



Aalto University
School of Electrical
Engineering

ELEC-E9550 – Magnetism and applications

Space weather Instrumentation

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Lecture content

- Brief space weather overview
- Basic measuring principles
- Ground-based instruments
 - *Vector magnetometers*
 - *Scalar magnetometers*
 - *All-sky cameras*
 - *Incoherent scatter radars*
 - *Neutron monitors*
- Ground-based infrastructure
 - *IMAGE magnetometer network*
 - *Greenland magnetometer network*

Lecture content

- Space based instrumentation
 - *Magnetometers*
 - *X-ray instruments*
 - *Plasma instruments*
 - *Mass spectrometers*
 - Space platforms
 - *ACE*
 - *DSCOVR*
 - *SDO*
 - Space weather services
 - *NOAA SWPC*
 - *Finnish Meteorological Institute*
 - Aurora Propulsion Technologies
 - *Plasma brake*
 - *E-sail*
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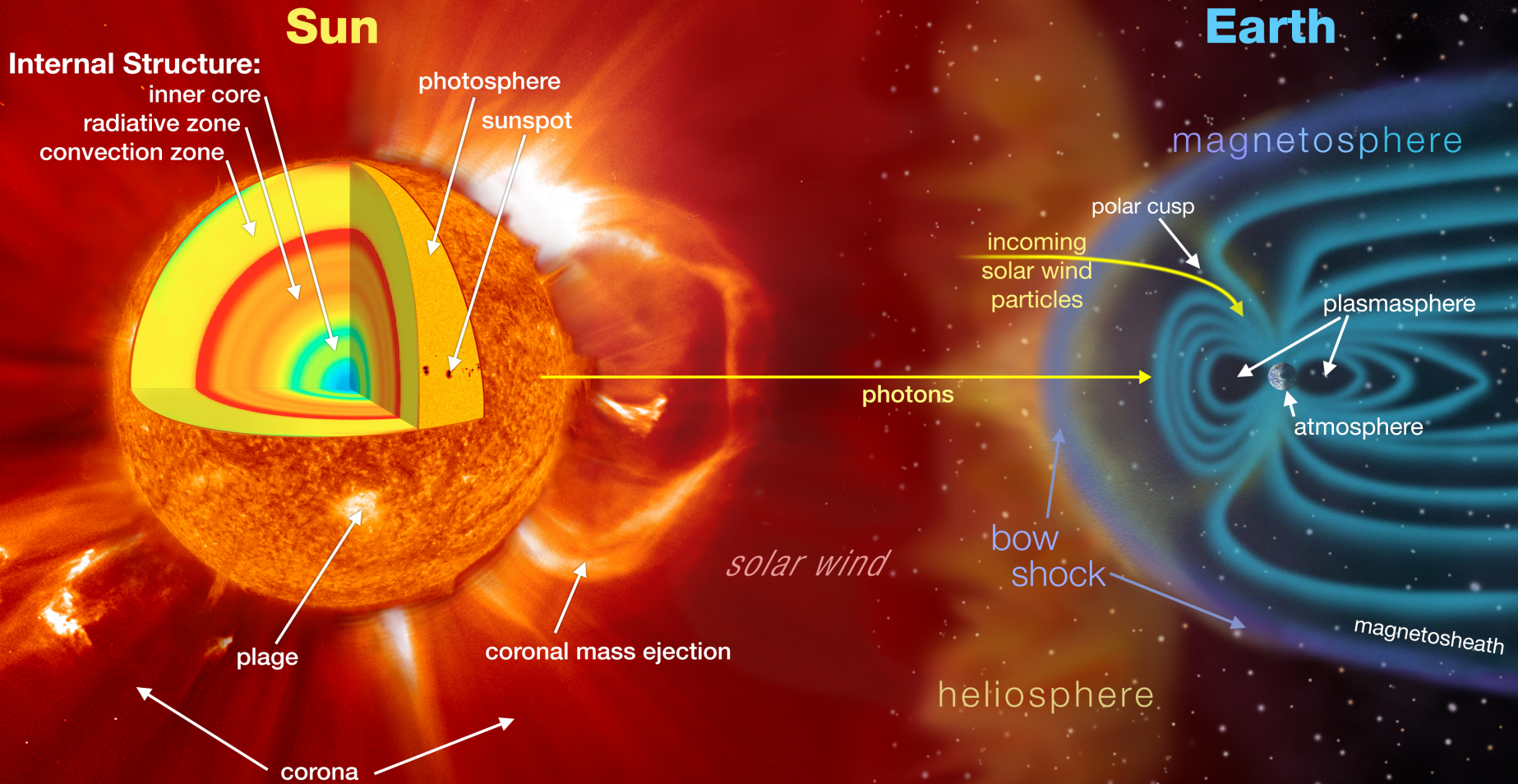
Lecturer introduction

