



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

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with Industrial Experience (Graduate Apprenticeship)

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# Acknowledgements

This is a placeholder

# Abstract

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# List of Abbreviations

Abbreviation	Definition
<b>SCADA</b>	Supervisory Control and Data Acquisition
<b>VHF</b>	Very-High Frequency
<b>UHF</b>	Ultra-High Frequency
<b>LOS</b>	Line-of-sight
<b>GrADS</b>	Grid Analysis and Display System
<b>VOACAP</b>	Voice of America Coverage Analysis Program
<b>RSGB</b>	Radio Society of Great Britain
<b>SDLC</b>	Software Development Lifecycle
<b>SSE</b>	Scottish and Southern Electricity
<b>NIST</b>	National Institute of Standards and Technology
<b>EAA</b>	European Accessibility Act
<b>MoSCoW</b>	Must have, Should have, Could have, Won't have
<b>DWD</b>	Deutscher Wetterdienst (German Weather Service)
<b>GRIB2</b>	General Regularly-distributed Information in Binary form (2 <sup>nd</sup> Edition)
<b>CDN</b>	Content Delivery Network
<b>S3</b>	Simple Storage Service
<b>AWS</b>	Amazon Web Services
<b>ICON</b>	Icosahedral Nonhydrostatic
<b>CNI</b>	Critical National Infrastructure

# 1. Introduction

Standing for ‘Supervisory Control and Data Acquisition’, SCADA telemetry is the hidden nervous system of the world, forming a critical component of national infrastructure. Embedded within utilities, manufacturing, transportation and pharmaceutical industries (DPS Telecom, n.d.), SCADA is a control system architecture that is used to supervise industrial processes and remote machines enabling real-time collation of data across wide geographical areas in addition to remote maintainability through dedicated control operator workstations.

Connectivity within SCADA networks can be achieved through a range of communication mediums depending on case-by-case operational requirements. Wired solutions that make use of ethernet or fiber-optic links are common in situations where assets are co-located or distributed within a short distance. In contrast, wireless radio-based networks are preferred when physical cabling is impractical- a common scenario best presented in the example of utilities where operational areas span cities, regions or entire countries. It is this wireless use case that is the motivation of the present investigation as these radio-based SCADA links operating in VHF and UHF frequency bands (Regulated utility companies must operate under specific licensed radio bands) are susceptible to interference from naturally occurring weather events that alters radio propagation through the extension or distortion of radio paths impacting the reliability of control systems that depend on line-of-sight (LOS) or near-LOS conditions.

This project aims to create a self-sustaining web application that integrates open-source meteorological data to estimate the probability and intensity of a phenomenon known as ‘atmospheric refraction’ or ‘tropospheric ducting’ events to assess the impact it may have on energy generation, transmission and distribution telemetry. By modelling these propagation anomalies and comparing predicted results with real-world impacts, the system can be modified over time for more accurate and improved results with the ultimate aim of providing a currently unseen insight into how environmental conditions may influence the performance of SCADA radio networks in the energy industry.

## 2. Research & Preparation

### 2.1 Tropospheric Ducting

Tropospheric ducting occurs when layers of the atmosphere create a temperature inversion combined with a change in humidity (ScienceInsights, 2026). 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.

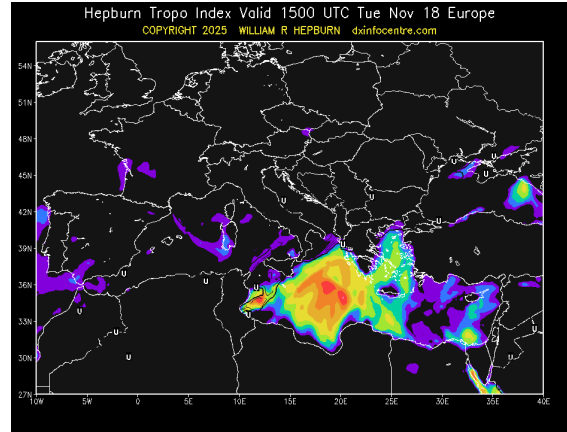


Figure 1 - Ducting prediction for continental Europe 18/11/2025

‘Radiation Inversion’ refers to the cooling that occurs to the earth’s surface once the sun drops and the warming radiation of our sun’s 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 (low down) cools also leaving the air higher up warmer and thus an inversion (Haby, n.d.).

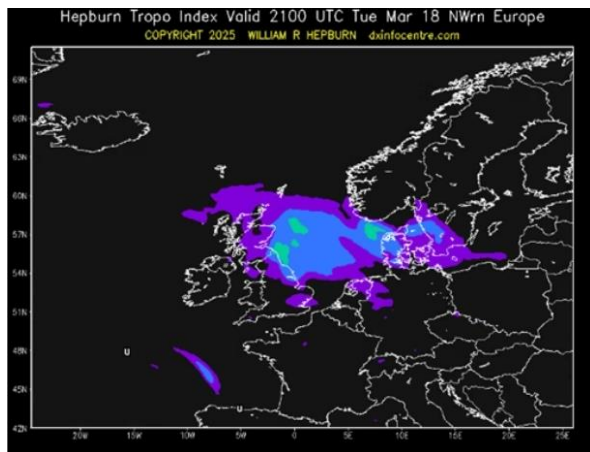


Figure 2 - Ducting prediction for north-western Europe 18/03/2025

‘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 (Naval Postgraduate School, n.d.).

