Swarm – The Earth’s Magnetic Field and Environment Explorers

Scientific Background
Magnetic fields play an important role in many of the physical processes throughout the Universe. Near the Earth in particular exists a large and complicated magnetic field:

- produced to a large extend by a self-sustaining dynamo, operating in the fluid outer-core,
- but also caused by magnetised rocks in the Earth’s crust,
- and due to electric currents flowing in the ionosphere, magnetosphere and oceans
- and by currents induced in the Earth by time-varying external fields.

The challenge is to improve our knowledge of the composition and processes in the interior and the surroundings of the Earth from magnetic field and other measurements as important contribution understanding the Earth System.

Mission Objectives
The Swarm mission will provide the best ever survey of the geomagnetic field and its temporal evolution, in order to gain new insights into the Earth System by improving our understanding of the Earth’s interior and physical climate.

Research objectives:
Related to the Earth’s Interior:
• Map the core flow
• Determine core dynamics
• Investigate jerks: their time-space structure and recurrence
• Understand core-mantle coupling and its implication for Earth rotation
• Perform 3D imaging of mantle conductivity
• Determine remanent and induced magnetisation of the lithosphere

Related to the Earth’s environment:
• Determine the position and development of the radiation belts and their near-Earth effects
• Investigate the time-space structure of the magnetospheric and ionospheric current systems on all time scales
• Monitor the solar wind energy input into the upper atmosphere and sense its effect on the thermospheric density
• Sound the electron density of the ionosphere/plasmasphere and relate it to magnetic activity

Swarm is a constellation to study the dynamics of the Earth’s magnetic field and its interactions within the Earth System.

Observational Requirements (in Orbit)

<table>
<thead>
<tr>
<th>Observation</th>
<th>Accuracy, stability</th>
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<tbody>
<tr>
<td>Magnetic Field Magnitude</td>
<td>global – 20 km length scales, 0.15 nT (σ); &lt; 0.05nT/3 months</td>
</tr>
<tr>
<td>Vector Magnetic Field</td>
<td>global – 2 km length scales, 0.5 nT (σ); &lt; 0.5nT/year</td>
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<tr>
<td>Vector Electric Field</td>
<td>global – 20 km length scales, 1.5 mV/m (σ); &lt; 0.5 mV/m/month</td>
</tr>
<tr>
<td>Electron Density Distribution</td>
<td>global - 20 km length scales, Precision 0.5 10⁻¹⁰/m³ RMS</td>
</tr>
<tr>
<td>Air Drag</td>
<td>global - 200 km length scales, Accuracy 2.5 10⁻⁸ m/s² (σ)</td>
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<tr>
<td>Local times distribution</td>
<td>changing over time</td>
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<tr>
<td>Mission duration</td>
<td>4 years</td>
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</tbody>
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Mission Elements
Space segment:
• Constellation of three satellites at two altitudes, 450 and 530km, where the lower pair, for the first time, will provide gradients
• Orbital planes, drifting apart, to optimise the distribution of measurements in space and time for addressing specific objectives during different periods of the mission
• Spacecraft with boom to provide magnetically clean accommodation for magnetometer instruments

Instruments and sensors:
• Scalar magnetometer
• Vector magnetometer supported by an attitude sensor
• Electric field instrument
• GNSS receiver for precise orbit determination
• Accelerometer for observing non-gravitational forces

Ground segment:
• Satellite operation and control
• Data processing and archiving centre

Level 1B data products:
• Magnetic field magnitude and vector components
• Ion drift and vector electric field, electron density
• Acceleration vector, and air drag and precise satellite orbit

At Level 2 global models will be produced related to the objectives.
Swarm

The Earth’s Magnetic Field and Environment Explorers

Mission Aim

The Swarm mission will provide the best ever survey of the geomagnetic field and its temporal evolution, in order to gain new insights into the Earth system by improving our understanding of the Earth’s interior and physical climate.
Magnetic Field Contributions

\[ R_E = \text{Earth radius} \sim 6371\text{km} \]

