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How GNSS and Beacon receivers can be used to monitor auroral ionosphere and space weather?

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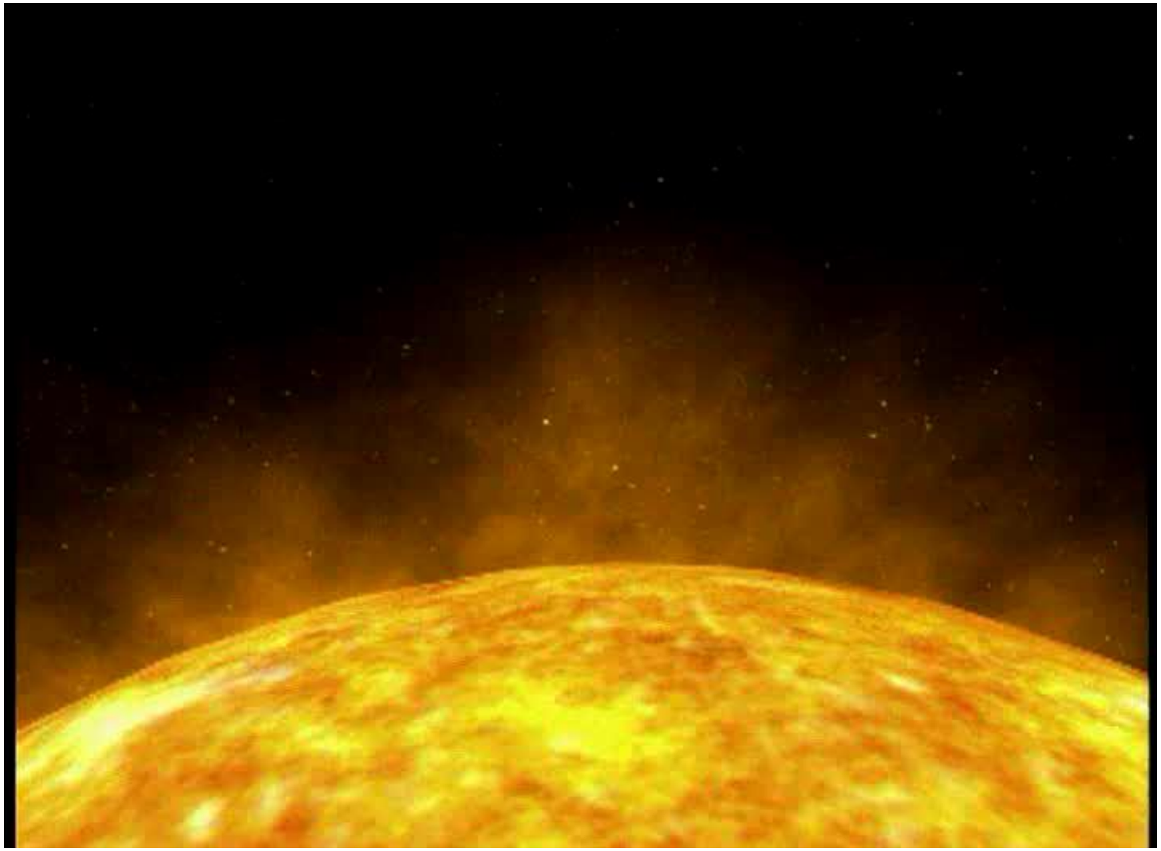
Special Thanks: J. Norberg (FMI),
A. Aikio and T. Nygren (University of Oulu)

Contents

- Space weather: What and why?
- Some ionospheric physics
- Probing ionosphere with Global Naviation Satellite System
- Why GNSS is not enough at high latitudes?
- Future prospects

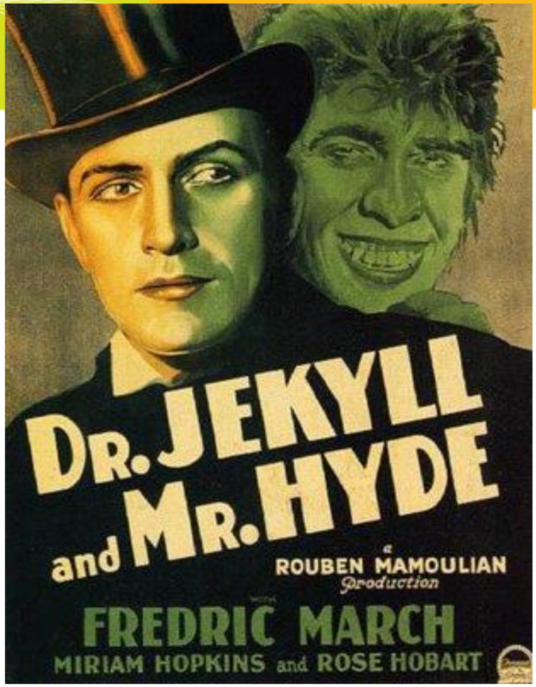
The impact of Solar eruption in the near-Earth space



Animation: NASA

Space weather has two faces

- **Solar eruptions cause rapid variations in the magnetospheric and ionospheric conditions**
- **Geomagnetic field guides processes particularly to the vicinity of magnetic poles**
- **Manifestations:**
  - Beautiful auroras
  - Potential problems in technology on ground and in space



