The MAGIC of CINEMA: First in-flight science results from a miniaturised anisotropic magnetoresistive magnetometer

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Abstract. We present the first in-flight results from a novel miniaturised anisotropic magnetoresistive space magnetometer, MAGIC (MAGnetometer from Imperial College), aboard the first CINEMA (Cubesat for Ions Neutrals Electrons and MAgnetic fields) spacecraft in low Earth orbit. An attitude-independent calibration technique is detailed using the International Geomagnetic Reference Field (IGRF), which in the case of the outboard sensor is temperature dependent. We show that the sensors accurately measure the expected absolute field to within 2% in attitude mode and 1% in science mode. Using a simple method we are able to estimate the spacecraft's attitude using the magnetometer only, thus characterising CINEMA’s spin, precession and nutation. Finally, we show that the outboard sensor is capable of detecting transient physical signals with amplitudes ∼20-60 nT. These include field aligned currents at the auroral oval, qualitatively similar to previous observations, which agree in location with measurements from the DMSP and POES spacecraft. Thus we demonstrate and discuss the potential science capabilities of the MAGIC instrument onboard a Cubesat platform.

1 Introduction

Data from magnetometers on spacecraft are typically used for one, or both, of two purposes: for the determination of the spacecraft attitude; and for measurement of physical processes local to, or indeed far from, the spacecraft. No measurement is perfect and the measurement of magnetic fields is particularly challenging given their low values and the particularly small nature of the variations that must be detected for some applications; see e.g. Acuña (2002) for a historical description of space magnetometer techniques. All sensor and spacecraft environments have different capabilities and every application of magnetometer data has different requirements in terms of cadence, accuracy, noise etc. thus the intended use cannot be isolated from the methods used to recover accurate magnetic field measurements, since one drives the other.

Attitude control knowledge often results in rather coarse requirements of just a few degrees (e.g. Natanson et al., 1990), corresponding to an absolute accuracy in a given field component ∼2000 nT or greater at low Earth orbit (LEO), equivalent to at least ∼4%. In contrast, for scientific applications the requirements are more stringent and depend on the precise goal: for example the ESA Swarm mission aims for sub-nT absolute precision (Friis-Christensen et al., 2006). However, if the scientific requirement is to be able to detect transient signals in magnetometer data at LEO, such as field-aligned currents at the auroral oval (e.g. the review of Baumjohann, 1982), then such absolute precision in the overall magnetic field is not required. It is therefore important to assess what it is possible to achieve with a magnetometer, given the quality of the sensor and the environment it is in.

Cubesats offer the possibility of low-cost spacecraft in orbit around the Earth equipped with scientific instruments e.g. for space weather monitoring purposes (c.f. Li et al., 2013). The Cubesat specification, however, constrains both dimensions (a three-unit Cubesat is 10 cm × 10 cm × 30 cm with no protuberant parts at launch) and total mass (∼4 kg for 3U) (e.g. Selva and Krejci, 2012). Furthermore, the dimensions restrict the amount of available power from solar cells to ∼2 W per unit (e.g. Bouwmeester and Gud, 2010). In terms of magnetic field measurements, typical fluxgate magnetometer instruments used for space plasma physics applications (e.g. Balogh et al., 1997) are thus unsuitable for use on
Cubesats since they exceed all of these constraints. Additionally, a full magnetic cleanliness program (e.g. Ludlam et al., 2008) is not possible with Cubesats, thus the raw data will be contaminated to some degree with fields of spacecraft origin. Therefore, in designing magnetometers (or indeed any scientific instrument) for Cubesat platforms there must be a trade-off in mass, power and/or precision levels which will affect the instruments’ capabilities.

Magnetometers flown on Cubesats thus far have typically been used for attitude purposes (e.g. Sarda et al., 2010). However, there may also be potential science applications for magnetometers on such spacecraft: Quakesat’s single-axis search-coil AC magnetometer has detected lightning-generated whistler mode waves (10-1000 Hz) and ELF bursts (10-150 Hz) simultaneously observed on the ground which were possibly due to earthquakes (Bleier and Dunson, 2005); and DICE’s DC vector magnetometer has detected ∼200 nT magnetic deflections due to field-aligned currents at the auroral oval during a marginally geomagnetically active period (Fish et al., 2014). The scientific capabilities that such lower quality sensors (necessitated by the constraints of Cubesats) offer are as yet not entirely clear. In this paper we assess one such example from the first CINEMA (Cubesat for Ions Neutrals Electrons and MAgnetic fields) spacecraft.

CINEMA is a 3U Cubesat equipped with avionics and science instruments (Vega et al., 2009) launched into low Earth orbit (LEO) on 13 September 2012, with orbital elements shown in Table 1 as a secondary payload from a P-POD dispenser. Two additional near-identical CINEMA Cubesats were launched on 3 November 2013 which we do not discuss in this paper. The spacecraft’s science instrumentation includes MAGIC (MAgnetometer from Imperial College), two novel miniaturised vector DC magnetometers using anisotropic magnetoresistive (AMR) sensors (Brown et al., 2012, 2014). One sensor, the inboard (IB), is contained within the spacecraft whereas the other, the outboard (OB), is on the end of a 1 m stacer boom in order to reduce the effect of spacecraft fields on the measurements. The two sensors and their relative axes are illustrated in Figure 1. Brown et al. (2014) provide a summary of the modes of operation of the instrument. The requirements of the MAGIC instrument are twofold. Firstly, the sensors (in particular the inboard) should provide measurements of Earth’s magnetic field at a level of accuracy suitable for attitude-determination purposes (Vega et al., 2009). Secondly, the outboard sensor should be capable of detecting transient science signals in addition to Earth’s field e.g. magnetic perturbations associated with magnetospheric current systems, important for space weather monitoring (c.f. Clausen et al., 2012).

