Chapter 10
Measuring the Earth's magnetic field

Previously

- When a measurement of the geomagnetic field is taken at any given point and time, the resulting value contains the superposition of fields having different origins and varying in magnitude:
  - A hydrodynamic dynamo in the Earth's fluid outer core (2900-5100 km depth) produces over 99% of the Earth's magnetic field → main or core field.
    - Changes in the strength and direction of the electric currents cause changes in the field on time scales of about a year and more (secular variations).
  - Magnetized rocks in the lithosphere (< 50 km depth) → lithospheric or crustal field.
  - Electric currents in the near-Earth space (> 100 km altitude) that are driven by solar activity → external magnetic field.
    - Irregular variations with periods from seconds to hours (transient variations).
- The coefficients of the IGRF model (for example) are based on magnetic measurements made by satellites and at the surface.

Content

- Magnetometers
- Geomagnetic observatories
- Automatic stations
- Satellite observations

Material: http://www.iugg.org/IAGA/index.html

Magnetometers

Definitions

- *Absolute instrument* means an instrument capable of giving the magnitude of the magnetic field or its component in absolute physical base units (e.g., m, kg, s, A, or their derivatives or angle compared to geographical direction or horizontal plane) or universal constants (e.g., gyromagnetic ratio of proton or electron).
- *Relative instrument* is an instrument which measures the deviation from an undetermined field. To know the value of the undetermined field, it is necessary to make an absolute measurement. In the case of a variometer this value is called a baseline.
- *Semi-absolute instrument* means a relative instrument which by frequent enough comparisons with absolute instruments gives acceptably high accuracy for the measurement in question.
- *Absolute measurements* are made using an absolute or semi-absolute instrument to achieve the required absolute accuracy.
- *Sensitivity* tells how many units at the output of an instrument correspond to one physical unit (e.g., how many bits for one nT).

- *Scale value* is the inverse of sensitivity.
- *Base value* is the value (usually almost constant) to be added to the recorded one to obtain the final component value in question.
- *Baseline value* is the same as base value, usually used in connection with magnetograms where a straight line for scaling exists.
- *Temperature coefficient* indicates how much a measured or recorded value depends on temperature (e.g., nT/^{0}C). It is based on a linear relation between magnetometer output and temperature.
- *Range* refers to the upper and lower limits of the values which can be recorded with the instrument in question (e.g., ±4000 nT).
- *Dynamic range* in the ratio between the maximum recordable amplitude and the resolution. Normally it is expressed in decibels (dB), and the formula for its calculation is $20 \cdot \log(A_{max}/A_{min})$ where A_{max} and A_{min} are the maximum and minimum amplitudes, respectively.

- *Resolution* describes what are the smallest changes recordable. The resolution is limited by the noise level.

- *Accuracy* decribes the real absolute accuracy. Accuracy of 0.1 nT says that the difference between the true value and the measured one is not more than 0.1 nT.

- *Mean square error* (m) is calculated from the scatter of the measurements.

  $$m = \left(\sum_{i=1}^{n} \frac{\nu_i^2}{n-1} \right)^{1/2},$$

  where ν_i is the deviation from the mean and n is the number of measurements.

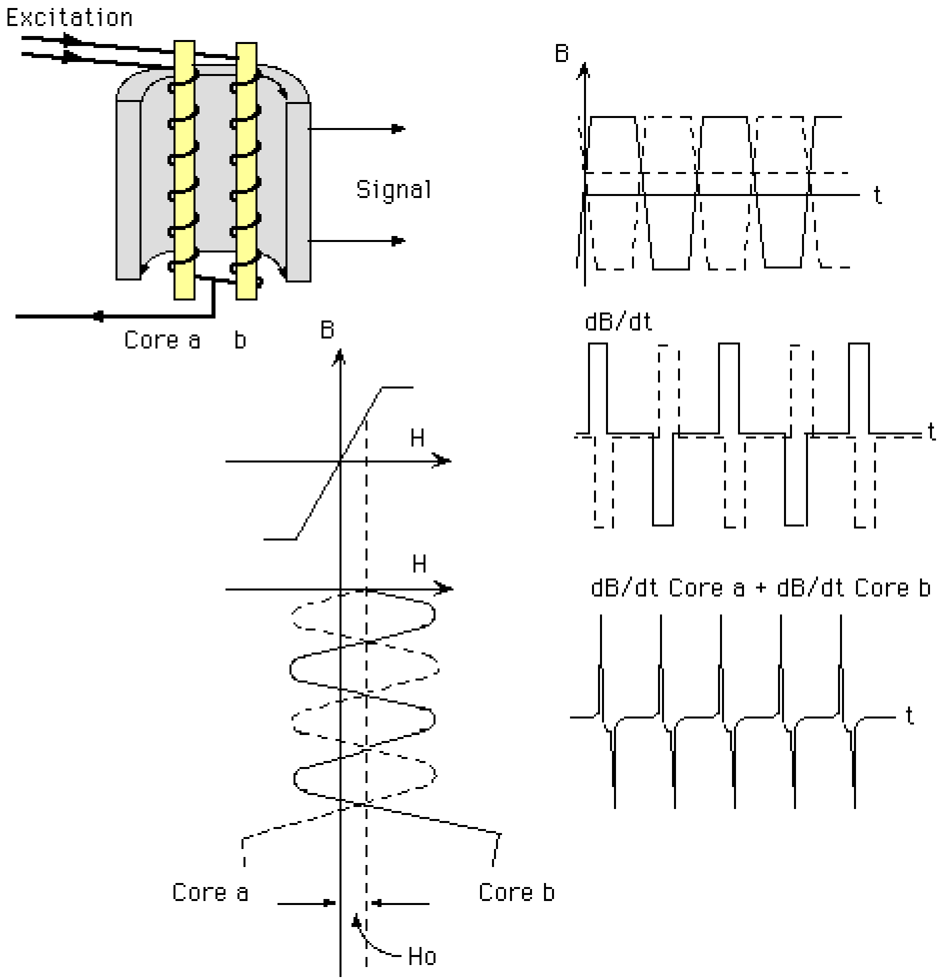
- *Systematic error* of a series of measurements is the deviation of the mean value from the true value.

- *Absolute accuracy* is determined by sum of the mean square error and the systematic error.

- *Relative accuracy* of a recorded event is the ratio between the accuracy of the recorded event and its amplitude, normally given in percents (%).
- *Precision* describes the scatter of values. Precision of 0.1 nT means that the values are within 0.1 nT from their mean value, but it says nothing of the accuracy.
- *Variometer* is a magnetometer which is used to record variations of the magnetic field.

Fluxgate magnetometer

- A fluxgate magnetometer consists of a small, magnetically susceptible core wrapped by two coils of wire.
- An alternating electrical current is passed through one coil, driving the core through an alternating cycle of magnetic saturation; i.e., magnetised, unmagnetised, inversely magnetised, unmagnetised, magnetised, and so forth.
- This constantly changing field induces an electrical current in the second coil, and this output current is measured by a detector.
- In a magnetically neutral background, the input and output currents will match.
- However, when the core is exposed to a background field, it will be more easily saturated in alignment with that field and less easily saturated in opposition to it. Hence the alternating magnetic field, and the induced output current, will be out of step with the input current. The extent to which this is the case will depend on the strength of the background magnetic field.



- Typically, a fluxgate magnetometer has a resolution of 0.1 nT (or even 0.01 nT) and a bandwidth from DC to 5 Hz.
- In fluxgate magnetometers constructed for observatory use or for other continuous monitoring of the magnetic field, there usually are three orthogonal sensors fixed to the same frame for the recording of the three components of the magnetic field. The sensor assembly is usually rather small and robust. Fluxgate magnetometers are becoming the most popular instruments at modern digital observatories due to their robust construction and reliable electronics.
- The fluxgate magnetometer measures the component along a particular axis of the sensor, so it needs to be oriented. It measures the magnetic field continuously, but drifts over time.

Proton precession magnetometer

- The sensor is usually a bottle containing some 200 – 500 cc proton rich liquid such as water (good but not practical in cold climate), alcohol or kerosene.
- Around the bottle there are about 1000 windings of copper or aluminum wire for applying a polarizing field to the liquid (fields up to 0.01 T are used) and for picking up the signal from the precessing protons after cutting off the polarizing field.
- In the measurement the bottle is oriented so that the polarizing field is roughly perpendicular to the measured field.
- When the polarizing field is cut off rapidly, the protons begin to precess around the magnetic field vector, whose magnitude is to be measured.
- The signal from the protons is small, only of the order of one microvolt in the coil, but its frequency is measurable for 1 – 5 seconds depending on the homogeneity of the measured field and the polarizing field used.

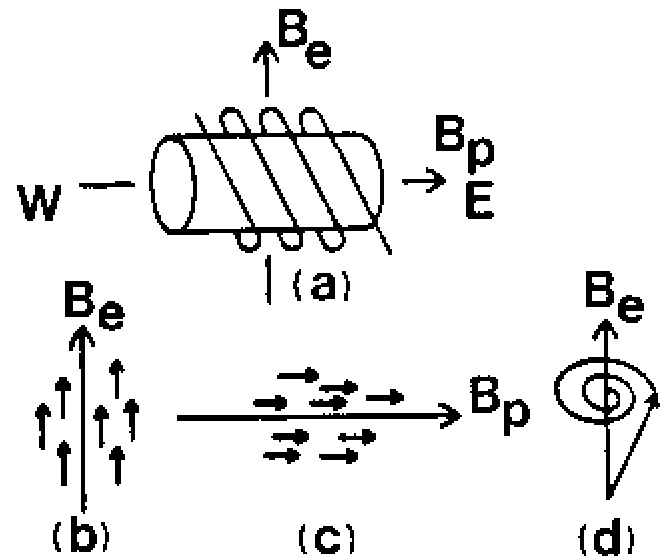


FIG. 9. Principle of the proton-precession magnetometer (after Kearey and Brooks, 1984). (a) Sensor with earth's magnetic field B_e, and magnetic field of instrument coil B_p. (b) Alignment of protons in earth's field, (c) Alignment of protons due to applied field, (d) Precession of protons around earth's field after coil current is switched off.

- The relationship between the frequency of the induced current and the strength of the magnetic field is called the proton gyromagnetic ratio γ

$$\omega = 2\pi f = \gamma B$$
$$\rightarrow B = 2\pi f / \gamma = g f ,$$
$$\text{where } g = 2\pi / \gamma = 23.487 \text{ nT/Hz}$$

- The polarization of the liquid in the sensor bottle takes, depending on the field used, usually 2 – 6 seconds.
- The longer times are used for getting more protons oriented into the direction of the field, which means a stronger and longer signal in the measurement, allowing higher sensitivity (0.1 nT) to be used.
- The proton precession magnetometer measures the strength of the field but not its direction, so it does not need to be oriented. Each measurement takes a second or more.

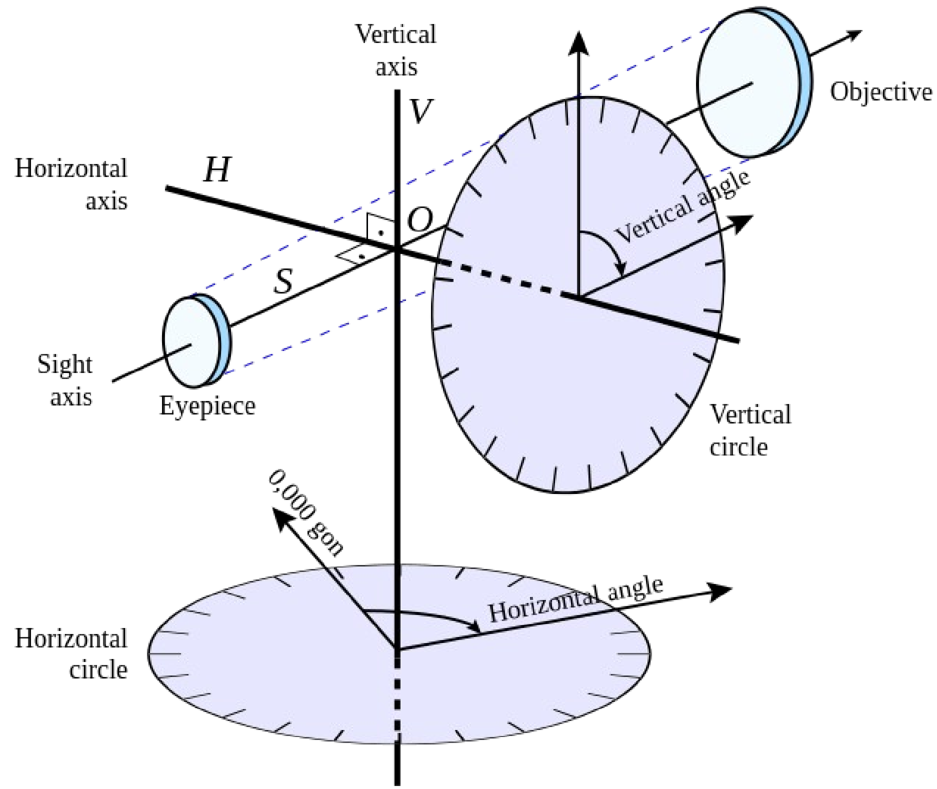
Overhauser magnetometer

- Uses the same fundamental effect as the proton precession magnetometer to take measurements.
- By adding free radicals to the measurement fluid, the nuclear Overhauser effect can be exploited. Rather than aligning the protons using a solenoid, a low power radio frequency field is used to align (polarize) the electron spin of the free radicals, which then couples to the protons via the Overhauser effect.
- This has two main advantages:
  - driving the radio frequency field takes a fraction of the energy of the solenoid (allowing lighter-weight batteries for portable units)
  - faster sampling as the electron-proton coupling can happen even as measurements are being taken.