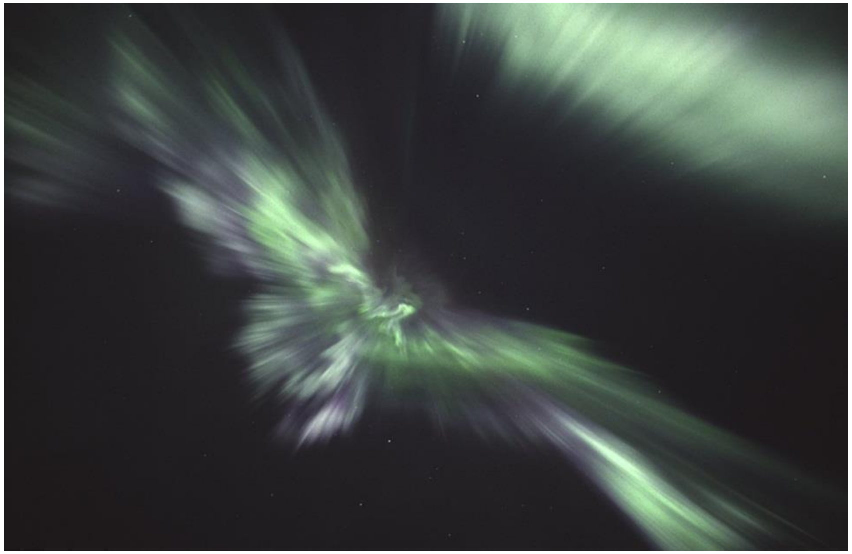
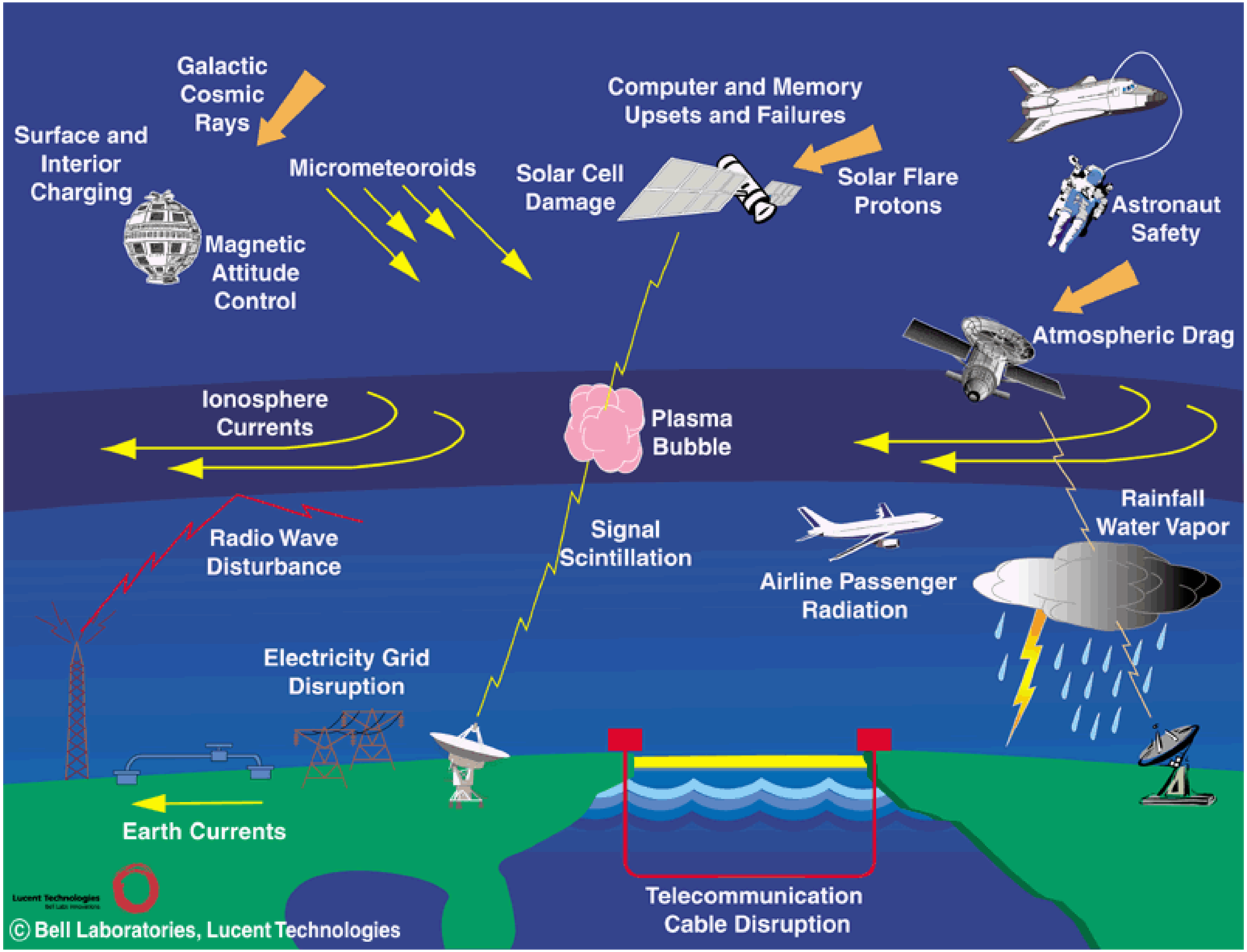


Photo: Jouni Jussila

Space weather: Societal impact



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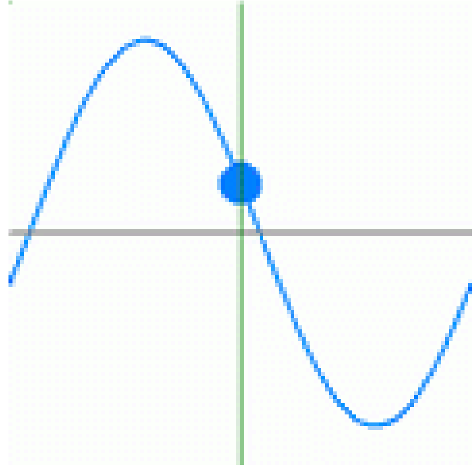
Plane wave



Amplitude (Intensity)

$$f(x,t)=\mathbf{A}\cos(kx-\omega t+\varphi)$$

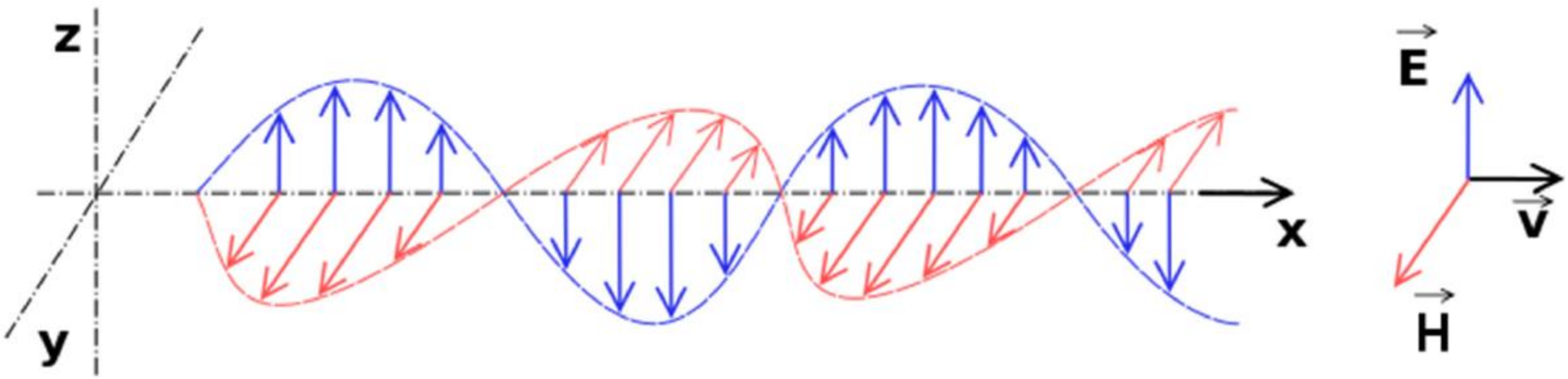
Wave number $k=\frac{2\pi}{\lambda}$

Frequency $T=\frac{2\pi}{\omega}$

Phase (0…2π)

- Plot: https://fi.wikipedia.org/wiki/Aalto
- Animation: https://commons.wikimedia.org/wiki/File:AC_wave_Positive_direction.gif#/media/File:AC_wave_Positive_direction.gif

