consider what happens when the duct is too thin to be of any consequence at all. The one-way path loss that will give ALCOR S/N = 18 dB on -20 dBsm is 160 dB. On a 4/3 earth, the path loss to a target at 5 m above the water would have that value if the range were 26.5 km. However, recall from Section II that the 4/3 earth is a valid concept only when the lapse rate of the refractivity is constant with height and its reciprocal is 4.0 times the (true) radius of the earth. For the lowest kilometer of air over land in a temperate zone, that condition is approximated, to a useful degree, much of the time. Over the sea around Kwajalein, it is hardly ever a good approximation.

Investigations of the earth-radius factor for overwater paths by Gray [6] and Misme [29] were cited in Section II. The latitudes of the paths were about 43° N for Misme and 15° to 25° N for Gray. Because Kwajalein is at 9° N, Gray's region presumably resembles it more closely than Misme's does, and because of the lower latitudes, and the absence of large islands, one expects the earth-radius factor to be somewhat larger than Gray's. When it is 2.5, a diffraction calculation gives 33.5 km as the range at which -20 dBsm at a height of 5 m will result in S/N =

18 dB at ALCOR. Dropping the factor to 2.0 decreases the range to 31 km. For the range to be less than this requires an exceptionally low earth factor at a time when the duct height is less than 10 m. In Marsden square 59, the probability of just the latter condition is a little less than 0.1. The statistics of the earth factor are unknown, and whether the statistics of earth factor and ducting are correlated is also unknown. Consequently, all we can say with assurance is that the confidence level for a range of at least 30 km exceeds 90 percent.

To get an impression of the relation between range and horizon distance, we can note that for ALCOR, a target 5 m above the water is on the radar horizon when the earth factor is 2.5 and the range is 32 km; for earth factor of 2.0 and 4/3, the distances are 28 and 23 km. In all three cases, the range for S/N = 18 dB on -20 dBsm 5 m above the water is a couple of kilometers greater than the horizon distance. When the duct is high enough to have an influence, "radar horizon" and "earth factor" have no significance.

In summary, the expected range for ALCOR to achieve 18 dB on the reference target, with continuous tracking down to 5 m, is at least 30 km more than 90 percent of the time, at least 50 km 60 percent of the time, and more than 100 km nearly half of the time.

We need now to consider how the maximum range for continuous tracking depends on the radar cross section. The problem is simple when the duct height is very small or very large.

First, suppose that the duct height is negligible. A diffraction calculation is then appropriate. The ranges at which ALCOR can track a target down to 5 m on a 5/2 earth are given in Table IA.

Second, on the basis of Figs. A-1 and A-6, and other calculations of the same kind by Hitney, assume that when the evaporation duct is very strong, and there is no advection ducting, the detectability of a target above the duct is about the same as if there were no duct. Then the limiting range is the greatest range at which the target can be tracked down to about 30 m when the ducting is so low as to have no effect. These distances, for S/N = 18 dB and a 5/2 earth, appear in Table IA. The range limits in the table vary as the 20th root of the cross section when the ducting is negligible, and as the 30th root when it is strong.

With intermediate duct height, say 10 or 15 meters, copious leakage out the top of the duct helps ALCOR to see targets that are above the duct, but are well below where the radar line of sight would be if the duct were absent (Fig. A-4). In this region, the power incident on the target changes with range much faster than quadratically. Consequently, the limiting range with a given duct height varies much more slowly than the fourth root of the radar cross section, though for continuous tracking it surely is more sensitive to cross section than it is in the cases of negligible or strong ducting. On the basis of a plausible model of how the field above the duct varies with range and with duct height, the NELC IREPS program calculates transmission loss to points in and above the duct. Such calculations are the basis for the central column of ranges in Table IA, which shows an approximately tenth-root dependence of ALCOR range on cross section when the duct height is 15 m.

TABLE IA

RANGE LIMIT FOR CONTINUOUS TRACKING DOWN TO 5 M.

Cross Section	Negligible Ducting	15-m Duct	Strong Ducting
-30 dBsm	29 km	115 km	48 km
-20	34	135	52
-10	38	160	56
0	42	200	61

Because the ALCOR signal will be ducted so much of the time, a bothersome question arises in connection with the need for accurate ranging: When there is ducting, what is the signal velocity? Because dispersion in a waveguide is such that the phase velocity decreases as freqency increases, the signal velocity is essentially the same as the group velocity, which is

$$u = \frac{d\omega}{d\beta}$$

when the wave is written as $\exp[i(\omega t - \beta x)$.

Alternatively,

$$u = v - \lambda(dv/d\lambda)$$

where v is the phase velocity. It is implicit in the first equation, and explicit in the second, that the group and phase velocities are different when, and only when, there is dispersion, i.e., when the phase velocity is a function of frequency. In a waveguide consisting of two parallel and unbounded perfectly conducting planes, with separation d, the phase constant is

$$\beta_n = \sqrt{\omega^2 \mu\epsilon - \left(\frac{n\pi}{d}\right)^2}$$

where μ and ε are the permeability and dielectric constant of the interspace and n is an integer. If n=0, the phase velocity ω/β and the group velocity $d\omega/d\beta$ have the same value, $(\mu\varepsilon)^{-1/2}$. This "principal" wave, which is transverse electromagnetic, has no analogue when one of the bounding planes is a nonconductor, because for this mode the electric field must terminate on charge at each boundary. When n=1, there can be a transverse electric or a transverse magnetic wave between the conducting planes. The expression for β_n applies to both of them, and

$$\beta_1 = \sqrt{\omega^2 \mu\varepsilon - (\pi/d)^2}$$

The phase velocity v is

$$\frac{\omega}{\beta_1} = \left[\mu\varepsilon - \left(\frac{\pi}{\omega d}\right)^2 \right]^{-1/2}$$

and the group velocity u is

$$\frac{d\omega}{d\beta_1} = \frac{1}{\mu\varepsilon} \left[\mu\varepsilon - \left(\frac{\pi}{\omega d}\right)^2 \right]^{1/2}$$

which reduces to

$$u = v_o\left[1 - \left(\frac{\lambda_o}{2d}\right)^2 \right]^{1/2}$$

where $v_o = (\mu\varepsilon)^{-1/2}$ is the velocity that the wave would have if the medium were unbounded, in which case it would be, by hypothesis, nondispersive, and λ_o is the wavelength associated with ω in that case.

The wave guided between the plates can be decomposed into two ordinary waves traveling with the same velocity as in open space and zigzagging between the plates [31,32]. The angle of incidence at each face must be such that the standing wave formed by the reflection has a node at the other face, which means that its sine is an integer multiple of $\lambda/2d$, where d is the height of the guide. The last of the equations for u says that the group velocity of the wave in the guide is found from the velocity of the zigzag wave by taking its component along the axis of the guide. If $\lambda_o/2$ is nearly as large as d, so that the wave is near cutoff, then the group velocity can be much smaller than the velocity in the free medium; for example, if $\lambda = \sqrt{3}d$, then the glancing angle of the zigzag wave is 60^o, and the group velocity is half of the free-medium velocity.

For an atmospheric duct, the situation is more complicated; the constraints cannot be satisfied by a pair of zigzagging plane waves. Nevertheless, it is evident that the duct cannot modify the group velocity so strongly as a metal guide can. As a model, suppose that the index of refraction is 1 + N above the duct and 1 + N + ΔN in the duct, with a discontinuity at the interface. A wave making a large glancing angle at the top of a duct will go through it, but a wave in the duct will be totally reflected if the sine of the angle of incidence is greater than $(1+N)/(1+N+\Delta N)$, which is $1-\Delta N$. This is the cosine of the glancing angle, and if the two-zigzag-wave model were valid, the ratio of the group velocity to the velocity in the free atmosphere above the duct would be $1-\Delta N$. A meteorologically plausible value for the strength of a duct could be 10 N units, which would mean $1-\Delta N = 10^{-5}$. It therefore appears that the range error caused by the slowing down of the signal in the duct will be on the order of 1 in 10^5.

The rigorous theory of a horizontally polarized wave guided in a plane dielectric slab on a perfectly conducting base has been worked out by Kahan and Eckart [33], and their work has been used by Langenberg [34] for a calculation of signal propagation in the duct. He took the jump in refractivity at the upper surface of the slab to be 50,100 or 150 N units. For the first of these cases, the cutoff frequency is 7.5 GHz divided by the duct height in meters. Up to the cutoff frequency, the wave has the velocity that is characteristic of the upper half-space. Above cutoff, there is dispersion. By 1.5 times the cutoff frequency, the group velocity has dropped to the value it would have in the slab material if that were unbounded. At a little over twice the cutoff frequency, the group velocity is less than the velocity in the slab material by 1 part in 10^5, which means less than the velocity in the overlying half-space by 6 parts in 10^5. This is the minimum value of the group velocity; as the frequency increases further, the dispersion diminishes and the group velocity slowly rises, approaching asymptotically the velocity that is characteristic of the slab material.

The postulated refractivity jump of 50 N units makes a strong duct. For a duct with a lesser jump, the velocity differences just cited would be diminished. The calculations support the belief that the evaporation duct at Kwajalein will perturb the signal delay by one or a few parts in 10^5. The amount will depend, of course, on the height and strength of the duct.

Two concomitant effects that may be observable are worth mentioning. The first is that horizontal and vertical polarizations will have different velocities and different attenuations in passage through the duct. One can look for a change in the polarization ratio of the return from a sphere near the water. A second effect that must be present, at least in principle, is a perturbation of the shape of the compressed wideband pulse, because the dispersion during transit will alter the phase relations in the signal. If this effect is large enough, it can make a re-entry vehicle look like a more extended target, which might look like a splash though the RV was still in the air.

Because horizontal and vertical polarizations have different phase velocities in the duct, there will be a tendency for the duct to diminish the depths of the dips between the lobes produced by reflection from the sea.

One wonders about the effect of rain on the evaporation duct; on this topic, there seem to be no published observations, or even opinions.

