Aust. J. Phys., 1990, **43**, 99–105

Elevated Duct Effects on Radar Ranges Using an Airborne Microwave Refractometer

S.B.S.S. Sarma

Radio Science Division, National Physical Laboratory,
New Delhi 110012, India.

Abstract

Anomalous distribution of humidity and temperature in the troposphere is responsible for significant changes in electromagnetic wave propagation and results in enhancement/degradation of radar ranges, elevation errors etc. The present investigation assesses atmospheric refraction effects in the tropics by producing radar ray traces which depict the path of the airborne radar rays using a three-dimensional ray tracing technique combined with the radio refractivity vertical profile derived using an airborne microwave refractometer. The radar rays at the target can be represented as a sum of normal modes and an assembly of rays reflected from the elevated ducts/layers. The radar range errors at small elevation angles are evaluated.

1. Introduction

Effects of atmospheric refraction on radar were detected towards the end of World War II. However, the difficulty in obtaining precise geophysical measurements and the mathematical complexity required for quantitative performance calculations prevented operational assessments of radio refractive effects for most countries. Hence, visualisation of the concept of an assessment system which could be used under operational conditions became necessary. These systems could be based on computers with interactive graphic displays for radars under existing conditions for tracking, navigation and position fixing. The most important aspect is the ability to produce ray traces which depict the path of the electromagnetic wave due to non-standard variations in the vertical distribution of water vapour, temperature and pressure (atmospheric refraction). Thus environmental information from meteorological sensors/airborne microwave refractometers and surface observations is necessary for depicting the ray path so as to assess the refractive conditions as a function of geographic area and season. These environmental conditions sometimes cause serious performance degradation in radar, especially modern surveillance and targetting radar. Rapid warming and drying of the air can cause the radio refractive index to decrease with height fast enough to refract an upward travelling electromagnetic wave downward. The level at which this phenomenon occurs is called duct formation. In other words, the duct is a layered condition of the atmosphere where there is a sharp drop in humidity between a lower layer of moist air and a higher layer of dry air.

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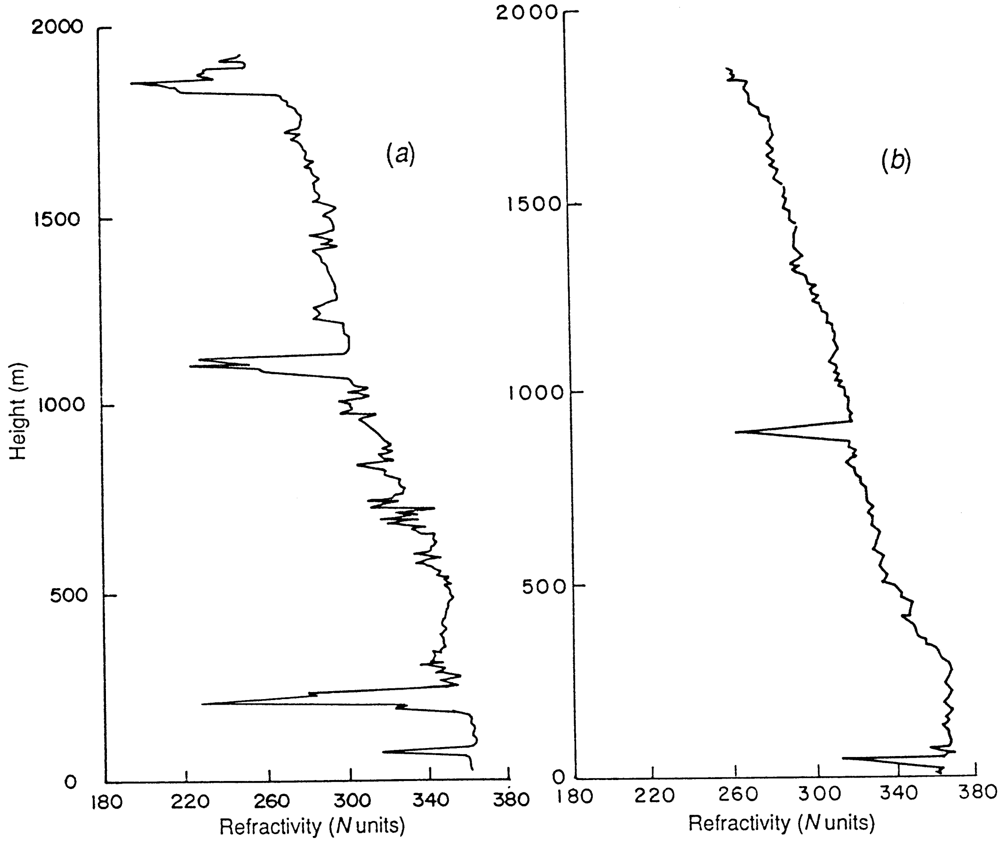

