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Experimental data that recorded higher-than-expected signals at 3087.7 MHz far beyond the horizon in the presence of an elevated duct are examined and compared to results from the radio physical optics (RPO) propagation model. RPO is a range-dependent hybrid model that combines ray optics and parabolic equation methods. Previous modeling of this same case study using waveguide methods for both the measured elevated duct and hypothetical evaporation ducts has been disappointing. However, when the elevated duct is allowed to rise slowly with increasing range, the RPO results closely match the observed signal levels, indicating that weakly attenuated Earth-detached, or whispering gallery, modes were the dominant propagation mechanisms.

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Whispering gallery effects in the troposphere

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Experimental data that recorded higher-than-expected signals at 3087.7 MHz far beyond the horizon in the presence of an elevated duct are examined and compared to results from the radio physical optics (RPO) propagation model. RPO is a range-dependent hybrid model that combines ray optics and parabolic equation methods. Previous modeling of this same case study using waveguide methods for both the measured elevated duct and hypothetical evaporation ducts has been disappointing. However, when the elevated duct is allowed to rise slowly with increasing range, the RPO results closely match the observed signal levels, indicating that weakly attenuated Earth-detached, or whispering gallery, modes were the dominant propagation mechanism.

INTRODUCTION

Pappert and Goodhart [1977] presented a case study of propagation at 3087.7 MHz in the presence of an elevated duct. In this case study the transmitter and receiver heights were 21 and 914 m above sea level, and measurements were made to about 700 km. The transmitter utilized a horizontally polarized standard gain horn antenna with a beam width of 32° on the coast of Point Loma in the city of San Diego. The receiver utilized an open-ended waveguide feed antenna with a beam width of 85°. The receiver and data collection systems were flown in an aircraft on an entirely overwater path westward from the transmitter site. The case selected was May 28, 1974, and the measurements were made on an outbound flight from 1853 to 2140 UT (1153–1440 PDT). Figure 1 shows modified refractivity profiles measured by radiosonde at the Point Loma transmitter site at 1909 and 2247 UT. Modified refractivity in M units is given by

$$M = 10^6(n - 1 + z/a)$$

where n is the refractive index, z is height above sea level, and a is the Earth's radius. Both profiles indicate that an elevated duct existed from approximately 350 to 700 m above sea level. Figure 1 also shows the transmitter and receiver heights, which were substantially below and above the elevated duct.

Figure 2, reproduced from Figure 17 of *Pappert and Goodhart* [1977] (with a legend correction), compares path loss in decibels versus range for the measured data with results calculated using a waveguide model and a trilinear refractivity profile based on the measured profiles of Figure 1. Reference curves for free-space and standard atmosphere losses are also included in Figure 2. The waveguide results match the measured data quite well at near-horizon ranges but overpredict the loss by more than 60 dB at the greater ranges. Pappert and Goodhart observed that the measured data are indicative of energy being transported by weakly attenuated modes and speculated that mode conversion processes from a range-dependent environment might be important in this case study. They also suggested that a strong low-level evaporation duct might account for the discrepancies between the modeled and measured loss values.

Hitney et al. [1978] reexamined this case study in terms of evaporation duct propagation. Since the evaporation duct was not expected to affect the relatively low microwave frequency of the experiment, accurate meteorological measurements near the sea surface were not made in the 1974 experiment. Therefore Hitney et al. used hypothetical multilevel refractivity profiles representing moderate, strong, and very strong evaporation ducts with duct heights of 12, 23, and 35 m, respectively, in their study. These profiles were used as input to a waveguide model similar to the one described by

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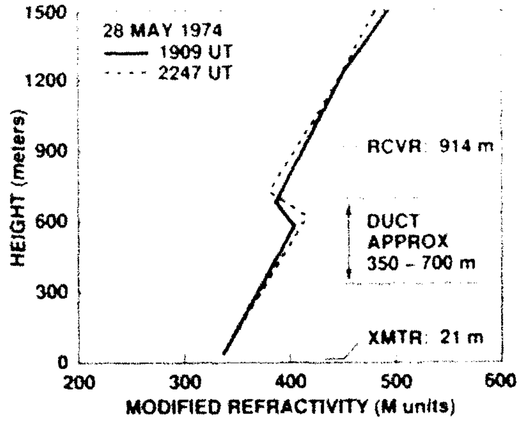

Fig. 1. Modified refractivity profiles measured by radiosonde on May 28, 1974, showing the elevated duct and the transmitter and receiver heights.