- Hello I am Pyry Peitso, researcher at Aurora Propulsion Technologies and part-time doctoral student at Aalto University
- Current work consists of plasma brake modelling, along with small satellite, mainly CubeSat, engineering and ESA project applications
- Background in space weather and space weather instrumentation
- Worked on Aalto-1 and AuroraSat-1 CubeSat missions as well as the ARO (Aurora Resistojet One) CubeSat propulsion system



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Why?



Economic factors

The Economic Impact of Space Weather: Where Do We Stand?

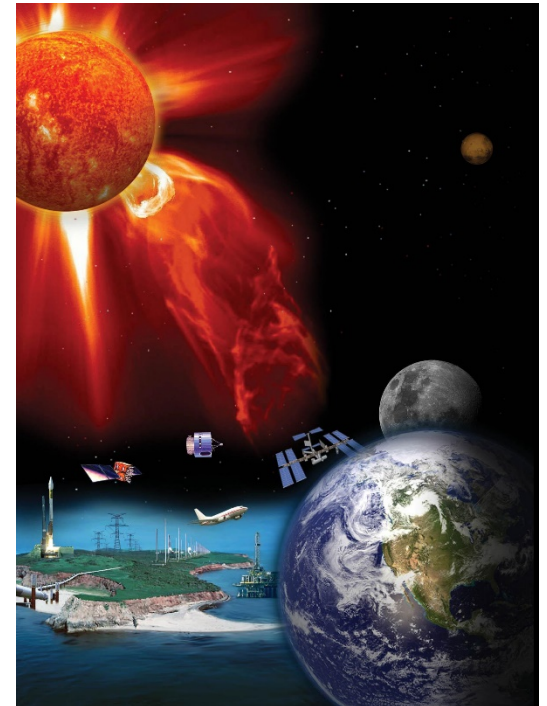
J.P Eastwood, E. Biffis, M.A. Hapgood, L. Green, M.M. Bisi, R.D. Bentley, R. Wicks, L-A. McKinnel, M. Gibbs and C Burnett, *Risk Analysis*, Vol 37, No 2., 2017

- “[f]or a 1989 Quebec-like event, the global economic impacts would range from \$2.4 – \$3.4 tn over a year”

Space weather overview

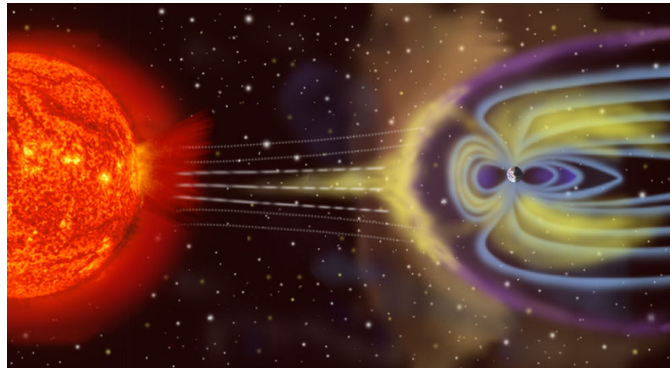
Definition of space weather

- Space weather refers to (mostly) solar originated effects
- Auroras only cosmetic effect
- Satellite errors, surface degradation
- Geomagnetically induced currents in infrastructure
- Power failures due to magnetic field fluctuations in electric power systems
- Communication disruptions and blackouts