Unfortunately, there have been a number of problems with the spacecraft’s systems hence only a limited amount of data has been retrieved from the first CINEMA spacecraft. In this paper we present the first in-flight MAGIC results from the two longest time intervals of MAGIC data obtained for which the onboard clock was reliable. In section 2 we describe the attitude-independent calibration procedure used on the raw data, through use of the International Geomagnetic Reference Field (IGRF). Following calibration, the attitude of the instrument is estimated using a simple magnetometer-only method as described in section 3. Finally, section 4 discusses the small amplitude (∼20-60 nT), transient (>21 mHz) science signals detected by MAGIC in science mode. These are revealed to be field-aligned currents at the auroral oval, which are corroborated by measurements from the DMSP and POES spacecraft. We, therefore, assess the science capabilities of the MAGIC sensors flown on CINEMA through

| 27 Sep 2012 | 19 Nov 2013 |
|------------|-------------|
| Perigee Altitude (km) | 478 | 495 |
| Apogee Altitude (km) | 786 | 751 |
| Inclination (°) | 64.68 | 64.67 |
| Period (min) | 97.35 | 97.18 |
| ΔTTLLE (h) | 27 | 37 |

| MAGIC Mode | Attitude* | Science |
|------------|-----------|---------|
| Sensor | IB | OB | |
| Duration (min) | 231 | 46 |
| Cadence (s) | 10-16 | 0.128 |
| Kp | 1.2 | 1.0 |
| Dst (nT) | -6 | 8 |
| AE (nT) | 48 | 31 |

Table 1. Summary of the MAGIC data used in this paper including the orbital elements of CINEMA, MAGIC modes and geomagnetic indices. *The attitude mode data used in this paper was taken from housekeeping data, hence has lower time resolution than specified in Brown et al. (2014).
the use of simple magnetometer-only methods and discuss the possibilities of utilising sensors similar to MAGIC for science purposes in the future.

2 Attitude-Independent Calibration

2.1 The Calibration Problem

The general calibration problem can be written as (e.g. Kepko et al., 1996)

\[
\begin{pmatrix}
  b_x \\
  b_y \\
  b_z
\end{pmatrix} = \begin{pmatrix}
  g_x \sin \theta_x \cos \phi_x & g_x \sin \theta_x \cos \phi_y & g_x \cos \theta_x \\
  g_y \sin \theta_y \cos \phi_x & g_y \sin \theta_y \cos \phi_y & g_y \cos \theta_y \\
  g_z \sin \theta_z \cos \phi_x & g_z \sin \theta_z \cos \phi_y & g_z \cos \theta_z
\end{pmatrix} \cdot \begin{pmatrix}
  B_{x,sc} \\
  B_{y,sc} \\
  B_{z,sc}
\end{pmatrix} + \begin{pmatrix}
  O_x \\
  O_y \\
  O_z
\end{pmatrix}
\]

where \( b \) consists of the measured magnetic field components from the sensors and \( B_{sc} \) are the real magnetic field vectors in orthogonal, spacecraft fixed coordinates. The gains \( g \) are the scale factors between the physical magnetic field values and the measured values; measurements are always in Volts but conventionally a preliminary scale factor (23,000 nT V\(^{-1}\)) is applied so that the gains are of order unity and dimensionless. The angles \( \theta \) and \( \phi \) correspond to the orientation of each sensor component. Note that the sensor triad is approximately orthogonal by construction i.e. \( \theta \sim (90,90,0)° \) and \( \phi \sim (0,90,0)° \), but in-flight calibration can often determine orientation to better than 0.1° i.e. better than the triad can be constructed on the ground, hence non-orthogonality must be allowed for in the calibration process. Finally, the offsets \( O \) are systematic errors in the measured fields either inherent to the sensor or due to spacecraft fields. The calibration parameters are, however, not constant over time and will drift depending on the quality of the sensor and the environment it inhabits e.g. the Cluster fluxgate magnetometers have been found to be remarkably stable with long-term offset drifts of 0.2 nT per year and a temperature dependence of 0.2 nT °C\(^{-1}\) (Alconel et al., 2014).

2.2 Method

While an initial determination of calibration parameters is usually performed on the ground before launch, unfortunately this was not done for either the inboard or outboard MAGIC sensors that were flown on CINEMA-1. Therefore the only calibration was determined in-flight, as detailed here. AMR sensors cannot achieve the ultra-high precision and stability of higher quality magnetometers such as fluxgates, indeed LEO spacecraft often utilise multiple sensors of different measurement types and capabilities in order to achieve the required precision (e.g. Olsen et al., 2003). Consequently, we aim for a calibration of sufficient quality that spin tone and spacecraft-generated fields do not significantly affect the requirements of the MAGIC instrument i.e. the ability to determine spacecraft attitude and detect transient physical signals.