V. IMPLICATIONS FOR TRADEX AND ALTAIR

TRADEX operates at 3.0 and 1.3 GHz. The distance to its geometrical horizon is greater than that of ALCOR, because the trunnion axis is 26 m above the water. Jeske and Brocks, on their 77 km path over the Bight of Heligoland, worked at 6.8 GHz radiated at a height of 29 m, 2.3 GHz at 28 m and 0.56 GHz at 35 m [12,13]. With receiving antennas at 31 ± 1 m, the enhancement of signal by 15 m duct was, roughly, 55 dB at 6.8 GHz, 20 dB at 2.3 GHz, and 5 dB at 0.56 GHz. Here "enhancement" is the difference between the signal level when there is a 15 m duct and the level when the duct is so low as to have a negligible effect. Lowering the receiving antenna to 6 m diminished the signal by roughly 12 dB at 6.8 GHz and also at 2.3 GHz [13]. The scatter of the data makes these figures uncertain by a couple of decibels, and the same is true of the enhancements, but here we do have values found in a straightforward way from copious experimental data taken at station heights close to those that are of interest for Kwajalein.

With the higher receiving antennas, the enhancements, in decibels, are nearly proportional to frequency. Linear interpolation on a log-log plot indicates enhancements of 27.5 dB at 3.0 MHz and 11.5 dB at 1.3 MHz. Jeske's experiments showed a 12 dB drop in signal when the transmitter antenna was lowered from 33 m to 6 m. To use this information, we need to know how much the diffracted signal would change if the antenna were lowered during a time of no ducting. We cannot tell from Jeske's data, because at 6.8 GHz they show no difference in the signal levels for zero duct height [13], which can be explained by assuming that at such times, tropospheric scatter dominated the propagation. He states [12] that the earth factor in that climate varies from 3 down to 1, or in rare cases even less, but that normally ("in Normalfall") it is 4/3; the 4/3 is well borne out by his plots of transmission loss vs. duct height when the frequency was 600 or 160 MHz (page 73 of [12]), though the evidence at 6.8 and 2.3 GHz is weak because of spread in the data on signal strength. On a 4/3 earth, lowering the antenna from 29 to 6 m would lower the 6.8 GHz signal by 22 dB. The observed lowering was 12 dB. The lowering therefore increased the enhancement at 6.8 GHz by 22 - 12 = 10 dB.

At 2.3 GHz on a 4/3 earth, the lowering would increase the transmission loss by 17 dB, and the observed amount was 12 dB, so with the low antenna the enhancement increased 5 dB. With the low antenna, the implied enhancements were 55 + 10 = 65 dB at 6.8 GHz, and 20 + 5 = 25 dB at 2.3 GHz.

With the high antenna, Jeske's three enhancements lie on a log-log plot of enhancement (in dB) vs. frequency. Assuming that the same is true with the low antenna, we find enhancements of 31 dB at 3.0 GHz (TRADEX S) and 15 dB at 1.3 GHz (TRADEX L) for stations at 32 m and 6 m above the water and 77 km apart, when the duct height is 15 m. For the 26 m and 5 m associated with TRADEX and our target, the enhancements -- to judge from some pertinent curves in [26] -- would be essentially the same as those given above for 32 m and 6 m.

A separate basis for estimation is [26]. Some of what is relevant appears in Fig. 2 of this report, but the original figures include curves for several other heights of duct, so that interpolation to 15 m is possible. One sees in Fig. 2 that for 3.0 GHz and station heights 5 m, 26 m, range 35 km, a 23 m duct reduces the loss to that through free space, namely 133 dB, which is 25 dB less than that on a 4/3 earth. Notice that 23 m happens to be the daytime median duct height in Marsden square 59. The family of curves in [26] includes one for a duct height of 8.5 m; by interpolation, one finds that a 15 m duct gives an enhancement* of 17 dB to the TRADEX S signal on a target 5 m

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*There is a semantic difference between "enhancement" as used here and as used earlier. There, the reference level was the propagation loss when the duct had zero height. At 77 km range and 6.8 MHz, that level was influenced by the tropo-scatter mode of propagation. Here the reference level is determined by diffraction over a 4/3 earth. In the present application, the difference is unimportant, because here we are dealing with lower frequencies, where the influence of tropospheric scatter on Jeske's data was much smaller, and he found that above the duct, the humidity gradient "in the normal case" was that of a 4/3 earth. Note also that at 35 km, the influence of troposcatter is much less than that at 77 km.

above the water at a range of 35 km.

There is also, in [26], a family of curves like those in Fig. 2 for 1.0 GHz (λ = 30 cm). Carrying out the same procedure for that frequency, we find an enhancement of 7 dB. Interpolating on log-log paper gives 8 dB as the enhancement for the TRADEX L (1.3 GHz) signal on the target just described.

Gathering these results together, we have TRADEX S one-way transmission enhanced by 31 dB at 77 km and by 17 dB at 35 km; whereas for TRADEX L the enhancements are only 15 and 8 dB, respectively. The estimates for 77 km are based on Jeske's measurements, and those for 35 km are based on Hitney's calculations. The enhancements are referenced to a 4/3 earth -- effectively, in Jeske's case, and explicitly, in Hitney's. From them, therefore, we can calculate expected path losses for the two distances when the duct height is 15 m. Table II displays the results. All that can be done by way of cross-check between the two different sources is to note that the enhancements based on Jeske are greater than those based on Hitney, and that this is appropriate, because at the larger distance, well beyond the horizon, the ducted field falls off more slowly than would the field diffracted over a 4/3 earth.

For S/N = 18 dB on -20 dBsm, TRADEX S, with the NB (narrowband) pulse, can tolerate a path loss of 156.5 dB. Table II leads us to expect a range of about 50 km when the

TABLE II

PREDICTED ONE-WAY PATH LOSS FOR TRADEX AT 3.0 AND 1.3 GHz OVER 35 AND 77 KM WHEN DUCT. HEIGHT IS 15 M. AND TARGET HEIGHT IS 5 M.

Frequency	Range	Loss On 4/3 Earth	Enhancement	Predicted Loss	Loss On 5/2 Earth	Loss On 6/3 Earth
3.0 GHz	35 km	158 dB	17 dB	141 dB	149 dB	152 dB
	77	217	31	186	189	197
1.3	35	153	8	145	147	148
	77	198	15	183	178	184

duct height is 15 m (i.e., about 70 percent of the time) and the target altitude is 5 m. Figure 2 shows that with such a duct, trapping is far from complete, and Figure A-12 in the Appendix, for TRADEX S with a 25 m duct, confirms that coverage at higher altitudes will not be reduced by a 15 m duct. With the WB pulse, the path loss for 18 dB S/N needs to be about 3 dB less; the expected range is about 3 km less than for the NB pulse. In about half of the daytime hours and one-third of all hours, the duct height in Marsden square 59 is at least 23 m. Figure 2 shows that the path loss at S band from TRADEX to a target 5 m above the water and 35 km away is equal to that through free space. Such strong trapping would result in a range of well over 100 km on a target in the duct. For scoring, the limit on range will be set by the need to track the target while it is above the duct. Figure A-12 shows that a 23 m duct has no great effect until the target has reached a height of about 400 m, and that there the range limit is about 130 km.

At L band, the L CHIRP pulse* can tolerate a one-way path loss of 148.5 dB for 18 dB S/N. Table II predicts a range of a trifle over 35 km on -20 dBsm at 5 m when the duct height is 15 m.

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*This pulse will be replaced by one with more bandwidth but the same energy; there will be no significant change in S/N.

However, for L band at Kwajalein, calculation of enhancement with regard to a 4/3 earth is not a good way to proceed, because a 15-m duct is only 65 wavelengths high, and the meteorology above the evaporation duct there is seldom that of a 4/3 earth. As was discussed in Section IV, the earth factor is a meteorological variable for which, in the Kwajalein region, a good representative value is 2.5. A column in Table II shows the one-way path loss if we use that earth factor and ignore the duct. A parallel column shows that if the earth factor at a particular time is 2.0, TRADEX L range estimates made on the basis of 2.5 will not be much in error, unless the duct is so high that the concept of earth factor is not applicable at L band.

Being able to ignore the duct and use diffraction theory to calculate range is a great simplification. Doing that, using an earth factor 2.5, one finds that TRADEX with L CHIRP has a calculated range of 37 km on -20 dBsm 5 m above the water, for S/N = 18 dB. About 70 percent of the time, the range will be at least a little more than that, because the influence of a 15 m duct, though not large, is not negligible. Especially in the daytime, higher ducts, with larger effect, will sometimes be present. Conversely, the ranges given above for TRADEX S will often be exceeded, because they ignore the fact that the earth factor will nearly always exceed 4/3. Consequently, the calculated ranges for TRADEX should be achieved somewhat more than 70 percent of the time. To summarize, they are, for -20 dBsm 5 m above the water: S NB 50 km, S WB 47 km, L CHIRP 37 km, LIDAR 29 km. About 30 percent of the time, the TRADEX S range will exceed 100 km.

ALTAIR, which operates at UHF and VHF, will never be influenced appreciably by the evaporation duct. The one-way path loss for 18 dB S/N on 20 dBsm is 139.5 dB for the UL pulse (415 MHz) and 128.5 dB for the VL pulse (155 MHz). The ranges for these losses over a 5/2 earth, from ALTAIR's elevation of 31.6 m to a target 5 m above the water, are 32 km and for the UHF and 19 km for the VHF. On a 4/3 earth, these distances would become 28 and 18 km; the ALTAIR range to our chosen target is very insensitive to the earth factor, because the range limit is set by interference, and is within the horizon.

In summary, for S/N = 18 dB on -20 dBsm at an altitude of 5 m, TRADEX S will have a range of at least 50 km 70 percent of the time, and 100 km 25 percent of the time.* For TRADEX L the effect of the evaporation duct is small, and for ALTAIR it is negligible. Estimated ranges are: L CHIRP 40 km, LIDAR 30 km, UL 30 km, VL 20 km.

