Feasibility of using platform magnetometers to observe and detect Space Weather events

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Executive Summary

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Introduction

Magnetometers are fundamental instruments used in planetary and space science. Magnetometers are able to measure the magnetic fields originating in the planet's interior, past fields encapsulated in rocks in the crust, as well as magnetic fields generated by the motion of charged particles in the plasma environments of ionospheres, magnetospheres and interplanetary space.

Currents in space plasma transfer energy over very large distances. The state of the Earth's magnetosphere is to a large extent dependent on the orientation and strength of the interplanetary magnetic field (IMF) just upstream. A southward orientation of the IMF enables magnetic reconnection between the IMF and magnetosphere, triggering geomagnetic storms and substorms. This is why IMF measurements in the Sun-Earth L1 point are essential for space weather modeling and prediction.

In the case of the plasma within the Earth's magnetosphere, currents are able to deposit significant energy in the Earth's upper atmosphere, causing ionization, heating and expansion of the neutral upper atmosphere, which in turn interacts with the charged particle environment in a complex, highly non-linear way. These processes induce variability in the level of atmospheric drag on satellites, as well as perturbations of radio communications, navigation signals and scientific observations relying on radio links. Currents in the ionosphere can also induce currents inside the Earth, affecting and possibly endangering man-made infrastructure, such as power lines and pipes. For these reasons, magnetometer measurements of ionospheric currents are essential observations in the field of space weather.

Due to the geometry and high altitude of magnetospheric and ionospheric current systems, satellite measurements are needed in addition to ground magnetic observatories, in order to reveal their detailed behaviour. Due to the large spatial extent of the currents, the variety of spatial scales of variability, as well as the sometimes very rapid fluctuations, adding simultaneous observations from many satellites will be extremely useful to enhance our understanding of space weather, and to be prepared to adjust our response to space weather in more sophisticated ways than is currently possible.

This is where the use of platform magnetometers comes in. On low Earth orbiting (LEO) satellites, magnetometers are often used as part of the attitude control subsystem. Although these instruments are not designed and implemented for space weather observation, they can nevertheless be used for this purpose.

In this study, data from the diagnostics magnetometers on LISA Pathfinder and the AOCS magnetometers of the ESA GOCE and Swarm satellites has been used (see Figure 1

Figure 1 The Billingsley 3-axis fluxgate magnetometers TFM100-S (left) of which 3 each are used as the 'FGM' instruments in the AOCS subsystems of Swarm and GOCE, and the TFM100G4-S, that was used as 'MGM' for magnetic diagnostics on LISA Pathfinder.

Mission	Instrument	dimensions	mass
Swarm	VFM	sensor: 8.2 cm diameter, processing unit: 10×10×6 cm	280 / 750 g
Swarm	TFM100-S	3.66×3.58×15.44 cm	200 g
GOCE	TFM100-S	3.66×3.58×15.44 cm	200 g
LPF	TFM100G4-S	3.51× 3.23×8.26 cm	100 g

Table 1 Some characteristics of selected scientific and platform magnetometers.

and Table 1), to analyse the performance and limitations of such instruments, for space weather use.

The Swarm satellites also each carry two scientific magnetometers: the ASM (absolute scalar magnetometer), providing a highly accurate absolute reference, and VFM (vector field magnetometer), providing very accurate 3-axis vector measurements. The satellites were specifically designed for making measurements of the highest possible accuracy. This allowed us to assess the performance of the platform magnetometers in an ideal environment, and against a highly accurate reference. The GOCE satellite is used as a test case of a mission that was not designed with magnetic cleanliness and space weather measurements in mind, but that can nevertheless contribute to this purpose.

