Research seminar on Sun-Earth connections

Space weather: Concepts and ground effects

Ari Viljanen
Finnish Meteorological Institute

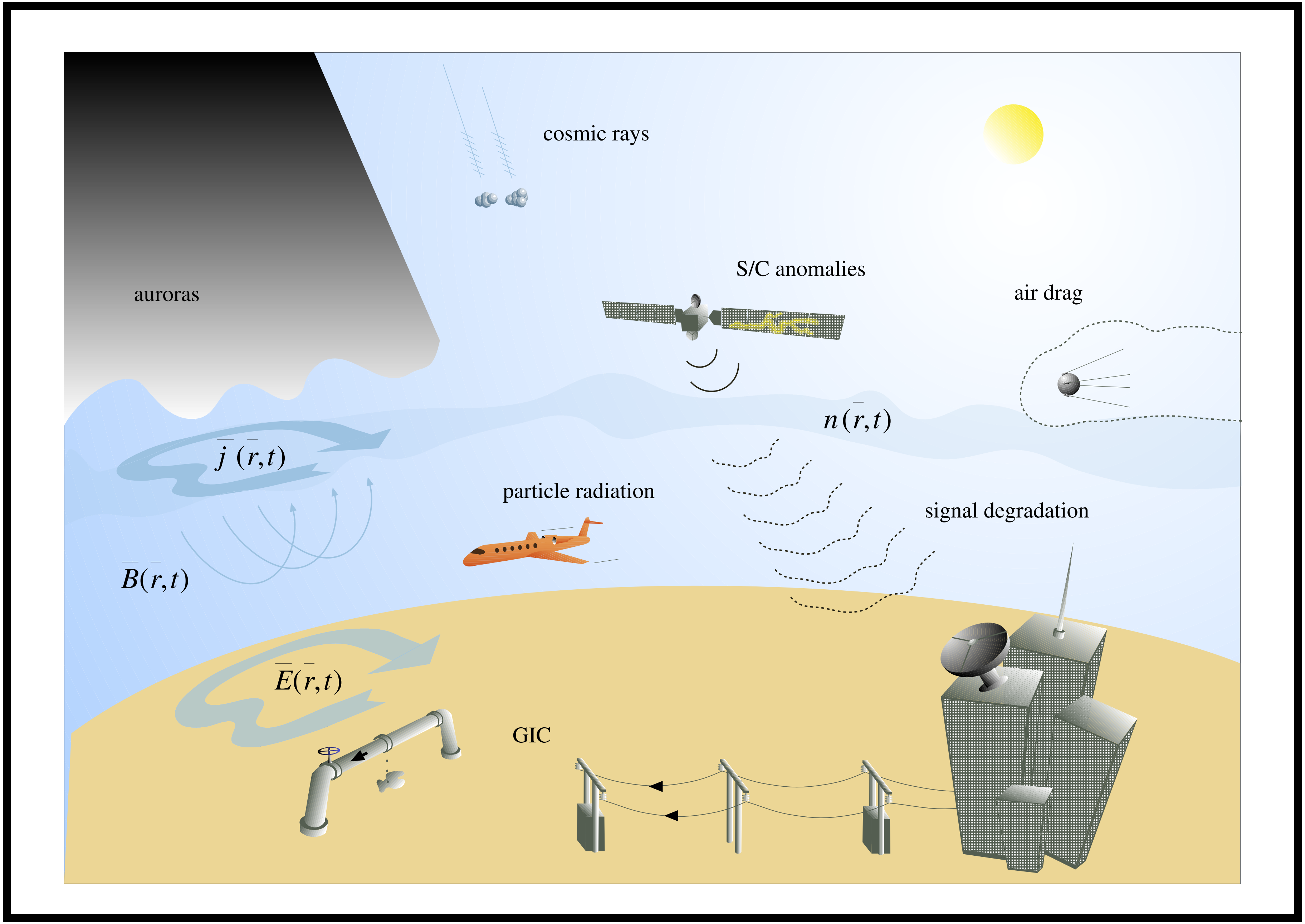
Contents

General

Space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human health.

Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of sosioeconomic losses.

The best-known space weather phenomena are enjoyable auroral displays.


cosmic rays
S/C anomalies
auroras
air drag
$\underline{j}\,(\underline{r},t)$
$n(\underline{r},t)$
particle radiation
signal degradation
$\underline{B}(\underline{r},t)$
$\underline{E}(\underline{r},t)$
GIC

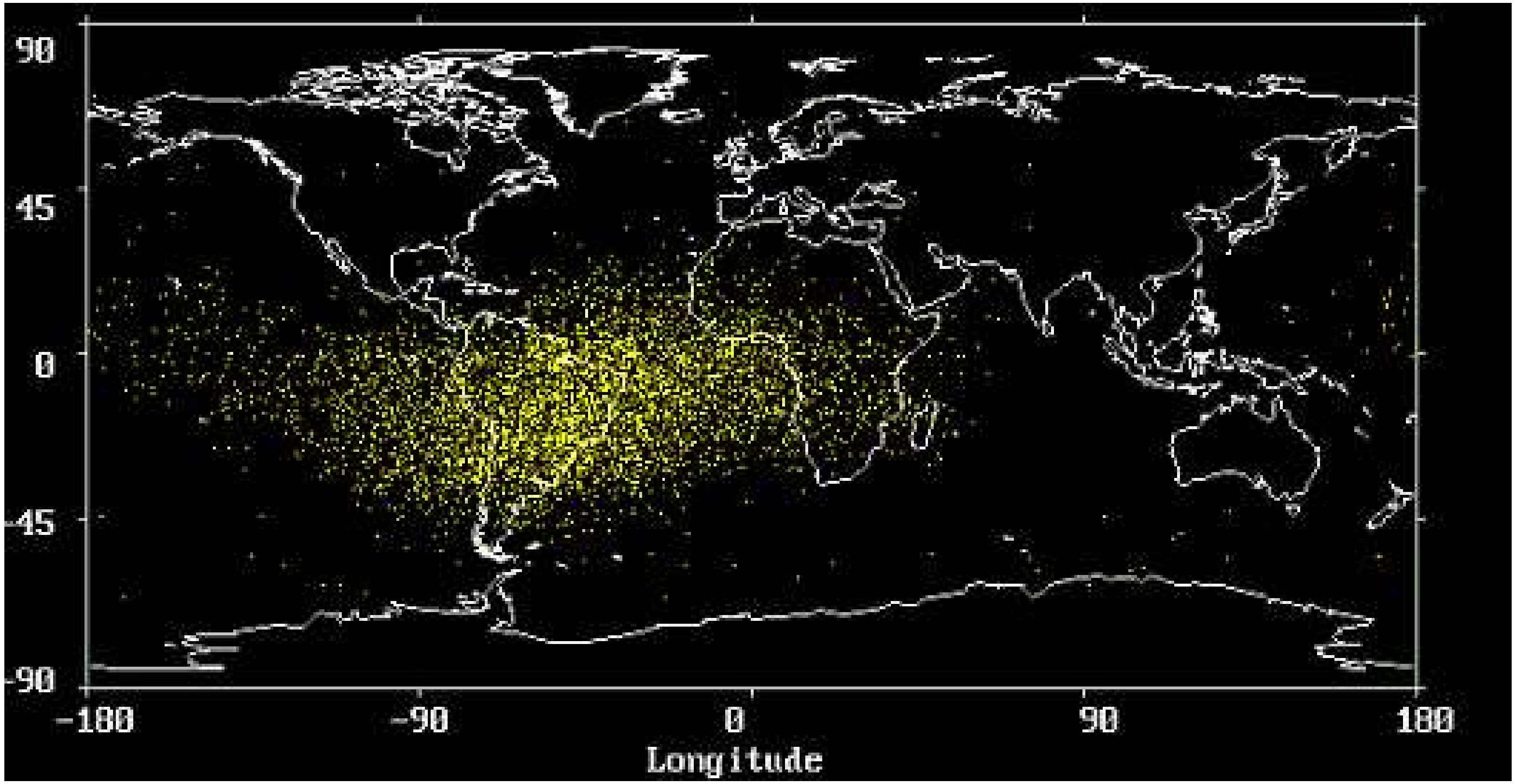
How to classify space weather events/effects?

- **Domains**
  - interplanetary space
  - magnetosphere
  - ionosphere
  - neutral atmosphere
  - earth surface
- **Phenomena**
  - particle energisation
  - radio frequency disturbances
  - cosmic radiation
  - solar particle events
  - geomagnetic induction
  - atmospheric weather
  - atmospheric drag

- **Systems (<u>customer</u>'s viewpoint)**
  - **spacecraft**
  - **manned space flights**
  - **aircraft**
  - **communications**
  - **navigation**
  - **power transmission**
  - **gas and oil transmission**
  - **telecables**
  - **railways**
  - **geophysical surveys**
  - **tourism**
- **Timescales**
  - **immediate effects**
  - **cumulative effects**

- **Single-event upsets in the spacecraft electronics**
- **Spacecraft surface and internal charging**
- **Tissue damages due to particle radiation**
- **Increased atmospheric drag**
- **Disturbances in HF communication and navigation systems (separate lecture by Juha-Pekka Luntama)**
- **Cosmic ray induced neutron radiation at airline hights**
- **GIC in long conductor systems on the ground**
- **Disturbances of geomagnetic surveys**
- **Possible modulation of the neutral atmospheric weather and climate**
- **Effects on migrating birds**

The geomagnetic field protects the Earth from charged cosmic ray particles, but not equally everywhere

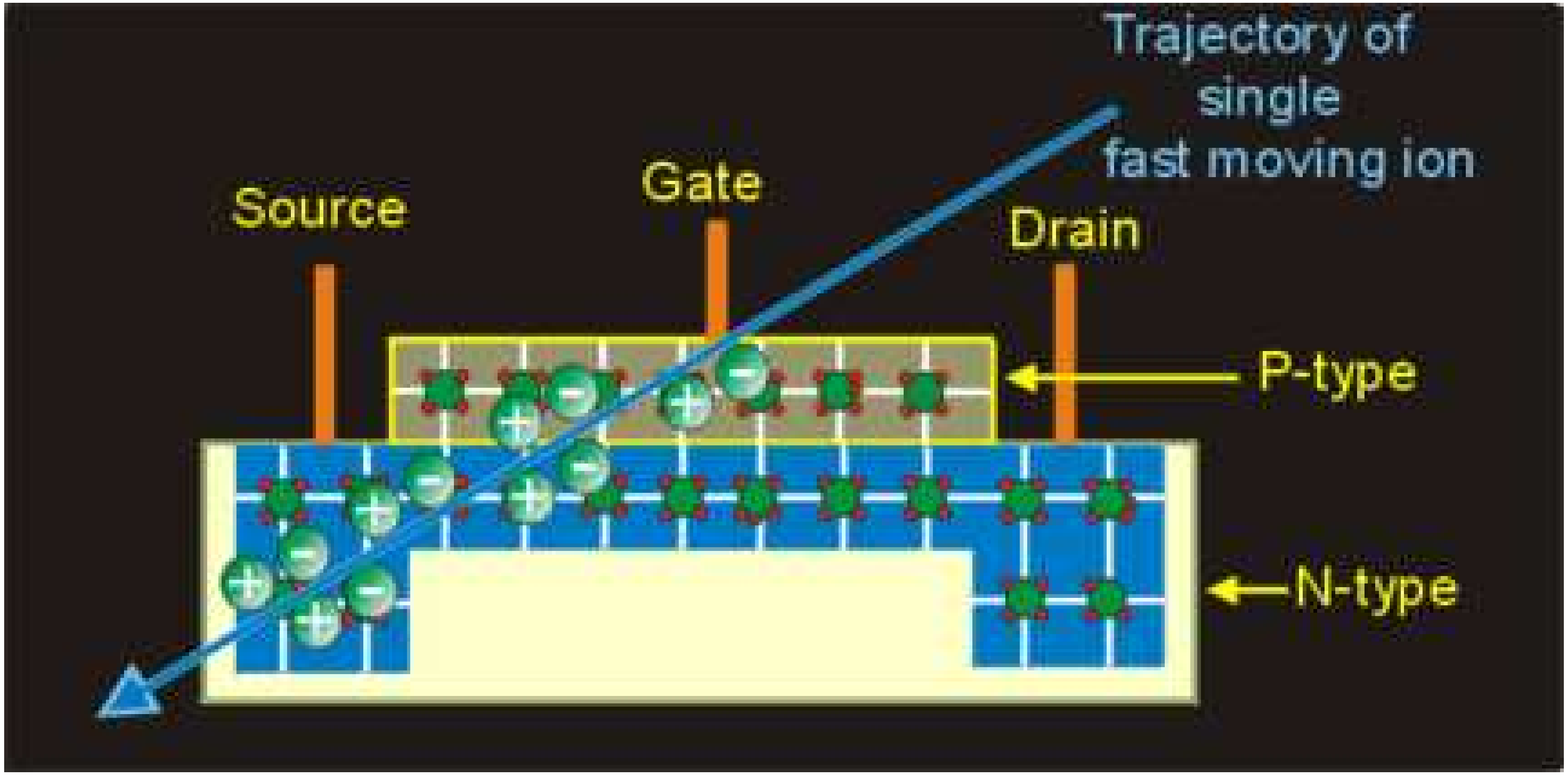


Satellite memory chip errors due to cosmic rays.

The South Atlantic magnetic anomaly is prominent.