‘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 at 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.

## REFRACTION

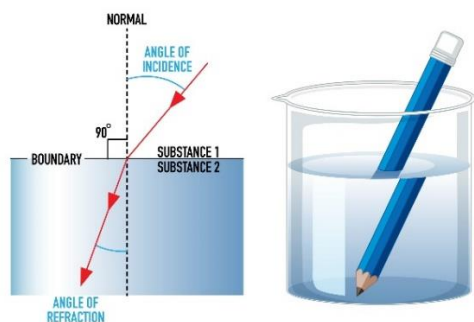


Figure 3 - A simple DIY refraction experiment (<https://sciencevision.in/refraction-of-light-and-refractive-index/>)

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 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, directly causing the same impact on radio waves (International Telecommunications Union, 2025) (Wallace & Hobbs, 2006) and its strength is governed by the refractivity index defined by the following formula.

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

- 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) (International Telecommunication Union, 2019)

Higher humidity, higher pressure and lower temperature all increase refractivity (Bean & Dutton, 1968) 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 RTTOV (Hocking, et al., 2022), 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 (Skolnik, 2008). This new value can then be further

used to find the refractivity gradient across vertical layers of altitude 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 effect to consider the height of the atmospheric condition values gathered so no matter the height being investigated, the results can remain consistent and fair.

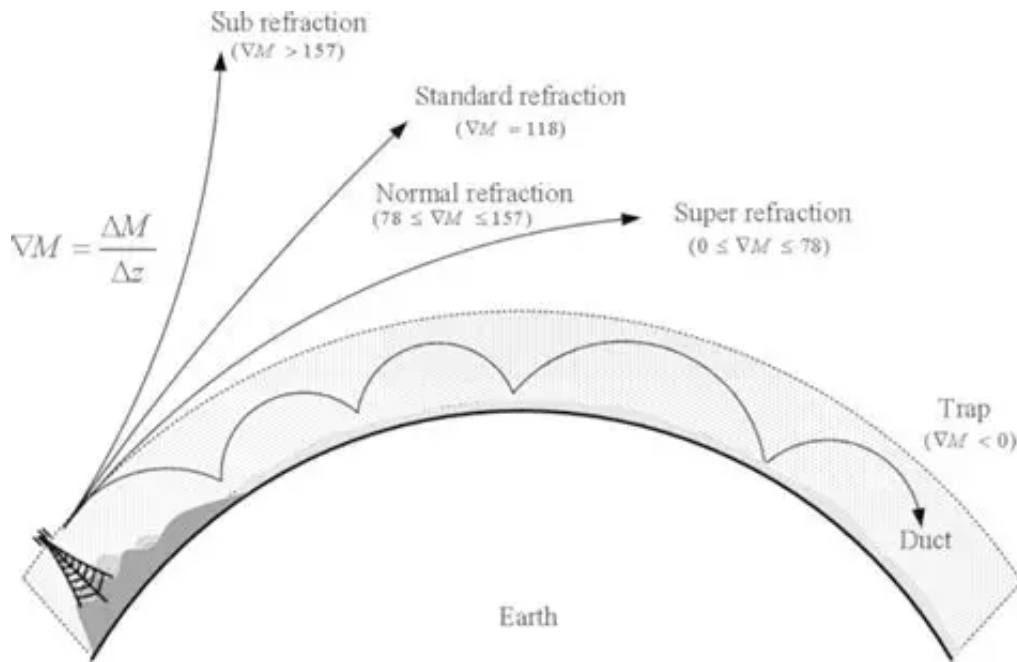


Figure 4 - Radio wave propagation according to the gradient of modified refractivity (Wang, et al., 2019)

## 2.2 Existing models

Now that physical principles underpinning tropospheric ducting have been established, we can explore existing forecasting approaches to identify methods, assumptions and computational strategies refined over decades of specialized research. Although these sources discussed do not share the exact objective pursued here (a pre-requisite for a dissertation topic), reviewing these is essential for placing the present work within the broader field of duct-prediction research. This process also helps to identify methodological gaps and opportunities for further innovation.

A prime example and the original motivator for my own model comes from William Hepburns tropospheric ducting forecast (Hepburn, n.d.). Hepburn's system provides global VHF/ UHF/ microwave ducting forecasts, updated each day, and presented in a proprietary colour scale system to indicate various propagation strength levels. The maps are generated using the GrADS 2.0 tool (earth science data visualization) and they rely on raw meteorological data provided by the Meteorological Service of Canada. Forecasts here are generated over 6 days with 3-hour intervals for the first 36 hours and 6-hour intervals for the remainder.