DI-flux magnetometer

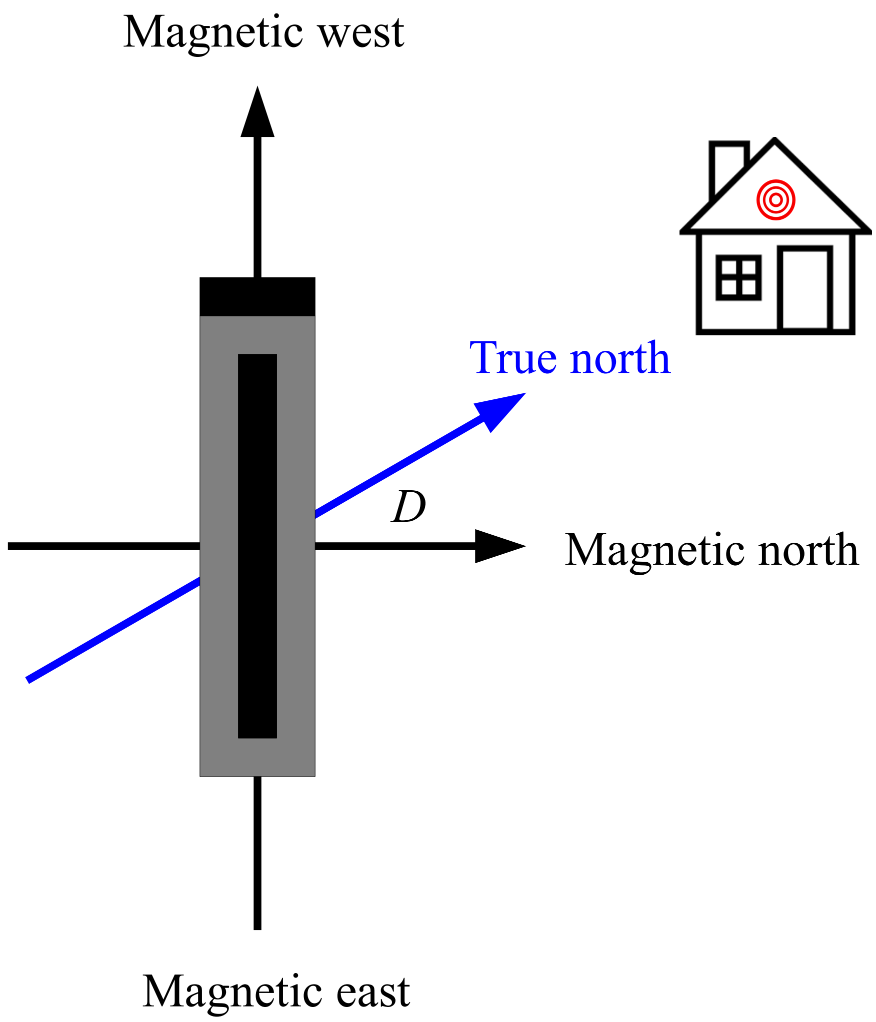
- Used to measure the declination (*D*) and inclination (*I*) of a magnetic field vector.
- Consists of a fluxgate magnetometer mounted on a non-magnetic theodolite telescope.
  - A theodolite is a precision instrument for measuring angles in the horizontal and vertical planes. It consists of a movable telescope mounted within two perpendicular axes (horizontal and vertical). When the telescope is pointed at a target object, the angle of each of these axes can be measured with great precision, typically to seconds of arc.
  - Not just any theodolite will do but it has to be non-magnetic.

Fluxgate magnetometer mounted on a non-magnetic theodolite telescope.



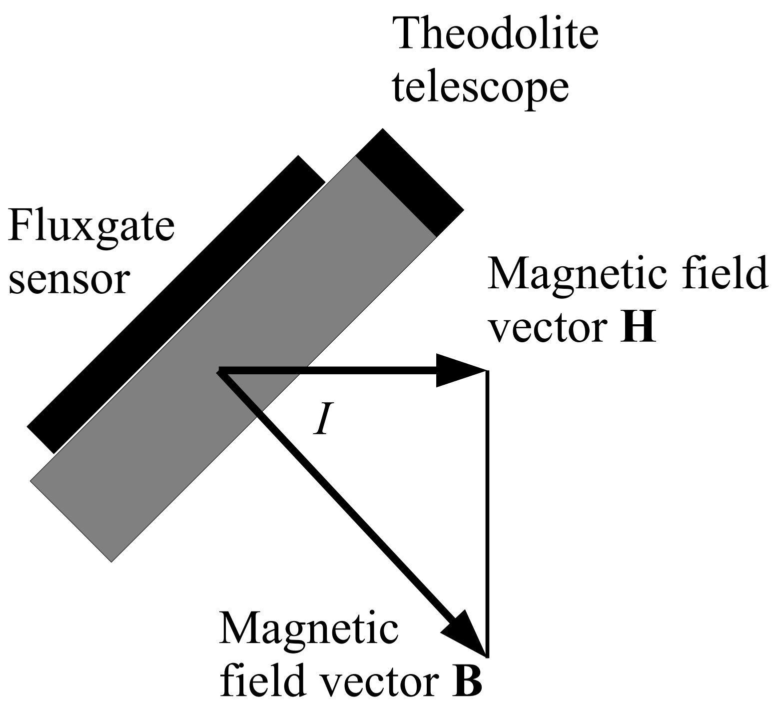
The axes and circles of a theodolite.

- *D* measurement:
  - The theodolite is turned horizontally until the fluxgate sensor indicates zero field. The axis of the telescope is now perpendicular to the magnetic north-south direction.
  - The direction of the magnetic north is compared with a known geographic reference direction, which gives the angle (D) from true north.



- The direction of the true north can be obtained using satellite positioning (e.g., GPS):
  - two receivers are placed approximately 150 m apart.
  - The azimuth of the great circle connecting the receives can be calculated from the coordinates of the receivers using spherical trigonometry.
- The accuracy obtained using commercial receivers is 5" – 10".

- *I* measurement:
  - The axis of the theodolite telescope is aligned with the direction of the magnetic north.
  - The telescope is tilted until the fluxgate sensor again indicates zero field. The axis of the telescope is now perpendicular to the magnetic field vector ***B***.
  - The tilt angle of the telescope gives the magnetic inclination *I*.



Absolute magnetic measurement

- The last step to complete the absolute measurement is to measure the strength of the magnetic field B at the same location where the declination D and inclination I were determined using the DI-flux magnetometer.
- This is done by replacing the theodolite with a proton magnetometer sensor, which then gives B.
- The vector components of the magnetic field are obtained as

$$
\begin{aligned}
X &= B \cos I \cos D \\
Y &= B \cos I \sin D \\
Z &= B \sin I
\end{aligned}
$$

- The precision of the vector components is 1–2 nT.

Geomagnetic observatories

- The objective of geomagnetic observatories is to record continuously, and over the long term, the time variations of the magnetic field vector and to maintain the accurate absolute standard of the measurements.
- The observations should cover the relevant periods: 1 s – 100 000 y and more.
- Currently, observatory records exist for the past ~150 years (some observations exist for the past 400 years).
- Satellite observations cannot yet replace the traditional ground-based observatories, because the life-times of satellite missions are relatively short, at most ~10 years.
- There are global, regional and local needs for geomagnetic observatories.

Global need for observatories

- An important global task is to monitor the secular variation of the magnetic field all over the world.
- Knowledge of the secular variation is essential in updating magnetic charts and theoretical modeling of the geomagnetic dynamo theory responsible for the generation of the field.
- Monitoring the secular variation is the most difficult task of the magnetic observatories because the annual changes are small. In the majority of areas of the world the number of magnetic observatories is not adequate for sufficiently accurate determination of the secular variation.
- A sufficiently dense global network is also needed for the calibration and control of magnetic survey satellites used in detailed surveys of the magnetic field.
- A global network is essential in monitoring magnetic storms and other magnetic variations, because these phenomena affect large areas of the Earth and have different effects in different areas.
- A global network is needed for research of current systems in the ionosphere and magnetosphere and induced currents in the crust and mantle. A more dense network than the present one is needed in the high-latitude areas due to their special role in a number of studies connected with magnetospheric phenomena, and also in the equatorial region, where the behavior of the equatorial electrojet needs detailed study. The variations of the magnetic field near the equator are also important for studies of the ring current in the near-Earth space.

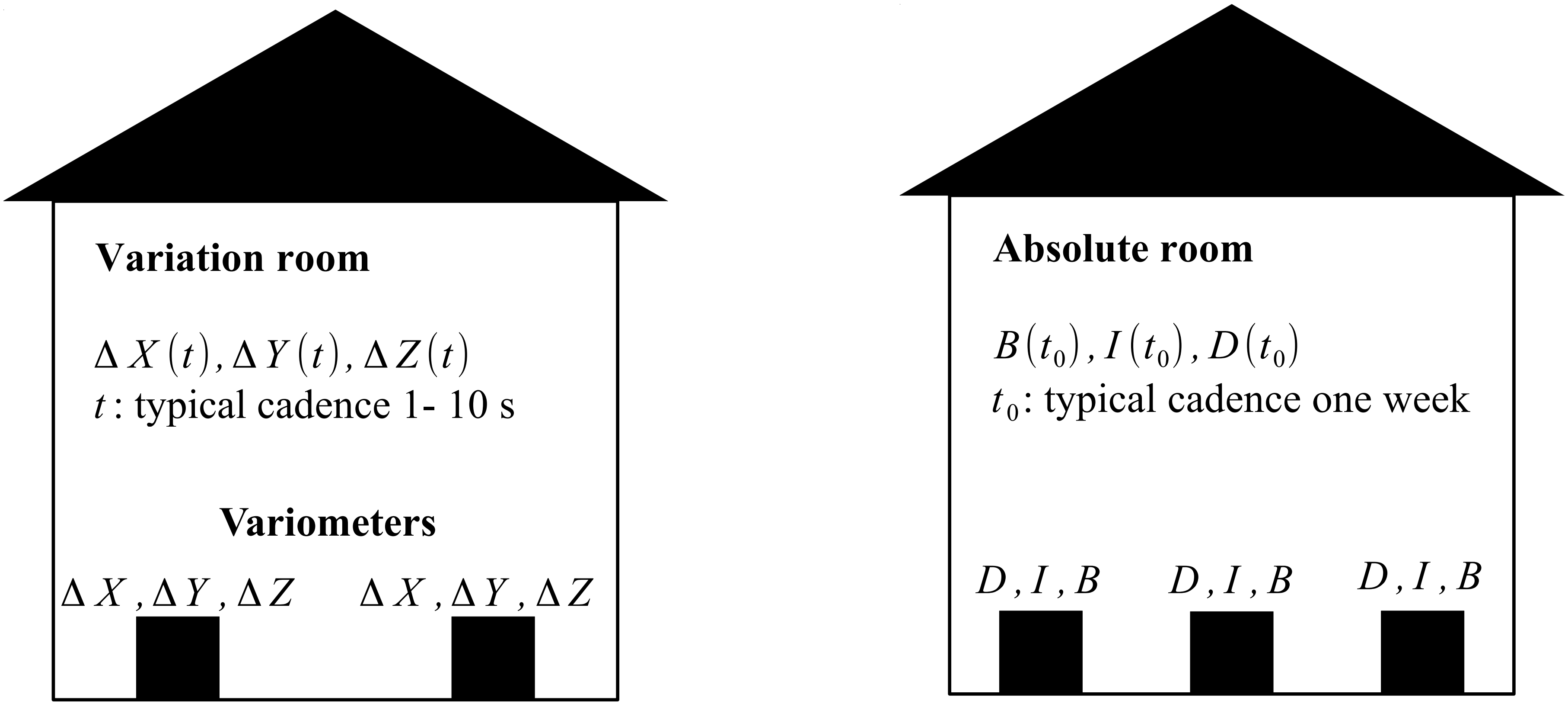
Regional need for observatories

- A global model of the Earth's magnetic field (e.g., IGRF) may differ by thousands of nT from the locally measured field.
- A typical regional need for a magnetic observatory is to serve as a base station for magnetic surveys. The data from the observatory or preferably from several observatories in the region are used in reducing the measured survey data to the desired epoch. The final product of a survey is usually a regional magnetic chart, which is later updated at regular intervals with the help of the secular variation recorded at the observatories, thus making a new detailed magnetic survey unnecessary. In many cases this means large savings of funds.
- Another regional use is working as a base station in magnetotelluric soundings.
  - Magnetotellurics is a method for inferring the Earth's subsurface electrical conductivity from measurements of the natural geomagnetic and geoelectric field variations at the Earth's surface. Investigation depth: 300 m – 10 km.

Local need for observatories

- From a local point of view, a magnetic observatory monitors the local magnetic variations, the knowledge of which is needed, for example, in connection with observed power failures or difficulties in telecommunications.
- An observatory provides facilities for calibration of magnetic instruments.
- Very often the observatory is the only place to obtain information on local geomagnetic declination and its change, and in the case of special phenomena like aurora, confirmation of the natural character of the phenomenon may be obtained from the observatory.
- Local anomalies originate in the crust and provide information about the properties of the rock complexes. Thus, local geomagnetic measurements are an important part of geophysical prospecting.

