Applying Numerical Weather Prediction Data to Enhance Propagation Prediction Capabilities to Improve Radar Performance Prediction

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ABSTRACT

Tactical decision aids (TDA) and tactical planning aids (TPA) used to support the warfighter are continuously evolving over time. The evolution occurs both in how a particular system is modelled; and, for electromagnetic systems, which are influenced by the environment, how the environment is represented. The environmental inputs to TDAs can take the form of simple environmental assumptions, bulk meteorological measurements, or numerical weather prediction (NWP) data generated by NWP models, such as the U.S. Navy's Coupled Ocean / Atmosphere Mesoscale Prediction System (COAMPS).

In the context of TDAs and TPAs that are used to provide radar setup guidance or performance predictions, the characterization of the refractive nature of the atmosphere is of prime importance. The characterization of atmospheric refractivity can be based on measurements, climatological data, or modelled using NWP data. NWP, in particular, is now allowing a better characterization of the environment in range, height, bearing, and time. The evolution from low fidelity approximations to higher fidelity model forecasts is allowing TDAs and TPAs to provide more relevant guidance, or performance prediction, to the warfighter.

This paper will cover the current implementation of NWP modelling to generate refractivity profiles for use in the Advanced Propagation Model (APM). A description is provided that demonstrates how the propagation model output feeds radar performance models, such as those found in the Advanced Refractive Effects Prediction System (AREPS). The paper will highlight the improvements in propagation prediction, resulting from increased fidelity in modelling the atmosphere using NWP data, as compared to previous propagation assessments using simple, theoretical environmental assumptions.

1.0 IMPORTANCE OF RF PROPAGATION

The understanding and inclusion of Radio Frequency (RF) propagation effects are central to providing meaningful systems engineering analysis of radar system designs, supporting test and evaluation efforts, and improving the fidelity of TPAs and TDAs used in radar system applications. For the purposes of RF propagation, the radar frequency range is defined between 3 MHz and 300 GHz. RF propagation is specifically defined to be the passage of electromagnetic (EM) waves through the atmosphere. For the purposes of this paper, the atmospheric region of interest is the troposphere.

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1.1   The Troposphere

The troposphere is defined to be the region of the atmosphere between the surface of the earth and approximately 10 km. This region consists of four principle regions that include: the roughness layer, the surface layer, the outer layer, and the inversion base. The boundary layer is the region that includes the roughness, surface, and outer layers, found below the inversion. The roughness layer is the layer that contains the roughness elements, such as terrain or ocean surface waves, which create friction with the atmospheric fluid, impacting the resultant RF propagation. The gradient of the refractivity of the troposphere can have significant impacts on RF propagation from surface emitters.

1.2 Refractivity

Refractivity is typically represented numerically using vertical profiles of either refractivity (N) or modified refractivity (M) versus height. Refractivity (equation 1)[1] is dependent on the meteorological parameters typically measured by meteorological radiosondes or provided by NWP models. Modified refractivity (equation 2) is proportional to refractivity (equation 1); and, is typically used because modified refractivity accounts for the curvature of the earth.

$$N = \frac{77.6 p_{air,mb}}{(T_{air,°C})+273.15} + \frac{(3.73\times10^5)(e_{mb})}{((T_{air,°C}))((T_{air,°C})+273.15)^2} \quad (1)$$

$$M = N + \left(\frac{z}{r_{earth}}\right) * 1e^6 \qquad (2)$$

Typical propagation environments are categorized as follows:

1.   Free space (F = 1)
2.   Near standard
3.   Sub-refractive
4.   Super-refractive
5.   Ducting

The "near standard" environment does not mean that this environment is common. This environment is based on a National Advisory Committee for Aeronautics (NACA), predecessor to the National Aeronautics and Space Administration (NASA), flight standard (Sissenwine et al. 1976)[2]. It represents an idealized, steady-state representation of the Earth's atmosphere from the surface to 1000 km during periods of moderate solar activity. Sub-refractive environments are propagation conditions that lead to reduction in radar detection range. While super-refractive environments often lead to increases in detection range. Ducting typically leads to significant increases in radar detection range, but can also invite unwanted detections of clutter and other sources.

1.3 Propagation Factor

RF propagation is quantified using the propagation factor (*F*). For many system engineering efforts, the radar range equation (equation 3) is employed. The radar range equation is in many cases the basis for TDAs and TPAs.

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$$SNR_n = \frac{P_t G_t G_r \lambda^2 (dc) t_{cpi}(\sigma) F_t^2 F_r^2}{(4\pi)^3 R^4 k T_o F_n L_{atm} L_{sys}} \quad (3)$$

Propagation factor is typically calculated using mathematical models (e.g. parabolic equation routines) such as the Advanced Propagation Model (APM) developed by SPAWAR Systems Center – Pacific (SSC PAC). Propagation models require as inputs information about the transmitter and the environment. The minimum required RF system inputs include antenna height, antenna pattern, antenna pointing angle, and transmit frequency. Antenna height and pointing angle can influence the trapping of RF emissions in ducting conditions because a critical angle condition must be met in order to trap RF energy. The transmit frequency will impact the propagation characteristics of the environment because RF frequencies respond to atmospheric effects differently based on the wavelength. Typical environmental inputs are refractivity profile(s), surface electrical parameters (e.g. conductivity and permittivity) and surface roughness.