Fig. 1. Height distribution of radio refractivity using an airborne microwave refractometer over Kanpur IIT: (*a*) 9 June 1983, (*b*) 10 June 1983, (*c*) 7 January 1985 and (*d*) 8 January 1985.

Sometimes this is also associated with a temperature inversion. This sharp decrease in humidity with height produces a sharp radio refractive index gradient (–157N) which can bend electromagnetic waves sharply to follow the humidity boundary far over the horizon. The radio refractive index n and the radio refractivity (usually expressed as N units) are related by the expression $N = (n - 1) \times 10^6$. Sometimes this downward wave does not strike the surface at higher elevations and an elevated duct formation takes place. This type of ray bending also takes place even under super refractive conditions where the radio refractivity gradient lies in the range of -156 to -77 Nunits per km. Raytracing techniques for studying electromagnetic wave propagation have been in existence for decades and are well documented. During recent years numerous computational algorithms have been developed to allow assessment of atmospheric refractive effects. This paper presents the effects of tropospheric low elevated ducts on microwave radar propagation (especially airborne radar range errors) using the data collected by an airborne microwave refractometer in the tropics. Atmospheric dispersion was not taken into consideration as it is

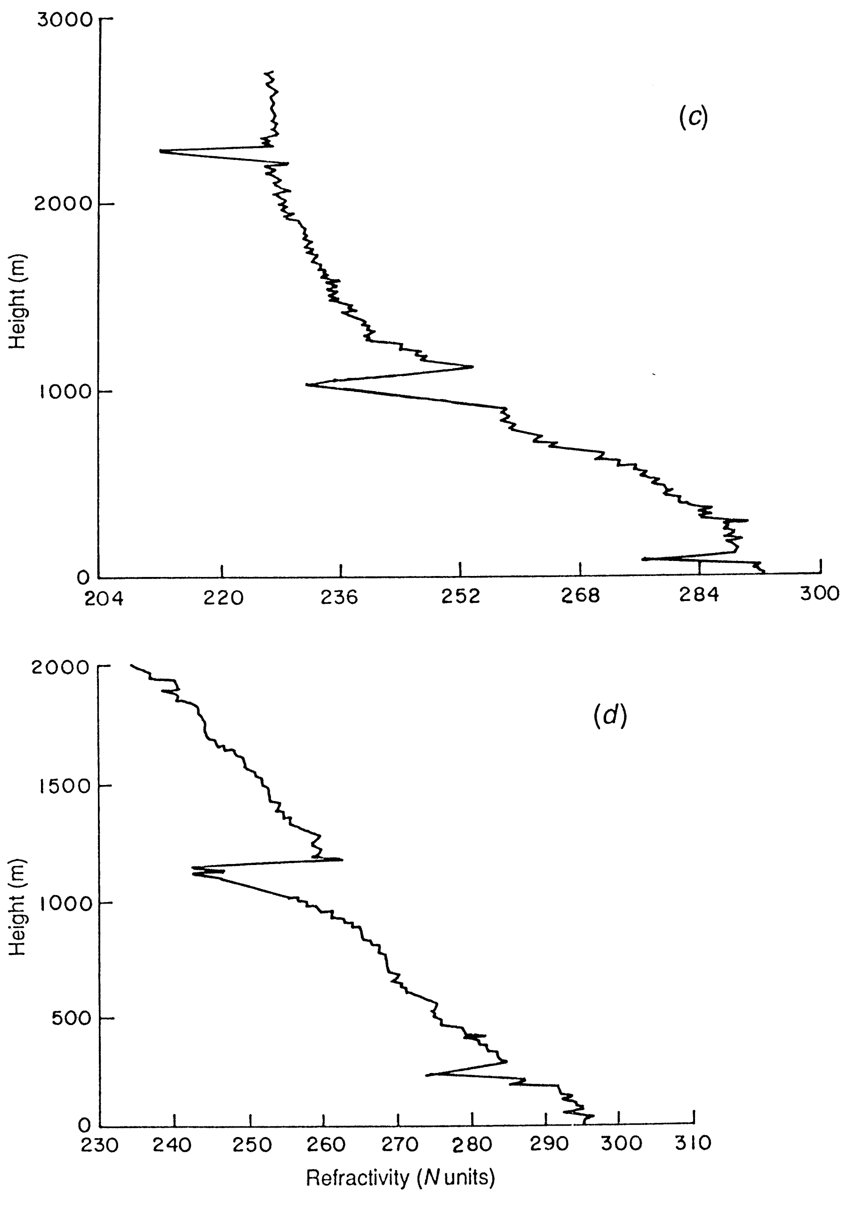

Fig. 1. *(Continued)*

not relevant in the troposphere. Horizontal homogeneity of the atmosphere was assumed as we have taken only the vertical profile of radio refractive index at the radar location. The fine structure of radio refractivity was retained in the lowest one km. The full-wave raytracing technique was used in the present calculations. We have concentrated in this paper on propagation at small elevation angles only and hence the necessary assumptions for small angle propagation in classical raytracing techniques are assumed to be valid. Under these circumstances duct trapping occured as we observed ground-based layers on a number of occasions. Hence, we expect a region of no radar propagation for different ranges of launch angle convering $\pm 0 \cdot 6°$, which is known as a radar hole. The principal contribution to the radar target range correction for atmospheric radio refractivity is due to the retardation of the propagation speed of the sensing field.

2. Method of Approach