Pappert and Goodhart [1977], and calculated results were compared to the experimental measurements. Figure 3, reproduced from Figure 3 of *Hitney et al.* [1978], shows the results of these comparisons. Figure 3 shows that evaporation ducts can affect signal levels far above the surface. However, only the very strong duct shows a reasonably good match to the measurements, and this duct strength is quite rare in the San Diego area. For example, historical data from the engineer's refractive effects prediction system [*Patterson et al.*, 1990] show a 35-m evaporation duct is expected far less than 1% of the time on an annual basis in the San Diego area. Thus it must be concluded that the evaporation duct is a possible, but highly unlikely, explanation for the higher-than-expected signal levels measured.

RADIO PHYSICAL OPTICS MODEL

The radio physical optics (RPO) propagation model is a range-dependent hybrid model that combines ray optics (RO) and parabolic equation (PE) methods to produce a relatively fast-running computer program. The PE model is based on methods

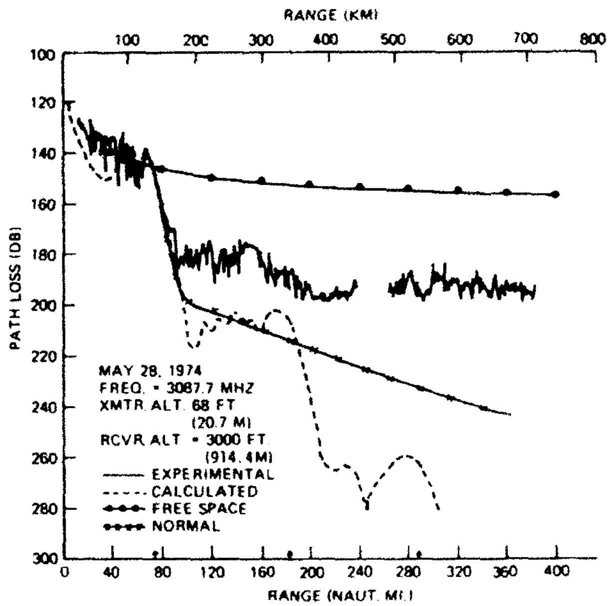

Fig. 2. Path loss versus range for May 28, 1974, showing experimental measurements (solid line) and calculations from waveguide methods (dashed line), reproduced from *Pappert and Goodhart* [1977].

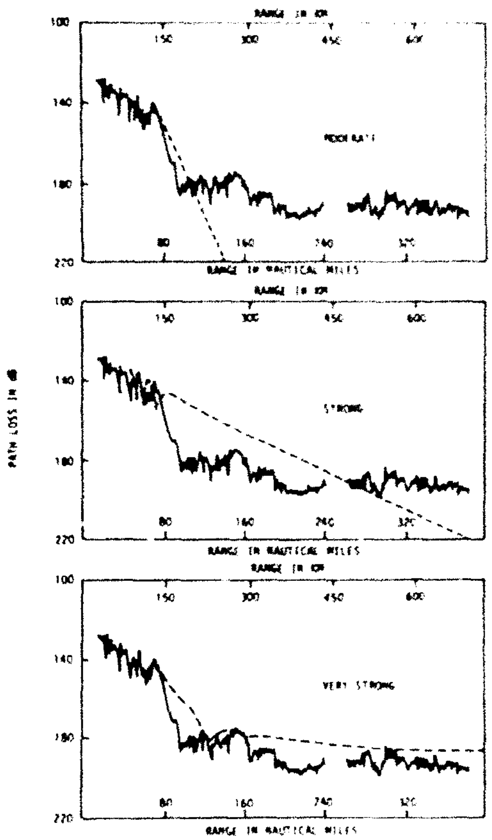

Fig. 3. Path loss versus range for May 28, 1974, showing experimental measurements (solid lines) and moderate, strong, and very strong evaporation duct models (dashed lines) from waveguide methods, reproduced from *Hitney et al.* [1978].