Visualization of the propagation factor is usually accomplished by plotting the propagation factor versus range and height for a specific bearing. Figure 1 is a typical example of a two way propagation plot. The region of propagation enhancement (red regions) located below 50 m is a trapping layer. Figure 2 is a plot of the refractivity profile used as input for the propagation models.
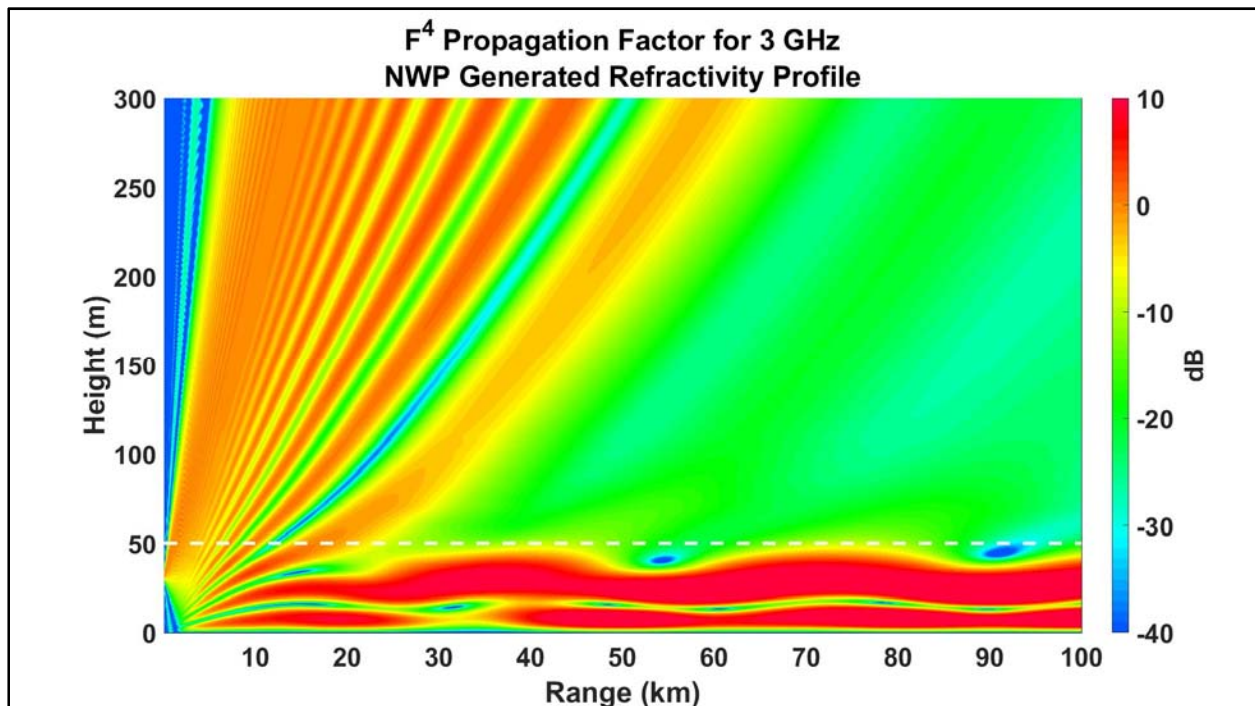

Figure 1: Example of a two-way propagation factor plot

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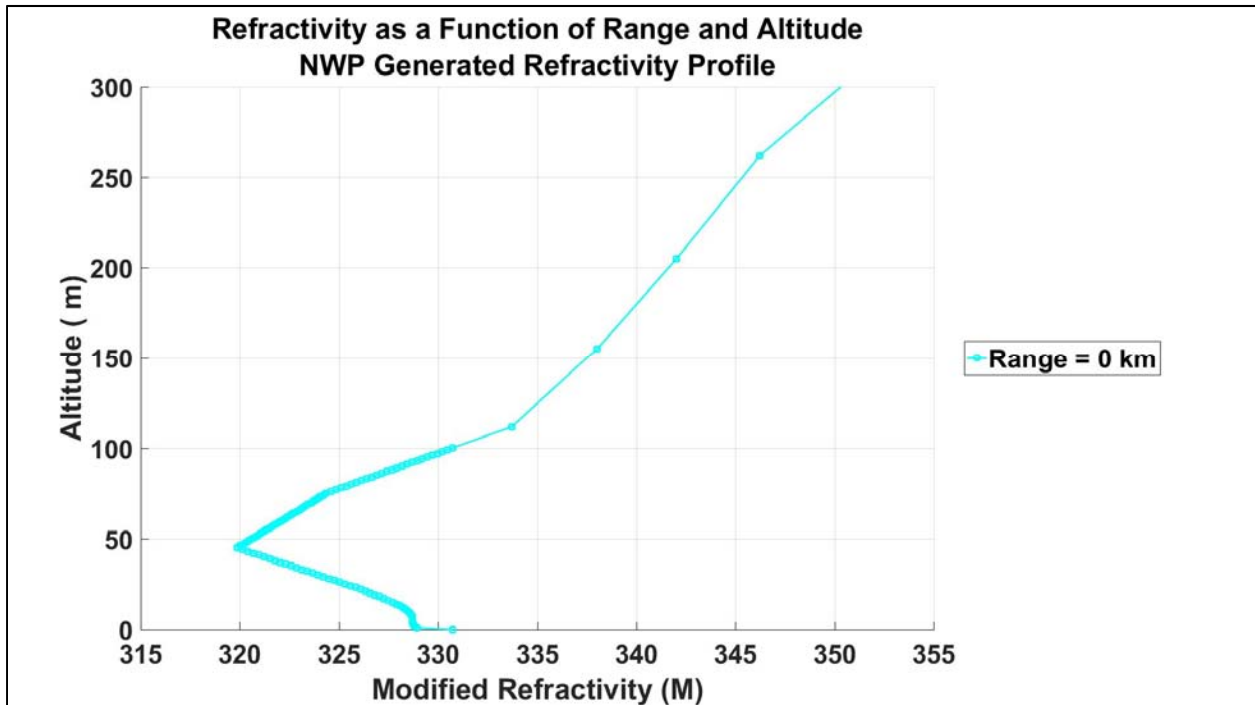Prediction Capabilities to Improve Radar Performance Prediction**

Figure 2: Example refractivity profile

Figure 2 shows a single modified refractivity profile versus height; however, modified refractivity, as well as refractivity, can be provided as range dependent profiles. If no measured or modelled profile is available but surface level measurements for air temperature, sea surface temperature, air pressure, relative humidity, and wind speed are known then an evaporation duct height can be calculated using a surface layer model such as the Navy Atmospheric Vertical Surface Layer Model (NAVSLaM)[3].