Radial Magnetic Field at Satellite Altitude

Example of the signal of the source contributions
**Primary Research Objective:**

**Core Field and Temporal Variations**

**Process**
- Geodynamo maintained by fluid motion

**Background**
- Advection and/or diffusion process
- Origin of Jerks
- Torsional oscillations and waves
- Core-mantle coupling mechanism

**Goals**
- Achieve higher resolution of core surface flow in space and time
- Constrain role of diffusion and waves
- Predict short-term evolution

Requires a model of the core field to 3000 km scales over periods of 3 months

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**Primary Research Objective:**

**Lithospheric Magnetisation**

**Process**
- Remanent and induced magnetisation in rocks

**Background**
- The magnetic signature is related to thermal structure and mineralogy

**Goals**
- Bridge the gap between present satellite and aeromagnetic survey resolution
- First ever top to bottom view of the lithosphere
- Improve understanding of tectonics and geological provinces

Requires a lithospheric field model to better than 360 km scales
**Primary Research Objective:**

**3-D Electrical Conductivity of the Mantle**

**Process**
- secondary magnetic fields due to electric currents in the mantle, induced by time-varying external (primary) fields

**Background**
- conductivity is sensitive to composition and temperature
- conductivity-depth profile given by frequency dependence of induced fields
- only 1-D models available, no information about conductivity inhomogeneities
- Unique tool for mantle study from space complementing seismology

**Goal**
- determine for the first time global models of mantle conductivity (3-D)

Derive global transfer functions (hours to months period, corresponding to 100 - 1000 km depth)

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**Primary Research Objective:**

**Earth’s Electrodynamic Environment**

**Process**
- Sun’s influence within the Earth System

**Background**
- Particle distribution: radiation belts etc.
- Field-aligned currents: solar wind energy transfer into upper atmosphere
- Ionospheric currents: redistribution of energy

**Goals**
- Model of large-scale external field dynamics to improve internal field models
- Distribution and dynamics of field-aligned currents

Requires simultaneous in-situ electric and magnetic field observations
Secondary Research Objectives
Magnetic Forcing of Upper Atmosphere

- What is the coupling mechanism between the magnetic activity and air density?
- Analysis of effect of cusp field-aligned currents on Joule heating

Requires multi-point simultaneous air drag, electric and magnetic field observations

Secondary Research Objectives
Ocean Flow

- Tidal and ocean circulation signature

Movement of seawater through main field: depth integrated flow generates electric currents causing secondary magnetic fields

Magnetic field correction using state-of-the-art tide and ocean circulation models or (partial) co-estimation
Summary of Research Objectives

Primary Objectives
- core dynamics, geodynamo processes, and core-mantle interaction
- lithospheric magnetisation
- 3-D electrical conductivity of the mantle
- electric currents in magnetosphere and ionosphere

Secondary Objectives
- magnetic forcing of the upper atmosphere
- magnetic signature related to ocean circulation

Theme: Earth’s Interior
Unique view “inside” the Earth from space for core, mantle & crust

Theme: Physical Climate
Sun’s influence within Earth system

Sampling at Satellite Altitude (400km)
Sampling, aliasing and observations

Sun-fixed frame

Earth-fixed frame

Mission Requirements

Single satellite
- Magnetic field magnitude and vector components
- Electric field vector components
- Electron density
- Air drag
- Position, attitude and time

Constellation
- 3 satellites:
  - 2 side-by-side in low orbit
  - 1 in higher orbit
- three orbital planes with two different near-polar inclinations
- Near polar orbits for global coverage

accurate enough at satellite altitude to measure the most demanding signals at finest spatial and fastest required temporal sampling
Mission Requirements Continued

Constellation Spatial Sampling
- Ideal east-west separation
- Suppression of contribution from large scale external sources
- Gradients observed at lowest possible altitude for highest sensitivity to lithospheric signal

Constellation Time Sampling
- Relative drift between the single high and two low orbital planes for local time separation
- Achieved by different inclinations and altitudes

Swarm Mission Elements

Space Segment
- S-Band Uplink/Downlink

Single Launcher
- Dnepr
- Cosmos
- Vega
- Rockot

Users

Ground Segment

CDAE
Command & Data Acquisition Element
Kiruna

MSCE
Mission Operation & Satellite Control Element
ESOC

PAE
Processing & Archiving Element
ESRIN

Satellite A
Orbit: 450 km/87.4 deg.