These forecasts have been widely referenced within the amateur-radio community and are frequently recommended as the primary tool for assessing VHF propagation conditions with sites such as the RSGB (Radio Society of Great Britain, n.d.) and DXZone (DXZone, n.d.) featuring Hepburn's site prominently.

Despite the associated influence of the project, the system exhibits several limitations that are relevant when propositioning the present work. Firstly, the forecasts are delivered exclusively as static and non-interactive images, requiring users to manually step through each time slice rather than allowing the user to explore the underlying meteorological values dynamically. Secondly, Hepburn's algorithmic methodology used for each generation is completely undocumented (at least in the public domain), making it difficult to evaluate the physical assumptions or computational steps used to derive resultant visuals. Finally, the system itself is explicitly intended for personal hobby use, and not in a specialized engineering environment such as that in which a SCADA radio network would operate. The site overall tailors for a wide range of users offering a very generic prediction model that covers the globe. It's results have been refined over two decades of observations and with the backing of an industry specialist, however despite all of this, there are of course still improvements to be made.

Looking beyond Hepburn's work, several other models and tools contribute to the broader landscape of radio-propagation forecasting, each with distinct aims and methodological foundations. VOACAP, for example, is a long-established HF sky-wave prediction system used extensively in professional and amateur contexts (Perkiömäki, 2025). VOACAP models the ionospheric layer of our atmosphere, 50 to 400 miles above the earth's surface (NASA, 2019) to find the maximum range of usable frequencies and overall reliability at any given time. To contrast dxinfocenter, the VOACAP model demonstrates the importance of transparent algorithms and open documentation, qualities that enable repeatable computational workflows which ordinarily is not possible in tools of this type.

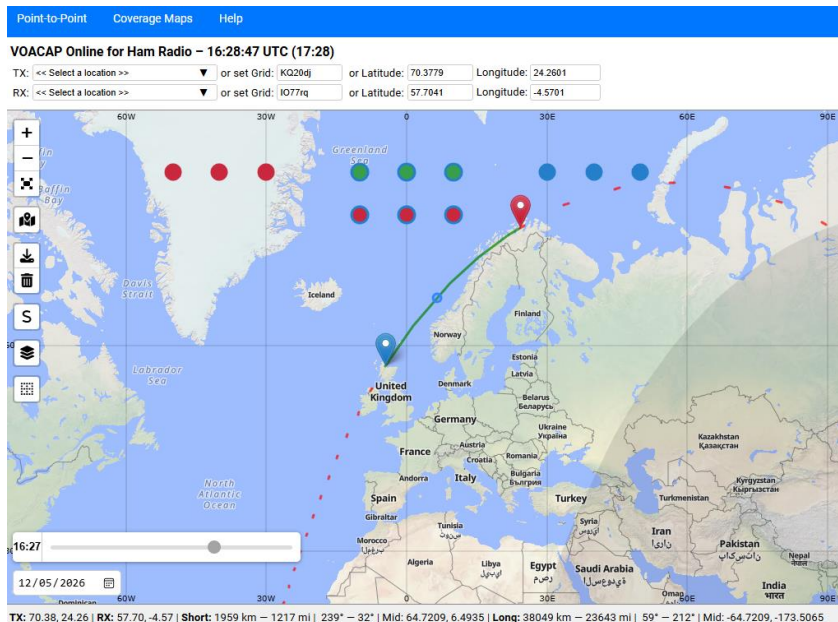


Figure 5 - VOACAP in action, available at <https://www.voacap.com/hf/>

To cap this off, another notable model is TropoMapper, an open-source tool again designed primarily for the amateur-radio operator which allows you to investigate point-to-point path analysis offering interactive visualizations of terrain profiles, fresnel zones, and predicted signal paths. While it provides a clear and modern UI experience with bountiful customization options for filtering exact radio tower locations and configurations, it does not generate area-wide refractivity-gradient fields or attempt to forecast ducting conditions over time. The emphasis over single radio links covering wide distances makes it perfect for radio hobbyists but equally unsuitable for assessing regional-scale propagation anomalies relevant to the UK SCADA study domain.



Figure 6 - TropoMapper tracing radio links on a continental range vs national

### 2.3 Comparison Table

	Hepburn's Forecast	TropoMapper	VOACAP
Purpose/ Scope	Global tropospheric ducting prediction for VHF, UHF and Microwave radio	Point-to-point propagation analysis	HF sky-wave prediction and ionospheric modelling
Data Source	Meteorological Service of Canada	User-Defined datasets (terrain/ elevation)	Ionospheric climatology and solar indices
Methodology	Unknown	Open-Source, full documentation	Full documentation
Interactivity	None, static images	Interactive 2D/3D maps	Moderate interaction, supporting GUI tools
Target Audience	Amateur hobbyists	Amateur operators	Amateurs and professionals
Relevance	Establishes precedent for ducting forecasts	Demonstrates modern UI and engineering tools	Proves value over transparent physics-based modelling

### 3. Systems Analysis and Design

Any successful software project must aim to follow the structure of the SDLC and to that affect, the development of the proposed forecasting platform requires a clear understanding of the system’s intended behavior, constraints, and operational priorities. The following sections therefore present a structured analysis of the system’s architectural model supporting the functional and non-functional requirements derived from the problem context, stakeholder needs, and limitations previously identified in existing propagation-forecasting tools.