Electromagnetic waves



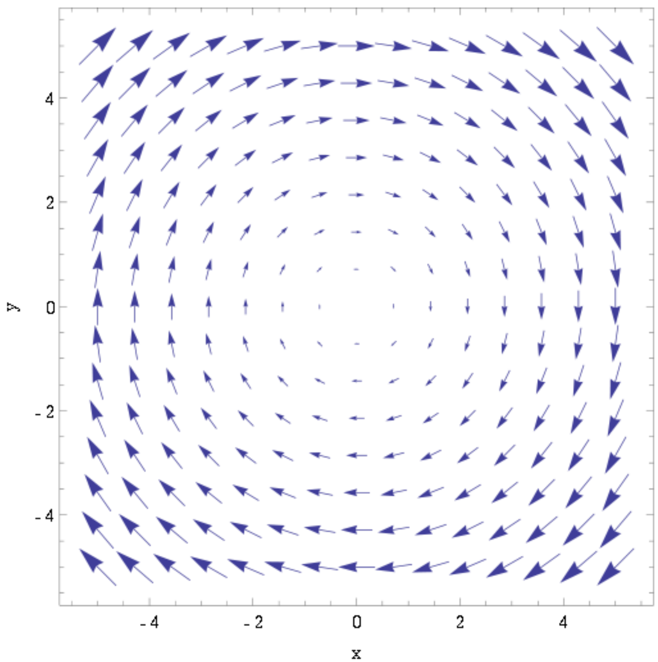
- Plane wave, linear polarization
- Homogeneous medium
- **E**= Electric field, **H**= magnetic field, **v**=propagation direction
- Behaves according to the Maxwell equations
- Figure: Wikipedia ”Electromagnetic radiation”

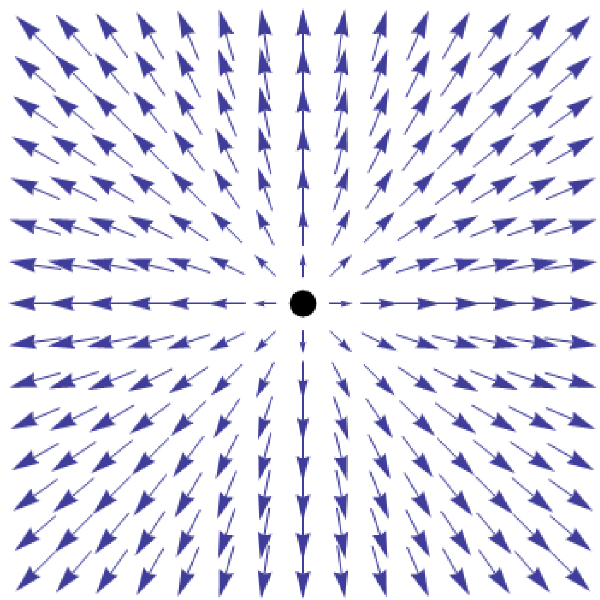
The Maxwell equations

- $\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon}$
- $\nabla \cdot \boldsymbol{B} = 0$
- $\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$
- $\nabla \times \boldsymbol{B} = \mu \boldsymbol{j} + \frac{1}{\mu\varepsilon}\frac{\partial \boldsymbol{E}}{\partial t}$

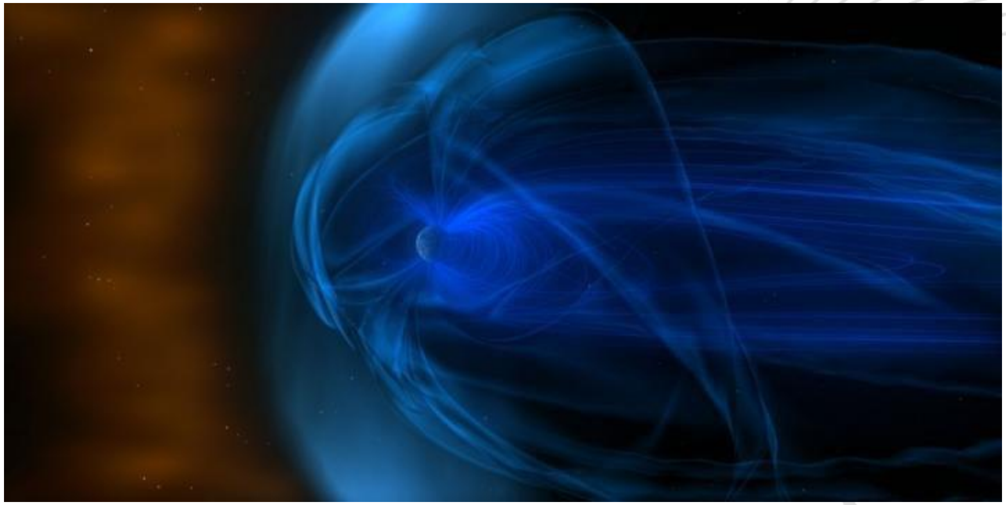
- ρ= charge density
- **J**= current density
- B=Magnetic field
- E=Electrid field
- μ=permeability
- ε=permittivity
- $\nabla\cdot$ = divergence
- $\nabla\times$= curl

James Clerk Maxwell
Scottish mathematician
1831-1879





Plasma and its waves



- **Maxwell:** Electric and magnetic fields, charges and currents are coupled with each other

- **Plasma:** dilute gas with charged particles where the above described coupling is exceptionally pronounced.

- Disturbances in plasma can grow rapidly and they often appear as waves.

- Plasma is the dominant state of matter in the space.

- **In the ionosphere** plasma is mixed with the neutral atmosphere which makes its modelling challenging