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*The latter estimate is based in part on the graphs in the Appendix, particularly Figs. A-11 and A-12, which indicate the possibility of continuous tracking down to 5 m at ranges of at least 100 km when the duct height is between 20 and 30 m; Fig. 13 says that duct heights in that interval are to be expected 25 percent of the time.

Ranges longer than the estimates can be expected when there is advection ducting, a sporadic condition in which the modified refractive index has a minimum at a height of many tens, or even several hundreds, of meters. This kind of duct, originating in movement of air masses, can cause strong trapping even of ALTAIR. According to Bean et al. [36], trapping of L-band radiation occurs at Kwajalein about 2 percent of the time in February, May, and November, and about 5 percent of the time in August. If need for a firmer estimate arises, one could be derived by statistical study of the refractivity profiles that have been recorded at Kwajalein since early in 1974.

VI. SUMMARY

Because humidity influences the dielectric constant of air, evaporation normally causes a minimum in the modified refractive index of air over the open sea. The region below the minimum is called the evaporation duct; it exists almost continually, but its height varies with location and with time. Far from land, the height of the duct at any one time is nearly constant over many tens of kilometers. The duct's effect on radio propagation is not governed solely by its height, but that is the only parameter used in most of the published work; customarily, it is calculated from measurements of temperatures, humidity, and wind speed.

When the height of the evaporation duct exceeds about 350 wavelengths, the radiation is trapped in the duct, so that except for some leakage at the top and absorption at the bottom, the propagation is in two dimensions rather than three, and the radiation can be ducted over the horizon. Evaporation ducts as high as 40 m are very uncommon, so only rarely are wavelengths as great as 10 cm fully trapped by the evaporation duct. Even without full trapping, however, the evaporation duct may cause a significant lessening of transmission loss on an over-the-horizon path.

A duct can be caused also by advection, the transport of air from one location to another, and ducts of this kind can be so high that they strongly affect wavelengths as long as a few meters. Their behavior and consequences lie outside the scope of this report, though they may occasionally exist at Kwajalein.

When the modified refractivity has a gradient that is invariant with height (a condition that precludes the existence of a duct) in the region in which propagation occurs, the resulting refraction can be taken into account by invoking a fictitious earth, whose radius is k times as large as that of the real earth. The value of k depends on the gradient of the refractivity, so it is a meteorological variable. Over land in temperate climates, the median value of k, for times when the gradient is nearly invariant, is 4/3. Over the ocean in the tropics, the gradient is usually larger in absolute value, and the radio horizon is consequently farther away than it would be on a 4/3 earth. Observations over the Caribbean and the Mediterranean suggest that for Kwajalein, a suitable median value for k is 5/2.

On the basis of a literature survey described in Section III, it is concluded that the evaporation duct nearly always has a significant effect on ALCOR's transmissions to targets just a few meters above the water. Section IV estimates, for example, that in nearly 80 percent of daytime hours ALCOR can see a

-20 dBsm target 5 m above the water at a range of 100 km. However, the field within a duct can be larger than the field above the duct; indeed, a very strong duct can diminish the field above it. For scoring, one must be able to track the target as it descends. For ALCOR, ducts higher than 25 m or lower than 5 m give ranges of only about 35 to 40 km on the specified target. Duct-height statistics for an open region in the Philippine Sea indicate that such ducting will occur at Kwajalein about one-third of the time. For about half the time, the -20 dBsm target can be tracked continuously down to 5 m at ranges of 100 km or more. When it becomes fully operational, a program now under development at Naval Electronics Research Center will yield calculations of coverage diagrams that are much more flexible and precise than what has been possible in this report.

When the ALCOR signal is strongly ducted, its velocity is somewhat less than it would be in the absence of the duct. If this effect were large, it would perturb the measurement of range. It is estimated in Section IV that the duct modifies the signal velocity by only a few parts in 10^5. The effect on velocity may be manifested in other ways than in range error, however. Because the signal velocity is different for the horizontal and vertical components of polarization, the duct will produce some depolarization, an effect that should be observable on the returns from spheres just before they hit the water. Also, the phase velocity of each polarization component is dependent on frequency. For ALCOR's wideband pulse, this dispersion may perturb the pulse compression, so as to make a point target seem to have an extent in range.

Calculations for TRADEX say that the S-band range will exceed 50 km 40 percent of the time, and will exceed 100 km about 30 percent of the time. Usually for L-band TRADEX and always for ALTAIR, the range to a low target is determined by the gradient of refractivity above the evaporation duct. It is to be expected that on the average this gradient is larger at Kwajalein than over a land mass in a temperate zone, and consequently that the appropriate earth factor (which will not exist unless the gradient is nearly invariant with height for many decameters above the evaporation duct) will be larger than 4/3. As a median value, 5/2 is suggested. For L CHIRP, the range on -20 dBsm 5 m above the water is estimated as 40 km. For ALTAIR's UL and VL pulses, the calculated ranges are 32 and 19 km, respectively.

The numbers generated in this report are estimates based on scattered data, crude theory, and fearless arithmetic. Uncertainties can be much reduced by examining data taken on sphere drops. The NELC program mentioned above will be invaluable in evaluating the effect of the duct on the region above it, as well as in it. Some preliminary runs, tailored to ALCOR and

TRADEX, are reproduced in the Appendix. They show that even for ALCOR, the trapping is never so strong as to diminish the range of detectability anywhere in the lowest kilometer of the atmosphere, but that with strong ducting, the range at which continuous tracking down to 5 m is possible may be less than the range of detectability on a target in the duct. A target in the duct can always be seen at a longer range by ALCOR than by TRADEX, but Figures A-6 and A-12 show that if tracking throughout the lowest kilometer is needed, TRADEX has the advantage over ALCOR when the duct is as high as 25 m; for a 15-m duct, however, Figures A-4 and A-10 award the advantage to ALCOR. The cross-over seems to occur at about 23 m. Figures 9 to 13 indicate that ALCOR has the advantage in about half the daytime hours and in about 65 percent of all hours.

ACKNOWLEDGEMENTS

It is a pleasure to give thanks here to J. V. Hitney; some of his many courtesies are acknowledged in detail in the body of the report. H. Jeske was a cordial and helpful correspondent to whom I am grateful. G. E. Brociner, of the Lincoln Laboratory library, was of inestimable help in the procurement of European documents.

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APPENDIX

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The graphs that follow were supplied by H. V. Hitney, who generated them with a program being developed at the Naval Electronics Laboratory Center, San Diego. They are for a 4/3 earth. The program functioned at low altitude in only a few cases, but some useful conclusions can be drawn. Leakage from the top of the duct can increase the detectability of a target above the duct, but as the duct height increases, the decrease in leakage can shorten the range at which the target can be seen when its altitude is a hundred or a few hundred meters. However, in the group of cases examined here, there is none in which the range of detection above the duct was less than it would have been if the duct were absent.

Each graph shows the maximum range at which -20 dBsm can be detected as a function of height above smooth sea.

INDEX OF CASES

Fig. A-1. ALCOR on 4/3 earth.

Fig. A-2. ALCOR with 5 m duct.

Fig. A-3. ALCOR with 10 m duct.

Fig. A-4. ALCOR with 15 m duct.

Fig. A-5. ALCOR with 20 m duct. Note compressed scale of ranges.

Fig. A-6. ALCOR with 25 m duct. Note compressed scale of ranges.

Fig. A-7. TRADEX S, NB chirp pulse, 4/3 earth.

Fig. A-8. TRADEX S, NB chirp pulse, 5 m duct.

Fig. A-9. TRADEX S, NB chirp pulse, 10 m duct.

Fig. A-10. TRADEX S, NB chirp pulse, 15 m duct.

Fig. A-11. TRADEX S, NB chirp pulse, 20 m duct.

Fig. A-12. TRADEX S, NB chirp pulse, 25 m duct.

Fig. A-13. TRADEX L, LIDAR pulse, 4/3 earth.

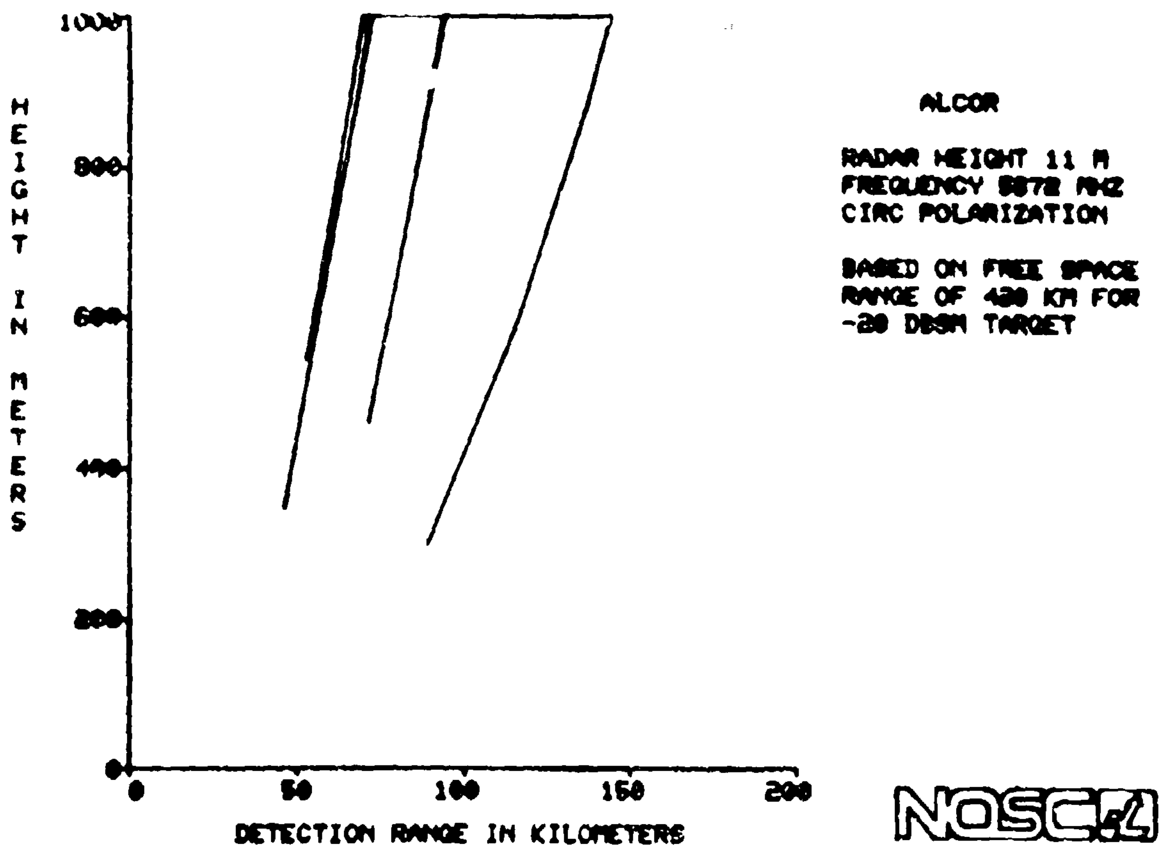
Fig. A-14. TRADEX L, LIDAR pulse, 5 m duct.