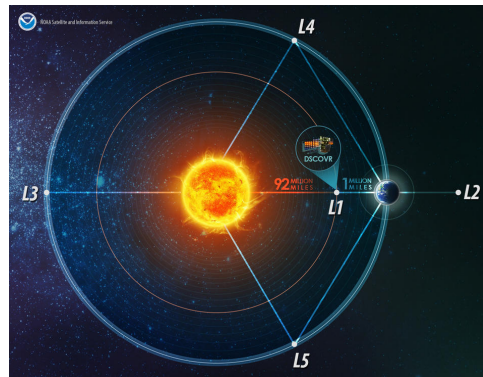
Basic space weather value chain

- Solar eruption releases charged particles
 - *CME, flare*
- Solar wind propagates particles throughout the interplanetary space
- Particles enter the Earth's Magnetosphere
- Current systems enhanced, magnetic field disturbed
- Ionospheric conditions change, affects propagation of radio waves



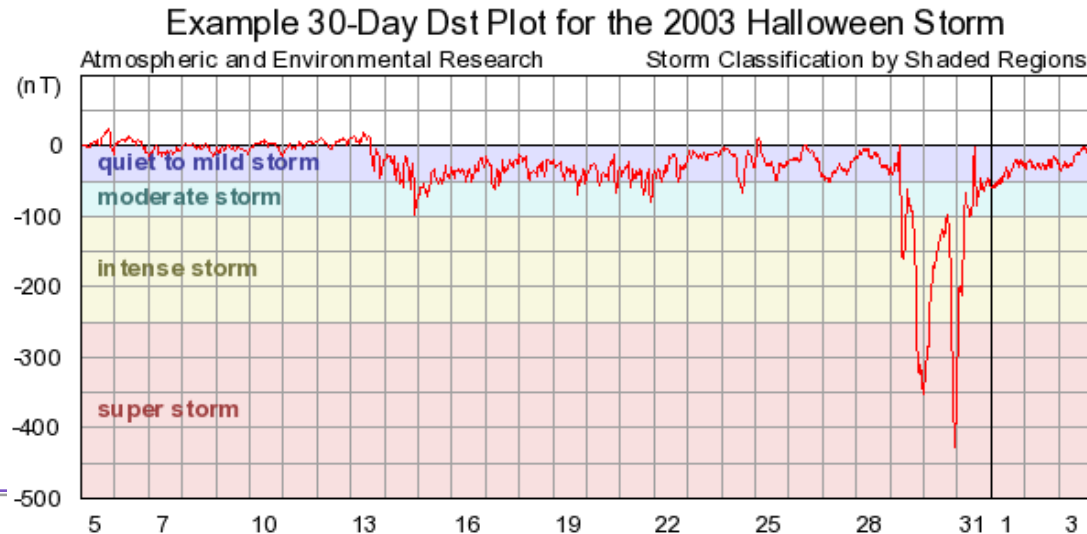
Space weather observations

- How to observe these effects?
- Solar surface can be monitored for eruptions
 - *Space based as well as terrestrial observations*
- Solar wind conditions can be observed with *in situ* equipment, though these are rare and expensive
- Terrestrial effects can be easily observed on the Earth surface
- Ionosphere can be measured using terrestrial radars



Activity indices

- Measurements from multiple sources are often combined into easy to interpret activity indices
- Disturbance storm time (Dst) index is one common measure of space weather activity
- It measures the strength of the ring current near the Earth's equator, and is often used as a proxy for global geomagnetic storms



NOAA Space Weather Scales

- *De facto* standard for space weather classification
- Three alert classes, G for geomagnetic storms, S for solar radiation storms and R for radio blackouts
- Scale goes from 0 to 5, normal situation is 0 for all three cases
- Alert class of 5 has been reached for all three, extreme events are off the scale