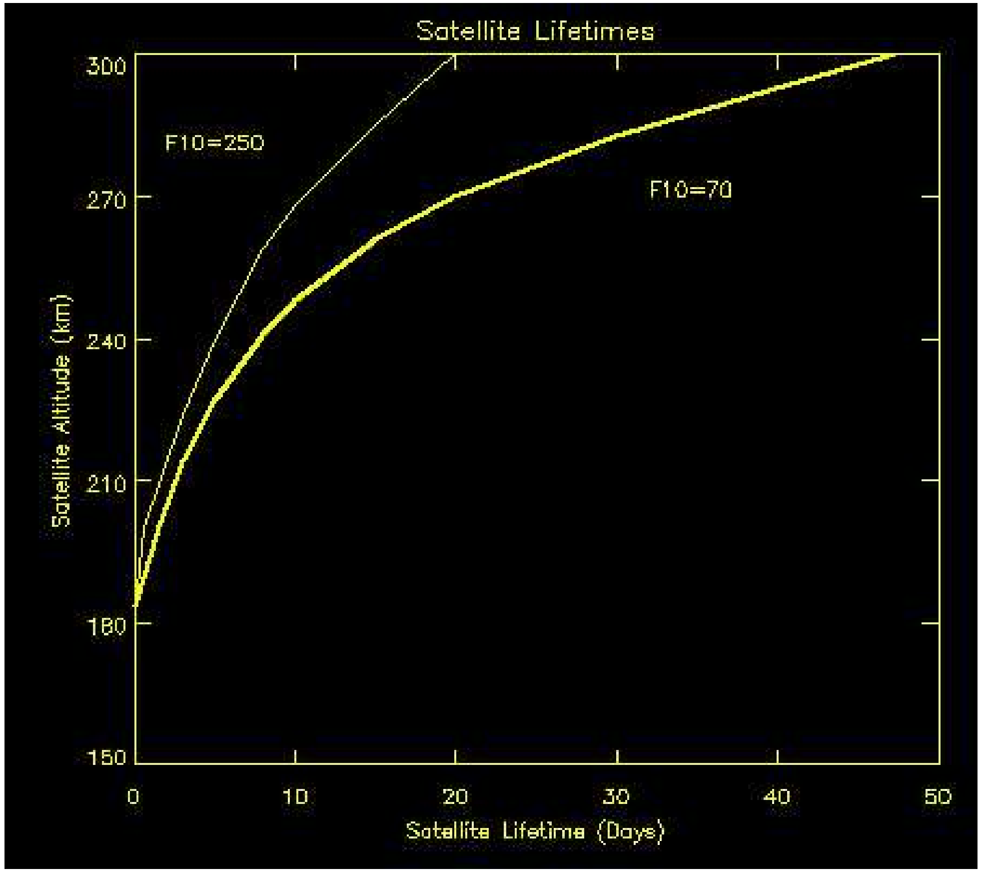
Source: University of Surrey

Even single high-energetic particles can destroy modern sensitive technology on spacecraft: miniaturisation has risks



Source: Natural Resources Canada

Low-orbit satellites inevitably lose height

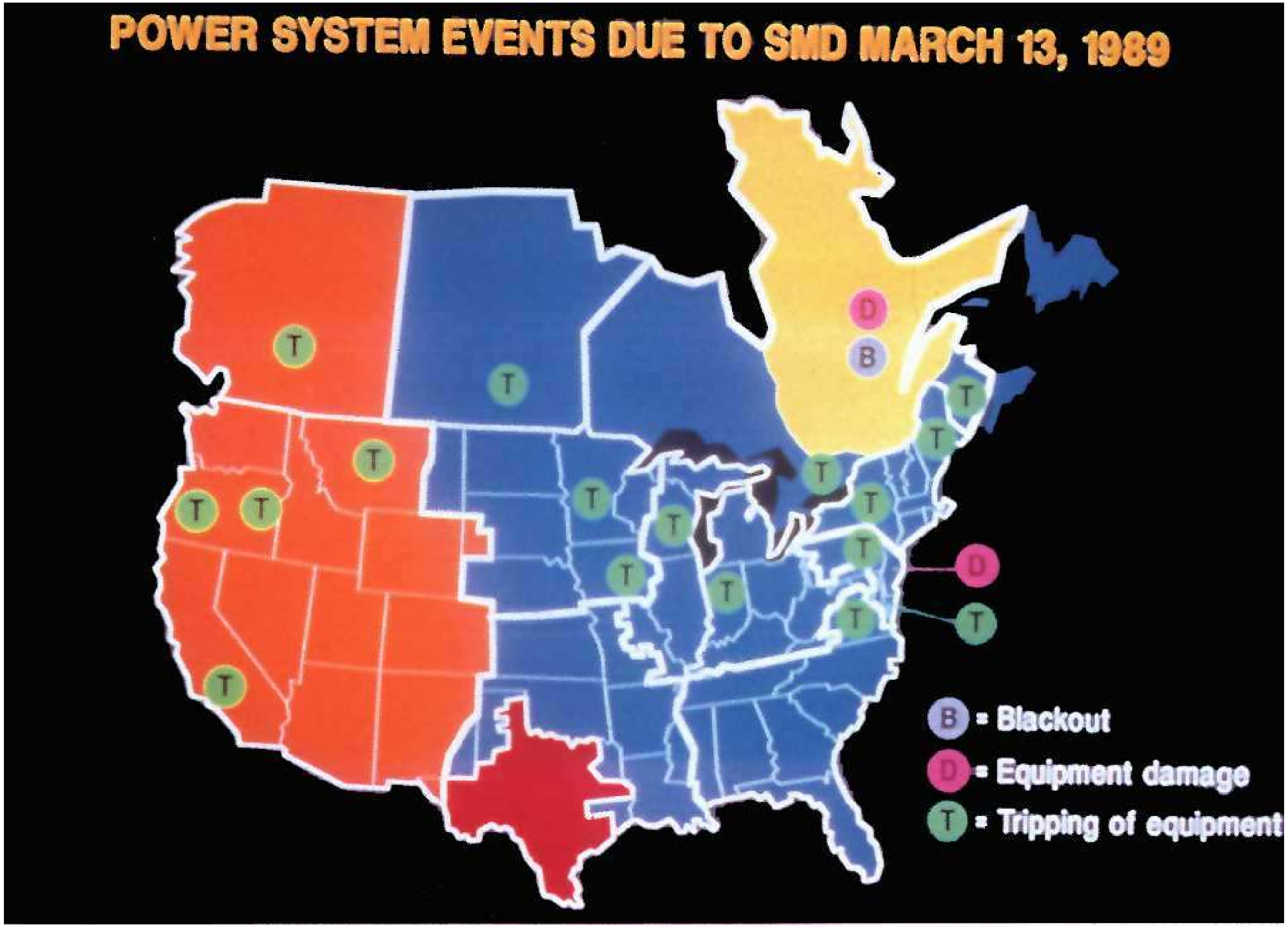


Lifetime of a satellite with effective mass to cross-section ratio of 100 kg/m^2.

F10 = solar flux at $\lambda = 10.7$ cm

Source: IPS - Radio and Space Services

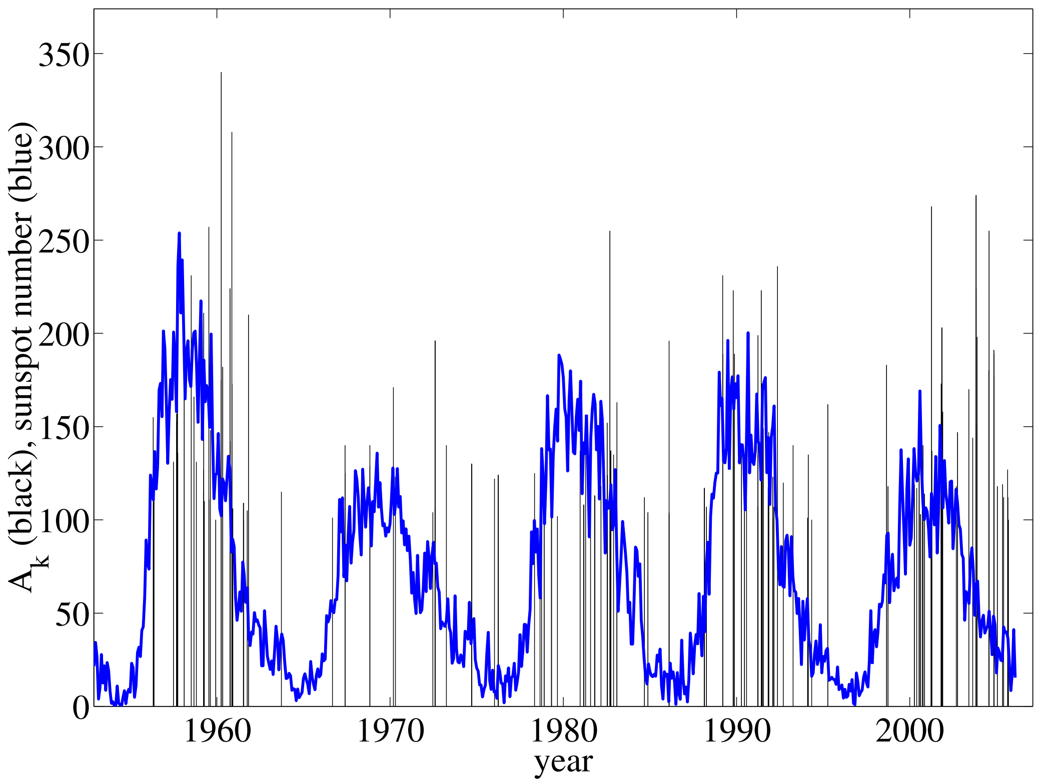
Effects may be continent-wide or even global



Source: image courtesy of Ben Damsky

Geomagnetic storminess is related to the solar activity

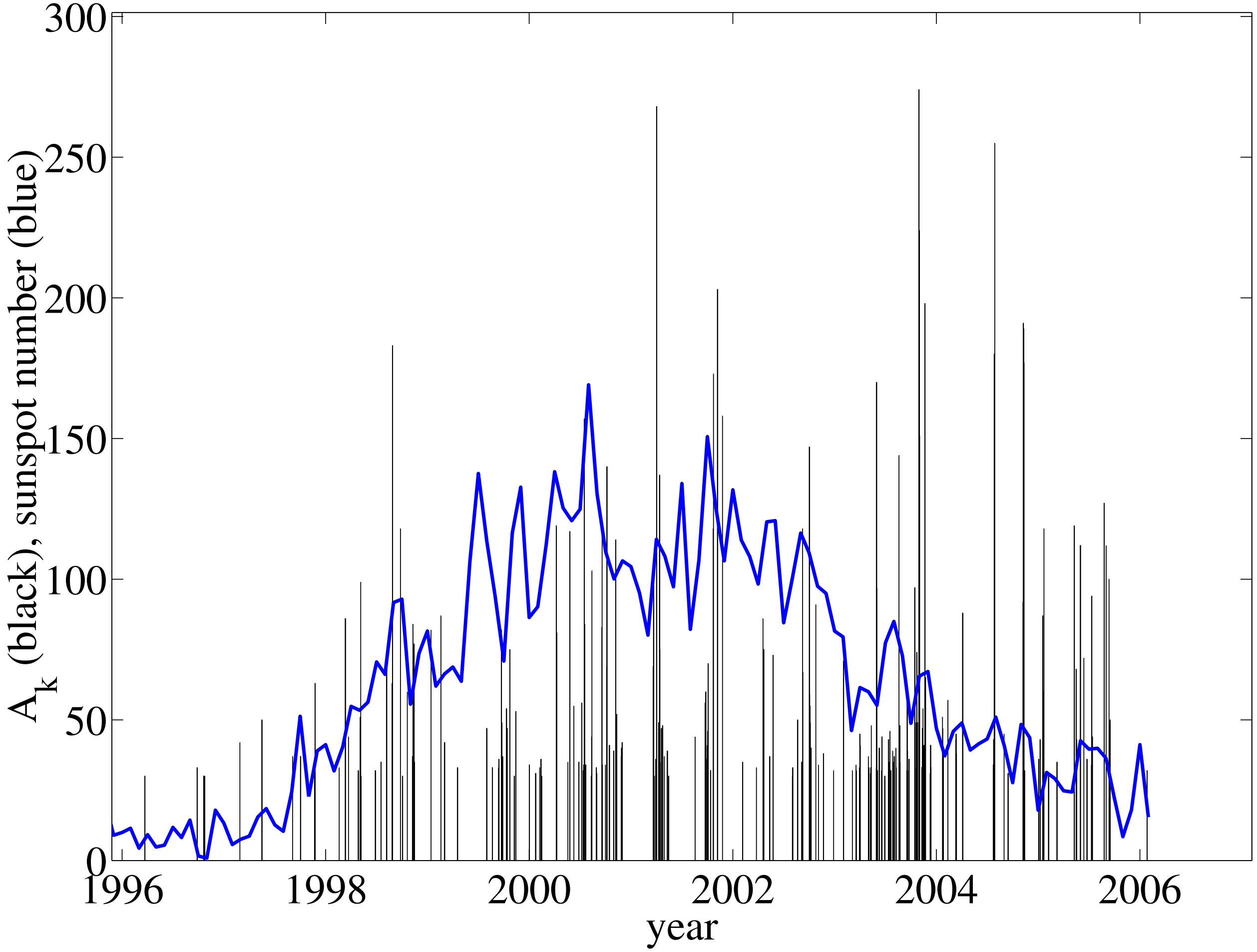
big magnetic storms at NUR (1953-2006) (A_k>100): 141 days (0.7 %)

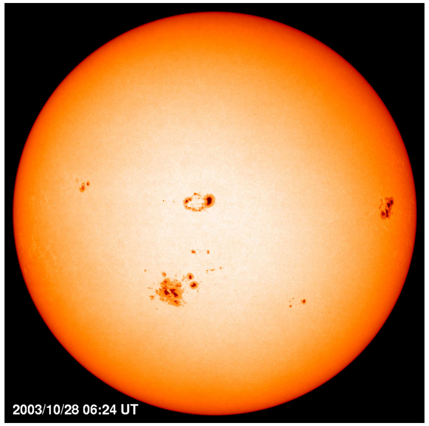


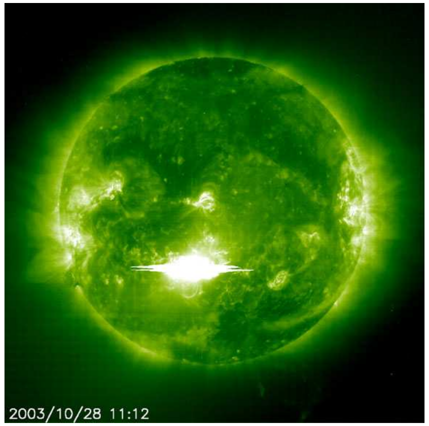
Problem: Is the occurrence of all space weather effects directly related to the sunspot number?