LISA Pathfinder

The investigations of LISA pathfinder data starts with the downloading of magnetometer, orbit and attitude data from the LISA Pathfinder Legacy Archive website. The data from each of the three axes on the four magnetometers contain considerable biases of several hundred nT, with respect to the IMF, which normally has a strength of only a few nT. The fact that these biases show similarities in terms of magnitude and timing of changing magnitude, for the four instruments, indicates that they are mainly due to stray fields originating from other equipment on the spacecraft. The timing of bias changes is furthermore closely linked to times of switching between the various experiments. In general, the biases can be considered to be piecewise constant, or at the worst, show a linear drift over time, so that the measurements are easily corrected. A simple removal of a daily mean bias already brings the magnetometer readings close together, and close to a signal that resembles the IMF. This is shown in Figure 2, in which 4-minute averages of the raw data sampled at 0.25 Hz are plotted. Only for a period of about 2 hours, a clear discrepancy between the 4 magnetometer readings is visible in this Figure, which can be traced back to spacecraft operations. The

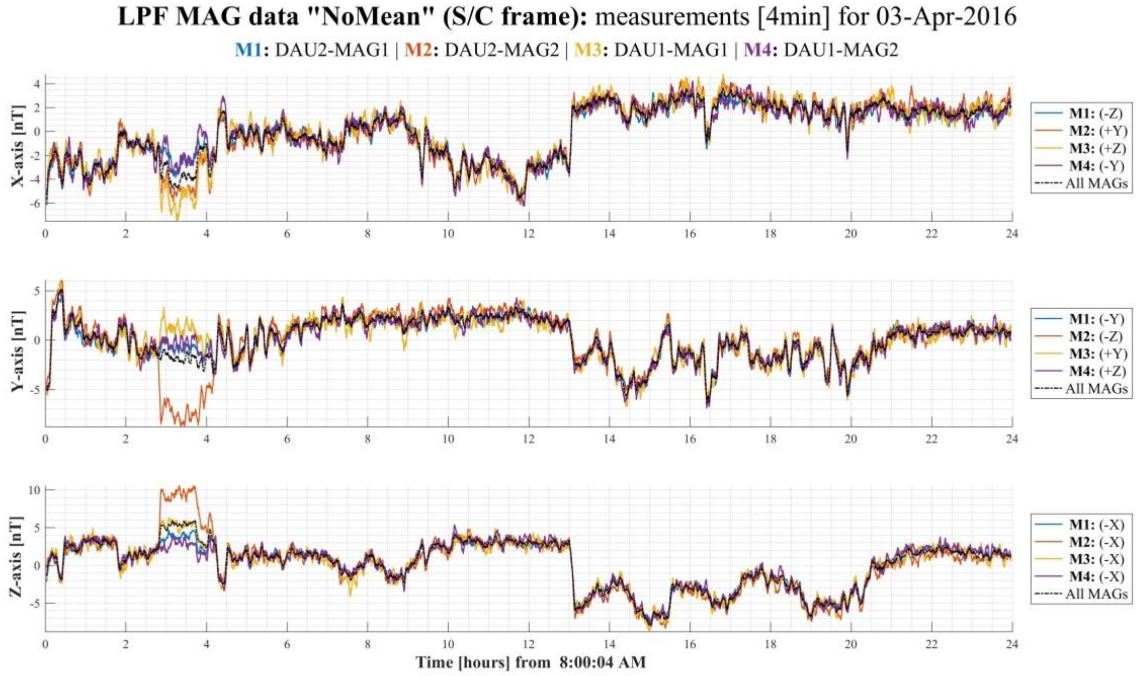

Figure 2 Measurements by the 4 individual magnetometers on LISA Pathfinder. For each of the 4 magnetometer's 3 axes, a daily mean has been removed from the measurements.

day of data plotted in this Figure was specifically selected to show this. On most days of our analysis, such discrepancies were not present.

Figure 3 shows a comparison of the readings from one of the LPF magnetometers with science data from the NASA ACE mission, which is dedicated to measuring the strength and orientation of the IMF. It is clear that both magnetometers measure the same variations in IMF. An analysis with the help of ACE solar wind speed data has shown that the time shift in the IMF measurements between the missions can be completely attributed to the different positions of LPF and ACE in their respective orbits around the Sun-Earth L1 point.