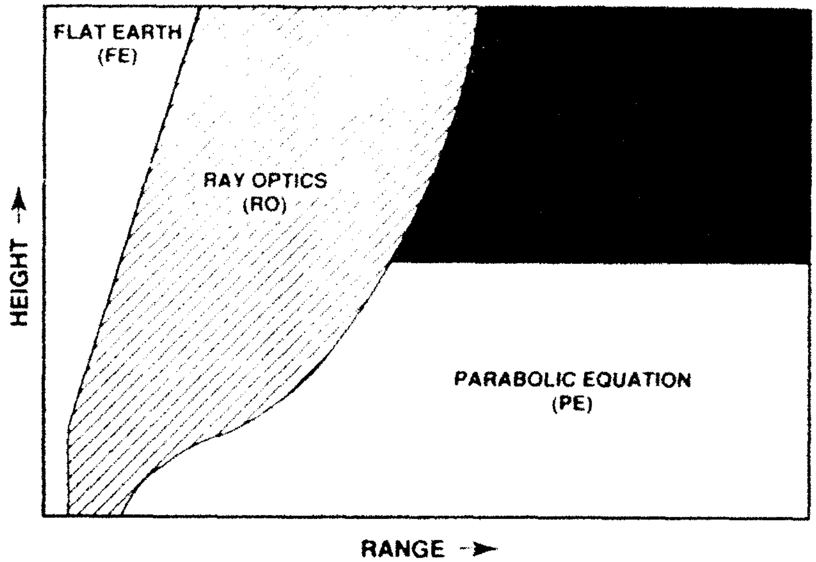

Fig. 4. The four radio physical optics (RPO) model regions.

described by *Tappert* [1977] and *Dockery* [1988]. One disadvantage of PE models applied to microwave problems is that inclusion of elevation angles above a fraction of a degree can result in very long computer execution times and large memory requirements. RPO overcomes this disadvantage by using a variety of RO methods above a small limiting elevation angle to compute propagation loss, thus keeping the larger angles out of the PE solution. In the RO methods, full account is given to focusing or defocusing along both direct and reflected ray paths and to the integrated optical path length difference between the two ray paths to give precise phase difference and hence accurate coherent sums of the RO components. To further enhance the speed of computation, the fast Fourier transform size of the PE model is variable but limited to a maximum of 1024 points. This implies a maximum receiver height for the PE model that depends on frequency, transmitter height, and refractivity profiles. For typical applications at 3 GHz the maximum PE receiver height is about 2500 m. For points above this height, but beyond the RO region, an extended optics model has been developed that uses ray optics methods that are initialized by the PE solution. Finally, for elevation angles above 5° or ranges less than 2.5 km, a flat-Earth model is used that ignores all refractive or curved-Earth effects. Figure 4 summarizes the relative location of the four RPO regions.

There are three primary advantages of the hybrid RPO model, as discussed by *Hitney* [1992]. First, it has proven to be from 25 to 100 times faster than pure split-step PE methods for many practical cases, with no loss in accuracy. Second, RPO can be applied to very wide elevation angles, whereas pure PE methods are generally restricted to small or moderate angles due to practical limitations on memory size. The third advantage is that the total memory requirement of RPO is quite modest, needing only 160K on IBM/PC-compatible computers.

COMPARISONS OF RPO TO MEASUREMENTS

The RPO model was applied to the case study of May 28, 1974, using a combination of the measured profiles shown in Figure 1 and assuming horizontal homogeneity. The exact refractivity profile used by RPO is given in Table 1 in terms of *M* units versus height. The results are presented in Figure 5 as

TABLE 1. Modified Refractivity Versus Height Profile Based on a Combination of the Two Measured Profiles of Figure 1

Height, m	Refractivity, *M* units
0	330
594	403
681	368
2000	539

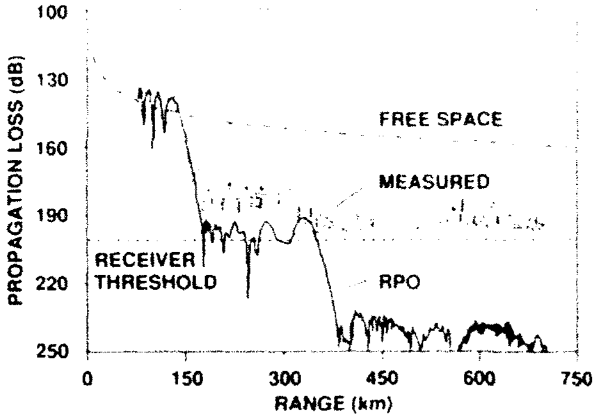

Fig. 5. Propagation loss versus range from RPO for the homogeneous elevated duct environment of May 28, 1974 (solid line), compared to experimental measurements (dotted line).

