MAGiC Twins
Science-grade Magnetometer and GPS Payload Proposal for DTUsat CALL FOR PAYLOAD Contest

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Introduction

The dynamics and unpredictability of Earth's magnetic field requires a continuous mapping of Earth's magnetic field from space. Description of the geomagnetic field for the twenty years between Magsat (1979-80) and Ørsted (1999-present) is therefore of much reduced quality compared to what could have been obtained with satellite data. The proposed payload will investigate the possibility of continuous monitoring of the Earth's magnetic field – knowledge which is essential for many practical applications like navigation and exploration – with a small and cheap satellite concept, which can also be used as a pioneer platform for future deployments of a nanosatellite fleet for multipoint measurements and/or for continuous monitoring of the Earth's magnetic field. The MAGiC (Magnetometer and GPS in Cubesat) payload has the following objectives (number in parenthesis indicates number of satellites required):

Scientific objectives:
- Geopotential Field Research (1)
- Solar wind magnetosphere interactions investigation (1*, 2)
- Study of ionospheric current systems (1*, 2)
- Precise orbit determination (1)

Technical objectives:
- Real scientific instrumentation (1, 2)
- GPS position (1, 2)
- Miniature boom (telescopic or Ørsted-style) (1, 2)
- Formation flying, dual satellite mission (2)
- Constellation control based on air drag (1, 2)

* Science partly descoped in the case of one satellite
The use of two satellites adds redundancy and this will increase the reliability of the mission.

This mission will be a pioneer for performing two-point measurements of the Earth's magnetic field, it will be the first cubesat-based formation flying mission, and it will be the first cubesat mission to control the orbit by means of air drag. This twin mini-Ørsted mission will allow students to gain experience with multipoint data processing before the launch of the ESA Swarm mission, which is currently scheduled to begin scientific operation in the middle of 2009.

Students at DTU will be designing, developing and implementing the hardware for the payload, while students at the University of Copenhagen will be managing the data analysis planning and execution.

Scientific Objectives

The scientific objectives are two-fold:

Geopotential Research: The magnetic field readings will allow for a determination of "IGRF-type" models of Earth's magnetic field (up to spherical harmonic degree n = 13 or so). Due to the lack of high-precision attitude data, only the magnetic field intensity will be used for this purpose. The practical inversion of the ill-posed problem of determining a potential field from intensity measurements only will be solved by utilizing a-priori information on the location of the dip-equator (defined by the places on Earth's surface where the magnetic field is purely horizontal). Mapping of Earth's magnetic field requires knowledge of the exact position. The availability of GPS position measurements for a fraction of the time (e.g. one orbit/day) provides an excellent possibility to determine position with an accuracy of, say, hundred meters, sufficient to measure magnetic field intensity with an accuracy of a few nT. Fortunately, along-track position errors result in much smaller magnetic field errors compared to vertical and across track position errors. The proposed payload will demonstrate the possibility of precise orbit determination (within ca. 100 m) from sporadic GPS measurements combined with models of the Earth's gravity field and air density. It is thereby also possible to determine the (average) air drag (air density) and its dependence on, e.g., solar activity.

Solar wind magnetosphere interactions investigation: Solar wind interactions with the Earth magnetic field generates a number of different current systems in Earth's magnetosphere and ionosphere: Distant currents in the outer magnetosphere, the magnetospheric boundary and the tail, the ring-current in the inner magnetosphere, currents flowing along field-lines from the outer magnetosphere to the polar ionosphere close to the Earth and ionospheric currents flowing horizontally in the polar ionosphere acting to close the field-aligned current loop. All of these current systems will influence the magnetic field as measured by a low Earth orbiting (LEO) satellite, and can therefore in principle be investigated by such. The current systems are highly dynamic, varying at a large range of time scales, partly due to the time variations of the solar wind and partly due to internal magnetospheric and ionospheric dynamics.