Geomagnetic observatory



→ $X(t_0) = B(t_0)\cos I(t_0)\cos D(t_0)$
$Y(t_0) = B(t_0)\cos I(t_0)\sin D(t_0)$
$Z(t_0) = B(t_0)\sin I(t_0)$

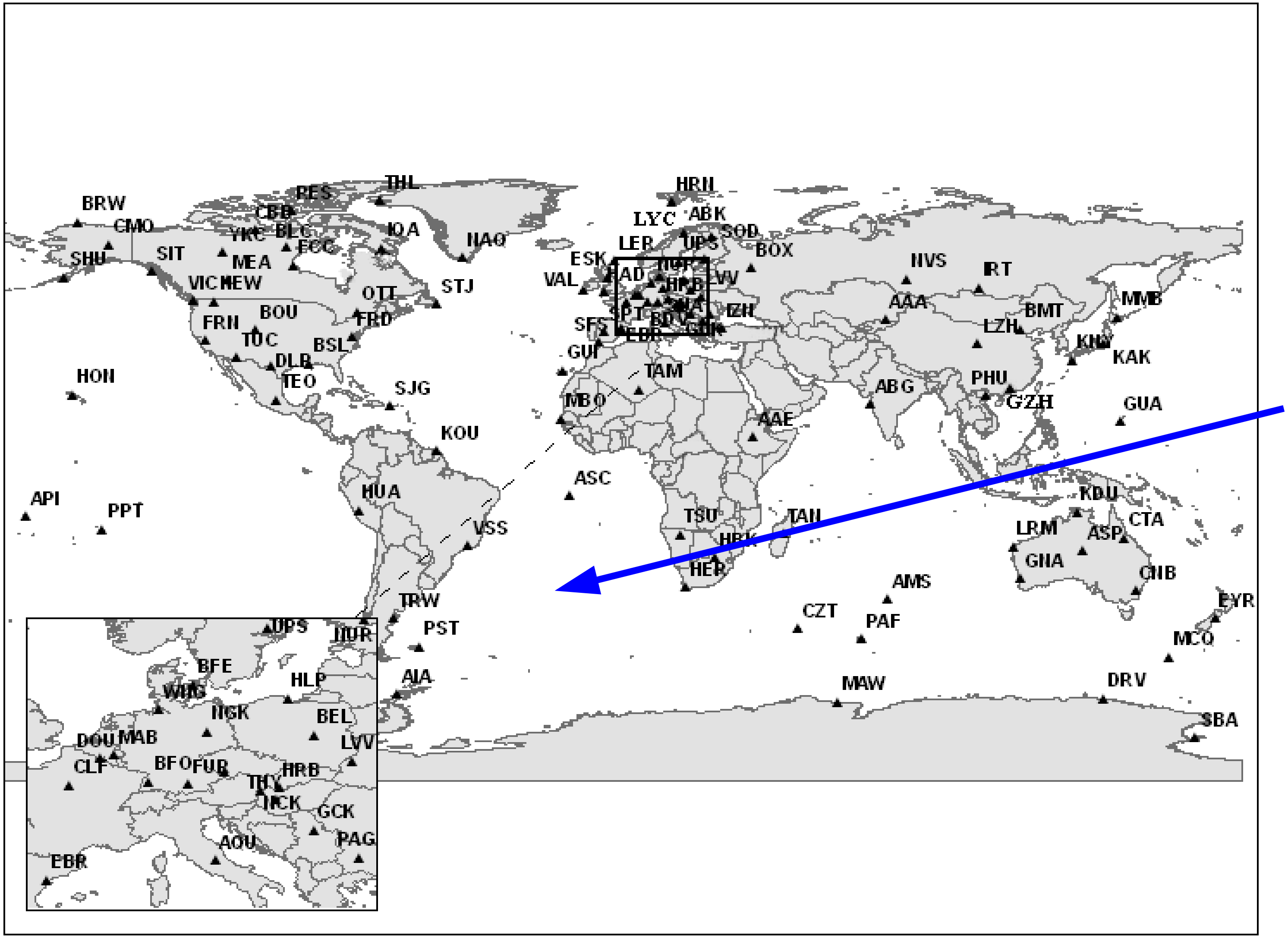
← $X(t_0), Y(t_0), Z(t_0)$

→ $X(t) = X(t_0) - \Delta X(t)$
$Y(t) = Y(t_0) - \Delta Y(t)$
$Z(t) = Z(t_0) - \Delta Z(t)$

INTERMAGNET

- International Real-time Magnetic Observatory Network

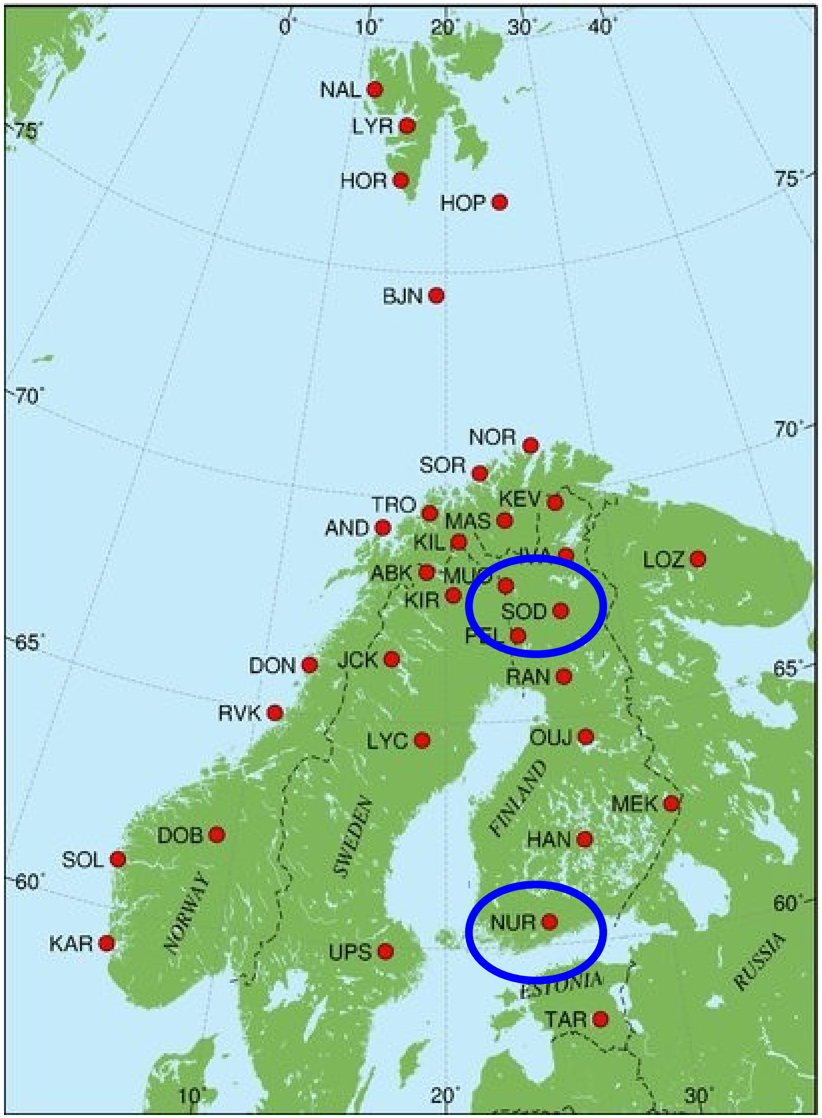
  http://www.intermagnet.org
- The INTERMAGNET program exists to establish a global network of cooperating digital magnetic observatories, adopting modern standard specifications for measuring and recording equipment, in order to facilitate data exchanges and the production of geomagnetic products in close to real time.
- A large number of geomagnetic observatories throughout the world are members of INTERMAGNET.
- Data availability: 1 min data since 1991, 1 s data from some stations since 2009.



There are large gaps in the network, especially over oceans.

Locations of the 144 INTERMAGNET magnetic observatories. Two of them are in Finland: NUR and SOD.

Geomagnetic observatories in Finland



The NUR and SOD geomagnetic observatories are part of the INTERMAGNET and IMAGE networks.

Nurmijärvi geophysical observatory

- Has been operating continuously since 1953.
- The geographic latitude and longitude and altitude of the observatory are:

  60.50^{0}N, 24.65^{0}E

  105 m.
- The observatory is running two three-component magnetometers, which are controlled usually once per week with absolute measurements.
- Another magnetic recording system at the observatory is a three-component pulsation magnetometer of the Sodankylä Geophysical Observatory.

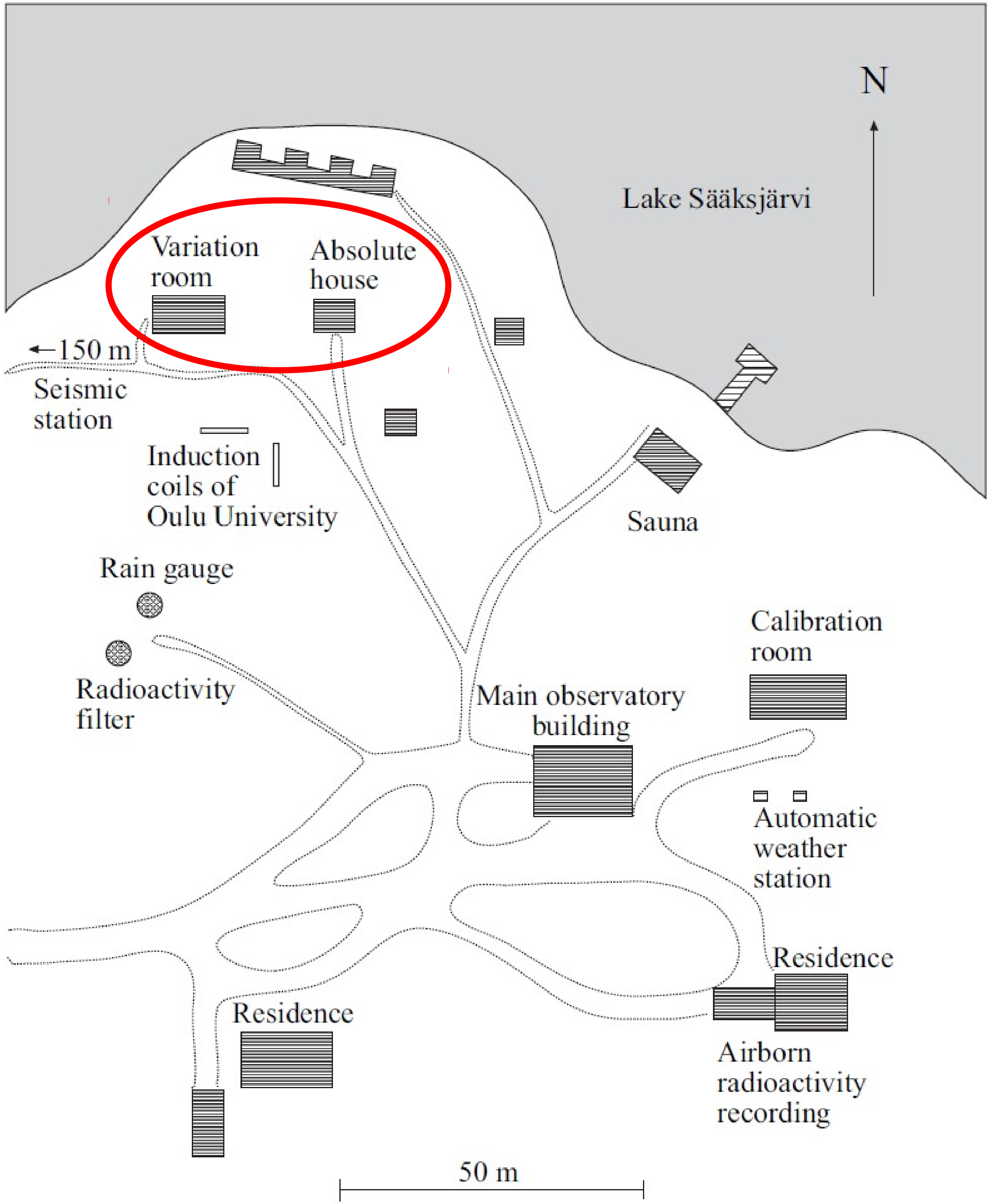
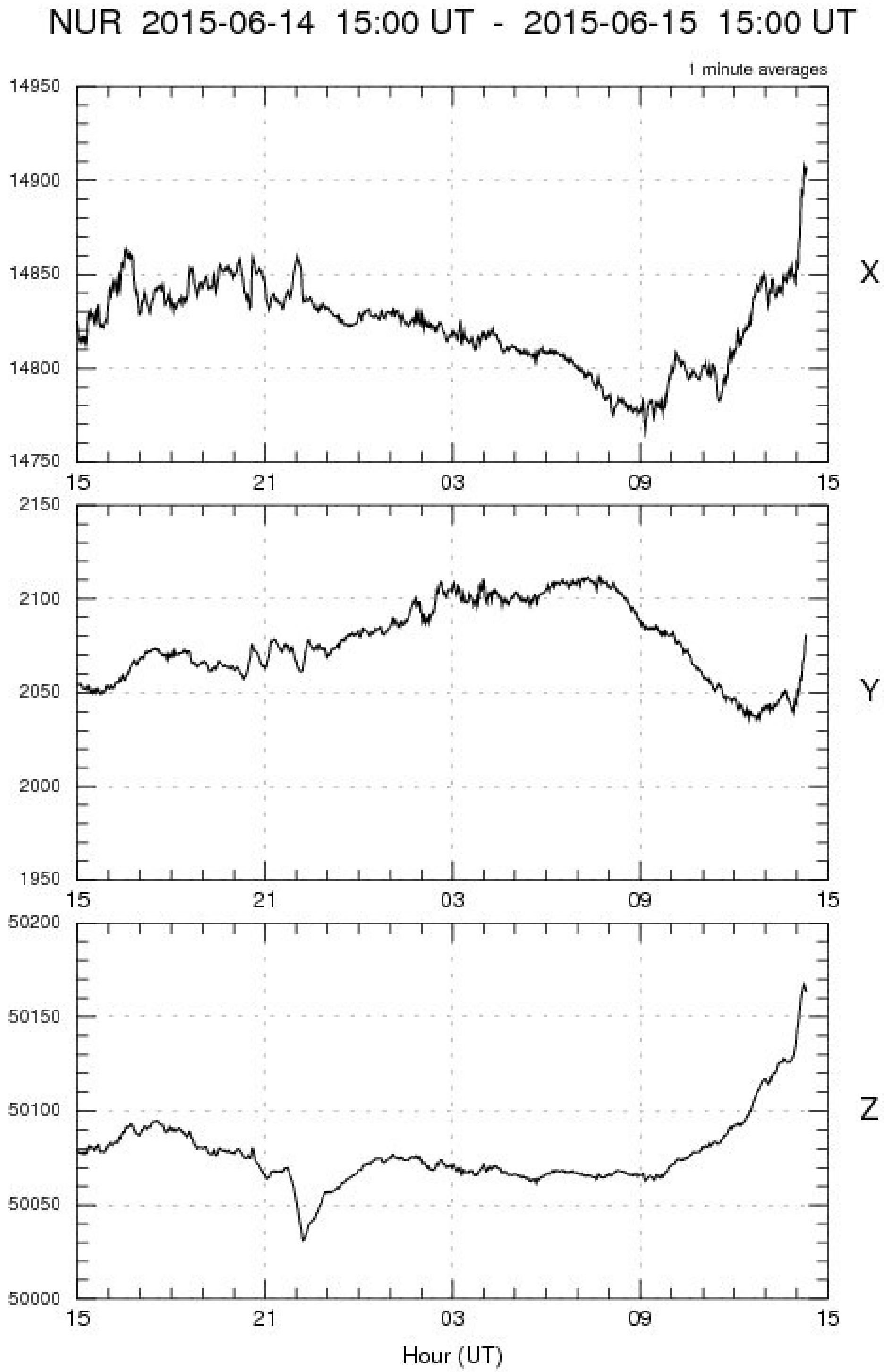


Figure 1: Map of the observatory area.

