# Instrumentation

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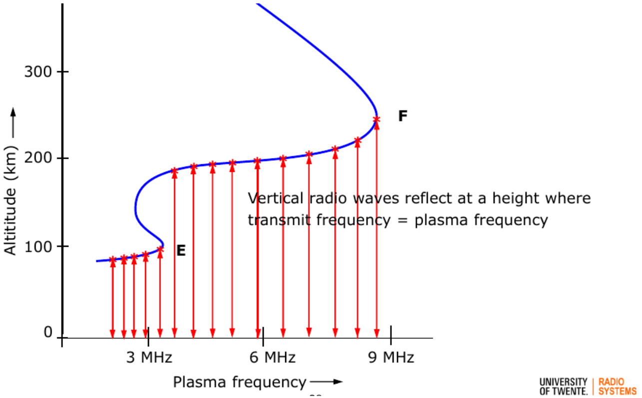
# Outline

# Introduction

How to observe the ionosphere, thermosphere, plasmasphere?
This region is difficult to access compared to the lower atmosphere.

1. *in situ* (sounding rockets, satellites): very good, but limited in coverage and expensive
2. Remote sensing:
    1. Trans-ionospheric signals (GNSS, radio telescopes,...)
    2. Reflection from the ionosphere (ionosonde, Doppler sounder,...)
    3. Incoherent scatter radar

# The principle of the ionosonde

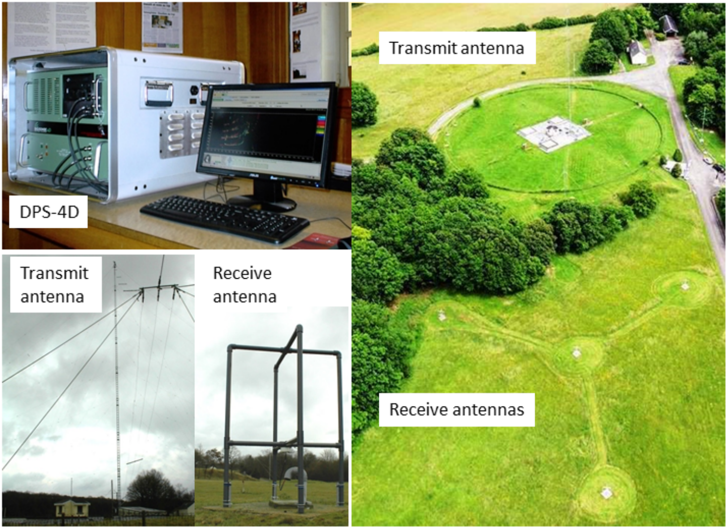



Plasma frequency determined by electron density $N_e$:

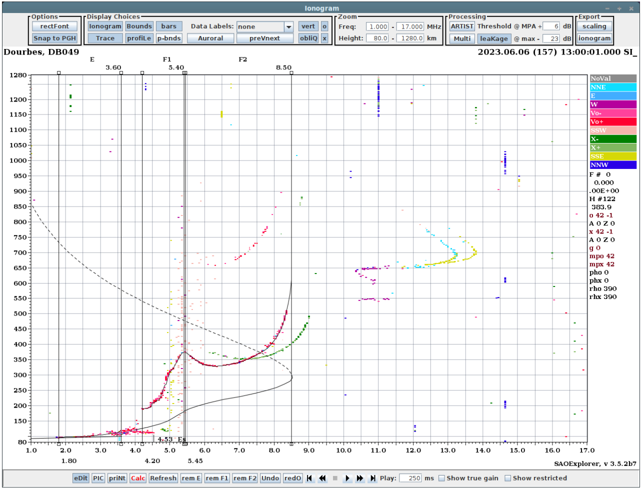
$$f_p = \frac{e}{2\pi}\sqrt{\frac{N_e}{\varepsilon_0 m_e}}$$

Echo arrival times are inverted into electron density profile.