Measurements of the time variations of the total magnetic field intensity at LEO-orbit can be used to investigate the magnetospheric currents and also the ionospheric currents. During geomagnetic storms the magnetospheric ring-current increase and act to decrease the magnetic field near the Earth. This means that energetic particles trapped in the Earths radiation belts will be able to penetrate to lower altitudes, thereby endangering astronauts and spacecraft (s/c) instruments. A detailed description of this magnetic field decrease, its spatial variation and relationship to the solar wind, is therefore a high priority. The spatial variations can be investigated statistically by combining single satellite measurements with solar wind data, or instantaneously by using multipoint measurements from widely separated spacecraft. The latter is possible either by the use of two DTU-satellites, or by combining DTUsat data with other magnetic field measuring LEO satellites.

The DTU satellites will fly through the field-aligned currents (FACS) in the upper polar ionosphere, and can be used to investigate time-variations in their structure and intensity, provided that the satellite attitude is stable during the passage. The structure of the FAC's is known to be highly filamentary, but by using a single satellite it is not possible to distinguish spatial variations from time variations. Two closely orbiting DTU-satellites can contribute significantly to our knowledge of the space/time structure of FAC's.

Technical Objectives and Challenges

In order to realize the science objectives the following is required:

- Accurate clock (1 ms or better)
- Inter satellite time synchronization (1 ms or better)
- Accurate orbit determination (better than 0.5 km)
- Attitude determination better than 1°
- No magnetic contamination

The first 3 requirements are fulfilled with the proposed GPS receiver, the attitude can for the sunlit part of the orbit be determined using MEMS sun sensors as developed for DTUsat, and the last requirement is fulfilled by mounting the magnetometer on a deployable boom and by designing the entire s/c with respect to a magnetic cleanliness program.

Payload and Operations Description

The proposed MAGiC payload therefore consists of two instruments: A miniature three axis fluxgate magnetometer and a GPS receiver. The magnetometer sensor will be mounted on a deployable boom. The control electronics for the magnetometer will be a miniaturized redesign of an existing space qualified design. It will feature A/D converters, voltage references, circuits to generate the necessary excitation currents for the fluxgate magnetometer, an RF front-end for the GPS receiver and a Spartan 3L FPGA. The FPGA will be used to control the magnetometer and to perform correlation of the GPS signals. The OBC will be used to calculate the orbit position based on the correlated data.

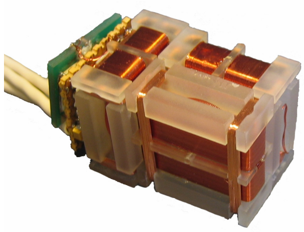

Figure 1 - Miniature magnetometer

The magnetometer will be mounted in a carbon-fiber cylinder on the top of a short boom. Two alternative boom designs will be discussed in the following section. It may be possible to mount MEMS sun sensors on the side of the magnetometer sensor. Likewise it is possible to mount a passive GPS patch antenna at the end of the boom, but another location may be required in order to archive the best signal strength.

In order to control the distance between the two satellites in the constellation, flaps on the sides of the satellites can be extracted to increase the air drag on one of the satellites, thus reducing or increasing the inter-satellite distance. A simple radio link with a PID controller can be used to monitor the distance between the two satellites and control the amount the flaps must be extracted by piezoelectric motors. It should be noted that if this system is to be used the orbit must be reasonably low. For an orbit altitude of 818 to 830 km such as for the first DTU satellite the air drag is simply too small to gain any effect.

Due to limited resources the GPS receiver and magnetometer will not be operated simultaneously. One proposed scenario is to operate the GPS receiver for one orbit per day, while operating the magnetometer during the remaining time. The magnetometer can operate in several different modes. A burst mode is used when the s/c passes the magnetic poles, while a nominal mode is used during the remaining part of the mission.

Boom Design

For a mission performing precise measurements of the Earth's magnetic field it is necessary to place the magnetometer some distance away from the s/c in order to minimize the noise from the satellite body. For a Cubesat mission such as DTUsat the required boom length has been estimated to 20 cm (s/c surface to boom tip). Two different designs will be considered: A telescopic boom made from carbon fiber and a miniature version of the Ørsted satellite boom. Each design is shown on the illustration below. Both designs will be stowed in the cubesat during launch and will be deployed by melting a string. It is envisaged that the mechanism used to deploy the antennas, similar to the one used on the first DTUsat, can be reused. If necessary two release mechanisms, one on each end of the wire, can be used for redundancy.

