MSc Earth and Planetary Magnetism

(DTU Space, Course 30745)

Lecture 2: Geomagnetic Observations from Ground Observatories and Satellites

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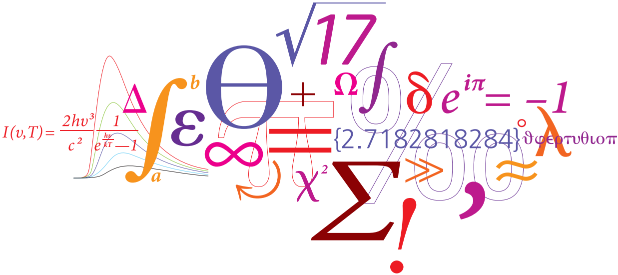
(with thanks Jürgen Matzka, GFZ)



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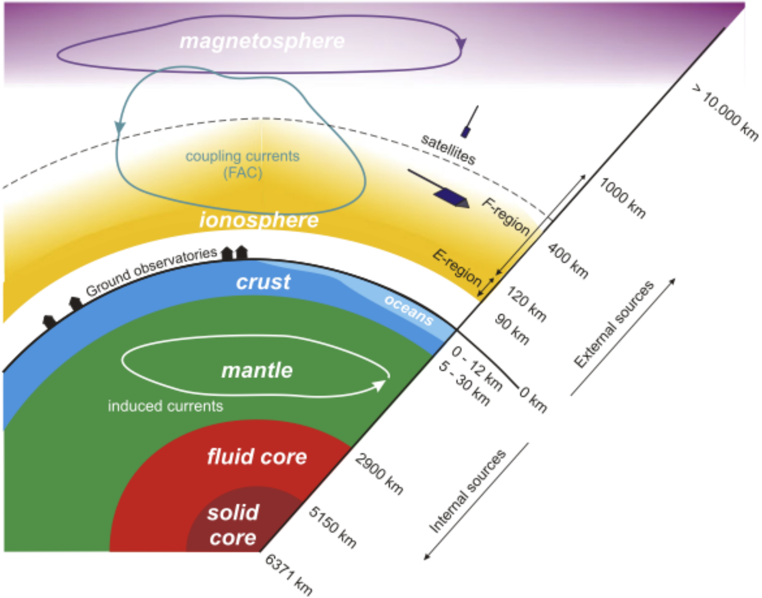
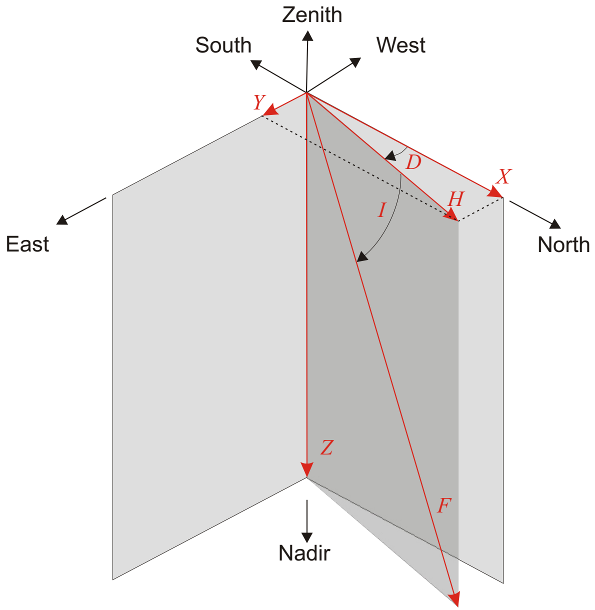
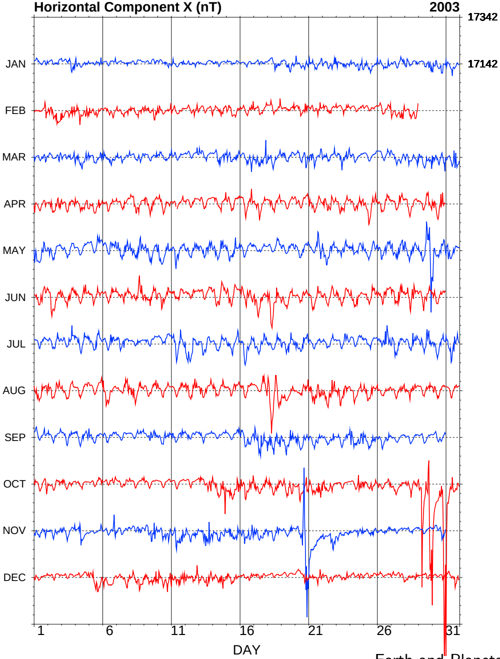
Sources of planetary magnetic fields: Natural electrical currents



