MODELLING EVAPORATION DUCT EFFECT IN RADAR SIMULATION

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ABSTRACT
Due to the change in the index of refraction of the atmosphere with altitude, electromagnetic (EM) waves can get trapped in a layer and travel long distances. These layers are called atmospheric ducts. Radar's performance is mostly affected by the ducts which are caused by evaporation of water. Evaporation duct changes the maximum detection range of radars operating at 3 *GHz* and above. Therefore, modelling the evaporation duct is of utmost importance in radar simulators as the frequency range in question is valid for almost all operational radars. However, analytical calculation of the ducting effect during the simulation would require allocating valuable processing time and power for this purpose. In this study, a simple but effective modelling of the ducting effect with minimum processing requirement has been developed based on the data obtained from commercial software tools utilizing complex EM propagation models for detection range calculations.

Keywords: evaporation duct, modelling ducting effect, radar simulation, refraction

1. INTRODUCTION

Tens of various radar models have been developed for evaluating radar performance since the production of the first radar. With rapidly advancing technology and growing experience, it has been possible to come up with near-real life EM propagation models that have excelled these radar models. However, perhaps as a natural outcome, these models, despite being powerful have also become extremely complex and rather slow.

Various needs may emerge from a radar model in different engineering applications; however, the most basic outcome from any radar model has been the maximum range that a specific radar can detect a target. The answer to this question has been produced by the radar range equation that was developed based on the attenuation in free space. Radar range equation simply calculates maximum range that a target can be detected utilizing the amount of the EM energy emitted by the transmitter, reflected from the target and received at the receiver. Naturally, losses caused by atmospheric and meteorological conditions during the EM propagation can also be utilized in this equation. The fact that how complicated should the radar equation be depends on the application.

Full EM propagation model in radar equation can be used in applications where there is no time constraint, such as the determination of the coverage area of a radar. On the other hand, the full propagation model may prove too slow in applications where a radar on a mobile platform is supposed to calculate probability of detection for many mobile targets. A much simpler radar range equations are needed for latter applications.

Refraction is the bending of electromagnetic waves caused by a change in the density of the medium through which the waves are passing. Because the density of the atmosphere changes with altitude, the index of refraction changes gradually with height. Like density, the temperature and moisture content of the atmosphere also decrease uniformly with an increase in altitude. However, under certain conditions the temperature may first increase with height and then begin to decrease. Such a situation is called temperature inversion. An even more important deviation from normal may exist over the ocean. Since the atmosphere close to the surface over large bodies of water may contain more than a normal amount of moisture, the moisture content may decrease more rapidly at heights just above the sea. This effect is referred to as moisture lapse.

Either temperature inversion or moisture lapse, alone or in combination, can cause a large change in the refraction index of the lowest few-hundred meters of the atmosphere. The result is a greater bending of the radar waves passing through the abnormal condition. The increased bending in such a situation is referred to as ducting and may greatly affect radar performance. The radar horizon may be extended or reduced, depending on the direction the radar waves are bent. The ducting that has the greatest effect on radar performance is the one that is caused by evaporation of water. The evaporation duct affects radar detection ranges at frequencies of approximately 3 *GHz* and above. Since the frequency range in question is the range in which almost all radars operate, it is of utmost importance that this effect be modelled. However, in a simulation, analytically calculating the ducting effect in every simulation cycle would require substantial computational time and processing power. In a radar simulation with a very large coverage area and hundreds of objects, this simply would be unrealizable.

In this study, we have developed a model for ducting effect that is simple, fast and requires minimum processing power. The proposed model is based on real radar data and outputs of commercial software tools that calculate radar range under different conditions.

The structure of the paper is as follows; atmospheric ducts, evaporation duct models, the commercial software tools whose outputs are used in the proposed model are described in Section 2. Section 3 outlines the factors that change the evaporation duct and details the proposed model. Finally, some concluding remarks are given in Section 4.

2. ATMOSPHERIC DUCTS

An electromagnetic duct is a channel/atmospheric layer, caused by the variation of index of refraction for EM waves that varies with altitude, in which EM waves can propagate over great ranges.

Ducts not only give extended radar detection ranges to radar within the duct, but they may also have other dramatic effects. For example as it can be seen in Figure 1, an airborne target that would normally be detected may be missed if the radar is within or just above the duct and the target is just above the duct. Also an airborne target that would normally be missed due to be located beyond the horizon may be detected as a result of the extended range (Skolnik 2008).