# The Dourbes Ionosonde



# A quiet, day-time example

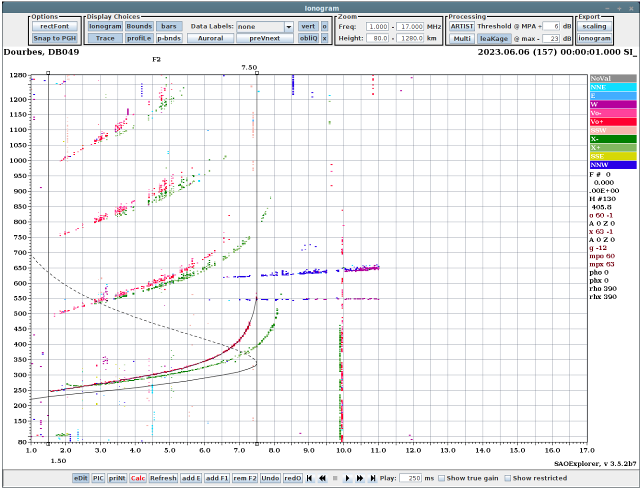



All the main layers visible.

Minor sporadic-*E*, up to 4.5 MHz.

(Oblique trace from Spanish ionosonde.)

# A quiet, night-time example

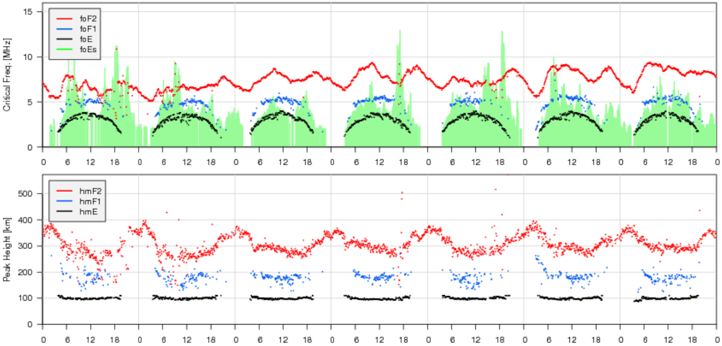



Only a single $F$-layer exists.

$foF_2$ is (somewhat) lower.

In this case, $hmF_2$ close to day-time value.

# Ionogram derived characteristics

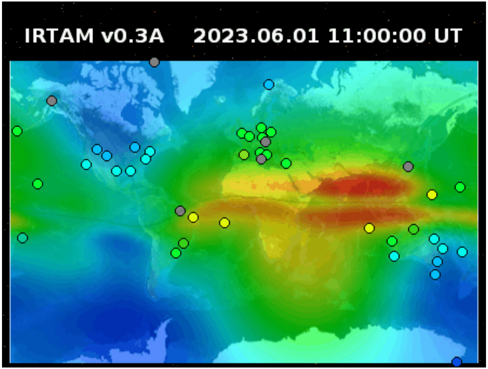



From the ionosonde, we can obtain (automatically, in real-time) most ionospheric weather parameters.

In order to monitor the ionosphere globally, data from many observatories is needed.

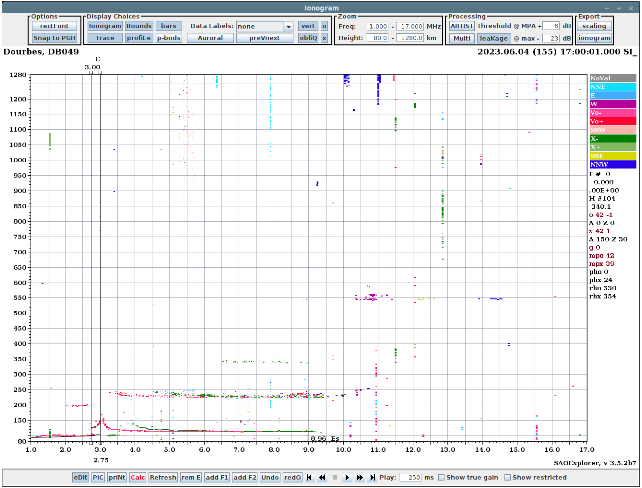

Giro is currently the most complete repository of ionosonde data, but there are others which may have additional observatories.