Category		Effect	Physical Measures	Average Frequency (1 cycle = 11 years)
Scale	Description	Duration of event will influence severity of effects		
Geomagnetic Storms				
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackout. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, spin/roll-down and attitude problems. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**	Ep5 ⁺	Number of storm events when G5 level was met (number of storm days) 4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will minimally trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect protective systems, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and southern California (typically 35° geomagnetic lat.)**	Ep4 ⁺	100 per cycle (80 days per cycle)
G 3	Strong	Power systems: possible widespread voltage control problems and some protective devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: unimpeded satellite navigation and low-frequency radio navigation problems may occur; HF radio may be intermittent and aurora has been seen as low as Illinois and Oregon (typically 30° geomagnetic lat.)**	Ep3 ⁺	200 per cycle (130 days per cycle)
G 2	Modest	Power systems: high-latitude power systems may experience voltage sags, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 25° geomagnetic lat.)**	Ep2 ⁺	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: small-scale disturbances can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: minority aurora is observed at mid and higher latitudes, aurora is commonly visible at high latitudes (southern Michigan and Maine)**	Ep1 ⁺	1700 per cycle (900 days per cycle)
* Based on this measure, but other physical measures are also considered. ** For specific locations see the NOAA Space Weather Prediction Center website (http://www.swpc.noaa.gov/predict)				
Solar Radiation Storms				
S 5	Extreme	Radiation: unserviceable high radiation based on exposure on EVA (extra-vehicular activity), passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Facilities operations: satellites may be rendered useless, emergency services on cross-lane may cause serious issues in some areas, star-trackers may be unable to locate sources, permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the solar region, and position errors radio navigation operations available.***	Flt level of: 10 MeV ⁺ proton/cm ² /ster ⁺	Number of events when Flt level was met** Fewer than 1 per cycle
S 4	Severe	Radiation: unserviceable radiation based on exposure on EVA, passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Facilities operations: many experience memory device problems and some on sensitive systems, star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the solar region and increased navigation errors over several days are likely.	10 ⁺	1 per cycle
S 3	Strong	Radiation: radiation based avoidance recommended for astronauts on EVA, passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Facilities operations: visible-swing upset, noise in sensitive systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar region and navigation position errors likely.	10 ⁺	10 per cycle
S 2	Modest	Radiation: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Facilities operations: infrequent visible-swing upset possible. Other systems: effects on HF propagation through the polar region, and navigation at polar cap locations possibly affected.	10 ⁺	27 per cycle
S 1	Minor	Radiation: none Facilities operations: none Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle
* Flt level is 1 rem/minute. Flt level "ster" unit** based on this measure, but other physical measures are also considered. ** These events are not necessarily harmful. *** High energy particles (100 MeV) are a factor of radiation risk to passengers and crew. Prudent systems are particularly susceptible.				
Radio Blackouts				
R 5	Extreme	HF Radio: Complete HF (high frequency)** radio blackout on the entire visible side of the Earth lasting for a number of hours. Results in an HF radio contact with aircraft and no voice services in this sector. Navigation: Low-frequency navigation signals used by maritime and aviation systems experience outages on the visible side of the Earth for many hours, corrections in positioning. Increased satellite navigation errors in positioning for several hours on the visible side of Earth, which may spread into the night side.	X5 (10 ⁺)	Number of events when peak brightness by class and by day ⁺ Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the visible side of Earth for one to two hours. HF radio contact is degraded for hours. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the visible side of Earth.	X4 (10 ⁺)	1 per cycle (4 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communications, loss of radio contact for about an hour on visible side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X3 (10 ⁺)	175 per cycle (140 days per cycle)
R 2	Modest	HF Radio: Limited blackout of HF radio communications on visible side of the Earth, loss of radio contact for hours of message. Navigation: Degradation of low-frequency navigation signals for hours of minutes.	X2 (10 ⁺)	200 per cycle (160 days per cycle)
R 1	Minor	HF Radio: Weak or minor disruptions of HF radio communications on visible side of the Earth, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	X1 (10 ⁺)	1000 per cycle (850 days per cycle)
* Flt, measured in the 1-10 MeV range, 90° W.*** based on this measure, but other physical measures are also considered. ** Other frequencies are also affected by these outages. URL: www.swpc.noaa.gov/N316/4code				