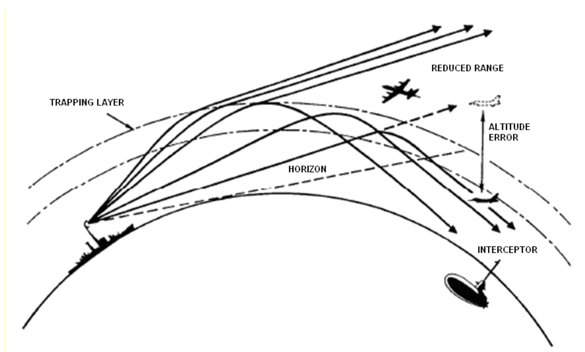


Figure 1: Ducting Effect on Radar Performance (Skolnik 2008)

Although ducts act like a waveguide for the energy, this waveguide does not have rigid and impenetrable boundaries. Therefore, energy is continually leaking from the duct.

Several meteorological conditions will lead to the forming of ducts. Ducts take different names and have different effects on EM waves according to the way and altitude they form. There are four different types of ducts, namely (Patterson et al. 1994)

- Surface ducts
- Surface-based ducts
- Elevated ducts
- Evaporation ducts

This study focuses on evaporation ducts that have the most effect on radar performance in terms of detection range.

2.1. Evaporation Duct

A change in the moisture distribution without an accompanying temperature change can lead to a trapping refractivity gradient. The air in contact with the ocean's surface is saturated with water vapour. A few meters above the surface the air is not usually saturated, so there is a decrease of water vapour pressure from the surface to some value well above the surface. The rapid decrease of water vapour initially causes the modified refractivity, *M*, to decrease with height. However, at greater heights the water vapour distribution will cause *M* to reach a minimum and, thereafter, increase with height. The height at which *M* reaches a minimum is called the evaporation duct height, as illustrated in Figure 2.

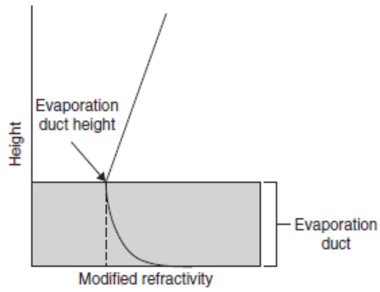


Figure 2: Refractivity for Evaporation Duct (Skolnik 2008)

Evaporation ducts exist over the ocean, to some degree, almost all the time. The duct height varies from a meter or two in northern latitudes during winter nights to as much as 40 *m* in equatorial latitudes during summer days. According to Engineer's Refractive Effects Prediction System (EREPS) Surface Duct Summary (SDS) database, on a world average, the evaporation duct height is approximately 13.1 *m* and evaporation ducts occur between 6-20 *m* at 72% of the time. Because the evaporation duct is much weaker than the surface-based duct, its ability to trap energy is highly dependent on frequency. Generally, the evaporation duct is only strong enough to affect electromagnetic systems above 3 *GHz*.

2.1.1. Evaporation Duct Models

Evaporation duct heights can be measured directly or calculated from meteorological measurements such as atmospheric pressure, air temperature and humidity at the air/sea interface.

Direct measurement devices are quite expensive and complicated. Direct measurement should not be attempted because, due to the turbulent nature of the troposphere at the ocean surface, a refractivity profile measured at one time would most likely not be the same as one measured at another time, even when the two measurements are seconds apart (Patterson et al. 1994).

For these reasons today's all modern evaporation duct height determination methods are raised from applications of meteorological measurements on techniques developed based on Monin-Oboukhov similarity theory (Monin 1954). Monin-Oboukhov similarity theory is a semi-empirical theory and its parameters are determined experimentally. An application of theory like Jeske technique (Jeske 1973) predicts the duct height with an *rms* error exceeding 7 *m* and the Paulus-Jeske correction (Jeske 1973; Paulus 1984, 1985, 1989) predicts the duct height with an error of 4.5 *m* (Ivanov 2006).

EREPS and Advanced Refractive Effects Prediction System (AREPS – A software tool developed to examine EM system performance) utilize Paulus-Jeske correction to determine evaporation duct height (Patterson et al. 1994, AREPS UM).