Variation measurements

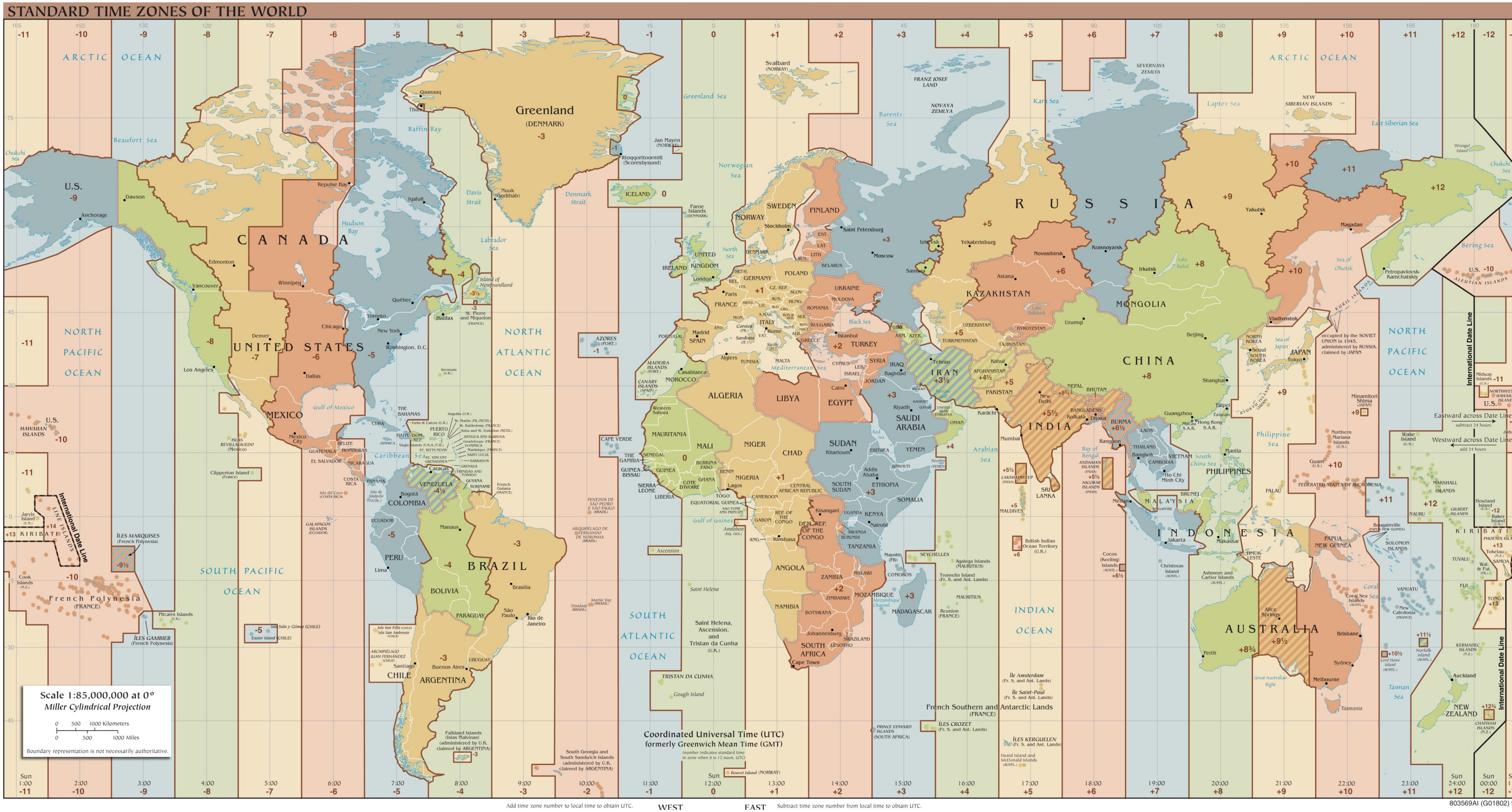
- The Nurmijärvi observatory is running two three-component magnetometers:
    1. A Danish suspended flux gate magnetometer (FGE-89) is the primary instrument.
    2. A Ukrainian LEMI-025 magnetometer operates as the second variometer.
    3. Since June 2013 a Canadian GSM-90 is also recording in the variation room.
- The sensors are directed in geographic north and east directions measuring the ΔX, ΔY and ΔZ components. The sampling rate is 1 s.
- The temperature in the variometer room is kept at 18ºC.
- Analog voltages from the FGE magnetometer are AD-converted in the variation room and the digital data are transferred through optical wires to the computers in the main observatory building. The digital data of the LEMI-025 and of the GSM-90 are transfered through wireless internet to the main observatory building. Linux-based software stores the data in three files as one-second, ten-seconds and one-minute averages. Timing is based on GPS time shared through the local network. The standard one-minute values are averages over one minute periods starting and ending at a half minute (e.g., 59:30 - 00:30, 00:30 - 01:30, 01:30 – 02:30). The given time is the starting minute at the center of the period (00, 01, 02 etc.).



The time is universal time (UT). The local time is UT + 2 h (during the daylight saving time UT + 3 h).

http://space.fmi.fi/image/realtime/UT/NUR/XYZlast24.html

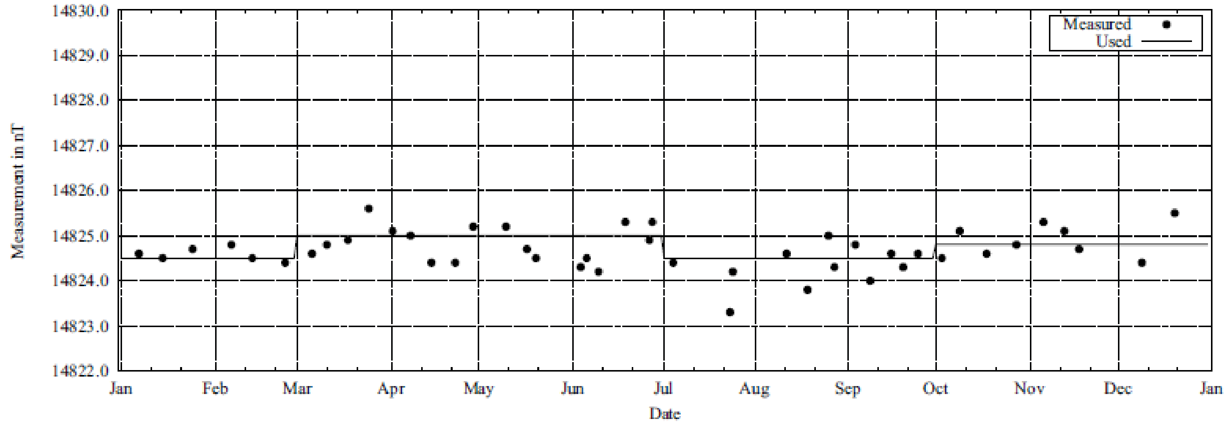
Universal time



Standard time zones of the world. The number at the bottom of each timezone specifies the number of hours to add to UT to convert it to the local time.

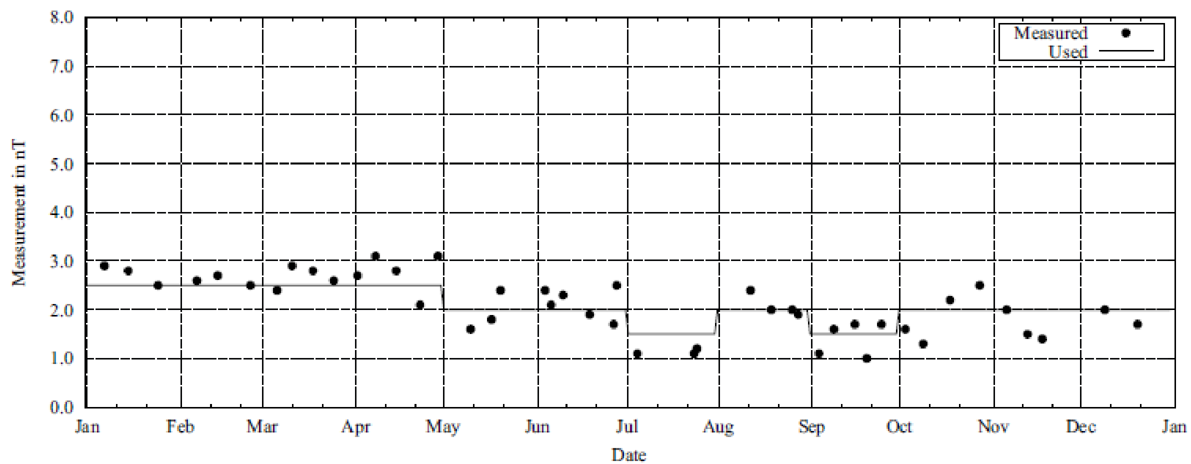
Absolute measurements

- The strength of the magnetic field (*B*) is measured with a Polish PMP-7 proton precession magnetometer.
- The declination and inclination of the magnetic field are measured with a DI-flux-magnetometer, which consists of a non-magnetic Zeiss-Jena theodolite (010B) and of a flux-gate element mounted on its telescope.
- The absolute measurements are made on average once a week.
- As an example, the baseline values determined for the suspended FGE for the year 2013 are shown in the figure:

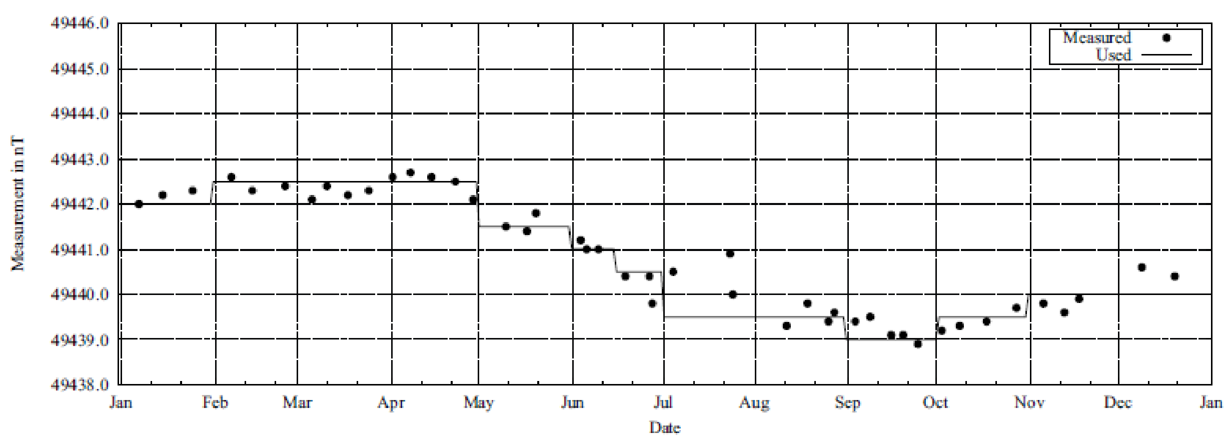


2013

(a) Baseline measurements for X component



(b) Baseline measurements for Y component



(c) Baseline measurements for Z component

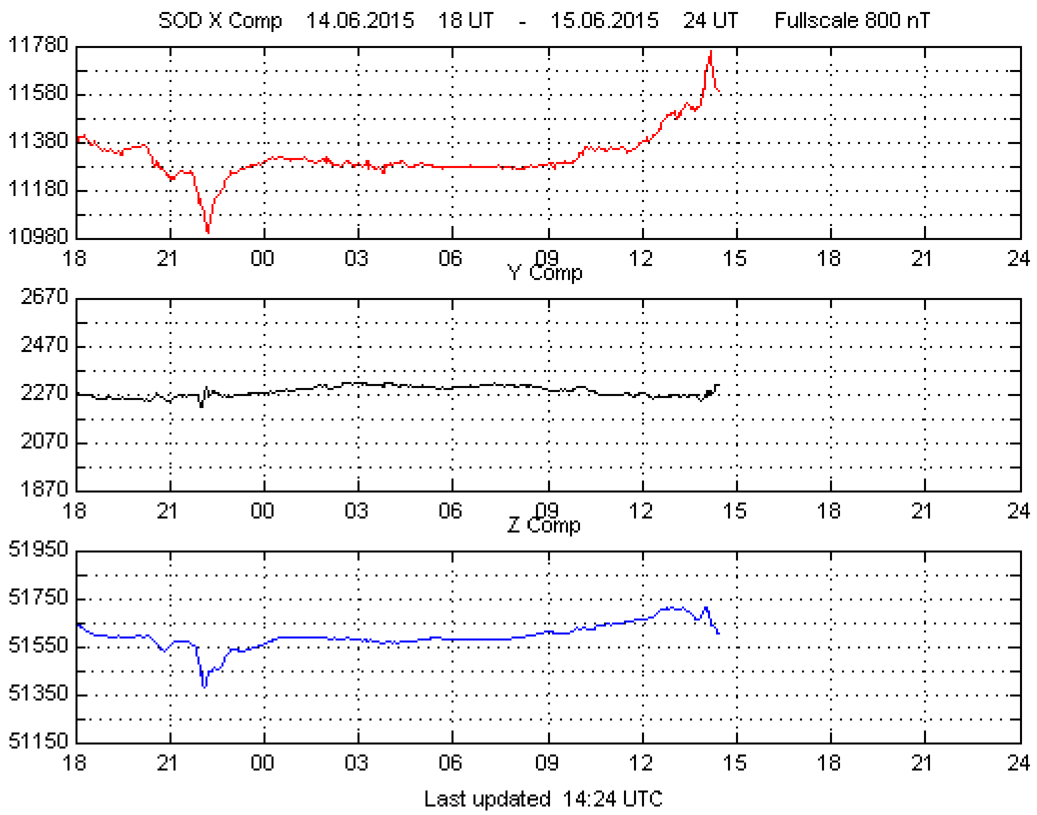
Sodankylä geophysical observatory

- Has been operating continuously since 1914 (the only gap in the time series is between 16th September 1944 and 1st January 1947 due to the destruction of the observatory during the war).
- The geographic latitude and longitude and altitude of the observatory are:

  67.37° N, 26.63° E

  180 m.

- Nowadays the observatory has three "normal" magnetometers: a Danish fluxgate magnetometer (FG) and two photoelectric torsion magnetometers, a Polish model (PSM) and a Russian model (RM).The FG has been in operation since 1996, the PSM since 1983 and the RM since 1996.
- Additionally, there are two magnetometers to measure the total magnetic field, an old proton magnetometer Elsec (nowadays used only during field campaigns) and a Canadian Overhauser magnetometer.
- For absolute measurements (once a week) there are two DI-flux magnetometers (Zeiss).
- Since the beginning of 2003, the main instrument has been the Danish magnetometer (FG) and the backup-instrument has been the Polish magnetometer (PSM). The sampling rate of the FG, PSM and RM is 2 Hz. The Overhauser magnetometer has a sampling rate of 0.2 Hz.

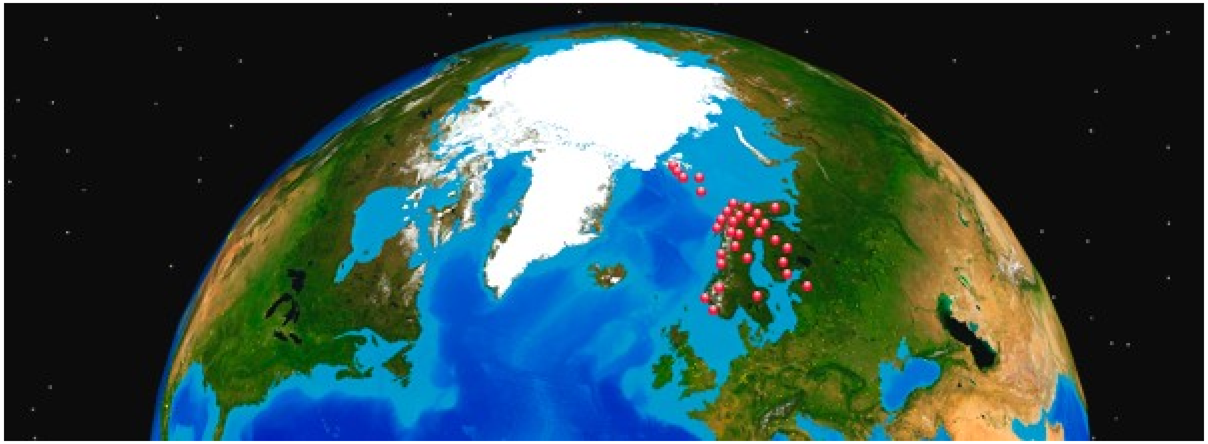


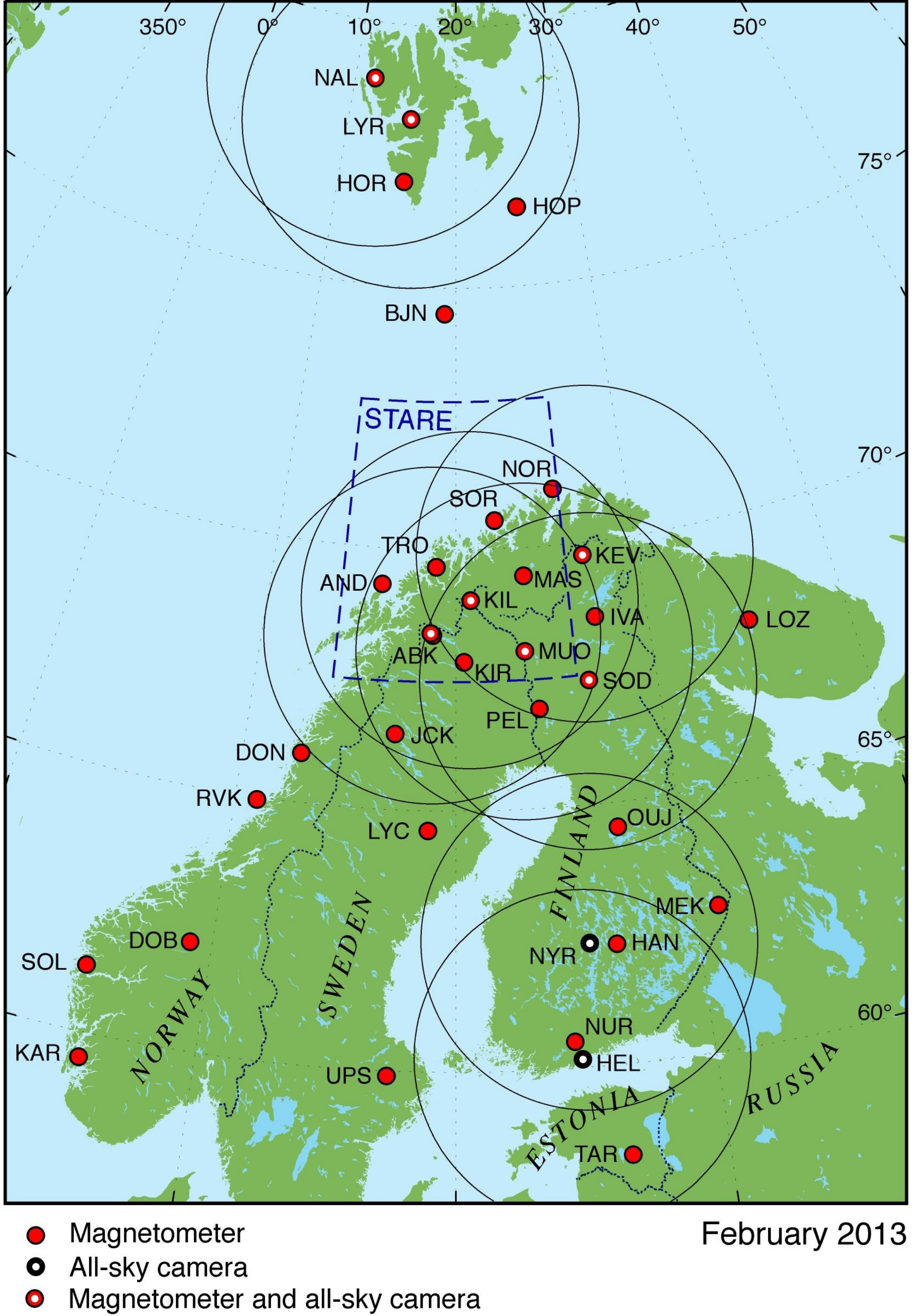
http://www.sgo.fi/Data/RealTime/magnetogram.php

Automatic stations

International Monitor for Auroral Geomagnetic Effects (IMAGE)

- The main difference between an observatory and an automatic station is that an observatory is usually manned, which guarantees a better quality of data and uninterrupted time series.
- IMAGE consists of 33 mostly automatic magnetometer stations maintained by 10 institutes from Estonia, Finland, Germany, Norway, Poland, Russia and Sweden.
- The prime objectives of IMAGE are to study auroral electrojets and moving two-dimensional ionospheric current systems.
- Together with other ground-based recordings (by radars, riometers, all-sky cameras) and satellite observations, IMAGE is an essential part in the investigations of high-latitude magnetospheric-ionospheric physics.




350°
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NYR
HAN
DOB
SOL
SWEDEN
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RUSSIA
TAR
February 2013
Magnetometer
All-sky camera
Magnetometer and all-sky camera