During the LPF mission a total of four magnetometer-carrying spacecraft were available in orbit around L1: WIND, ACE, DSCOVR and LPF. The three other missions were dedicated to measuring the IMF, and were therefore better calibrated and provided higher data rates. The LPF magnetometer measurements therefore do not offer unique measurements of how the IMF affects Earth, but the data is nevertheless very valuable in order to study spatial scales of IMF variability at L1.

Although the study report focuses only on the first three months of LPF data, a publication on the analysis of the full mission duration is being planned.

Swarm and GOCE

For Swarm and GOCE, platform magnetometer and torquer data was obtained from housekeeping data archives, while precise orbit and attitude information was available from the mission's science data products. For GOCE, also thruster activation data was used, that had already been available for thermosphere data product processing.

Figure 4 provides an overview of time series of various data during this calibration process.

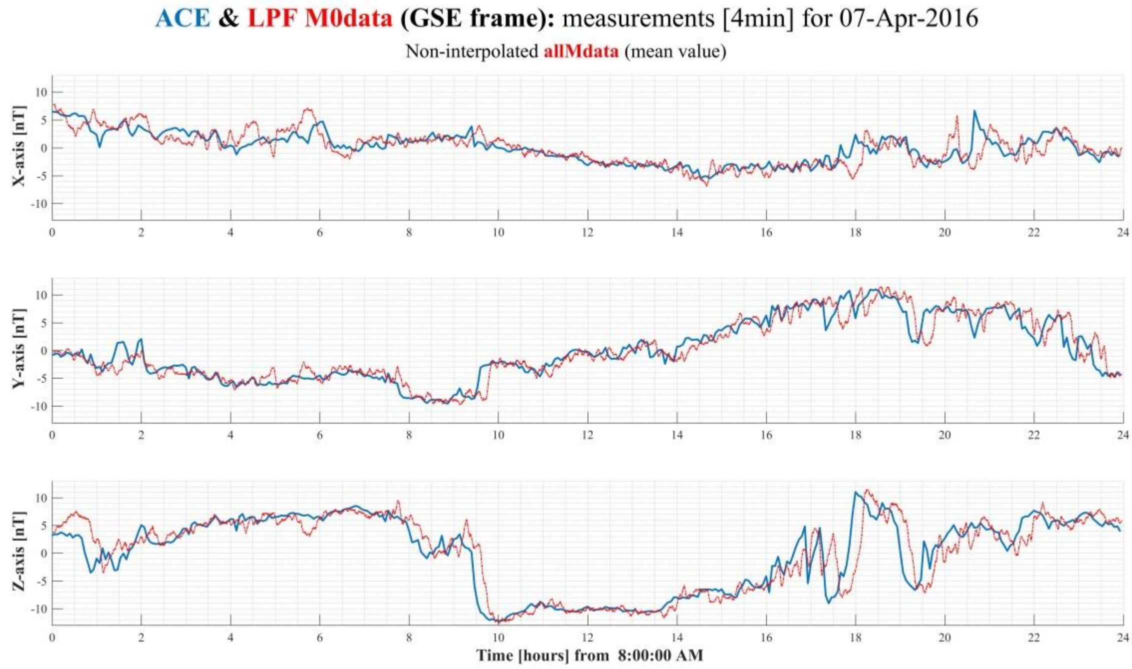

Figure 3 Comparison of the mean-removed measuresements of one of the LPF magnetometers with those of the well-calibrated ACE satellite magnetometer.

	X	Y	Z
Uncalibrated FGMa	104.94	442.07	274.54
Added calibration	57.20	15.01	40.91
Added MTQ correction	52.13	13.93	32.82
Added orbit correction	23.36	9.97	17.78
VFM	5.89	10.43	9.24

Table 2 Median Absolute Deviation (MAD) of calibration residuals (in nT) with respect to CHAOS6 on Swarm Alpha, for uncalibrated and several applied calibration and characterization steps. Comparison was done in FGM's reference frame.

