Visualising and Predicting Tropospheric Ducting Impact on Radio-Based SCADA Networks

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Written by: Oliver Holden – 2537336

Supervisor: Laud Ochei

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This is a placeholder

Declaration of Originality

I, Oliver Holden declare that the dissertation entitled “Visualising and Predicting Tropospheric Ducting Impact on Radio-Based SCADA Networks” is my own work and that to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma at any university or equivalent institution.

I also now declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project’s design and conception or in style, presentation, and linguistic expression is acknowledged such as from inputs provided by my assigned project supervisor.

Any view expressed in this thesis are those of the author and do not necessarily reflect the views of the University of Dundee.

Abstract

Table of Contents

Acknowledgements 2

Declaration of Originality 2

Abstract 2

Introduction 4

Placeholder 4

Tropospheric Ducting and Radio Waves 5

Introduction

Placeholder

(PDF) Tropospheric Ducting: A Comprehensive Review and Machine Learning-Based Classification Advancements

Banafaa, Mohammed & Muqaibel, Ali. (2025). Tropospheric Ducting: A Comprehensive Review and Machine Learning-Based Classification Advancements. IEEE Access. PP. 1-1. 10.1109/ACCESS.2025.3537160.

The Importance Of SCADA Radio Communication In Modern Infrastructure Systems – Best Online Resource

Welch, A. C. (2025). *The importance of SCADA radio communication in modern Infrastructure Systems – Best online resource*. Retrieved October 20, 2025, from https://redefinetacoma.org/the-importance-of-scada-radio-communication-in-modern-infrastructure-systems/

Tropospheric Ducting and Radio Waves

Tropospheric ducting occurs when layers of the atmosphere create a temperature inversion combined with a change in humidity. If we consider “normal” conditions, we can easily observe that temperature lowers with altitude (a fact known to anyone who has ever climbed or hiked before!). The higher you rise, the colder it gets. A temperature ‘inversion’ in this context refers to a layer of warm sitting above cooler air, a phenomenon by itself that isn’t all that rare. Temperature inversions are not caused by weather or ground terrain solely as commonly thought, but instead we see this due to several different inversion events.

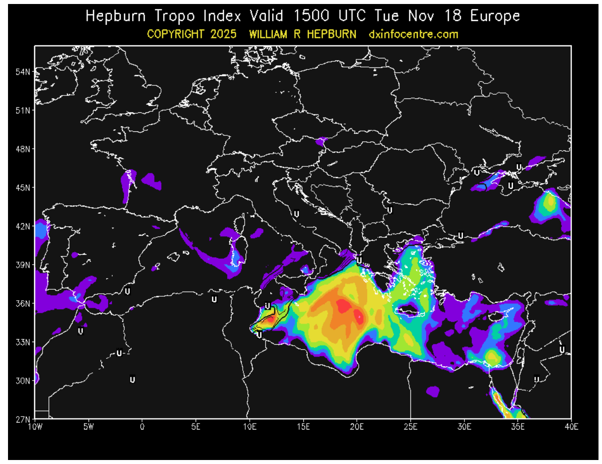

Figure 1 - Ducting prediction for continental Europe 18/11/2025

‘Radiation Inversion’ firstly makes reference to the cooling that occurs to the earths surface once the sun drops and the warming radiation of the suns rays can no longer reach us. At night, when the ground quickly loses its heat due to radiative cooling of the surface, the air closest (lower down) cools also leaving the air higher up warmer and thus an inversion.