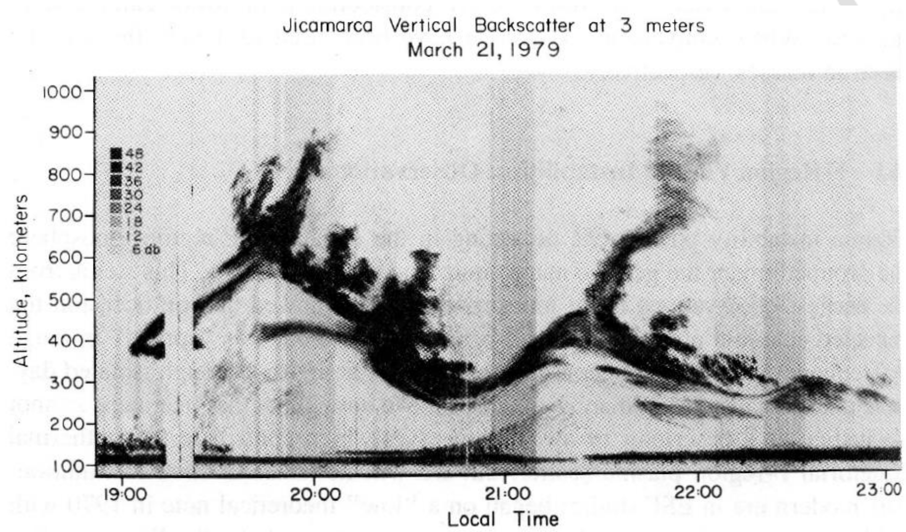
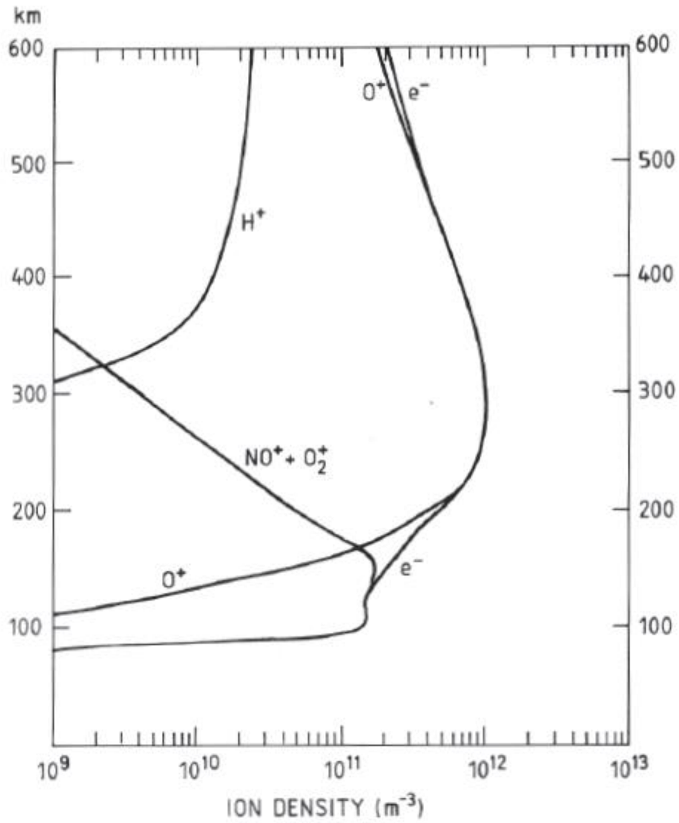
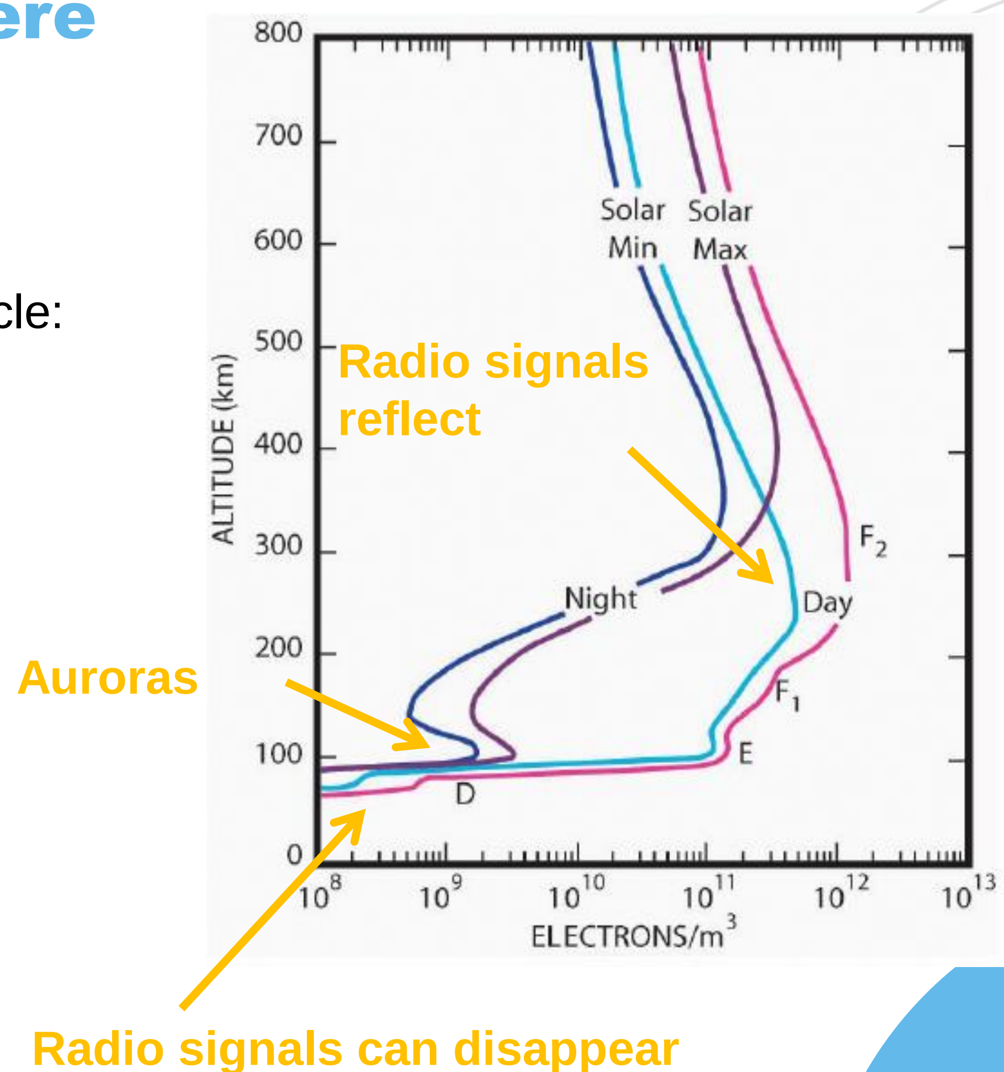


Fig. 4.1. Range–time–intensity map displaying the backscatter power at 3-m wavelengths measured at Jicamarca, Peru. The gray scale is decibels above the thermal noise level. [After Kelley *et al.* (1981). Reproduced with permission of the American Geophysical Union.]

The structure of ionosphere

- **Three layers**: F, E, D
- **Variations in the electron density**
  - Day-night variations: 100x
  - Variations according to the solar cycle: 10x in upper parts of F-layer
  - Auroras: 100x variability in E-layer





