Institution: Imperial College London

Unit of Assessment: 9 Physics

Title of case study: P8 - Space science magnetometer adapted for commercial use as a satellite attitude sensor

1. Summary of the impact (indicative maximum 100 words)

The Space & Atmospheric Physics (SPAT) group's magnetometer laboratory at Imperial has developed a small and lightweight magnetic field instrument intended to be flown on future generations of extremely small satellites or planetary landers. The instrument will be used for planetary research or plasma physics in the space environment, and also has application for attitude determination on satellites in Earth-orbit, by comparison with the geomagnetic field ('digital compass'). In 2010 Imperial Innovations granted Satellite Services Ltd (now the SSBV Aerospace and Technology Group) an exclusive 3-year license to market the design for the commercial satellite sector. Satellite Services have sold seven units (circa. € 10,000 per unit) with further commercial sales anticipated in the coming years. Sales of the device have contributed significantly to SSBV's company turnover, indicating the economic impact of the SPAT group's research.

2. Underpinning research (indicative maximum 500 words)

The Space & Atmospheric Physics group (SPAT) at Imperial is internationally recognised as a leading centre for research in planetary and space-plasma physics. This success is built on 4 decades of involvement with agencies such as NASA, ESA (European Space Agency), CNSA (Chinese National Space Agency), and others. The group is particularly recognised for building magnetic field instruments which are embarked on agency-provided missions. SPATs success stems from combining the building of the instruments for space-flight with the scientific interpretation and analysis of the data returned. Recent highlights of this program include the ESA 'Cluster' and 'Ulysses' missions, the NASA 'Cassini' mission and the Chinese 'Double Star' mission, all of which carried an Imperial-led magnetometer as a scientific payload.

Underpinning this work is a vigorous programme of instrument development. Whilst the instruments on Cluster, Cassini and Solar Orbiter use 'Fluxgate' type sensors, the SPAT group has recently developed an instrument using 'magnetoresistive' sensors [1]. Anisotropic magnetoresistive sensors are low-cost commercially available devices typically used in mobile phones, vehicles etc., for magnetic orientation and position sensing. The novel adaptation (described by Brown et al. in [1]) applies the group's fluxgate knowledge to improve the performance of the magnetoresistive sensors. These developments are:

1. Driven, first-harmonic detection utilising the sensor's built-in 'set/reset' polarisation to effect automatic offset compensation

2. Closed-loop operation using magnetic feedback to improve linearity.

When compared to a sensor operated without these developments, the new design offers improved stability, linearity and accuracy.

The new instrument has recently been flown on the short-lived US satellite CINEMA (CubeSat for Ions Neutrals Electrons and Magnetic Fields) [2]. CINEMA was a CubeSat spacecraft designed to

study Space Weather by making measurements of the magnetic field and energetic ions and electrons in near-Earth space.

The developments described by Brown et al. in the 2012 paper [1] have recently been selected by the journal Measurement Science and Technology as one of its highlights of 2011-2012, in the instrumentation category (http://iopscience.iop.org/0957-0233/page/Highlights%20of%202011-2012). The papers were chosen by the editorial team and editorial board as having been highly rated by referees and readers, downloaded and cited highly, and being examples of high-quality, well-executed, outstanding research.

The research was performed entirely at Imperial College by Patrick Brown (senior research officer, at Imperial 15/08/1997-present) and Trevor Beek (electronics technician, at Imperial 12/07/1965-present) under the direction of Chis Carr (Head of the magnetometer laboratory, 15/10/1990-present). This work was funded by STFC as part of the SPAT group's rolling grant [G1], which funded all of the group's scientific activities in space plasma physics, as well as instrument development. The research occurred during the period 2007 to 2012 which covers two 'rolls' of the rolling grant.

3. References to the research (* References that best indicate quality of underpinning research)

Reference to the magnetometer research:

[1] * P Brown, T Beek, C Carr, H O'Brien, E Cupido, T Oddy and T S Horbury, "*Magnetoresistive magnetometer for space science applications"*, Measurement Science & Technology, 23, 025902 (2012). DOI

Reference to the CINEMA project:

[2] * R.P. Lin, G.K. Parks, J.S. Halekas, D.E. Larson, J.P. Eastwood, L. Wang, J.G. Sample, T.S. Horbury, et al., "*CINEMA (Cubesat for Ion, Neutral, Electron and MAgnetic fields)*", American Geophysical Union, Fall AGU, Talk #SM42A-09 (2009)

N.B. Paper [1] was selected by the journal Measurement Science and Technology as one of its highlights of 2011-2012, in the instrumentation category, http://iopscience.iop.org/0957-0233/page/Highlights%20of%202011-2012. The papers were chosen for having been highly rated by referees and readers, downloaded and cited highly, and being examples of high-quality, well-executed, outstanding research.

Grant details

[G1] STFC, ST/H002383/1, '*A Rolling Programme of Space Physics'*, PI: M.Dougherty, value: £2, 089,728, period: April 2010 to March 2013.