In view of the stringent accuracies involved in targetting radar the range error R_e is given by $R_e = R_t - R_s$, where R_t is the radar range (given by the product of half the round trip travel time of a radar pulse reflected by a target and the speed of light in vacuum) and R_s the geometric straight line separation between target and radar. The estimate of the radar range error is determined by dividing the troposphere into thin layers of varying radio refractive index as a continuous funtion of height. Thus the range error/correction is determined by the actual raytracing. Input parameters are the vertical radio refractive index profile (obtained using the airborne microwave refractometer), radar altitudes with respect to the mean sea level, surface refractive index, terrain elevation, etc.

Radio refractivity vertical profile information in the tropics over the height range 0 to 3 km has been collected using the microwave refractometer developed by Sarma *et al.* (1989) and is to be used as an input parameter for estimating the range error. This refractometer has a dynamic range of $(400 \pm 1)\,N$units and an accuracy better than $1\,N$unit. The frequency response is of the order of a few hundred Hz. To obtain this vertical profile information the aircraft flight pattern consisted of spiral ascent and descent at time intervals sufficiently small to repeat the order of magnitude of variability of the refractivity in vertical and horizontal directions.

3. Results and Discussions

During this experimental program we observed for the first time well-defined ground-based and elevated stable layers and ducts at low and high altitudes in a tropical country, India, using an airborne microwave refractometer. Typical vertical profiles of radio refractivity are given in Fig. 1, which shows the presence of ground-based and elevated ducts at various heights. These ducts are missing in typical radiosonde/meteorological sensor profiles as depicted in Fig. 2 (simultaneous flights of refractometer and radiosonde taken over the Bay of Bengal) due to non-standard behaviour of the troposphere, and these are responsible for giving rise to radar range errors. Under these abnormal conditions the usual predicted standard atmospheric models are not applicable in evaluating the radar target ranges at any site. In fact radar waves may be reflected or even trapped, and the standard range corrections become grossly inaccurate and formation of regions with no communication of air target detection may take place. Table 1 lists the mean values of the vertical gradients of radio refractive index across the inversions, which are often very large (approximately $-2 \cdot 4 \times 10^3\,N\,\mathrm{km}^{-1}$). Similar large values have also been reported by Lane (1965), Clarke and Pertle (1979), Tourgenev and Kivva (1978) and Kabanov and Tourgenev (1980). The thickness of these layers/ducts has also been given but it is very difficult to determine whether these layers