# Global, real-time monitoring and modelling




Combining real-time derived characteristics from a world-wide network on ionosondes allows modelling the global ionosphere.
But: the availability of real-time data is sparse, and not uniformly covering all regions.

# Sporadic-*E*

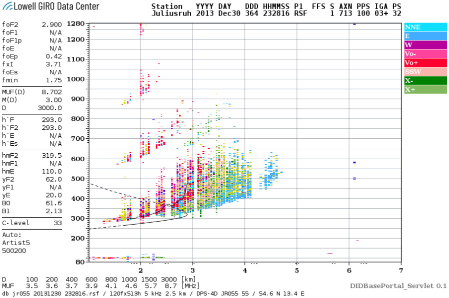


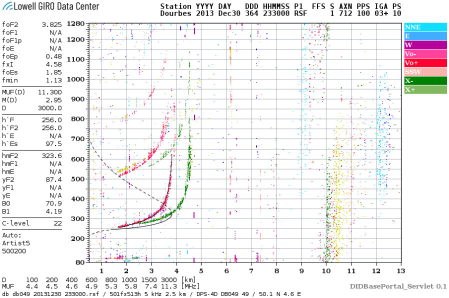

Sporadic *E*-layers: very thin but very high electron density layers below the *F* layer.

Little effect on the *TEC*, but makes Ionosonde soundings impossible.

Also lower ionosphere absorption can prevent ionogram soundings.

Example of expanding auroral oval during geomagnetic disturbances.

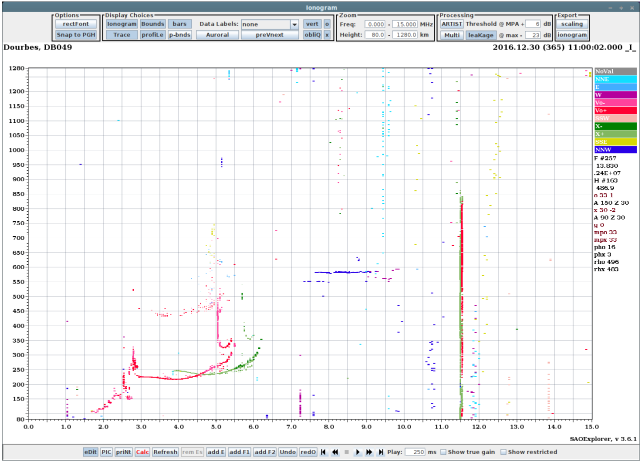



The auroral oval extends here to between Juliusruh (55°N, left) and Dourbes (50°N, right). Spread-*F* in ionograms is associated with scintillation in GNSS signals.

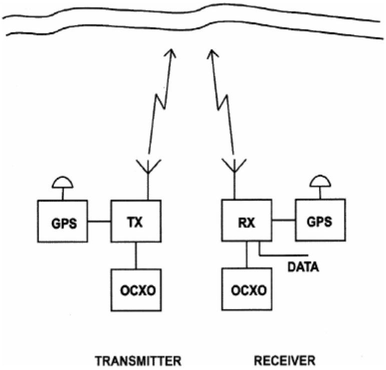
# Medium scale TIDs

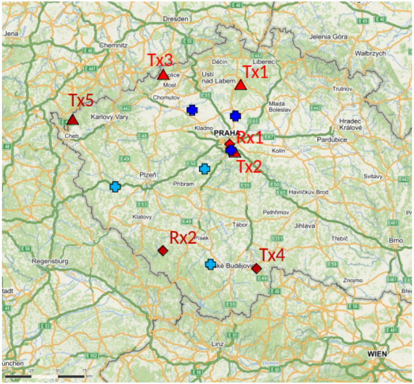
Electron density gradients and small scale travelling disturbances can be seen as distortions to the “normal” ionogram traces.



