IOPscience iopscience.iop.org

Home Search Collections Journals About Contact us My IOPscience

A radiation tolerant digital fluxgate magnetometer

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2007 Meas. Sci. Technol. 18 3645

(http://iopscience.iop.org/0957-0233/18/11/050)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 130.160.4.77
The article was downloaded on 27/08/2013 at 11:35

Please note that terms and conditions apply.

Meas. Sci. Technol. **18** (2007) 3645–3650 doi:10.1088/0957-0233/18/11/050

A radiation tolerant digital fluxgate magnetometer

H O'Brien, P Brown, T Beek, C Carr, E Cupido and T Oddy

Space Magnetometer Laboratory, Department of Physics, Imperial College London, London SW7 2AZ, UK

E-mail: h.obrien@imperial.ac.uk

Received 15 June 2007, in final form 20 September 2007
Published 16 October 2007
Online at stacks.iop.org/MST/18/3645

Abstract
Fluxgate magnetometers have a long heritage of measuring the magnetic fields aboard space missions to all regions of the solar system. Fluxgate sensors have the stability, mass and resolution required for the space environment. However, future missions demand reductions in the mass and power of the electronics associated with these sensors and electronics designs which can survive the harsh radiation environment of space. Here a new design concept and first results are presented for a fluxgate magnetometer which combines the benefits of digital detection and digital feedback control with the low-noise amplification provided by tuning the sensor. It is also compatible with a mass optimized sensor using common sense/feedback windings. This design has been developed from the analogue design used for the Double Star mission. Moving the field extraction from the analogue to the digital domain reduces the component count and therefore the mass. The use of sigma–delta analogue-to-digital and digital-to-analogue conversion architecture embedded in a field programmable gate array offers the possibility of realizing a complete design able to operate up to a total ionizing dose of radiation of 100 krad without shielding.

Keywords: radiation tolerant, fluxgate magnetometer, digital magnetometer

1. Introduction

The challenge for space-borne magnetometer instruments is to reduce power and mass resources while maintaining the high performance of existing designs. This is particularly true in the cases of space plasma missions featuring constellations of small spacecraft and instrumentation aboard planetary landers (Hapgood *et al* 2005). Most commonly, measurement of the dc magnetic field (0–30 Hz) in space has been achieved using fluxgate magnetometers (Acuña 1974). Fluxgate sensors are rugged and robust, possess a wide dynamic range (10^{-3}–10^{-10} T), are low mass compared to other sensors (such as vector helium sensors) and can operate over a wide temperature range (Acuña 2002). The very best fluxgates have resolutions of the order of 10 pT, noise densities of less than 10 pT $Hz^{-1/2}$ around 1 Hz and offset stabilities of the order <100 pT $^{\circ}C^{-1}$ over typical mission lifetimes.

Space-grade fluxgate instruments most commonly use second harmonic detection where the field proportional signal appears at twice the frequency of the sensor drive. Typically, they are designed to operate in a closed loop with the detected field proportional voltage fed back into coils surrounding the sensor core to back-off the measured field. Traditionally, the detection electronics have been implemented in the analogue domain featuring a discretely built closed loop for each axis in the case of a tri-axial instrument. Digitization of the sensor signal is achieved by sampling the feedback voltage with an analogue-to-digital converter (ADC), known as consequential digitization (Cerman *et al* 2005). Further processing occurs in the digital domain prior to transfer of the magnetic field data to the spacecraft data handling system. A considerable level of design heritage means a series of very high performance analogue designs have successfully flown throughout the solar system (Balogh *et al* 1992, Dougherty *et al* 2004, Carr *et al* 2005). These analogue designs have been mass optimized but will always require external ADCs.

In recent years, designs which move the detection electronics from the analogue to the digital domain, thus

 © 2007 IOP Publishing Ltd Printed in the UK

reducing the number of analogue components required and removing the requirement for an external ADC, have been employed (Primdahl *et al* 1994). So-called digital fluxgate magnetometers sample the sensor signal using an ADC. Processing and extraction of the field proportional information occur in the digital domain. The feedback signal is calculated and routed back into the sensor via a digital-to-analogue converter (DAC). The field extraction can take place in a variety of devices, and implementations within digital signal processors (DSP), application specific integrated circuits (ASIC) and field programmable gate arrays (FPGA) have been described (Auster *et al* 1995, Henriksen *et al* 1996, Forslund *et al* 2007). The technology is now mature enough that magnetometers featuring performance approaching that of the best analogue instruments are currently operational in-flight (Zhang *et al* 2006).