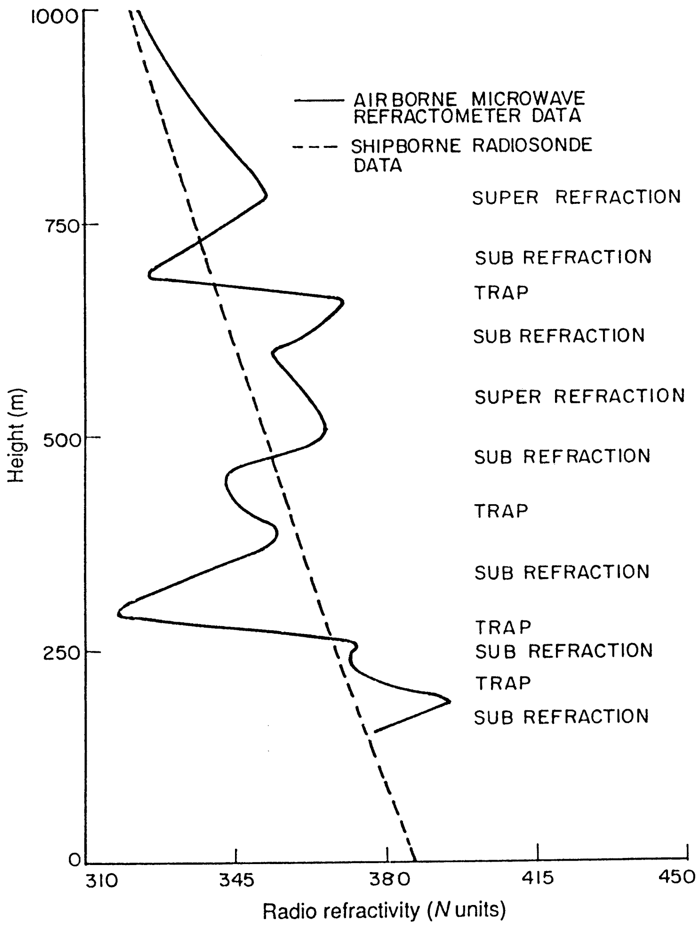

Fig. 2. Height distribution of radio refractivity taken from simultaneous flights in June 1988 of an airborne microwave refractometer and radiosonde.

Table 1. Distribution of ground-based and elevated ducts/layers over Kanpur airstrip

Date	Height of duct/layer (m)	Thickness of duct/layer (m)	Vertical radio refractivity gradient (N km^{-1})
9.6.1983	57	19	−2420
	150	67	−1920
	1000	63	−1269
	1800	63	−952
10.6.1983	25	25	−2165
	915	52	−853
7.1.1985	76	76	−210
	915	152	−157
	2135	76	−223
8.1.1985	243	61	−166
	915	91	−219