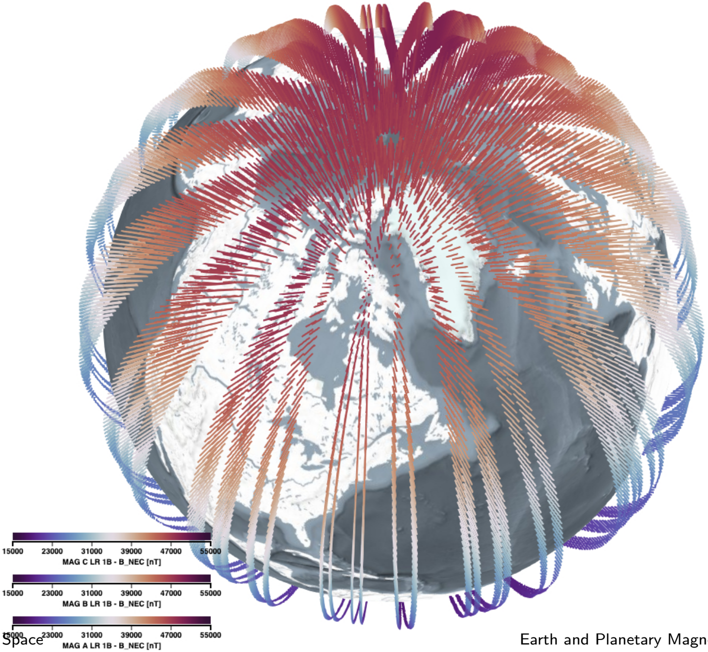
Geomagnetic Elements



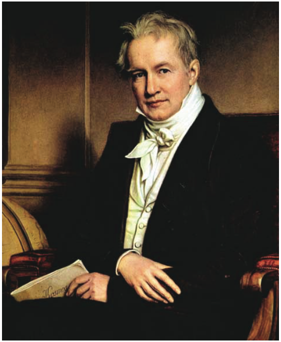
Brorfelde: hourly variations over a year

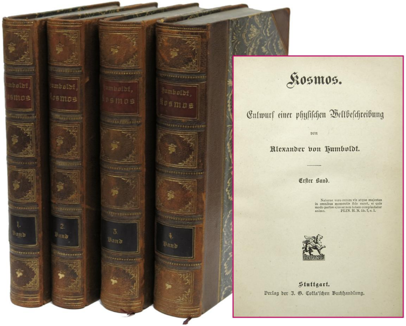


Example of Swarm data from 18th Oct 2018



Origin of magnetic variations has long fascinated scientists



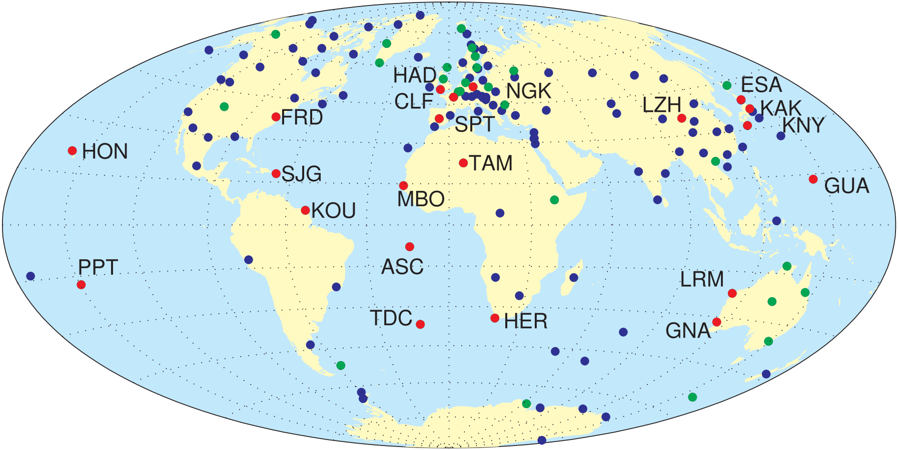


"The mysterious march of the magnetic needle is dependent both on space and time, on the course of the sun, and on its own place on the surface of the Earth" Alexander Von Humboldt, Kosmos, 1845

Overview of geomagnetic data sources

- **Ground observatories**
  - Worldwide network (including INTERMAGNET), vector + intensity
  - Advantage: Longer time series, reliable records
- **Airborne surveys**
  - Mostly intensity measurements for region studies
  - Typically from planes flying $\sim$ 300m altitude, and also now drones...
- **Marine surveys**
  - Magnetometers towed behind ships, mostly intensity
  - Only individual tracks
- **Ground surveys**
  - Primarily to characterize localized anomalies, mostly intensity
- **Low-Earth-Orbit Satellite observations**
  - POGO (NASA), 1965-1971, altitude 410-1510 km, intensity only
  - Magsat (NASA), Nov 1979-May 1980, 350-550 km, vector + intensity
  - Ørsted (Denmark), Feb 1999- ?, 650-850 km, vector + intensity
  - CHAMP (Germany), Jul 2000- Sept 2010, 250- 350 km, vector + intensity
  - Swarm (ESA), Nov 2013- ?, now: 1x510km, 2x450km, vector + intensity
  - Advantage: Global coverage