Such digital implementations do reduce the overall component count compared to analogue designs and provide enhanced flexibility as design changes are implemented through software rather than through changing analogue components. However, they are not without limitations. A major design constraint on space magnetometers is that the electronics should be hardened against upset and damage due to ionizing radiation. In order to benefit from the fluxgate's wide dynamic range and facilitate operation both in-flight and during ground testing the ADC and DAC require a large bit width, N, typically of the order of 20. At present there is a lack of converter technologies delivering radiation hardened devices featuring sufficient bits. Consequently, space magnetometers requiring high N utilize high accuracy but lower bit width parts and typically must include spot shields or watchdog circuits to mitigate susceptibility to latch-up as well as employing gain stages to match the ADC bit width to the needed dynamic range. To respond to this problem, a magnetometer design which combines the magnetometer feedback control loop with the individual radiation tolerant components of a sigma–delta ($\Sigma\Delta$) modulation loop, resulting in a design with direct digital output, without the requirement of separate ADC or DAC chips, has been described (Magnes *et al* 2003). This design is now being migrated to a radiation hardened ASIC manufacturing flow (Valavanoglou *et al* 2007). Future proposed missions such as Jupiter Europa Orbiter will require converter technologies that can operate up to a total ionizing dose (TID) of the order of Mrad. Thus magnetometer designs featuring mass and power optimizations, together with ADC/DAC combinations that are inherently radiation tolerant, could have considerable benefit over current digital fluxgate designs.

Combining the magnetometer and sigma–delta control loops does open up the possibility of producing a magnetometer made entirely from radiation tolerant components. However, this design requires a sensor with separate windings for sense and feedback. For the Double Star mission, a very stable, low noise, mass optimized sensor was designed (Carr *et al* 2005) which makes use of a single winding for sense and feedback functions, thus reducing both the mass of the sensor and the mass of the sensor harness, as fewer wires are required. Furthermore, the accompanying analogue electronics for this sensor capitalize on the low-noise amplification gained by tuning the fluxgate sensor to the second harmonic (Acuña 1974). A tuned sensor essentially produces a sinusoidal wave signal at twice the drive frequency, the amplitude and phase of which provide information about the amplitude and sign of the magnetic field. This offers an attractive target for digital signal processing.

In this paper, we examine the possibility of providing a digital magnetometer which combines the advantages of using a tuned sensor with common sensor sense and feedback windings with the design flexibility of field extraction and feedback control in the digital domain and the radiation performance of using $\Sigma\Delta$ modulation. The result is a design almost entirely implemented in an FPGA, without the requirement of separate ADC or DAC chips. The design samples the second harmonic signal directly without the need for an external synchronous demodulation stage and has a direct digital readout of the magnetic field from the FPGA. The only discrete analogue blocks left in the fluxgate sense electronics are the tuning circuit, an amplifier, the discrete components associated with the $\Sigma\Delta$ ADC and DAC and the feedback voltage to current converter. Everything else is implemented in the FPGA. Sections 2 and 3 describe respectively the original analogue design and its new digital implementation. The results in section 4 show that such a concept is feasible and section 5 discusses the advantages of the design. The paper finishes with conclusions and future work to realize a flight prototype.

2. Tuned analogue fluxgate magnetometer design

Figure 1 shows a block diagram of the analogue electronics for a single axis of the magnetometer flown on the Double Star mission. A parallel capacitor across the sense winding tunes the sensor output to the second harmonic of the 15 kHz drive frequency, F_0 (Carr *et al* 2005). In the analogue design the field magnitude and direction are extracted from the magnitude and phase of the tuned sensor $2F_0$ signal using a synchronous detector, in conjunction with a reference $2F_0$ square wave bearing a fixed-phase relationship to the drive waveform. In a closed loop configuration, the instrument operates in a null mode by generating a feedback current in the feedback winding which exactly cancels out the field present in the sensor. Any changes in the field are detected by the sense winding and the feedback current adjusted to compensate in response to the changing integrator output. The voltage driving the feedback current is the measure of the magnetic field and is fed to the separate ADC via range control amplifiers which determine the resolution and range of the digital field measurement. Traditional fluxgate magnetometer designs have used a separate feedback winding for backing off the measured field; however, in this mass optimized design, the same winding around the sensor core is used for both field detection (as a sense winding) and to back-off the field (as a feedback winding).