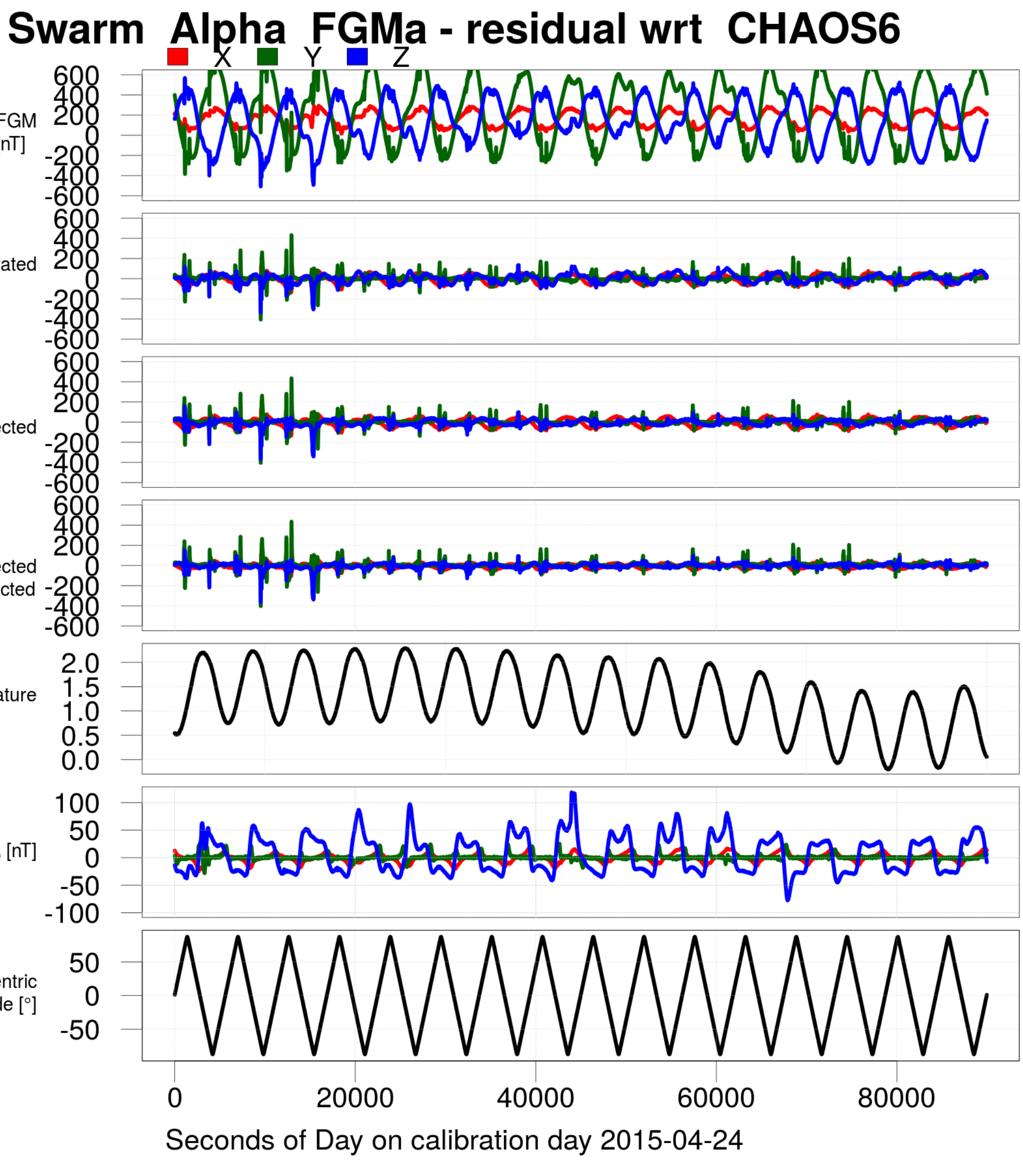

Figure 4 Evolution of residuals for Swarm Alpha (FGMa - CHAOS6) by applying calibration steps. 1st panel (FGMa), 2nd panel (FGMa, calibrated), 3rd panel (FGMa, calibrated, MTQ corrected), 4th panel (FGMa, calibrated, MTQ Corrected, orbit corrected). FGMa temperature, effect of Magneto-Torquers (MTQ) and Geocentric Latitude have been added in the last panels.