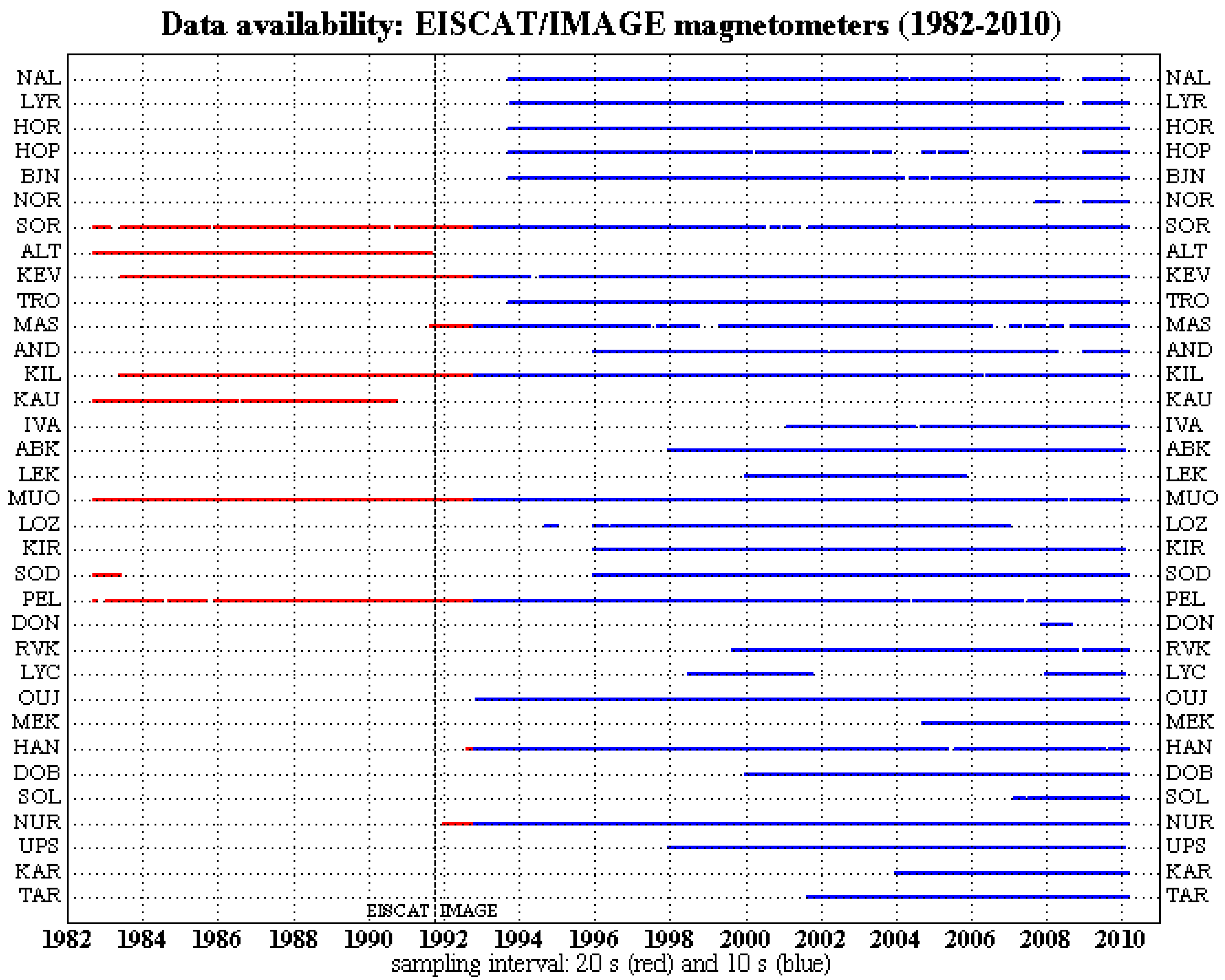
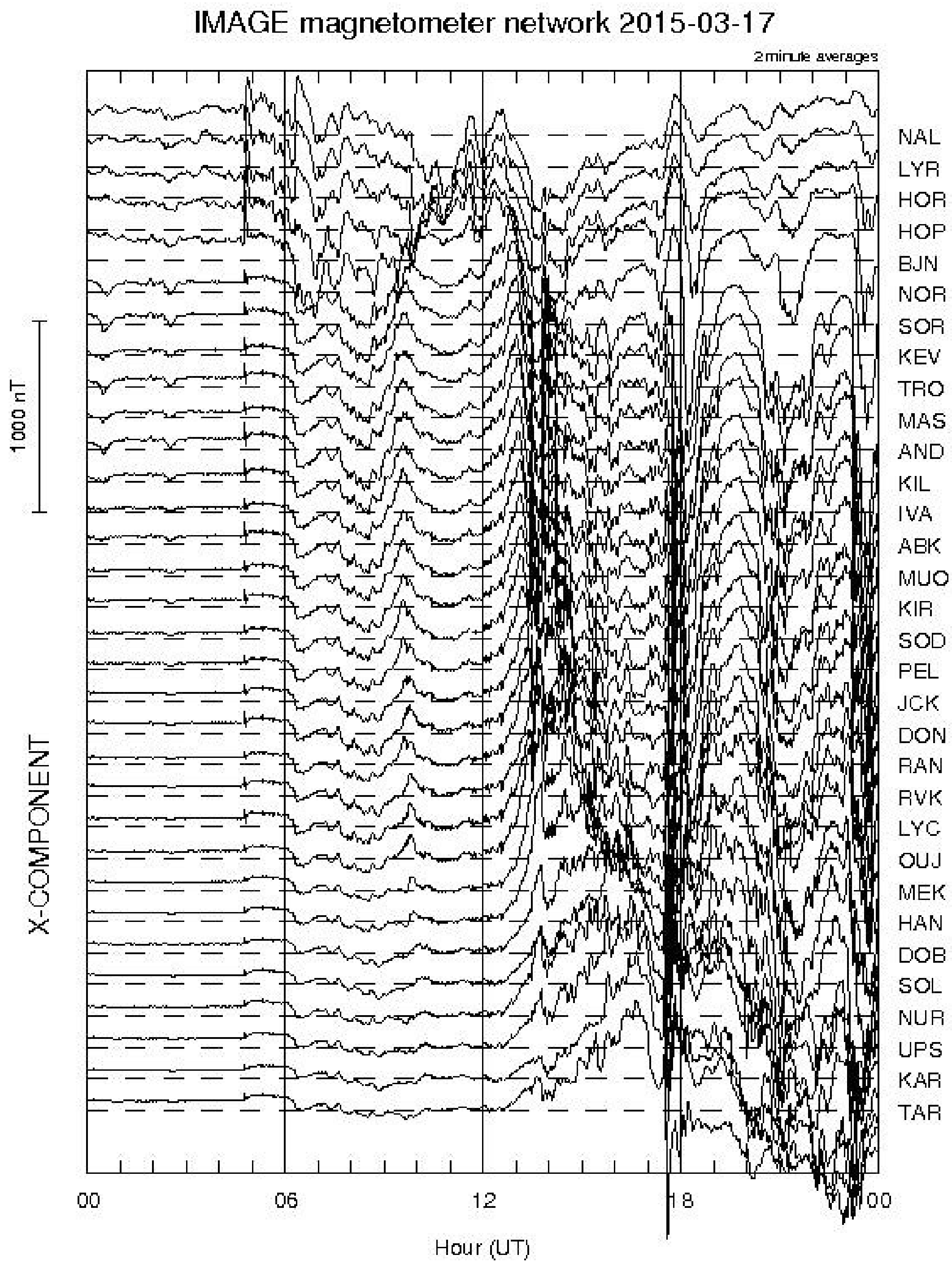
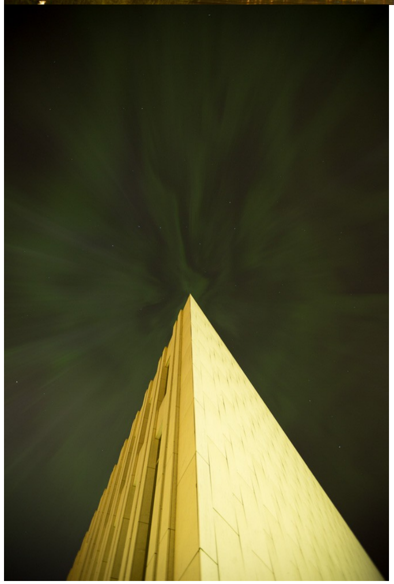


IMAGE real-time data:
http://www.space.fmi.fi/image/beta/?page=real_time
Archived data:
http://www.space.fmi.fi/image/data.html

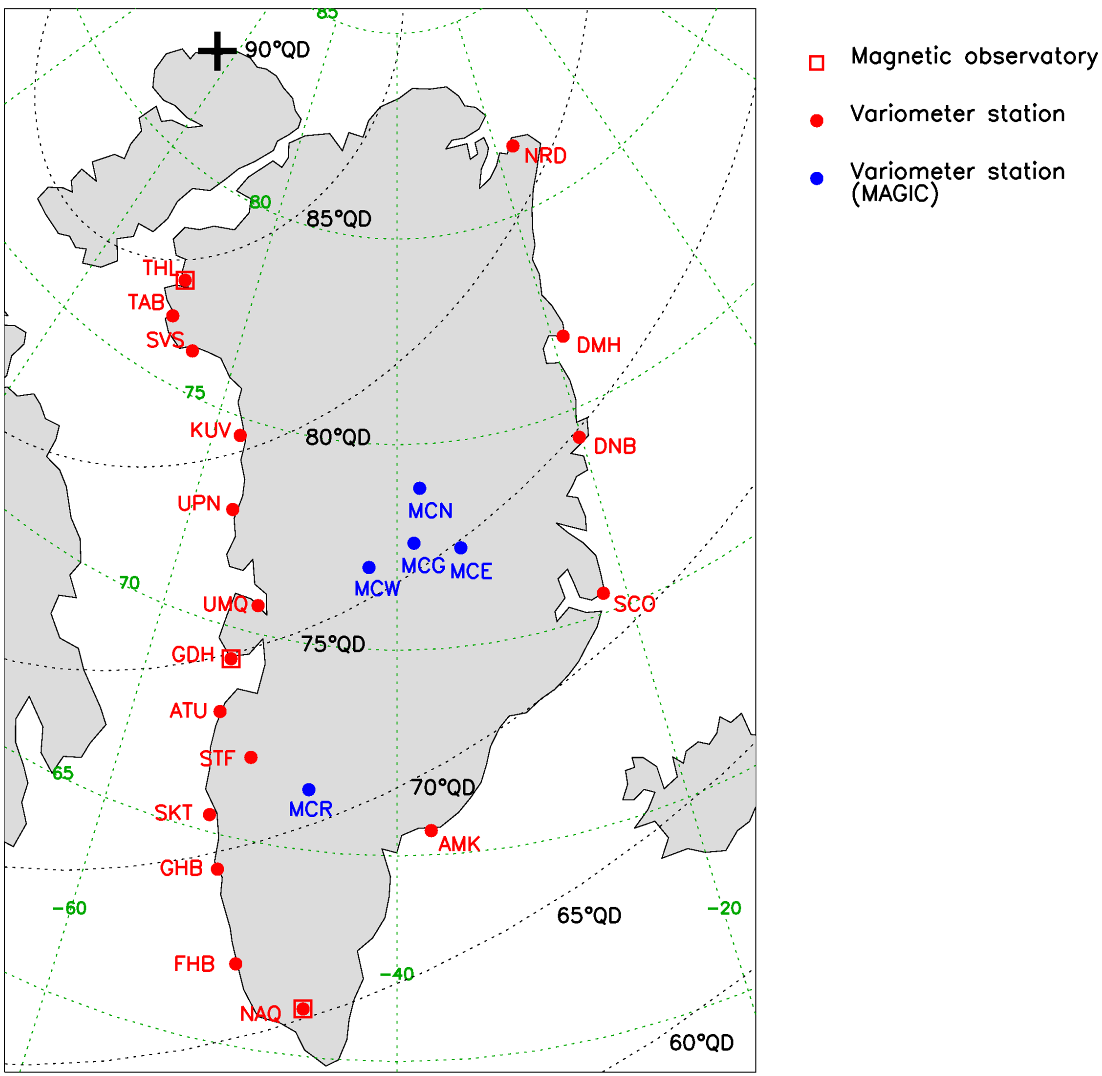




Helsinki, near Finlandia Hall, 18 March 2015, 00:48–01:21 LT.

Photos: Pekka Lähteenmäki, Ursa

Other magnetometer networks



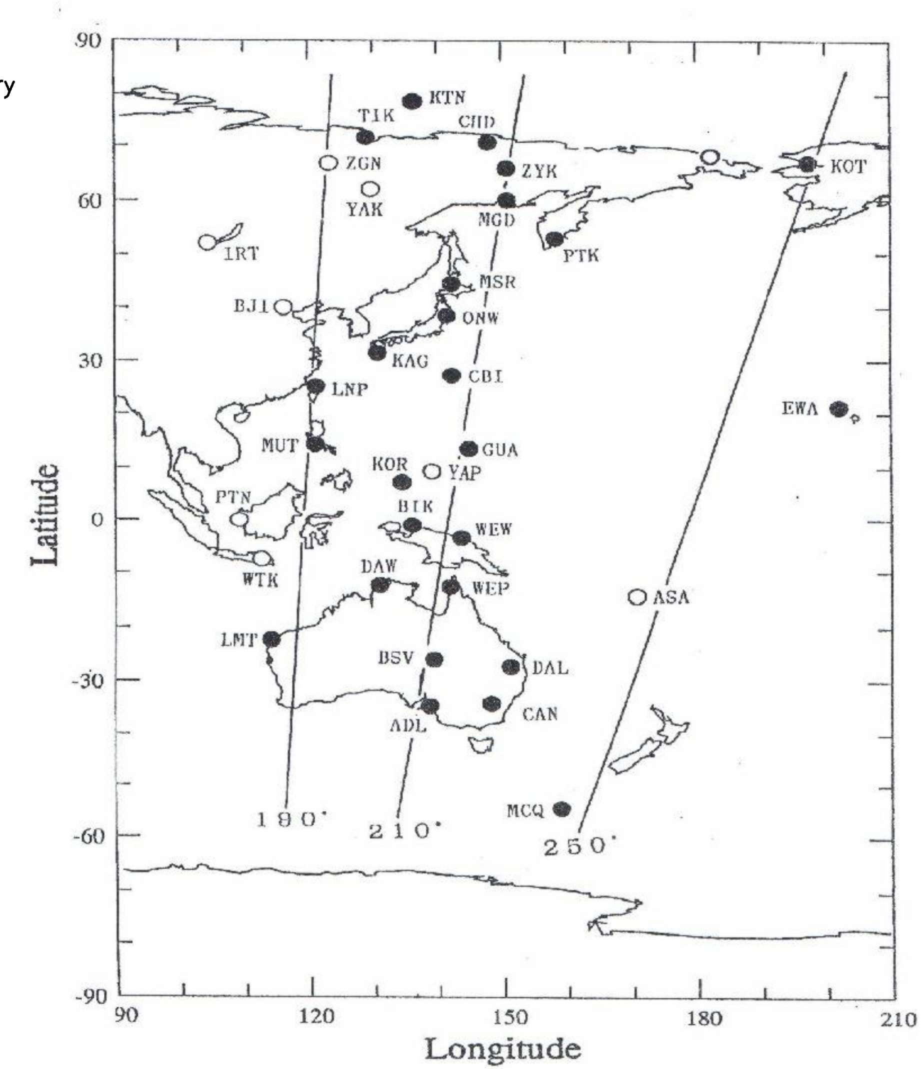
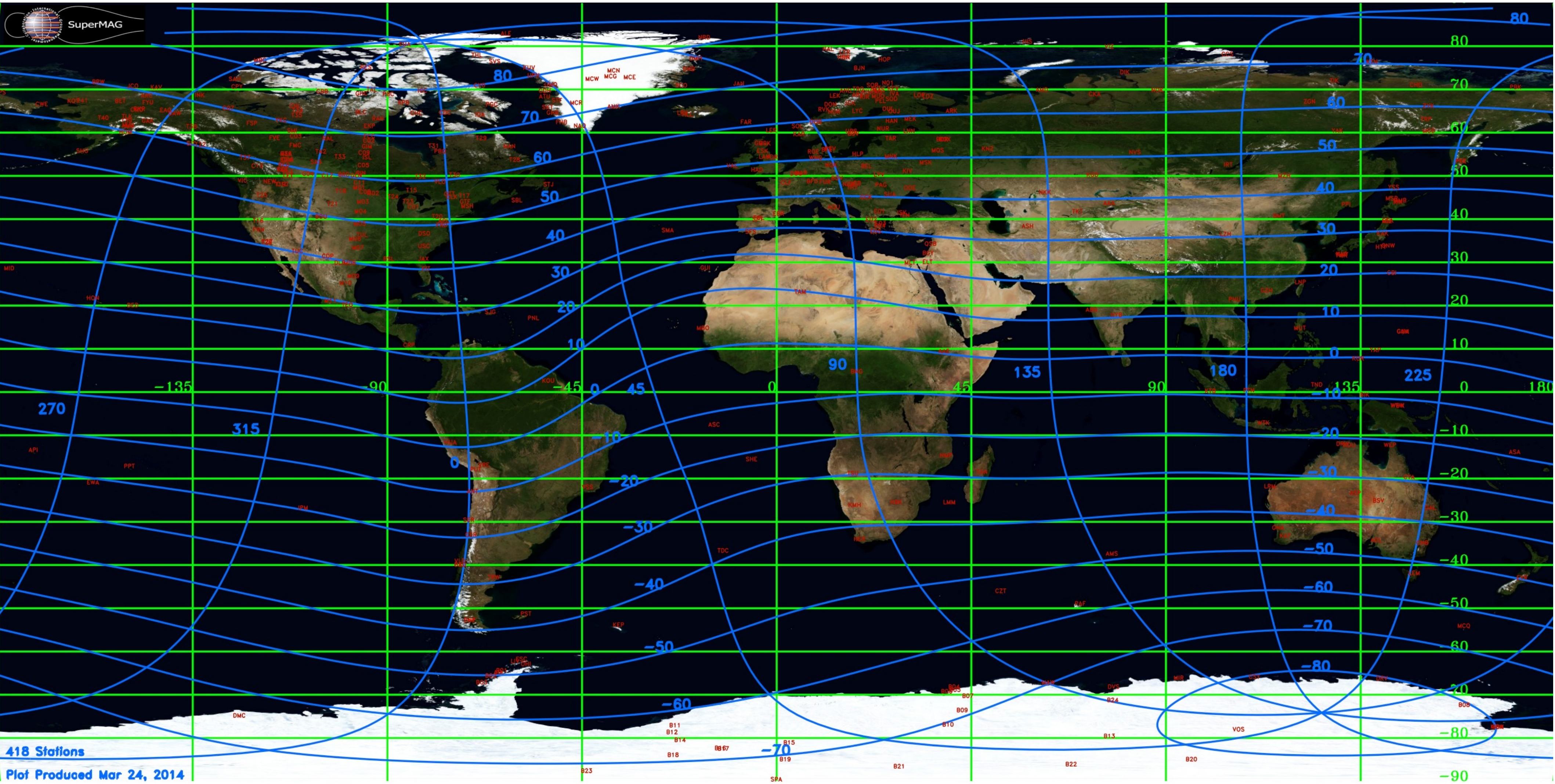
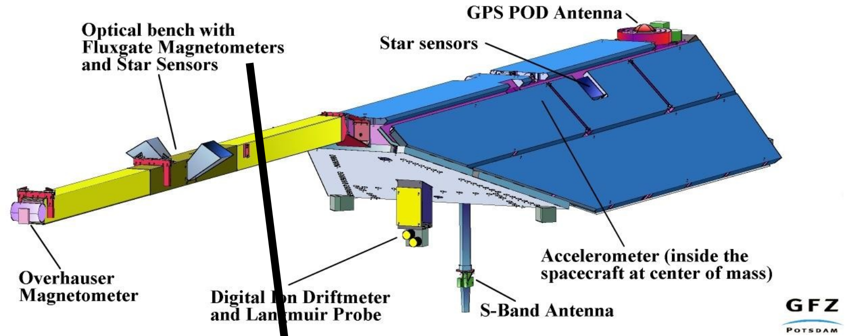