The present solar cycle: we are close to the minimum

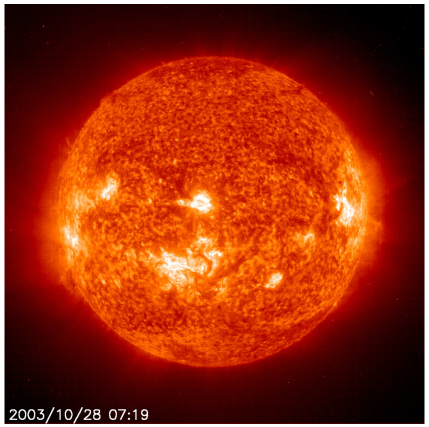
big magnetic storms at NUR (1996-2006) (A_k>30): 241 days (6.5 %)

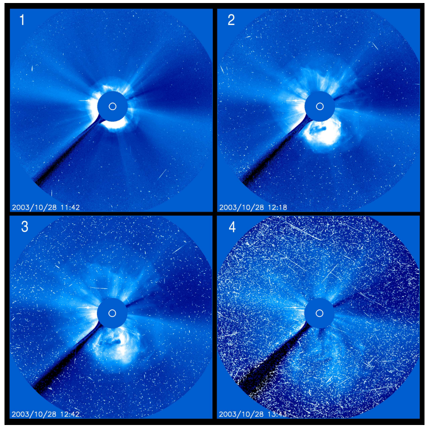




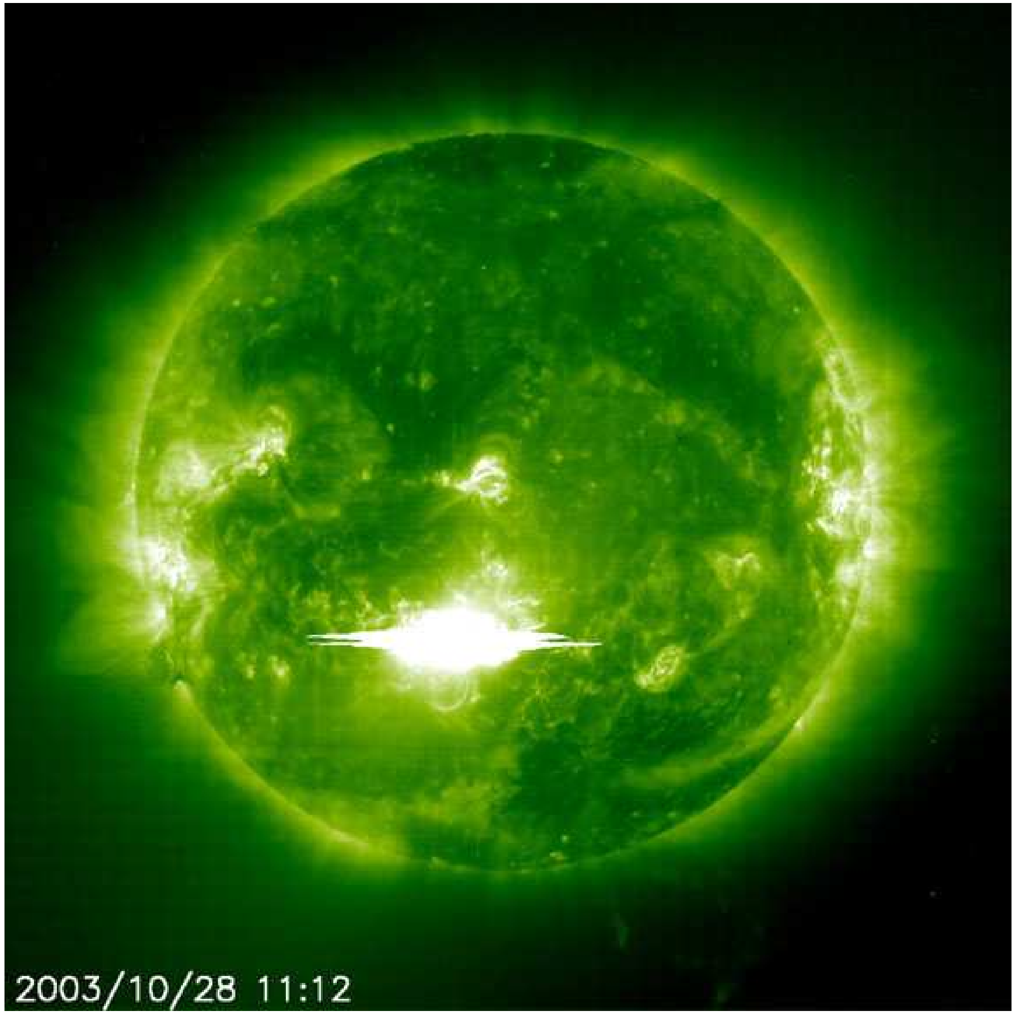


October 2003





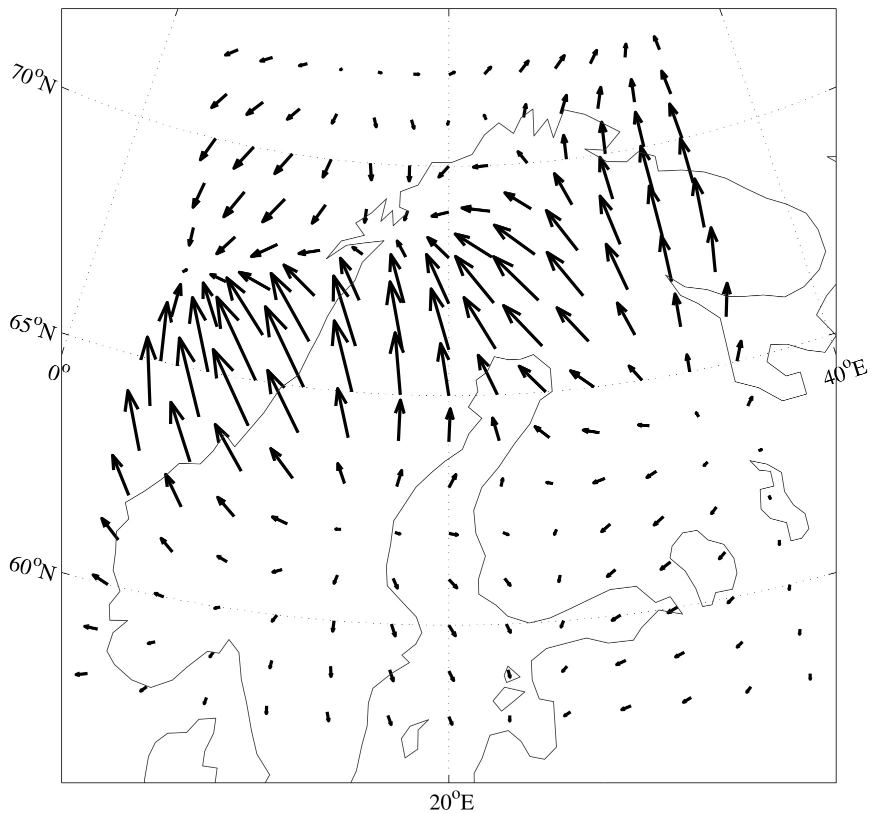
The solar origin of the storm



Source of solar images: courtesy of SOHO (ESA & NASA)

The first geomagnetic ground impact: sudden impulse

20031029 06:11:40



max(|dH/dt|) = 72.9 nT/s

Figure shows interpolated values. Largest measured value: 77 nT/s.

Some reported effects of the October 2003 storm: space

- ISS astronauts into service module for radiation protection
- Japanese space agency declared Midori-2 communications satellite as a total loss after losing contact on 25 October
- ACE & Wind solar wind satellites lost plasma observations
- Some of the 4 Cluster spacecraft had processor resets; recovered
- Stardust comet mission went into safe mode due to read errors
- SMART-1 had auto shutdown of engine due to increased radiation level in lunar transfer orbit
- CHAMP satellite was decelarated twice as usual in the atmosphere
- GOES-8 X-ray sensor turned itself off; not recovered

Some reported effects of the October 2003 storm: aviation

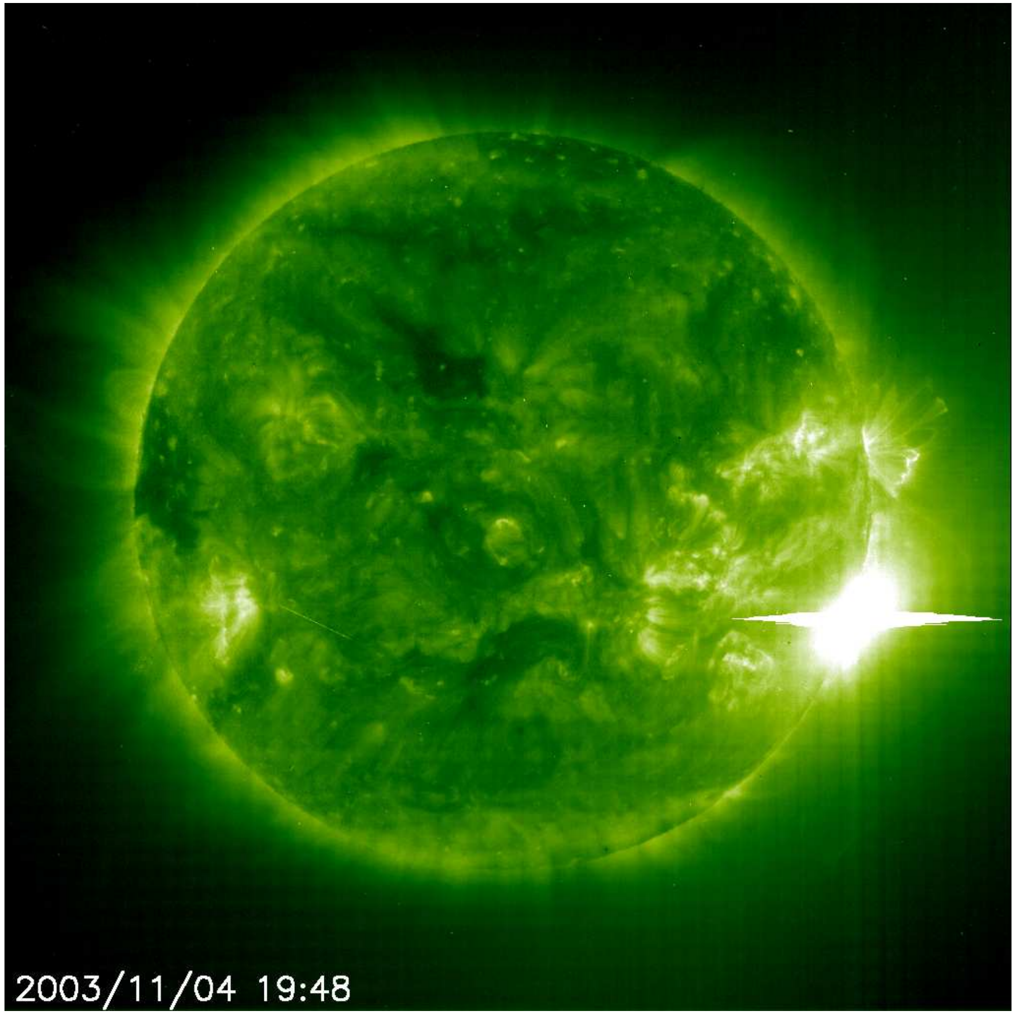
- Airlines rerouted polar flights due to bad HF/VHF communication
- FAA issued the first-ever alert on radiation doses received by airplane passengers above 25 Kft
- FAA tested a warning system for the first time, alerting airlines to the possibility of higher doses of radiation that passengers would receive on northerly routes
- European aviation was affected because of possible problems for voice-radio communications

Some reported effects of the October 2003 storm: ground

- Problems at 15 power transformers in South Africa
- Power system failure in Malmö, Sweden (Oct. 30, 21:07 LT)
- High latitude GPS receiver outages
- Several radio blackouts occurred at some frequencies, at some other frequencies abnormally good propagation
- Saturation of solar radio spectrograph data in Italy
- Auroras in New Mexico, Texas, Florida; Germany, Austria, Italy; Australia

Remember also the **atmospheric effects** of the solar proton events (previous week lectures by Pekka Verronen and Annika Seppälä)

What could the monster flare have caused?



Source of solar images: courtesy of SOHO (ESA & NASA)

Geomagnetically induced currents: general

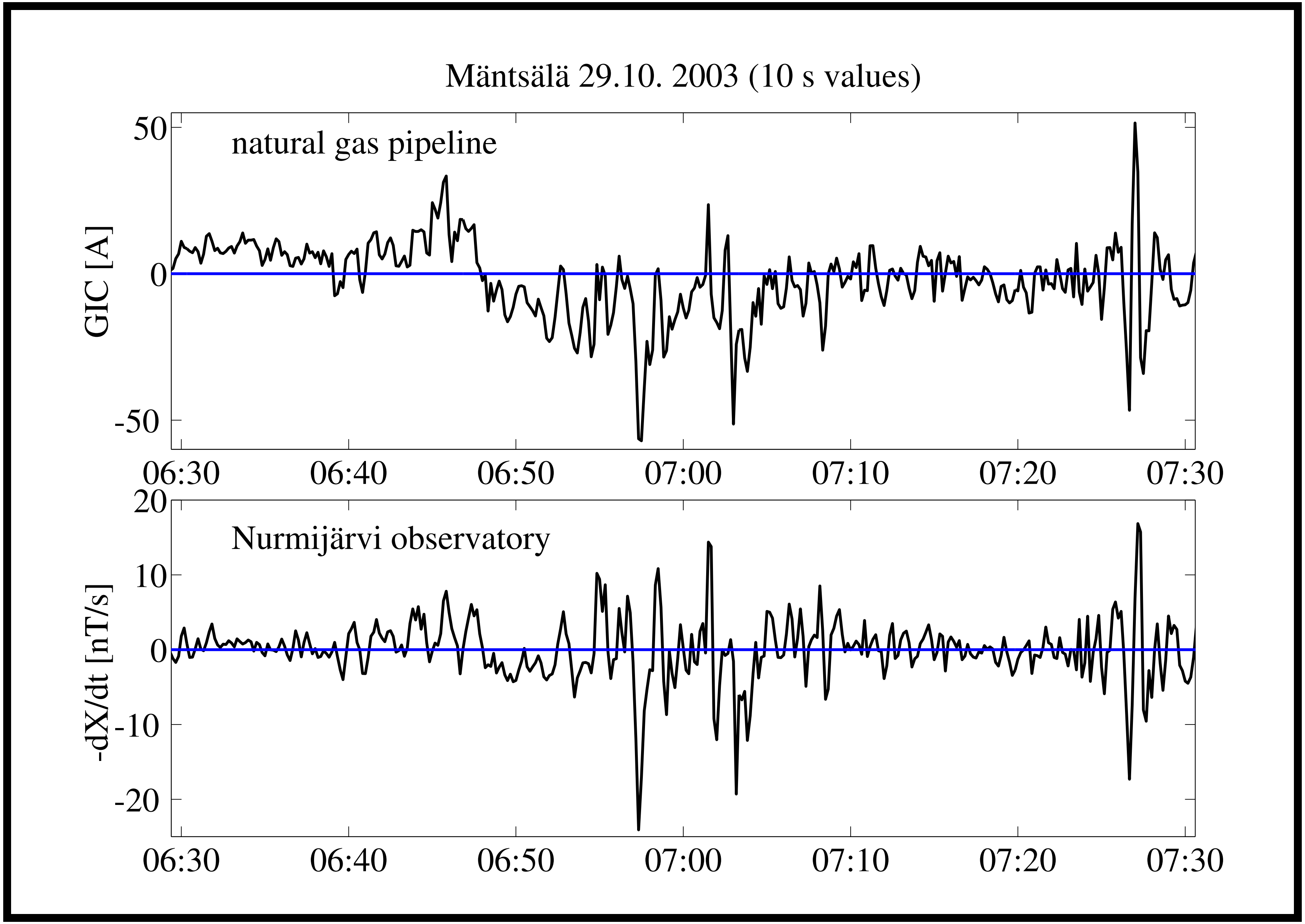
Geomagnetically induced currents flow in man-made conductor systems during geomagnetic variations.