3. Tuned digital fluxgate magnetometer design

For a digital field extraction design, the synchronous detector and integrator are transferred into the digital domain. As in the conventional digital fluxgate (Auster *et al* 1995), an ADC is included in the loop following the pre-amplifier and a DAC

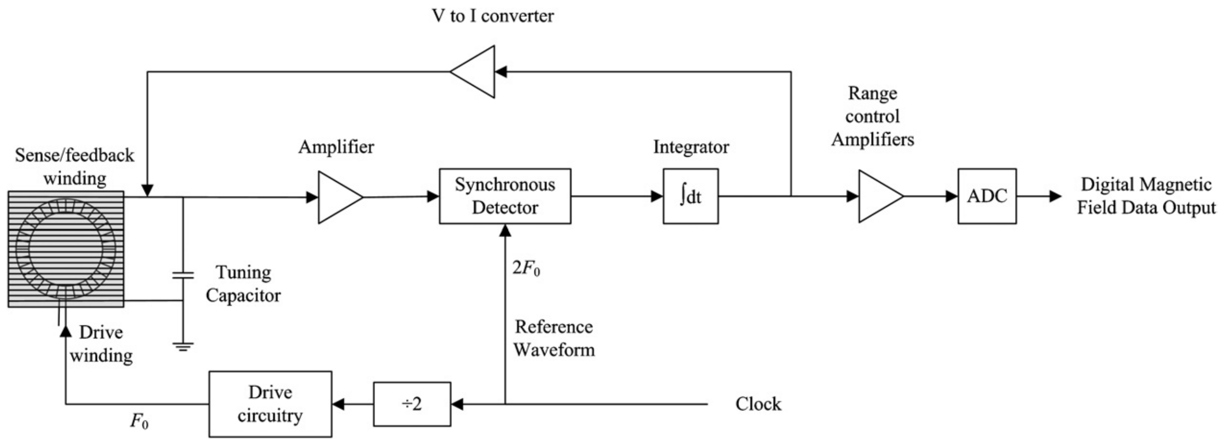

Figure 1. Block diagram of a single axis of the analogue fluxgate magnetometer used for the Double Star mission.

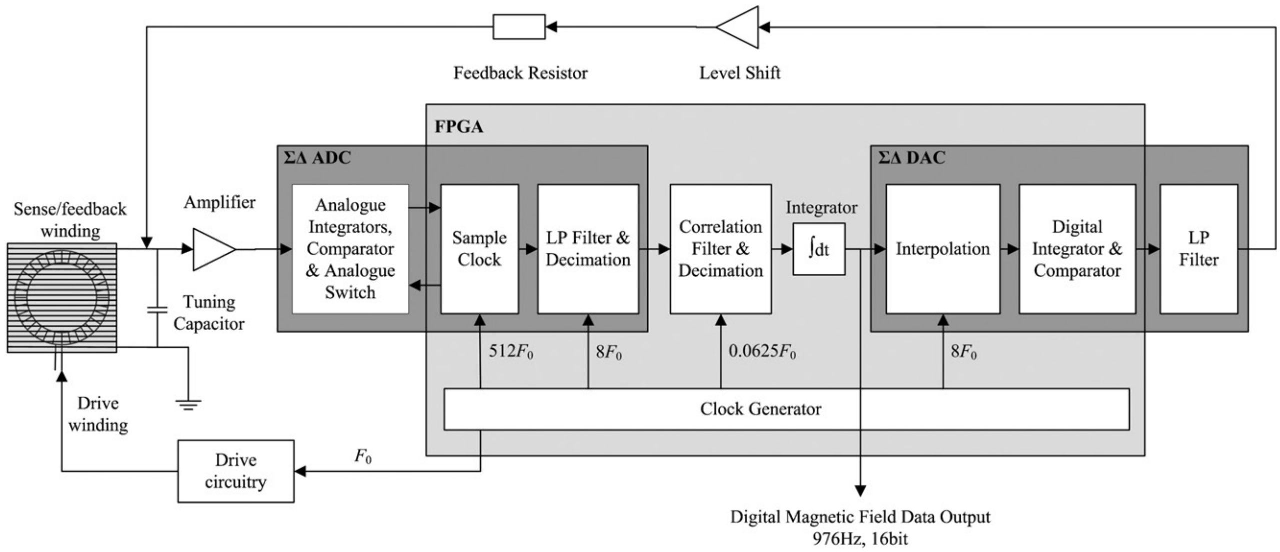

Figure 2. Block diagram of a single axis digital fluxgate magnetometer. All components are available in radiation tolerant versions, providing a radiation tolerant overall design.

is incorporated prior to the voltage to current converter (in this case a feedback resistor). The drive frequency is 15.6 kHz. The digital design for a single axis is shown in the block diagram in figure 2.