To ensure that the design remains focused, feasible and aligned with the project’s objectives, each requirement identified will be mapped against the MoSCoW method. This approach distinguishes essential capabilities from desirable enhancements thus enabling a coherent design strategy that supports both the core forecasting functionality and the wider usability, security and maintainability expectations.

#### 3.1 Functional Requirements

Priority	Requirement	Description
<b>Must have</b>	Display key radio telemetry end locations	The system shall display geographic locations of key energy assets owned and operated by SSE plc. This will cover the energy distribution, transmission and generation businesses on an interactive map.
<b>Must have</b>	Provide forecast visualization	The system shall present at least 5 days of weather-derived refractivity forecasts with data available at 6-hour intervals at minimum.
<b>Should have</b>	Include user guidance	The system shall provide a clear, accessible explanation of how to interpret forecasting outputs and associated colour scaling.
<b>Must have</b>	Support CRUD operations	All site/ location entries shall support Create, Read, Update and Delete functionality
<b>Must have</b>	Enforce secure authentication	Any function that can alter system data or affect other users shall require authentication via an encrypted login process.
<b>Should have</b>	Support multiple viewing mediums	The system shall operate correctly on a range of viewing devices including desktops, tablets and mobile phones however the primary focus will be for enhanced viewing on desktops.
<b>Must have</b>	Validate user inputs	All user-submitted data shall undergo appropriate validation to prevent malformed, incorrect or potentially unsafe input.
<b>Should have</b>	Provide threshold-based alerts	The system shall generate notifications when forecasted refractivity-related conditions exceed a defined threshold for any registered site/ location.
<b>Must have</b>	Handle missing or delayed data	The system shall be capable of identifying and working with missing, delayed or incomplete datasets where appropriate.
<b>Should have</b>	Log critical system actions	The system shall record key actions both user generated and backend operations with 30 days of historical logs available for review.
<b>Could have</b>	Automated housekeeping	The system shall automate most administrative backend tasks to ensure operations run on time and data cleanups are carried out when required.

### 3.2 Non-Functional Requirements

Priority	Requirement	Description
<b>Should have</b>	Concurrent users	The system should support at least 20 concurrent users without performance degradation.
<b>Must have</b>	Password policy compliance	Password validation should comply with NIST 2025 guidelines for digital identity (NIST, 2025).
<b>Must have</b>	Secure password storage	Passwords shall be stored using an established one-way hashing algorithm.
<b>Should have</b>	Password lifecycle management	A password-change policy should be enforced for system accounts including but not limited to remote access and database credentials.
<b>Should have</b>	Performance expectations	Map layers and forecast data should be loaded within an acceptable time.
<b>Must have</b>	Forecasting data resolution	Spatial resolution of forecasting data must be less than or equal to 0.09° (10km)
<b>Should have</b>	Useability and accessibility	The interface should be intuitive, consistent, and accessible to users with varying technical backgrounds. The system should aim to conform to standards set out by the European Accessibility Act (European Union, 2019)
<b>Could have</b>	Maintainability	The system should be modular and structured to allow future extensions.
<b>Must have</b>	Data integrity	The system should ensure that stored and transmitted data remains accurate and unaltered.

### 3.3 Application Design

The overall architecture of the AtmosWatch application integrates cloud-hosted infrastructure, data-processing services and security features into a cohesive forecasting environment. The diagrams below illustrate the major system components, their deployment locations and the dataflows that support each key aspect of the system’s function. Through mapping these elements at this high level, the architecture highlights how each layer can collectively satisfy our defined requirements.