Satellite B
Orbit: 450 km/87.4 deg.

Satellite C
Orbit: 530 km/86.8 deg.
Payload (1)

**Payload (2)**

<table>
<thead>
<tr>
<th></th>
<th>Heritage</th>
<th>Open Development Activities</th>
</tr>
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<tbody>
<tr>
<td>ASM (A)</td>
<td>Airborne application</td>
<td>Space qualification</td>
</tr>
<tr>
<td>ASM (B)</td>
<td>Sounding rockets</td>
<td>Space qualification</td>
</tr>
<tr>
<td>VFM</td>
<td>Ørsted, CHAMP, SAC-C</td>
<td>Miniatrised data processing unit is pending qualification and is expected to fly on Proba 2 in 2005</td>
</tr>
<tr>
<td>EFI</td>
<td>Atmospheric and Dynamic Explorers and Defence Meteorological Satellites</td>
<td>None identified</td>
</tr>
<tr>
<td>ACC</td>
<td>Space Shuttle, Mimosa</td>
<td>Adaptation of power interface</td>
</tr>
<tr>
<td>Associated Equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attitude Determination</td>
<td>Ørsted, CHAMP, GRACE</td>
<td>New generation of data processing unit under qualification</td>
</tr>
<tr>
<td>Precise Orbit Determination</td>
<td>CHAMP, GRACE</td>
<td>None identified</td>
</tr>
</tbody>
</table>
### Satellite (1)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>A</th>
<th>B</th>
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</thead>
<tbody>
<tr>
<td><strong>Spacecraft Mass</strong></td>
<td>400 kg</td>
<td>240 kg</td>
</tr>
<tr>
<td><strong>Spacecraft Average Power Consumption</strong></td>
<td>167 W</td>
<td>125 W</td>
</tr>
<tr>
<td><strong>Solar Arrays Dimensions</strong></td>
<td>4.4 sqm</td>
<td>4.7 sqm</td>
</tr>
<tr>
<td><strong>Power Storage</strong></td>
<td>Spacecraft Mass</td>
<td>Lithium-Ion Battery</td>
</tr>
<tr>
<td><strong>Spacecraft Dimension</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Length</strong></td>
<td>7.85 m</td>
<td>6.31 m</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>1.50 m</td>
<td>2.02 m</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>1.03 m</td>
<td>0.84 m</td>
</tr>
<tr>
<td><strong>Boom length</strong></td>
<td>5.4 m</td>
<td>4.0 m</td>
</tr>
<tr>
<td><strong>Boom Direction</strong></td>
<td>Anti - flight</td>
<td></td>
</tr>
<tr>
<td><strong>Attitude &amp; Orbit Control</strong></td>
<td>Three-axis stabilised (magnetic torquers, cold gas)</td>
<td></td>
</tr>
<tr>
<td><strong>Telemetry/ Telecommand</strong></td>
<td>S-Band, 1 Mbps downlink and 4 kbps uplink</td>
<td></td>
</tr>
<tr>
<td><strong>Data Generation: Day &amp; Satellite Data Storage Capability</strong></td>
<td>125 Mbytes</td>
<td></td>
</tr>
<tr>
<td><strong>Data Storage Capability</strong></td>
<td>1000 Mbytes</td>
<td>512 Mbytes</td>
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</tbody>
</table>

### Satellite (2) Payload Accommodation

- Vector Field Magnetometer (VFM)
- Absolute Scalar Magnetometer (ASM)
- Electric Field Instrument (EFI)
- Accelerometer (ACC)

EFI

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Earth Explorer User Consultation Meeting 19 and 20 April 2004