An evaporation duct is a common occurrence over the ocean resulting from the water vapor gradient between the ocean surface and the atmosphere just above the surface. The calculated evaporation duct can then be appended to a standard atmosphere profile. A standard refractivity profile is a profile for which the modified refractivity changes 118 M units per kilometre. Figure 3 shows the calculated propagation factor for a four meter evaporation duct appended to standard atmosphere.
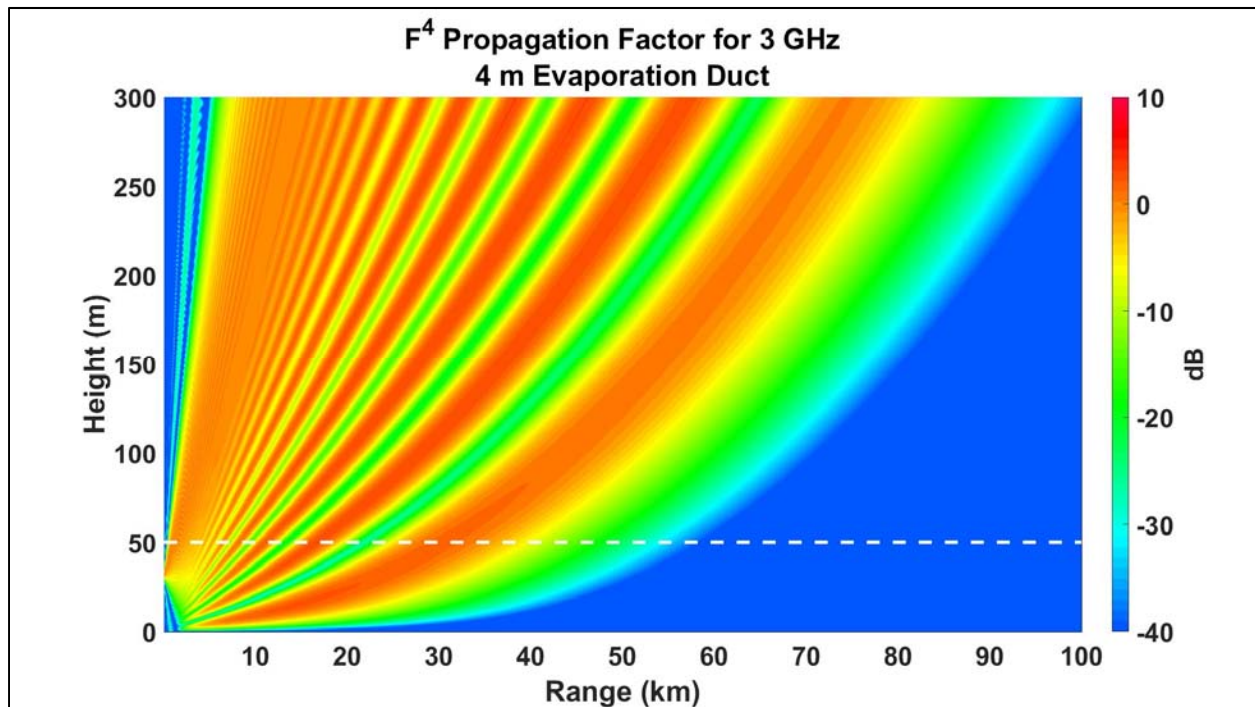
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**Figure 3: Calculated propagation factor (two-way) for a four meter evaporation duct appended
to standard atmosphere**

Compare figure 3 with figure 1, which is based on the refractivity profile shown in figure 2. The profile
shown in figure 2 also contains a four meter evaporation duct in addition to the upper level ducting feature.
Clearly there are differences in the resultant propagation due to the upper-level ducting feature. This
difference highlights the importance of capturing the vertical refractivity profile through either radiosonde
measurement or numerical weather prediction modelling.

2.0 EVOLUTION OF REFRACTIVITY MODELLING

Just as capturing a more accurate vertical representation of a single profile will improve propagation
prediction, capturing the range dependence of the atmospheric refractivity is also important. Capturing the
range dependency through measurement can be cost prohibitive, not realizable at all (e.g. area denial), or
introduce temporal differences. Given these limitations, an increasingly viable option is to use NWP
models.