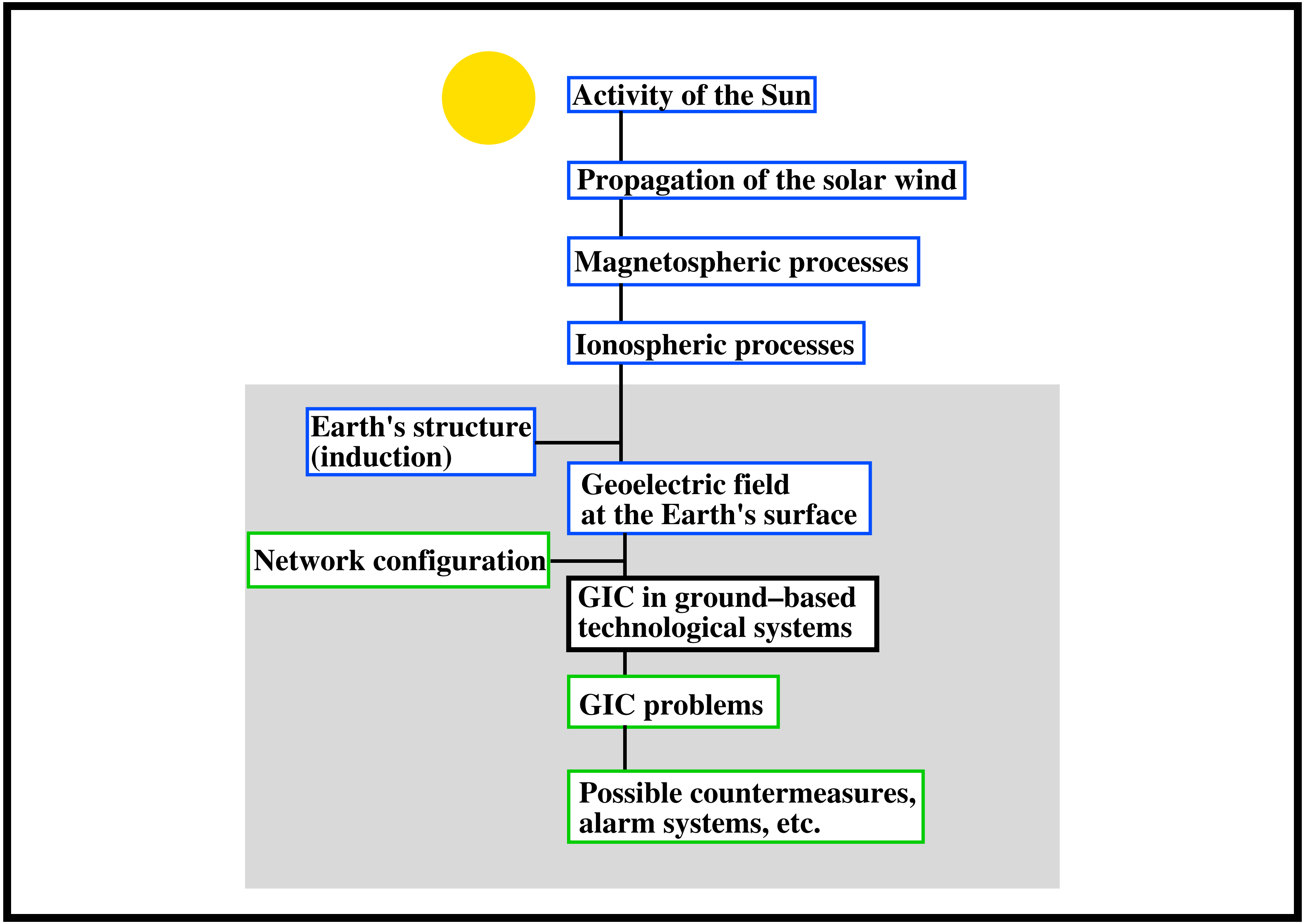
Faraday's law: an electric field is associated with a time-varying magnetic field $\rightarrow dB/dt$ is a good indicator.

This geoelectric field drives currents in all conducting materials, and especially within the earth as well as in technological conductor systems.

GIC are most easily observed in wide power grids, pipelines, railways, etc.

GIC is a quasi-DC phenomenon: relevant frequencies < 1 Hz.

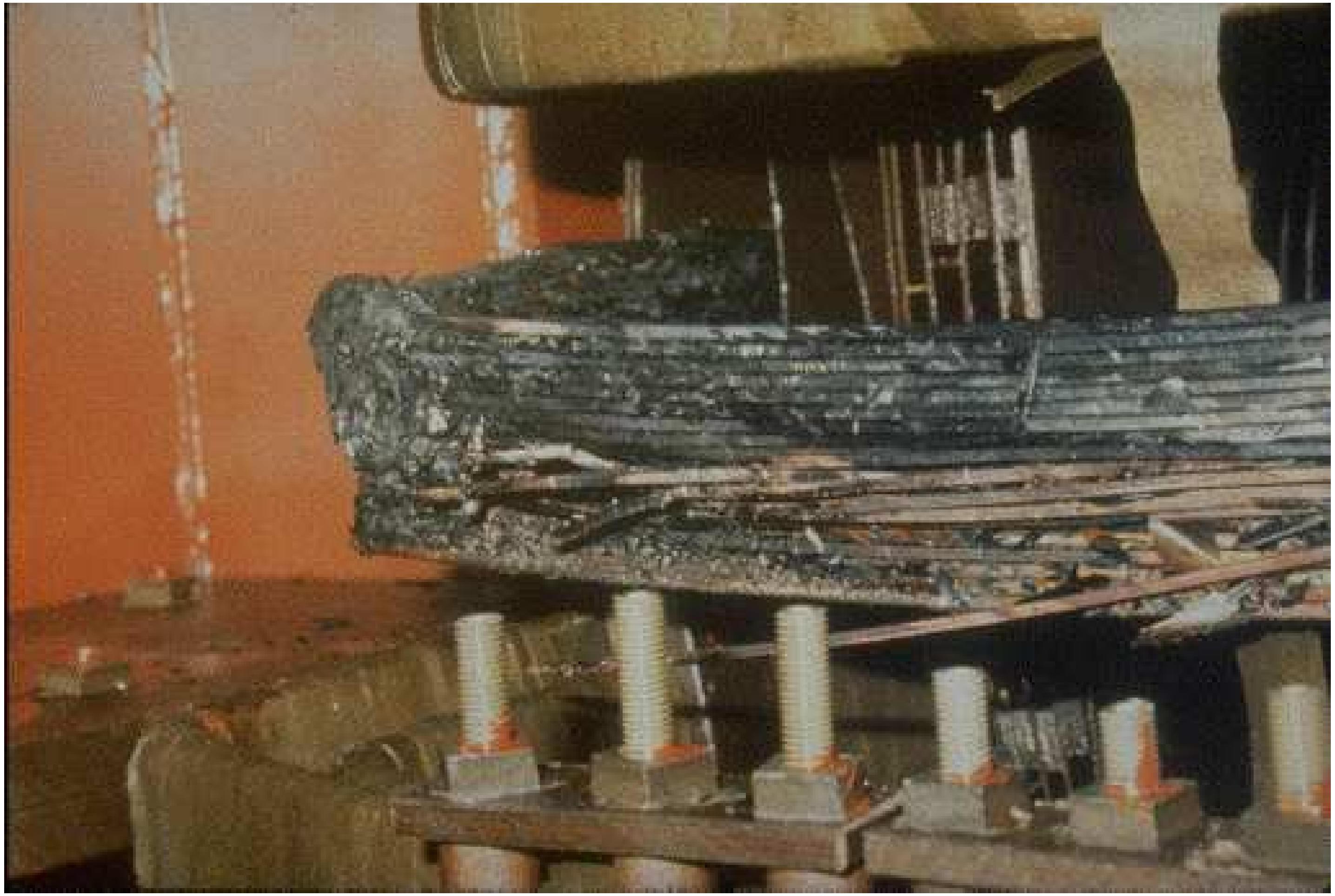

Mäntsälä 29.10. 2003 (10 s values)
natural gas pipeline
GIC [A]
50
0
-50
06:30
06:40
06:50
07:00
07:10
07:20
07:30
Nurmijärvi observatory
-dX/dt [nT/s]
20
10
0
-10
-20
06:30
06:40
06:50
07:00
07:10
07:20
07:30


Activity of the Sun
Propagation of the solar wind
Magnetospheric processes
Ionospheric processes
Earth's structure (induction)
Geoelectric field at the Earth's surface
Network configuration
GIC in ground–based technological systems
GIC problems
Possible countermeasures, alarm systems, etc.

Famous and less famous GIC events

- Sep 1859: Widespread disturbances in telegraph systems (Carrington storm, the largest one ever observed?)
- May 1921: Fires in telegraph equipment in Sweden
- Feb 1958: Disruption of communications in the cross-Atlantic cable; interruption of two coaxial phone cable systems in Finland
- Aug 1972: Shutdown of an AT&T cable in the mid-western USA
- Jul 1982: Train traffic lights turned unintendedly to red in Sweden
- Mar 1989: Québec blackout
- Oct 2003: Malmö blackout; damages in South Africa

Extreme effect: New Jersey, March 1989: melted transformer



Source: image courtesy of Public Service Electric and Gas and Peter Balma

GIC studies in Finland

- Intense GIC studies between FMI and industry since the end of 1970's
- High-voltage power system: Imatran Voima (now Fingrid)
- Natural gas pipeline: Neste (now Gasum)
- Recordings by Fingrid (power grid) and Gasum & FMI (pipeline)
- Largest GIC in the power grid: 200 A (Rauma, Mar 24, 1991)
- Largest GIC in the pipeline: 57 A (Mäntsälä, Oct 29, 2003)
- Nowcast service for Gasum: aurora.fmi.fi/gic_service/

Calculation of GIC in a given condutor system

1. Determine the geoelectric field associated with geomagnetic variations. This is a purely geophysical problem, which is independent of the technological system.

2. Determine GIC due to the given geoelectric field in a conductor system whose topology and resistances are known.

Two basic configurations of conductor networks:
1. Discretely grounded system (power grid)
2. Continuous contact with the ground (buried pipeline)

Simple estimation of the geoelectric field

Reflection of a vertically propagating plane wave at the surface of a uniform conductor.

At the earth's surface (xy plane)

$$E(\omega) = -\frac{\omega B(\omega)}{\sqrt{\omega^2 \mu_0 \epsilon + i\omega\mu_0\sigma}} = \frac{ig(\omega)}{\sqrt{\omega^2 \mu_0 \epsilon + i\omega\mu_0\sigma}} \tag{1}$$

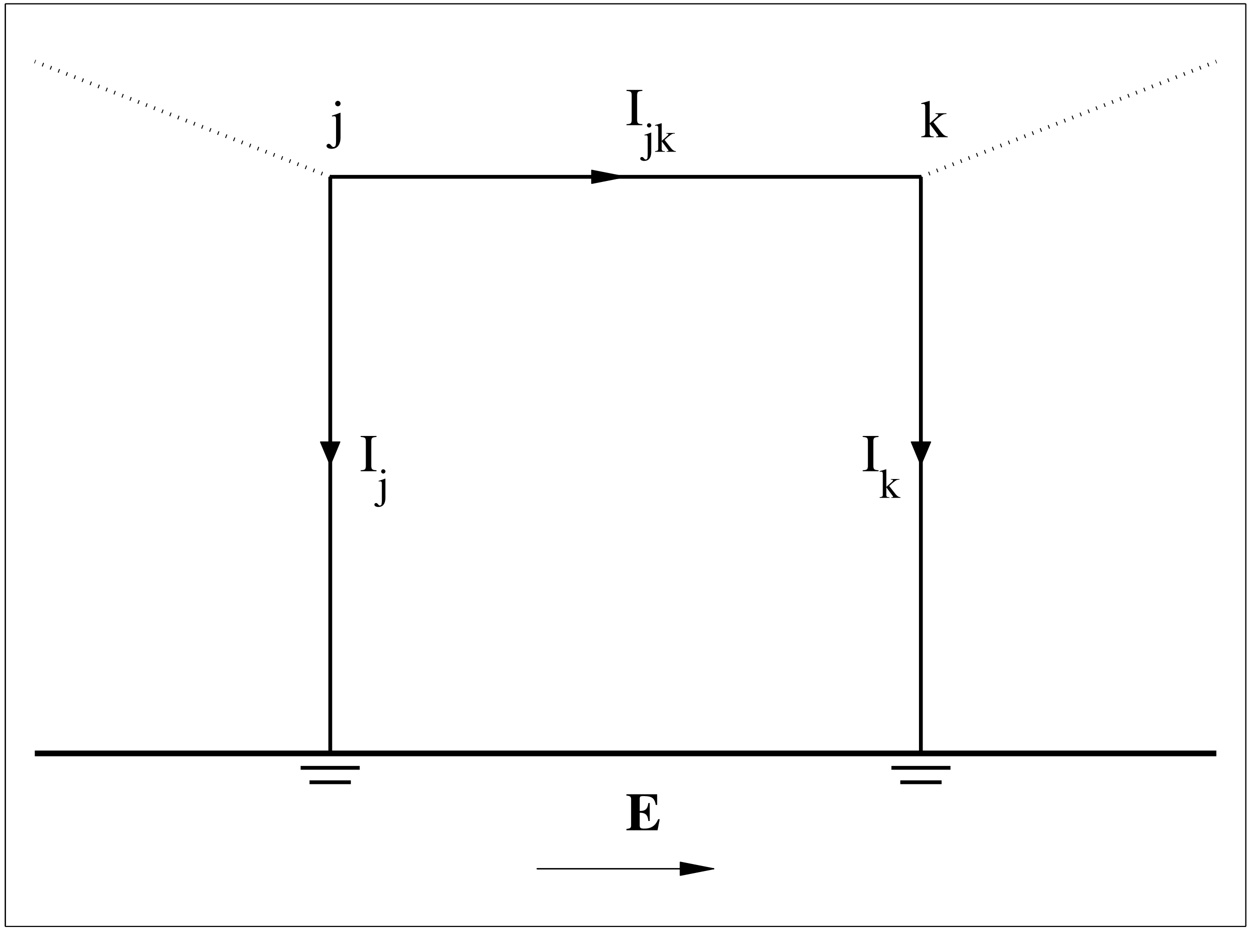
where $E = E_y, g = dB_x/dt$. At low frequencies

$$E(\omega) = \sqrt{\frac{i}{\omega\mu_0\sigma}}\, g(\omega) \tag{2}$$

Denoting $g(t) = dB(t)/dt$ we have $g(\omega) = -i\omega B(\omega)$, leading to

$$E(t) = -\frac{1}{\sqrt{\pi\mu_0\sigma}} \int_{-\infty}^{t} \frac{g(u)}{\sqrt{t-u}}\, du \tag{3}$$

After determining the geoelectric field, calculate the currents it drives in a conductor system: DC model.



