



INTERNSHIP REPORT RADIO OBSERVATIONS OF THE IONOSPHERE

**Development of an ionosonde and data analysis for
troubleshooting radio instruments in Longyearbyen**

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Abstract

Radio instruments are extensively used to probe the Earth's ionosphere. They generally operate continuously and autonomously, gathering measurements of various ionospheric parameters, depending on the instrument type. As such, reliable hardware and software are essential for long-term monitoring of the ionosphere.

In this report, we set up an ionosonde in Longyearbyen (Svalbard) to measure ionospheric electron density profiles, to complement the already running instruments at the KJELL HENRIKSEN OBSERVATORY. Based on an existing ionosonde design, we added a watchdog to its amplifier to increase reliability for a long-term use. The hardware we built was tested and works well; the software however is still failing on the receiving end, preventing the ionosonde from obtaining usable ionograms. Consequentially, we could not check whether this instrument was interfering with the neighbouring SuperDARN installation.

In parallel, we refined the analysis of the data from PRIDE, a Doppler radar used to probe movements of ionospheric disturbances. While there is still room for improvement on the quality and plotting of the data, the resulting spectrograms have shown the instrument was operational in December 2023 and July 2024. We also isolated an ionospheric wave event using this data and compared it with magnetograms, showcasing a method that could be used for future analysis.

Résumé

Les instruments radio sont largement utilisés pour sonder l'ionosphère terrestre. Ils fonctionnent généralement de manière continue et autonome, mesurant divers paramètres de l'ionosphère, selon leur type. Ainsi, du matériel et des logiciels fiables sont essentiels pour un suivi long terme de ces paramètres.

Dans ce rapport, nous avons déployé une ionosonde à Longyearbyen (Svalbard) pour mesurer des profils de densité électronique de l'ionosphère, en complément des instruments déjà présents et fonctionnels à l'OBSERVATOIRE KJELL HENRIKSEN. Partant d'un modèle déjà existant, nous y avons ajouté un chien de garde pour augmenter sa fiabilité pour un usage long terme. Le matériel ainsi construit fut testé et fonctionne bien ; le logiciel, en revanche, provoque encore des erreurs coté récepteur, empêchant l'obtention d'ionogrammes utilisables. Par conséquent, nous n'avons pas pu vérifier si cet instrument interférait avec l'instance de SuperDARN présente à ses côtés.

En parallèle, nous avons affiné l'analyse des données de PRIDE, un radar à effet Doppler mesurant les mouvements de perturbations ionosphériques. Si les résultats obtenus peuvent encore être améliorés, les spectrogrammes ont montré que cet instrument fonctionnait en décembre 2023 et juillet 2024. Nous avons également détecté un cas d'onde ionosphérique avec ces données, que nous avons ensuite comparées à celles des magnétomètres voisins, montrant une méthode applicable à l'ensemble des données de cet instrument.

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Introduction

Radars are one of the primary components in experimental ionospheric physics as they allow for remotely probing this layer of the atmosphere. The different radar systems give us measurements of multiple scalar properties of the plasma (density, composition), and to different components of the vectorial properties (velocity). At the KJELL HENRIKSEN OBSERVATORY, a large observatory operated by UNIS housing optical and radio instruments used for studying the ionosphere, these radars are also used to gain insight on the physics of auroras.

In particular, ionosondes are radar instruments aiming at providing a vertical electronic density profile of the ionosphere. In Longyearbyen, such an instrument has been missing for years, and it would be of interest to set up one to fill this gap. However, this instrument works in a similar frequency range as the already deployed SuperDARN radar, which creates the risk of interferences between the two; as the SuperDARN radar is part of an international network, obtaining complementary measures should not come at the cost of the latter's reliability.

Besides, another instrument, the Polar Research Ionospheric Doppler Experiment (PRIDE), a Doppler sounding radio instrument for probing movements of local disturbances in the ionosphere, has been in operation for the past six years. Meant to measure the vertical velocity of the ionised layers at about 200 km in altitude, by recording the DOPPLER shift of the received signal, it is still unsure whether it is functioning properly or not.

After laying the groundwork with a theoretical model of the ionosphere and with a review of the different radar instruments present at the KJELL HENRIKSEN OBSERVATORY that are relevant for this work, we will aim at setting up an ionosonde in Longyearbyen, before asserting whether it interferes with the SuperDARN installation, and, if it does, how much perturbation the ionosonde induces in the latter's measures. Complementarily, we seek in this report to analyse data from the PRIDE radar to make it exploitable in order to check if the instrument is working, and how we can use its data for finding ionospheric events.

1 Theoretical overview and modelling of the ionosphere

1.1 Structure of the ionosphere

The ionosphere is an important part of the Earth's atmosphere, starting at an altitude of around 60 km and extending over 1000 km high. At these altitudes, the air pressure is very low, at only around 2 Pa at 60 km high, down to around 10^{-4} Pa at 100 km; this is from about a thousand to ten million times lower in order of magnitude than the atmospheric pressure at ground level.

The ionosphere also has the particularity of containing charged particles, making it a region filled with a natural plasma. Since plasmas are a conductive medium, they modify the behaviour of electromagnetic (EM) waves; in particular, the ionosphere can refract and reflect frequencies lower than 30 MHz, and eventually make them propagate back towards the ground. This was the reason for its discovery in the early 20th century by HEAVISIDE and KENNELLY, during the time when shortwave radio was being pioneered, after MARCONI first established transatlantic radio telecommunication.

It is itself stratified in three layers:

D layer: Situated between 60 km and 90 km high, this layer is usually weakly ionised; the electron density is somewhere between 10^2 cm^{-3} and 10^4 cm^{-3} . The plasma in this layer can attenuate high frequency (HF) radio signals. At polar latitudes, it can become so ionised during polar storms that it starts absorbing them completely [1]. This is called a polar blackout.

E layer: Situated between 90 km and 160 km high, this layer bends and reflects shortwave radio signals. The electron density in this layer has an order of magnitude of 10^5 cm^{-3} . Under certain circumstances, some thin and much more ionised layers can appear inside this E layer; these are called sporadic-E [2].

F layer: Situated between 160 km and 1000 km high, this layer also bends and reflects short-wave radio signals. The electron density can reach orders of magnitudes of 10^5 cm^{-3} to 10^6 cm^{-3} . During daytime, this layer splits in two, with the F1 region sitting below 180 km, and the F2 region sitting above 200 km [3].

1.2 Atmospheric plasma and stability of the layers

Two phenomenons participate in parallel to create the ionosphere: the first is the ultraviolet ionisation from the sun radiation, and the second is the ionisation by energetic particles from the solar wind. This radiation also participates in the atomisation of neutral molecules of the atmosphere, on which we will not elaborate in this report. All these phenomenons dissipate the incoming energy from the solar radiation and particles hitting the Earth, and protect us from their high levels of energy.

The inverse process also exists, in the form of recombination (ions and electrons) and attachment (electrons and neutral particles). They compensate for the ionisation, and along with the transport of the ionised material, allow for an equilibrium to be reached, instead of the atmosphere becoming fully ionised [3].

1.2.1 Ionisation from ultraviolet radiation

If the solar rays reach the Earth's atmosphere at an intensity I_∞ and an angle θ_0 , the intensity of the ray will decrease as it gets absorbed by the atmosphere over the length of its trajectory, following the equation between z and $z + dz$:

$$dI = \sigma_\nu n_n(z) \frac{dz}{\cos(\theta_0)} I(z) \quad (1)$$

With $n_n(z)$ the neutral particles density at height z , and σ_ν the absorption cross-section for neutral particles.

Since only a certain fraction of the absorbed radiation is used for the ionisation, we can define κ_ν as the ultraviolet photo-ionisation efficiency, and a photo-ionisation rate per unit of volume, $q_\nu(z)$:

$$q_\nu(z) = \kappa_\nu \frac{dI}{dz} \cos(\theta_0)$$

Which then gives:

$$q_\nu(z) = \kappa_\nu \sigma_\nu n_n(z) I(z) \quad (2)$$

With the hypothesis of an isothermal atmosphere following a one dimensional barometric law, we get:

$$n_n(z) = n_0 \exp\left(-\frac{m_n g z}{k_B T_n}\right) \quad (3)$$

With z the altitude, g the gravitational acceleration, k_B the BOLTZMANN constant, m_n the mass of a neutron, and T_n the temperature of the neutrons. And with an integration of [eq 1] over the ultraviolet ray trajectory as it enters the atmosphere, we get:

$$I(z) = I_\infty \exp\left(-\frac{\sigma_\nu n_0 k_B T_n}{m_n g \cos(\theta_0)} \exp\left(-\frac{m_n g z}{k_B T_n}\right)\right)$$

Combining this last result with [eq 2], we obtain the CHAPMAN production function [3], which is written:

$$q_\nu(\zeta) = q_{\nu 0} \exp\left(1 - \zeta - \frac{\exp(-\zeta)}{\cos(\theta_0)}\right) \quad (4)$$

Where $\zeta = z - z_0/H$, in which we defined $H = \frac{k_B T_n}{m_n g}$ as the scale height for this system. This function is plotted in [fig 1a] as a solid line.

1.2.2 Ionisation from energetic particles

In the auroral region, which extends from about 60° to 75° latitude in both hemispheres, where it is most likely for charged particles coming from the solar wind to enter the atmosphere (see section 1.3.2), the neutral particles from the atmosphere can be hit by these energetic particles from the solar wind and be ionised (mostly by electrons). Under these circumstances, ionisation of the atmosphere can continue even in the nighttime, albeit less intensely, when ultraviolet ionisation stops [3].

If we write W_{ion} as the energy required for the ionisation of a neutral particle of the atmosphere, we get that between z and $z + dz$, the amount of energy lost by a single electron from the solar wind is:

$$dW(z) = \kappa_e \sigma_n n_n(z) W_{ion} dz$$

Where κ_e is the collisional ionisation efficiency, σ_n is the neutral particles cross-section, and $n_n(z)$ is the density of neutral particles at height z . With this, $\sigma_n n_n(z)$ is the inverse mean free path for an electron.

The amount of particles ionised between z and $z + dz$ is therefore proportional to the energy lost by all the energetic electrons; this way we get:

$$q_e(z) dz = F_e dW$$

$$q_e(z) = \kappa_e F_e W_{ion} \sigma_n n_0 \exp\left(-\frac{m_n g z}{k_B T_n}\right) \quad (5)$$

Where F_e is the electron flux, and $n_n(z)$ was replaced with the barometric law [eq 3].

This ionisation can also be accompanied by an excitation of the neutral particle which, when releasing its excitation energy, may emit a photon in the visible frequency range. This light emission is at the root of auroras.

1.2.3 Continuity equation for electron density

In addition to these two ionisation processes, recombination and attachment participate in reducing the amount of ionisation in the ionosphere.