2.1 Single Profiles versus Range Dependent Profiles

Figures 4 and 5 are two plots of the refractivity profiles that were used as input to the propagation model
that generated the propagation factor output shown in figures 6 and 7. The first profile in figure 5 is the
same profile shown in figure 4. Comparisons between figures 6 and 7 demonstrate the importance of
capturing range dependency. For example, note the point 50 m in height (dashed white line) at 50 km. At
this point there is approximately a 10 dB difference in two-way propagation factor.
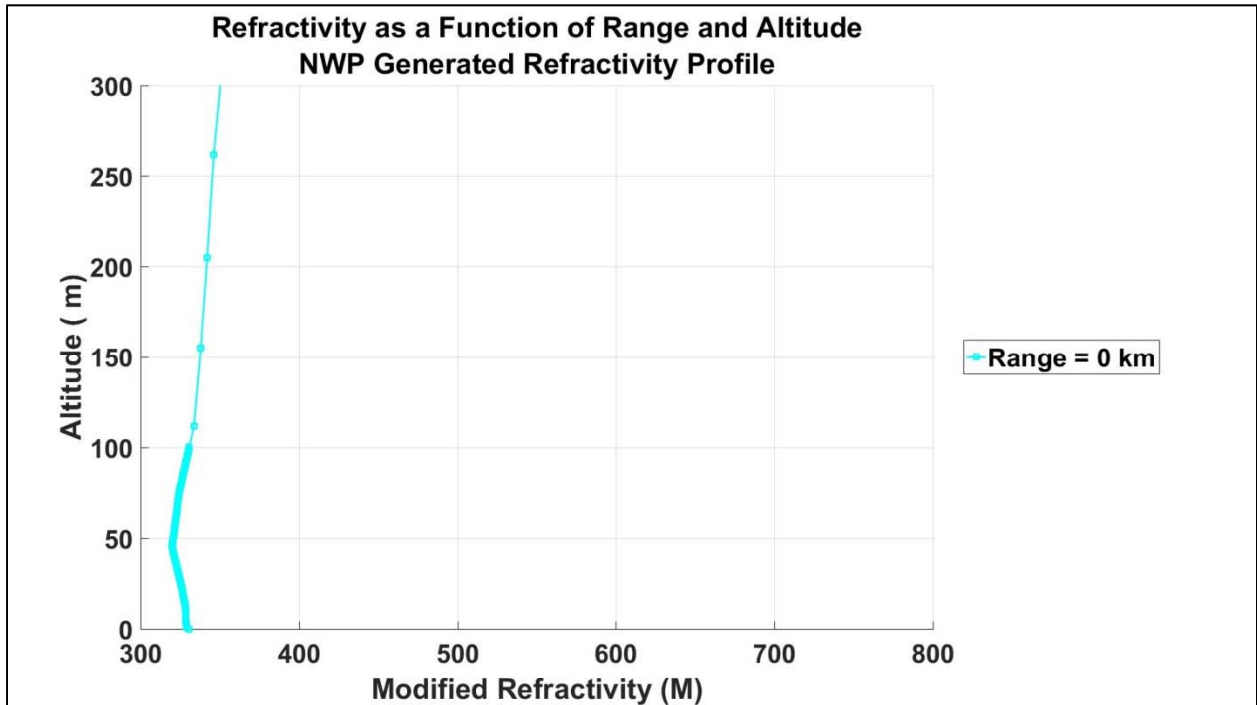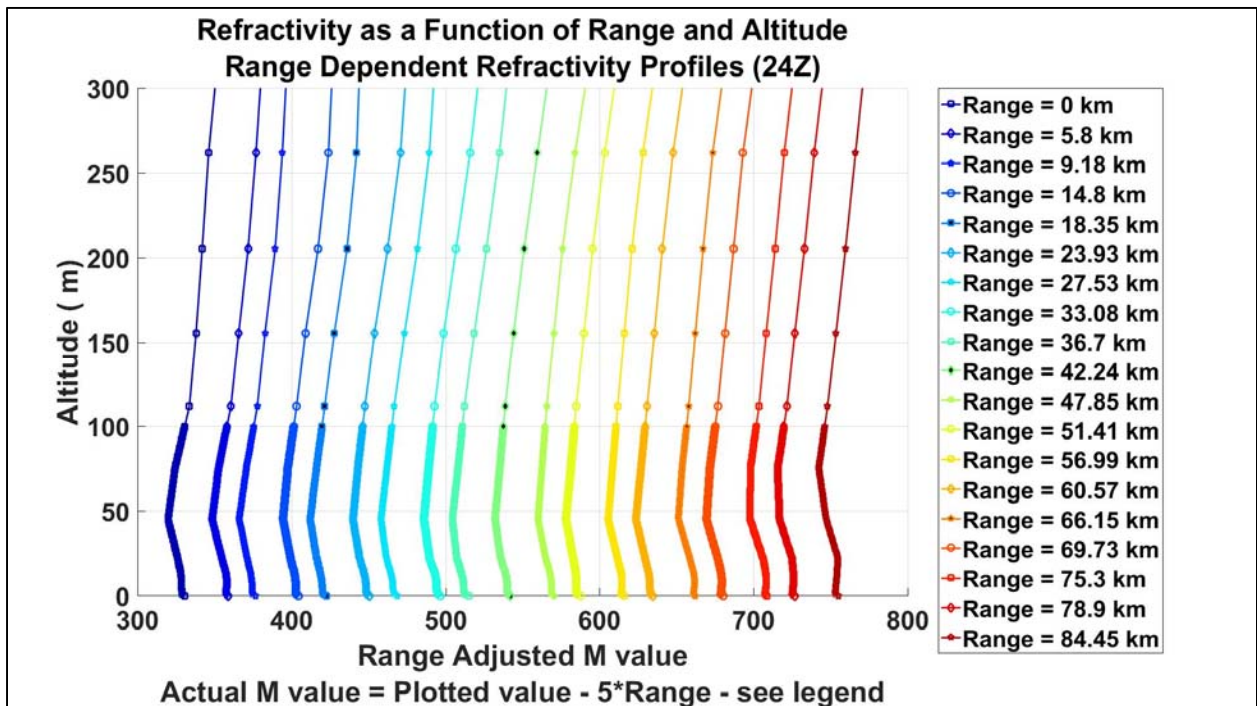
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Figure 4: Single Profile (NWP Generated)

Figure 5: Range Dependent Profiles (NWP Generated)