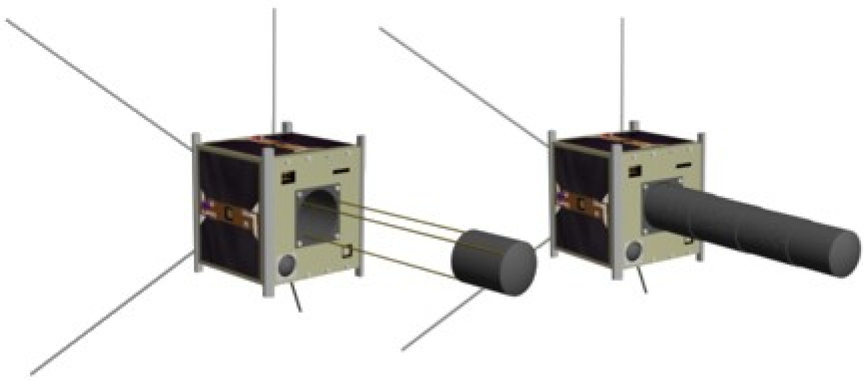

Figure 2 - DTUsat with two different boom designs
(left:Miniature Ørsted boom; right: Telescopic boom)

The telescopic boom will consist of 4 elements that will be deployed by a strong spring. A slightly conical design of the cylinder elements will ensure the rigidity and stability of the boom in the deployed position.

The Ørsted boom consists of three 1x1 mm^2 longerons made of an epoxy / fiber glass compound. They are fixed at the bottom of the well in the cubesat, and mounted through hinges on the top mercedes-structure of the boom. The longerons are very flexible allowing the complete structure to be stowed in a very small space. The spring-like properties of the longerons ensure that the boom will be unfolded to a fairly rigid structure.

Mass and Volume Requirements

The following table shows the volume and mass requirements of the MAGiC payload. Only one of the two boom designs will be selected for implementation.

Sensor head (mass including cylinder)	25 x 25 x 45 mm^3	50 g	
Ørsted-style boom	~ 40 x 40 x 55 mm^3	~ 25 g	] or
Telescopic carbon fiber boom	~ 50 x 50 x 60-70 mm^3	~ 40 g	
Passive GPS patch antenna	25 x 25 x 4 mm^3	9 g	
PCB w/electronics	~ 50 x 90 x 8 mm^2	~ 100 g	
Flaps		~ 25 g	
Harness		~ 15 g	
Subtotal		**224 - 239 g**	
10 % margin for partly new design		23 g	
Total		**247 - 262 g**	

Communication Requirements

The magnetometer can be run in several different modes, some that may be interesting for this mission are:

Mode	Resolution @ Frequency	Scalar measurements	Vector measurements
Burst	20 bit res @ 50 Hz	3042 bytes/min	9046 bytes/min
Nominal	22 bit res @ 10 Hz	642 bytes/min	1846 bytes/min
High-res	24 bit res @ 1 Hz	102 bytes/min	226 bytes/min

This amount of data includes magnetic measurements, house keeping data (2 temperatures and 2 voltages), status information, a time stamp and protocol overhead. The calculations are based on the ESA ECSS-E-70-41A protocol, packet size equals one minute of measurements, and data compression is utilized. However for vector measurements attitude information is required, which is not included in the data calculations. Note that data compression based on offset/deltas requires that the s/c is not spinning too fast.

The GPS will generate 626 bytes per 10 minutes, including protocol overhead.

When the GPS is operating no attitude information is required. Depending on the orbit of the satellite the window for communication varies drastically.

Simulations using STK based on a sun synchronous orbit and a minimum elevation angle of 10 degrees result in the following windows:

Altitude	450 km	650 km	850 km
Communication Window	23 min / day	39 min / day	55 min / day

Although DTUsat was launched in a sun synchronous orbit with an altitude of 818x830 km, the following calculations are based on a 650 km orbit, and thus communication can take place during several windows for a total of 39 minutes per day.