Recombination can be described as proportional to the amount of encounters between electrons and ions, themselves proportional to the densities. Since the ionosphere is initially neutral, we consider the plasma to be locally neutral, so that the density of electrons n_e and ions n_i are the same. We can thus write this loss term due to recombination as:

$$l_r = \alpha n_e^2$$

Attachment can be described as proportional to the amount of encounters between electrons and neutral particles. Since the latter are the main components of the ionosphere, especially

in the lower parts of the ionosphere, we consider electrons to be diluted in a constant amount of neutral particles. The loss factor due to attachment can thus be written:

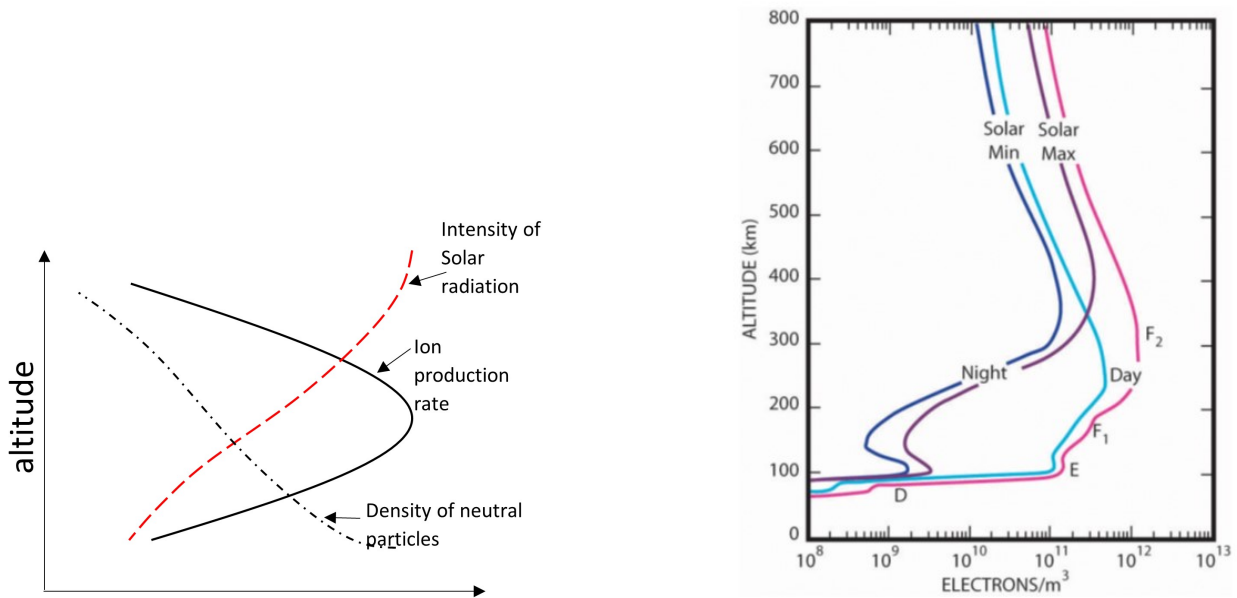
$$l_a = \beta n_e$$

When combining all of these terms together, we obtain the continuity equation for electron density in the ionosphere, describing the state of equilibrium the ionosphere reaches under different conditions:

$$\frac{dn_e}{dt} = q_e + q_\nu - \alpha n_e^2 - \beta n_e \quad (6)$$

Because q_ν is proportional to I_∞ , which depends on the time of the day and the latitude, this factor evolves at a much slower pace than n_e . When integrating this equation on shorter times, we can consider it to be a constant. In a similar fashion, q_e depends on the intensity of the solar wind, which evolves in time at the pace of solar activity, with a typical evolution time of 8 years; we will thus also consider it to be constant.

In effect, the electron density tends to track the slower evolutions of q_ν and q_e on the longer times, and can be thus used as a proxy for the effects of the solar wind and other space weather effects on the upper atmosphere.



(a) Simplified profile of solar radiation, neutral particles density and ion production rate

(b) Typical electronic density profiles under different circumstances

Figure 1: Theoretical vertical profiles of the ionosphere (Credits: L. Baddeley)

The combination of these processes result in a profile closer to those depicted on [fig 1b], which is more accurate than the simplified Chapman model.

It can modelise, for instance, the electron density drop in the absence of direct sunlight in the D region, when the ultraviolet ionisation stops during nighttime. This leads to the disappearance of the D region, where the recombination process is predominant, due to the layer's lower ionisation and higher density compared to higher altitudes.

At higher latitudes, the E region is mostly ionised by energetic particles that can also arrive during the nighttime.

As for the F layers, contrary to the F1 layer which follows solar illumination rather closely, the F2 region is reinforced by the transport of electrons due to diffusion, winds, and geomagnetic effects, and can thus also persist after sundown for a certain time [3].

1.3 Particle motion and currents in the ionosphere

1.3.1 Plasma frequency

In this section, we consider a plasma with fixed ions and mobile electrons; as the latter have a much smaller mass, they can react much faster than the ions to a perturbation, so in case of rapid oscillations, it can be a reasonable assumption [3].

If we consider a small displacement δx of a small volume of electrons, a small electric field δE will be created, causing a repel force on the electrons. This process keeps the plasma in its quasi-neutral state. For the whole volume of electrons, this gives the electron fluid continuity equation:

$$\frac{\partial \delta n}{\partial t} = -n_e \frac{\partial \delta v_{e,x}}{\partial x}$$

which combined with the fundamental principle of dynamics and POISSON's law:

$$\begin{aligned} \frac{\partial \delta v_{e,x}}{\partial t} &= -\frac{e}{m_e} \delta E \\ \frac{\partial \delta E}{\partial x} &= -\frac{e}{\epsilon_0} \delta n \end{aligned}$$

give us the following equation:

$$\frac{\partial^2 \delta n}{\partial t^2} + \frac{n_e e^2}{m_e \epsilon_0} \delta n = 0$$

This gives us a typical oscillation frequency called the plasma frequency [3]:

$$\omega_p = \frac{n_e e^2}{m_e \epsilon_0} \quad (7)$$

1.3.2 Cyclotron frequency

In this section, we are considering the movement of the charged particles in a frame of reference with no electric field $\underline{E}$ and a constant magnetic field $\underline{B}_0$. Here, we will take into

account the LORENTZ force and a viscous friction force coming from the collision of the particle with those of the medium:

$$m \frac{d\mathbf{v}}{dt} = q\mathbf{v} \wedge \mathbf{B}_0 - m\nu_c \mathbf{v} \quad (8)$$

With $\mathbf{v}$ the speed of the particle, q its charge, m its mass and ν_c the collision frequency. Here, we also suppose that the medium is immobile in the frame chosen earlier.

We can choose a Cartesian system of reference such that $\mathbf{B}_0$ is aligned along the z-axis. Projecting the previous equation on the three cardinal axes give us a system of equations:

$$\begin{aligned} m \frac{dv_x}{dt} &= +qB_0 v_y - m\nu_c v_x \\ m \frac{dv_y}{dt} &= -qB_0 v_x - m\nu_c v_y \\ m \frac{dv_z}{dt} &= -m\nu_c v_z \end{aligned} \quad (9)$$

This system can be solved by combining the equations on v_x and v_y using the complex variable $\chi = v_x + iv_y$. Solving the resulting equation on χ give us:

$$\chi = \lambda_0 \exp(-\nu_c t) \exp(-i \frac{qB_0}{m} t) \quad (10)$$

With λ_0 a constant that depend on initial conditions.

We can also now write $\omega_c = \frac{qB_0}{m}$ the characteristic frequency of the system, called the cyclotron frequency.

To refine this analysis, we can consider the case where $\nu_c = 0$, which describes the movement of the particle when neglecting the collisions. In such conditions, we find by solving the equation on v_z [eq 9] that the particle will propagate with constant velocity along the magnetic field line. Then, the solution for χ [eq 10] simply boils down to the equation for a circle in the complex field. In other terms, the charged particle will describe a helicoidal trajectory around the magnetic field line.

On the other hand, if $\nu_c \neq 0$, the particles will slow down due to the collision. We can calculate, for instance in the D layer, $\omega_{ce} \simeq 8.8 \times 10^6 \text{ rad s}^{-1}$ for electrons, $\omega_{ci} \simeq 1.3 \times 10^2 \text{ rad s}^{-1}$ for the ions, and ν_c is, in order of amplitude, between 10^{-7} Hz and 10^{-11} Hz .

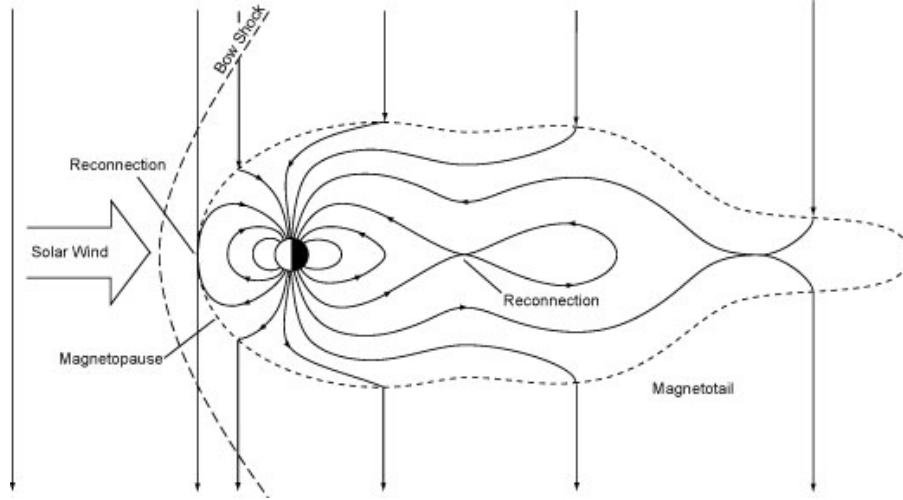


Figure 2: Simplified figure of the Earth's magnetic field (Wikimedia Commons / Public Domain)

Thanks to this result, we can understand that charged particles coming from the solar wind will be deviated by the Earth's magnetic field. Some of these particles will get guided in a helicoidal motion around the magnetic field lines, and eventually encounter the ionosphere near the magnetic poles where the field lines enter back into the Earth [fig 2], and interact with the particles present in the plasma.

1.3.3 $E \wedge B$ drift

In reality, the ionosphere is not a plasma devoid of electric field; there exists currents of multiple origins that affect the behaviour of the plasma mass. Let us then consider the presence of an electric field $\underline{E}$ in the previous frame of reference.