Fig. A-15. TRADEX L, LIDAR pulse, 10 m duct.

Fig. A-16. TRADEX L, LIDAR pulse, 15 m duct.

Fig. A-17. TRADEX L, LIDAR pulse, 20 m duct.

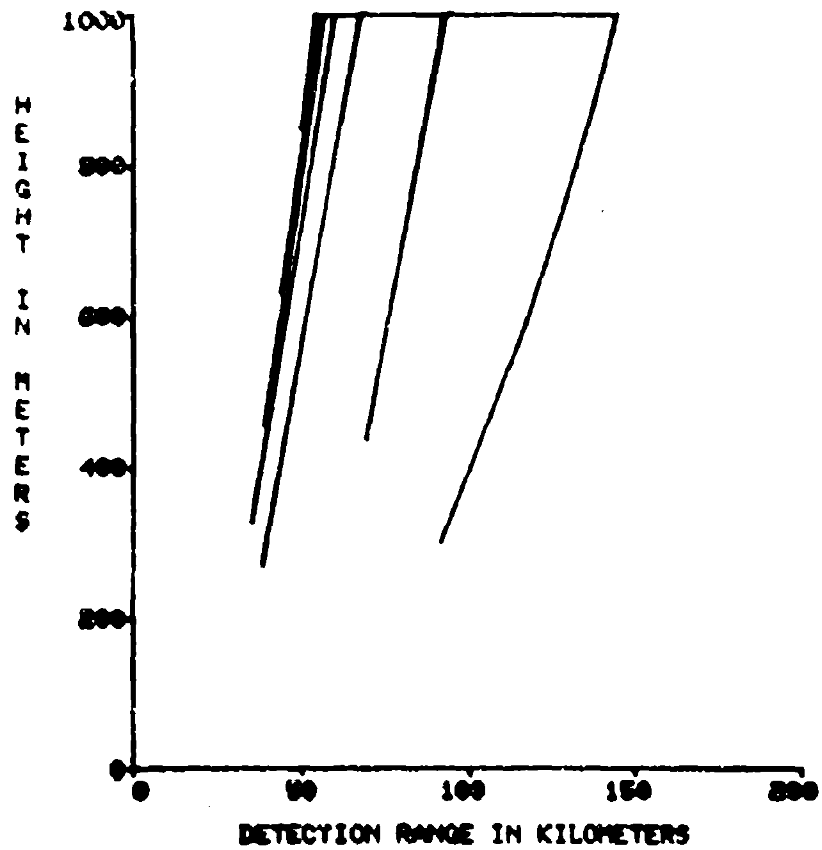
Fig. A-18. TRADEX L, LIDAR pulse, 25 m duct.



LOCATION STANDARD
TIME SAME

(PLOT.EDIT.LIST.SUMRY.[illegible] OBS.COVER.END)

Fig. A-1.



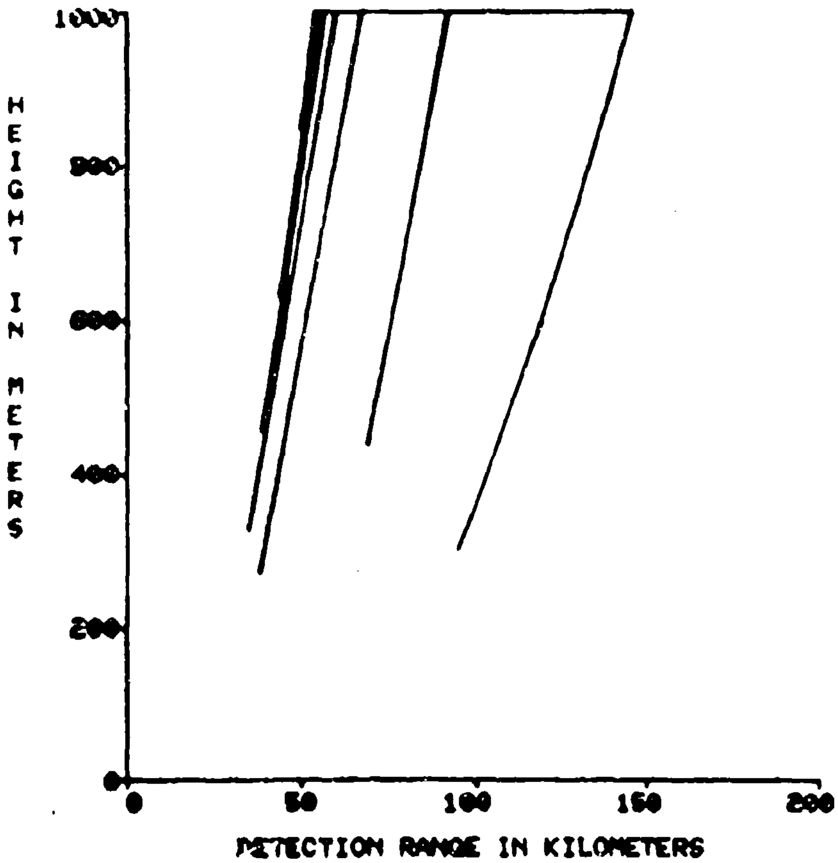
ALCOR

RADAR HEIGHT 11 M
FREQUENCY 5672 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 400 KM FOR
-80 DBSM TARGET

LOCATION DUCT 5
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-2.



ALCOR

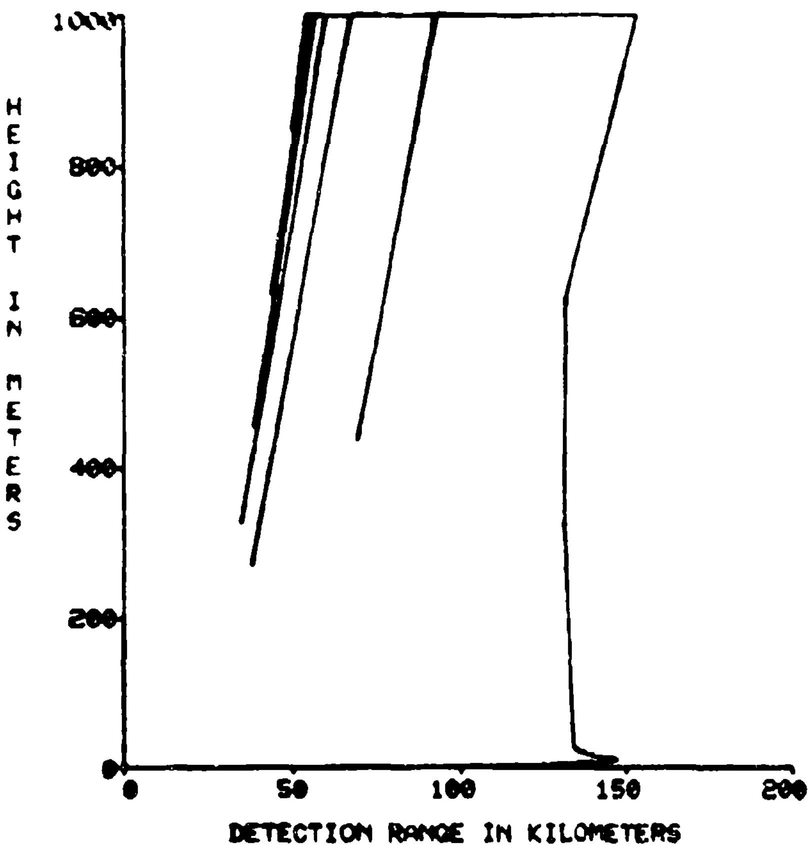
RADAR HEIGHT 11 M
FREQUENCY 5872 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 400 KM FOR
-20 DBSM TARGET

LOCATION DUCT 10
TIME CAVE

(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-3.