Ground magnetic observatories: global network

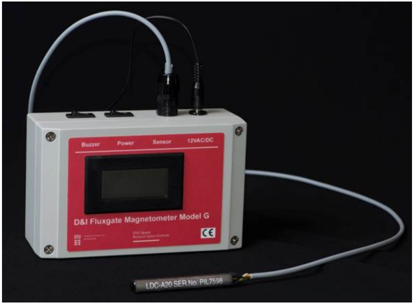


Example: BFE: Brorfelde Observatory, Denmark

Datastream 1 Hz full vector XYZ, ...


...manual calibration.


Types of observatory magnetometer



Scalar magnetometer:

- Proton precession, Overhauser or optically pumped
- Based on quantumphysics and time measurement
- Magnetic field strength
- Absolute accuracy

Directional magnetometer:

- Fluxgate sensor
- Measures magnetic field along sensor axis
- Needs scalevalue /offset
- Temperature dependence
- Drift

Proton precession magnetometer

- Also known as proton magnetometer or PPM
- Scalar instrument, measuring magnetic field strength
- Quantum mechanic effect and a frequency measurement
- Frequency or time measurements can be done very accurately, very cheap:

  - GPS time signal, DCF77, radio transmitted frequency normal, quartz
- Combining the quantum mechanic effect and a sufficiently accurate time

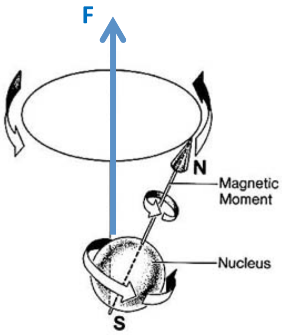
  measurement results in an absolute measurement.

Proton precession magnetometer

- The measurement is based on the free precession of protons, the angular precession depends linearly on the magnetic field:

  $\omega = 2\pi f = \gamma_p F$

  with the gyromagnetic ratio of the proton $\gamma_p = 2.6751525 * 10^8 \pm 40\ T^{-1}s^{-1}$ being a natural constant.



Proton precession magnetometer

- The gyromagnetic ratio γ relates the mechanical and magnetic moment of a sub-atomic particle.
- (The gyromagnetic ration of the electron γ_e is about 658 times higher than γ_p and magnetometers based on electron spin (optically pumped magnetometers) are therefore more accurate. Not discussed here.)
- A large number of protons in a magnetic field develop a magnetization because their magnetic moments will be preferentially aligned with the field (quantum mechanics).
- Typically 300 ml of water, alcohol or jet fuel contain a useful amount of protons

Proton precession magnetometer

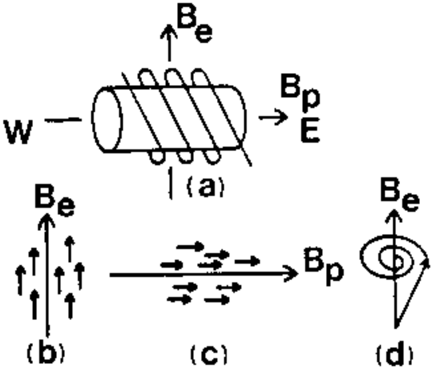
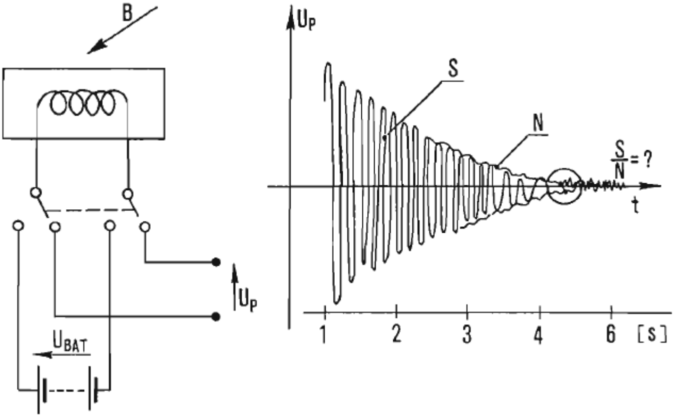


FIG. 9. Principle of the proton-precession magnetometer (after Kearey and Brooks, 1984). (a) Sensor with earth's magnetic field B_e, and magnetic field of instrument coil B_p. (b) Alignment of protons in earth's field, (c) Alignment of protons due to applied field, (d) Precession of protons around earth's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

Proton precession magnetometer



Typically 300 ml liquid, 1000 windings, induce signal of microvolt with approx. 25 nT/Hz or 0.04 Hz/nT.