Application of Kirchhoff's laws gives earthing currents

$$\mathbf{I} = (1 + YZ)^{-1}\mathbf{J} \tag{4}$$

and currents along transmission lines

$$I_{jk} = V_{jk}/R_{jk} + ((Z\mathbf{I})_j - (Z\mathbf{I})_k)/R_{jk} \tag{5}$$

Voltage between two nodes j and k: line integral along the power line

$$V_{jk} = \int_j^k \mathbf{E} \cdot \mathbf{dl} \tag{6}$$

$$\mathbf{J} = (J_1, ..., J_N);\ J_i = \sum_{m \neq i} \frac{V_{mi}}{R_{im}} \tag{7}$$

Assume a spatially uniform electric field. Then GIC at a transformer earthing or along a transmission line is

$$GIC(t) = aE_x(t) + bE_y(t) \tag{8}$$

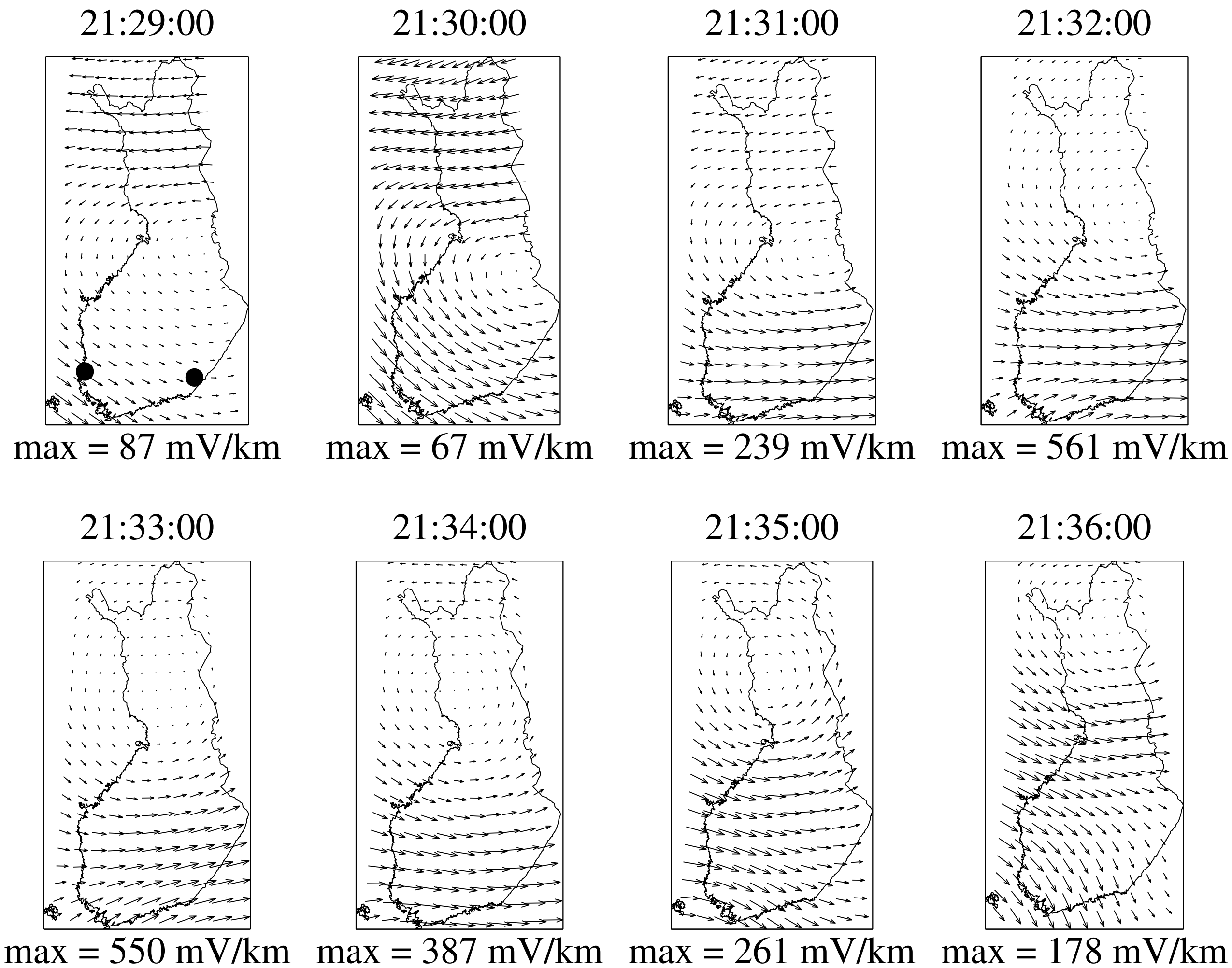
where a and b depend only on the geometry and resistances of the network.

Typical resistances in Finland: from 0.1 Ω to a few Ω

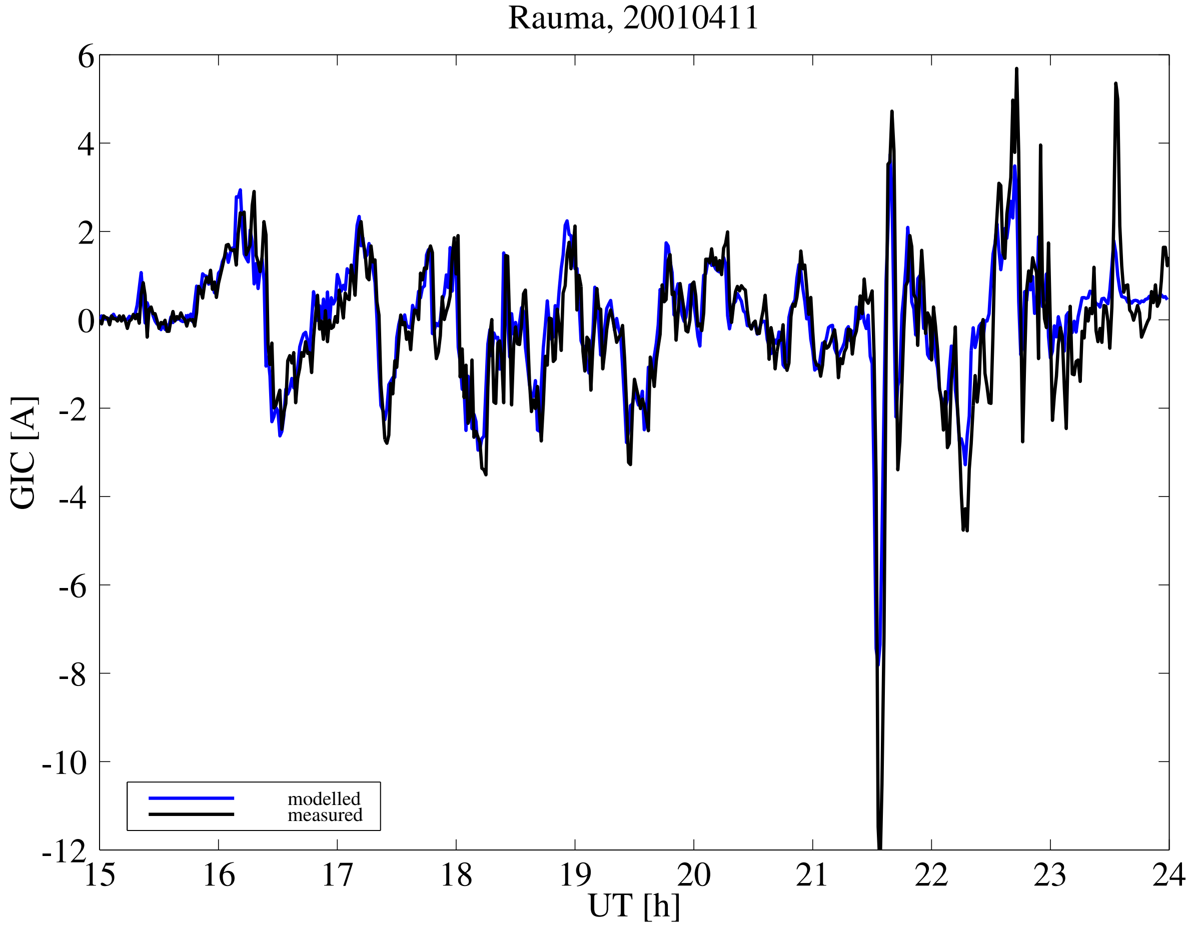
Regional geoelectric field in Finland: up to about a few V/km

Magnitudes of a, b: up to 100 Akm/V

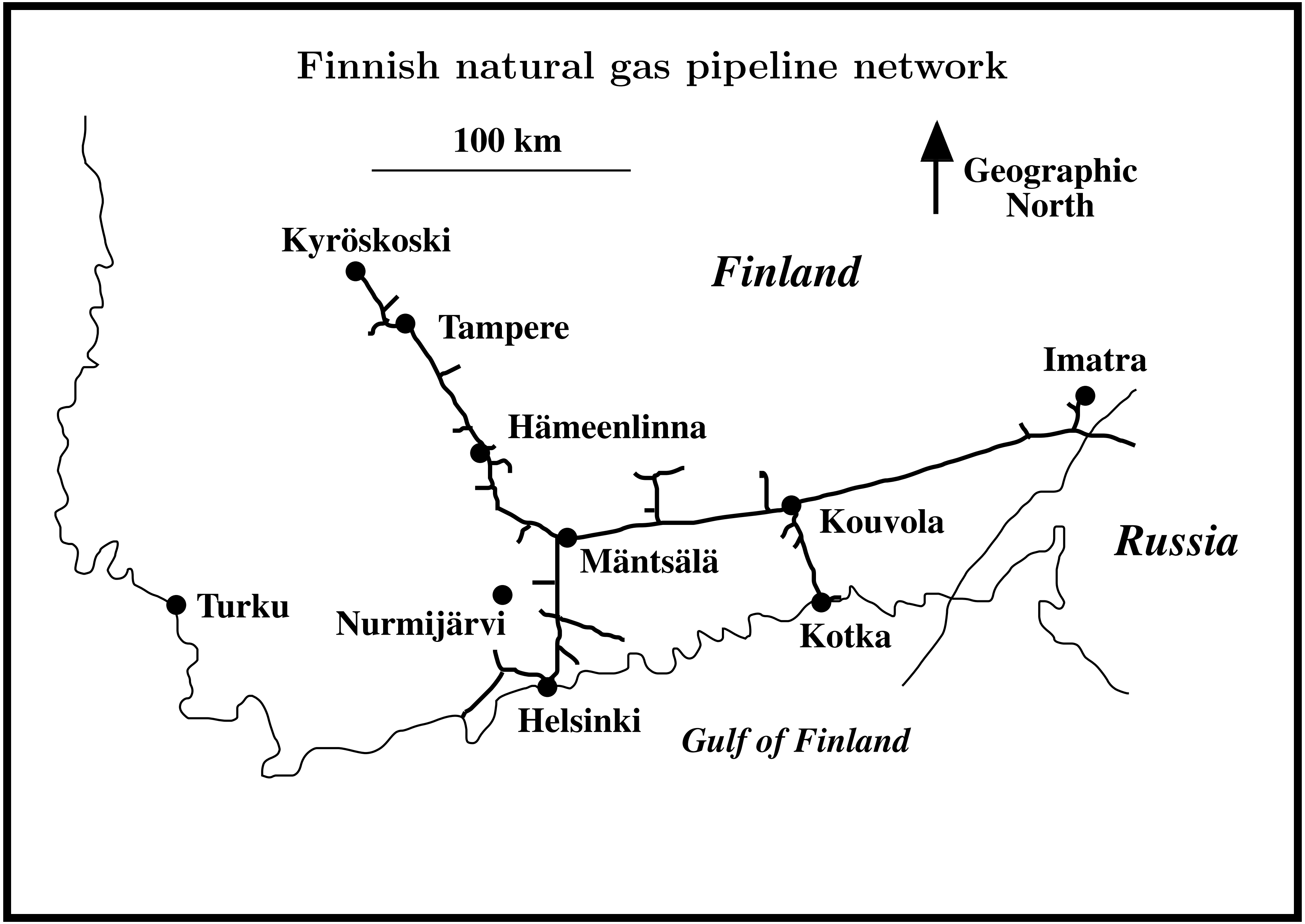
Generally, the electric field is non-uniform. However, the use of the plane wave method locally provides a roundabout way.



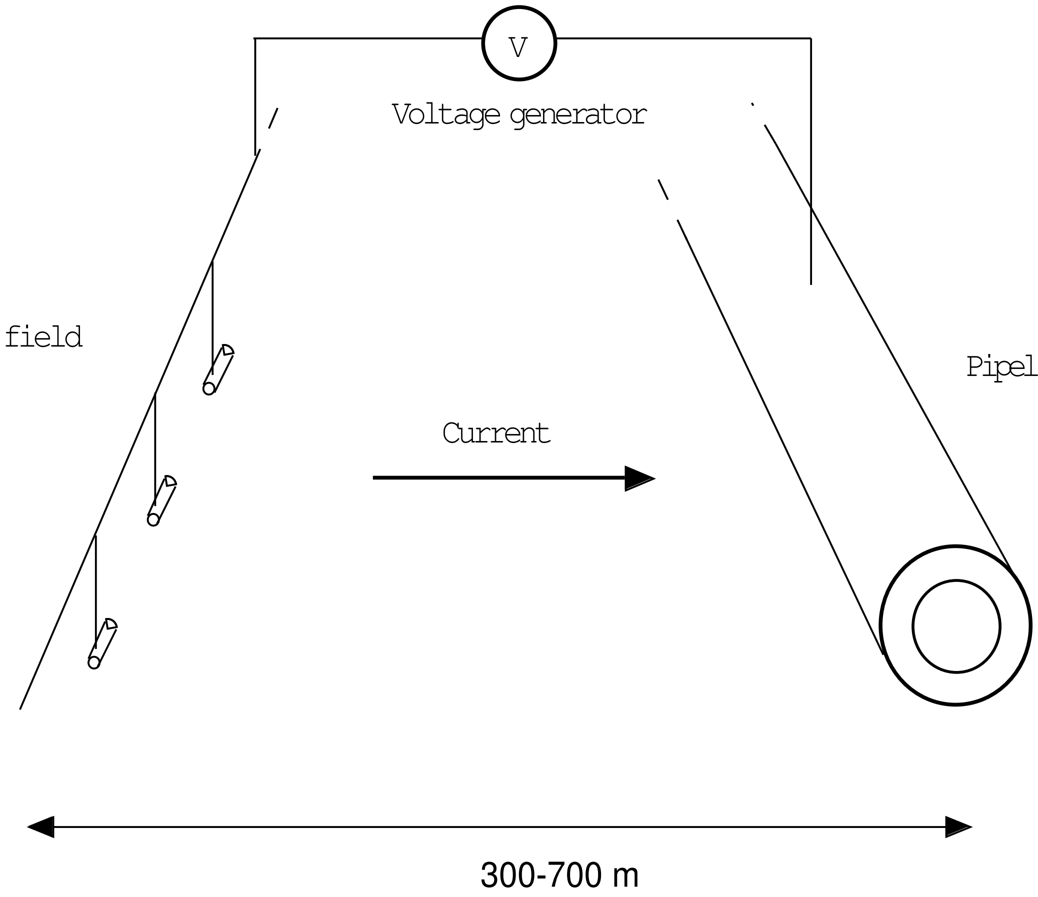
Calculated horizontal electric field on April 11, 2001.



Measured and **calculated** GIC at the Rauma 400 kV transformer station on April 11, 2001.