ALCOR

RADAR HEIGHT 11 M
FREQUENCY 5872 MHZ
CIRC POLARIZATION

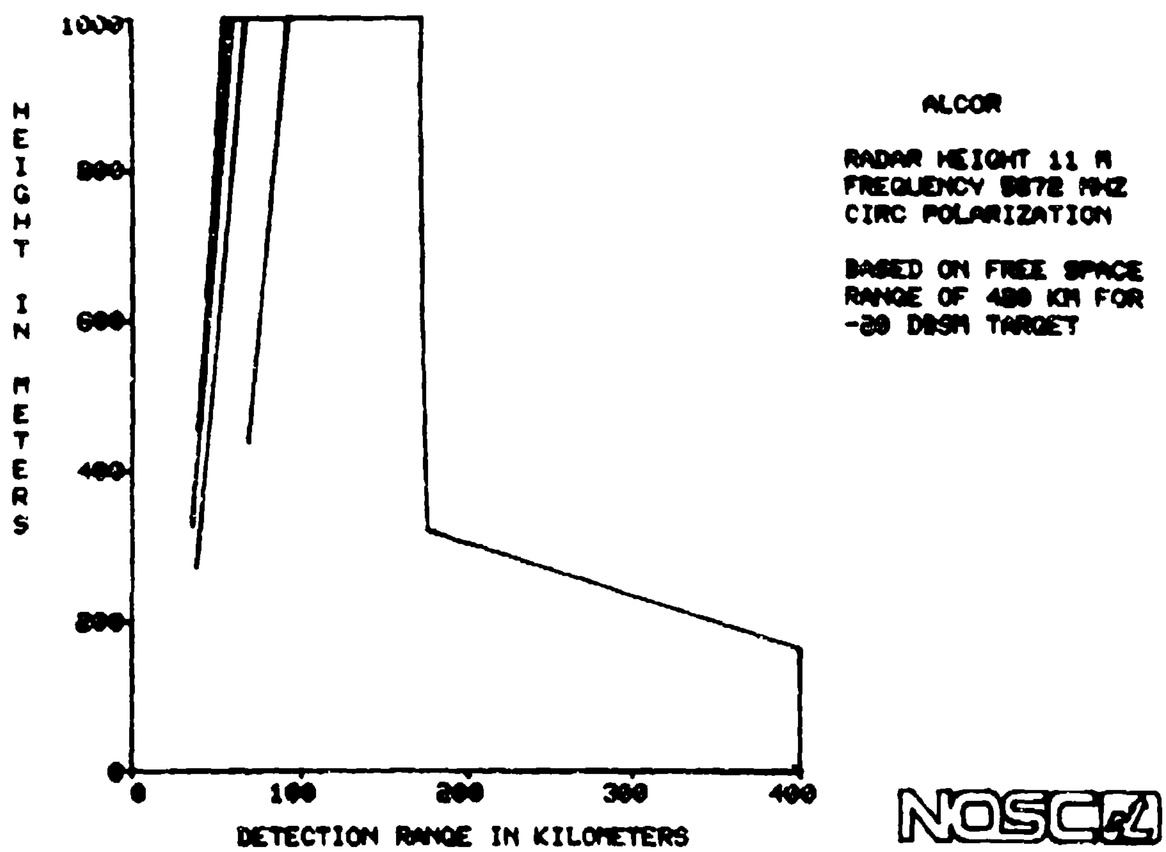
BASED ON FREE SPACE
RANGE OF 480 KM FOR
-20 DBSM TARGET

NOSC

LOCATION DUCT 15
TIME SAME
(PLOT,EDIT,LIST,SUMRY,RAYS,LOSS,COVER,END)?

Fig. A-4.

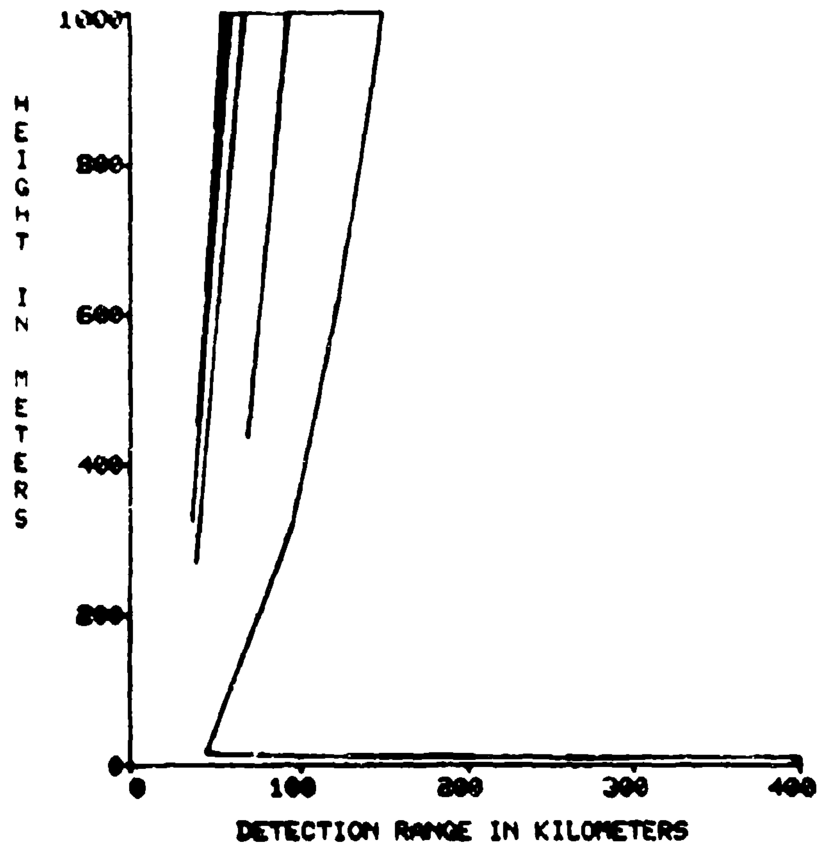
TN 78-6(A-5)



LOCATION DUCT 80
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-5.

TN 78-6(A-6)



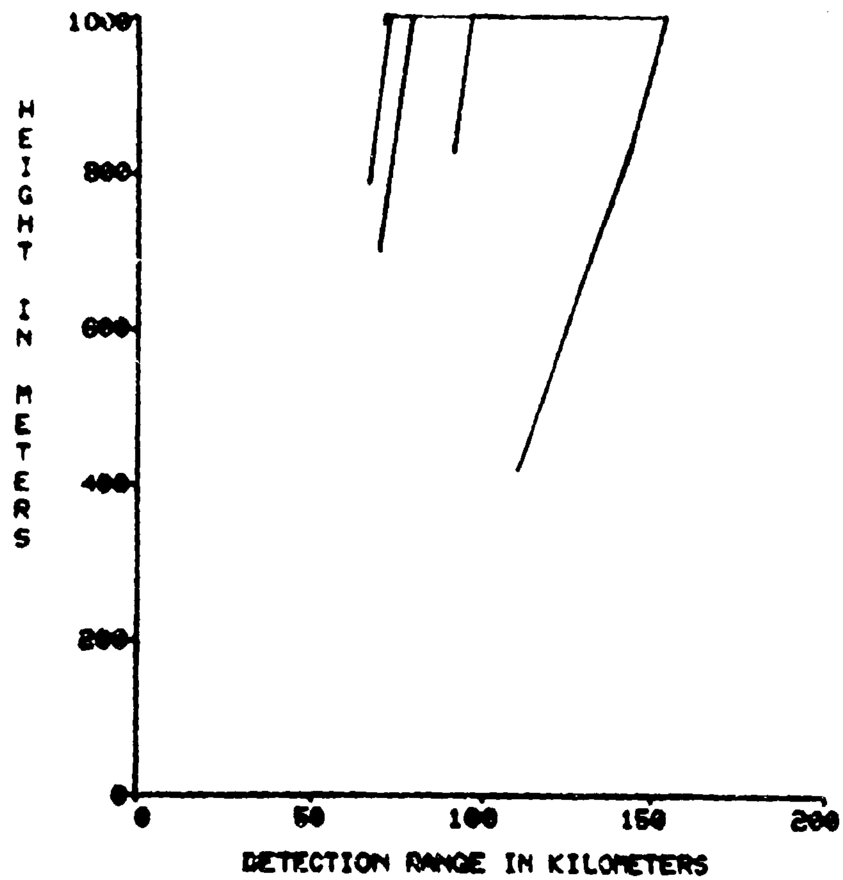
ALCOR

RADAR HEIGHT 11 M
FREQUENCY 5872 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 400 KM FOR
-30 DBSM TARGET

LOCATION DUCT 85
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-6.



TRADEX S

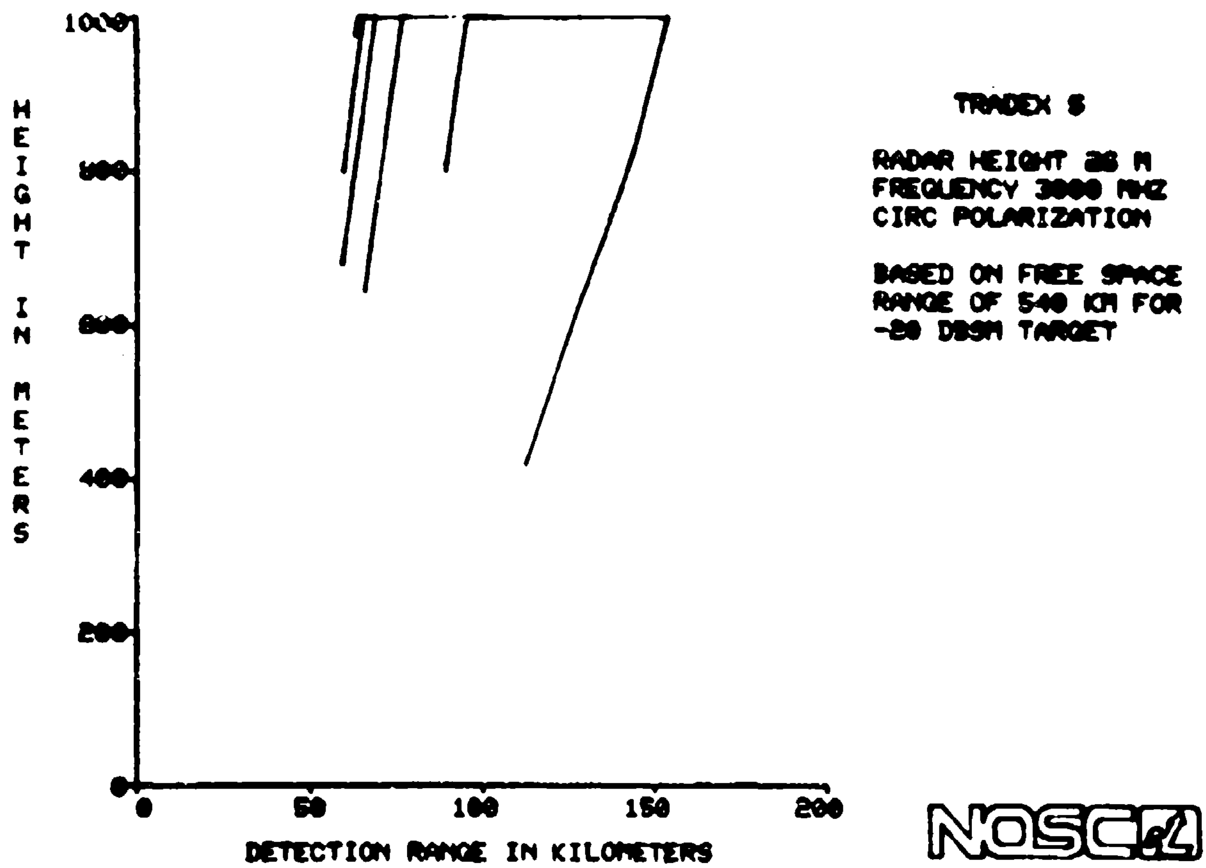
RADAR HEIGHT 26 M
FREQUENCY 3000 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 540 KM FOR
-80 DBSM TARGET

LOCATION STANDARD
TIME SAFE
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-7.