To measure the geomagnetic field at all latitudes:

25.000 nT -> 1000 Hz

65.000 nT -> 2600 Hz

Proton precession magnetometer

Magnetic field gradients

•Give an overlap of different frequencies and make measurement in large gradients impossible

•Reducing the volume of the sensor helps

Electromagnetic noise

•The induction coil picks up EM noise.

•Combining two sensors with antiparallel coils, such that measurement signal adds and external signal cancels out.

Fluxgate magnetometer

- Measures magnetic field along sensor axis
- The output is a voltage or current roughly proportional to the magnetic field
- Needs calibration
- Drift of zero point with temperature and ageing
- Insensitive to gradients

Fluxgate magnetometer

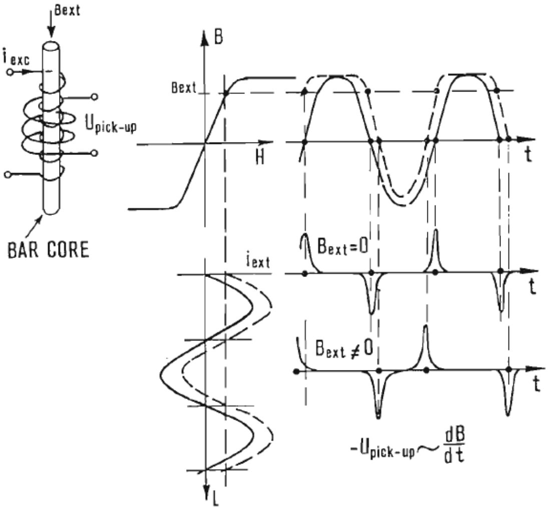


Figure 4.16. Waveforms of a fluxgate sensor with the core consisting of a single bar.

For $B_{ext} \neq 0$ there comes a 2nd harmonic signal that is proportional to B_{ext}.

Fluxgate magnetometer

Operate as null-instrument (feed back).

Add bias field to decrease the measurement range, allowing for higher resolution.

Use pick up coil for feed back and bias current.

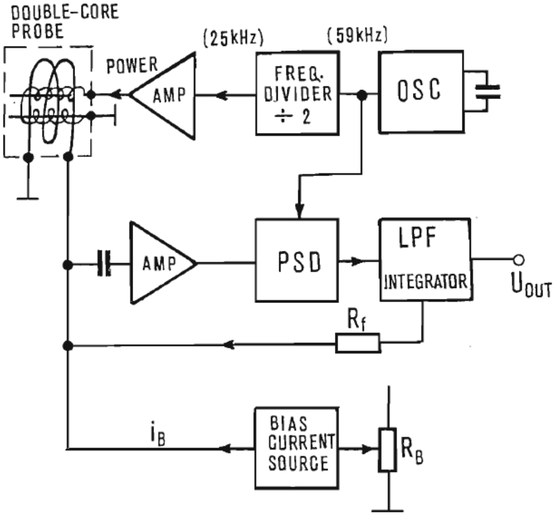


Figure 4.18. Block diagram of a fluxgate magnetometer with feed-back and with a separate unit for the production of bias current for the compensation of main part of the field. PSD = phase sensitive detector, LPF = low pass filter.

Variometer

Fluxgate sensors:

- Field along 3 axes (N, E, Z)
- Scale value (frequency response)
- Linearity
- Offset (measures variation only)

Setup:

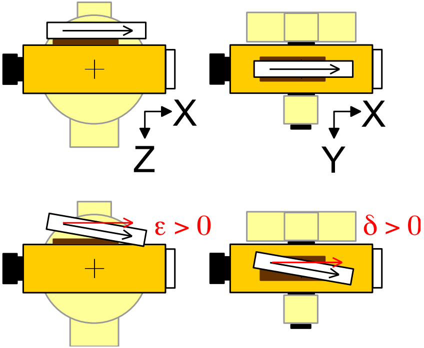
- Orthogonality (marble cube)
- Orientation (suspension)

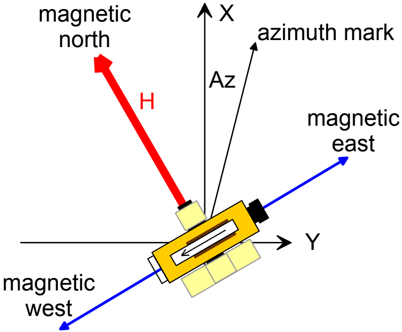
Essentials:

- Temperature stability
- Long term stability

Direction Determination: DI fluxgate

- Fluxgate sensor is not absolute (scalevalue, offset, drift,...)
- Magnetic axis is by default misaligned w.r. to the optical axis
- Use null-method (no need for scalevalue)
- Measure in different positions: procedure is absolute
- Theodolite can be used for sun and star observations





Observatory setup

Constant temperature.