### 3.3.1 High-Level Overview

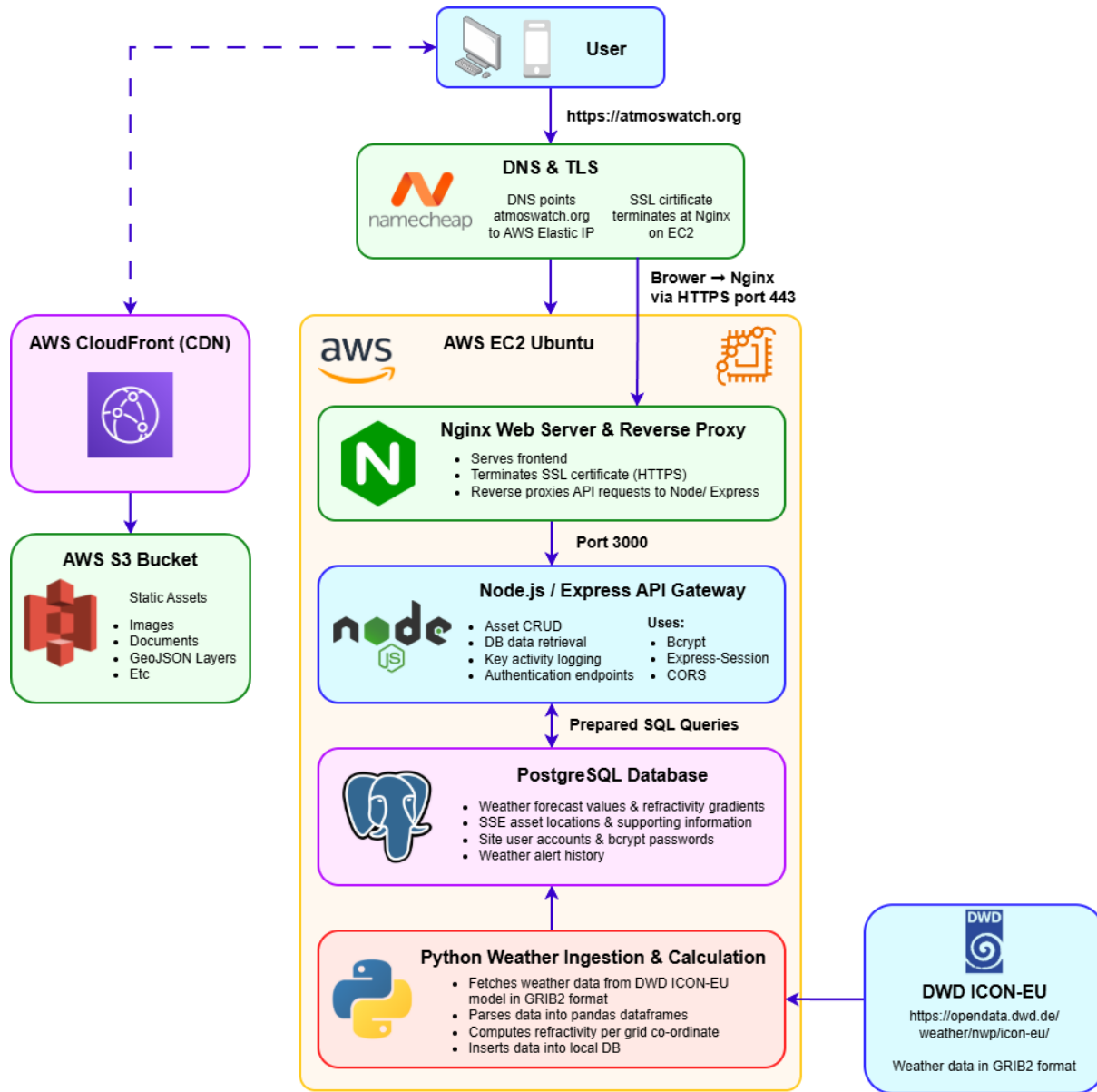


Figure 7 - Full AtmosWatch system overview designed via draw.io

The AtmosWatch system operates across several interconnected layers, each responsible for a distinct function of the forecasting workflow. At the outermost boundary, users access the platform through a web browser using HTTPS with DNS resolution provided through the registrar namecheap.com and certificate-secured communication terminating at the Nginx web server on the AWS EC2 instance. Static site asset including images and documents are stored within a dedicated S3 bucket and served via CloudFront for fast global access through caching.

Within the EC2 instance itself, Nginx functions as both a web server and a reverse proxy. It serves the frontend application and forwards all API requests to the custom API gateway (Node.js/ Express). Within the API layer, manages all authenticated and non-authenticated operations. Authentication itself is implemented by using express-session, bcrypt hashing (one-way encryption) and CORS policies, ensuring secure handling of user credentials and session state.

For the important meteorological data, ingestion and calculation occurs in dedicated python scripts separated from the frontend files and logic. With a third housekeeping script, the data pipeline is automated to run once daily, to query GRIB2 files from the DWD ICON-EU model. Relevant atmospheric variables are extracted, and both the refractivity and refractivity gradient values are calculated with the help of pandas data modelling. The processed results are committed directly into the local PostgreSQL instance. This db also stores map asset locations, user accounts, alerting history and holds the potential for various operation logs to be stored.

From the user's perspective in the frontend application, the mapping function interacts with the system through asynchronous requests to the API gateway exclusively to cover the retrieval of forecasting data, asset information and user specific values. The architecture ensures a clear separation between data ingestion, backend logic, storage and presentation while maintaining the simplicity and above all else maintainability expected of a monolithic deployment model. The resulting structure here not only supports the current project requirements while leaving open the possibility of future reworks or modularisation into a microservice solution.