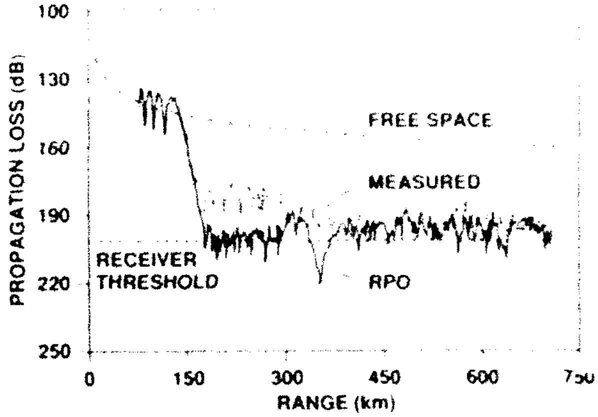

Fig. 6. Propagation loss versus range from RPO for the elevated duct environment of May 28, 1974, with duct rising at a slope of 1:1500 (solid line) compared to experimental measurements (dotted line).

propagation loss versus range at 914 m compared to the measured radio data. In this paper, path loss and propagation loss are equivalent, both being the ratio, in decibels, of the transmitted to received power assuming loss-free isotropic antennas. The RPO results were calculated assuming an omnidirectional antenna for consistency with the waveguide results, but there would be virtually no difference in loss at the greater ranges if the actual transmitter antenna pattern had been used. Reference lines are also included in Figure 5 for free-space and receiver-threshold loss values. These RPO results show a strong similarity to the results of Pappert and Goodhart presented in Figure 2, which indicates that the RPO and waveguide models are equivalent for the homogeneous case. Unfortunately, the exact profile used by Pappert and Goodhart could not be determined. *Hitney* [1992] has shown that RPO and waveguide methods give identical results when applied to identical profiles.

Since no refractivity measurements were made away from the transmitter site in the 1974 experiment, there is no way to ascertain how the refractivity profile may have changed along the propagation path. However, Figure 19 of *Hitney et al.* [1985] shows a duct similar to those of Figure 1 that rose with a slope of 1:800 (that is, 1 m in height for every 800 m in range) on an overwater radial away from Point Loma. Also, Figure 4.24 of *Kerr* [1951] shows a layer with a slope of about 1:1000, and Figure 3 of *Guinard et al.* [1964] shows a layer with a slope of about 1:1700, both of which were observed in the San Diego area. A discussion of the meteorological conditions that result in these rising ducts is given by Guinard et al. A few cases of range dependency were therefore modeled by RPO with constant slopes up to 1:800 using the same refractivity profile at the transmitter as was used for Figure 5. The best fit of these range-dependent cases was one with a slope of 1:1500, the results from which are shown in Figure 6. This case used the profile from Table 1 at range zero and the profile from Table 2 at 750 km. Note the modeled loss levels at the far ranges are in good agreement with the measured data, even though at the near over-the-horizon ranges they are not much better than the homogeneous case. In this case, allowing the duct to rise very slightly has increased the signal levels by about 50 dB compared to the homogeneous case.

The reason why the range-dependent modeled signals are much higher than the homogeneous case is apparent in the coverage diagram of Figure 7, which represents the same case as Figure 6. Figure

TABLE 2. Modified Refractivity Versus Height Profile Assumed at 750 km for the Rising Duct Case With Slope of 1:1500