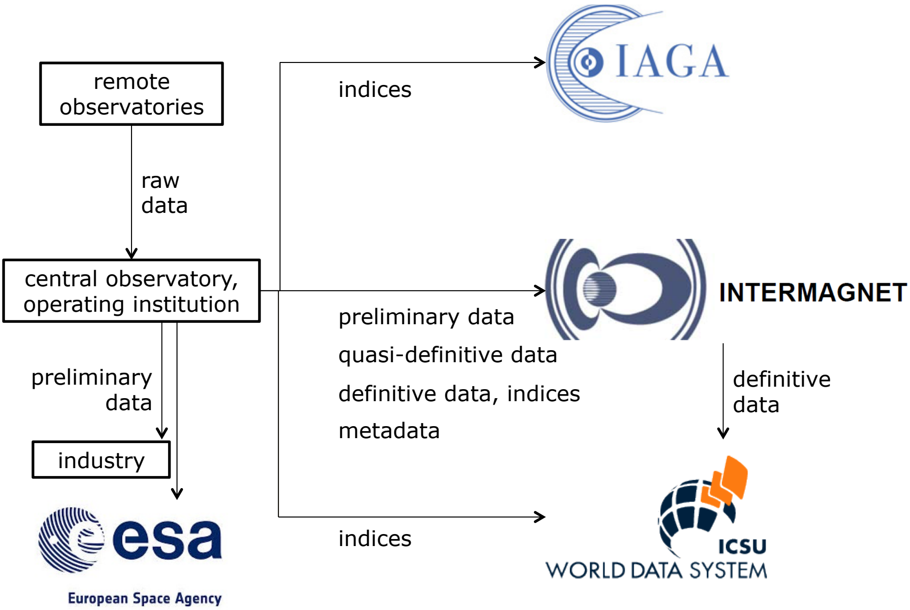
Window and removable panel for azimuth mark and sun observation.

Protection against weather, nonmagnetic, cheap to setup and maintain.

Pillars independent from the building.

Area has to be free of magnetic anomalies and electric (DC) currents.

Distribution of data

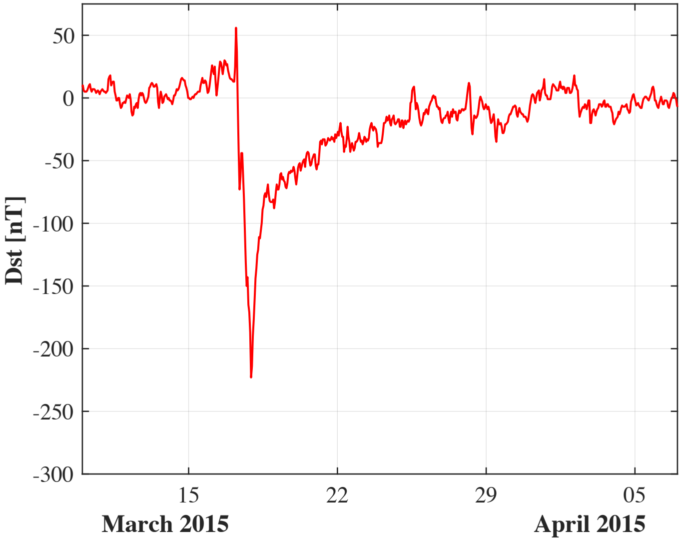


Dst index of the equatorial ring current activity level

- Dst or Disturbance Storm-Time is designed to be a measure of geomagnetic disturbances produced by the equatorial ring current that flows in the radiation belts at 6-10 Earth radii.
- Derived from the averaged of the disturbances in the horizontal field (after removal of slowly changing field and daily variations) from 4 near-equatorial observatories: Hermanus (South Africa), Kakioka (Japan), San Juan (Puerto Rico) and Honolulu (USA).
- **1 hour time-resolution (derived from hourly means of H)**

More details regarding the derivation of the Dst index:
`http://wdc.kugi.kyoto-u.ac.jp/dstdir/dst2/onDstindex.html`

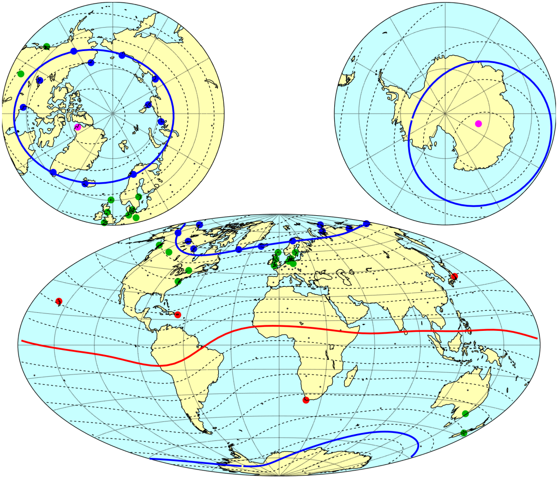
An example of Dst: St. Patrick's day storm, 2015