In literature, there are many studies analysing the effects of evaporation ducts on the radar performance. Paulus (1984) has developed the first evaporation duct model for IREPS (Integrated Refractive Effects Prediction System), Marom (1988) has analysed the effects of evaporation ducts on radar detection performance and presented some design and operational considerations which can improve the detection performance of radar, Reilly and Dockery (1990) has studied effects of evaporation ducts on radar sea return and therefore radar detection performance and presented a model for radar sea return, Paulus (1990) has considered existing radar sea return models and investigated the effects of evaporation ducts on grazing angles, Patterson et al. (1990) has applied IREPS model to EREPS, Paulus (1994) has compared EREPS model outputs with real data and Lin and Yong-gang (2008) has analysed effects of horizontally heterogeneous evaporation ducts on radar detection performance.

All of these studies are conducted to analyse the effects of evaporation ducts on radar performance, in order to improve radar designs and operational considerations and to present models of realistic EM propagation in the presence of evaporation duct. So all of the models resulted from these studies emerge as inappropriately complex and slow for a radar simulation desired to produce results fast. This causes a necessity to develop a simple, accurate and fast modelling of the evaporation duct effect unlike the ones present in the current literature. For this purpose the outputs of the complex and most commonly used EREPS, AREPS and Computer-Aided Radar Performance Evaluation Tool (CARPET - developed by an independent Dutch research organization called TNO) (Huizing & Theil) models are analysed.

EREPS, AREPS and CARPET software tools all have incorporated evaporation duct effects into their models. All of these three tools use Patterson et al.'s (1990) model for evaporation duct, developed for Naval Oceans System Centre (NOSC) and EREPS. This model first defines the propagation factor (*F*) in terms of height and gain equations and then defines range and height gain equations in the regions of evaporation duct effect as many other models do. The propagation factor which is the base of all advanced propagation models is also a part of the basic radar equation.

Careful examination of these equations will reveal that these equations depend basically on the radar frequency, duct height, radar and target heights. Moreover, analysis of the propagation factor curves produced by CARPET for various atmospheric and meteorological data has shown that, when ducting is present, the propagation factor also depends on only these four parameters. This fact provides means for developing a simple yet efficient model for the evaporation duct effect, details of which are presented in the following section.

3. PROPOSED EVAPORATION DUCT MODEL

In order to fully understand the effects of the parameters, namely, radar frequency, radar height, target height and ducting height on the propagation factor curves many different simulations have been run for various values of the parameters. It has been observed that all of the curves can be easily represented by three linear equations that are defined in three different regions, thus the curves can be defined by three points at maximum.

Based on these results, we conducted some studies on generating a baseline data set for propagation factor curves each defined by three points using predetermined data and reproducing the propagation factor curve for a given set of input data based on the baseline data set.

Note that, producing the baseline data set is of utmost importance for minimizing the errors of the curves that will be reproduced based on the baseline data set. Therefore, effects of these four variables on the propagation factor in the presence of evaporation duct have been analysed in detail.

3.1. Effect of the Radar Frequency

It was mentioned that the evaporation duct affects radar detection ranges at frequencies of approximately 3 *GHz* and above. Propagation factor curves with respect to the detection range for radar frequencies 3.5, 5, 7, 9, 11 and 15 *GHz* are shown in Figure 3 and the analysis of Figure 3 corroborates with the lower limit of 3 *GHz*.

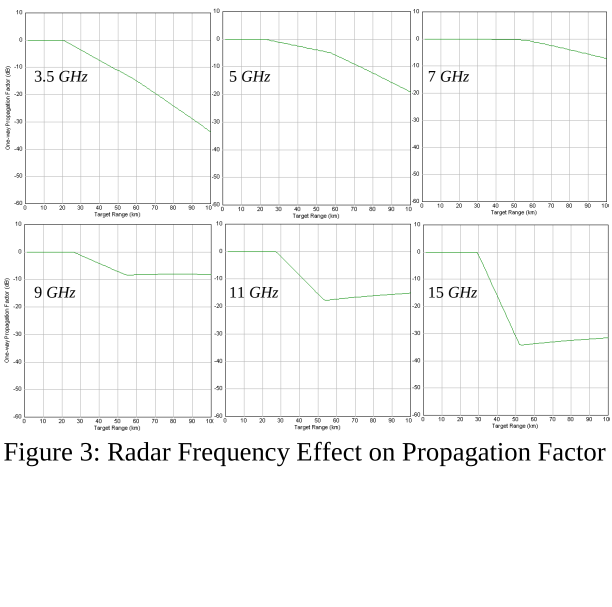


Figure 3: Radar Frequency Effect on Propagation Factor

The results from the CARPET software suggest that the baseline data set should contain at least one propagation factor curve for each radar band between 2.5 *GHz* and 15 *GHz*, i.e. E, F, G, H, I, J bands.