To revert to the previous situation, we can consider another frame of reference moving at a certain velocity $\underline{v}_D$, which we can choose to cancel the electric field in the new frame using the formula:

$$\underline{E}' = 0 = \underline{E} + \underline{v}_D \wedge \underline{B}_0$$

Multiplying the former equation by $\underline{B}_0$ and developing the double vectorial product, gives us the following expression for $\underline{v}_D$:

$$\underline{v}_D = \frac{\underline{E} \wedge \underline{B}_0}{B_0^2} + \underline{B}_0 \frac{\underline{B}_0 \cdot \underline{v}_D}{B_0^2} \quad (11)$$

In the case where $\underline{v}_D$ is transverse to $\underline{B}_0$, this velocity is simply expressed as:

$$\underline{v}_D = \frac{\underline{E} \wedge \underline{B}_0}{B_0^2}$$

After analysing a given movement in this frame of reference like we did in the previous section, we can come back to the primary frame; the speed composition formula will add this drive velocity v_D to that of the studied object, hence the name $E \wedge B$ drift [4].

This $E \wedge B$ drift is independent of the possible charge of the studied particles, which means that ions and electrons are subjected to the same drift speed, and will move about as one. This has important consequences on the global movements of the ionosphere. At higher latitudes, it induces a convection movement of the ionised particles, which transport local anomalies in electron density.

1.3.4 Mechanical waves in the ionosphere

Among all the mechanical waves observed in the ionosphere, there exists two types of waves that are particularly interesting for the study of the ionosphere: atmospheric gravity waves (AGW) and ultra-low frequency Magnetohydrodynamic waves (ULF MHW) [5].

☞ Atmospheric gravity waves

At any interface between two stable fluids of different density, gravity waves can form and propagate when this interface is subject to a perturbation. If a local perturbation sets an elementary surface of this interface in a vertical motion, this local deformation will spread to the neighbouring elementary surfaces under the influence of the gravity, which tends to overshoot when flattening the interface; waves on the sea are the best visual example of gravity waves.

In the atmosphere, these interfaces are less dramatic than that of the sea; this way, vertical deformations can shoot further up or down in the atmosphere, setting a whole air column into motion, then propagating sideways under the influence of the gravity; these are called atmospheric gravity waves. Many atmospheric processes may initiate such waves, like storms or auroras for instance, especially in the high latitudes.

These waves may be responsible for the transport of travelling ionospheric disturbances (TID), which are local perturbations of the electronic density in the ionosphere, from the lower parts of the ionosphere, up to the lowest part of the F layer [6].

☞ Ultra low frequency magnetohydrodynamic waves

ULF waves in the ionosphere are wave with a frequency comprised between 10^{-3} Hz and 5 Hz, which is smaller than the typical plasma frequency or cyclotron frequency; this is the reason for their name.

These waves can be described using MHD equations, which combine MAXWELL equations and NAVIER-STOKES equations:

$$\begin{aligned}\frac{\partial n}{\partial t} + \text{div}(n\mathbf{u}) &= 0 \\ n(m + M)\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \text{grad})\mathbf{u}\right) &= -\text{div}(\mathbf{P}) + \mathbf{j} \wedge \mathbf{B} + \mathbf{f}_{ext} \\ \mathbf{E} + \mathbf{u} \wedge \mathbf{B} &= \eta \mathbf{j} + \frac{1}{en}(\mathbf{j} \wedge \mathbf{B} - \text{div}(P_e) + \frac{m}{e} \frac{\partial \mathbf{j}}{\partial t})\end{aligned}$$

With n the density of the fluid, $\mathbf{u}$ the speed of the fluid, η the conductivity, P the total pressure (thermal and magnetic), P_e the exterior pressure, m the mass of the electrons, M the mass of the ions.

In such a description, ions and electrons move as one as a fluid.

These equations allow us to see the coupling between the magnetosphere and the ionosphere, which is at the core of how space weather affects the Earth's surroundings. ULF waves can carry energy and can thus modulate several ionospheric parameters. They also modulate Earth's magnetic field, and are thus susceptible to modifying the $\mathbf{E} \wedge \mathbf{B}$ drift and the movements of local irregularities on which the radar signals may reflect [5].

1.4 Electromagnetic waves propagation in the ionosphere

1.4.1 Appleton-Hartree equation

The Appleton-Hartree equation gives us a theoretical formula for the ionosphere refraction index, n . This allows for the description of the path a radio signal follows, and how the low frequency EM waves propagate in the plasma. These EM waves are gradually bent as the refraction index increases, in a similar fashion as light rays in an optical fibre; eventually, their path can be curved back towards the ground [fig 3].

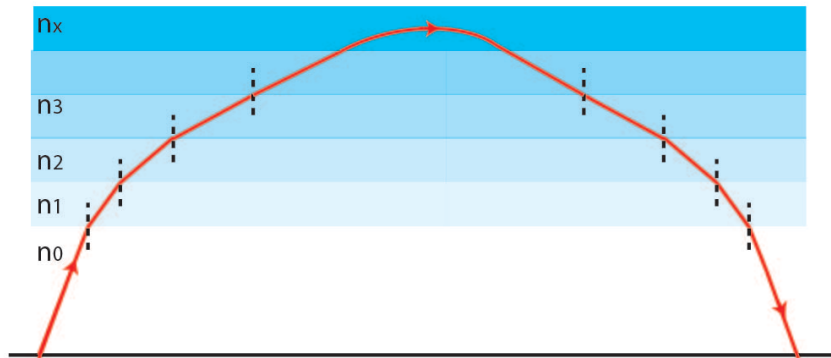


Figure 3: Theoretical trajectory of HF radio signals in the ionosphere (Credits: L. Baddeley)

The equation is as follows [4]:

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1-X-iZ)} \pm \sqrt{Y_L^2 + \frac{Y_T^4}{4(1-X-iZ)^2}}} \quad (12)$$

With

$$X = \omega_p^2/\omega^2 \quad Y = \omega_c/\omega \quad Z = \nu_c/\omega$$

Where ω is the frequency of the propagating wave, ω_p is the plasma frequency, ω_c the electron cyclotron frequency, ν the electron collision frequency, and the indices T and L referring to the transverse and longitudinal projections of the Y quantity. That is, if θ is the angle defined between the wave's direction of propagation and the geomagnetic field, $Y_L = Y \cos(\theta)$ and $Y_T = Y \sin(\theta)$.

1.4.2 Wave modes and plasma cut-off frequency

The plasma cut-off frequency is the limit frequency at which a wave becomes evanescent and no longer propagates in the medium. Because of this, if a wave with this frequency encounters the plasma, it will refract on the interface. To calculate this cut-off frequency, we can set $n = 0$ and solve the Appleton-Hartree equation [eq 12]. Here, we also choose to neglect the collisions with $Z = 0$.

The presence of the $\pm$ sign gives two solutions for n , which translates to two modes of propagation. The equation written with a $+$ sign only provides one solution [eq 13]; this mode is called the ordinary mode, or *O-mode*.

$$0 = 1 - X = 1 - \frac{\omega_p^2}{\omega^2} \quad (13)$$

The equation written with a $-$ sign, however, provides two solutions; this mode is called the extraordinary mode. In particular, the solution [eq 14] is called *X-mode* and [eq 15] is called *Z-mode*.

$$0 = 1 - X + Y = 1 - \frac{\omega_p^2}{\omega^2} + \frac{\omega_c}{\omega} \quad (14)$$

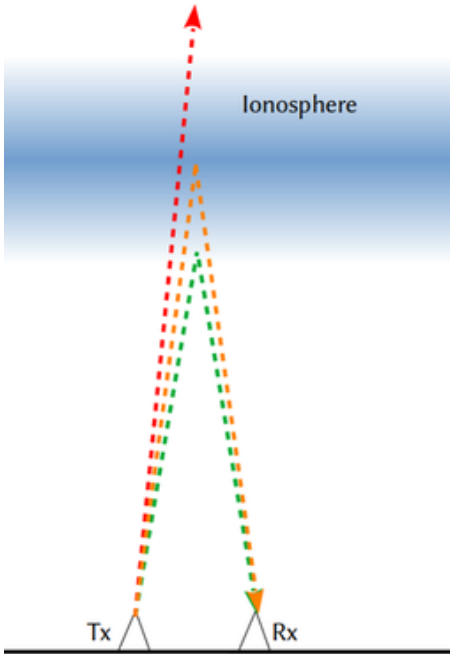
$$0 = 1 - X - Y = 1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_c}{\omega} \quad (15)$$

2 Radar instruments at the Kjell Henriksen Observatory

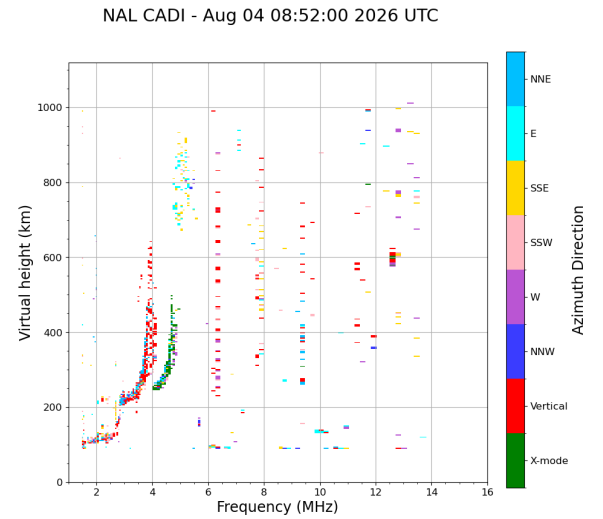
2.1 Ionosonde

Ionosonde are a type of radar used to vertically probe the ionosphere. These instruments were first developed in the 1920s, and are now somewhat widespread across the globe. Using two HF antennas, one for transmission and one for reception, or a single one switching between the two modes, the ionosonde sweeps through many frequencies between 1 MHz and 30 MHz, and measures the time between emission and reception for each signal of a given frequency.

As the plasma density gradually increases with the height [fig 1b], so does the plasma frequency [eq 7], and thus the plasma cut-off frequency. Therefore, a higher frequency will be reflected at a higher altitude.



(a) Diagram of the working principle for ionosondes, where TX is the transmitter and RX the receiver [7]



(b) Example ionogram from the Ny-Ålesund ionosonde. (Credits: Tromsø Geophysical Observatory (TGO) at UiT The Arctic University of Norway)

Figure 4: Working principle and data plots for ionosonde systems

To plot the vertical profile as a function of a distance, we convert the measured time t into a virtual height h' , calculated as if the wave was travelling at the speed of light and in a straight line:

$$h' = \frac{ct}{2} \quad (16)$$

In reality, since the EM wave follows a curvilinear path, and slows down as the index given by [eq 12] increases, the real reflection height is always smaller than the virtual height [fig 5]. Accessing it is more complicated, which is why virtual height is preferred. To do so, we are using t as expressed more rigorously in terms of group velocity v_g and curvilinear abscissa along the path taken by the signal, which can be expressed as a function f of the real height h [eq 17]. Since f can be computed using [eq 12] and the SNELL-DESCARTES law, and v_g also is linked to the index n , we can invert this formula to obtain h .

$$t = 2 \int_0^{f(h)} \frac{ds}{v_g} \quad (17)$$

In the ionogram shown in [fig 4b], we can identify the different layers presented previously [fig 1b]. Among the F2 region in the previous figure, the curve splits in two vertically similar and parallel components that correspond to the differed receptions of ordinary and extraordinary waves modes. In general, it is preferred to use the ordinary mode wave for simplicity, as combining [eq 13] and [eq 7] give us a direct link between the electron density and the transmitted frequency.