# Continuous wave Doppler sounding

The principle of a continuous Doppler sounding system (CDSS) is similar to the ionosonde, but using forward scattering.

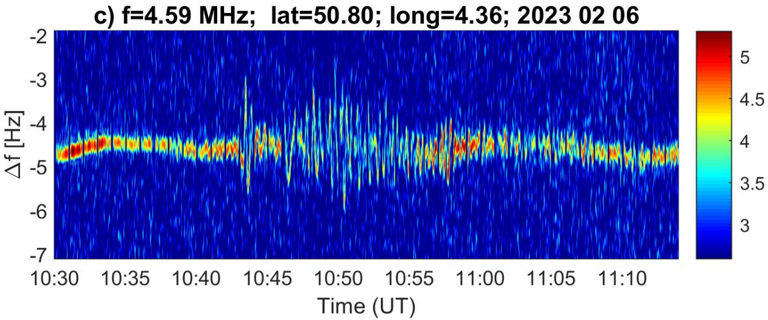



Each transmitter/receiver link operates continuously on a single frequency. Many links can be combined.

# CDSS observations

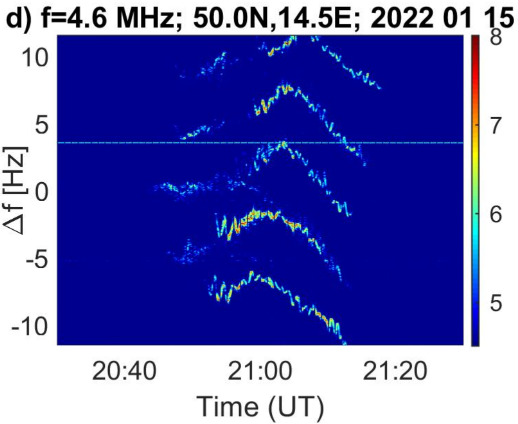
Continuous-wave sounding allows detection of ionospheric disturbances at shorter time resolution.




However: only a single frequency is sounded, so no complete electron density profile can be obtained. Instead, only a measurement at a single height is obtained.

# Multi-point CDSS

When using multiple CDSS sounding links at similar frequencies, direction movement of passing disturbances can be determined.



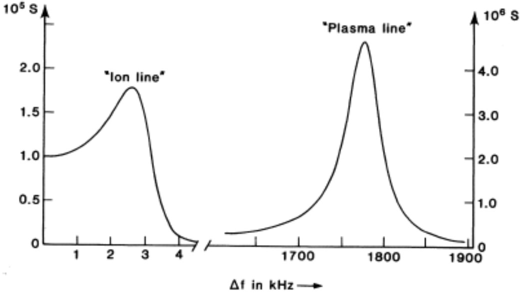

The height of the reflection still has to be determined from other observations, e.g. from a nearby ionosonde.

# Incoherent scatter radar

Radio waves below $f_p$ are reflected by collective movement of electrons. Higher frequencies are still scattered (incoherently) by individual electrons, with effective radar cross-section

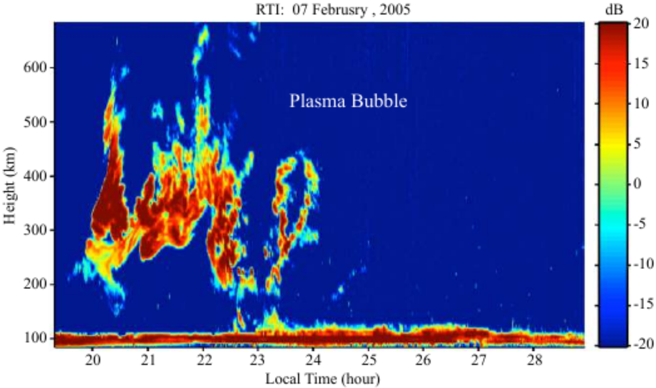
$$\sigma = \frac{N_e 4\pi \left(r_e \sin\psi\right)^2}{\left(1 + \left(\frac{4\pi D}{\lambda}\right)^2\right)\left(1 + \frac{T_e}{T_i} + \left(\frac{4\pi D}{\lambda}\right)^2\right)}$$

(because of the presence of ions, electrons are not really free and scattering comes from fluctuations in electron density)




Spectrum of incoherent reflections allows determination of many characteristics.