3.2. Effect of Evaporation Duct Height

Figure 4 illustrates the detection probability produced by CARPET for two different radars located at 20 *m* operating at 2.5 *GHz* and 8 *GHz* for the evaporation duct heights of 10 *m* and 25 *m*. In the figure the detection probability varies from 100% for the red colour to 0% for blue. As it can be seen from the top left and bottom right subfigures, the 10 *m* duct does not have a major effect on 2.5 *GHz* radar and the 25 *m* duct does not have a major effect on 8 *GHz* respectively. On the other hand, as it can be seen from top right and bottom left subfigures, the effects of 10 *m* duct on 2.5 *GHz* and 25 *m* duct on the 8 *GHz* radars are rather substantial respectively. As these results indicate, evaporation ducts forming at high altitudes are effective in low frequencies whereas they are effective in high frequencies, when they form at lower altitudes.

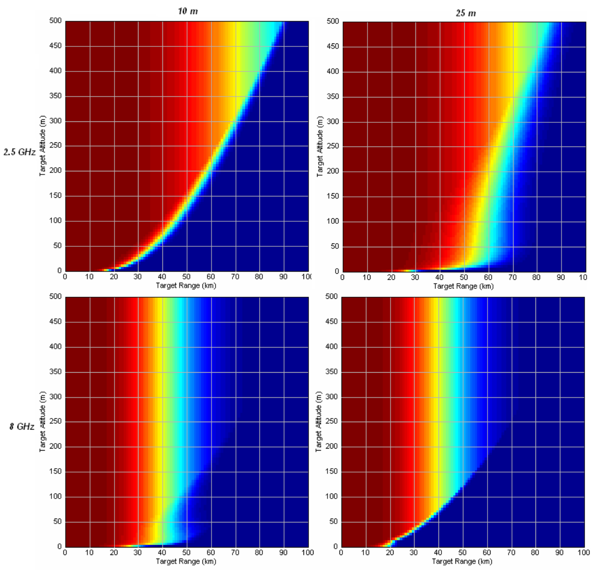


Figure 4: Evaporation Duct Height Effect on Radar Coverage

Average evaporation duct height around the world is 13.1 *m* and this height has the most effect for the frequencies between 6-9 *GHz* (H-I Bands) at which most of the surface and navigation radars operate. When these facts are considered, it is intuitive to set the evaporation duct height to the average duct height of 13.1 *m* in the baseline data set.

With further analysis it is noticed that when evaporation duct is elevated, similar effects are observed in lower frequency ranges. This effect can be observed on the coverage diagrams in Figure 5. As an example the coverage diagrams of 15 *m* duct on 5 *GHz*, 13 *m* duct on 6 *GHz* and 10 *m* duct on 8 *GHz* are quite similar. This implicates that the effects of different duct heights can be obtained by shifting the radar frequency in accordance with the difference between the duct height and 13.1 *m*.

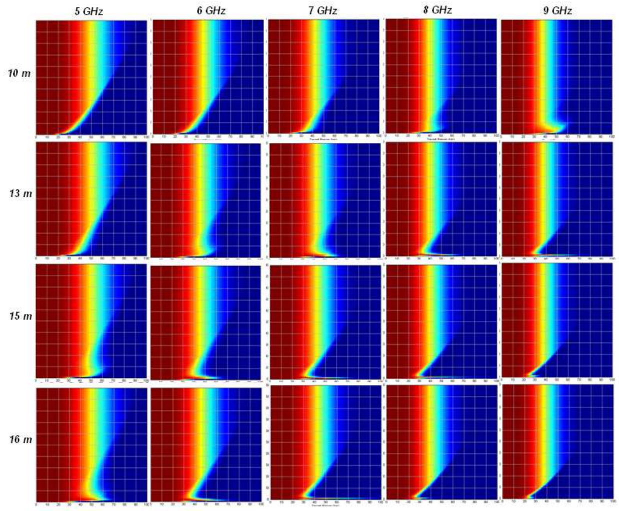


Figure 5: Evaporation Duct Height, Radar Frequency Range Relation

3.3. Effect of Radar and Target Height

In Figure 6, radar coverage diagrams are given for 13.1 *m* evaporation duct and 10 *m*, 20 *m* and 30 *m* radar heights respectively. In can be seen that the radar being located above or below the duct height creates no apparent difference in radar performance as the height difference between a ship borne radar and evaporation duct is usually negligible and the angles between the transmitted EM waves and duct borders are usually narrow enough for allowing the duct to bend these waves.