The ionosonde thus allows us to be able to continuously obtain an altitude profile of the ionospheric electron density, up to the F-region peak. As discussed earlier, the density and altitude of the F-region can be used to determine how the solar wind and space weather effects our upper atmosphere.

In 2020, such an ionosonde was developed and deployed at the KHO using a software defined radio (SDR). It was meant to replace the former one that was previously decommissioned, leaving the KHO without such an instrument for several years [8]. This new prototype ionosonde however did not stay up for a very long time, and has since been disassembled again.

This ionosonde version transmits with a power of 1 W and uses coded signals to recognise its own emission above the noise level. It operates 24/7 to constantly monitor the ionosphere and its evolutions.

2.2 PRIDE

PRIDE is a bistatic system; it resembles an oblique ionosonde in its architecture, where the transmitter and receiver antennas are far away from each other; however, the transmitter antenna is set to emit signals at a single frequency of 4.45 MHz. When the layers of the ionosphere shift, the altitude at which the signal reflects also shifts, modifying its frequency because of the Doppler effect. This shift is registered by the receiver antenna, from which we can deduce the modification of the reflection height [5].

This radar is the first Doppler sounder deployed at high latitudes. Its transmitter is located in the Polish research station in Hornsund, and its receiver is at KHO, 130 km away.

It mainly focuses on the gravity waves and ULF MHD waves previously mentioned.

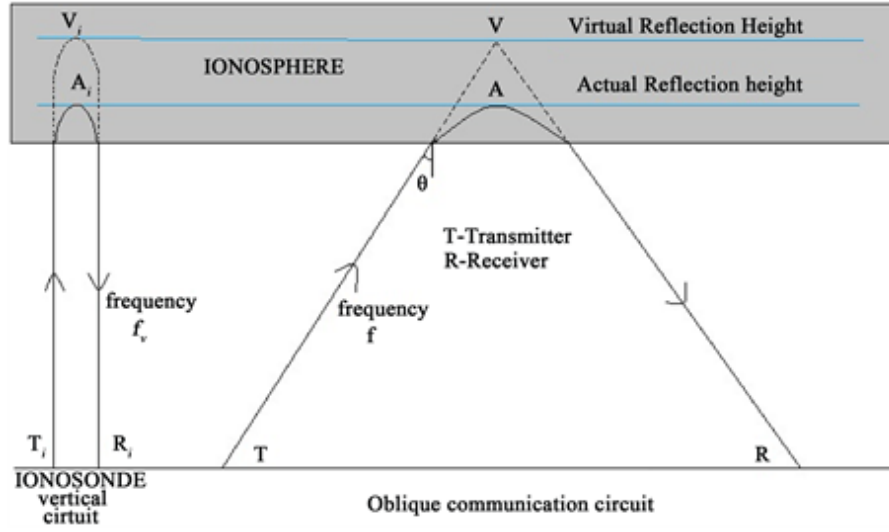


Figure 5: Diagram showing the difference between virtual height and actual reflection height [9]. Left corresponds to ionosondes, right to PRIDE and other oblique sounding radars.

As calculated in [5], the equation for the frequency shift related to the Doppler effect induced by the $\underline{E} \wedge \underline{B}$ drift is:

$$\Delta f = -2 \frac{v_z \cos(\theta_i)}{c} f \quad (18)$$

With $f = 4.45$ MHz, and v_z the $\underline{E} \wedge \underline{B}$ drift speed. In Longyearbyen, the inclination of the magnetic field lines is $\theta_i = 82^\circ 28'$; this high value is representative of the inclination at high latitudes; this severely reduces the observed frequency shift, which is why deploying this instrument on Svalbard is a technical challenge.

More precisely, with a vertical speed $v_z \propto 800 \text{ m s}^{-1}$, the Doppler shift for the PRIDE radar should be around $\Delta f = 2 \text{ Hz}$.

This instrument typically transmits with a power of 20 W. It operates 24/7.

2.3 SuperDARN

SuperDARN is an international network of radars aiming at measuring the horizontal speed of the particles in the ionosphere near the poles, to map the global convection movements of the plasma, as described in [eq 11] at about 220 km in altitude. It is also useful for detecting atmospheric gravity waves and meteors. One of these radars has been built next to Longyearbyen to contribute to this project.

SuperDARN instances generally use frequencies between 8 MHz and 20 MHz; on Svalbard, this radar typically uses frequencies around 10 MHz and 12 MHz. It sends radio waves in a slanted direction over the horizon. These signals can backscatter on local density instabilities

that are aligned with the magnetic field, or bend back towards the Earth, bounce on the surface and come back to the radar [fig 6].

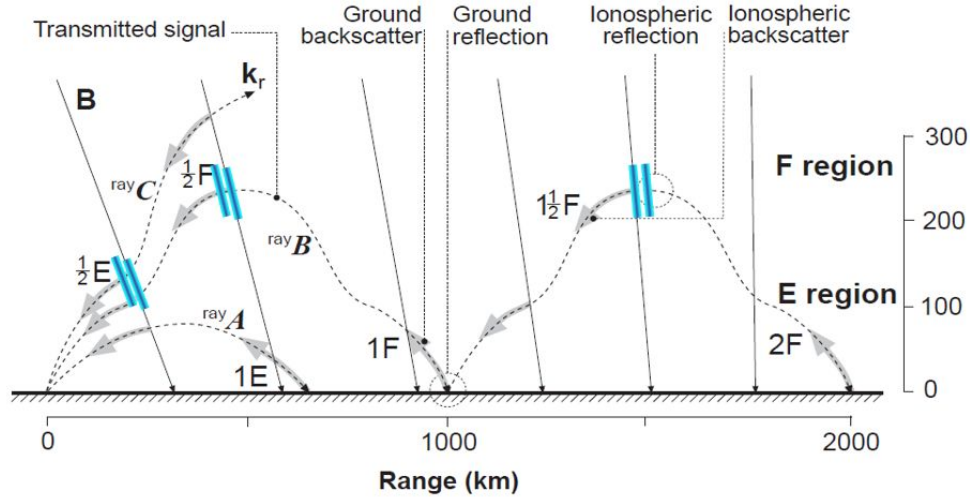


Figure 6: Diagram of the paths and reflection points of the EM waves emitted by SuperDARN

The antennas are mounted on masts in two longitudinal arrays. The main array measures 300 m long, with 16 antennas mounted on 18 masts, and is used for transmission and reception; this array is able to divide the field of view in 16 directional beams to increase measurement precision. Behind this array is the secondary array, consisting of 4 antennas and 6 masts on a 125 m long line, used for reception only.

This instrument typically transmits with a power of 200 W, with peaks at 1 kW. It operates 24/7.



Figure 7: Picture of the Longyearbyen SuperDARN radar in spring

3 Building and deploying the ionosonde

3.1 Architecture considerations

Since ionosondes have existed for a long time, there exists multiple designs for them. However, the democratisation of SDR and improvements in computer power changed the way such instruments are thought; with this in mind, this ionosonde was originally designed with a set of specifications chosen to simplify the system's hardware as much as possible, replacing it with heavier reliance on software.

As ionosondes built with this design are able to work together, with a receiver from one location listening to the transmitter from another in an oblique ionosonde fashion, the amount of data obtained from the ionosphere increases quadratically with the amount of ionosondes using this design. Making it low-cost and easy to deploy was therefore in the interest of its very development. The computational requirements can easily be met with basic computers and no particularly powerful computers are needed.

The detailed specifications can be found in [8].

To avoid any interference or data corruption, two computers are used to ensure complete separation between the transmitter and the receiver. Each computer uses its own SDR, and both are synchronised on GNSS time; this synchronisation is necessary for coding and decoding the signal, which is how the time between emission and reception is computed with high enough precision.

In this installation, we use two universal software radio peripheral (USRP) N210 developed by ETTUS RESEARCH.

3.2 Hardware

3.2.1 Amplifier unit

🔊 Specifications

This amplifier unit comes from the pre-existing ionosonde design described in [8]. Since we aim at creating a low power ionosonde, it was estimated that a 30 dBm transmit power, which corresponds to 1 W, was enough to receive a signal faintly above noise level. Also, this value is less than the maximum 10 W effective radiated power authorised by NKOM, the Norwegian authority on radio transmissions.

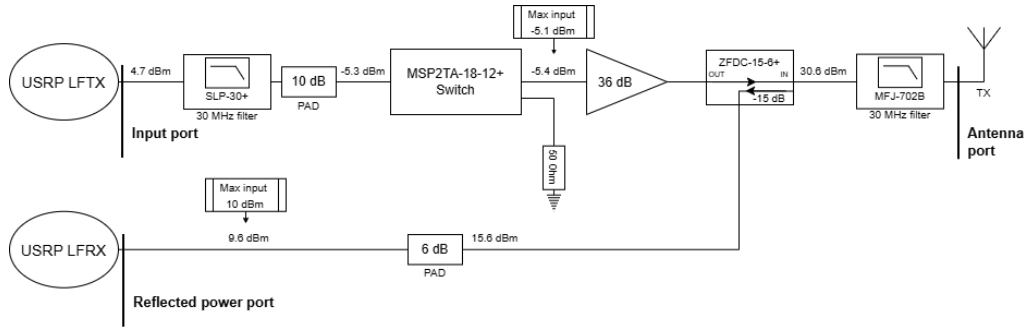


Figure 8: Diagram of the amplifier unit circuit with maximum power for all connections

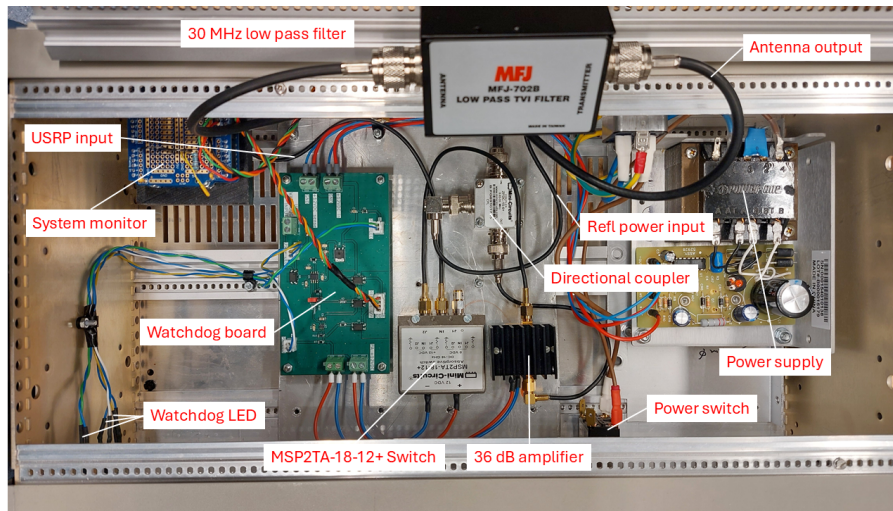


Figure 9: Picture of the finished amplifier unit

To avoid noise in the transmitted signal and to avoid transmitting harmonics, we first use a 30 MHz low-pass filter on the USRP output, to serve as an antialiasing filter, removing any harmonics that come from the digital to analogue conversion before amplification [fig 8] (Cannot be seen on [fig 9]). No digital filter can alone be sufficient for this task.