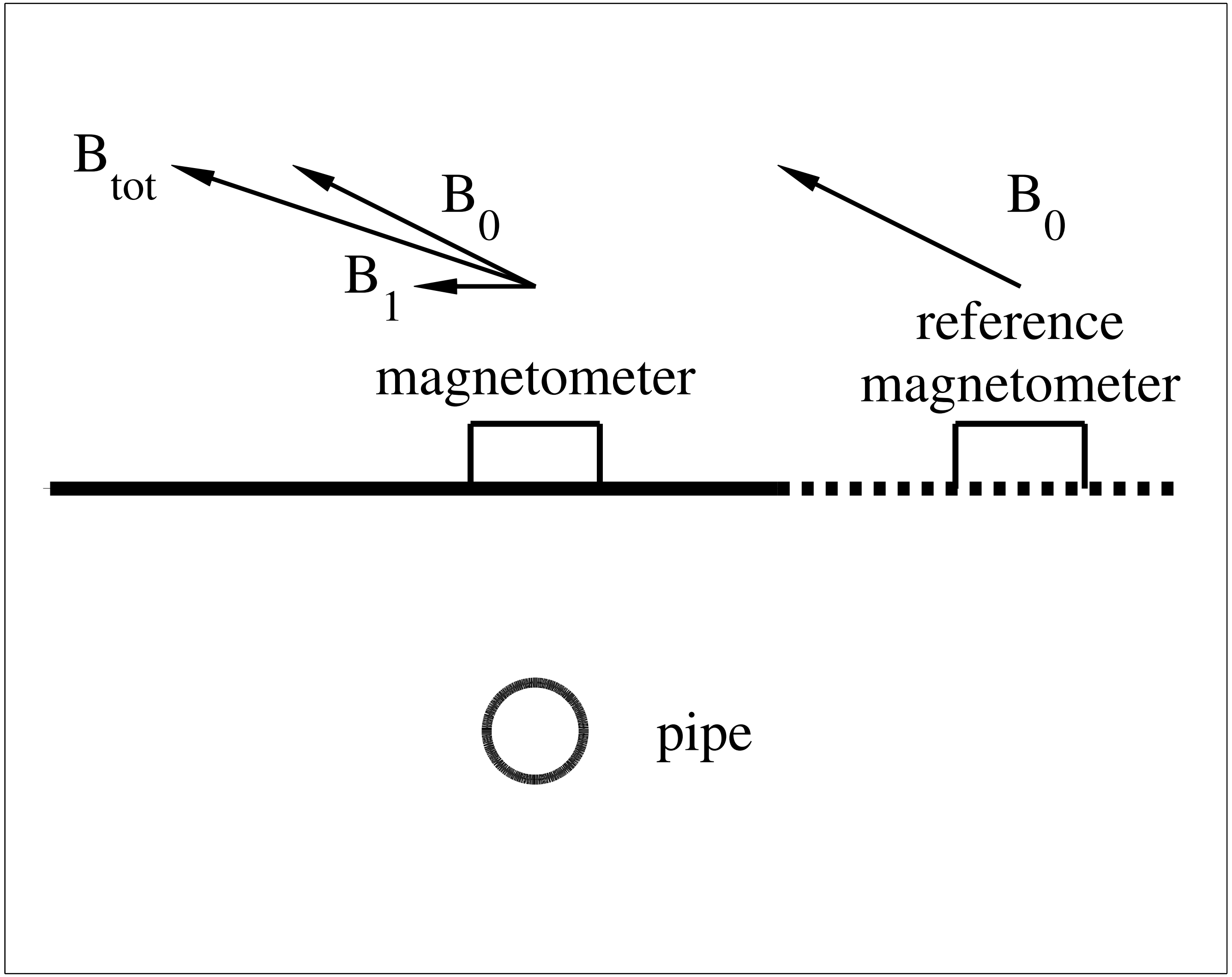

Finnish natural gas pipeline network
100 km
Geographic
North
Kyröskoski
Finland
Tampere
Imatra
Hämeenlinna
Kouvola
Russia
Mäntsälä
Turku
Nurmijärvi
Kotka
Helsinki
Gulf of Finland

Corrosion protection

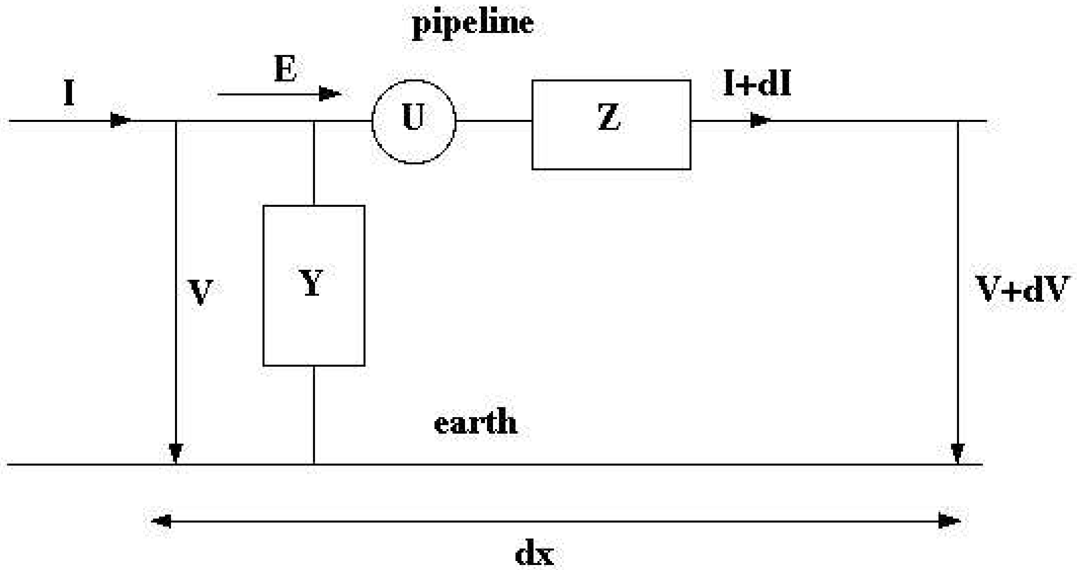


GIC is a nuisance, but it is still quantitatively unknown how much it increases the corrosion rate and shortens the lifetime of a pipe.

Measurement technique



Distributed source transmission line theory



$$\frac{d^2V}{dx^2} - \gamma^2 V = \frac{dE}{dx}$$

$$\frac{d^2I}{dx^2} - \gamma^2 I = -YE$$

$$\gamma = \sqrt{ZY}$$

Geomagnetically induced currents: state-of-the-art

Large GIC occur mostly during night-times

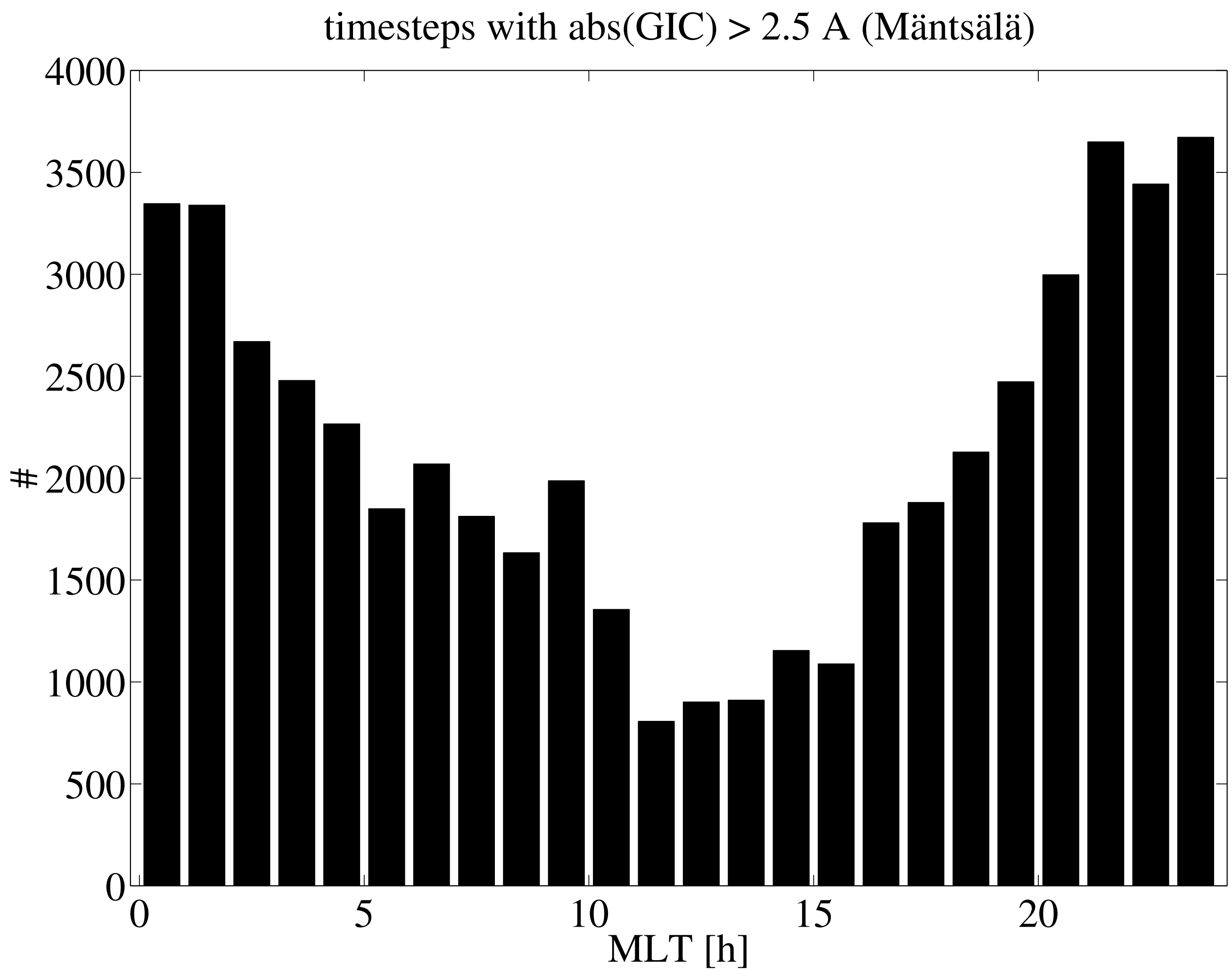
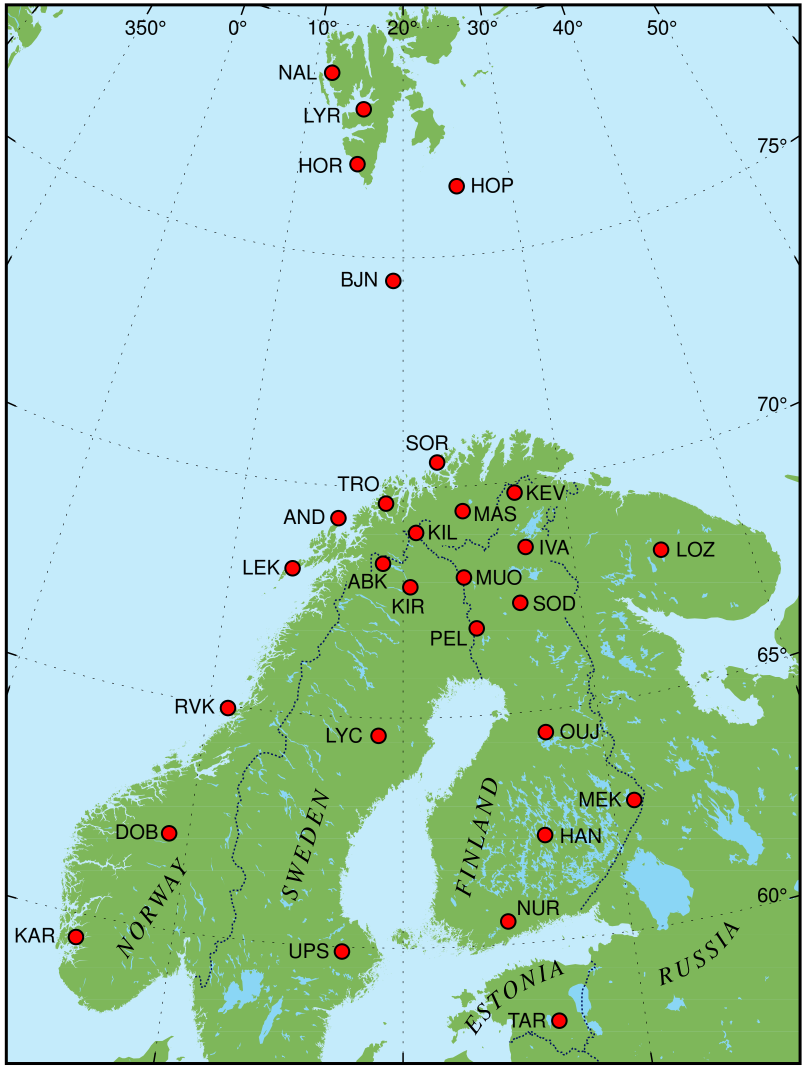
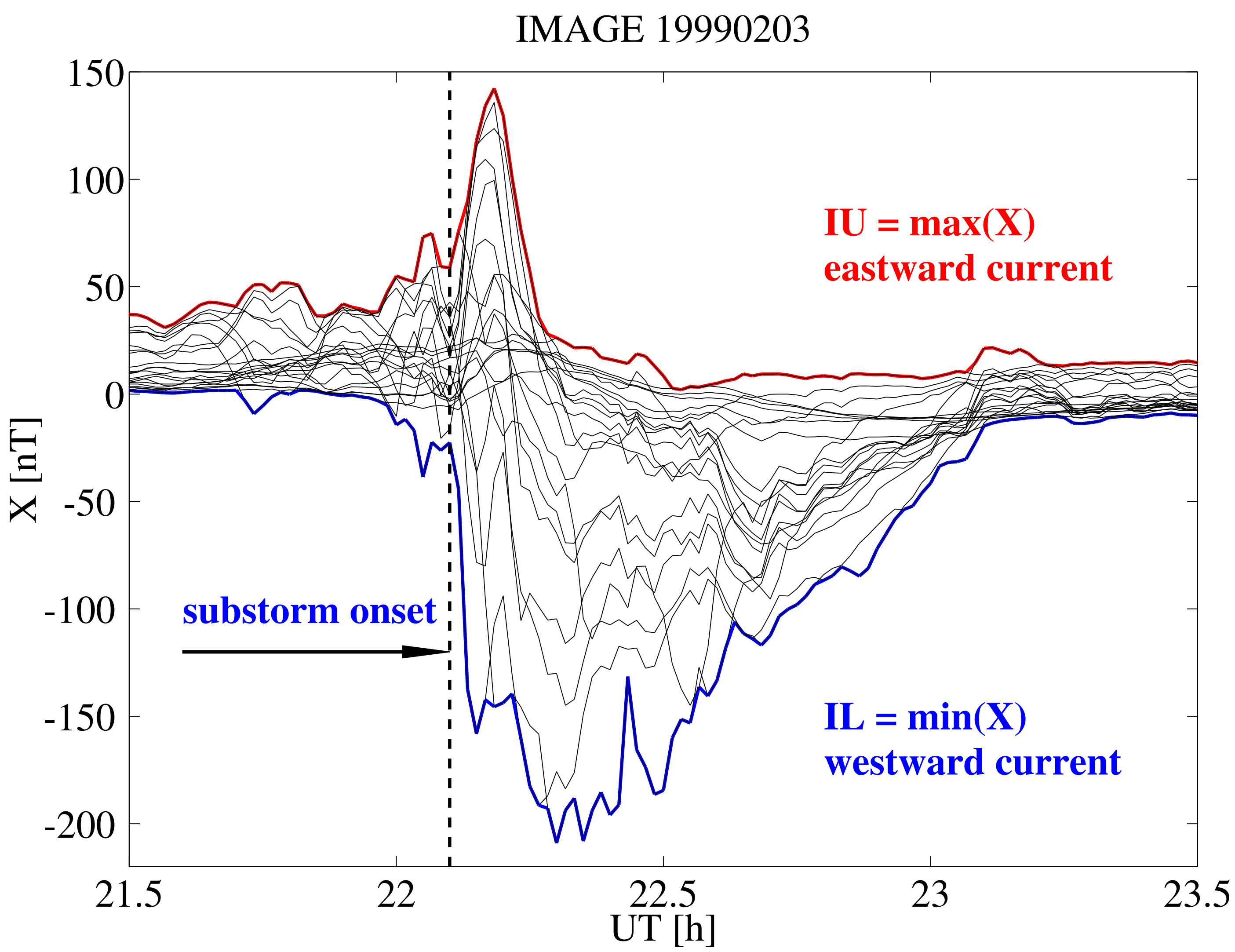