Kp, a planetary range index for geomagnetic disturbance

- First the quiet-day variation pattern has to be removed from the magnetic signal.
- Then local disturbance levels are determined by measuring the range (difference between the highest and lowest values) during **3-hour time intervals** for the most disturbed horizontal magnetic field component.
- The range is then converted into a local K index taking the values 0 to 9 according to a quasi-logarithmic scale, which is station specific.
- Applying special conversion tables, a standardized index Ks for each of 13 selected observatories is determined. These are expressed in a scale of thirds (28 values):
$$0o, 0+, 1-, 1o, 1+, 2-, 2o, 2+, ..., 8o, 8+, 9-, 9o$$
- The global geomagnetic index Kp is the average of the 13 'Kp stations' (with Brorfelde and Lovö, as well as for Eyrewell and Canberra, combined so that their average enters into the final calculation so the divisor is 11).

Ground stations used in geomagnetic disturbance indices



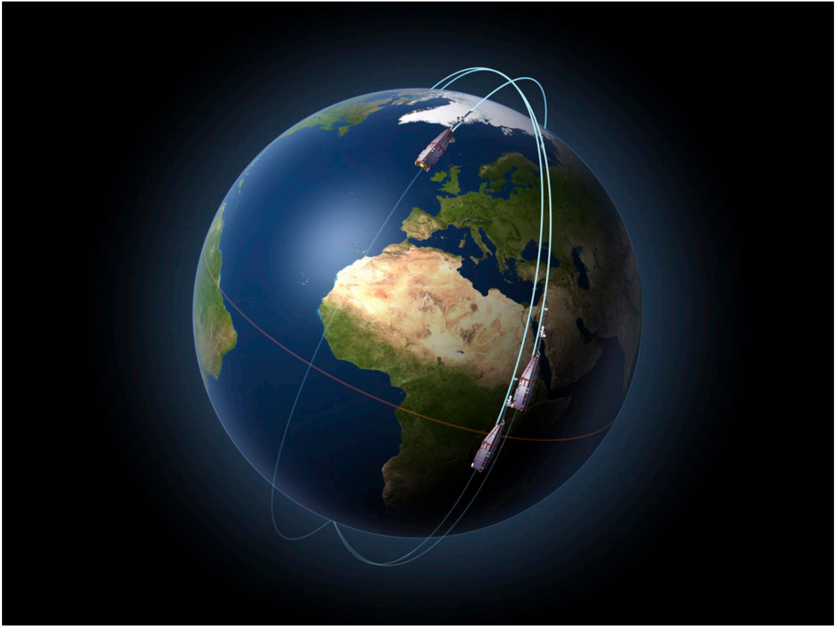
red dots = Dst stations

green dots = Kp stations

[blue dots = AE stations, not considered here]

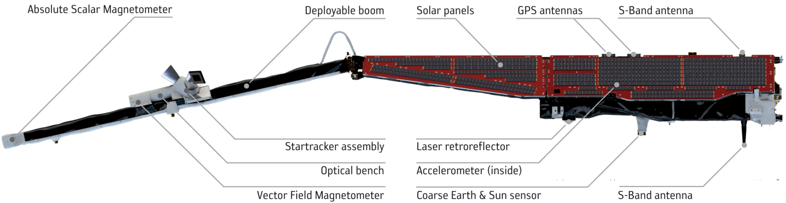
[purple dots = PC stations, not considered here]

Data from the Swarm Mission: Orbits



Swarm Launch, November 2013

Swarm: Instruments Overview



Swarm: Stray field corrections
Corrections for stray fields

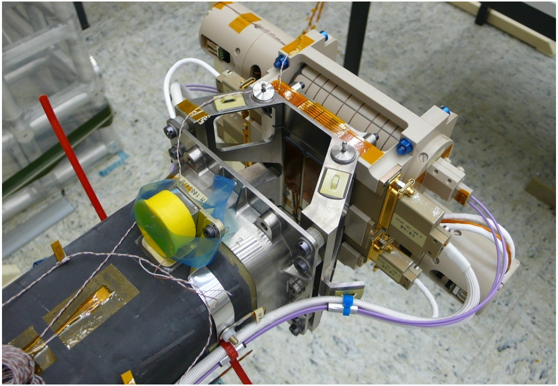
'Stray' magnetic fields intrinsic to the instruments and the spacecraft body exist and may be divided into three categories:

- Static (and state/operation dependent) magnetization
- Induced by electrical currents
  (e.g. due to solar panel array, battery charging, magneto-torquer coils)
- Magnetization in soft magnetic materials induced by ambient fields

- Onboard *Swarm* there was found to be an additional, stray/disturbance field dependent on angle of solar illumination, that is now characterized in-flight.