Most space plasma scientific spacecraft are spin stabilised and spectral methods are applied to determine calibration parameters (Kepko et al., 1996), even when the physical field is not known, since incorrect determination of the calibration parameters results in residual spin tones in the de-spin data. However, in LEO the magnetic field changes rapidly due to the spacecraft motion (~50-90 nT s\(^{-1}\)), hence the assumption in this method of a constant field over a spin period does not apply. Furthermore since the spacecraft’s attitude is to be determined from the magnetometer data (see section 3), we must as a first instance use an attitude-independent method of calibration (e.g. Foster and Elkaim, 2008; Springmann and Cutler, 2012). Such methods rely on knowledge of the magnitude of the expected geomagnetic field at the spacecraft location.

We determine the spacecraft position at each time from a two-line element (TLE) set using the SGP4 orbit propagator (Hoots et al., 2004; Vallado et al., 2006). The average time difference from the TLE epoch (the time at which the orbital parameters are referenced) \( \Delta T_{\text{LE}} \) is noted in Table I. The use of the propagator thus requires the onboard clock be well calibrated, a factor which limited the number of obtained data intervals from MAGIC which could be used. From the spacecraft positions we calculate the expected field from IGRF \( \mathbf{B} \). This model of Earth’s inherent magnetic field is accurate to around 5 nT at LEO on average (Maus et al., 2005). However, since IGRF does not include contributions to the magnetic field from magnetospheric current systems, calibration parameters should strictly be determined during geomagnetically quiet times. This was the case for the two intervals used in this paper, as shown in Table I.

All MAGIC datapoints out of the range of the instrument and large amplitude spikes were removed before calibration. The attitude-independent calibration procedure used is an iterative procedure. First an initial guess of the (assumed constant) offsets, gains and angles are made. Equation II is then inverted at each time \( t \) yielding estimates of the calibrated magnetic field vectors in spacecraft fixed coordinates \( B_{sc} \). The square difference in field magnitude from IGRF is then calculated as

\[
\epsilon = \sum_{i=1}^{N} \left( |B_{sc}^i| - |B^i| \right)^2
\]

where \( N \) is the number of datapoints. This algorithm is then iterated in order to minimise \( \epsilon \), using the Nelder and Mead (1965) method to obtain successive estimates for the calibration parameters. This is repeated until stable solutions (\( \leq 0.01\% \)) are obtained, typically taking \( \sim 1,500 \) iterations.
2.3 Results

2.3.1 Attitude Mode

Raw attitude mode data from the inboard MAGIC sensor is shown in the second panel of Figure 2 with a comparison of the measured field magnitude (grey) and IGRF given in the third panel. We despiked the 10-16 s cadence data by removing any datapoints which differed from the previous by more than 10,000 nT. While the uncalibrated data showed similar variations to IGRF over long timescales, there are shorter timescale oscillatory variations in the data due to the under-estimated calibration parameters. Furthermore, MAGIC generally overestimated the field strength in the raw data. We applied the attitude-independent calibration procedure to the data, with the determined calibration parameters displayed in the first row of Table 2.

In order to reliably extract calibration parameters from attitude independent procedures, the data must have good coverage of the attitude sphere, given by the components of calibrated data normalised by the field magnitude (Foster and Elkaim, 2008). We estimate the data coverage by binning the attitude sphere into 192 equal area bins (cylindrical projection), finding that 69% of these contained datapoints. Furthermore we use a $\chi^2$ test for complete spatial randomness to quantify clustering of the data on the attitude sphere, finding $\chi^2 \sim 4\chi^2_{0.025}$ where $\chi^2_{0.025}$ corresponds to the upper limit of the 95% confidence interval for a Poisson distribution hypothesis. We therefore deduce that, while there was some clustering, there was fair coverage of the attitude sphere over this interval.

The resulting calibrated magnetic field strength is shown in blue in Figure 2 (third panel), with the percentage error displayed in the fourth panel. The root mean squared deviation (RMSD) from IGRF of the calibrated attitude mode data was 1.95% over this interval. These differences are likely due to drifting or time-varying offsets and gains not captured by our constant calibration procedure, since the differences (fourth panel) are oscillatory and close to the periods (and harmonics thereof) of the oscillations seen in the raw data (second panel). Nonetheless, the level of accuracy in the absolute field is sufficient for attitude determination, as we demonstrate in section 3. The despun attitude mode data is shown in the bottom panel of Figure 2.

2.3.2 Science Mode

Science mode data from the outboard MAGIC sensor is shown in Figure 3 in the same format as before. Again, before calibration we removed data points out of range and despiked the 128±4 ms resolution data using a threshold difference of 500 nT. It is immediately clear that from oscillations in $|b|$ that the offsets were larger for this interval than for the attitude mode data. Furthermore, while the inboard sensor underestimated the geomagnetic field, the outboard generally underestimated it. We applied the attitude-independent calibration procedure only on the first datapoint of each packet (5 s cadence) since these are the datapoints for which times are given (all other times were interpolated), resulting in the parameters listed in the second row of Table 2. Indeed the determined offsets and gains agree with our initial hypothesis in comparison to the attitude mode data. The offsets (which include DC fields of spacecraft origin) for this early development sensor are much larger (by at least a factor of 2) than those determined on the ground for subsequent further-developed AMR sensors (Brown et al., 2014), whereas the gains are within the expected range.