Height, m	Refractivity, *M* units
0	330
1094	465
1181	430
2000	537

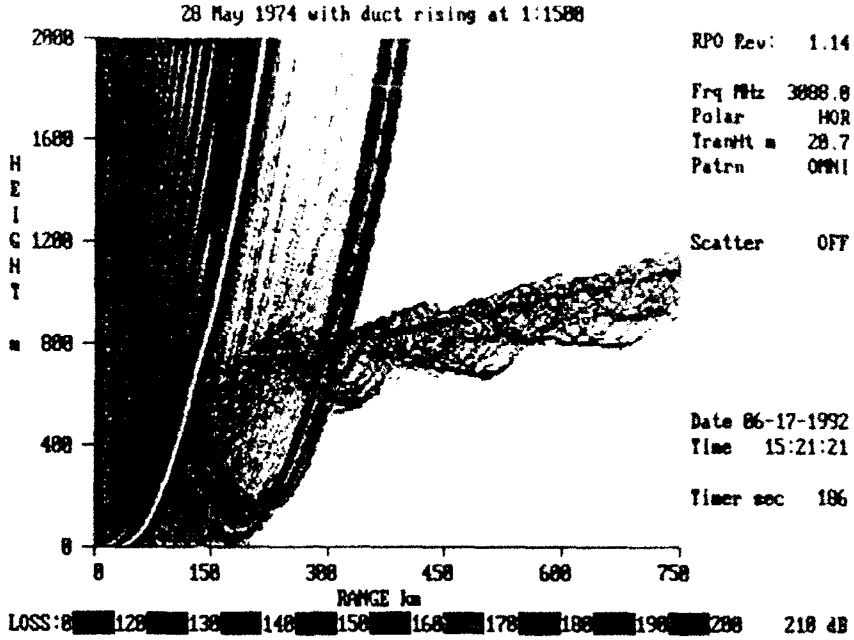

Fig. 7. Coverage diagram from RPO for the elevated duct environment of May 28, 1974, with duct rising at a slope of 1:1500.

7 shows propagation loss in 10-dB increments on a gray scale on a height-versus-range display. It is apparent that an aircraft flying level at 914 m would intersect the duct at ranges greater than 400 km, where the received signals would be dominated by the Earth-detached modes, or whispering gallery effects, associated with the elevated duct. The Earth-detached modes in the elevated duct are clearly excited by the source that is well below the duct and propagate with very low attenuation rates.

A few other range-dependent refractivity environments were modeled by RPO to see if the measured signal levels between about 150 and 300 km could be better matched. The best match was found using a duct with an upward slope of 1:750 between 0 and 250 km and no slope beyond 250 km. Again, the refractivity profile at the transmitter was the same as used in the homogeneous case. The results for this case are presented in Figure 8 as propagation loss versus range at a receiver height of 914 m. The overall comparison of this modeled case and the measurements is quite good at all ranges. Similar range-dependent refractivity structure, characterized by a duct that rises for a few hundred kilometers and then levels out, has also been observed in the San Diego area.

Many other combinations of range-dependent ducting could be modeled, and perhaps a fit to the measured data better than Figure 8 could be achieved. However, since definitive meteorological measurements were not made, it will never be possible to determine with certainty what propaga-

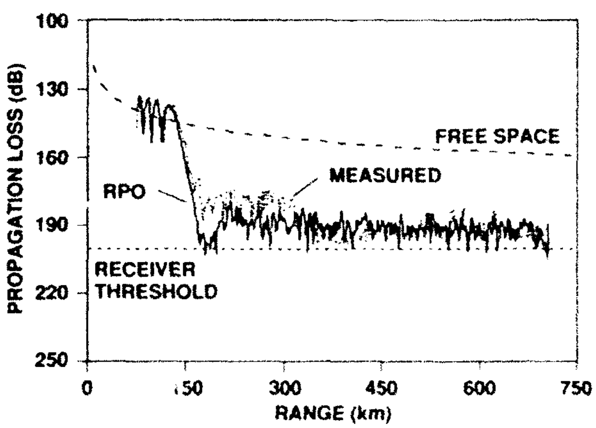

Fig. 8. Propagation loss versus range from RPO for the elevated duct environment of May 28, 1974, with duct rising at a slope of 1:750 to 250 km and no change beyond 250 km (solid line) compared to experimental measurements (dotted line).

tion mechanisms were responsible for the relatively high signal levels measured. The modeling presented here appears to confirm the conjecture of Pappert and Goodhart that the high signals resulted from weakly attenuated modes associated with the elevated duct, but modified by mode-conversion, or range-dependent, effects. These results also confirm a proposal by *Wait* [1968] that the usually neglected whispering gallery modes can substantially contribute to the total field in transhorizon propagation. In any case, the modeling presented here seems to be a much more likely explanation of the high signals than the evaporation duct model presented by *Hitney et al.* [1978].

This study suggests that elevated ducts may be more important than often considered at ranges far beyond the horizon. A recent investigation by *Hitney* [1991] used RPO in a parametric study of elevated ducting scenarios to infer trapping layer height from long-term over-the-horizon propagation measurements at 547 MHz, with quite good results.

CONCLUSIONS

It is concluded that the signal levels measured on May 28, 1974, at the greater ranges most likely resulted from whispering gallery effects in an elevated duct that sloped upward with range away from the transmitter.

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