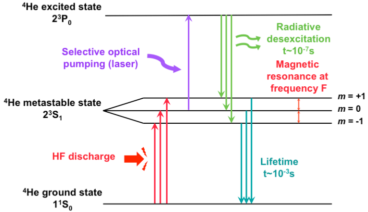
  For further information see Tøffner Clausen et al., (2016)
  `http://www.earth-planets-space.com/content/68/1/129`

Swarm: ASM Instrument
Absolute scalar magnetmeter (ASM)



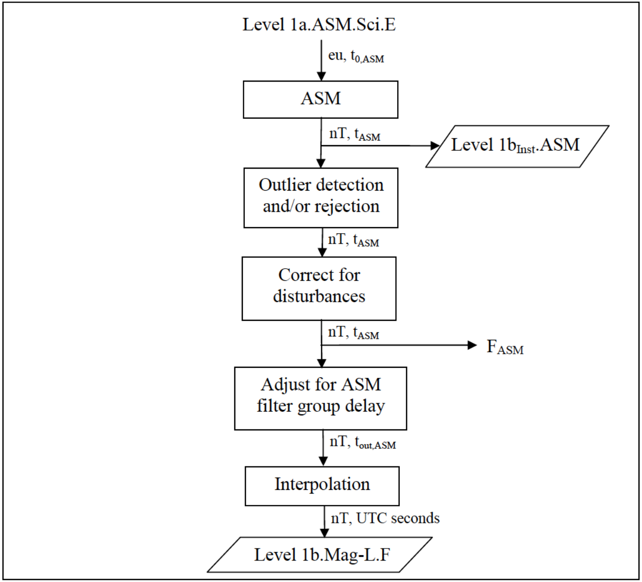
- ASM is a magnetic field to frequency converter based on atomic spectroscopy of 4He.
- It exploits the Zeeman effect, with the signal being amplified by optical pumping.
- $B_0 = \mathrm{F}/\gamma^{4He}$, with γ^{4He} / $2\pi = 28$ GHz/T.

Swarm: ASM Instrument
Absolute scalar magnetmeter (ASM)

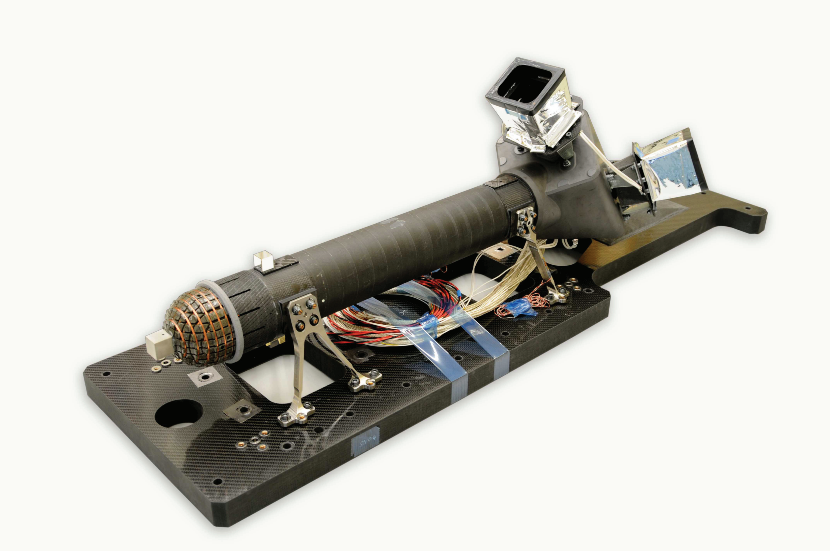


- Helium atoms are excited to the 2^3S_1 metastable state by means of a high frequency discharge
- In the presence of a magnetic field B_0, this level is split into three sub-levels whose energy levels are separated, via the Zeeman effect,
- A radiofrequency field B_{RF} is applied. When its frequency F matches the Larmor frequency ω_0 of the Zeeman sublevels, magnetic resonance occurs and transitions are induced between the sublevels.
- A selective pumping from one of the Zeeman sublevels to the 2^3P_0 state is performed, via frequency-tuned linearly-polarized laser light.
- This optical pumping makes it easier to detect the resonance.