This goes into a switch controlled by a watchdog (see next section), which closes only when transmitting properly. When the switch is closed, the signal is directed through a 36 dB amplifier, before feeding the antenna.

As the real antenna is not a perfect component, and because it may break due to weather conditions or wear, parts or all of the signal can be reflected back into the amplifier unit. To avoid any damage on the components, a bifurcating switch is used to divert the reflected signal, and feeds it into the transmitter USRP receiver daughterboard. This signal is monitored, so that if it becomes strong, serves as a warning that something is going wrong with the ionosonde.

Some hardware components have a maximum input power specified to avoid damaging the component. It is thus necessary to add passive attenuation devices (PAD) to reduce the power

of the signal entering such components (Cannot be seen on [fig 9]).

First, the 36 dB amplifier has a maximum input of -5.1 dBm. With a maximum output power for the transmitter SDR of 4.7 dBm, we can calculate that a 10 dB PAD needs to be added before the amplifier. As this component, if not powered, can be damaged if an RF signal is sent through it, a switch was added just before to cut any transmission if the amplifier is not powered.

Similarly, with a maximum input of 10 dBm for the receiver USRP, we need to add a 6 dB PAD on this input line.

The maximum power on each part of the line and the attenuation of every component can be found on [fig 8].

🔍 Verification

After building the system, we validated the amplifier by measuring its gain on the frequency range used by the ionosonde.

For this, we used a *Siglent SSA3032X* spectrum analyser. With this instrument, thanks to its built-in tracking generator, it is possible to automatically plot the gain of the system given the desired frequency range. The generator output was linked to the amplifier input, and the output of the latter was linked back to the spectrum analyser; the other cable connections in the system were terminated; then, by powering the amplifier, the gain could be plotted directly.

On [fig 10], the gain was normalised to 0 dB for a gain of 1. We can see that the measured amplification is not a perfect constant for all frequencies; however, for frequencies under 30 MHz, the gain is a roughly constant 26 dB; for frequencies above 30 MHz, the gain quickly decreases as a result of the *MFJ-702B* 30 MHz physical low-pass filters installed in the circuit after the amplifier [fig 8].

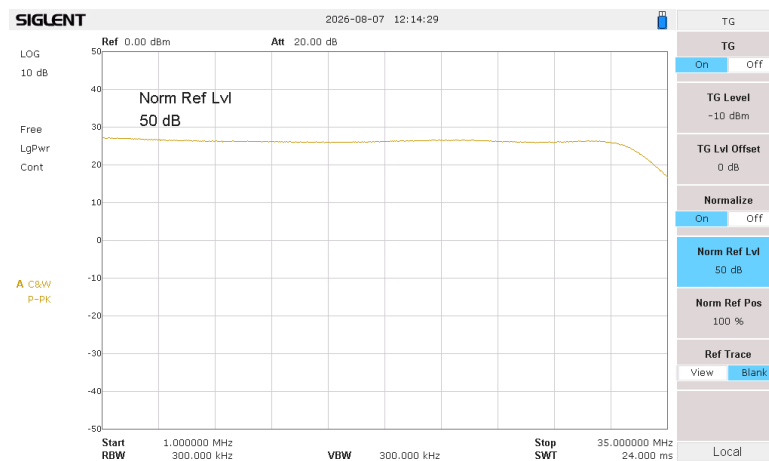


Figure 10: Graph of the amplifier gain in decibels over the ionosonde frequency range

Since this 26 dB value does correspond to the theoretical value (36 dB amplifier minus the 10 dB PAD placed on the amplifier box input), then the maximum transmit power for the combined USRP and amplifier box, which we calculated again, is indeed the desired output power of 30 dBm.

It should also be noted that this is a lot more than the estimated minimum needed transmission power calculated in [8] for this system.

3.2.2 Watchdog

🐶 Specifications

As with any other hardware or software piece, there may arrive some cases when the ionosonde is not working properly. In these cases, we want to avoid any problematic transmissions, as these might interfere with the neighbouring instruments, or even become illegal. To supervise the system's good behaviour, we added a watchdog.

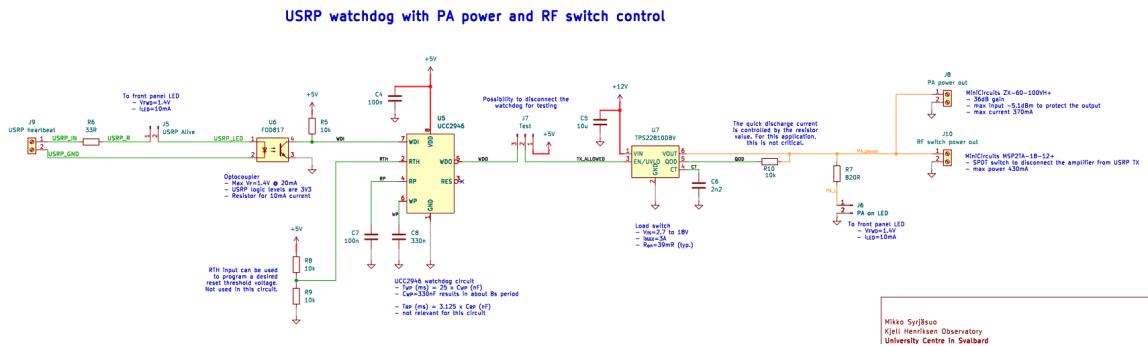


Figure 11: Diagram of the watchdog circuit

Built inside the amplifier unit, the main watchdog board acts as a power switch for the amplifier and controls the signal switch in the amplification line [fig 8]. It is powered by a 12 V continuous power supply; this power supply is transformed in a 5 V continuous tension used for operating the switches.

Inside the USRP transmitter daughterboard, a general purpose output pin is made to switch between on and off states by the software every time the transmitted frequency changes. This pin is used to assert the good behaviour of the SDR, and is taken as an input by the watchdog. When this pin triggers, the board allows transmission for the following 8 seconds by closing a switch. When this switch is closed, the 12 V tension is applied to the 36 dB amplifier and to the signal switch.

For testing purposes, a bypass was also added to constantly close the switch, allowing continuous transmissions without the need to listen to the triggering pin. This bypass can be set up by manually changing the position of the jumper intended for this purpose.

To monitor the state of these power lines, we use two interfaces. The first interface is purely physical, and involves three LED on the amplification unit front panel.

The first LED is linked to the 12 V supply voltage, turning on with the power supply. The second LED is linked to the switch, turning on when it closes and off when it opens; this LED monitors whether the antenna can transmit a signal or not. The third LED is directly linked

to the triggering pin from the USRP, changing state alongside it every time the transmitted frequency changes.

The second interface is digital, and allows for checking remotely the state of the ionosonde transmitter. For this interface, an Arduino board is used to convert the electrical signals sent through the Watchdog board communication port to a numeric signal sent to the computer via its USB serial port.

The Arduino board was coded to notify the transmission computer of any change of state in the 12 V supply tension, 5 V tension or transmission switch. To make sure the Arduino board is alive, it was also equipped with a thermometer and made to send the measured temperature every five minutes to the transmitter computer.

All these notifications are registered, timestamped and logged in a file by a Python script running on the transmitter computer [fig 12]. All the code related to the watchdog can be found on the Github page https://github.com/OlivierGdM/Ionosonde_watchdog.

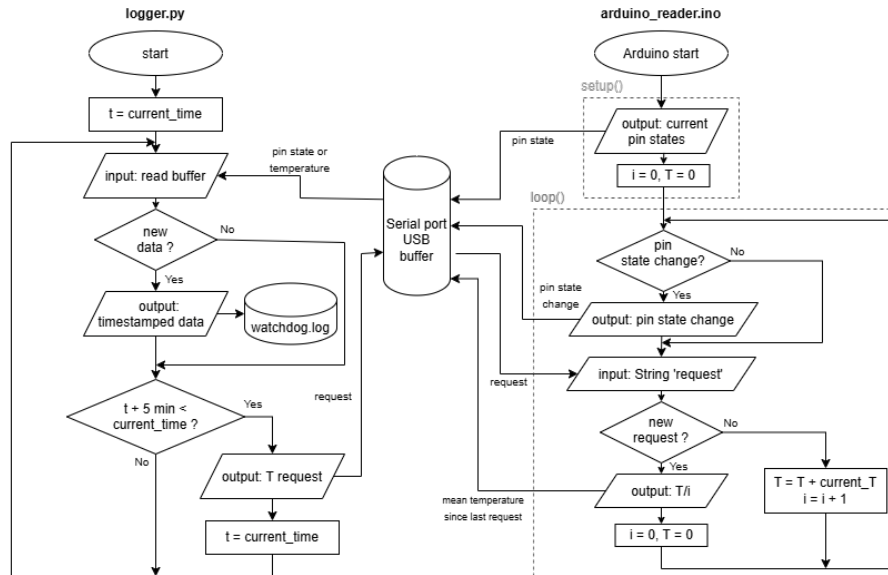


Figure 12: Watchdog process workflow

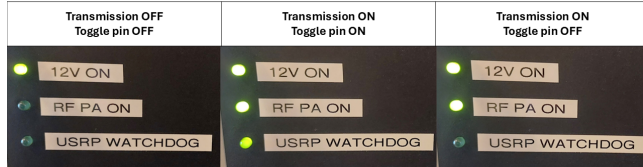
Verification

To test the blinking of the LED and the logs, we used the ionosonde software to control the USRP transmit frequencies. As the system was still in testing, we used a dummy load on the output.

With a change of frequency programmed every 5 seconds, we confirmed that the triggering LED was indeed changing state every 5 seconds too. Since the watchdog was designed to cut transmission when no frequency change happens for 8 seconds, the transmission switch LED did also stay on for the whole duration of the sweep [fig 13a].

The logs also showed the power state of the amplifier unit, and also the state of the transmission switch. Every five minutes, the temperature was also logged, showing the Arduino

board was still alive [fig 13b].