Factors controlling ionospheric electron density

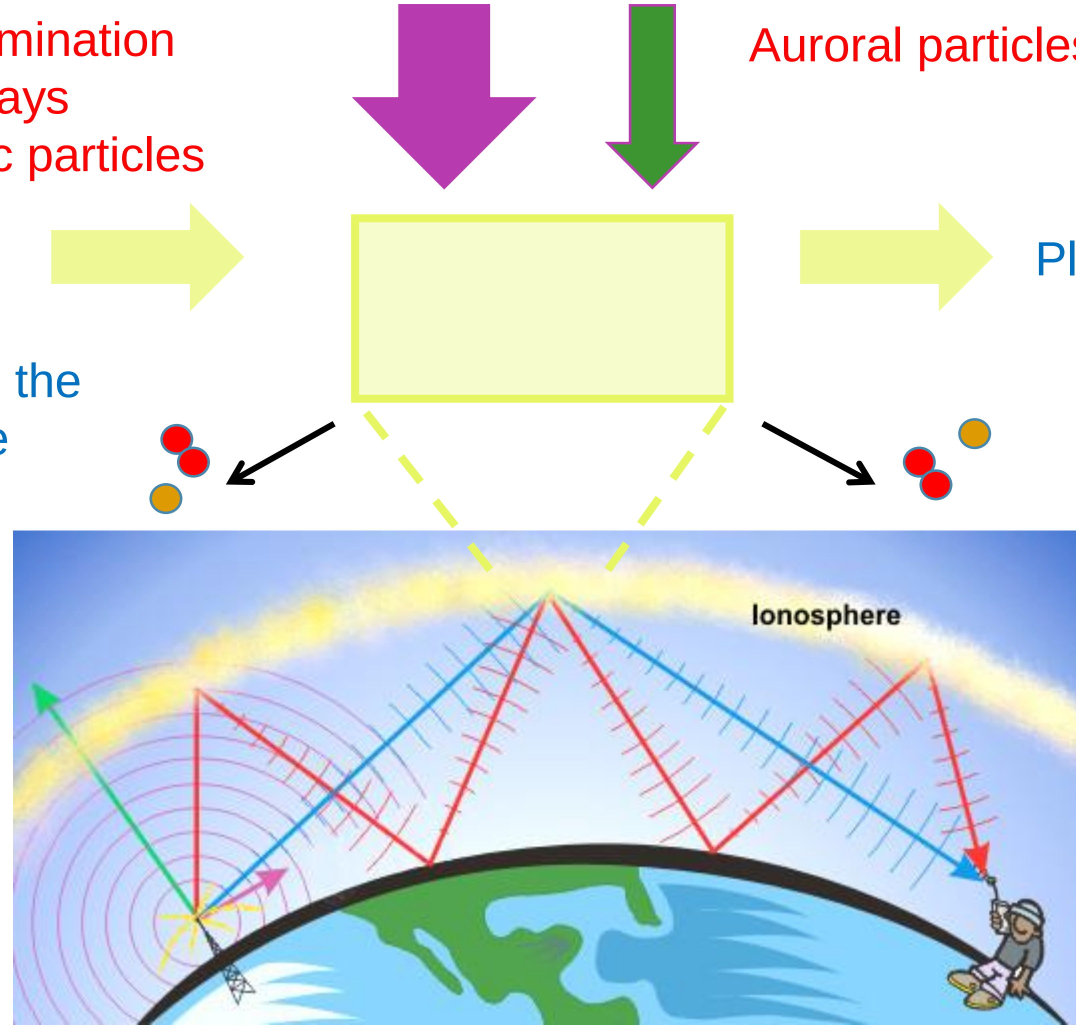
Solar illumination
EUV, X-rays
Energetic particles

Auroral particles

Plasma drift

Plasma drift

Loss of charge into the neutral atmosphere (recombination)



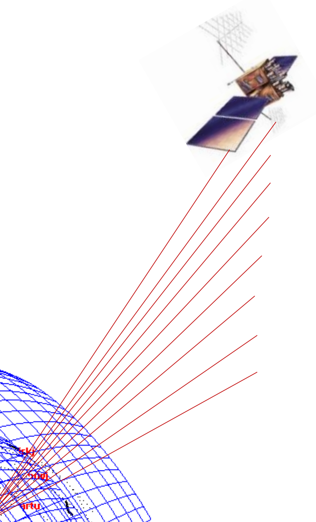
Dense GNSS receiver networks are widely used in ionospheric research

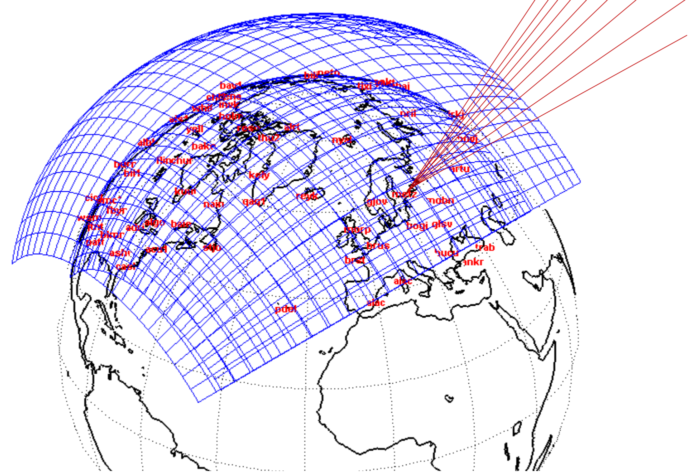
- From the combination of L1 and L2 signals integrated electron density (N_e) along the signal path can be deduced

- Near-Real-time data available from several networks
→ Suitable approach also for operational services

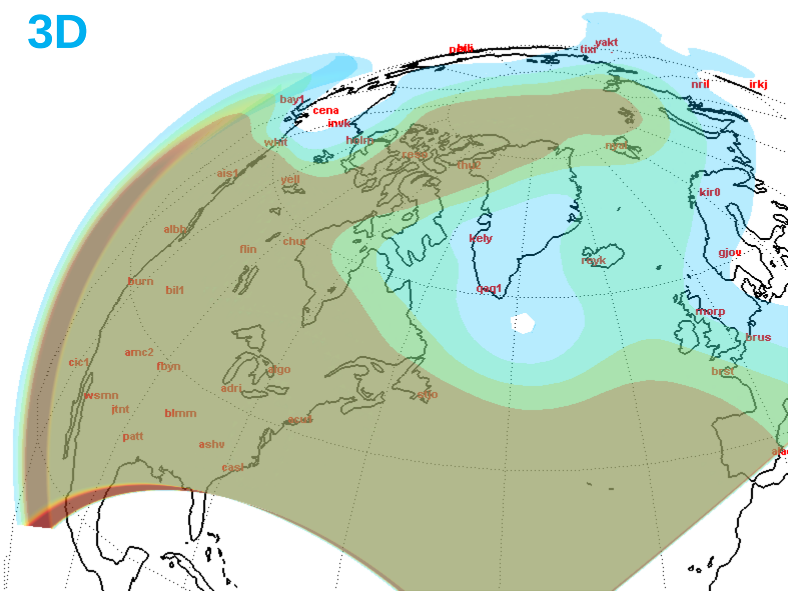
- Works well particularly at low and middle latitudes and in global scales