TN 78-6(A-8)

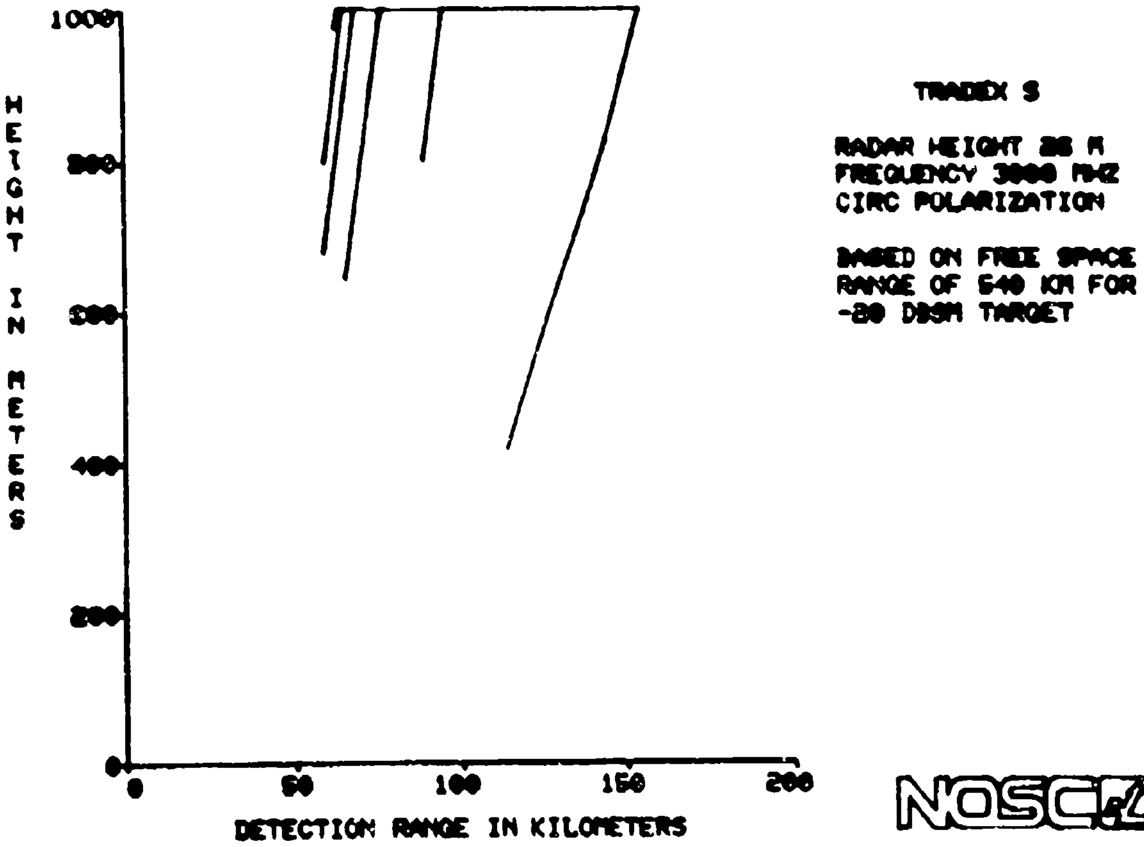


LOCATION DUCT 5
TIME SAME

(PLOT,EDIT,LIST,SUMRY,RAYS,LOSS,COVER,END)?

Fig. A-8.

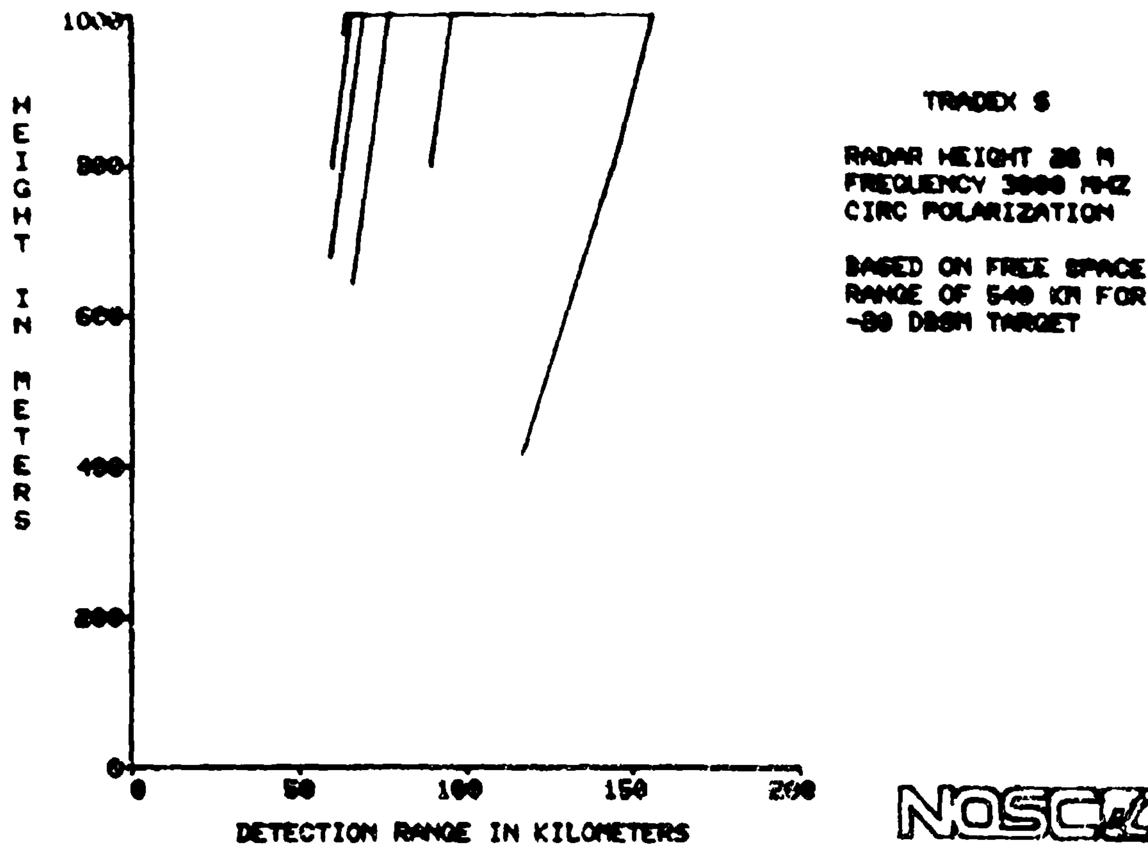
TN 78-6(A-9)



LOCATION DUCT 10
TIME SAVE
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

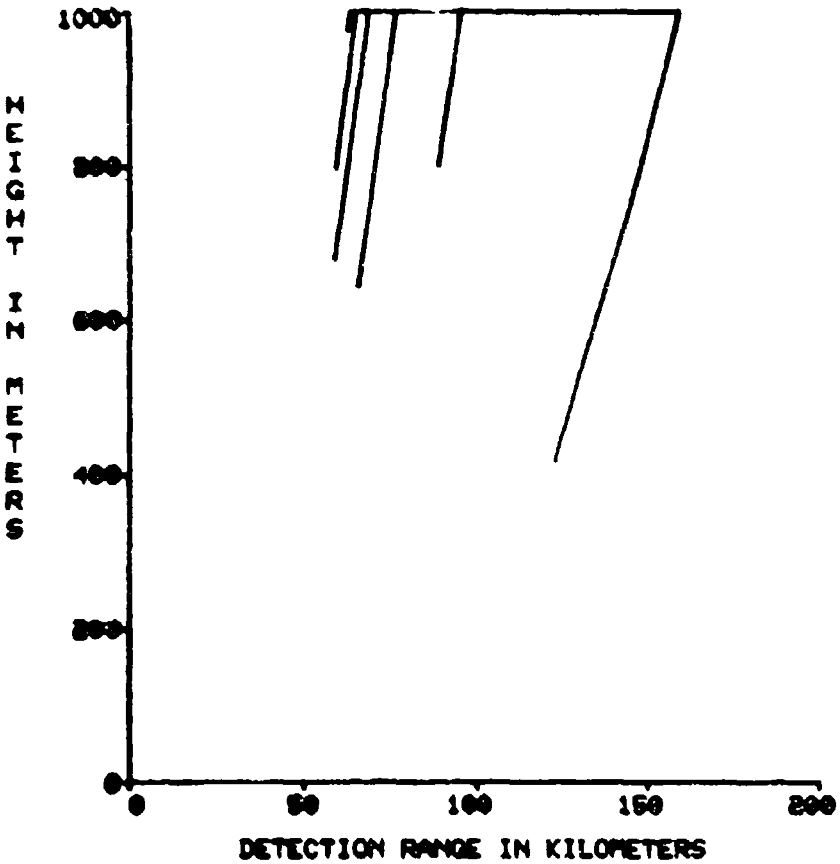
Fig. A-9.