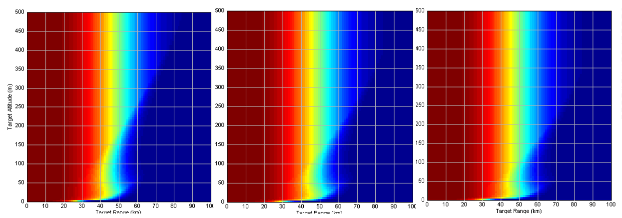


Figure 6: Radar Height Effect on Radar Coverage

The equations for the propagation factor usually include the height gain twice in order to account for the target and radar heights. For example, propagation factor for diffraction region can be defined as follows, where *V(r)* is range gain function, $U(Z_r)$ and $U(Z_t)$ are height gain functions for radar and target heights respectively.

$$F^2 = V(r)U(z_r)U(z_t) \qquad (1)$$

This suggests that both the radar and target heights have the same effect on the propagation factor curve at those heights. That is, the propagation factor curve for a scenario where the radar is located at 10 *m* and the target at 30 *m* will be the same as the propagation factor curve for the scenario with the radar located at 30 *m* and target at 10 *m*. In other words, the detection probability for a target at 30 m altitude by a radar at 10 *m* is exactly the same as the detection probability for a target at 10 *m* altitude by radar at 30 *m*.

3.4. The Proposed Model

The proposed model for the evaporation duct involves using tabulated data that are produced utilizing the outcomes detailed in previous subsections. The tabulated data was previously referred to as the baseline data set and is given in Table 1. Table 1 presents the propagation factor curves, employed as the baseline data set, as obtained from the CARPET software for 13.1 *m* evaporation duct height, 20 *m* radar height, E, F, G, H, I and J radar band frequencies and 3 different target altitude intervals.

The curves given in Table 1 serve as an extension to the radar simulation for modelling effect of evaporation duct to the radar signal propagation and detection distance. During the simulation, the propagation factor is linearly interpolated from the values given in Table 1 to the operator defined duct and target heights and radar frequency. This way, very efficient, accurate and simple modelling of the ducting effect is achieved without increasing the computational load of the radar simulator. Adding new functions to an intrinsically complex and computationally loaded simulator without elevating the load is desirable.

The proposed model has been tested by comparing the propagation factor curves obtained through the evaporation duct model added radar simulator and the ones produced by the CARPET software. An example comparison is given in Figures 7 and 8 for a radar operating at 5.5 *GHz* on a 20 *m* high target. As it is seen from figures both outcomes are very similar and the difference is small enough to be ignored.

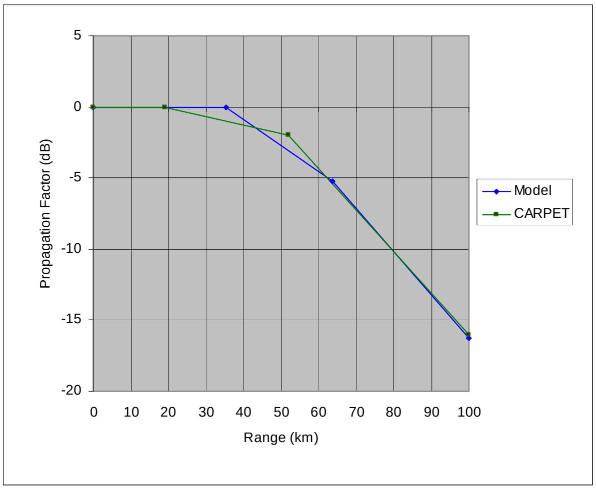


Figure 7: Comparison of Proposed Model and CARPET Output in terms of Propagation Factor