### 3.3.2 Weather Prediction Dataflow

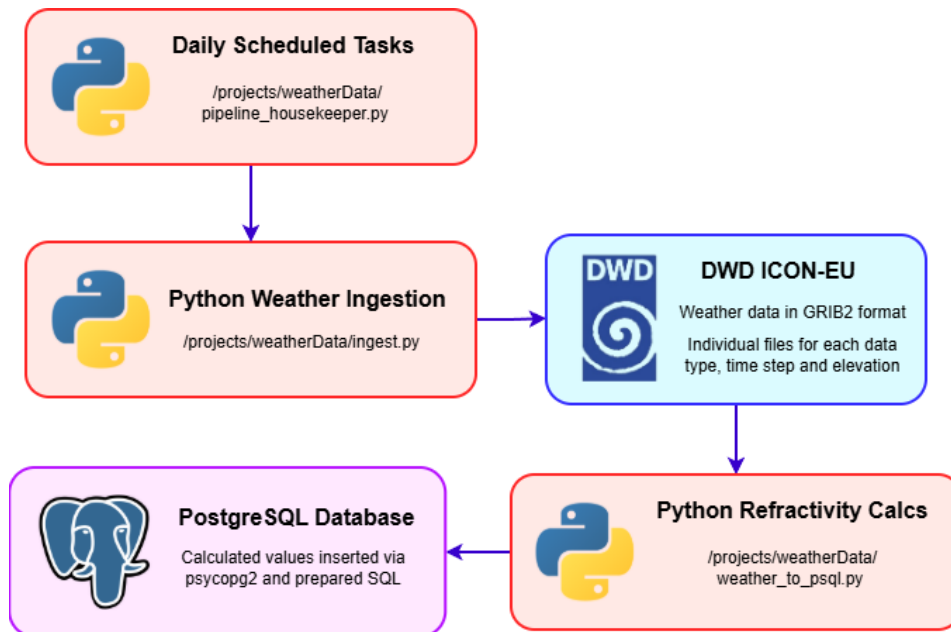


Figure 8 - Drilled down dataflow diagram for the weather ingestion and calculation workflow

During the design process, several decisions had to be made regarding the selection of an appropriate meteorological data source as this forms a central pillar supporting the development of the entire system. In choosing a source, considerations of performance, cost, scientific validity and accuracy were essential, given that the platform aims to generate refractivity-based predictions at a spatial resolution fine enough to capture mesoscale tropospheric ducting phenomena affecting site radios with footprints of only a few metres. The operational domain spans latitudes 63°N to 48°N and longitudes -15°W to 10°E, representing a 15° × 25° region covering the United Kingdom of Great Britain and Ireland (including Orkney, Shetland, and the Faroe Islands), as well as parts of mainland Europe (Sweden, Denmark, Germany, the Netherlands, Belgium, and France). This wider coverage is necessary due to the frequent cross-border radio interference observed across the English Channel and North Sea.

When evaluating options for sourcing meteorological data, the freely available API-based service provided by Open-Meteo was initially considered due to its ease of integration and lack of licensing restrictions. However, the service imposes a strict limit of 10,000 API calls per 24-hour period, with each coordinate query counting as a full request. Assuming a minimum of two forecast cycles per day, the system could allocate at most 5,000 API calls (or 5,000 grid points) per run. Under this constraint, it is possible to calculate the maximum achievable spatial resolution  $R$  (in degrees) across the 15° × 25° domain using the following relationship:

$$N = \frac{15}{R} \times \frac{25}{R} = \frac{375}{R^2}$$

With the constraint  $N \leq 5000$ , solving yields:

$$R \leq 0.2739^\circ$$

Given that a single degree of latitude is equivalent to 111.32km (pootcalculator.com, n.d.), this corresponds to a minimum spatial resolution of 30.5km. Such a coarse resolution is incompatible with the system's objective of modelling mesoscale refractivity gradients, where ducting structures often form over scales of 1-10km (Haack, et al., 2010). For further context, the distance between the University of Dundee's tower building and the city of Perth Royal Infirmary is also roughly 30km, meaning the entire separation between the two major cities would be represented by a single grid cell if this proposed system held this resolution. In fact, at this scale, tropospheric ducting predictions become scientifically meaningless, as the gradients driving duct formation cannot be determined to any degree of certainty.

To investigate a slightly different route, Open-Meteo also offers an alternative form of data collation within a "bounding-box" endpoint. Although a single request can return a 100-point grid, this does not change the API call limitation as each returned point within the bounding box is still billed towards the overall 10,000 daily limit. The resolution remains unchanged.

Changing our requirements to forecast only once per day, doubling our overall point limit ( $N \leq 10,000$ ) improves resolution only marginally.

$$R \leq 0.1936^\circ$$

$$0.1936^\circ \times 111.32 \approx 21.6\text{km}$$

This result again remains far above the non-functional requirement of 0.09° (10km) or better resolution for meaningful refractivity-gradient modelling. Achieving this standard requires a large quantity more API calls (points) which we can calculate exactly in the following way:

$$R = \frac{10}{111.32} = 0.0898^\circ$$

$$N = \frac{375}{0.0898^2} \approx 46,503 \text{ calls/ points}$$

This result shows an increase of more than quadruple the daily API limit offered by Open-Meteo, even before considering the multiple timestep requirement previously set-out which under a 6-hour step would bring our total calls up to 186,012. Consequently, all API-based approaches fail to meet the special and temporal requirement of the system.