Assuming a TM link of 9600 bps, an average downlink window of 39 minutes per day and allocating 25% of the downlink capacity for the payload (as specified on www.dtusat.dtu.dk) results in the possibility of transferring 702000 bytes per day. Assuming the GPS is turned on for one orbit per day this means that the magnetometer can be operated for the following durations:

Mode	Resolution @ Frequency	Scalar measurements	Vector measurements
Burst	20 bit res @ 50 Hz	3,8 hours/day	1,28 hours/day
Nominal	22 bit res @ 10 Hz	18 hours/day	6,3 hours/day
High-res	24 bit res @ 1 Hz	114 hours/day	51 hours/day

Platform Requirements

Apart from the mass and volume requirements already mentioned in a previous section, the MAGiC payload requires the following to be available from the satellite bus:

Power Requirements: Operating at 10 Hz, the magnetometer payload will consume about 200 mW, when operating at 50 Hz, the power consumption will be about 250 mW. Scalar and vector measurements consume the same amount of power. However, due to the limited downlink capacity the magnetometer will not be turned on continuously in burst mode, but will be operating continuously, except when the GPS is operating.

The GPS correlator and RF front-end are estimated to consume less than 250 mW when operating. The GPS system is required to operate only for short intervals, for instance one orbit per day, and is not required to be operated at the same time as the magnetometer.

Onboard Computer Requirements: The onboard computer will work as storage for the magnetometer data, and will be utilized to calculate the position from the correlator data. As correlation is performed in the FPGA the requirements on the OBC is limited, a few MIPS is expected. Note that when the GPS is operating the OBC does not need to perform propagation to estimate the current position.

Attitude and Orbit Determination Requirements: For scalar measurements there are no requirements for attitude determination. In order to utilize the vector measurements attitude determination better than 1° is required. If possible 0.1° is preferable. This can for instance be achieved by the DTUsat sun sensors for the sunlit part of the orbit. A magnetometer can be used to perform coarse attitude determination during eclipse periods.

Orbit determination will be performed from the GPS receiver within the MAGiC payload.

Attitude and Orbit Control Requirements: The attitude does not need to be very well controlled, as long as the s/c is not spinning unreasonably fast, and the parameters can be reasonably well determined as described in the previous paragraph. Again, since we are performing measurements of the magnetic field, ACS based on permanent magnets is not possible. On the other hand attitude control based on magnetotorquers can be used but may only be operated at known intervals in order to correlate to the magnetometer data. Orbit control is based on air drag using flaps on the satellite.

Other Requirements: The s/c bus must be designed to minimize disturbances on the magnetic measurements. Therefore a magnetic cleanliness program must be implemented.

Conclusion

The combined magnetometer and GPS payload proposed here is useful, not only for educational purposes, but also for scientific purposes, as data for studying of field aligned currents will solve the time/space ambiguity in the case of using two satellites. The payload also provides data for scalar measurements for monitoring the earth's magnetic field. Furthermore the combined miniature magnetometer and GPS receiver are instruments that have great potential for use on many future missions, including small, inexpensive missions for a continual study of the magnetic field of the Earth.

The GPS receiver will be developed by students with a supervisor from M&I, Ørsted-DTU. The magnetometer payload is a miniaturized version of an existing design, and will be done by M&I, Ørsted-DTU. Boom design may be done by mechanical students, but resources at M&I, Ørsted-DTU can be assigned to this part of the project. Scientific data management will be performed by students at the University of Copenhagen, under supervision from Danish National Space Center.

The payload proposed in this document is fairly ambitious. The mission will, however, still be useful if constellation control based on air drag is not implemented, for instance if the altitude of the orbit is too high. Likewise it is possible to launch only one satellite, but this means that redundancy will be lost, and that some of the scientific objectives will be descoped, for instance study of field aligned currents will not be able to distinguish the space/time ambiguity.