The constant calibration parameters for the science mode data yield a RMSD from IGRF of 3.07%. While this error is in part oscillatory, as with the attitude mode data, the field strength is significantly overestimated at the start of the interval and underestimated at the end. It is known that AMRs have a high dependency on temperature compared to fluxgates (Brown et al., 2014), therefore a thermistor was packaged with the outboard sensor so that temperature effects could be taken into account. The top panel of Figure 4 indeed shows that the temperature of the sensor varied a lot over this interval, rising from around 70°C at the start to just under 100°C at the end, with some small oscillations also at similar periods to those seen in the magnetometer data. The large temperature variations are likely due to the sensor’s low thermal inertia since it was not potted as well as the fact that CINEMA had been in direct sunlight for ~3 days prior to this interval.

While the temperature dependence of all the calibration parameters for a sensor would ideally be determined on the ground before launch, Brown et al. (2014) showed that the offsets and gains of MAGIC AMR sensors have an approximately linear relationship with temperature and Fish et al. (2014) used a linear temperature relationship in their AMR ground calibration. Therefore, we subsequently applied a temperature dependent calibration to the science mode data to account for the large temperature drift during this interval. This was achieved by modifying the attitude independent procedure, requiring a linear relationship of the offsets and gains with the temperature measured by the thermistor at each time e.g. $O_x(t) = c_x T(t) + d_x$ where $O_x(t)$ is now a time-varying magnetometer offset, $T(t)$ is the temperature measured by the thermistor and $c_x$ and $d_x$ are the constants estimated through the iterative calibration procedure. The overall calibration parameters (raw → temperature calibrated) are listed in the third row of Table 2 and shown as a function of time in the bottom two panels of Figure 4. The gains have little temperature dependence and are extremely similar for all three sensor axes. The offsets, on the other hand, show a larger dependence on the temperature (particularly in one component), moreso than that determined for later developed sensors which were potted with epoxy resin to increase the thermal inertia of the sensors (Brown et al., 2014).
Figure 2. Attitude mode data from the inboard MAGIC sensors. From top to bottom: magnetic latitude (blue) and magnetic local time (orange) of CINEMA, raw data from the three sensors (x,y,z in blue, green, red) with field strength shown in black; comparison of the raw (grey) and calibrated (blue) data to IGRF (black); percentage error of the calibrated field strength to IGRF where the shaded area indicates the root mean squared error; comparison of despun calibrated data (solid) with IGRF (dotted) in GEI coordinates.

Table 2. List of determined calibration parameters. For temperature calibration, $T$ is in °C.
The temperature calibration removes the over (under) estimation of the field at the start (end) of the interval and also reduces the amplitude of oscillating deviations, as shown in red on the third and fourth panels of Figure 3. This calibration results in a RMSD from IGRF of 1.23%, indicated by the red area (Figure 3 fourth panel), which is just over 1.5× more accurate than the inboard sensor in attitude mode. In this paper we perform no further calibration on the science mode data, therefore we treat this RMSD as the absolute accuracy of the outboard MAGIC sensor in science mode. The data covered 85% of the attitude sphere (not shown) with less clustering than before ($\chi^2 \sim 2\chi^2_{0.025}$), thus the calibration parameters are likely reliable. Again we present the despun science mode data, using the method described in section 3, in the final panel of Figure 3.

3 Attitude Determination

Following the attitude-independent calibration of MAGIC, we wish to use the magnetometer data to estimate the spacecraft/sensor attitude at each data point.

3.1 Method

Upon deployment the spacecraft would have been randomly tumbling in its orbit. Whilst an attitude control system was developed for CINEMA utilising magnetorquers (Vega et al., 2009), unfortunately one of the torque coils was not operational meaning that CINEMA did not successfully detumble. A common method of spacecraft attitude determination is through comparing measurements of vector quantities in spacecraft fixed coordinates to reference vectors, such as IGRF in the case of magnetic fields. To uniquely determine the attitude at any time thus requires (at least) two independent vector measurements (e.g. Wertz, 1978). Had CINEMA successfully detumbled, the sun sensor would have provided a second vector in addition to the magnetic field (Vega et al., 2009). However, since this was not available we must therefore estimate the spacecraft attitude using the magnetometer data only.

To represent rotations we use unit quaternions $q = \langle \cos \frac{\Theta}{2}, \sin \frac{\Theta}{2} \hat{w} \rangle$, where $\hat{w}$ is the axis of rotation about which a rotation of $\Theta$ is applied. The rotation from the (calibrated) measured field $\mathbf{B}_{sc}$ in orthogonal, spacecraft fixed coordinates to IGRF $\mathbf{B}$ in the GEI frame at time $t^i$ is given by

$$\langle 0, \mathbf{B}^i \rangle = q_i \langle 0, \mathbf{B}_{sc}^i \rangle q_i^*$$