TN 78-6(A-10)



LOCATION DUCT 15
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-10.



TRADEX S

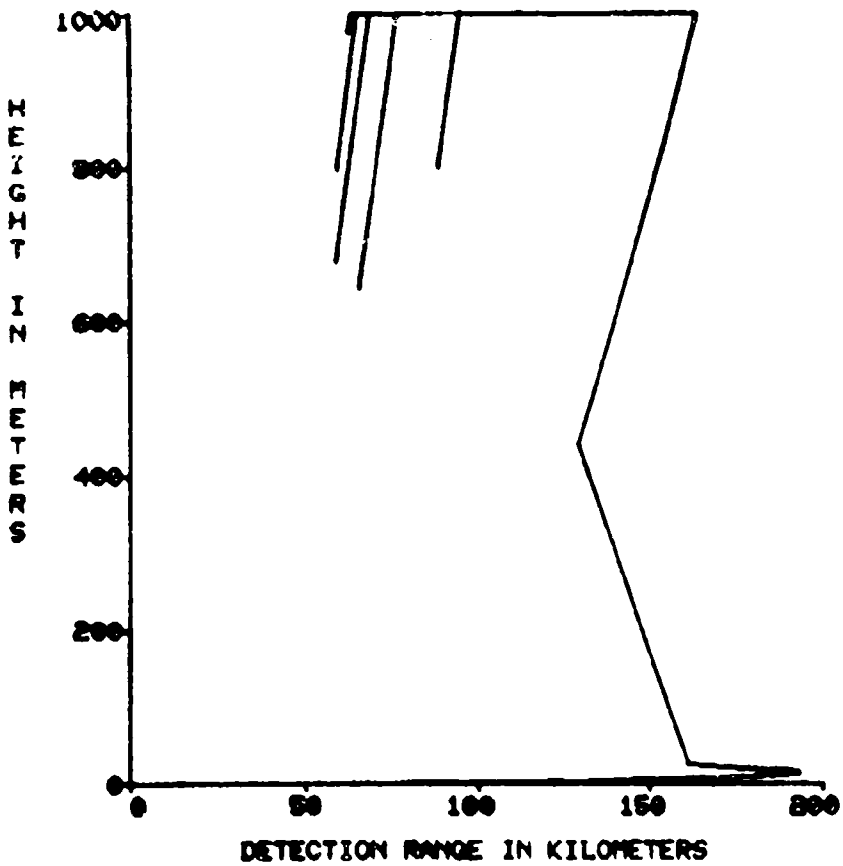
RADAR HEIGHT 26 M
FREQUENCY 3000 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 540 KM FOR
-20 DBSM TARGET

LOCATION DUCT 20
TIME SAME

(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-11.



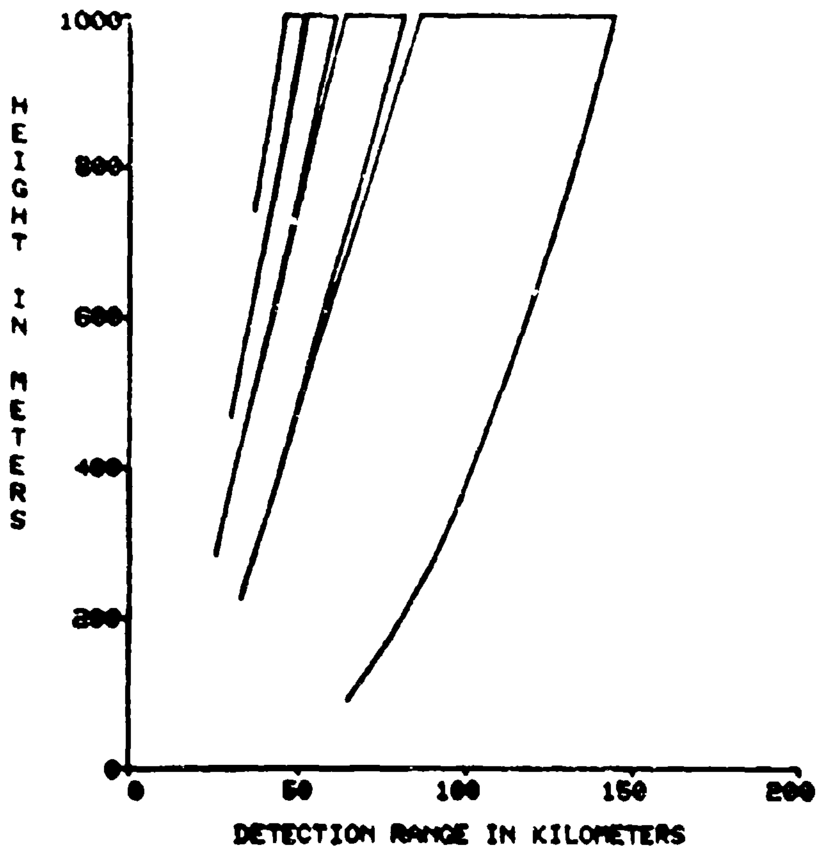
TRADEX 3

RADAR HEIGHT 28 M
FREQUENCY 3000 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 540 KM FOR
-20 DBSM TARGET

LOCATION DUCT 25
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-12.



TRADEX L

RADAR HEIGHT 36 M
FREQUENCY 1300 MHZ
CIRC POLARIZATION

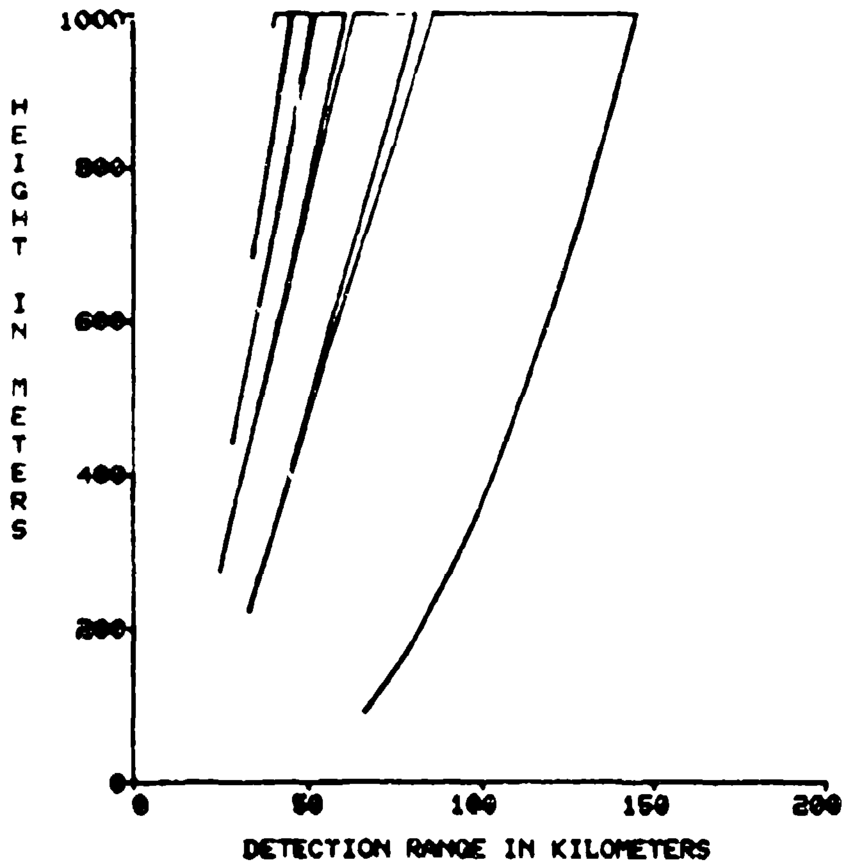
BASED ON FREE SPACE
RANGE OF 300 KM FOR
-30 DBSM TARGET

LOCATION STANDARD
TIME SAME

(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-13.

TN 78-6(A-14)



TRADEX L

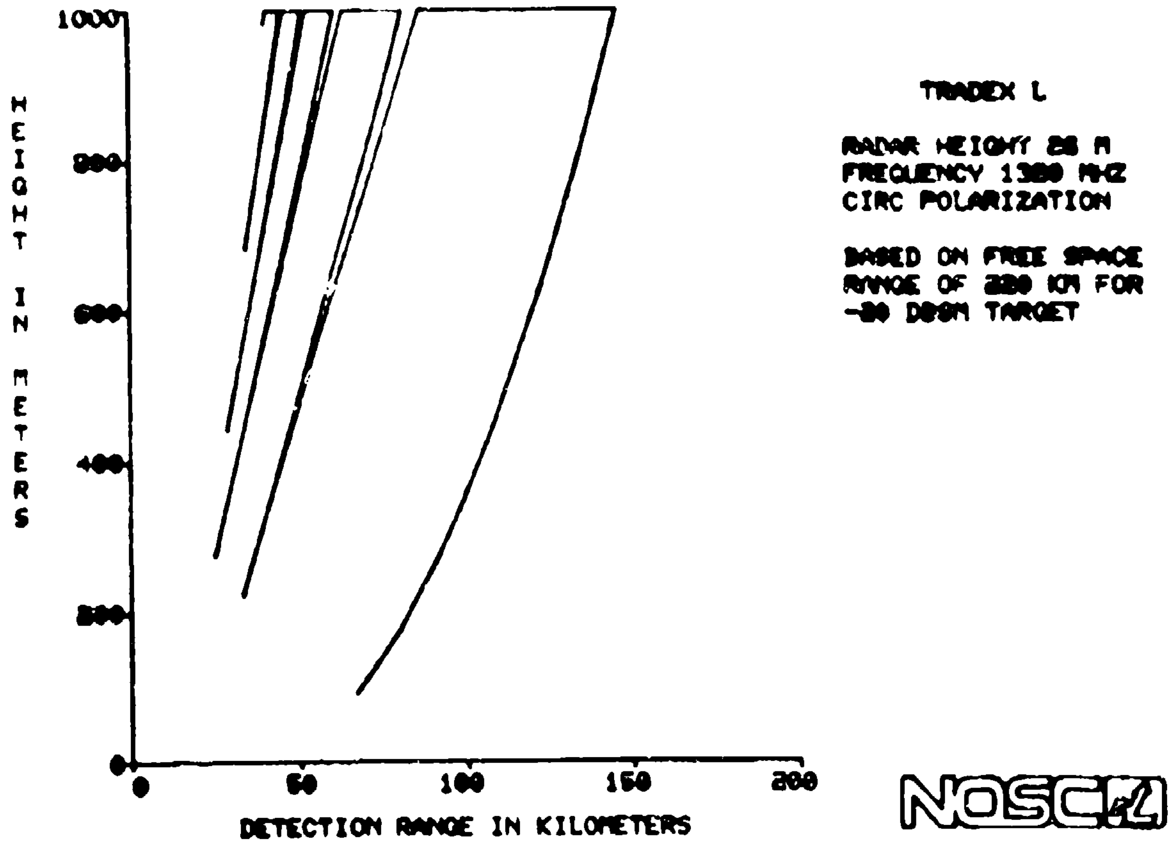
RADAR HEIGHT 28 M
FREQUENCY 1300 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 200 KM FOR
-20 DBSM TARGET