(a) Pictures of the blinking LED

```
2026-07-14T11:25:57.868895+00:00 - Serial connection established
2026-07-14T11:25:59.412645+00:00 - 12V: ON
2026-07-14T11:25:59.428843+00:00 - 5V: ON
2026-07-14T11:25:59.429049+00:00 - TX: OFF
2026-07-14T11:30:10.440204+00:00 - TX: ON
2026-07-14T11:30:59.545774+00:00 - T: 24.66
2026-07-14T11:32:47.774985+00:00 - TX: OFF
2026-07-14T11:33:05.311230+00:00 - TX: ON
2026-07-14T11:35:47.654792+00:00 - TX: OFF
2026-07-14T11:36:00.181024+00:00 - T: 24.69
2026-07-14T11:36:05.186835+00:00 - TX: ON
2026-07-14T11:38:47.533391+00:00 - TX: OFF
2026-07-14T11:39:05.069455+00:00 - TX: ON
2026-07-14T11:41:00.315149+00:00 - T: 24.52
2026-07-14T11:41:02.818047+00:00 - TX: OFF
2026-07-14T11:46:01.450421+00:00 - T: 24.72
2026-07-14T11:51:02.083820+00:00 - T: 24.68
2026-07-14T11:56:02.716548+00:00 - T: 24.75
2026-07-14T12:01:03.357245+00:00 - T: 24.78
2026-07-14T12:06:03.992799+00:00 - T: 24.69
2026-07-14T12:08:15.270678+00:00 - 12V: OFF
2026-07-14T12:08:15.278863+00:00 - 5V: OFF
```

(b) Screenshot of the Arduino log

Figure 13: The two human-machine interfaces of the watchdog

3.2.3 Antennas

Transmitter antenna

One of the most important aspect for this transmitter antenna is its voltage standing wave ratio (VSWR or SWR) bandwidth. This refers to the frequency spectrum where the antenna transmits effectively, without too much power loss. Parts of this loss can be a fraction of the signal reflected back into the system; this may usually cause some damage, which is why it is important to only transmit into a range with a good SWR. However, in our case, the reflected power is already managed by the instrument, as seen previously, but even if we can safely transmit with a bad SWR, it would still mean these transmissions are inefficient, and should be avoided. In practice, we aim at having an SWR of 2:1 or less, which is considered as a good ratio.

For transmission, we chose to use a dipole antenna. As the radiation pattern of dipole antennas have two nulls, we can aim one of them towards SuperDARN; by installing the antenna parallel to the direction of SuperDARN which is located only a few hundred meters away, we hoped to reduce possible interferences with it [fig 14]. This was more easily done than with more omnidirectional antennas.

To get a wide SWR bandwidth, we chose to use a terminated folded dipole antenna. Compared to open-end dipole antennas and simple folded dipole antennas, these antennas have the same gain and radiation pattern, but the added resistor in the upper wire reduces the feed-point impedance in many of the frequencies in our desired range.

Besides, we installed the antenna in an inverted-V shape [fig 14]; compared to other setups, the inverted-V allows for a good SWR on a wider bandwidth using the same dipole antenna, whilst being easy to set up. The antenna is thus hanging from its middle point, and the two sides are tightened to the ground using weights. To avoid loosing too much of its efficiency, the angle formed at the hanging point should be greater than 90°.

These two characteristics of the system are what allows us to have a 1 MHz to 30 MHz SWR bandwidth, which is necessary for transmitting all the frequencies available to us without the need for a tuner.

The antenna is hanging from a 9 m high pole. As the highest frequency we may transmit is 30 MHz, which has a wavelength of 10 m, the ground effect will be noticeable. This is even more true for frequencies of around 5 MHz, which have wavelengths of about 60 m. This ground effect increases the radiation resistance, as the ground will absorb parts of the transmitted signal. It will however also make the antenna more directional towards the sky, which is good for our application [10].



Figure 14: Picture of the transmitter antenna at SPEAR, with SuperDARN in the background

☞ Receiver antenna

The receiver antenna is a small loop active antenna that was already installed at the KHO. This choice is the result of a compromise made between the clarity of the received data and the amount of information extracted from it.

That is, a magnetic loop antenna is better than a dipole antenna when working in a noisy area, such as the KHO, where a lot of electrical components are present. This is because a loop antenna reacts to the magnetic field, when a dipole antenna reacts to the electric field. This way, much the man-made electrical noise is not registered by the receiving system.

It comes at the cost, however, of not being able to discern between the ordinary and extraordinary propagation modes for the signal wave described in [eq 12]. We thus get a less noisy signal at the cost of some information on the received EM waves.

To receive and differentiate between O mode and X mode for the received signal, we would have to use two dipole antennas perpendicular to each other; this would require setting it up far away from the KHO, which is not easy to do on Svalbard.

Loop antennas also have the advantage of being very small and easy to set up. However, its small size requires it to have an amplifier for receiving HF waves; in our case, this electronic component is integrated at the basis of the antenna, hence the name active, and ensures it matches the 50Ω impedance in its feed-point for every frequency.

🔍 Verification

After setting up the transmitter antenna at SPEAR, we used a *RigExpert AA-600* antenna tester to verify the SWR over our frequency range. As we can see on the following graph [fig 15], the SWR sits mostly comfortably under 2:1 for all frequencies between 2 MHz and 24 MHz, which is almost exactly the range where the frequencies for which we are currently allowed to transmit are [fig 16]. For frequencies above 24 MHz, the SWR barely goes above 2:1, which can still be considered good.

With these characteristics, it would be possible in the future to obtain more frequencies in this range and transmit them without modifications to the current instrument, for better resolution.

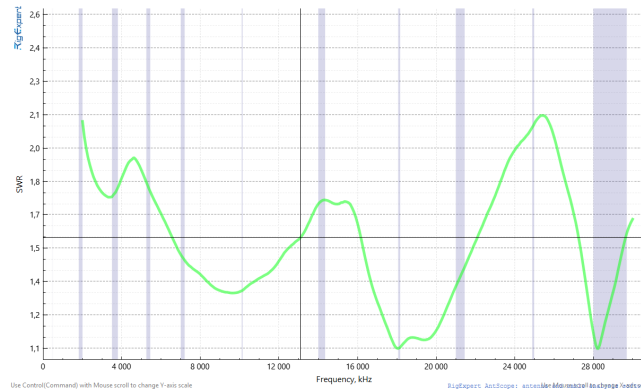


Figure 15: Graph of the standing wave ratio for the transmitter antenna

It should be noted that the results can also be improved by using other antennas for different sections of the bandwidth, at the cost of more complexity in the hardware. This is done at Institutet för rymdfysik (IRF) for instance. This practice is compatible with the software, which automatically switches another general purpose pin, if configured to do so, with this exact intent in mind.

3.3 Software

All the code described in the following subsection can be found on the Github page <https://github.com/OlivierGdM/ionosonde> on the *LYR* branch.

3.3.1 Frequencies and waveforms configuration

To define frequencies used in the sweep, in accordance to the transmission licence obtained from NKOM [fig 16], we simply had to modify the configuration file associated with the software.

These frequencies listed in the licence are associated with a bandwidth; most of them having a 100 kHz bandwidth, and some of them having a 50 kHz or 30 kHz bandwidth. The frequency list was pasted into the config file, and each frequency was associated to a waveform created by the software, to respect the bandwidth constraint.

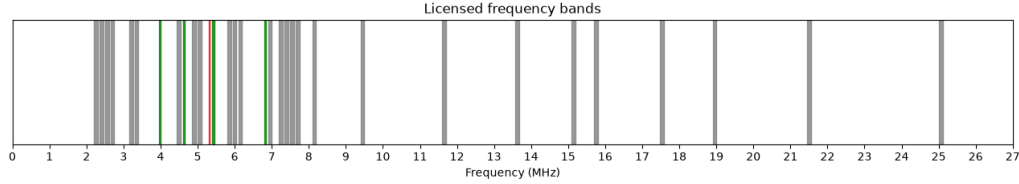


Figure 16: Diagram of the frequencies allowed for transmission. Bandwidths: grey = 100 kHz, green = 50 kHz, red = 30 kHz.

To check the validity of the waveforms and the legality of the transmission, we used a spectrum analyser to measure the bandwidth of the three waveforms. By centring the spectrum analyser on the emitted frequency, selecting a narrow enough frequency span and selecting a thin enough bandwidth resolution, the measures showed the transmitted waveform were compatible with the constraints. [fig 17]

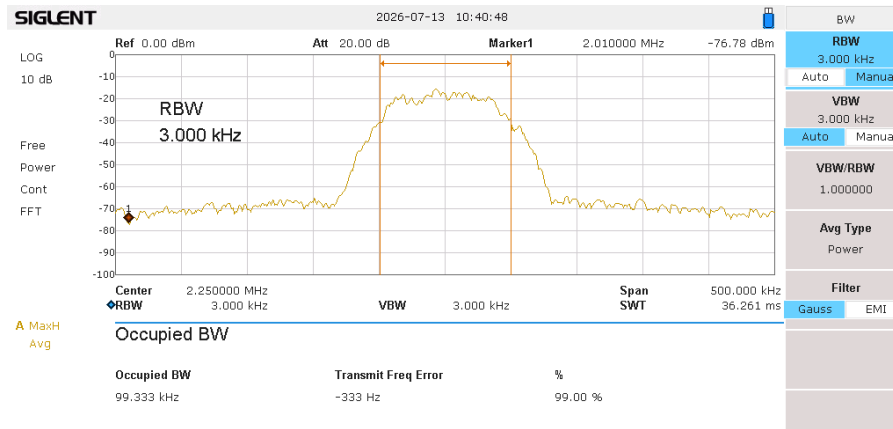


Figure 17: Measurements of the transmitted broadbands with the different waveforms

3.3.2 Signal coding

Instead of relying on transmitting a high power signal to discern it above the noise level on the receiver side, we aim at transmitting a low power coded signal which, knowing the code, allows us to find it buried beneath the base noise level.

The code used in this software is a pseudorandom code generated with a seed associated to the ionosonde setup; here, this pseudorandom code is a binary sequence transmitted by the signal through its phase. Going through the sequence, every time a bit changes, the phase is shifted 180°. This digital modulation is called binary phase shift keying (BPSK).

On its end, the receiver computer can generate the exact same random number sequence using the seed chosen for the ionosonde, and deconvolute the phase of the received signal. Since the received signal consists of noise with the transmitted signal buried in, it first needs to be shifted temporally until the phase shifts and the binary code become coherent in order to find the transmitted signal.

To synchronise the two computers, the USRP are connected to GNSS antennas to align the two ends of the software on the same clock. The code being entirely deterministic with a given seed, the receiver computer can measure the temporal shift very precisely, as it knows at what exact GNSS time such or such phase shift occurred on the transmission end. This time shift give us access to the virtual height of the reflection.

3.3.3 Software workflow

The software is separated in four processes working together on the two computers.