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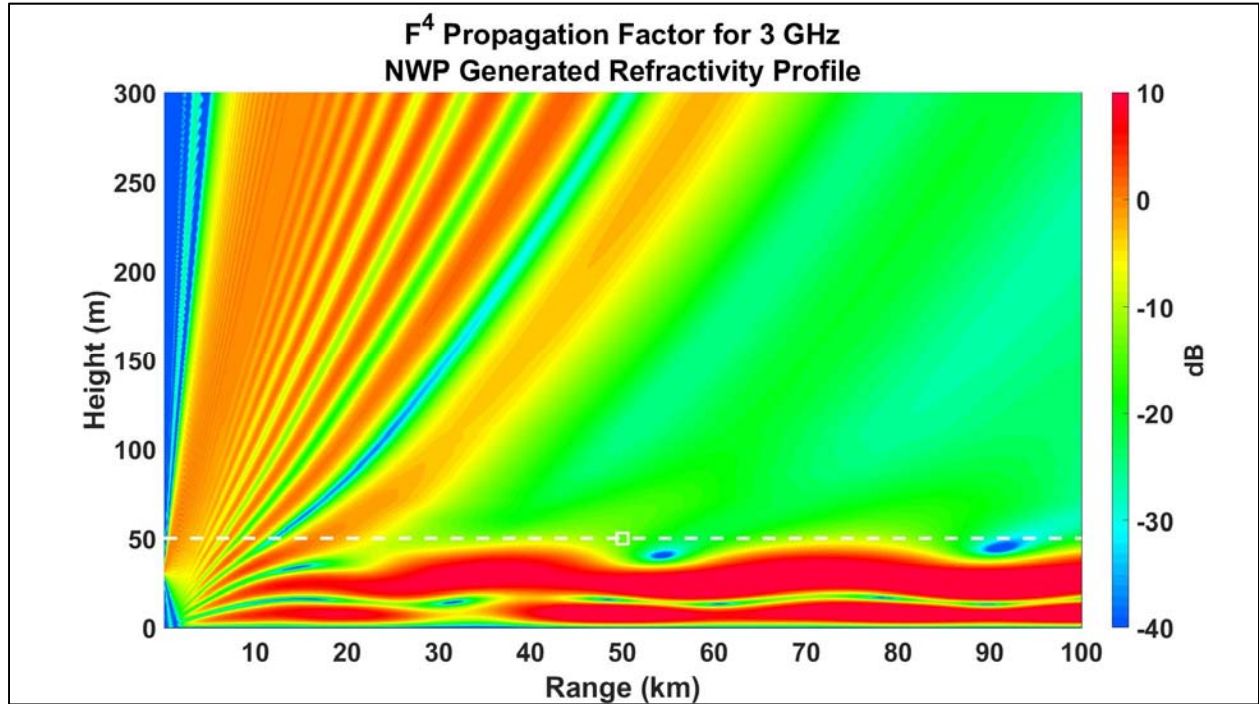
Figure 6: Two-way propagation factor calculated using a single refractivity profile
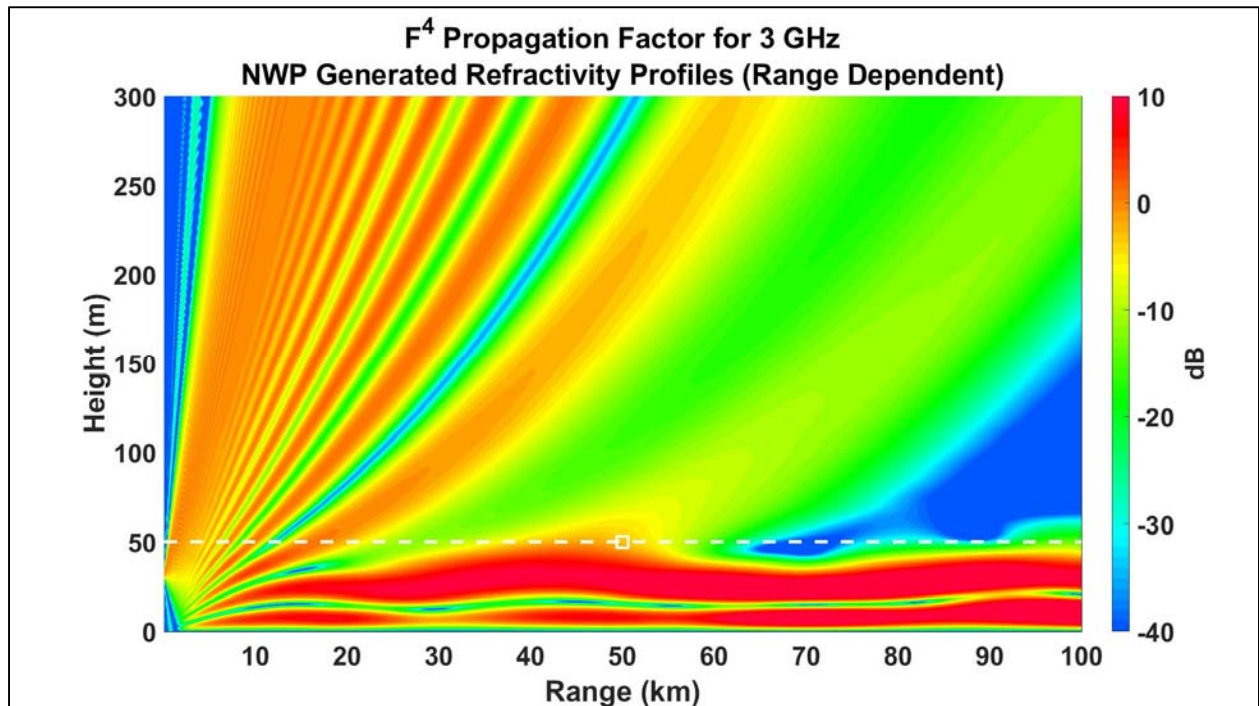
Figure 7: Two-way propagation factor calculated using range dependent refractivity profiles

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2.2 Azimuthal and Temporal Propagation Variations