(3)

where $q^*$ is the conjugate quaternion. We know the family of possible solutions at each time.
\begin{align}
q_i(\Phi) &= \left< \cos \frac{\Phi}{2}, \sin \frac{\Phi}{2} \right> \left< \cos \frac{\Theta}{2}, \sin \frac{\Theta}{2} \right> \left( \mathbf{B}_i \times \mathbf{B}_i \right) \\
\cos \Theta &= \frac{\mathbf{B}_{sc}^i \cdot \mathbf{B}_i}{\left| \mathbf{B}_{sc}^i \right|} \tag{4a} \\
\cos \gamma &= \frac{\mathbf{B}_{sc}^i \times \mathbf{B}_i}{\left| \mathbf{B}_{sc}^i \times \mathbf{B}_i \right|} \tag{4b}
\end{align}

which corresponds to firstly a rotation from the observed to expected field, followed by some arbitrary rotation about the expected field by \( \Phi \). Inverting Equation 3 and taking the time derivative (indicated here by dots) gives

\[ \langle 0, \dot{\mathbf{B}}_i^e \rangle = \dot{q}_i^* \langle 0, \mathbf{B}_i \rangle q_i + q_i^* \langle 0, \mathbf{B}_i \rangle q_i + q_i^* \langle 0, \dot{\mathbf{B}}_i \rangle \dot{q}_i \tag{5} \]

that is changes in the measured magnetic field can be due to changes in the spacecraft’s attitude i.e. rotation or due to the real field changing i.e. spacecraft motion. In LEO the latter is significant, at \( \sim 50-90 \text{nT s}^{-1} \) for CINEMA.

It is clear from the data that CINEMA was spinning slowly e.g. in the attitude mode data (second panel of Figure 2) there were \( \sim 10 \) oscillations of the magnetic field over an entire orbit. Given the cadence of the magnetometer data, the attitude of the spacecraft should thus have only changed by a few degrees at most between each datapoint. We therefore implement a simple method of attitude estimation here, choosing the attitude quaternion \( q_i(\Phi) \) which best fitted the next data point i.e. the one which minimised the angle between \( q_i(\Phi) \langle 0, \mathbf{B}_i^e \rangle q_i^* \langle 0, \mathbf{B}_i \rangle \) and \( \mathbf{B}_i \). This method thus results in attitude estimates at each datapoint, accurate to a few degrees (c.f. Natanson et al. [1990]).

\subsection{3.2 Results}

\subsubsection{3.2.1 Attitude Mode}

Figure 5 shows the estimated attitude of CINEMA using the described method, represented as the three Euler angles

\[ q = \left< \cos \frac{\gamma}{2}, \sin \frac{\gamma}{2} \right> \left< \cos \frac{\beta}{2}, \sin \frac{\beta}{2} \right> \left< \cos \frac{\alpha}{2}, \sin \frac{\alpha}{2} \right> \tag{6} \]

revealing that the spacecraft was spinning about the IB x-axis at \( \sim 12 \) min period, along with substantial nutation/precession at \( \sim 8 \) min period. This is consistent with the raw data (second panel in Figure 2), whereby the y and z axes contained the largest oscillations at the spin period with similar amplitudes whereas the x axis showed much smaller oscillations at a shorter period. Despun attitude mode data is displayed in the bottom panel of Figure 2.

This nominal spin axis is along the boom direction (see IB axes in Figure 1). CINEMA’s moment of inertia tensor should be largest about the boom axis if it successfully deployed. Therefore, one would expect the spacecraft to spin predominantly about this axis given the initial tumbling out of the P-POD and that the one of the torque coils was not operational. Since the magnetometer data shows the spacecraft was indeed spinning about the boom axis, we take this as evidence, corroborated by spacecraft onboard systems, that the boom did indeed successfully deploy.

\subsection{3.2.2 Science Mode}

Before determining the attitude for the science mode data, we applied a low-pass filter using the Morlet wavelet with a cutoff of 21 mHz to remove high frequency signals and noise. The cutoff was chosen such that spin tones, as shown in Figure 4 remained. We transform the left-handed sensor axes of the outboard into the same right-handed system as the inboard (see Figure 1) and subsequently apply the attitude determination procedure every 5 s to the filtered data. The expected relative orientations of the sensor axes have been corroborated by gradiometer mode data (not shown), whereby data from both sensors are recorded simultaneously (Brown et al. [2014]).

The results showed that in the year between the attitude and science mode data in this paper, CINEMA’s attitude had substantially changed. This is clear from the power spectra of \( \mathbf{B}_{sc}^i \) in Figure 6, where there are three different tones (corresponding to spin, precession and nutation) present in all three components. This is unlike the attitude mode data where only two tones were present, one of which was largely confined to a single axis. The result is that the Euler angles (not shown) are far more complicated than those displayed in Figure 5.

The despun science mode data is displayed in the bottom panel of Figure 5. We show power spectra of these compo-
4 Field Aligned Currents (FACs)

While we have shown that attitude information can be extracted by comparing the MAGIC data with IGRF, the requirements of the instrument additionally included the ability to detect transient physical signals in the time series, due to either spatially or temporally confined phenomena. We transformed the despun MAGIC science mode data in a field-aligned system $(\nu, \phi, \mu)$, where $\mu$ is aligned with IGRF, $\nu$ is perpendicular to IGRF pointing radially outwards, and $\phi$ is the usual azimuthal direction; subsequently band-pass filtering the data to reveal transients. A lower cutoff of 21 mHz was used to remove spin tones due to errors in calibration and the upper cutoff was set at 1.8 Hz in order to reduce noise and remove quasi-periodic spikes in the data of spacecraft origin.