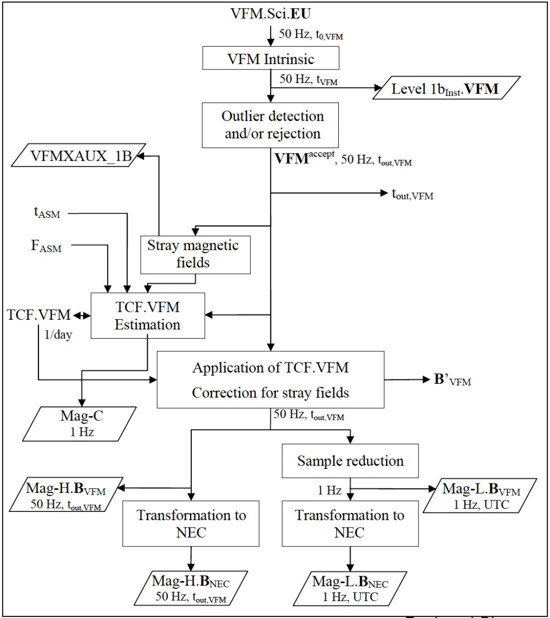
Swarm: ASM processing
ASM: Data processing flow



Swarm: VFM
Vector Field Magnetometer (VFM), integrated system with optical bench and star camera



Swarm: VFM processing
VFM, Data processing flow



Swarm VFM calibration
VFM, Calibration

- The VFM magnetometer is calibrated in-orbit using the scalar ASM data.
- The instrument output $\mathbf{E} = (E_1, E_2, E_3)^T$ (in engineering units, eu) is connected to the applied magnetic field $\mathbf{B}_{\mathrm{VFM}} = (B_1, B_2, B_3)^T$ (in the magnetometer coordinate system) according to

$$\mathbf{E} = \underline{\underline{\mathbf{S}}} \cdot \underline{\underline{\mathbf{P}}} \cdot \mathbf{B}_{\mathrm{VFM}} + \mathbf{b} \tag{1}$$

where

$$\mathbf{b} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} \underline{\underline{\mathbf{S}}} = \begin{pmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_3 \end{pmatrix} \tag{2}$$

where $\mathbf{b}$ is an offset vector (in eu), $\underline{\underline{\mathbf{S}}}$ is a matrix of sensitivities (in eu/nT), and

$$\underline{\underline{\mathbf{P}}} = \begin{pmatrix} 1 & 0 & 0 \\ -\sin u_1 & \cos u_1 & 0 \\ \sin u_2 & \sin u_3 & \sqrt{(1 - \sin^2 u_2 - \sin^2 u_3)} \end{pmatrix} \tag{3}$$

transforms a vector from the orthogonal magnetic axes coordinate system to possibly non-orthogonal magnetic sensor axes

- The 9 parameters $b_i, S_i, u_i,\ i = 1, \ldots, 3$ describing the linear VFM magnetometer are estimated by linearized least-squares, minimizing the mean squared difference between $F_{\mathrm{VFM}} = |\mathbf{B}_{\mathrm{VFM}}|$ and the field intensity F_{ASM}.

Swarm: Data selection for constructing geomagnetic reference models

Typical selection criteria include:

- Sampling rate: typically *1 minute* for global modelling, for global data sets

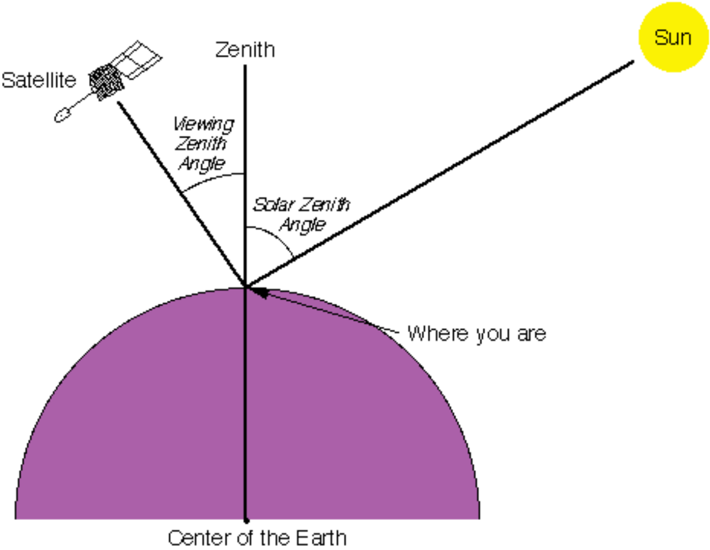
- Exclude times when field due to external current sources (i.e. from magnetospheric/ionospheric currents) are large. This involves implementing threshold values/rates of change of *geomagnetic activity indices e.g. Dst, Kp* derived from ground observatories (see next slides)

- Use only *night-time* data (using sun zenith/elevation angle) to minimize impact of tidally-driven ionospheric current

More on the Kp Index:
`https://www.gfz-potsdam.de/en/kp-index/`

More on the Dst index:
`http://www.ngdc.noaa.gov/stp/GEOMAG/dst.html`

Explanation: Solar Zenith Angle



More details see:
`http://sacs.aeronomie.be/info/sza.php`