The use of NWP models also allows the temporal and azimuthal differences in propagation to be captured. Figures 8 and 9 show the resulting propagation factor calculated using range dependent refractivity profiles that are separated in time by one hour. As can be seen by comparing the two figures, there can be significant differences in the propagation characteristics. In particular, note how the trapping layer has refracted downwards at distance over the course of one hour.
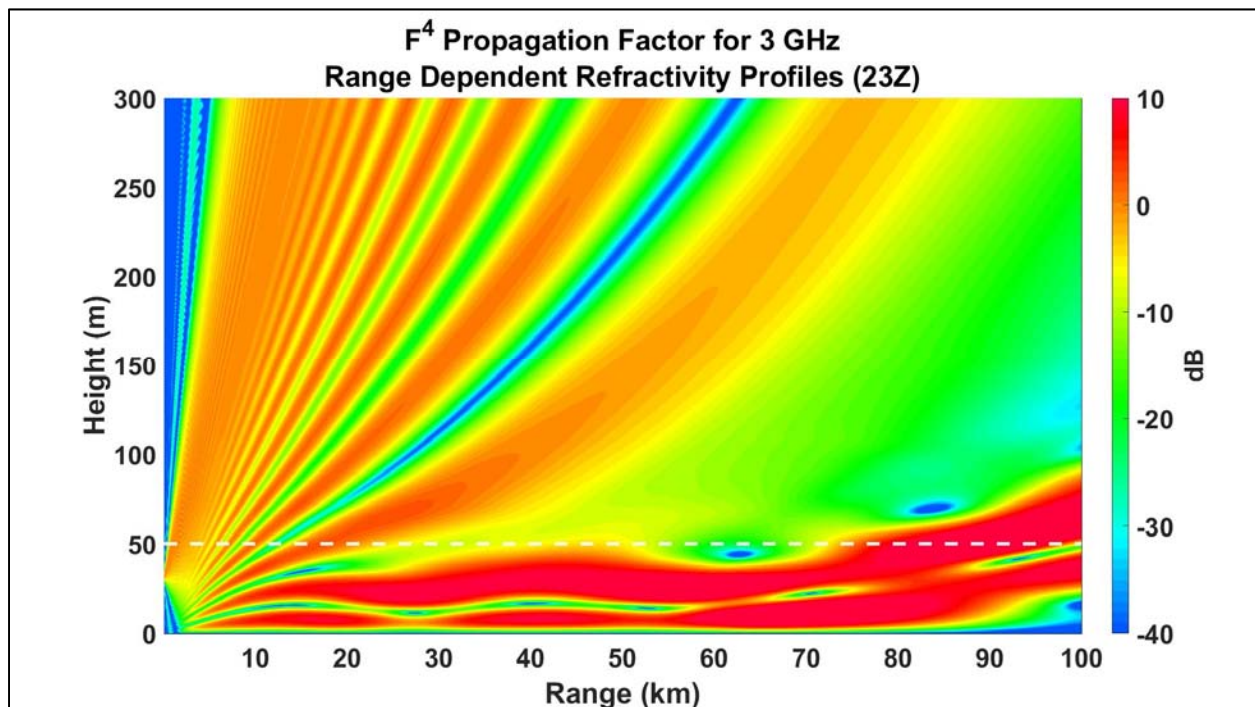

Figure 8: Two-way propagation factor calculated using range dependent refractivity profiles for hour 23 Z

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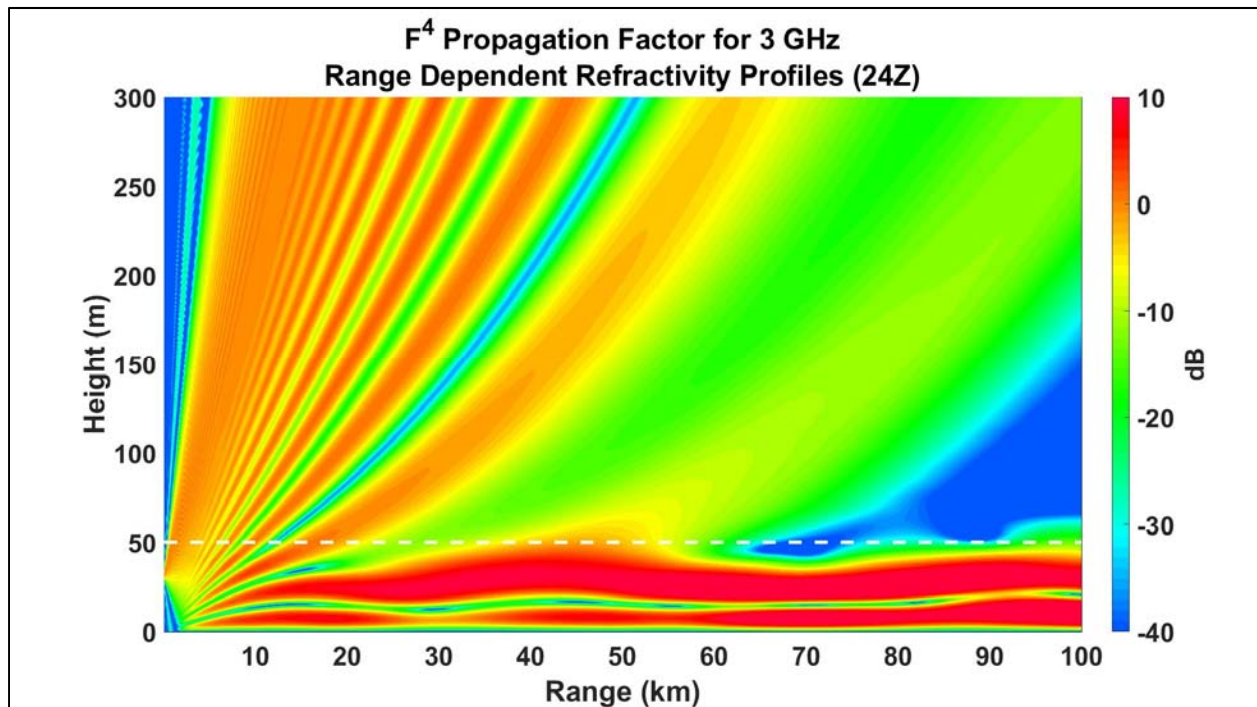Prediction Capabilities to Improve Radar Performance Prediction**