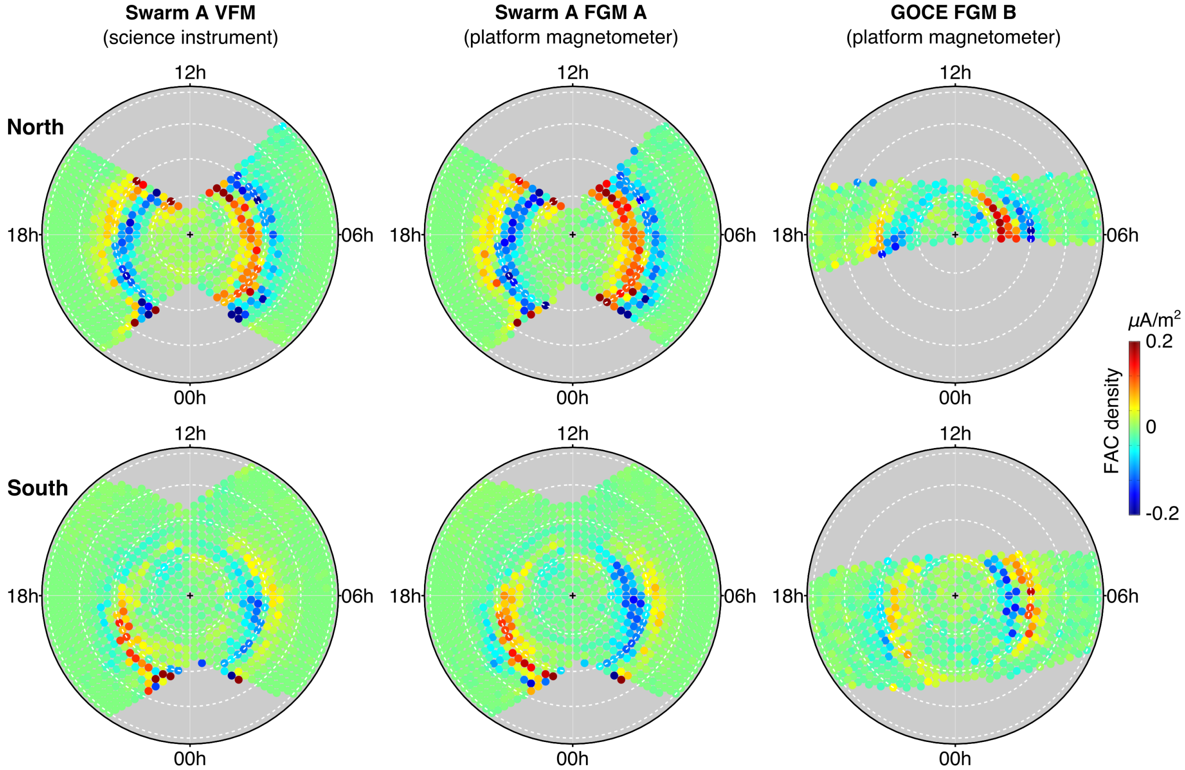

Figure 5 Field-aligned currents determined from GOCE and Swarm calibrated magnetometer data, binned by magnetic latitude and local solar time.

Table 2 provides a comparison of CHAOS-6 residuals for uncalibrated and calibrated Swarm FGMa data, as well as equivalent data from the VFM science instruments. It can be seen that the final calibrated FGMa residuals are of the same order of magnitude as the VFM residuals, although somewhat higher for the X- and Z-axes, as expected. Note that these numbers include the natural variability of the magnetic field, for example due to magnetospheric and ionospheric currents during quiet and moderate days. The signal of interest due to field-aligned currents during space weather events is many times the level of these residuals.