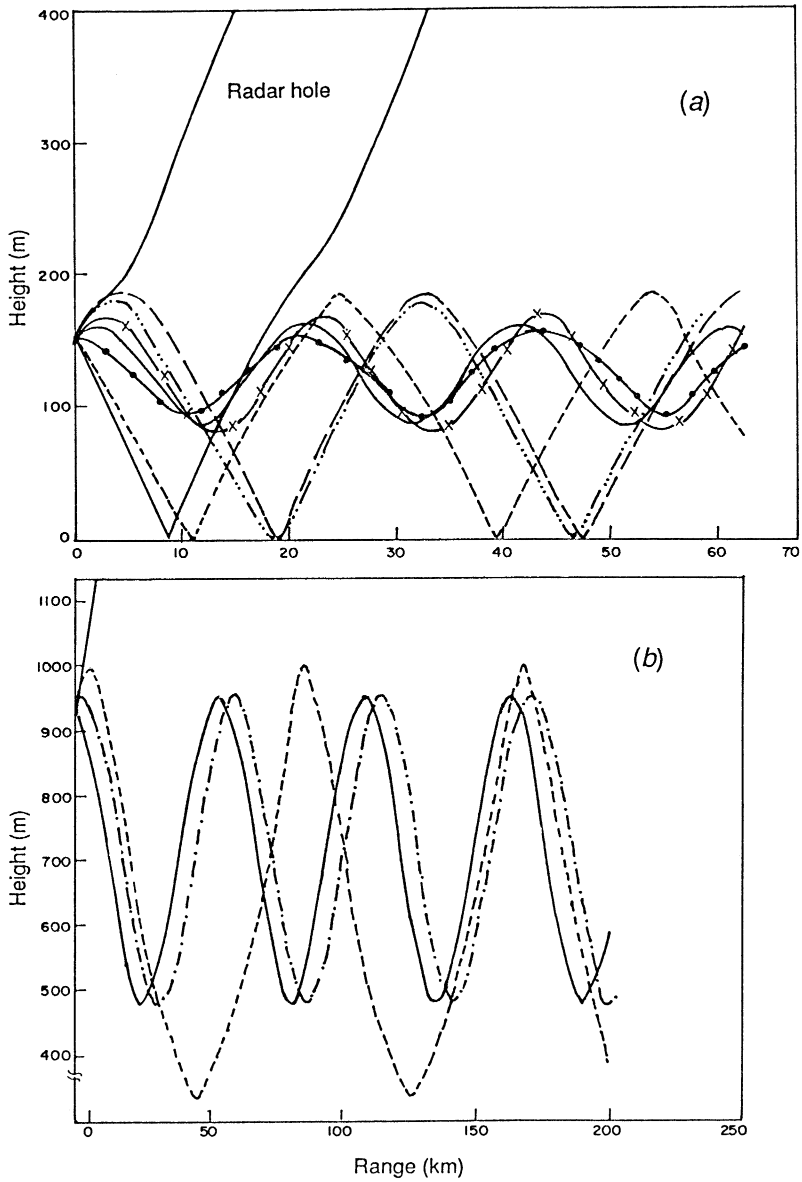

Fig. 3. Raytracing plots from 9 June 1983 of radar range with the transmitting antennae within the duct at (*a*) 150 m and (*b*) 1000 m.

are always horizontal in all cases as aircraft take spiral ascents/descents only at one place. The observed duct widths varied from 20 to 150 m. In view of these stable steep gradients revealed by the microwave refractometer soundings, radar waves may be reflected by these layers by backscattering. Another interesting feature observed in Table 1 is the layer between 900 and 1000 m on consecutive days (9 and 10 June 1983) and also at 915 m on 7 and 8 January 1985. This observation indicates the presence of a strong stable layer over the observing site in the topics at around 900 m. However, this conclusion must be subject to further verification since we have observed at that particular site only for four days over a span of two years.

An airborne microwave radar beam should pass through refractive layers present in the troposphere at random depending on the altitude, location, local climate, etc. Thus radar range is a function of the fine structure of the vertical radio refractivity profile in the atmospheric volume under consideration. Radar coverage diagrams indicate the areas in the far field of a radar where the target might be detected. These diagrams are drawn by raytracing through the atmosphere. Thus raytracing provides the theoretical approach for range correction calculations in the context of various atmospheric conditions and at various times and locations. Raytracing permits the integration of the refractivity effects along the path and estimates the excess electromagnetic propagation time for a given source–target geometry. In the present case model raytracing computations were performed when the airborne radar is within the duct through numerical integration described by Ghosh (1976), taking into consideration all parameters such as the vertical refractivity profile, radar coordinates, target coordinates, radar frequency, elevation angle, etc. A model vertical profile of 9 June 1983 was fed into the raytracing program and various rays were launched in positive and negative elevation angles ranging from $-0 \cdot 6°$ to $+0 \cdot 6°$ in steps of $0 \cdot 02°$. The various ray paths possible are shown in Fig. 3 for two duct heights. Here the duct is assumed to be uniformly illuminated to twice the free space range and the downgoing rays are only traced to the surface. Corrections for refractive bending are achieved through this raytracing procedure over the actual ray path traversed by the radar pulse taking into account the actual refractivity profile over the entire altitude range. From the analysis of the present data, radar errors of about 10 to 50 m were observed for radar ranges of 50 to 200 km for various elevation angles within $-0 \cdot 6°$ to $+0 \cdot 6°$. Thus, use of an airborne microwave refractometer in any surveillance aircraft can mitigate radar range errors using this method, even on a real time basis since both the radar and microwave refractometer operate simultaneously.

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Manuscript received 22 August, accepted 28 November 1989.