Swarm

19

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Earth Explorer User Consultation Meeting 19 and 20 April 2004

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20
Satellite (3) System Architecture

ATTITUDE ORBITAL CONTROL
- Attitude Sensor (3 Camera Heads)
- Magnetorquers
- GPS Receiver
- Coarse Sun (and Earth) Sensor
- Inertial Measurement Unit

COMUNICATIONS
- Antenna
- Radio Frequency Electronics
- Telemetry/Telecommand Unit

OBDH
- On Board Data Handling

PRIMARY PAYLOAD
- Absolute Scalar Magnetometer
- Vector Field Magnetometer
- Electric Field Instrument
- Accelerometer

POWER
- Solar Generator
- Battery
- Processor

PROPULSION
- Thrusters
- Tank Electronics

ATTITUDE ORBITAL CONTROL

THERMAL
- Heaters

On Board Data Handling

COMMUNICATIONS

Launcher

Swarm Satellites within the DNEPR Fairing

Fairing Envelopes
Ground Segment (1)

S-Band
Uplink = 4kb/s
Downlink = 1Mb/s

1000 Mbit data generation per satellite per day

Contact time per day (Kiruna)
Higher orbit: 4300 s
Lower orbit: 3100 s

Ground Segment (2)

Lower orbit contact window with the Kiruna ground station

Swarm Daily Visibility (Kiruna)

- Upper Satellite = 9 orbits per day
- Lower Satellites = 8 orbits per day
System Performance (1) Level 1b

![Graph showing error budget components](image1)

- VFM sensor noise
- Linearity error
- Alignment & calibration error
- Pointing knowledge error
- Residual stray field variations
- Timing uncertainty
- ASM error
- Total error
- Requirement

Stray Field Uncertainty at VFM Location

System Performance (2) Level 1b

![Graph showing error budget components](image2)

- Requirement
- Error Budget
- Numerical Simulation
- Numerical Simulation
- Numerical Simulation

Vector magnetic field product

Scalar magnetic field product
**Technical Summary**

- Swarm is a technically mature mission concept
- The observational requirements can be met with the proposed satellite designs
- No risks are associated with the platform and the payload
- Spacecraft design is based on a new generation of existing sub-systems and instruments
- Ground segment is based on existing ESA infrastructure
- The mission is ready to go into Phase B immediately and is compatible with a launch date end of 2008
Mission Performance

Earth’s Interior
- Core dynamics and geodynamo processes
- Lithospheric magnetisation
- 3D Mantle conductivity
- Ocean circulation

Earth’s Environment
- Ionosphere-magnetosphere current systems
- Magnetic forcing of the upper atmosphere

Satellite D level 1b data
Satellite C level 1b data
Satellite B level 1b data
Satellite A level 1b data

Mission performance simulator:
- all relevant magnetic field contributions
- full mission lifetime
- Separation of source contributions
- Comparison with “true” input models
- Quality assessment of constellation

- Match against desired performance
- Benefit of the Swarm constellation

Mission Performance: Core Dynamics

- With Swarm: local time coverage and improved quality
- Without Swarm: only ground station data

Core models to 2850 km scales every 3 months match requirements
Mission Performance: Lithosphere

- A: 4-5 times more accurate than CHAMP
- Lower pair A+B (gradient) for detail
- Higher C separates external sources
- Model to degree 110-133 bridges gap with airborne, marine & ground surveys

Performance requirements can be met

Mission Performance: 3-D Mantle Conductivity

- Electro-magnetic induction in the mantle due to external field changes
- Longer periods relate to greater depths

Required 3-D recovery up to 1000 km depth possible
Mission Performance: External Fields

- Field aligned current determination
- Curl-B technique applied to lower pair data

"True world" Model

Estimated from lower pair

Radial current density at 400 km

New approach taking advantage of constellation

Mission Performance: Iono- & Plasmasphere

Electron density variation from in-situ plasma data related to local time

2-D electron density slices in CHAMP orbit plane: In-situ electron density combined with radio sounding from the GPS navigation instrument