$$\mathrm{TEC} = \int_S^R N_e \, ds$$



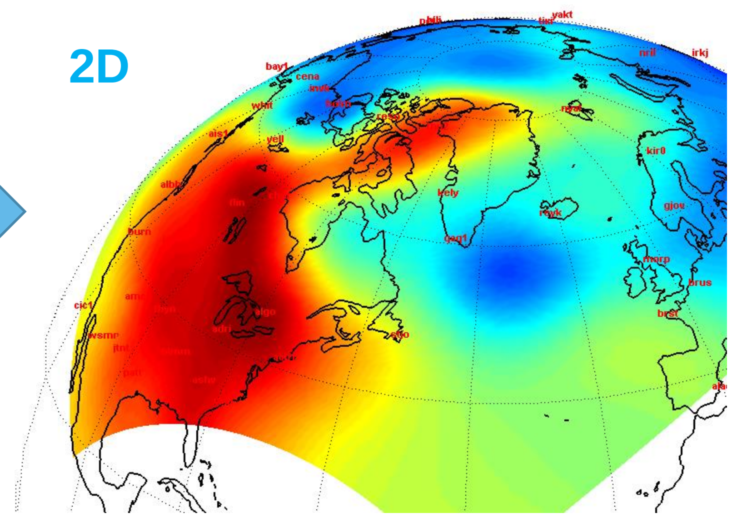


3D



Altitude integration

2D

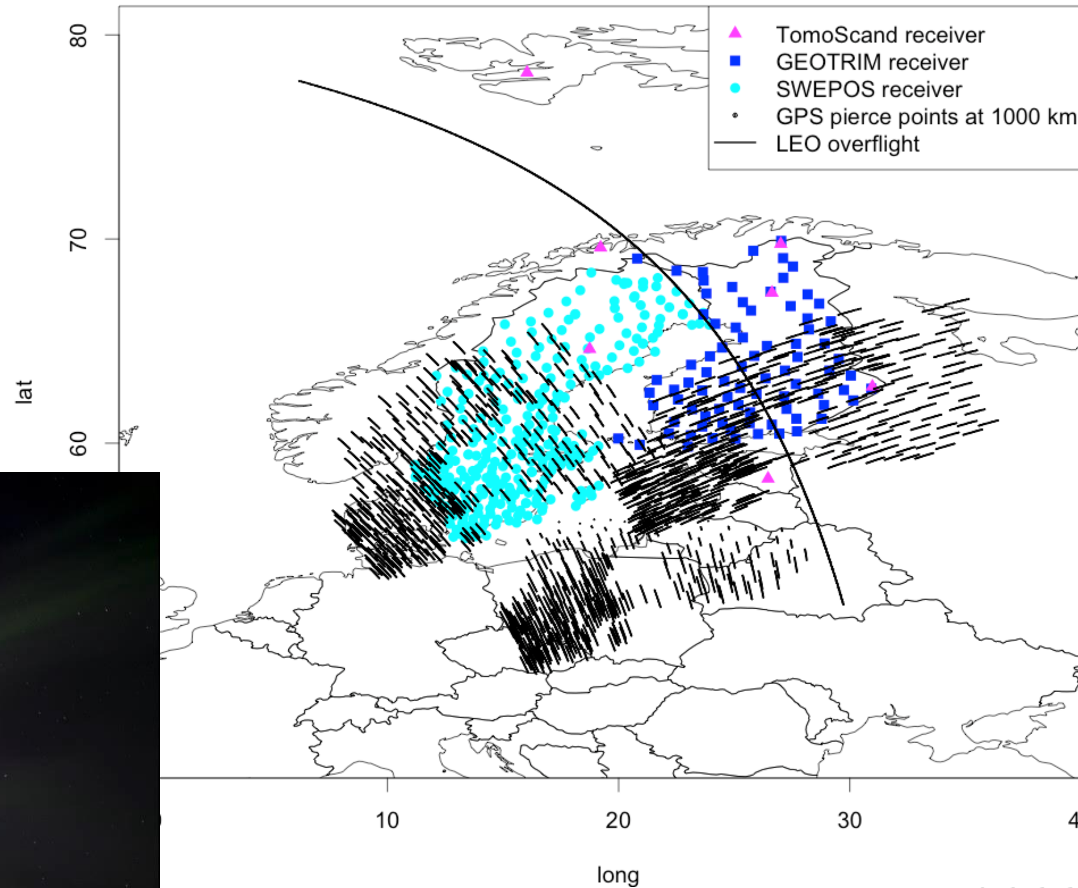


Figures: Pokhotelov et al, 2010

Challenges in the Arctic ionosphere

- Auroral activity causes dynamic small scale structures in the ionosphere → high space and time resolution needed

- GNSS signals available only at low elevation angles → less information from the regions where the disturbances are strongest



Video: Sauli Koski

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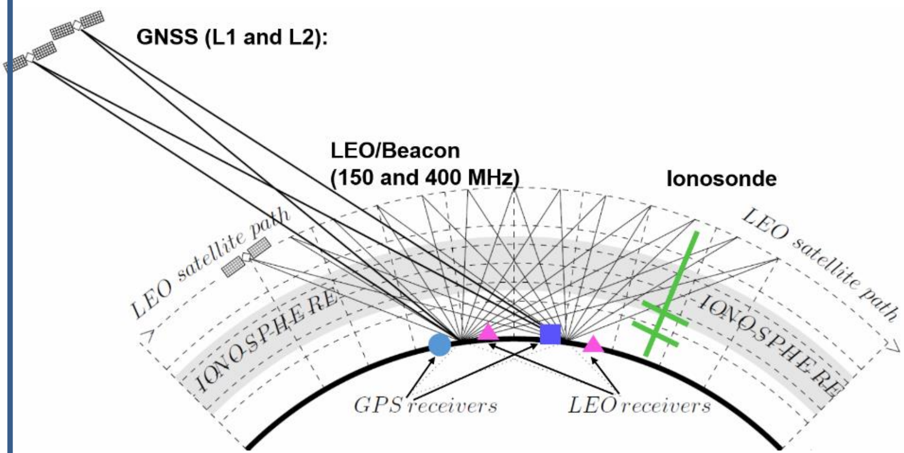
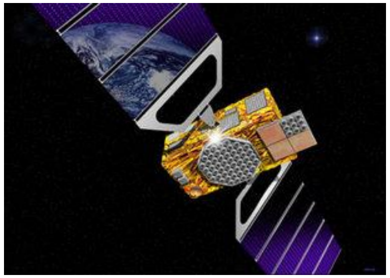
UNIVERSITY of OULU

TomoScand – IONOSPHERIC TOMOGRAPHY

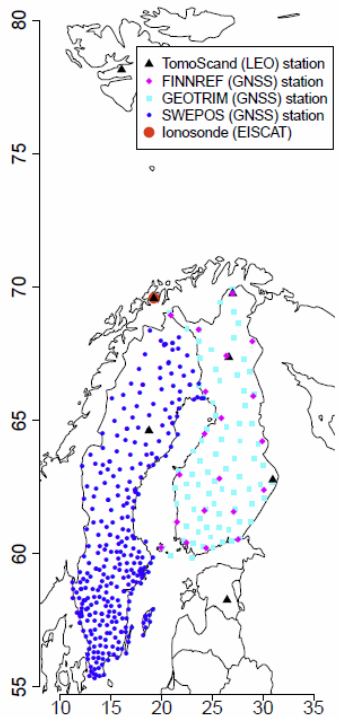
3D reconstruction for ionospheric electron density (Ne) over Fennoscandia
Spatial resolution 5-20 km (typically ~100 km in global inversions)