April 7, 2011

Basic measuring instruments and principles

What are we actually measuring

- Space weather manifests itself in numerous different ways
 - The Sun is responsible for (almost all) space weather phenomena
 - *Direct observations of solar eruptions*
 - This is mostly through different current systems caused by charged particles
 - Changes in different magnetic fields are an easy, economic and straightforward way to measure these changing circumstances
 - *Surprisingly large amounts of information can be gleamed from a rather unsophisticated instrument from the 19th century*
 - Several overlapping systems -> effects sometimes difficult to differentiate -> lots of open scientific questions -> good field for research!
-

Tesla [T]

- Magnetic field flux density is measured in a rather unintuitive unit, the tesla (T), in base SI units $\text{kg s}^{-2} \text{A}^{-1}$
- Fields in the order of magnitude of teslas have been achieved in laboratories, Earth field is in the range of 10000s of nanoteslas (nT), while neutron stars could have fields in the strength of 10^{10} T
- Nanotesla is the basic unit of space weather, rule of thumb is that 5 nT change in the interplanetary magnetic field z-direction (IMF) signifies that *Something Is Up*
- Changes at the Earth surface are typically in the scale of hundreds of nanoteslas, in case *Something Is Up*



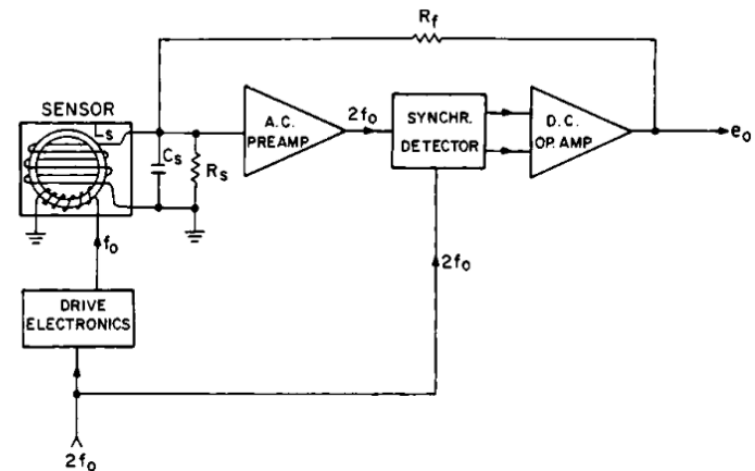
Magnetometer operating principles

- Fluxgate magnetometer is the most widely used space weather instrument
- Developed in the 19th century, historical measurements quite useful even today
- Notable application in submarine detection
- Danish FGM-FGE fluxgate magnetometer, with supporting electronics depicted



Magnetometer operating principles

- Ferromagnetic core is driven to saturation by a periodic current
- Current creates magnetic field -> induces a new current into the ferromagnetic core
- Measure the asymmetry between the original current and the induced current -> determine the external magnetic field
- Artificial magnetic fields, i.e. almost anything done by humans, disrupts measurements -> magnetometers deployed far from cities and such