On the transmitter computer, the main process drives the USRP to send signals of pre-definite frequencies, bandwidths and power to the amplifier, as well as measuring the eventual reflected power from the antenna. In parallel, the watchdog process monitors the information sent by the Arduino board and logs them into a file [fig 12].

On the receiver computer, the two other processes work in parallel. First, the receiver process saves the sweep processed by the second USRP into the temporary memory. Then, the analyser process reads the temporary raw files and plots the ionograms, saving them to the disk.

The flowcharts for the transmitter process, receiver process and analyser process can be found in [8].

Except for the watchdog which was coded for our project, this software was already installed on other ionosondes. Available to us was also the configuration files for the ionosondes in Uppsala and Lycksele.

Besides some code modernisation, we modified the timing for the triggering pin linked to the watchdog. In previous versions, the pin would trigger every time the USRP was programmed to tune to a new frequency. Because of the timing, the first frequency of every sweep would not be transmitted, as more than 8 seconds elapsed between sweeps. In our installation of the code, we modified this behaviour: now, the watchdog is petted right before transmission, and only if the USRP is correctly tuned.

3.4 Issues encountered with the instrument

Once the ionosonde was set up and the software was installed, we tried to receive at the KHO the signal sent at SPEAR. However, two main issues arose when starting the software. The first one being related to the receiver USRP crashing when running the receiver process, and the second one being the absence of received signal at KHO.

3.4.1 USRP crashes

During the testing of the software, it often happened that the USRP unit would stop responding after a few minutes, often about 15 minutes after starting the program. We eventually figured out the issue was not coming from our code modifications, as the scripts used for the receiver were untouched in their architecture. Instead, the issue was coming from the configuration file customized to our specifications, since running the same code with the Uppsala or the Lycksele configuration files didn't cause the USRP crash. It should also be noted that the custom Longyearbyen configuration file would not crash the transmitter process.

At the time of writing this report, this issue still needs to be solved.

3.4.2 Reception issues

During the times when everything was working simultaneously, that is when the receiver process was working, the program would only register noise, and would produce empty or inconsistent ionograms. To address this issue, we gradually checked the different stages of the signal and the system.

☞ Checking the transmission

To check whether the system was correctly transmitting, we used GQRX SDR, a program designed for controlling an SDR. With this software and our loop antenna, we couldn't observe any trace of the transmitted signal from the KHO. However, when getting close to the antenna with an *AirSpy HF+* SDR and a small portable antenna at SPEAR, we could indeed receive direct transmission and observe the frequency sweep with the different bandwidth sizes [fig 18]. Therefore, we knew that the transmitter end was working properly.

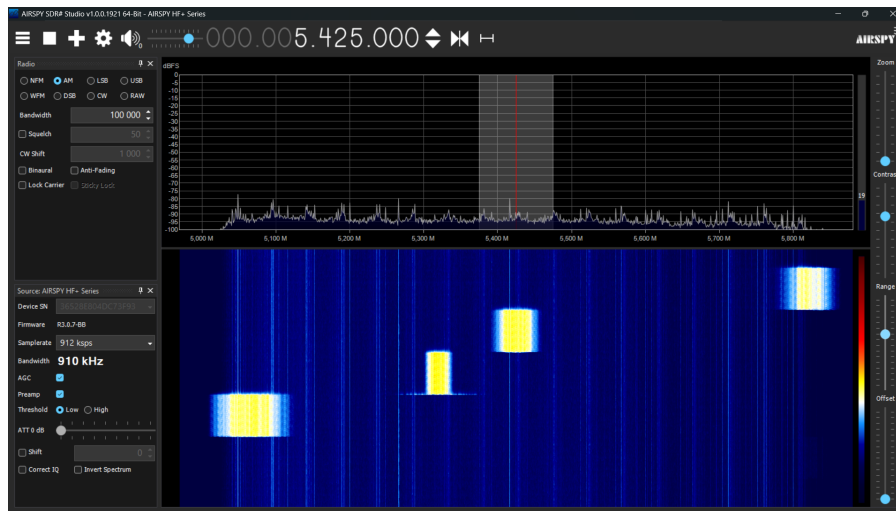


Figure 18: Capture of the transmitted sweep registered close to the antenna

☞ Checking the receiver antenna

At the KHO, the loop antenna was also working around our frequency range, as we could receive signals from the neighbouring NAVAID emitting at 326 kHz for the nondirectional beacon ADV in Adventdalen, and at 350 kHz for the beacon LON situated at the airport. Closer to the frequency range we used afterwards, we could also listen to NRK RADIO broadcasted in Longyearbyen at 1.485 MHz.

We should therefore at least have received direct signals from the ionosonde transmitter, which is located less than a kilometre away from KHO. If even these direct signals were not received because of a low transmission power, there was no chance we could have received signals reflecting on the ionosphere.

It is possible and most likely that the transmitted signals, because of their low-power, were not showing up clearly in the spectrogram registered at the KHO. Because of the high amount of noise at these frequencies, both natural and man-made, it is difficult to visually interpret the spectrum and dig out the short duration pulses sent by the ionosonde.

✂ Signal coding and decoding

During our tests, we double-checked to ensure the binary files containing the signal code were the same on both computers. If there were a difference, the ionosonde would not find the signal, which could have explained the empty ionograms.

It is also possible that the two computers were not perfectly synchronised on GNSS time; in particular, the receiver process would often freeze when using the Uppsala configuration file, and suddenly display in the log file the list of all the frequencies it listened to and at what time. However, it is likely that this listening time was only a timestamp that didn't correspond to reality. If such is the case, then it might be that this issue is linked to the aforementioned issue about USRP crashes and error inducing configuration file.

At the time of writing this report, this issue also needs to be solved.

3.4.3 Next objectives

These two issues are critical to the system and direly need to be solved. Since they might be linked together, we should concentrate on the one we understand the least, which is the USRP crashes; with any luck, solving this issue could solve the other one; but if they are not the same problem, then having a consistently working USRP would largely facilitate the debugging of the second.

Understanding the origin of the receiver process freezes might also pinpoint the origin of the crashes themselves.

Only once the USRP crashes are solved should we concentrate on the reception issues. As said previously, it is not impossible that the issue finds its origin in a bad synchronisation between the two computers. Using longer pulses, up to 7.5s in the normal configuration, or even using minutes-long pulses (with first bypassing the watchdog), could help the receiver computer extract the signal from the noise, as the longer the pulse is, the less power is needed in the signal for it to be detected. With longer pulses, it is more likely for the receiver computer

to listen to a frequency at a time when it is being emitted, even if the clocks are desynchronised a little.

On the longer term, once the ionosonde is properly working, it will be important to verify whether it is interfering with SuperDARN or not. To quickly look through the data, a prototype visual tool similar to the one coded for PRIDE [fig 21] was created for SuperDARN. Since it is not entirely polished and finished, expanding it first could most likely significantly reduce the time spent analysing SuperDARN data. This code is available on the Github page https://github.com/OlivierGdM/SuperDARN_visual_tool.

To check for interferences, we would have to save some SuperDARN data with and without the ionosonde working at the same time in normal conditions, and analyse the raw data directly. As the two instruments are not using the same frequencies exactly, and as the pulses' bandwidths are not larger than what is allowed, there should be no overlap and no interferences.

To go further, it could also be possible to have the ionosonde transmit frequencies used by SuperDARN, and analyse the data with and without the ionosonde transmitting in the meantime. This is more likely to cause interferences; however, if no interferences are observed, then it would mean the two instruments could work in parallel without any issues.



Figure 19: Picture of the transmitter antenna at SPEAR

4 PRIDE data analysis

4.1 Objective

Since the PRIDE radar was installed, a few years ago, a lot of raw data has been collected and stored for processing, as the analysis software wasn't ready yet for a good refining of the data. The first working version of the code, described in [5], was giving a very crude and noisy output of the signal, as it was the first version to successfully convert the output signal of the instrument into a spectrogram.

The objective here was thus to fine-tune this program to obtain exploitable spectrograms, and verify if the instrument was actually working as intended or simply altogether. Currently, this instrument is not operational, so the following tests are conducted on data collected in December 2023 and July 2024, which is only a small fraction of the total available data.

All the code described in this section can be found on the KHO-DopplerRX Github page <https://github.com/UNISvalbard/KHO-DopplerRX>.

4.2 Signal processing and data visualisation

4.2.1 Processing principle

The first part of the signal processing is a conversion from physical electrical output to numerical data. First sampled at a frequency of 250 kHz, the physical signal is then decimated to a 100 kHz sample frequency. This 250 kHz sample had some missing data samples, due to the way the USRP streams the data to the computer. This is discussed more widely and fixed in [5] to get usable samples. The data is then saved into hourly *hdf5* files as a quadrature signal, on which we worked for fine-tuning the analysis.

As this is the raw data of the instrument, which we want to publish, we converted them into 24h *netcdf* files, since this format is adapted to saving large time-series and add relevant metadata on the side, and in particular for providing both the origin and the nature of the data. However, this comes at the cost of having to save the in-phase and quadrature parts of the signal, that is the real and complex part of the measured data, into two time series, since *netcdf* files cannot store complex values.

For further analysis, we took into account the nature of the phenomenon we seek to observe, which are ULF wave and AGW. Since these happen at a frequency of less than 5 Hz, a 100 kHz sampling frequency is too large; also, since noise is often described as a high frequency component of the signal, we chose to decimate the data further by a factor 10.

However, to keep the interesting part of our data intact, that is the power peak we detect when a reflection happens, we downshift the signal before the antialiasing filter and down-sampling of the decimation happen.

This complex signal can then be processed into a spectrogram with a Fourier transform. Thanks to the previous downshift, the spectrogram's maximum power points, when a clear

reflection happens, are centred around zero. To emphasize this central axis, which is the evidence of a reflection, a second low pass filtering can be applied.

To observe these clear reflections, for each timestamped slice of the spectrogram, we keep only the frequency of maximum power, which give a frequency time series, reducing the dimension of the spectrogram by one; this is called the maximum power spectral density (max PSD) time series

In the very end of this process, we saved the spectrograms and max PSD time series into 24h *netcdf* files for internal use, and avoid having to compute them every time we seek to visualise the data.

It should be noted that for improved results on the edges of the spectrogram, data from the previous and following days should be taken into account in the FFT; this is room for improvement.

4.2.2 Data visualisation and visual tool

The computed spectrogram and max PSD time series can then be plotted with matching timestamps. For faster plotting, we downsample the data again; in the end, the measured data is decimated three times before visualisation.

By default, the plots display the whole day of data. This gives an overview that allows us to see the times when the receiver antenna actually detected the signal; when the max PSD plot shows a continuous line, a signal is detected, but when a cloud of points are displayed instead, the receiver is only registering noise [fig 20].