The two perpendicular components of the magnetic field are shown in Figure 7 revealing transient signals of ~20-60 nT in amplitude particularly at the start of the interval when CINEMA was at high magnetic latitudes in the southern hemisphere. Through the Ampère-Maxwell law $j = \nabla \times B / \mu_0$, the field-aligned currents (FACs) associated with these magnetic perturbations can be estimated using the method of Lühr et al. (1996), namely

$$j_\parallel = \frac{1}{\mu_0 v_\perp} \frac{d}{dt} [B_\perp \cdot \hat{n}]$$

where $v_\perp$ is the spacecraft orbital speed perpendicular to IGRF and $\hat{n} = \mu \times v / |\mu \times v|$ is a unit vector perpendicular to both IGRF and the orbital velocity. This method can lead to a factor 2 under-estimation of the current density due to the finite extent of the (assumed infinite) current sheets Lühr et al. (1996). The calculated FACs are displayed in the second panels of Figure 7, showing currents of up to a few $\mu$A m$^{-2}$. We highlight (grey areas) the times of the two periods of FACs between 16:35-16:50 UT when CINEMA was traversing the polar cap, where the $S = \log_{10}\frac{J}{\mu m^2 s}$ parameter (not shown) of Heilig and Lühr (2013) was used to identify the boundaries. The FACs are qualitatively similar and of similar amplitude to those determined from CHAMP magnetic field data at the auroral oval Xiong et al. (2014).

To check whether these field aligned currents are consistent with the location of the auroral oval, we use Total Energy Detector (TED) data from the NOAA Polar Orbiting Environmental Satellites (POES) Evans and Greer (2004) and SSJ/5 Precipitating Particle Sensor data from the Defense Meteorological Satellite Program (DMSP) spacecraft. Figure 8 displays auroral oval crossings of these spacecraft 45 min either side of the FACs observed by CINEMA, where the tracks have been coloured by the observed total energy fluxes. The POES TED instrument measures energy fluxes into the atmosphere of both ions and electrons in the range 50-20,000 eV, whereas for DMSP we display only the electron fluxes in the range 30-30,000 eV from SSJ/5. CINEMA’s trajectory is shown as the black lines and the two periods of field-aligned currents identified in Figure 7 are also highlighted. The locations of these FACs are in fairly good agreement with the position of the auroral oval as evidenced from the precipitating particle data, thus we are confident that MAGIC did indeed detect field-aligned currents at the auroral oval.

A further period of FACs was detected by MAGIC between 17:04-17:12:20 UT with amplitudes of typically ~0.5 $\mu$A m$^{-2}$. During this time CINEMA was near the magnetic equator and only a few degrees eastward of the dawn day-night terminator on the ground. Given this location, we suggest that these could be due to equatorial plasma bubbles, the FAC signatures of which have been detected by CHAMP Park et al. (2009) revealing similar amplitudes to those presented here. Unfortunately there is no independent measurement to confirm this interpretation.

5 Discussion

In the calibration of the MAGIC data, as presented in section 2 we have used an attitude-independent method
Our method of attitude estimation (section 3) can be applied to CINEMA only because its tumbling motion is suitably slow. Had CINEMA successfully detumbled and spun-up, then the method described here would not have been required since sun sensor data could have been combined with that from MAGIC to uniquely define the spacecraft attitude (Vega et al., 2009). On the other hand, more sophisticated methods of magnetometer-only attitude determination do exist (Natanson et al., 1990; Searcy and Pernicka, 2012). These methods would necessitate further modelling than is possible for CINEMA, since they require measures of the spacecraft inertia tensor and any external torques (such as gravity gradients and drags) acting upon it. It is possible that such attitude modelling could be implemented in the future to better constrain spacecraft attitude.

At present, the determination of physical signals in the MAGIC data (section 4) is limited by a number of factors since both calibration and attitude are all determined through
6 Conclusions

We have presented the first in-flight science results from MAGIC (MAGnetometer from Imperial College), a novel miniaturised vector DC magnetometer using anisotropic magnetoresitive (AMR) sensors, aboard CINEMA (Cubesat for Ions Neutrals Electrons and MAgnetic fields) spacecraft in low Earth orbit. We have detailed our attitude-independent (and temperature dependent in the case of science mode) calibration procedures, which result in root mean squared deviations in field magnitude from IGRF of 1.95% and 1.23% respectively for the inboard (in attitude mode) and outboard (science mode) sensors respectively. Such levels of accuracy in the overall magnetic field are certainly sufficient for attitude estimation (c.f. Natanson et al., 1999). Indeed, through the use of magnetometer data only we estimate CINEMA’s attitude to within a few degrees using a simple method, thus characterising the spacecraft’s spin, nutation and precession and successfully satisfying the first requirement of the MAGIC instrument.

Furthermore, we have presented evidence that MAGIC is capable of detecting transient physical signals (∼20-60 nT) in addition to simply IGRF, thereby accomplishing the other requirement. These signals were an order of magnitude smaller than those detected by the science AMR on the DICE Cubesat during a marginally geomagnetically active period (Fish et al., 2014), indeed MAGIC has an order of magnitude superior resolution and noise floor than the DICE SciMag instrument. The determined field-aligned currents observed by MAGIC (∼0.5-2 µA m²⁻²) show qualitative agreement with previous observations from the CHAMP spacecraft (Park et al., 2009; Xiong et al., 2014) and those detected at the auroral oval are consistent in location with other available datasets, namely DMSP and POES. Therefore, to our knowledge, MAGIC is the highest sensitivity vector DC magnetometer flown on a Cubesat to date for which conducting scientific studies is feasible. While AMR sensors cannot achieve the absolute precision of magnetic field measurements at LEO such as Swarm (Friis-Christensen et al., 2006), certain scientific applications do not require such high levels of precision for which sensors similar to MAGIC could play a role. Indeed we have demonstrated that simple methods applied to only the magnetometer data can yield useful scientific results such as the locations of field-aligned currents, even during geomagnetically quiet times. The relatively low cost of Cubesats offers the possibility in the future of employing a constellation of spacecraft with MAGIC sensors e.g. for the purposes of space weather monitoring.