Figure 9: Two-way propagation factor calculated using range dependent refractivity profiles for hour 24 Z

Figures 10 and 11 are plots of propagation factor calculated using range dependent profiles along two different azimuthal bearings. As in the temporal case, there are significant differences in the resulting propagation characteristics.
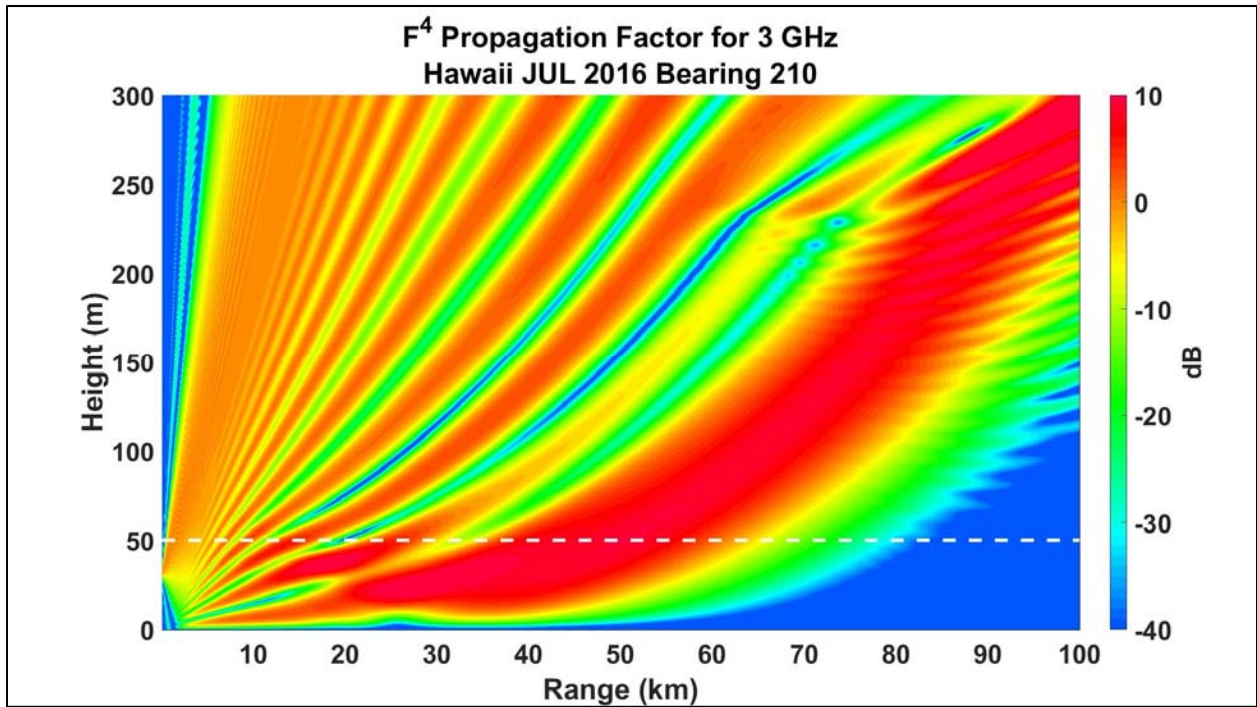
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Figure 10: Calculated propagation factor along bearing 210
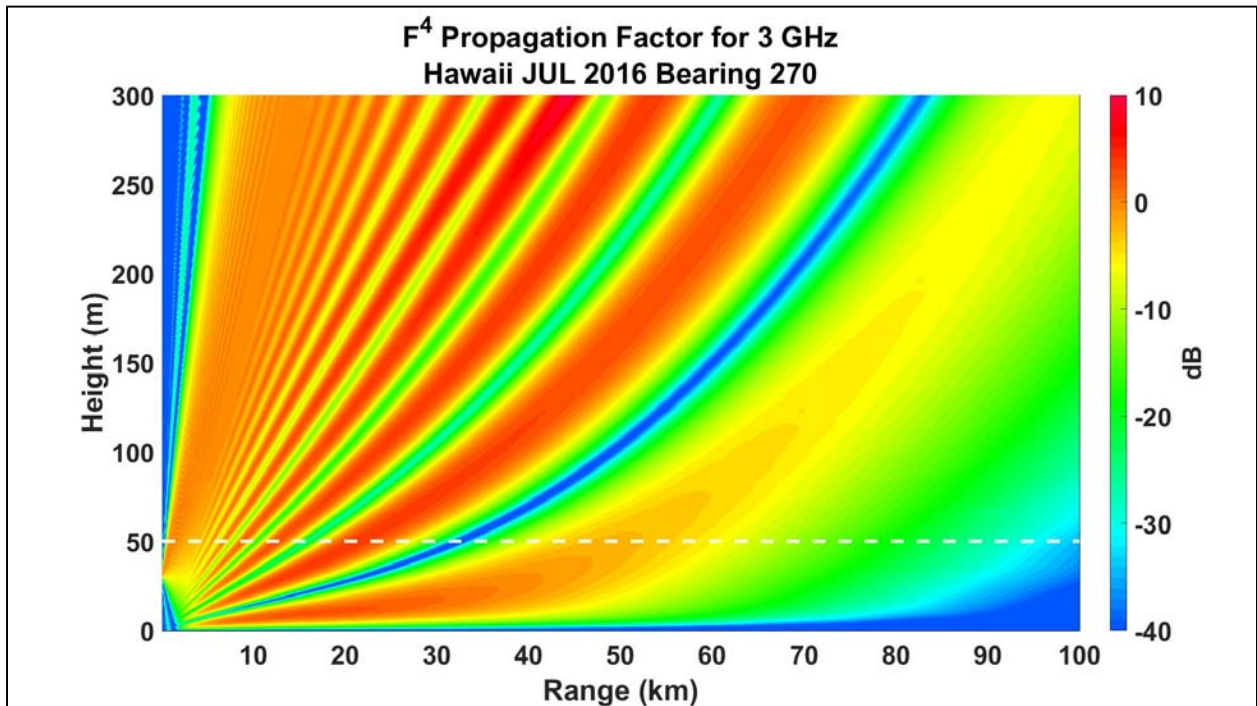
Figure 11: Calculated propagation factor along bearing 270