IMAGE Magnetometer Network

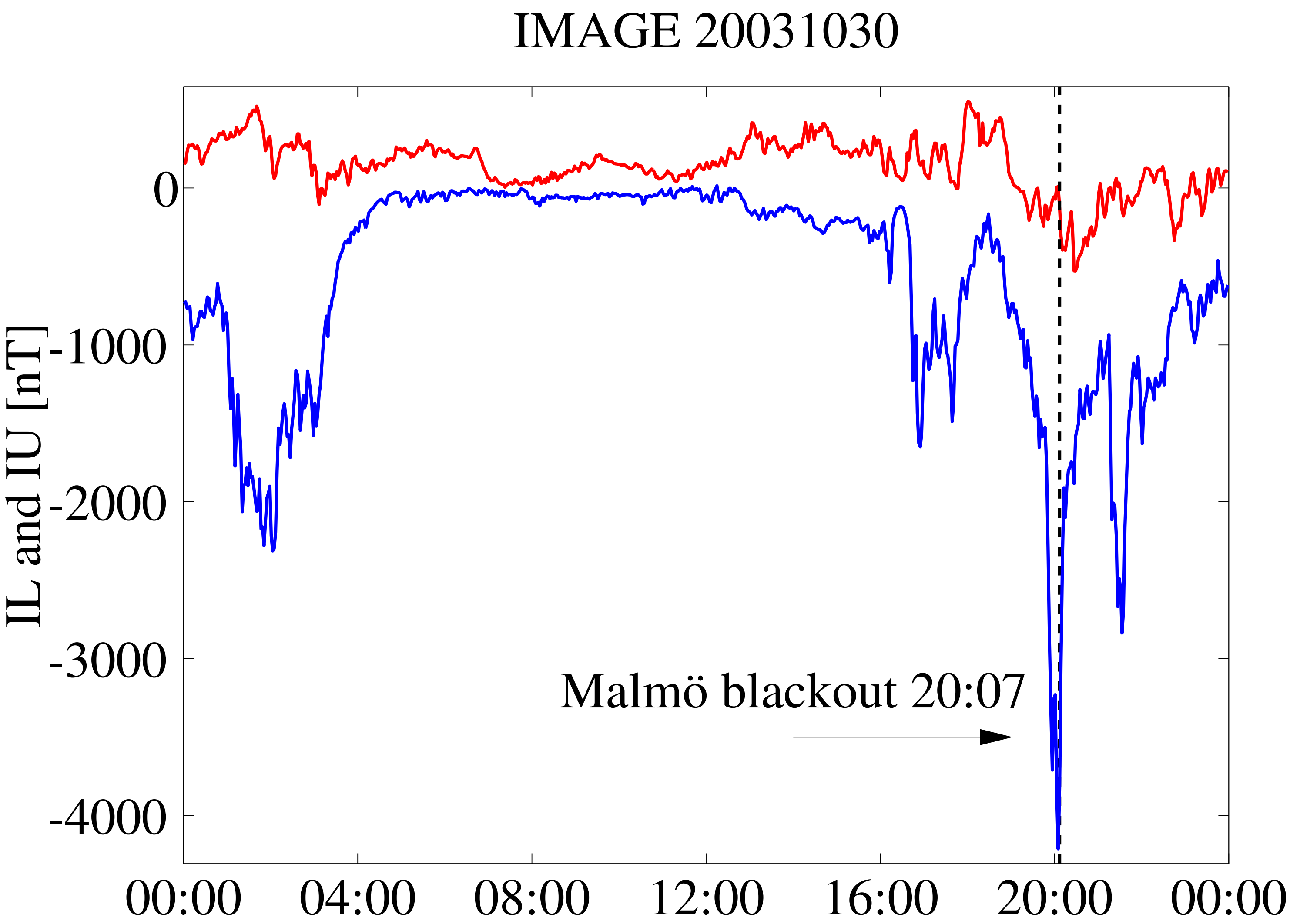


October 2004

Substorms occur around the local midnight

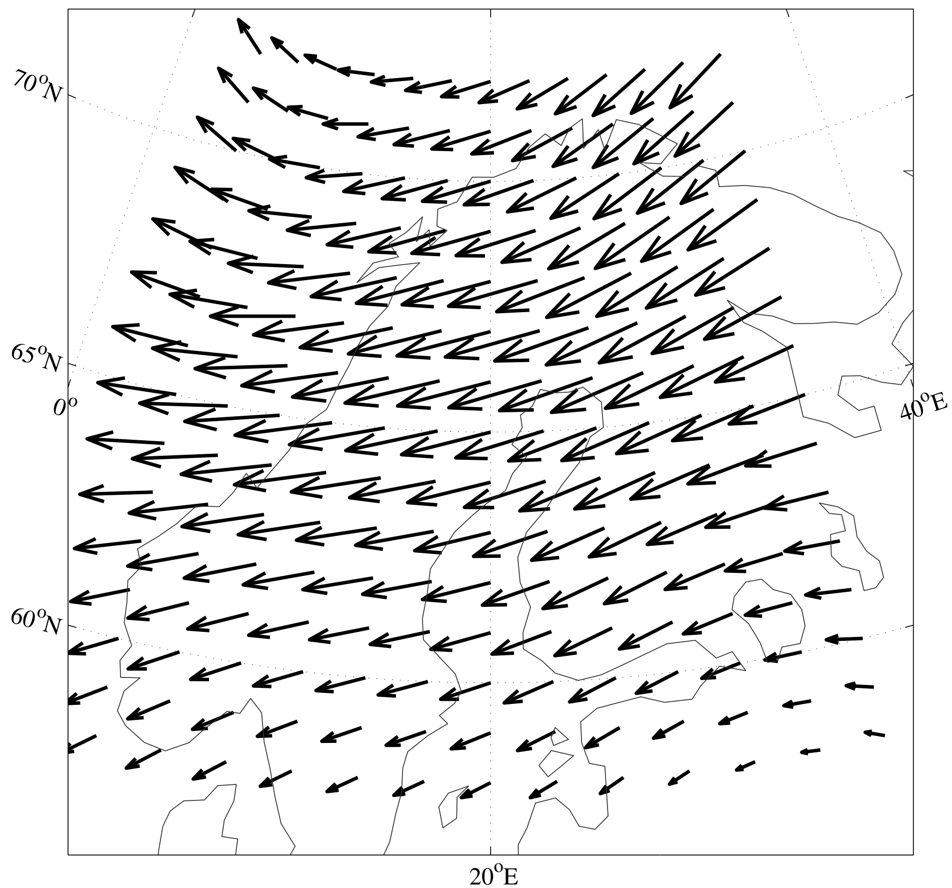


Substorms are a major cause of GIC problems



Ionospheric (equivalent) currents look often smooth without any prominent rapid changes in geometry

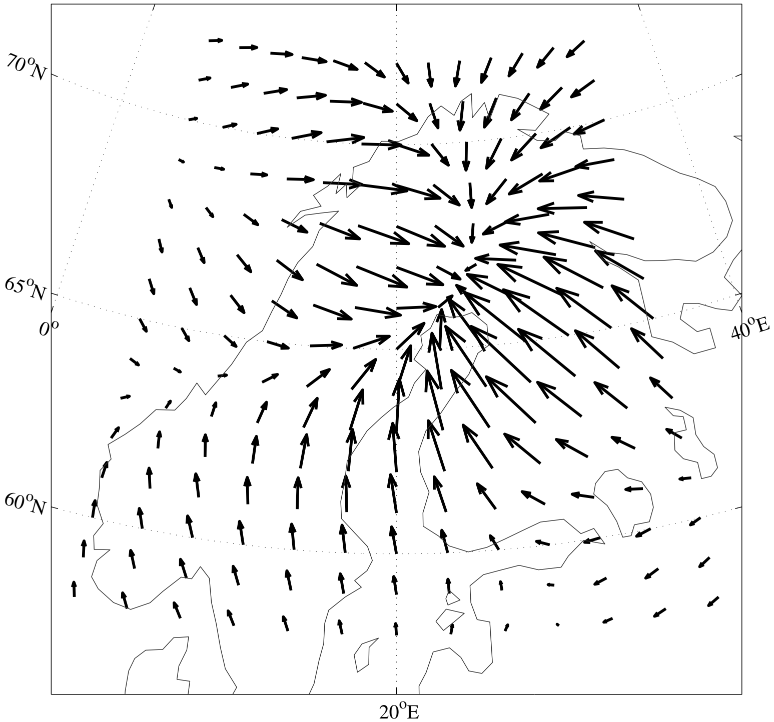
20031030 20:07:00



max(|H|) = 3843 nT

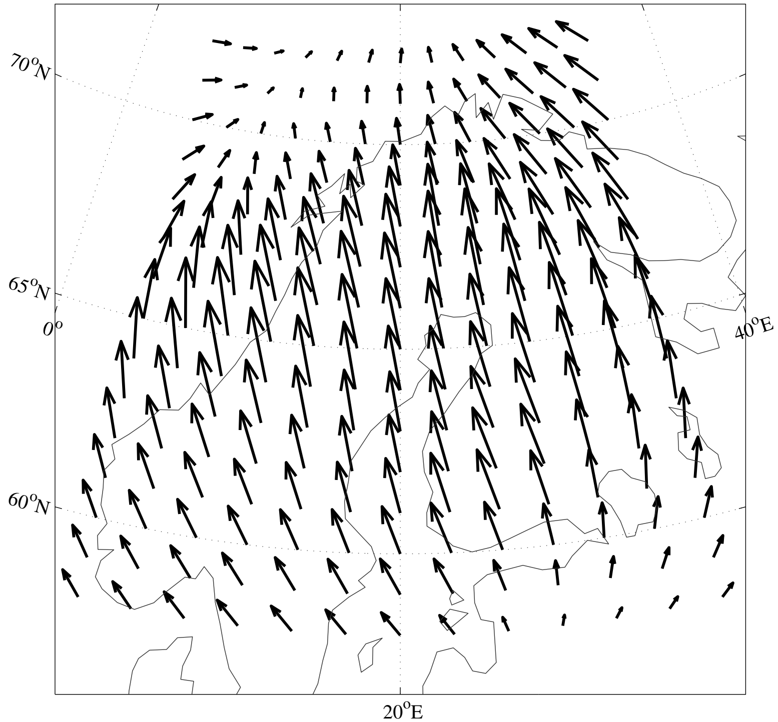
Two nearby timesteps may have very different $d\mathbf{H}/dt$:

20031030 20:06:30



max(|dH/dt|) = 28.4 nT/s

20031030 20:08:40

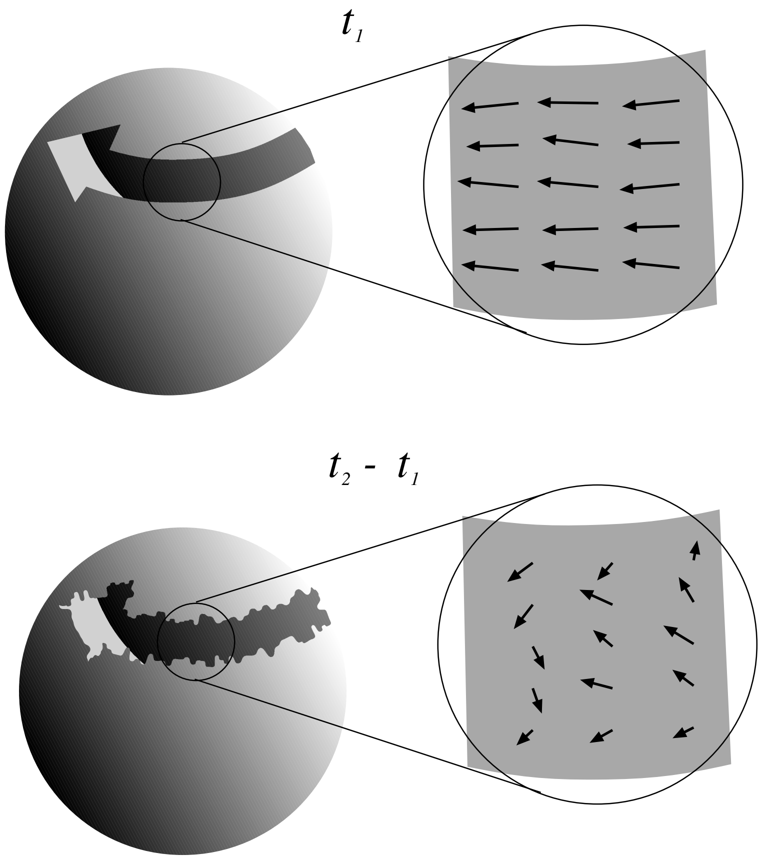


max(|dH/dt|) = 34.1 nT/s

→ completely different ground electric fields and GIC

(animations: $\mathbf{H}$ vs. $d\mathbf{H}/dt$)