NOSC

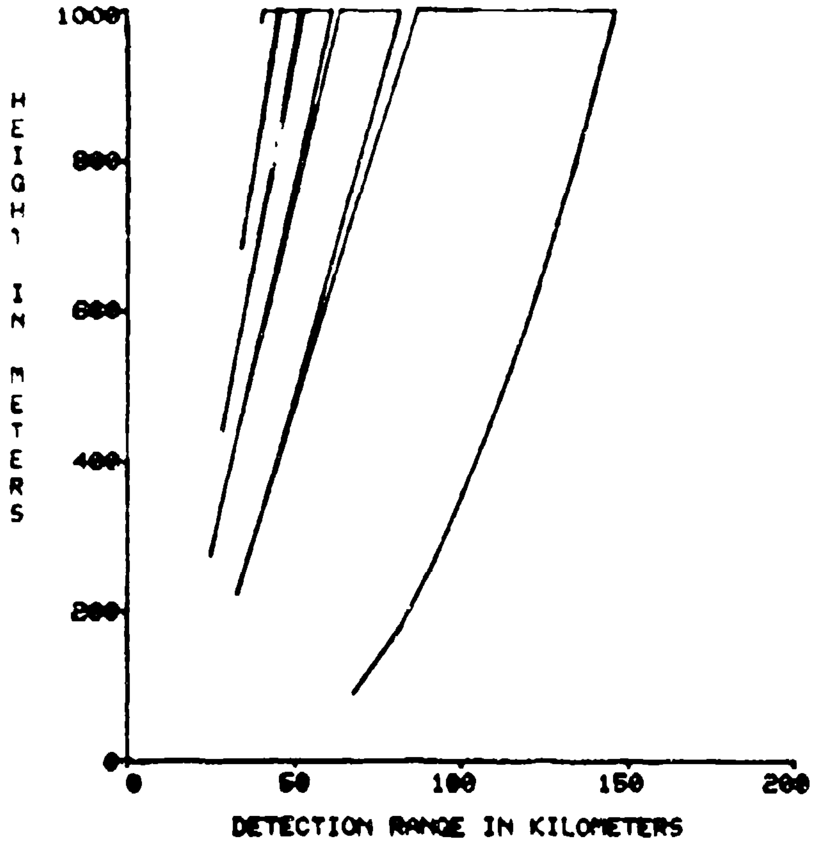
LOCATION DUCT 5
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-14.



LOCATION DUCT 10
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-15.



TRADEX L

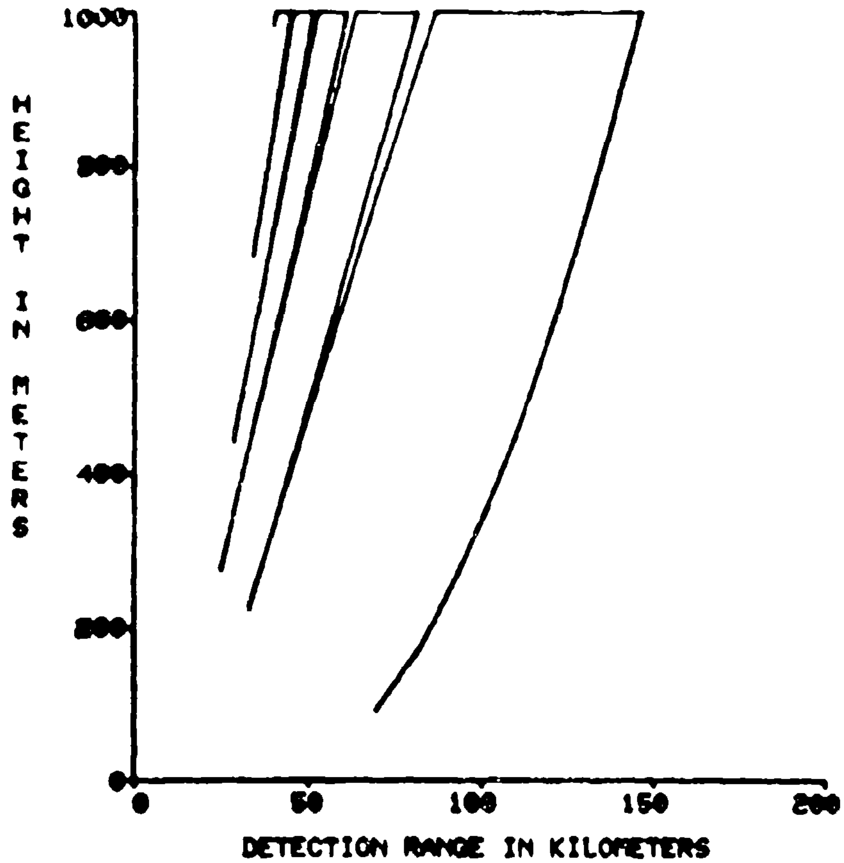
RADAR HEIGHT 26 M
FREQUENCY 1300 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 280 KM FOR
-20 DBSM TARGET

NOSC

LOCATION DUCT 16
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-16.



TRADEX L

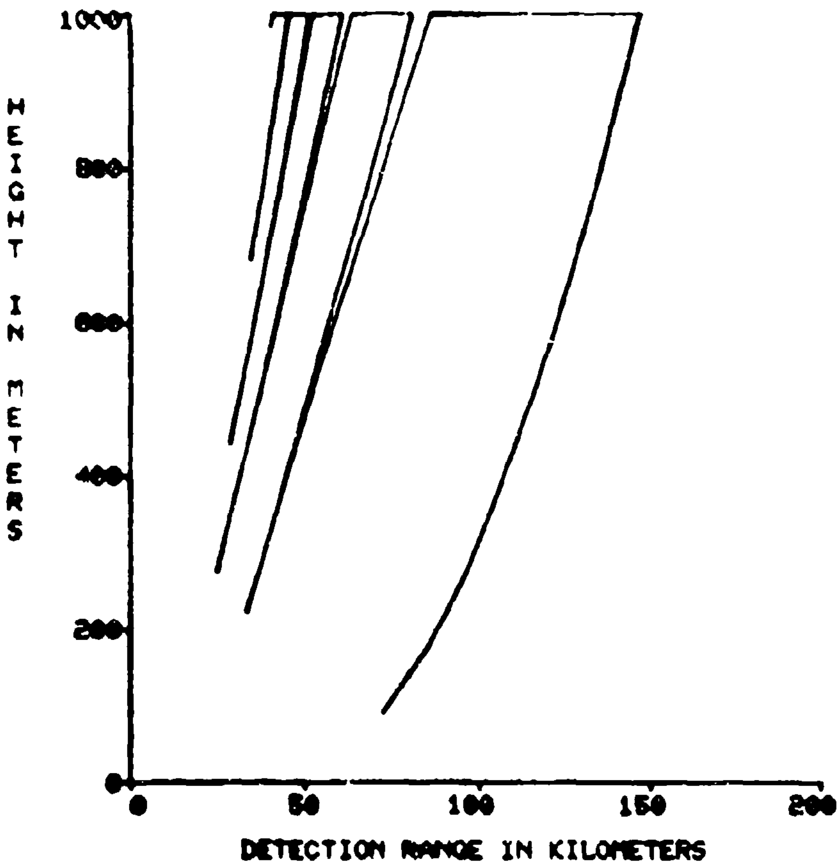
RADAR HEIGHT 20 M
FREQUENCY 1300 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 200 KM FOR
-20 DBSM TARGET

NOSC

LOCATION DUCT 20
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-17.



TRADEX L

RADAR HEIGHT 86 M
FREQUENCY 1300 MHZ
CIRC POLARIZATION

BASED ON FREE SPACE
RANGE OF 220 KM FOR
-20 DBSM TARGET

LOCATION DUCT 26
TIME SAME
(PLOT.EDIT.LIST.SUMRY.RAYS.LOSS.COVER.END)?

Fig. A-18.

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The principal intent is to provide a basis for understanding the influence of the evaporation duct, a low region of strong refraction existing nearly all the time on the open sea, with varying thickness. There is a survey of the literature, followed by application of published data to the task of estimating the effect of the evaporation duct on the performance of the radars at Kwajalein when the target height is only a few meters. It is concluded that this duct has negligible effect at VHF, UHF, and L-band, that at times it causes a large extension of the coverage of the S-band radar, and that it very importantly extends the range of the C-band radar on targets at heights such as 5 meters. Attention is given to the effects of the duct on signal velocity, pulse compression, and polarization ratio. There is also a discussion of the effect of the atmosphere over tropical ocean on the location of the radio horizon for frequencies that are too low to be influenced by the evaporation duct.