To overcome these constraints, the project adopts a GRIB2-based ingestion pipeline using the DWD ICON-EU model. Unlike point-based APIs, GRIB2 files contain complete, pre-generated model fields for the entire domain at resolutions of 0.0625° (roughly 7km) or better. The model offers files to cover all required variables at each grid point for every forecast timestep, at 60 different elevations for a maximum forecasted step of +120 hours (5 days). This approach trades API convenience for computational autonomy, allowing the system to extract refractivity-relevant fields directly using python scripting and pandas data-handling tools before inserting all processed values into the local PostgreSQL instance.

In summary, the choice of the DWD ICON-EU GRIB2 pipeline is particularly well-suited to this application for three main reasons.

- High spatial resolution – The approximately 7km per grid co-ordinate offered exceeds the minimum requirement of 10km expected for a successful forecasting system
- Temporal resolution – DWD offers many weather variables in one-hour steps up to +78 hours and then three-hour steps until +120 hours, again meeting and exceeding the five day and six-hour step requirement previously set out in the system requirements.
- Open access – DWD provides unrestricted, cost-free access to all GRIB2 files and downloads without rate limitations.

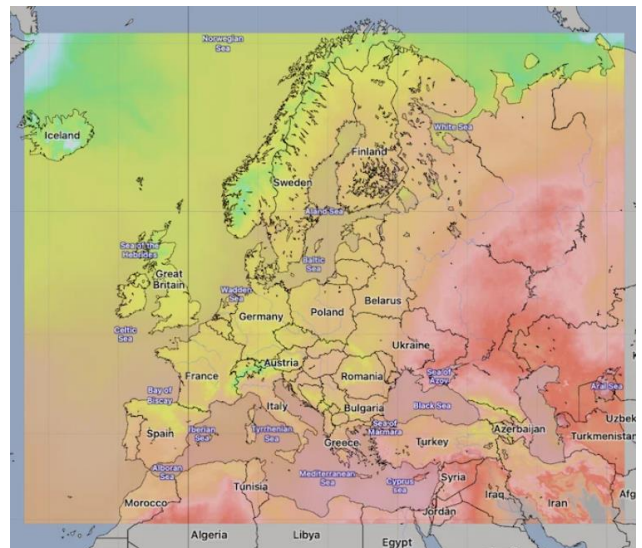


Figure 9 - ICON-EU weather model full domain. (Open-Meteo, n.d.)

The choice of this method is not only a technical preference, but a methodological necessity associated to the desire for accurate and dependable predictions of radio outage at CNI sites across the United Kingdom.

### 3.3.3 Authentication Dataflow

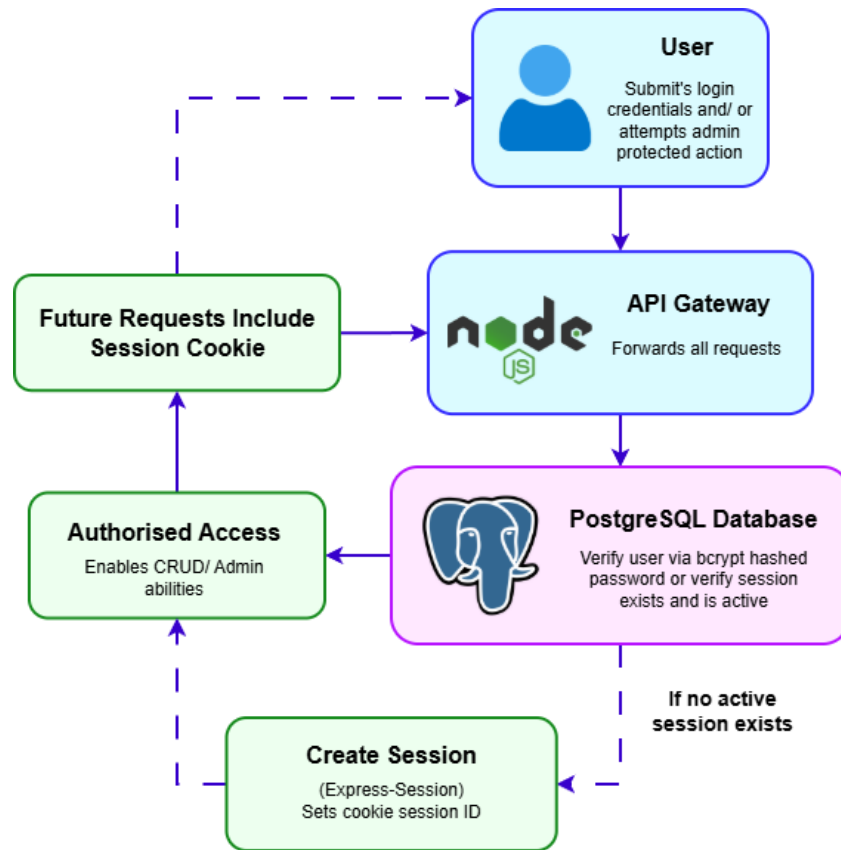


Figure 10 - Drilled down dataflow diagram for the authentication dataflow

The design of the authentication dataflow was shaped by the need to balance security, simplicity and operational suitability for a monolithic, cloud-hosted forecasting platform. Because the system provides administrative CRUD capabilities and exposes potentially sensitive operational data, a robust authentication mechanism was required to ensure that only authenticated users can modify site records, manage assets or trigger backend processes. The chosen approach being session-based authentication implemented through express-session and bcrypt reflects a deliberate alignment with industry established security practices while remaining compatible with the systems architectural constraints.