Acknowledgements. We dedicate this paper to Prof. Bob Lin of University of California Berkeley who sadly passed away soon after CINEMA-1’s launch. It was his inspiration, drive and enthusiasm which made the CINEMA mission possible. We also thank Alain Hilgers at ESA/ESTEC for support. Development of the hybrid sensor and flight units has been funded by ESA under the General Support Technology Programme (Contract number 4000106430). M. O. Archer is thankful for funding from STFC grant ST/I505713/1. We thank NOAA for POES and DMSP data.

References

M. H. Acuña. Space-based magnetometers. Rev. Sci. Instrum., 73: 3717–3736, 2002. doi:10.1063/1.1510570
L. N. A. Alconel, P. Fox, P. Brown, T. M. Oddy, E. L. Lucel, and C. M. Carr. An initial investigation of the long-term trends in the fluxgate magnetometer (FGM) calibration parameters on the four Cluster spacecraft. *Geosci. Instrum. Method. Data Syst.*, 3:95–109, 2014. doi:10.5194/gi-3-95-2014

A. Balogh, M. W. Dunlop, S. W. H. Cowley, D. J. Southwood, J. G. Thomlinson, K.-H. Glassmeier, G. Musmann, H. Lühr, S. Buchert, M. H. Acuña, D. H. Fairfield, J. A. Slavin, W. Riedler, K. Schwingenschuh, and M. G. Kivelson. *The Cluster and Phoenix missions*, chapter The Cluster magnetic field investigation, pages 65–91. Springer Netherlands, 1997. doi:10.1007/978-94-011-5666-0_3

W. Baumbjohann. Ionospheric and field-aligned current systems in the auroral zone: a concise review. *Adv. Space Res.*, 2:55–62, 1982. doi:10.1016/0273-1177(82)90363-5

T. Bleier and C. Dunson. ELF magnetic field monitoring of the San Simeon M6.4 quake from both Quakesat and a ground network. In *Proceedings of the International Workshop on Seismoelectromagnetics*, Tokyo, Japan, March 2005, 2005.

J. Bouwmeester and J. Guo. Survey of worldwide pico- and nanosatellite missions, distributions and sub-system technology. *Acta Astronaut.*, 67:854–862, 2010. doi:10.1016/j.actaastro.2010.06.004

P. Brown, T. Beek, C. Carr, H. O’Brien, E. Cupido, T. Oddy, and T. S. Horbury. Magnetoresistive magnetometer for space science applications. *Mes. Sci. Technol.*, 23:025902, 2012. doi:10.1088/0957-4458/23/2/025902

P. Brown, B. J. Whiteside, T. J. Beek, P. Fox, T. S. Horbury, T. M. Oddy, M. O. Archer, J. P. Eastwood, D. Sanz-Hernández, J. G. Sample, E. Cupido, H. O’Brien, and C. M. Carr. Space magnetometer based on an anisotropic magnetoresistive hybrid sensor. *Rev. Sci. Instrum.*, 85:125117, 2014. doi:10.1063/1.4904702

L. B. N. Claussen, J. B. H. Baker, J. M. Ruohoniemi, S. E. Milan, and B. J. Anderson. Dynamics of the region 1 birkeland current oval derived from the active magnetosphere and planetary electrodynamic response experiment (AMPERE). *J. Geophys. Res.*, 117:A06233, 2012. doi:10.1029/2012JA017666

D. S. Evans and M. S. Greer. *NOAA Tech. Mem. 1.4*, chapter Polar Orbiting Environmental Satellite Space Environment Monitor-2 instrument descriptions and archive data documentation. Space Environment Center, Boulder, Colorado, 2004.

C. S. Fish, C. M. Swenson, G. Crowley, A. Barjatya, T. Neilsen, J. Gunther, I. Azeem, M. Pilinski, R. Wilder, D. Allen, M. Anderson, B. Bingham, K. Kendall, S. Burt, B. Byers, J. Cook, K. Davis, C. Frazier, S. Grover, G. Hansen, S. Jensen, R. LeBaron, J. Martineau, J. Miller, J. Nelsen, W. Nelson, P. Patterson, E. Sterberg, J. Tran, S. Wasson, C. Weston, M. Whiteley, Q. Young, J. Petersen, S. Schaire, C.R. Davis, M. Bokaie, R. Fuller, R. Baktur, S. Sojka, and M. Cousins. Design, development, implementation, and on-orbit performance of the Dynamic Ionosphere Cubesat Experiment Mission. *Space Sci. Rev.*, 181:61–120, 2014. doi:10.1007/s11214-014-0034-x

C. C. Foster and G. H. Elkaim. Extension of a two-step calibration methodology to include nonorthogonal sensor axes. *IEEE Aerosp. Electron. Syst. Mag.*, 44:1070–1078, 2008. doi:10.1109/MAES.2008.4655364

E. Friis-Christensen, H. Lühr, and G. Hulot. Swarm: A constellation to study the Earth’s magnetic field. *Earth Planets Space*, 58:351–358, 2006.