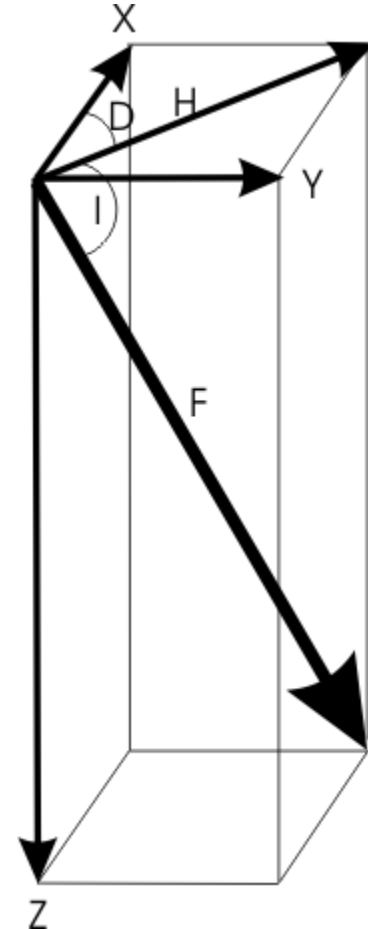


Magnetometer operating principles

- Rugged and simple instrumentation, basic setup requires electricity, rudimentary heating and instrument cover and data logging capabilities
- Due to the nature of the phenomena, long timeseries and high time resolution (seconds) is preferred
- Change of the magnetic field is often more useful than the absolute value, due to Earth base field's rather significant differences across the globe
- When looking at different measurements remember that in addition to 10000 nT size changes across the globe, the poles also drift in early timescales

Vector vs scalar

- Vector instruments measure different components of the magnetic field
- Either XYZ or HZD, these can also be calculated from each other
- Scalar instruments measure the absolute value of the magnetic field
- Used mostly for calibration purposes due to increased emphasize on accuracy



All-sky cameras

- Sometimes called whole sky cameras
- Specialized cameras used to photograph auroras, fisheye lens allow for a very wide field of view
- Usually take automatic images throughout the the night, so rather large data volume



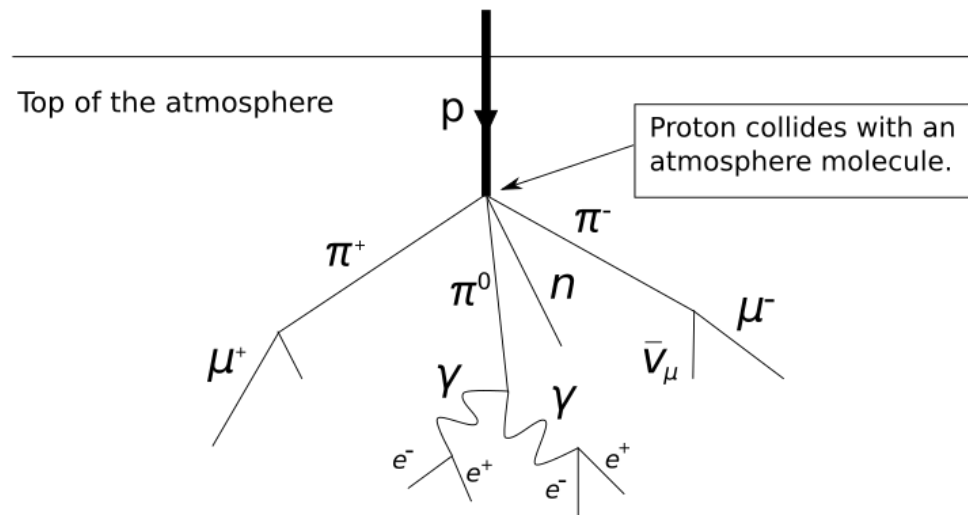
Incoherent scatter radars

- High power ground based radars
- Work by beaming a signal to the ionosphere, where it is scattered
- The resulting scattered signal is measured and the results are compared to the original signal sent
- Allows for study of wide range of ionospheric parameters, such as electron density and temperature, ion temperature, mass, plasma drift velocity etc.
- EISCAT (European Incoherent Scatter Scientific Association) located partly in Finland



Neutron monitors

- Instrument to measure hadronic component in atmospheric secondary radiation related to cosmic rays
- Actually measures showers of secondary particles from cosmic ray interaction with Earth magnetic field
- Study of cosmic rays allows for indirect studies of solar activity



Magnetometer networks

- Magnetometer measurements are usually conducted by large chains of stations
- Calibration of measurements synchronized across the whole chain
- Usual products are activity indices, in addition to single station measurements
- Location of magnetometer chain gives information about different current systems around the Earth, measurements from the equator look significantly different compared to measurements from polar regions