# ISR observations




A major advantage of ISRs is that they can observe above the height of highest electron density.

# Trans-ionospheric radio signals

Passive monitoring of trans-ionospheric signals provides observations complementary to active radio soundings.

- Advantage: provides data also above the ionospheric peak.
- Disadvantage: only provides information integrated along line-of-sight.

GNSS receivers are cheaper and smaller than active sounding instruments, so there are denser networks of observatories.

In a similar way, radio telescopes and riometers can monitor the ionosphere by tracking astronomical radio sources.

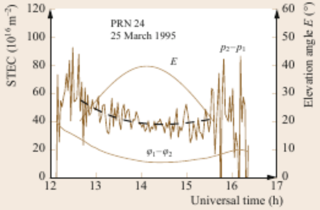
# Total electron content

Refractive index for radio signals in a magnetised plasma:

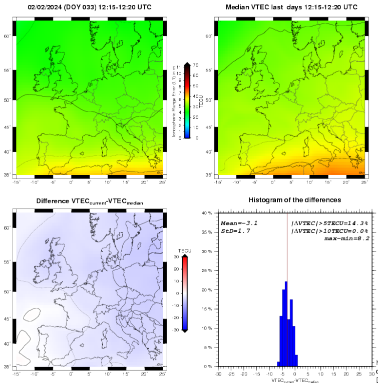
$$n = \sqrt{1 - \frac{2f_p^2\left(f^2 - f_p^2\right)}{2\left(f^2 - f_p^2\right) - f_g^2 \sin^2\theta \pm \sqrt{f_g^4 \sin^4\theta + 4\left(f^2 - f_p^2\right)^2 f_g^2 \cos^2\theta}}}$$

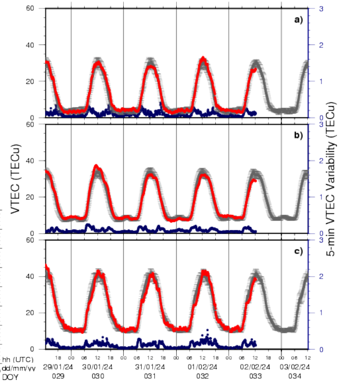
Lowest order independent of magnetic field:

$$n \approx 1 - \frac{f_p^2}{2f^2} \approx \frac{40.3m^3s^{-2}}{f^2} TEC$$



Dense networks of GNSS receivers can be used to calculate detailed maps of vTEC.

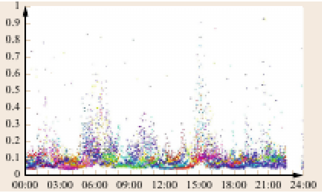


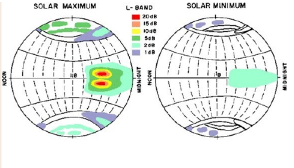



# Scintillation measurements

Scintillation of trans-ionospheric signals can provide information about small-scale structuring.