B. Heilig and H. Lühr. New plasmapause model derived from CHAMP field-aligned current signatures. *Ann. Geophys.*, 31:529–539, 2013. doi:10.5194/angeo-31-529-2013

F. R. Hoots, P. W. Schumacher Jr., and R. A. Glover. History of analytical orbit modeling in the U.S. space surveillance system. *J. Guid. Control Dynam.*, 27:174–185, 2004. doi:10.2514/1.9161

E. L. Kepko, K. K. Khurana, M. G. Kivelson, R. C. Elphic, and C. T. Russell. Accurate determination of magnetic field gradients from four point vector measurements - part I: Use of natural constraints on vector data obtained from a single spinning spacecraft. *IEEE T. Magn.*, 32:377–385, 1996. doi:10.1109/20.486522

X. Li, Q. Schiller, L. Blum, S. Califf, H. Zhao, W. Tu, D. L. Turner, D. Gerhardt, S. Palo, S. Kanekal, D. N. Baker, J. Fennell, J. B. Blake, M. Loop, G. D. Reeves, and H. Spence. First results from CSSWE cubesat: Characteristics of relativistic electrons in the near-Earth environment during the October 2012 magnetic storms. *J. Geophys. Res.*, 118:6489–6499, 2013. doi:10.1002/2013JA019342

M. Ludlam, V. Angelopoulos, E. Taylor, R. C. Snare, J. D. Means, Y. S. Ge, P. Narvaiz, H. U. Auster, O. Le Contel, D. Larson, and T. Moreau. The THEMIS magnetic cleanliness program. *Space Sci. Rev.*, 141:171–184, 2008. doi:10.1007/s11214-008-9423-3

H. Lühr, J. F. Warnecke, and M. K. A. Rother. An algorithm for estimating field-aligned currents from single spacecraft magnetic field measurements: a diagnostic tool applied to Freja satellite data. *IEEE T. Geosci. Remote*, 34:1369–1376, 1996. doi:10.1109/36.544560

S. Maus, S. Macmillan, F. Lowes, and T. Bondar. Evaluation of candidate geomagnetic field models for the 10th generation of igrf. *Earth Planets Space*, 57:1173–1181, 2005.

G. A. Natanson, S. F. McLaughlin, and R. C. Nicklas. A method of determining attitude from magnetometer data only. In *Flight Mechanics/Estimation Theory Symposium*, pages 359–378. NASA Goddard Space Flight Center, 1990.

J. A. Nelder and R. Mead. A simplex method for function minimization. *Computer Journal*, 7:308–313, 1965. doi:10.1093/comjnl/7.4.308

N. Olsen, L. Tøffner-Clausen, T. J. Sabaka, P. Brauer, J. M. G. Merayo, J. L. Jørgensen, J.-M. Leger, O. V. Nielsen, F. Primdahl, and Torben Risbo. Calibration of the ørsted vector magnetometer. *Earth Planets Space*, 55:11–18, 2003.

J. Park, H. Lühr, C. Stolle, M. Rother, K. W. Min, and I. Michaelis. The characteristics of field-aligned currents associated with equatorial plasma bubbles as observed by the CHAMP satellite. *Ann. Geophys.*, 27:2685–2697, 2009. doi:10.5194/angeo-27-2685-2009

K. Sarda, C. Grant, S. Eagleson, D. Kekez, and R. Zee. Canadian advanced nanosatellite experience 2 orbit operations: Two years of pushing the nanosatellite envelope. In *Proceedings of the 61st International Astronautical Congress*, pages 1–13, 2010.

J. D. Seary and H. J. Pernicka. Magnetometer-only attitude determination using novel two-step kalman filter approach. *J. Guid. Control Dynam.*, 35:1693–1701, 2012. doi:10.2514/1.57344

D. Selva and D. Krejci. A survey and assessment of the capabilities of Cubesats for Earth observation. *Acta Astronaut.*, 74:50–68, 2012. doi:10.1016/j.actaastro.2011.12.014
J. C. Springmann and J. W. Cutler. Attitude-independent magnetometer calibration with time-varying bias. *J. Guid. Control Dynam.*, 35:1080–1088, 2012. doi:10.2514/1.56726.

D. A. Vallado, P. Crawford, R. Hujsak, and T. S. Kelso. Revisiting spacetrack report #3. In *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, number AIAA 2006-6753, Keystone, Colorado, 2006.

K. Vega, D. Auslander, and D. Pankow. Design and modeling of an active attitude control system for cubesat class satellites. In *AIAA Modeling and Simulation Technologies Conference*, number AIAA 2009-5812, Chicago, Illinois, 2009. doi:10.2514/6.2009-5812.

J. R. Wertz. *Spacecraft attitude determination and control*. D. Reidel, 1978.

C. Xiong, H. Lühr, H. Wang, and M. G. Johnsen. Determining the boundaries of the auroral oval from CHAMP field-aligned current signatures - part 1. *Ann. Geophys.*, 32:609–622, 2014. doi:10.5194/angeo-32-609-2014.