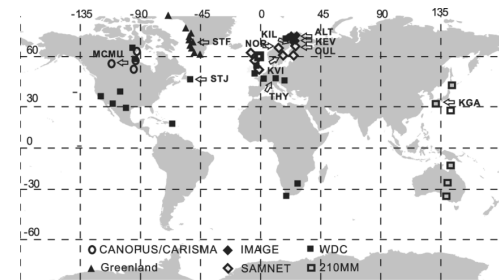
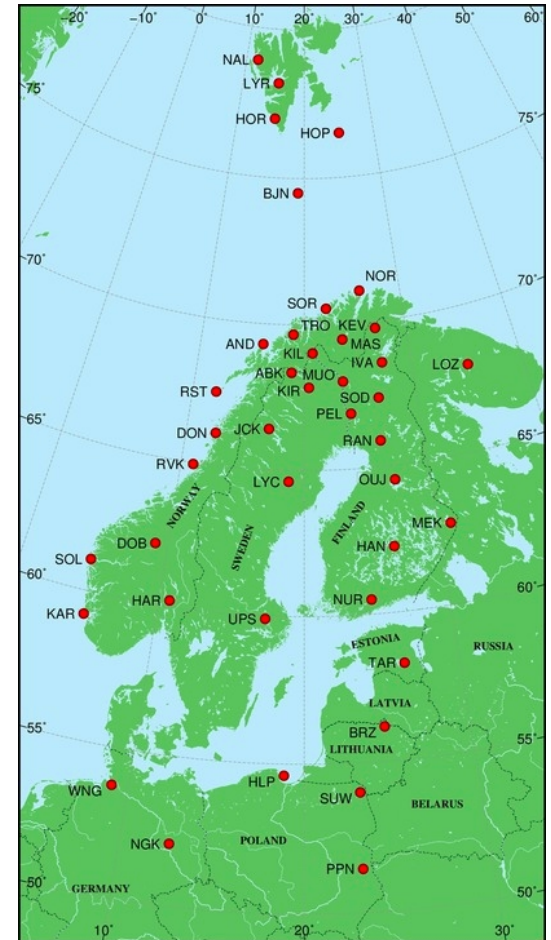


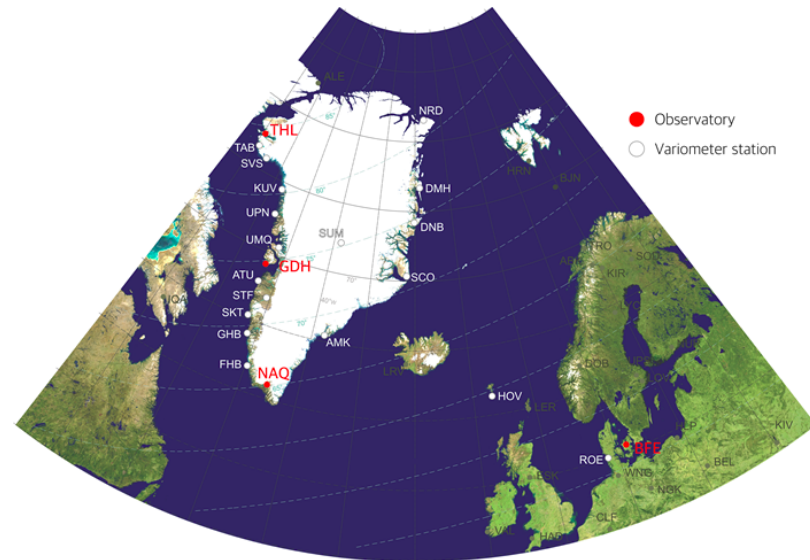
IMAGE magnetometer network

- International Monitor for Auroral Geomagnetic Effects (IMAGE)
- 41 stations maintained by 8 institutes
- Main objective to study auroral electrojets as well as moving current systems, the large latitudinal coverage making IMAGE well suited for this
- High quality data and long time series available



Greenland magnetometers

- Danish Technical University (DTU) operated 19 station network located in Greenland
- Compared to IMAGE, stations are situated more poleward, allowing for measurements of different current systems, such as quite direct solar wind interaction at the polar cap regions
- High quality data, with also long time series available though not as long as IMAGE stations



End of part I

Coming next: space based instrumentation

Space based instruments