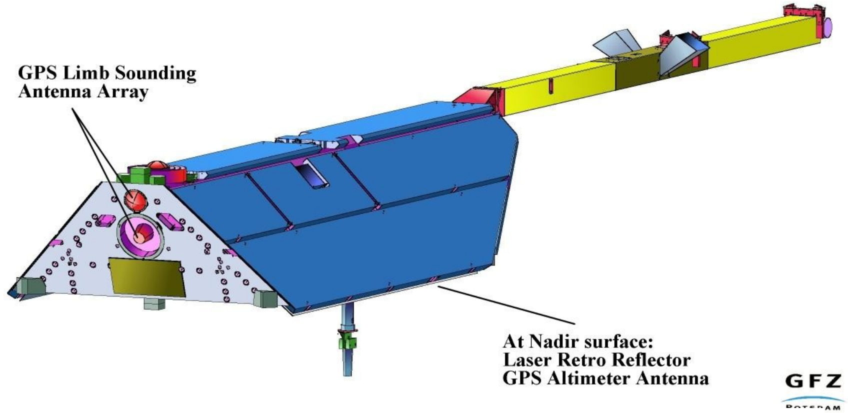
Fig. 1. Map showing the locations of the 190°, 210° and 250° MM chain stations in geographic coordinates (see Table 1).

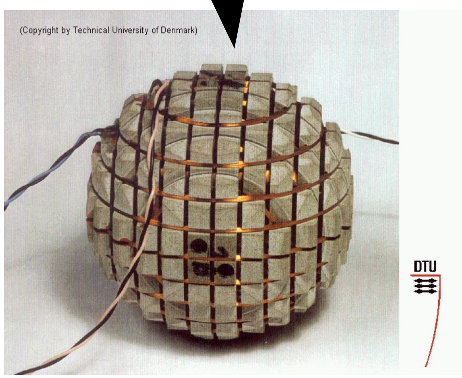

SuperMAG
418 Stations
Plot Produced Mar 24, 2014

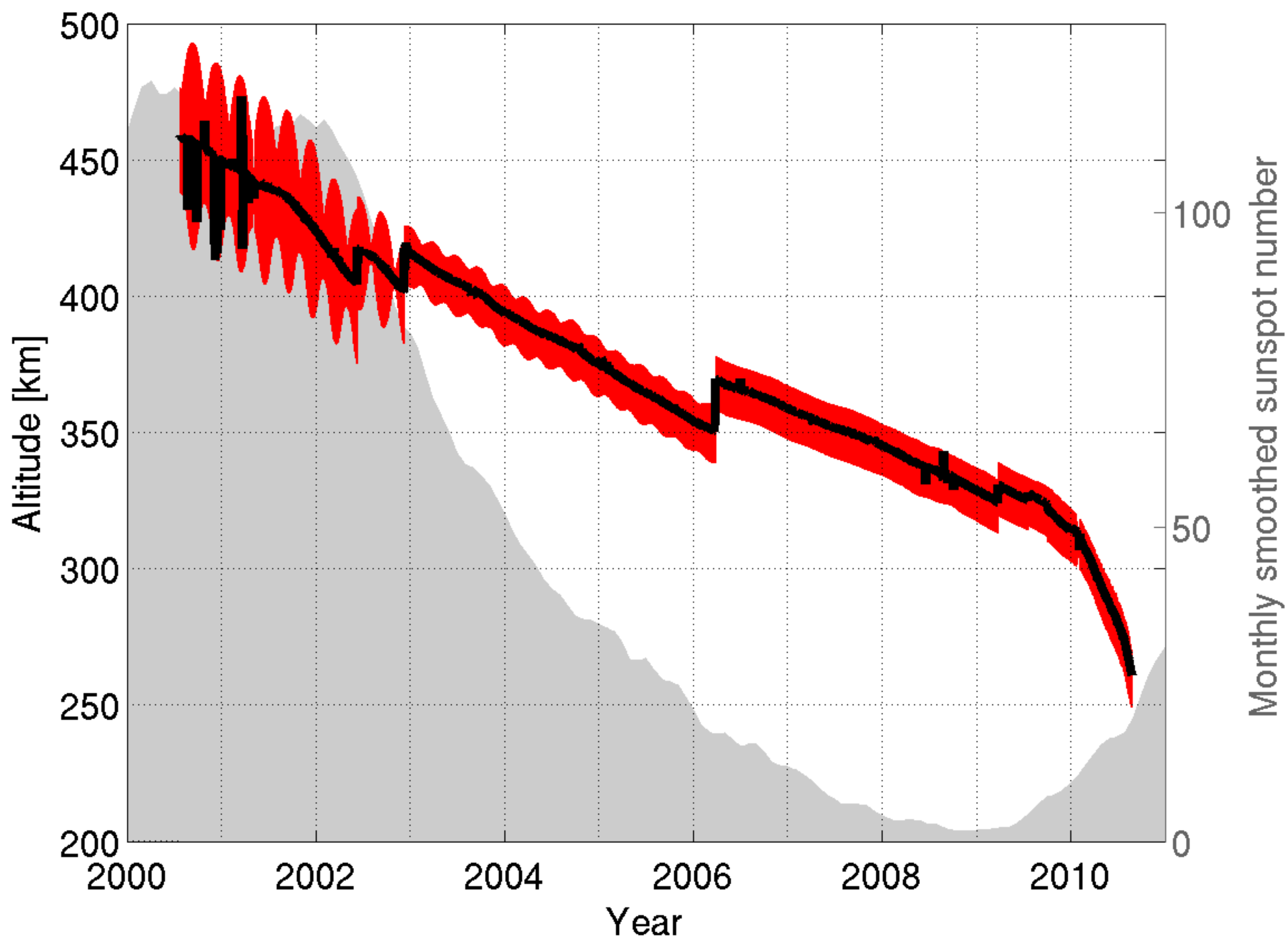
Satellite measurements

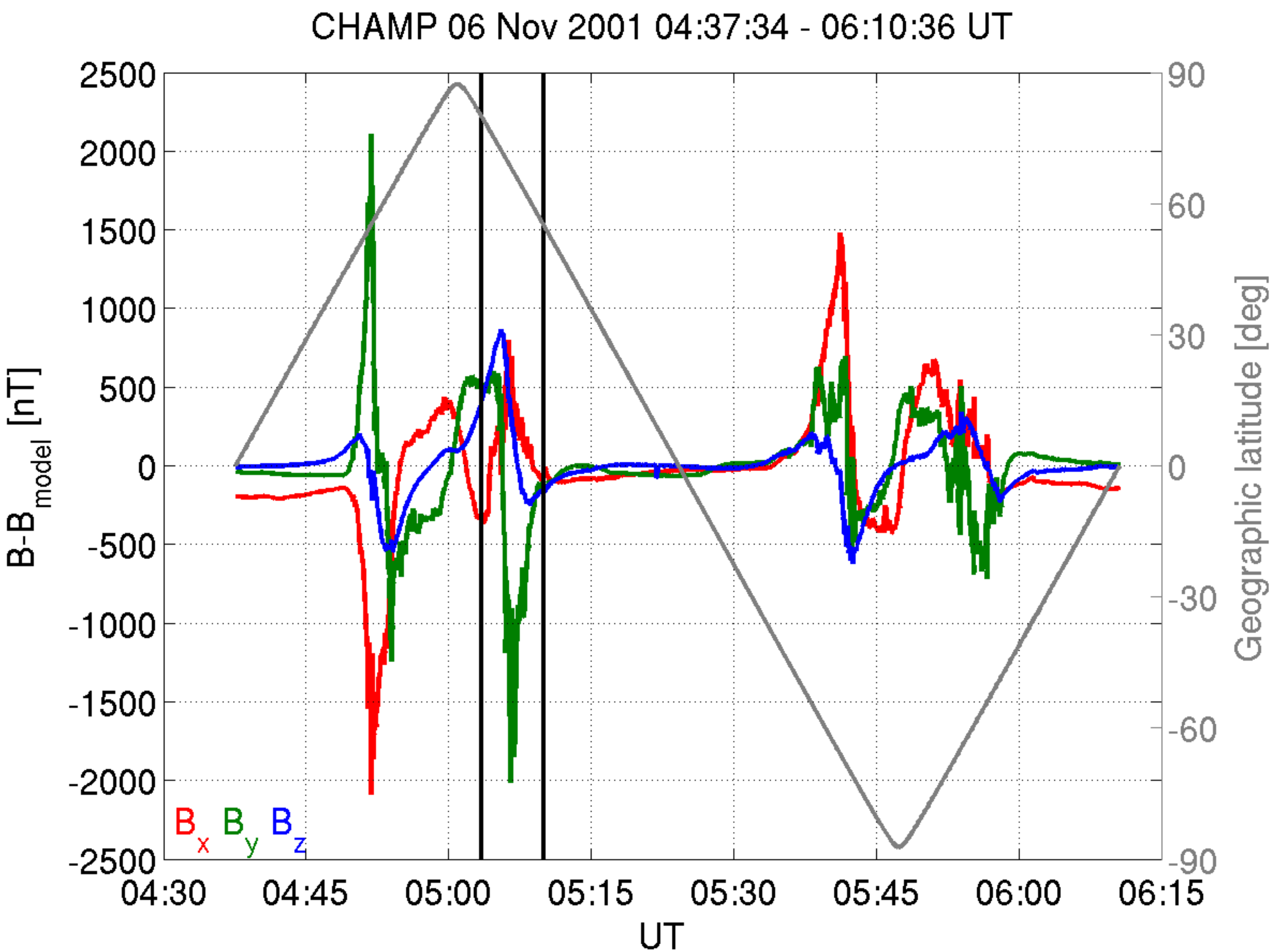

GPS POD Antenna
Optical bench with
Fluxgate Magnetometers
and Star Sensors
Star sensors
Overhauser
Magnetometer
Digital Ion Driftmeter
and Langmuir Probe
Accelerometer (inside the
spacecraft at center of mass)
S-Band Antenna
GFZ
POTSDAM