Input: GNSS and LEO/Beacon signals

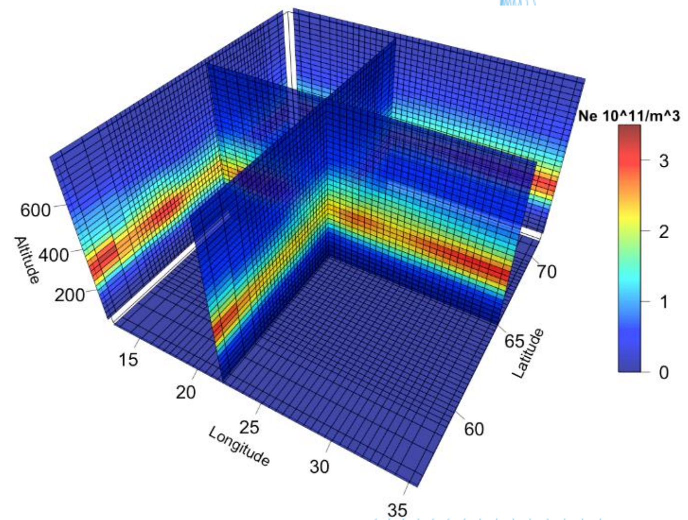




Bayesian statistical inversion



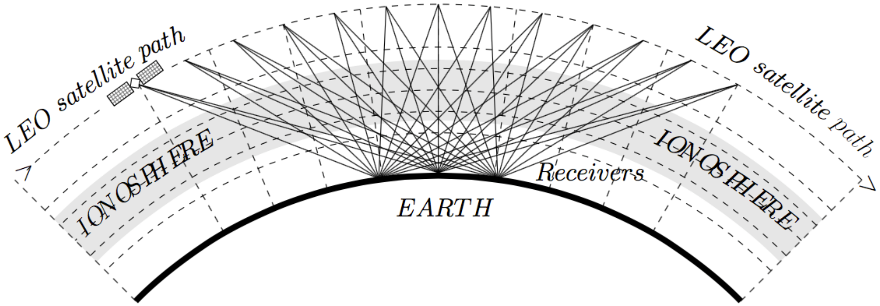
3D image of electron density



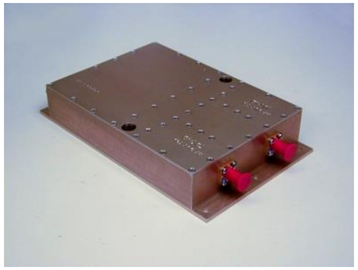
- **GNSS**: Continuous signal but limited in latitude and elevation angle
- **Beacon**: A snapshot over the whole area with a range of elevation angles but available only ~4 times per day

TomoScand approach – pros and cons

- **Challenges**
  - Signal paths do not cover all directions → support from other instrumentation needed
  - Availability of Beacon transmissions in the future?



- **Advantages**
  - High space resolution
  - Understandable regularization of the ill-posed problem
  - Systematic error estimates
  - Cheap technology, tested already in CubeSats

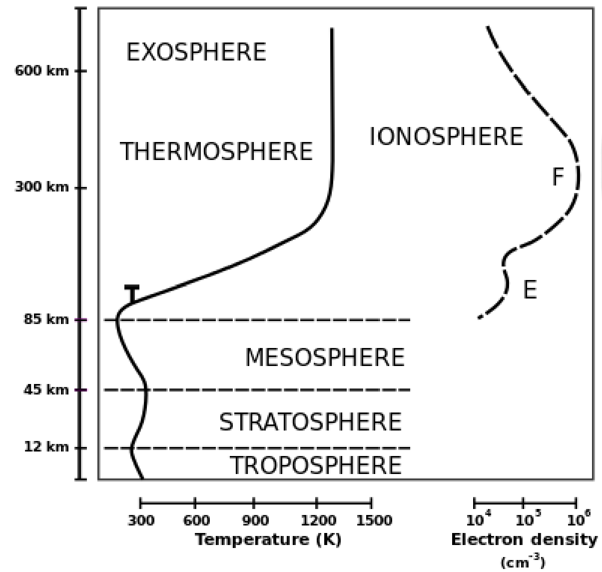


Figures: J. Norberg; Syntech Microwave; IBIMAGEM

Support to TomoScand by ionosondes

- HF radio waves reflect from the ionosphere
- Ionosfääric refractive index:
- $\mathbf{n^2=1-\left(\frac{2\pi f_p}{2\pi f}\right)^2}$
- $N_e=10^{10}\text{-}10^{12}\ m^{-3} \rightarrow$ 1-8 MHz
- Ionosonde provides altitude profile of eletron density up to the F-layer maximum.

$$f_p = \frac{1}{2\pi}\left(\frac{e^2 n_e}{\epsilon_0 m_e}\right)^{1/2} = \left(80\frac{n_e}{\mathrm{m}^{-3}}\right)^{1/2}\ \mathrm{Hz}$$



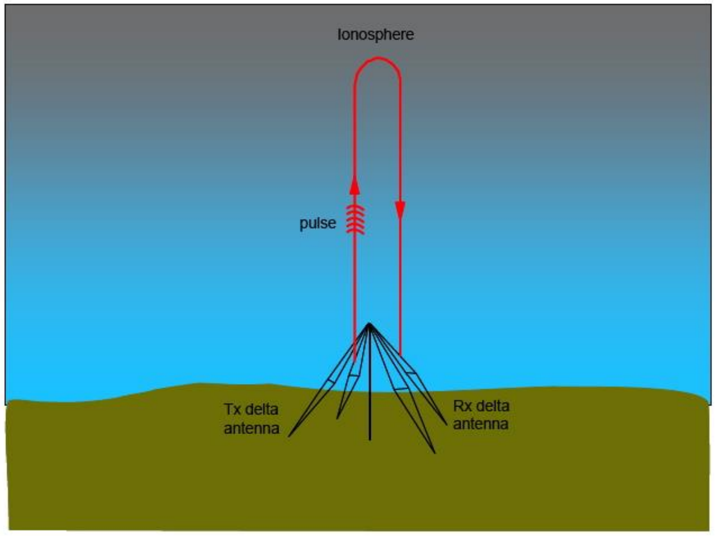
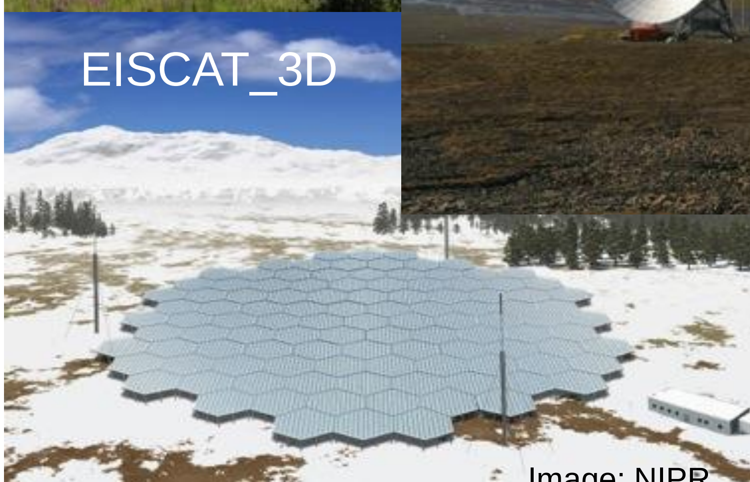