- Correction for local plasma density improves internal magnetic field models
- Three orbital planes will improve the tomography of the iono- & plasmasphere
Mission Performance: Ocean Circulation

- Tidal models are quite good except some components
- Ocean flow (ECCO model 1°x1°): magnetic field signal is detectable

- Tidal and ocean flow correction are possible
- Tidal signal is separable, improvement of tidal models may be done
- Estimation of oceanic flow is still under investigation

International Context Selection

**International Union of Geodesy and Geophysics (IUGG):** one of the scientific unions within International Council for Science (ICSU)

**International Association of Geomagnetism and Aeronomy (IAGA):**

- Services
- Definition standards
- Instrument standards
- World data centres
- Permanent working groups on reference models
- Observational programmes
- Study groups

**International Geomagnetic Reference Field (IGRF):** Main field and changes, combined satellite and observatory data; next (9th) generation

**World Digital Magnetic Anomaly Map (WDMAP):** Task group IAGA, 2003

**International Living with a Star Programme (ILWS):** Stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity. Sponsors: Canada, Russia, ESA, NASA, and Japan; 26 members: Swarm priority in Ionosphere-Thermosphere task group.
Link to other Missions

- International Decade of Geopotential Research, IUGG (IAGA & IAG), 1999

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<tbody>
<tr>
<td>Ørsted (DK)</td>
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<td>CHAMP (GER)</td>
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<td>SAC-C (ARG/USA/DK)</td>
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<td>GRACE (USA/GER)</td>
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<td>GOCE (ESA)</td>
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<tr>
<td>Swarm (ESA)</td>
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Legend:
- Absolute magnetics with precise attitude determination
- Gravity static and time variable
- Combination of absolute magnetics and gravity

- Continuation of current missions greatly improves the estimation of the secular variation of the core field (full solar cycle)
- Analysis of existing data will benefit from Swarm models and tools

User Community Readiness

- Ørsted
  - Denmark
  - Data centre data, models software
  - Global users
  - Dedicated user workshops

- CHAMP
  - Germany
  - Data centre data, models software

Preparation for Swarm: End-to-End mission performance simulator and related studies.
Group of leading European Institutes and NASA

- Processing strategy is adapted to constellation: refinements, quality assessment and multi-satellite calibration needs further elaboration beyond simulator environment

- Direct involved community under IAGA, and geomagnetism section of AGU
- Interdisciplinary community within IUGG, AGU and EGU will benefit from Swarm. For example: the Special Bureau for the Core of the IERS Global Geophysical Fluids Centre, IAG, 1998

- Several communities are preparing joint exploitation of available and planned missions within ILWS
- National funding programmes and agencies support existing and future mission exploitation in for example Denmark, Germany, France, the UK and USA
Application Potential

- Earth’s interior modelling: seismology and gravity: lithosphere, mantle, core-mantle
- Modular, Scalable, Self-consistent, Three-dimensional (MoSST) model of the geodynamo: data assimilation scheme for forecast of core dynamics for Earth rotation, core-mantle coupling
- Determination of regional heat-flux: continental region with lateral variation in thickness of magnetic layer
- Directional drilling in oil and gas industries, and navigation
- Space weather: radiation damage, power failure etc.
- Long-term climate changes from secular variation impacting the incoming cosmic ray fluxes (cloud condensation)

Summary

- The sources of the magnetic field range from the Earth’s core to the magnetosphere
- No other physical parameter has this diverse sensitivity
- This provides a unique capability to probe the Earth’s core, mantle and crust from space
- This requires good characterisation of the Earth’s external environment
- Swarm builds on scientific and technical experiences gained from Ørsted and CHAMP (aims at 4-5 times higher single-satellite accuracy)
- The innovative three-satellite constellation facilitates a dedicated space-time mapping of phenomena under study. It is demonstrated that this is required for progress in geomagnetic research
- Instrument provision supported by CNES (ASM) and by ESA’s Space Science Directorate through a collaboration with Canada (EFI)

Swarm will strengthen Europe’s leading role in geomagnetic research from space