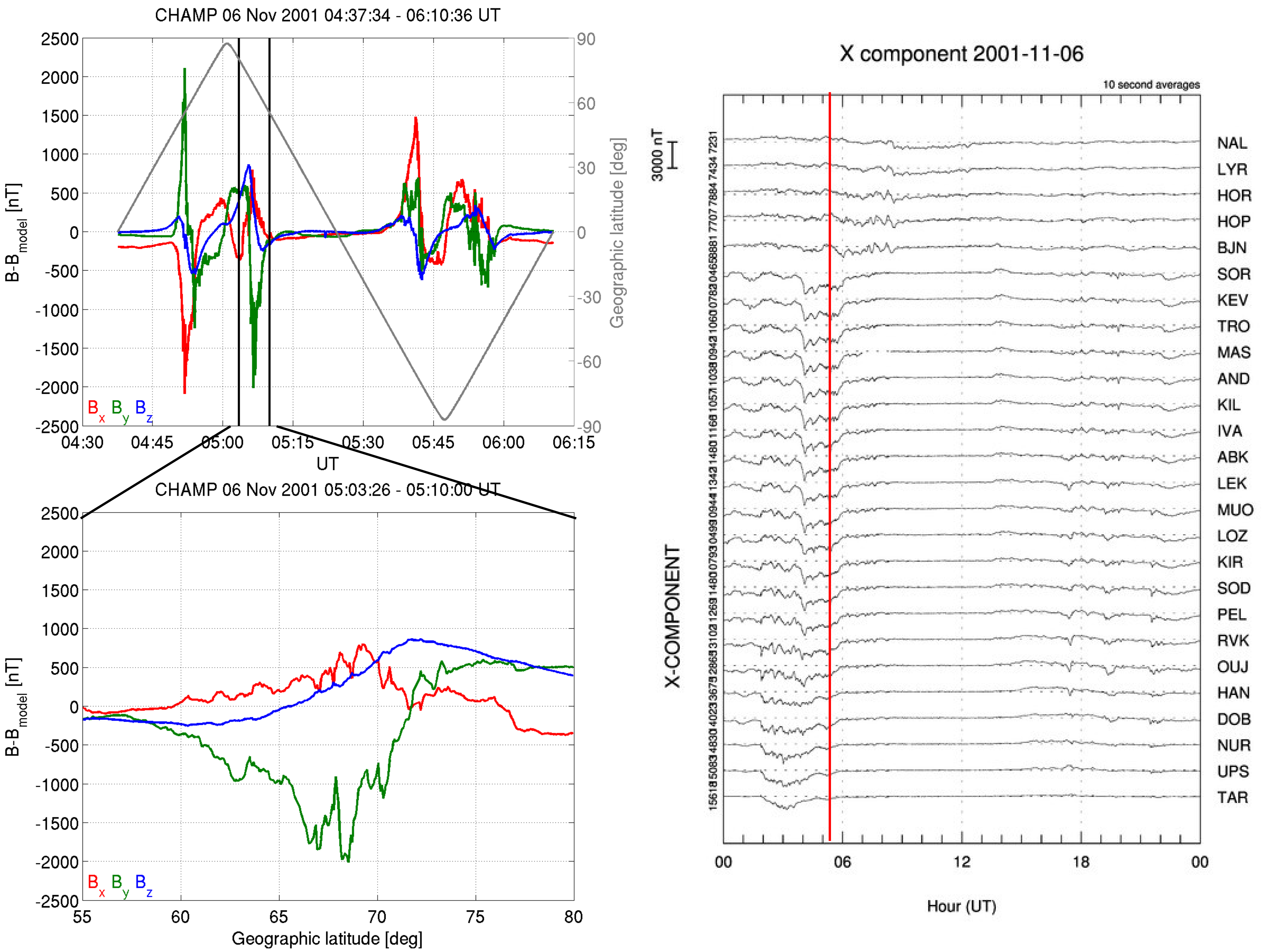
CHAMP


GPS Limb Sounding
Antenna Array
At Nadir surface:
Laser Retro Reflector
GPS Altimeter Antenna
GFZ

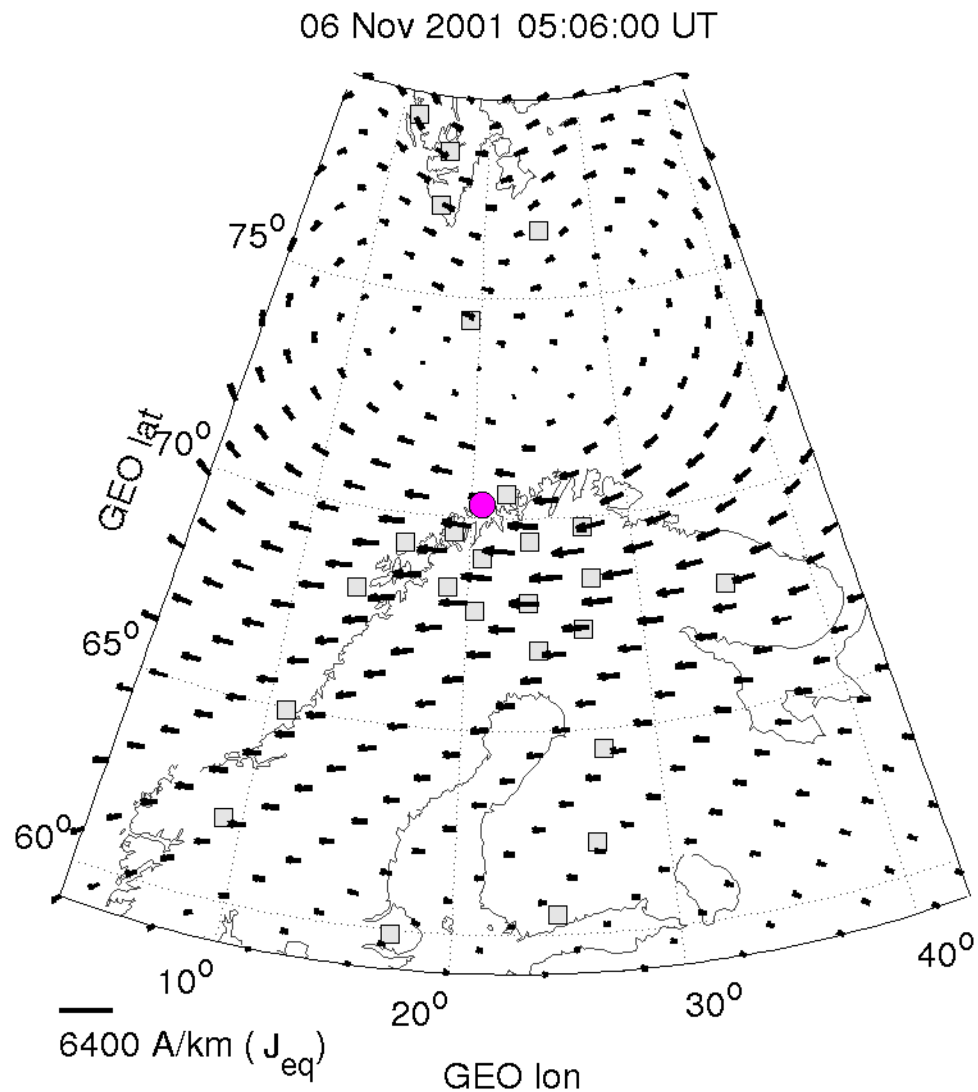

(Copyright by Technical University of Denmark)
DTU


Altitude [km]
500
450
400
350
300
250
200
Monthly smoothed sunspot number
100
50
0
2000
2002
2004
2006
2008
2010
Year


CHAMP 06 Nov 2001 04:37:34 - 06:10:36 UT
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
B-B model [nT]
90
60
30
0
-30
-60
-90
Geographic latitude [deg]
04:30
04:45
05:00
05:15
05:30
05:45
06:00
06:15
UT
Bx By Bz



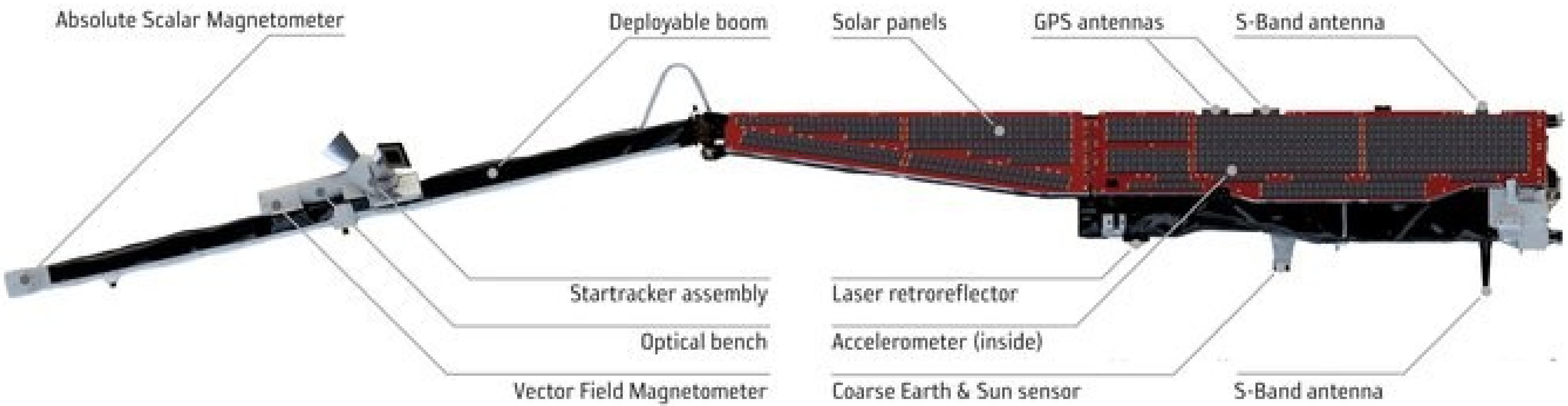
CHAMP 06 Nov 2001 04:37:34 - 06:10:36 UT
B-B$_{model}$ [nT]
Geographic latitude [deg]
UT
04:30
04:45
05:00
05:15
05:30
05:45
06:00
06:15
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
90
60
30
0
-30
-60
-90
B_x B_y B_z
CHAMP 06 Nov 2001 05:03:26 - 05:10:00 UT
B-B$_{model}$ [nT]
Geographic latitude [deg]
55
60
65
70
75
80
B_x B_y B_z
X component 2001-11-06
10 second averages
3000 nT
X-COMPONENT
NAL
LYR
HOR
HOP
BJN
SOR
KEV
TRO
MAS
AND
KIL
IVA
ABK
LEK
MUO
LOZ
KIR
SOD
PEL
RVK
OUJ
HAN
DOB
NUR
UPS
TAR
00
06
12
18
00
Hour (UT)

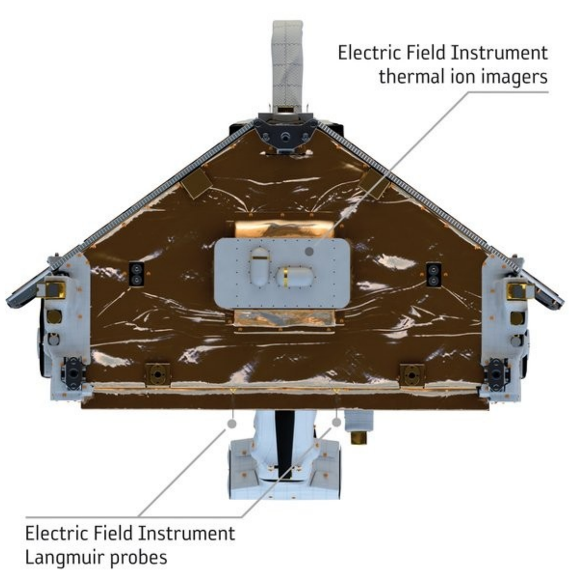

06 Nov 2001 05:06:00 UT
GEO lat
75°
70°
65°
60°
10°
20°
30°
40°
6400 A/km (J_{eq})
GEO lon

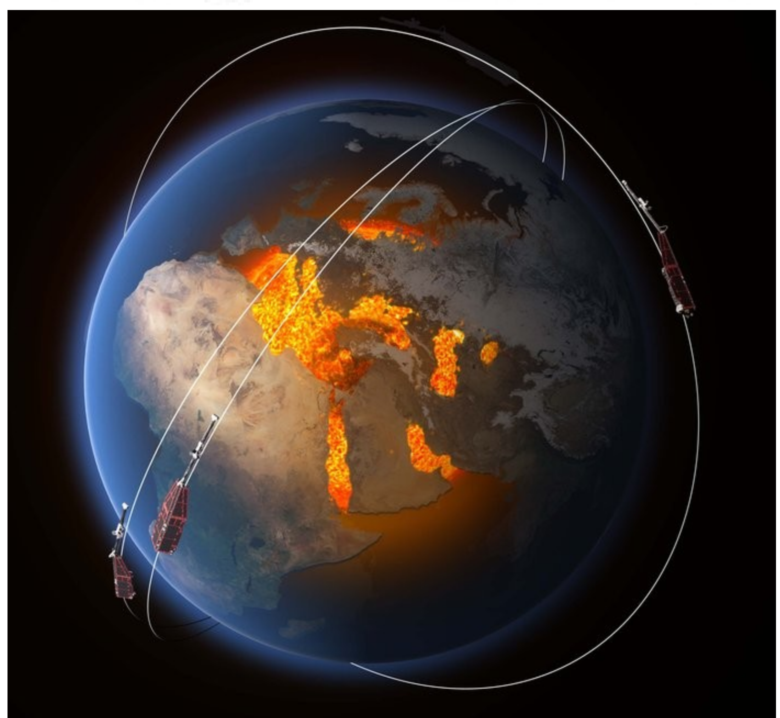
Launched: 22 November 2013

Duration: 4 years (following 3-month commissioning phase)

SWARM







- The Swarm mission is designed to measure the magnetic signals that stem from the Earth's core, mantle, crust, oceans, ionosphere and magnetosphere.
- This is expected to lead to better understanding of the processes that drive the Earth's dynamo, which currently appears to be weakening.
- The mission will offer a unique view inside the Earth to study:
  - Core dynamics, geodynamo processes and core–mantle interaction.
  - Magnetism of the lithosphere and its geological context.
  - 3D electrical conductivity of the mantle related to composition.
  - Magnetic signature related to ocean circulation.
- In addition, Swarm data will be used to study the Sun's influence on the Earth system by:
  - Analyzing electric currents in magnetosphere and ionosphere.
  - Understanding the impact of solar wind on dynamics of the upper atmosphere.