Figure: www-amateur-radio-wiki.net

Validation with high power radars



Slide by:
Esa Turunen
Sodankylä
Geophysical
Observatory

EISCAT high power radars

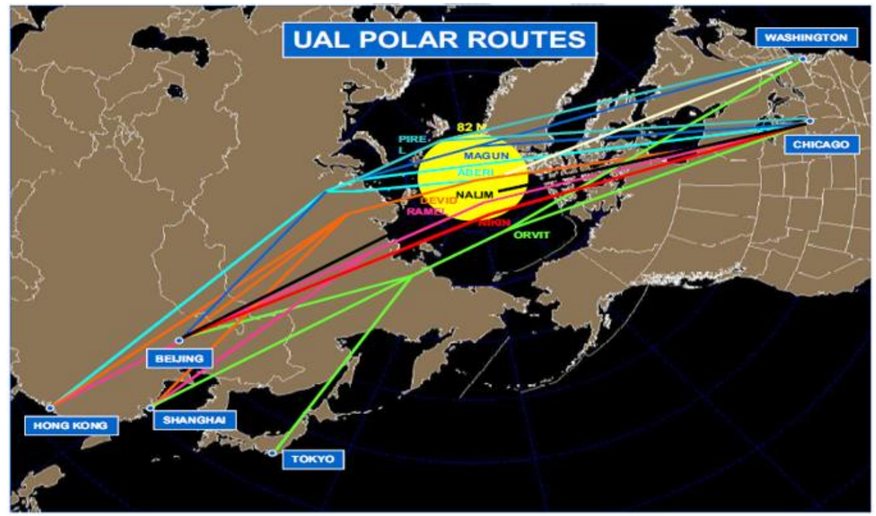
-Transmitter in Tromsö

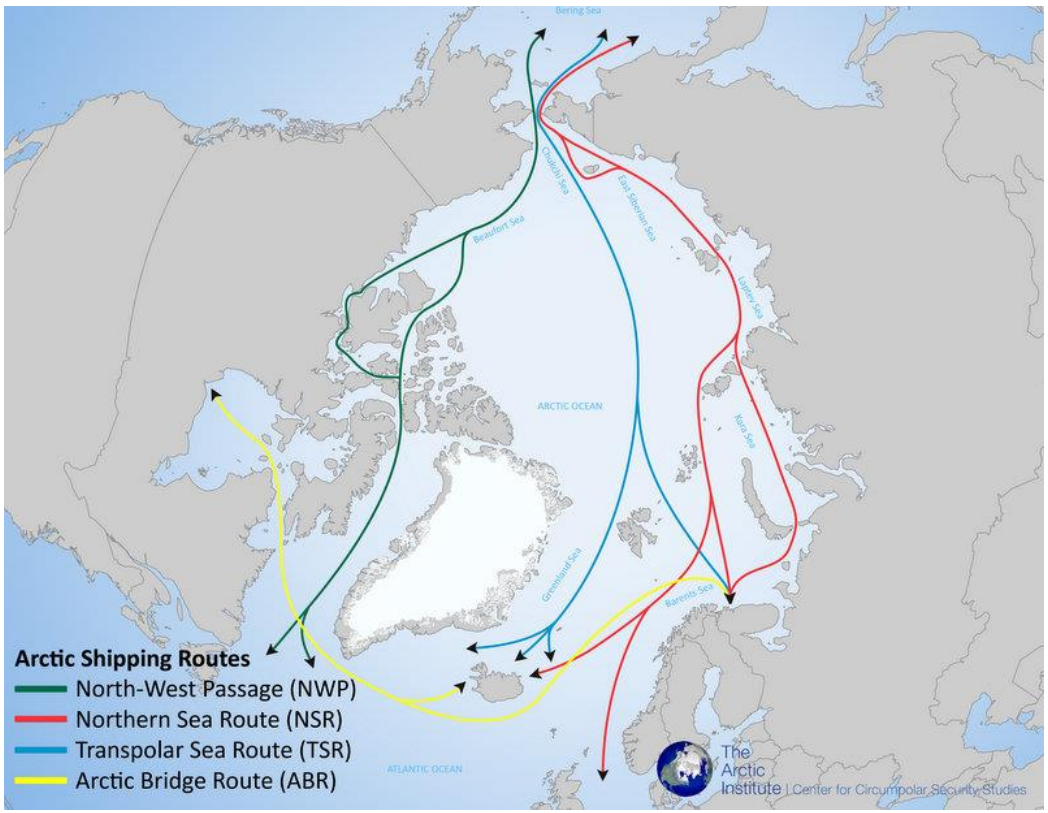
-Receivers in Kiruna and Sodankylä

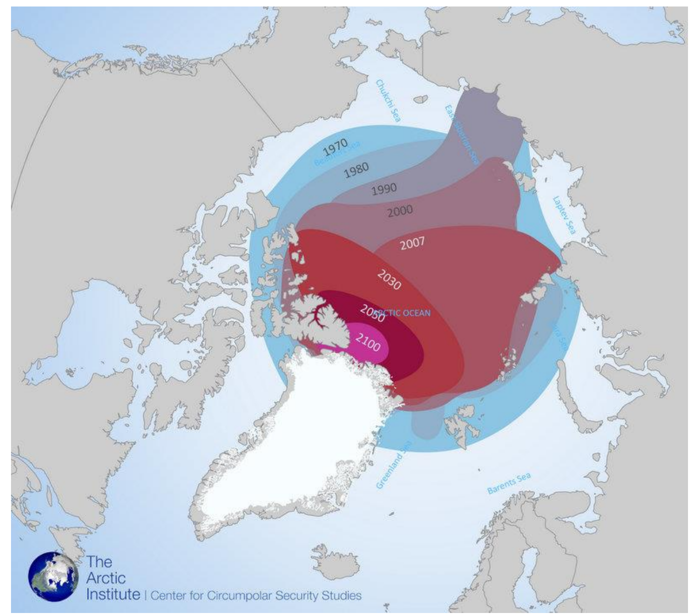
-EISCAT_3D: 3D image on ionospheric properties including plasma density and velocity

Why is this important?

- Over the horizon communication with HF radio waves is used in arctic shipping and in aviation on polar routes
- HF reflection conditions depend critically on ionospheric electron density conditions
- Global warming opens new routes for artic shipping → significant reductions in time and costs







Figures: Wikipedia United Airlines The Arctic Institute

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Thanks for your attention!