Session-based authentication was selected over token-based alternatives such as JWT because the platform operates entirely within a controlled domain served via Nginx and does not require multi-client or cross-server authentication. By maintaining server-side session-state, the system avoids the risks associated with long-lived stateless tokens and ensures that session invalidation, expiry and renewal can be managed centrally. Passwords are hashed using bcrypt, providing a proven and computationally expensive one-way hashing mechanism that mitigates brute-force and rainbow-table attacks due to the incorporated random salt value. This aligns with modern recommendations for secure password storage such as those provided by the Open Worldwide

Application Security Project (OWASP, n.d.) and supports the system’s non-functional requirements for security and data integrity.

The authentication dataflow also benefits from the placement of Nginx as a reverse proxy. All login requests are terminated over the HTTPS protocol, ensuring encrypted transport before being forwarded to the custom API gateway. Session cookies are issued with secure attributes, preventing access from client-side scripts and reducing exposure to cross-site scripting (XSS) or session-fixation attacks. Since all authentication-protected actions such as modifying site locations or accessing system logs are routed through the API gateway, the system maintains a single enforcement point for access control, simplifying auditing and reducing overall attack surface.

Overall, the authentication design reflects a balance between security and maintainability. It may not make use of the most complex of options however bcrypt holds well-supported libraries, aligns with the AtmosWatch’s monolithic deployment model, and provides a clear, auditable flow of credential verification, session management, and privilege enforcement (If we introduce a user role feature). This ensures that administrative functions remain protected without introducing unnecessary architectural complexity.

### 3.3.4 Static Asset Retrieval

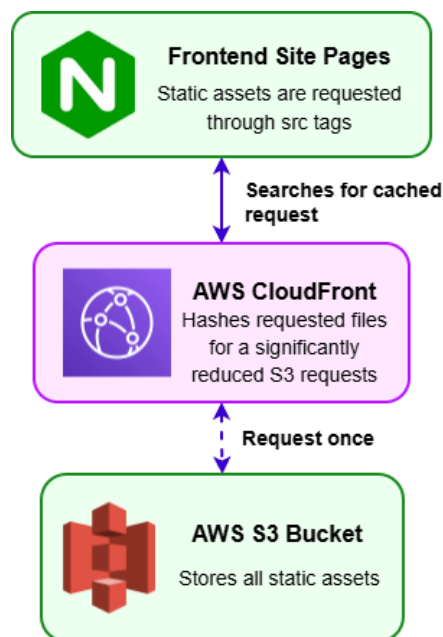


Figure 11 - Drilled down dataflow diagram for the static asset retrieval dataflow

The design of the static asset retrieval dataflow reflects the need for fast, reliable, and globally accessible delivery of non-dynamic resources such as website images, documents, and GeoJSON map layers. These assets do not require real-time computation and therefore benefit from being served through a dedicated content delivery mechanism rather than from the main

application server. To achieve this, the system employs AWS S3 as the primary storage location and AWS CloudFront as a global content delivery network (CDN), ensuring that static resources are distributed efficiently and retrieved with minimal latency regardless of the number of users.

When a user accesses the platform, the browser requests each called asset directly from CloudFront, which caches frequently accessed files at edge locations geographically closer to the user. This reduces load on the EC2 instance and avoids unnecessary backend processing, allowing the server to focus on all of its dynamic operations like its authentication, CRUD, and forecast retrieval. Because CloudFront acts as a caching layer in front of S3, repeated requests for the same asset are served from the nearest edge node rather than the origin bucket, significantly improving performance and reducing bandwidth consumption.

The separation of static and dynamic content also enhances security and maintainability. Static assets are delivered over HTTPS through CloudFront's managed TLS termination, while dynamic API requests are routed through Nginx and the Node/Express backend. This ensures that the EC2 instance is not exposed directly for static file retrieval, reducing the attack surface and preventing unauthorized access to internal directories. Furthermore, storing GeoJSON layers in S3 allows them to be updated independently of the application codebase, supporting modularity and simplifying deployment workflows.

### 3.3.5 System Design

1. User design
2. Architectural design
3. Component design
4. Database design

### 3.3.6 System Models

1. Context diagram of system
2. Sequence diagram
3. Use case diagram
4. Flow(chart) diagram
5. Class diagrams

## 4. System Implementation and Testing

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