Small scales are important

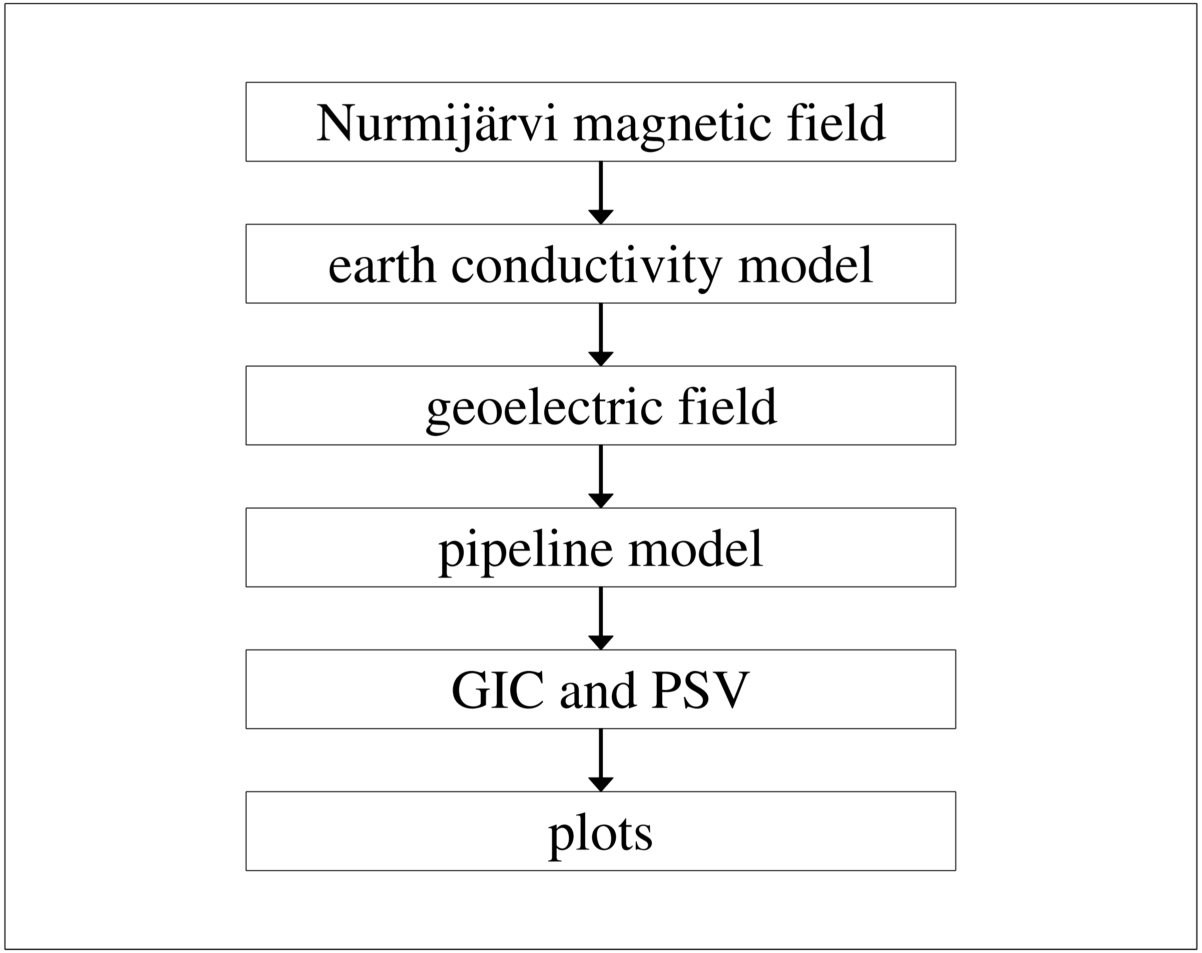


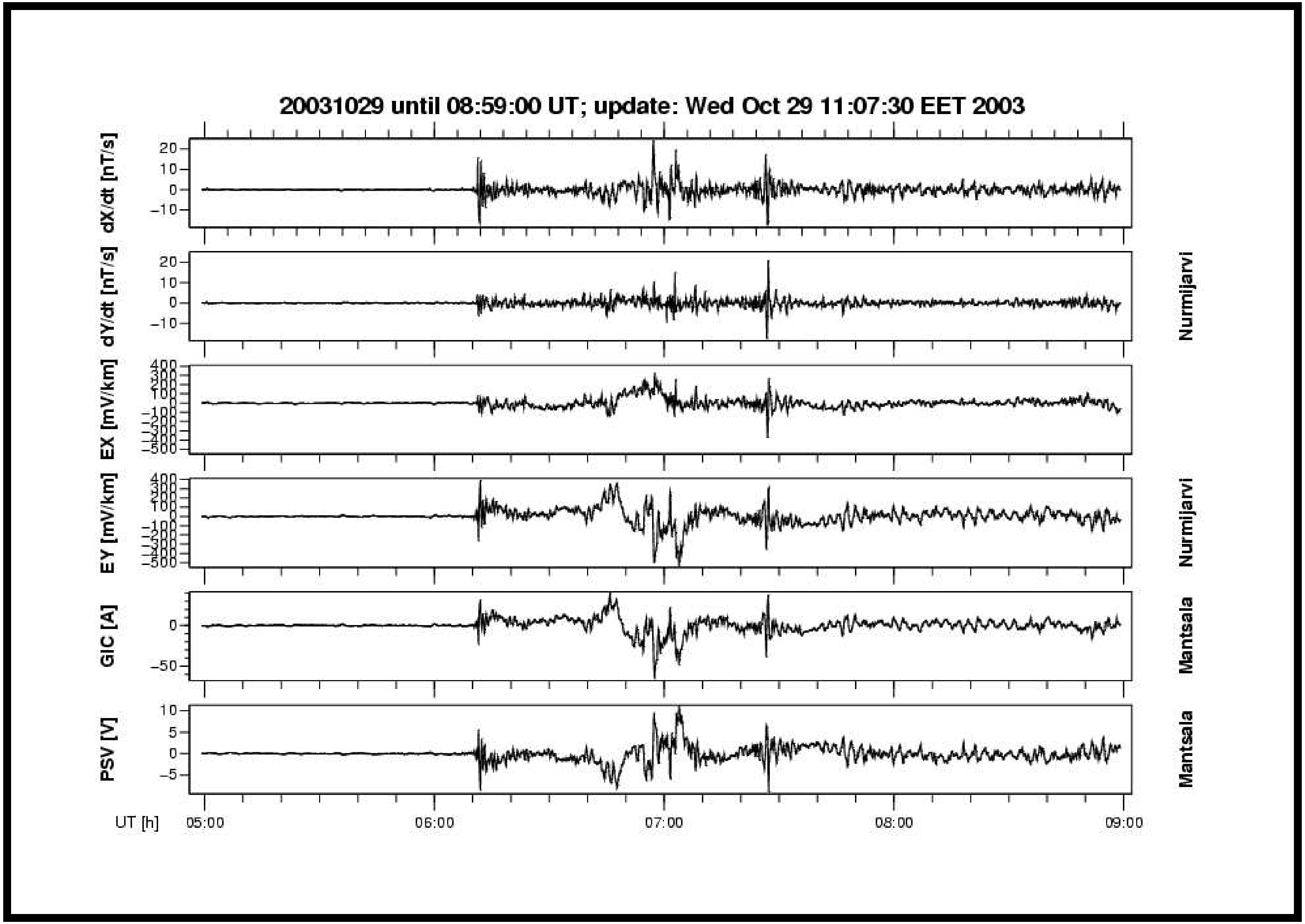
How to quantify spatial and temporal variations?

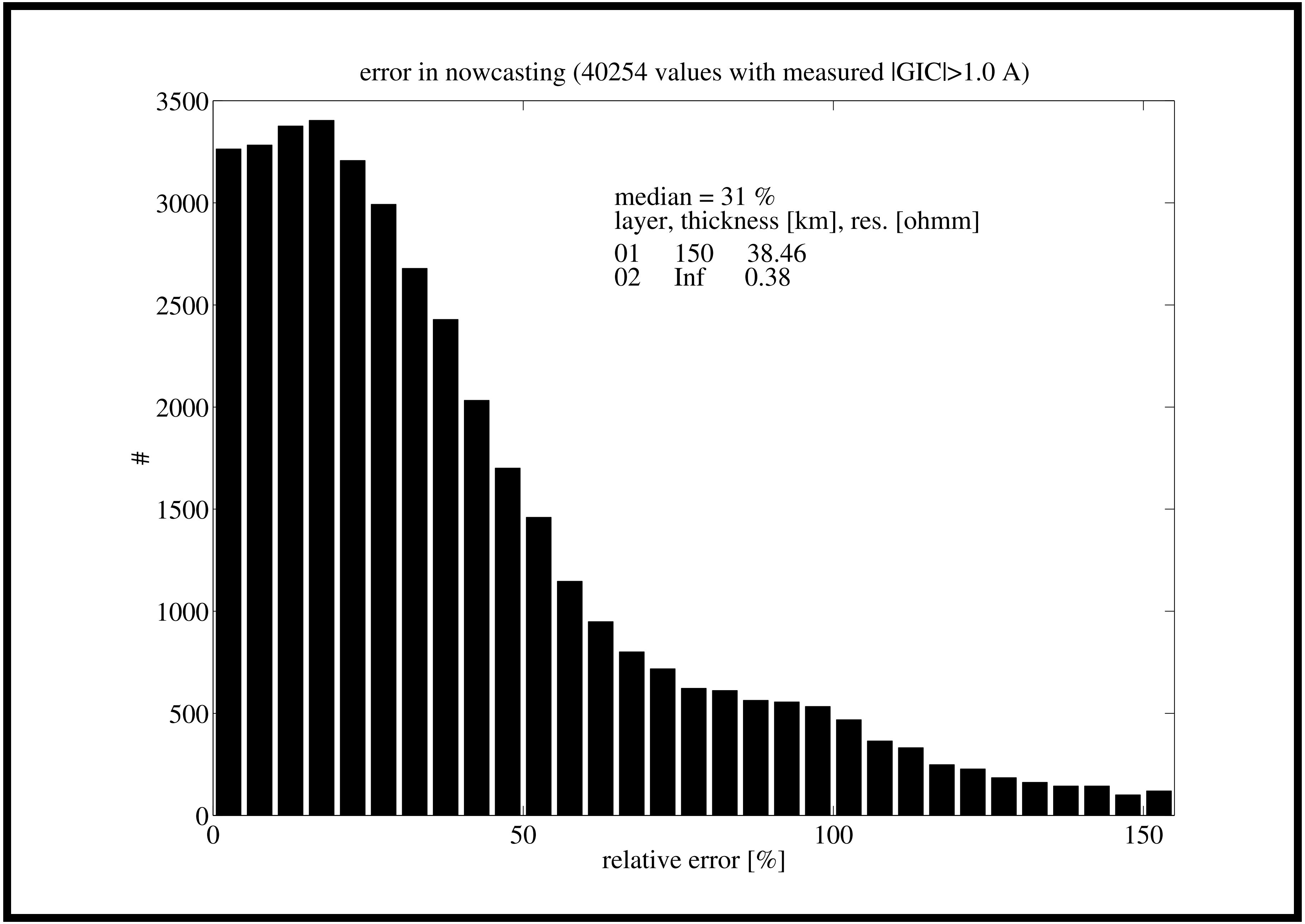
Is there any real hope to forecast GIC?

From research to products: we can nowcast: GIC Now!

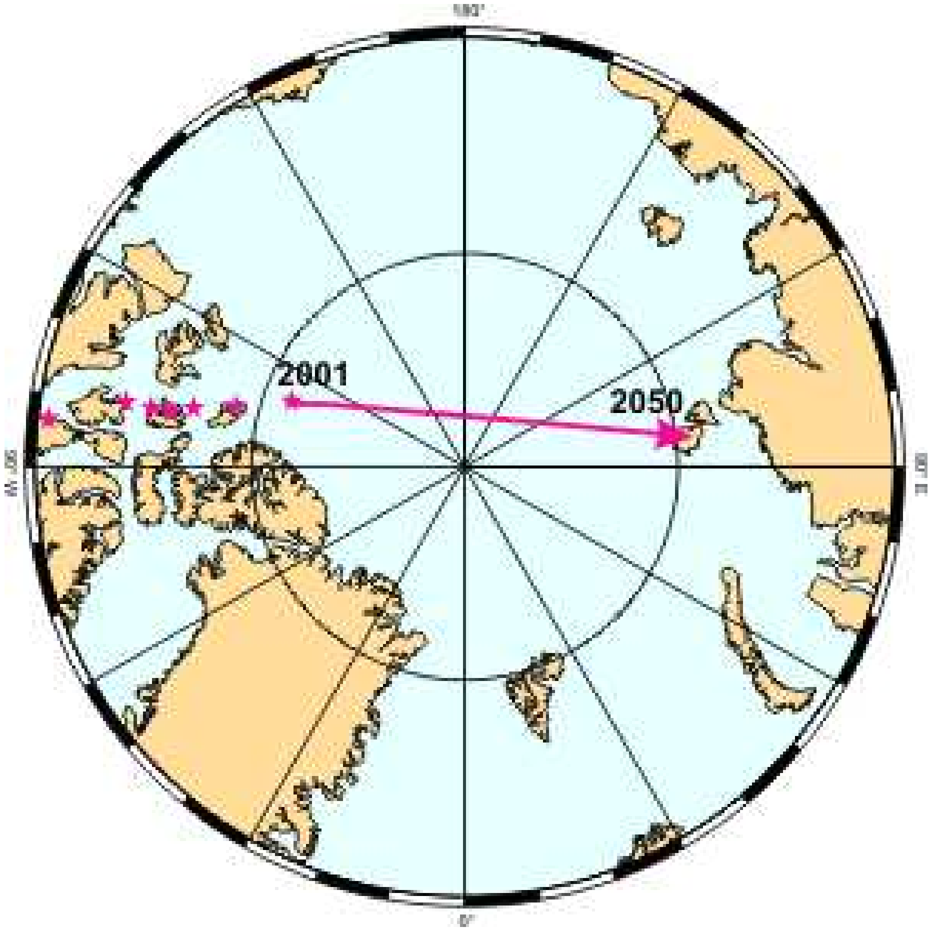
Principle of calculation




20031029 until 08:59:00 UT; update: Wed Oct 29 11:07:30 EET 2003
dX/dt [nT/s]
dY/dt [nT/s]
EX [mV/km]
EY [mV/km]
GIC [A]
PSV [V]
Nurmijarvi
Nurmijarvi
Mantsala
Mantsala
UT [h]
05:00
06:00
07:00
08:00
09:00


error in nowcasting (40254 values with measured |GIC|>1.0 A)
median = 31 %
layer, thickness [km], res. [ohmm]
01 150 38.46
02 Inf 0.38
#
relative error [%]
0
500
1000
1500
2000
2500
3000
3500
50
100
150

Finally, what would happen if the north magnetic pole changed its location as extrapolated below?



Source: Natural Resources Canada

References

Jansen, F., 2003: Report of Failures or Effects due to the Space Weather Storms in October/November 2003.
http://www.physik.uni-greifswald.de/
~sterne/Sternwarte/html/eng/FinalfailuresOctNov2003.html

Koskinen et al., 2001: Space weather effects catalogue. Finnish Meteorological Institute Reports, 2001:1.

Pulkkinen, A., 2003: Geomagnetic Induction During Highly Disturbed Space Weather Conditions: Studies of Ground Effects (Ph.D. Thesis). Introduction part available at e-thesis:
http://ethesis.helsinki.fi/julkaisut/mat/fysik/vk/pulkkinen/
See especially Chapter 1.

Webb, D., 2003: Anomalies related to recent solar activity.
http://beauty.nascom.nasa.gov/~ptg/anomalies.pdf

WWW sites

Today's space weather:
http://www.sec.noaa.gov/today2.html

spaceweather.com:
http://www.spaceweather.com/

Space Weather European Network:
http://www.esa-spaceweather.net/swenet/

Auroras Now!:
http://aurora.fmi.fi/

GIC Now!:
http://aurora.fmi.fi/gic_service/

Proceedings of the Second European Space Weather Week:
http://www.esa-spaceweather.net/spweather/workshops/eswwII/esww2-proceedings.html

Exercises:

Kick-off: March 15, 10-12, 1D23c (Dynamicum ATK class, to the right from the front door)

Be at the front desk at 10 o'clock sharp, you need a visitor badge.

If you have not chosen the exercise, select it from
http://www.ava.fmi.fi/~minna/researchseminar/exercise/
and contact minna.palmroth@fmi.fi