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}} \qquad \sigma_\varphi = \sqrt{\frac{1}{N-1} \sum_{i=1}^{2} \left(\varphi_i - \langle \varphi \rangle\right)^2}$$




Global variation of amplitude scintillation fades at L band (after Basu et al. 1988a, b, colored by A.W. Wernik)

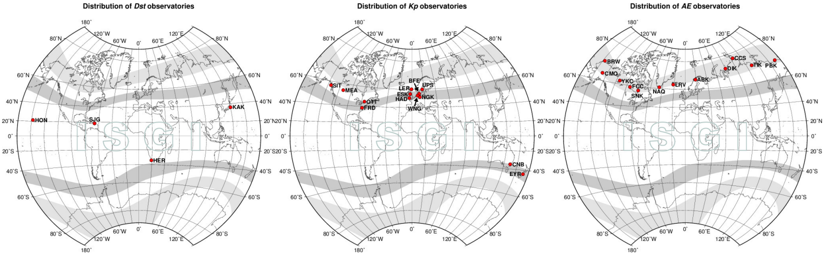
Very different physical processes can produce scintillation in GNSS signals.

# Strengths & limitations of ionospheric instruments

- Ionosondes: The standard for observing the bottom-side ionosphere. Full electron density profile, but no observations of the top-side and limited time-resolution. Rather expensive.
- Doppler sounders: Cheap and relatively simple instrument. Ideal for short time resolution, but only a single frequency (and therefore: a single height) is observed.
- GNSS receivers: Relatively cheap and easy to operate. Can be used in dense networks, but only provides integrated measurements, not height profile.
- ISRs: Provide a lot of details, including about the topside ionosphere. Very expensive to build and operate, so limited data coverage (in space and time). The neutral thermosphere is in general more difficult to observe than the ionosphere.

# Ground based magnetometers

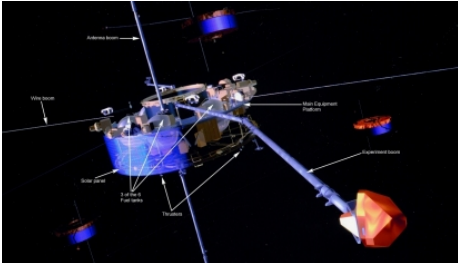
The main part of the magnetic field is the Earth's internal field, but the short term variations are due to magnetospheric/plasmaspheric/ionospheric currents.

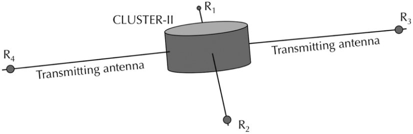



Various magnetic activity indices indicate currents in different regions.

# Cluster mission & WHISPER instrument

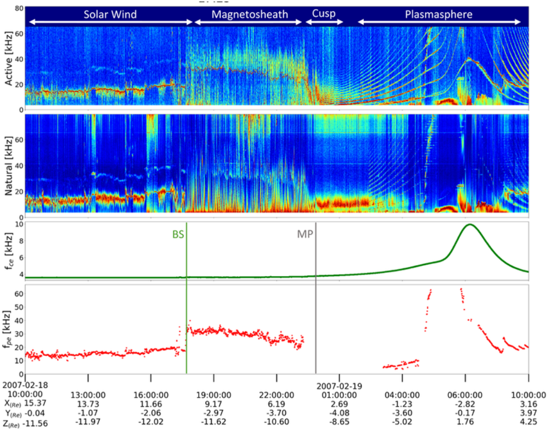
Cluster II is a constellation comprising four identical satellites on (different) elliptical, GEO-crossing orbits.
Each satellite carries instruments for measuring electron and ions in the magnetosphere as well as **E** and **B** fields.
WHISPER (Waves of High frequency and Sounder for Probing of Electron density by Relaxation) can be used to obtain electron density.



# Whisper data

The Whisper instruments makes both passive recordings and active soundings in the 2–80 kHz band; data is presented as a **E** field spectrogram.




From the observed plasma frequency, the electron density is obtained.
Various other resonances can be observed; careful interpretation of the spectra is needed.

The end!

Questions?

References:


- R.D. Hunsucker (1991): *Radio Techniques for Probing the Terrestrial Ionosphere*, Springer-Verlag.
- P. Teunissen & O. Montenbruck (2017): *Springer Handbook of Global Navigation Satellite Systems*, Springer International Publishing.