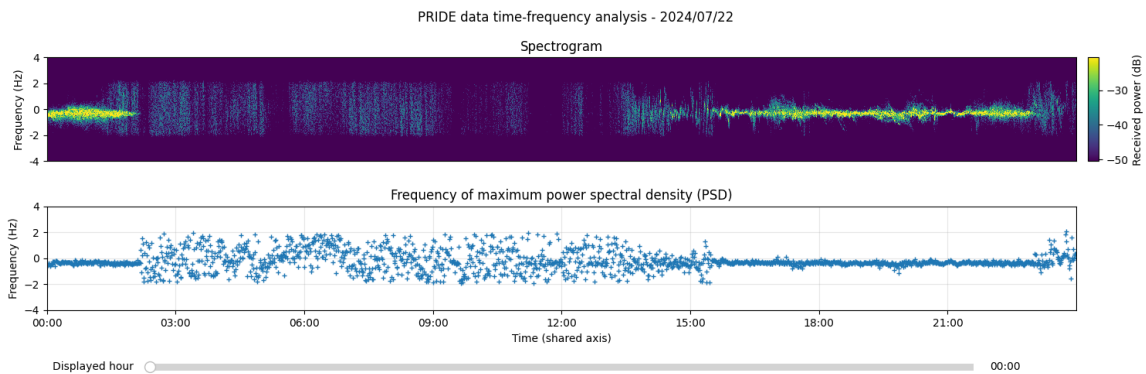


Figure 20: Spectrogram obtained with data from the PRIDE radar

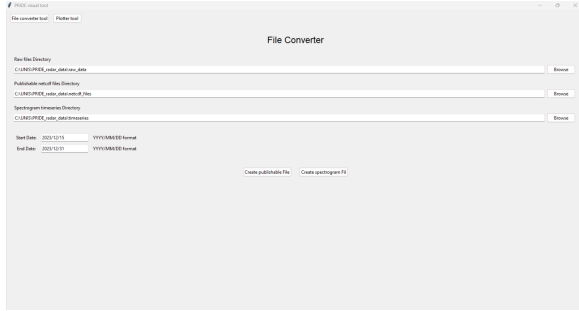
To make data manipulation easier, we created a frontend for the program, which we name visual tool, which allows for converting the data from raw *hdf5* files to publishable and then to spectrogram *netcdf* files, without having to modify the code or any configuration file [fig 21a].

This tool also makes it easier to plot the data, with only a few clicks. This significantly speeds up the process of sifting through the data for results interpretation [fig 21b].

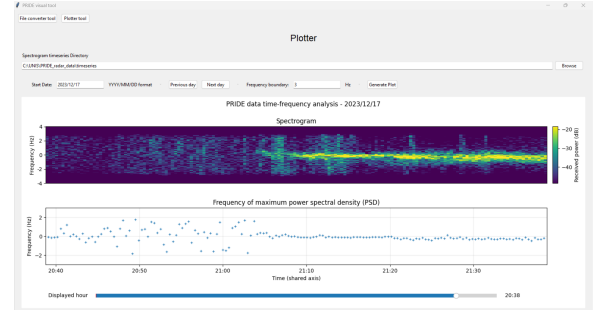
For plotting data over a reduced time range, this tool comes with a scrollbar which allows for moving a one-hour window across the 24 hours of data; essentially, the whole width of

the spectrogram only shows data from one hour, with a starting display time than can be dynamically modified.

An option to zoom-in on the vertical axis was also added to adapt the window to the order of magnitude of the Doppler shift we seek to detect (about 2 Hz) [eq 18].



(a) Visual tool converter window



(b) Visual tool plotter window

Figure 21: PRIDE Visual Tool

4.2.3 Software validation

To check whether the analysis was working correctly, we tested this process using data provided by the Japanese HF Doppler Sounding Experiment (HFDOPE) [11]. In particular, we used the data cited by the HFDOPE Group as a good example, which is the data from the Awaji island radar from April 14th, 2022.

This allowed us to confirm that our code was working as intended, as it could reproduce the spectrograms and max PSD plots obtained with the Japanese code. However, it showed the limitations of the PRIDE data itself, as the spectrograms obtained with the latter are much more noisy, and not as sharp as those from the HFDOPE radars.

While this could originate from the radar itself, or from previous steps in the analysis, mainly those resulting in the raw *hdf5* files, it is also possible that the stark differences in ionospheric conditions between Svalbard and Japan are responsible for the noisy spectrograms.

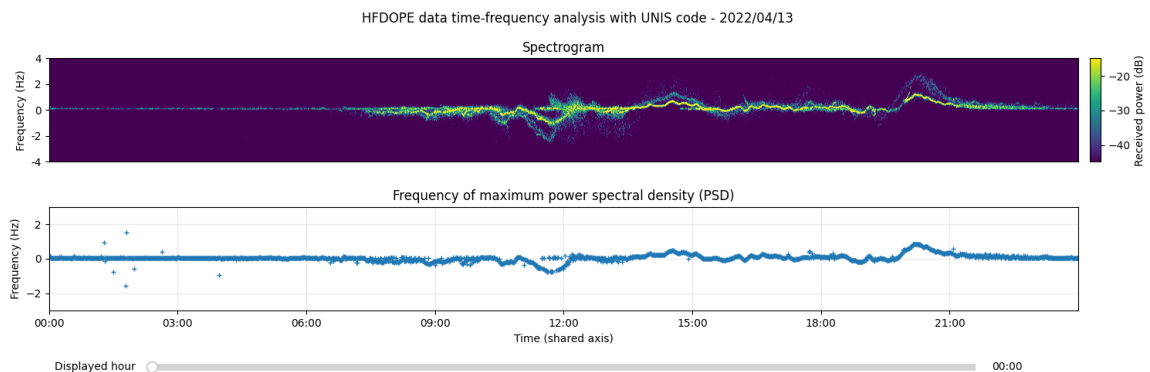


Figure 22: Spectrogram from the HFDOPE AWJ radar data obtained with UNIS code

4.3 PRIDE data interpretation

4.3.1 PRIDE validation

Now that we have compared PRIDE spectrograms to Japanese instruments spectrograms, we can say that PRIDE seems to be working, or at least that it has worked in the past.

Indeed, we can often observe, especially during the midnight sun in summer, a concentration of the scattered points in a line around the central line of the max PSD plot (from 15:30 to 23:00 in [fig 20]). These lines can form when the ionised plasma moves coherently in one direction; since we can see this line, it means that we have received a signal coming from Hornsund at this point in time.

On the same figure, we can also see clouds of points, which happen when no signal is registered, or when the local plasma density disturbances do not move coherently. This makes up most of the spectrograms observed during the winter as the ionosphere is a lot less ionised than in summer, but even a very few dozens of minutes showing a line are enough to show the instrument is working; this was the case in December 2023.

4.3.2 Comparison with magnetometer data

As the line described previously is the result of a coherent movement of local density disturbances of the plasma, it allows for the visualisation of waves travelling at the reflection altitude. In particular, we can use the data from PRIDE to find waves with a period of 10 to 30 minutes, and an amplitude of 2 Hz; to check their nature, we can compare the obtained spectrograms to magnetometer data [fig 23].

In this example, we can remark that both plots show waves with a 20-minute period and a good 1.5 Hz amplitude for the spectrogram. For the magnetometer data, only the Y component was showing this kind of waves, which tends to point towards a TID rather than ULF waves. For a more in-depth comparison, it would be necessary to take the Fourier transform of both these events and compare the frequencies.

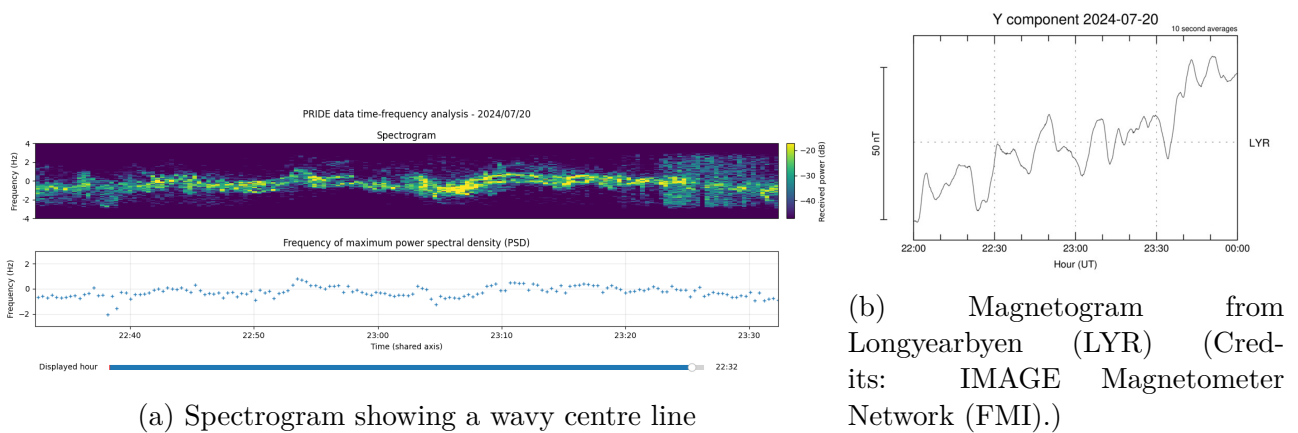


Figure 23: Comparison of a PRIDE spectrogram with magnetometer data on a possible ULF event, on July 20th, 2024.

Conclusion

During the time of this internship, some important milestones were achieved for improving and expanding on the data obtained with radar instruments for ionospheric research on Svalbard.

Most importantly, we were able to create and deploy a new ionosonde system at the KHO, in Longyearbyen. Starting from scratch, we used the blueprints from an existing ionosonde system to create an amplifier box, upon which we improved by adding a watchdog system for safety and reliability. Then, the transmitter antenna was deployed with the intent of keeping it up and running for a few years, at least. These two considerations allow us to qualify this radar as an instrument, rather than a prototype.

We were also able to improve on the analysis process for the PRIDE radar data, getting cleaner spectrograms, and emphasizing the exploitable fragments of the data. Besides, this allowed us to confirm that this instrument has indeed worked in the past. This now allows us to use the data for actual interpretation, and can be used to try finding ULF waves or gravity waves.

However, some points still need to be addressed, particularly about the ionosonde. First, the instrument does not yet work in its current state. Some software debugging is still required to understand the reason why the receiver USRP keeps on crashing when working with some configuration files; second, when transmitting normally, we are unable to see the received signal, and the software seems only to produce empty ionograms.

About PRIDE too, some improvement can still be made, especially on the quality of the data and its visualisation. As this instrument also produces a lot of noise very often, it could be that the hardware needs to be improved for it to work more reliably.

Then, once these instruments are deployed, we will be able to have a new way of visualising and finding ionospheric phenomenons like the gravity waves, ULF waves or auroras happening above Longyearbyen, and particularly for material waves with PRIDE.

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