4. Details of the impact (indicative maximum 750 words)

There are two principal uses of magnetometers in space:

1. For space science and planetary research; this is the field in which the SPAT group has traditionally been active (see section 2).

2. For satellites in earth-orbit, a magnetometer can also be used to return the direction of the magnetic field, which can be compared with the known earth-field in order to obtain the pointing direction or 'attitude' of the satellite (the magnetometer is used like a sophisticated

'digital compass').

The SPAT group developed our miniaturised magnetometer for the first of these applications, i.e. for physics research in space, however it was soon clear that the new design could be applied to the second with commercial benefits, since most satellite manufacturers need an attitude magnetometer and will purchase these from specialist suppliers. Prior to our impact, most of these commercial magnetometers used fluxgate sensors which are relatively large and heavy (e.g. http://www.bartington.com/three-axis-fluxgate-magnetometers.html). Some satellites have used magnetoresistive sensors, however these do not have the performance of the SPAT instrument. Consequently, the design fills a gap in the market for a small, lightweight (~200 grams), high-performance yet relatively cheap satellite attitude magnetometer.

One such company, which had previously marketed a fluxgate instrument to the commercial satellite sector, is the UK-based company SSBV Space & Ground Systems UK (formerly called Satellite Services Ltd). In 2010 the company approached the SPAT group to engage in commercialisation activity that to successfully transferring the electronics know-how and a license for the sensor heads. In October 2010, Imperial Innovations granted Satellite Services an exclusive 3-year license to market the design [A, B]. The license terms required Satellite Services to make a one-off payment to Innovations of $30k plus a royalty for each subsequent unit sold [A, B]. The license allows Satellite Services to integrate Imperial's electronics design into its own attitude and orbit determination system so that it can be sold as an integrated package [C]. For instance, in cubesat applications the magnetometer comes as part of the SSBV Attitude Control System (ACS) board which can also host additional ACS sensors and actuators. In microsat applications the additional electronics is integrated with the sensor head resulting in a very compact unit that is simple to accommodate. SSBV market the instrument as a low cost magneto-resistive magnetometer designed for use in low earth orbit smallsats and cubesats [C].

As at January 2013, Satellite Services has ordered 8 units from Imperial Innovations, 7 of which have been sold to various clients including academic groups in France, Spain and China, and also a commercial satellite customer in Russia [B]. As reported by the company, customers "*are using the units for controlling the attitude of their satellites in a robust and low cost way enabling a new generation of missions to be developed*" [B].

As corroborated by the CEO of Satellite Services Ltd [B], with a price per unit of roughly €10,000 these units have contributed significantly to the turnover of the company. In addition, the magnetometer technology has allowed the size and cost of space-based magnetometers to be reduced significantly, whilst simultaneously increasing their robustness to the harsh space and launch environments [B]. This has therefore not only impacted the end users economically, but more importantly also improved on previous technologies available, assisting in improved and more successful launches within the satellite sector. The magnetometer is also on sale through CubeSatShop.com, a webshop that offers a broad range of standardized, off-the-shelf components and subsystems for CubeSats and nanosatellites [D]. CubeSatShop.com offers the Imperial designed magnetometer for €11,000.

This new design will fly on the TechDemoSat mission [E], which is a British technology-demonstrator satellite designed to give spaceflight experience to new technologies developed in the UK. TechDemoSat is scheduled to be launched in Kazakhstan in the first quarter of 2014. In support of this activity, the TSB awarded Imperial a Knowledge Transfer Partnership which funded an Imperial RA to spend 6-months working with Satellite Services. At the end of this KTP, the RA entered full-time employment with the company.

SSBV have approached Imperial Innovations regarding the potential renewal of the license [B]. Imperial Innovations consider the benefits of the magnetometer will extend to other markets and are currently undertaking a business analysis in this regard [B].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Letter from Business Development Director, SSBV Space & Ground Systems, SSBV Aerospace & Technology Group, 14/01/13 (letter available from Imperial on request).

[B] Letter from Senior Executive-Technology Transfer, Imperial Innovations, 22/10/13 (letter available from Imperial on request).

[C] SSBV Magnetometer Datasheet, http://www.ssbv.com/resources/Datasheets/SSBV_Magnetometer_Datasheet_1g.pdf (archived here)

[D] CubeSatShop.com page for the SSBV Magnetometer, priced at 11,000 Euros, http://www.cubesatshop.com/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=90&category_id=7&option=com_virtuemart&Itemid=69 (archived at https://www.imperial.ac.uk/ref/webarchive/dyf on 22/10/13)

[E] TechDemoSat-1 mission webpage, http://www.sstl.co.uk/Missions/TechDemoSat-1/TechDemoSat-1/TechDemoSat-1--The-Mission (archived at https://www.imperial.ac.uk/ref/webarchive/fyf on 22/10/13)