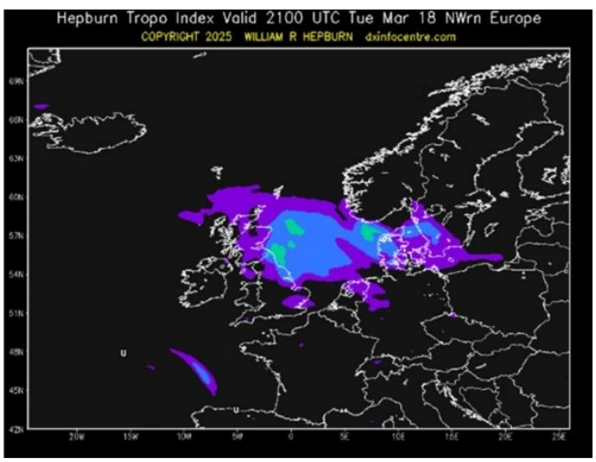

Figure 2 - Ducting prediction for north-western Europe 18/03/2025

‘Subsidence Inversion’ is associated with the behavior of air within high-pressure systems. In these conditions, large bodies of air gradually sink from higher altitudes toward the surface. As the descending air moves into regions of greater atmospheric pressure it is forced to compress which naturally leads to warming. This now warmed layer sits aloft above cooler surface air that remains settled forming a stable structure preventing vertical mixing. This sharp definition between layers is where we see the formation of refractive ducts.

‘Advection Inversion’, possibly the most common form of inversion, forms when a layer of warm air moves horizontally over an area of significant lower temperature such as large bodies of water or areas with snow coverage creating a similar effect to subsidence inversion in the forming of a duct. Looking to figures 1 and 2, you may note that the areas of the strongest ducting (coloured from strength values obtained from the ‘Hepburn Index’ of tropospheric duct strength) occur over the sea and often follow the curves of the coastline.

Together, these inversion events can form boundaries in both temperature and humidity which foster an environment for an atmospheric duct as we see the product of the phenomenon, effects known as refraction. Like the childhood science experiment of placing a small object into

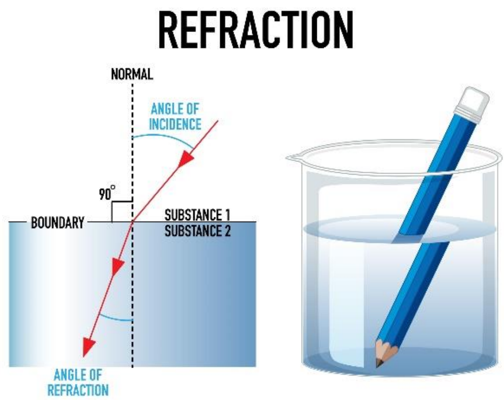

Figure 3 - A simple DIY refraction experiment (https://sciencevision.in/refraction-of-light-and-refractive-index/)

a glass of water which can be observed to cause bending of light (the object under the water appears to be disconnected from the object above the waterline). This test directly proves the theory of 'Snell's law' which describes the effects occurring while a ray of light crosses the boundary of two separate mediums (in this case air/ water)

This same effect is present in our atmosphere, and its strength is governed by the refractivity index defined by the following formula.

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

- N is the measure of how much the refractive index of air differs from a vacuum state and changes in N with variable height to determine the 'bend'
- P is the atmospheric pressure in the measurement of hectopascal (hPa) or millibar (mb)
- T relates to temperature in Kelvin (K) as the base unit of temperature for the international system of units
- e is water vapour pressure to be calculated in hectopascal units (hPa)

Higher humidity, higher pressure and lower temperature all increase refractivity affecting both light and radio wave propagation and this form of calculation is often used by various weather models such as the European Centre for Medium-Range Weather Forecasts (ECMWF), widely considered to be the most accurate model currently available. In this form, the values returned are difficult to work with, so we further calculate the M-units or Modified Refractivity which helps us determine the refraction gradient.

When radio waves travel near the earth's surface, the curvature of the planet naturally bends radio waves back downwards and to understand this, we can use the refractivity gradient to determine whether the atmospheric conditions are causing waves to bend more or less than the earth's curve bends below.

So firstly, we calculate M (Modified Refractivity) with the value of N (Refractive Index).

$$M = N + 0.157h$$

With 'h' representing the height above sea level in meters and 0.157 being the constant that comes from the geometric relationship between the earth's curvature and the path that radio waves follow through the lower atmosphere. This new value can then be further used to find the refractivity gradient which determines if a duct will have formed through the following.

$$\frac{dM}{dh} > 0$$

So as the M profile would increase naturally with gains in altitude, this new calculation counters this affect to consider the height of the atmospheric condition values gathered.