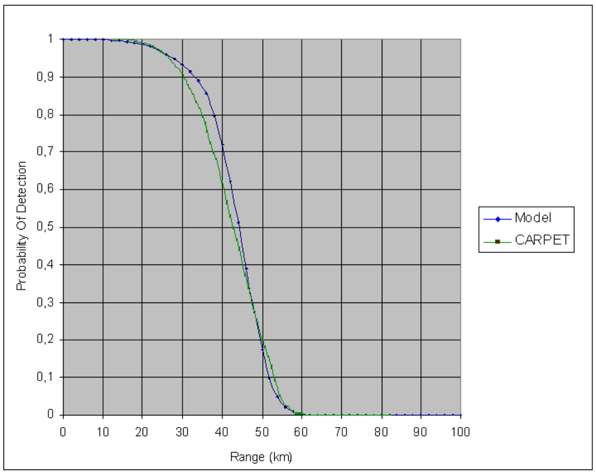
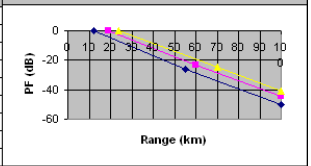
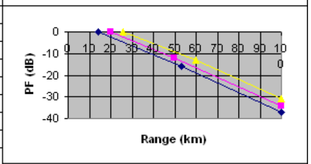
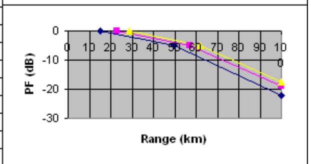
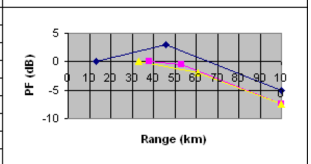
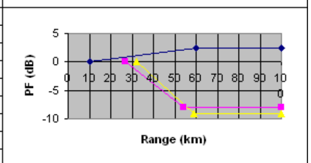
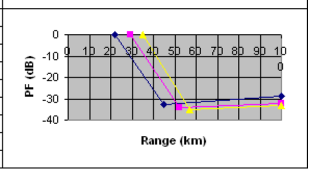


Figure 8: Comparison of Proposed Model and CARPET Output in terms of Detection Probability

Table 1: 13.1 m Evaporation Duct Propagation Factor Curves

13.1 m Evaporation Duct Height Propagation Table					
Band	**Frequency (GHz)**	**Target Height (m)**	**Range (km)**	**PF (dB)**	**Graph**
E	**2,5**	**15**	12	0	
			55	-26	
			100	-50	
		30	19	0	
			60	-23	
			100	-44,5	
		45	24	0	
			70	-25	
			100	-41	
F	**3,5**	**15**	14	0	
			53	-16	
			100	-37	
		30	20	0	
			50	-12	
			100	-34	
		45	26	0	
			60	-13	
			100	-31	
G	**5**	**15**	15	0	
			50	-5	
			100	-22	
		30	23	0	
			57	-5	
			100	-19	
		45	29	0	
			62	-5	
			100	-17,5	
H	**7**	**10**	13	0	
			46	3	
			100	-5	
		30	38	0	
			53	-0,5	
			100	-7,5	
		45	33	0	
			61	-2	
			100	-7,5	
I	**9**	**5**	10	0	
			60	2,5	
			100	2,5	
		30	27	0	
			54	-8	
			100	-8	
		45	32	0	
			59	-9	
			100	-9	
J	**15**	**15**	22	0	
			45	-32,5	
			100	-29	
		30	29,5	0	
			52	-34	
			100	-32	
		45	35	0	
			57	-35	
			100	-33	

4. CONCLUSIONS

In this study, a simple, efficient and accurate yet computationally cheap modelling of evaporation duct effects has been presented. The possibility of occurrence of evaporation ducts is very high and their effects to radar model are significant. Therefore, it is rather important to come up with an accurate and simple model that does not increase the already elevated computational load of the simulator. The proposed model is a tabulated extension to a big radar simulation where hundreds of radars take observations from hundreds of targets. The baseline tabular data have been obtained utilizing commercial software tools such as CARPET, AREPS and EREPS. The baseline data of the propagation factor curve has been obtained depending on the radar frequency, duct height, radar height and target height and employed in the radar simulator instead of utilizing online complicated and signal level calculations. The proposed model has produced near perfect results compared to the commercial modelling tool called CARPET. Application of the effects of different atmospheric ducts is left as further study.

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