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2.3 Impacts to Probability of Detection

Figure 12 is a plot showing the impacts to probability of detection that can result from azimuthal differences in propagation conditions. The performance was calculated for a system operating at 3 GHz mounted 30 m above sea level against a 0 dBsm target at 50 m. On this plot, each detection radial indicates probability of detection less than 90% (red) or greater than or equal to 90% (black). Note the range extension in the southwest quadrant (210 – 215 degrees) as compared to the northwest quadrant (270 – 315 degrees). Each radial is separated by five degrees. Probability of detection is derived from signal-to-noise ratio (equation 3), which is dependent on the propagation factor.
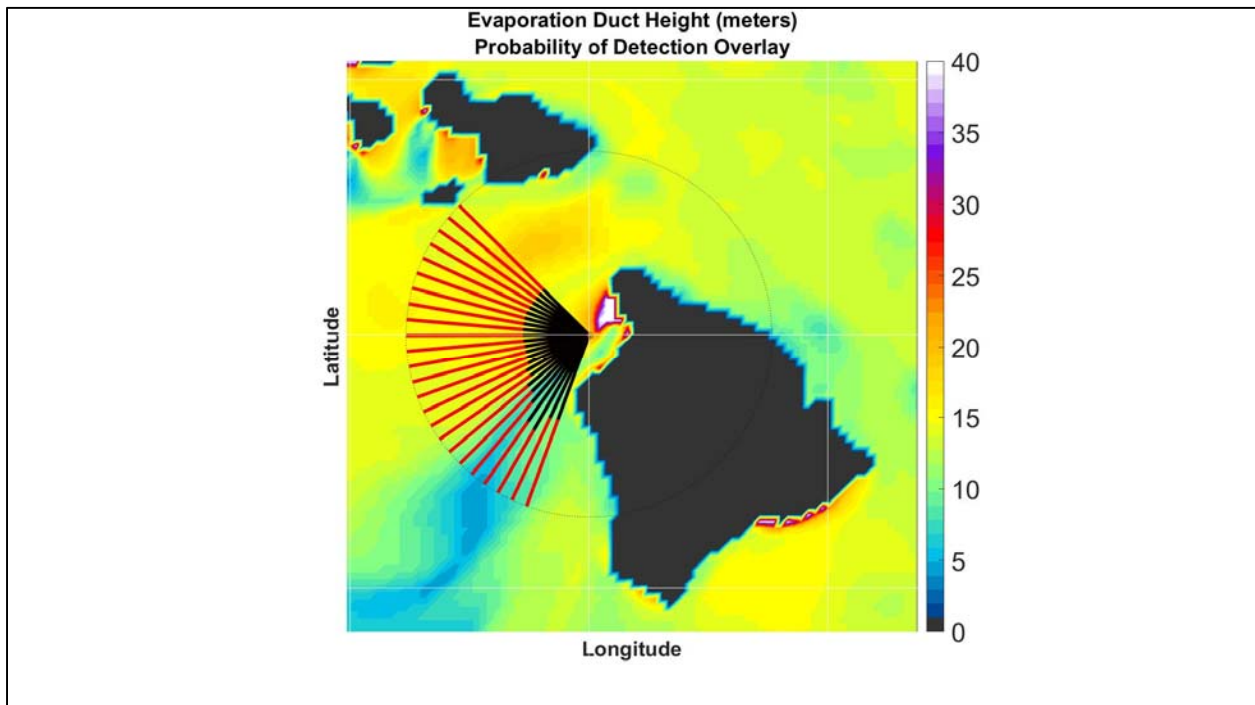

Figure 12: Probability of detection versus azimuth overlaid with evaporation duct height

3.0 SUMMARY

To summarize, the refractive nature of the atmosphere will impact the propagation of RF waves. RF propagation is quantified using propagation factor, which is calculated using mathematical models. The accuracy of the propagation calculations is directly related to how well the atmospheric refractivity is measured or modelled. By advancing the representation of the atmospheric refractivity from evaporation ducts appended to a near standard atmosphere to range dependent profiles, the accuracy of predicting RF propagation is improved. An increasingly viable approach to capturing the range dependency of the atmospheric refractivity is to use numerical weather prediction models. As the fidelity of calculating propagation factor improves, the output of tactical planning/decision aids that rely on RF propagation becomes more accurate and relevant to the warfighter.

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4.0 REFERENCES

[1]   Engineer's Refractive Effects Prediction System (EREPS) Version 3.0; Technical Document 2648, May 1994; Patterson,W.L. et al; Naval Command, Control and Ocean Surveillance Center; San Diego, CA.

[2]   Sissenwine, N., M. Dubin, and S. Teweles, COESA Cochairmen, 1976: U. s. Standard Atmosphere, 1976. Stock No. 003-017-00323-0, U. S. Government Printing Office, Washington, D. C. USA.

[3]   Frederickson, P. A., Department of Meteorology, Naval Post Graduate School, Monterey, CA.