Calibration of the GOCE platform magnetometers was performed in a similar way. Although of course a scientific magnetometer was not available on GOCE, the data was compared with that of the CHAMP satellite for verification. The calibrated platform magnetometer data of both Swarm and GOCE was subsequently processed, using the Swarm Field-Aligned Current processor.

Figure 5 shows maps, in geomagnetic local time and latitude coordinates, of the average pattern of field-aligned currents from the AOCS instruments, as well as from the Swarm VFM instrument. The Figure shows that all instruments were able to nicely capture the expected pattern of region 1 and region 2 field-aligned currents.

As an example of the multi-instrument space weather case studies that were performed, Figure 6 shows GOCE space weather data, IMF data and ground-magnetometer based geomagnetic activity indices. The GOCE data includes the new field-aligned currents, for 2.5 days surrounding the onset of the April 5, 2010 geomagnetic storm, as well as thermosphere density and wind data derived from the satellite's accelerometer measurements.

We can see clearly in this Figure that the field-aligned currents and auroral electrojets are driven by the interplanetary magnetic field. It is well known that the energy exchange

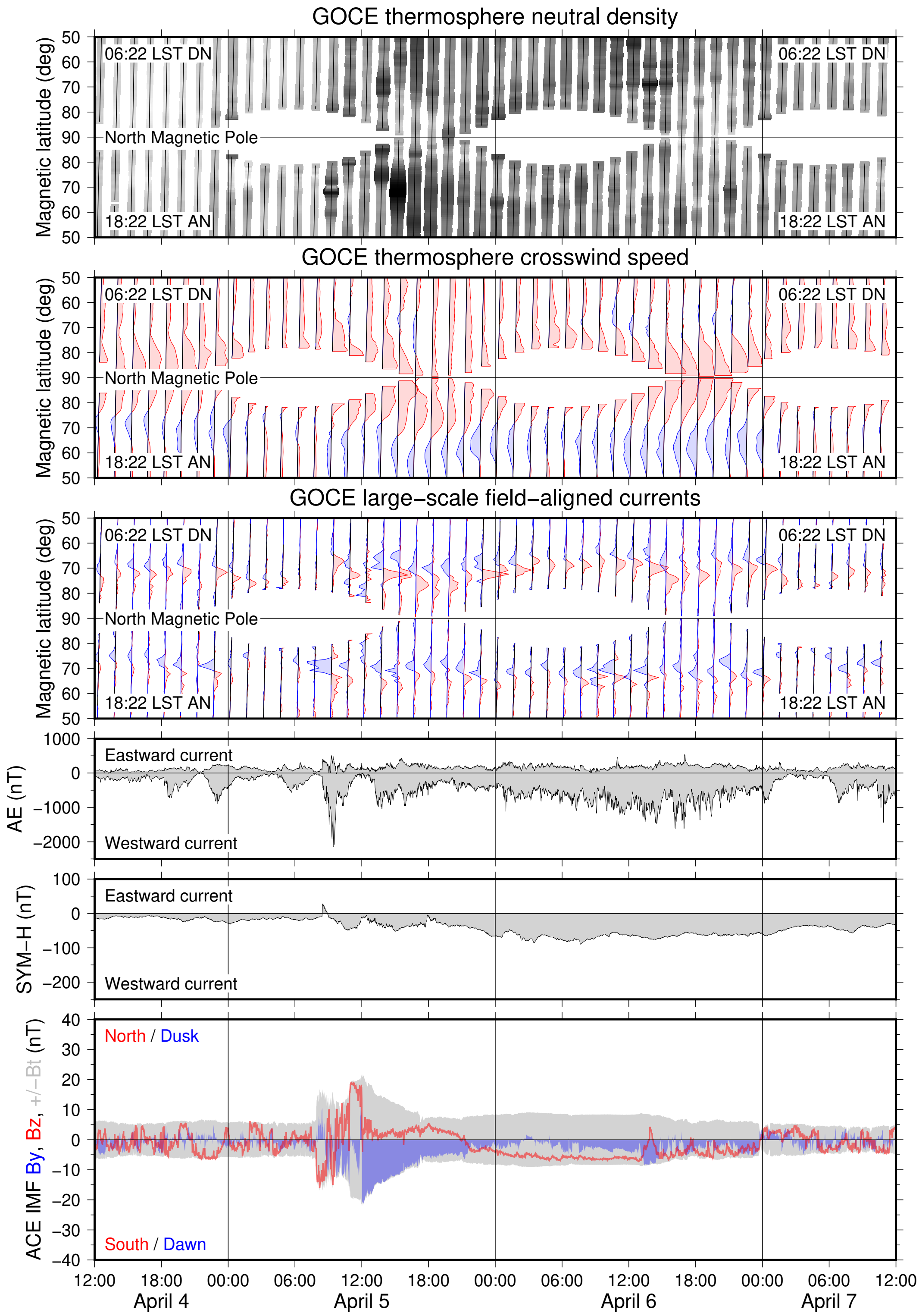

Figure 6 Detailed view of GOCE data surrounding the April 5, 2010 geomagnetic storm. The horizontal space between orbits corresponds to a field-aligned current density of 2 μA/m^2, a wind speed of 800 m/s and density of 50 g/km^3.

between the solar wind and magnetosphere, and the magnetosphere and ionosphere is especially effective during a southward pointing IMF.

The field-aligned currents measured by GOCE feed into the horizontal currents, as indicated by the increase in the AE index, measured by ground magnetometers at high latitudes, during times of high field-aligned currents. These currents cause extensive Joule heating of the upper atmosphere as well as heating due to particle precipitation. This heating is evident from the increase of the thermosphere neutral density, in the top panel of both Figures. The heating causes a redistribution of the mass in the thermosphere, which induces wave activity, which is also clearly visible in the density plot in the form of density enhancements spanning up to a few tens of degrees of latitude at most. Because the waves are traversing the globe, these enhancements occur at different latitudes as the storm progresses.

The mass redistribution due to the heating by the currents, as well as the motion of the ions, also clearly induces changes in the thermospheric wind, as measured by GOCE. The general pattern, seen in Figure 6 is that during times of high activity, the wind speed increases in the polar cap region (magnetic latitudes above 80 degrees). A return flow pattern at magnetic latitudes in the 60-70 degrees magnetic latitude range on the dusk side is also enhanced, and moves equatorward, even reaching 50 degrees North.

Conclusions and recommendations

The project has clearly shown, through the analysis of data from the Swarm, GOCE and LISA Pathfinder missions, that platform magnetometer data are extremely useful to complement science class magnetometers in the detection and characterization of field-aligned currents and the strength and direction of the interplanetary magnetic field. The somewhat lower data product quality from these instruments, when compared to reference instruments and missions, are due to the lower instrument specifications, differences in platform handling (lower sampling rate in telemetry) and higher level of stray field perturbations. But in all cases the resulting data are entirely acceptable for the selected purposes, when augmenting high accuracy measurements made by reference missions. The usefulnesss of the data has been demonstrated in several space weather case studies. It should be noted that the reference missions, such as CHAMP and Swarm, and the overall field models derived from their measurements, are essential for calibration of the platform instruments. The increased temporal/spatial sampling that is obtained by having additional satellites is of major benefit.

Within the scope of this project, we have only been able to study some first cases. The results of the study make it clear that for those cases, the data processing is mature enough for the data to be used in space weather and space science analysis, and that expansion to space missions with similar design characteristics is warranted.

Further study is needed, however, on the obtainable performance when using platform magnetometer data on mechanically and electrically more complex satellites, such as those with reaction wheels and rotating solar arrays. This needs to be further investigated.

In addition, as follow-on activity it would be particulary interesting to partner with one or more large European space contractors, to assess the cost aspects of integration of the use of platform magnetometers into a dedicated space weather data stream, during mission preparation phases. It is expected that this cost will be significantly lower than making adjustments to data streams for already operational missions, and ceretainly lower than having dedicated magnetometer space weather satellites.

The results of the project, and the recommendations put forward here, and much more extensively in the final report, should provide a baseline for such further studies.