In order to generate a fully radiation hard design, an FPGA was chosen to implement the field extraction, with $\Sigma\Delta$ architecture partially integrated into the same chip providing the ADC and DAC. The use of $\Sigma\Delta$ architecture eliminates the need for radiation susceptible separate ADC and DAC components. A second-order $\Sigma\Delta$ ADC loop (Candy 1997) with single bit quantization, clocked by the FPGA at 8 MHz (512 times the drive frequency, F_0), is shown in detail in figure 3. This loop provides the high frequency single bit stream into the FPGA. The bit stream is also fed back to the integrators via an analogue switch which translates the digital bits from the FPGA from 3.3 V (digital 1) and 0 V (digital 0) to $+V$ and $-V$ chosen to be around twice the maximum and minimum of the amplified, nulled sensor waveform.

A cascade of four integrator-comb pairs in the form of an efficient low pass decimation finite impulse response (FIR) filter (Hogenauer 1981) is implemented in the FPGA to complete the analogue-to-digital conversion, resulting in a 13 bit, 125 kHz ($8F_0$) digital representation of the sensor waveform voltage.

For this tuned design, the synchronous detector is replaced with a 128-tap band-pass decimation FIR filter to extract the magnitude and phase of the $2F_0$ component, providing a measure of the magnitude and direction of the ambient magnetic field. The output of this filter is the digital magnetic field component at a frequency of 976 Hz. This filter can be thought of as a correlation with a cosine wave at frequency $2F_0$ over 32 periods. Correlation with a reference waveform generated at large fields has been used to successfully extract the magnetic field from a sensor waveform (Primdahl *et al* 1994). For a tuned sensor, this reference waveform is a cosine wave. As the filter length covers a whole number of periods of F_0, it has the advantage over a simple pass-band filter of nulls at F_0 and $3F_0$ (for which a correlation with $2F_0$ average to zero across a period of F_0), thus minimizing noise from drive breakthrough. The 16 bit field component is fed out of the FPGA along 16 lines to a National Instruments 6534 digital I/O card in a PC, running a LabView software programme which stores and plots the data in real time.

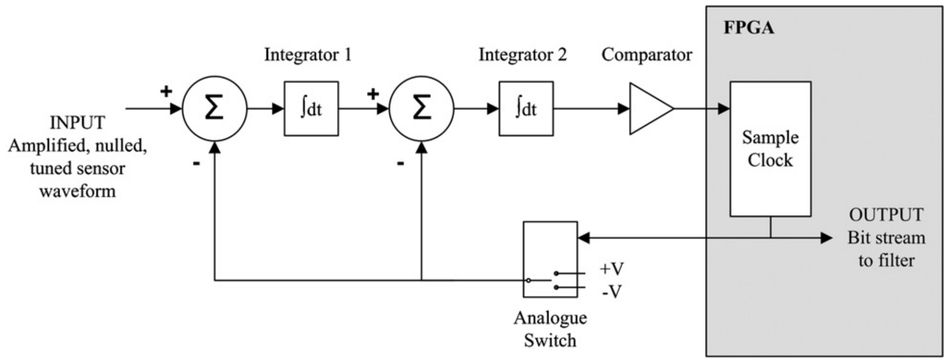

Figure 3. Block diagram of a second-order sigma–delta modulator implemented with an FPGA. The FPGA clocks the output of the comparator and feeds this back to the analogue switch.

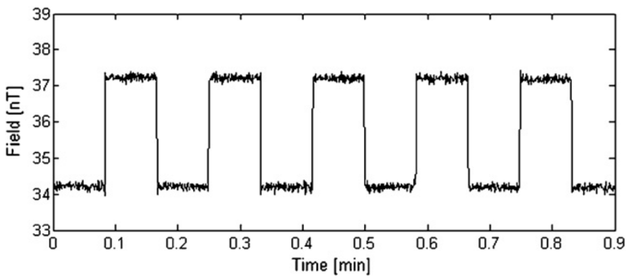

Figure 4. Plot of the FPGA output data filtered and decimated to 22 Hz with a 3 nT 100 mHz square wave applied.

For the feedback loop, the field is integrated and put through a first-order $\Sigma\Delta$ DAC loop clocked by the FPGA at 125 kHz ($8F_0$). For this first implementation of the design, and because this is dc field measurement, there is no interpolation function implemented into the DAC; instead, the same value of the field is fed into the DAC control loop 128 times to provide oversampling of 128. The resulting 125 kHz bit stream is passed through an analogue low pass filter, consisting of a simple RC design to complete the digital-to-analogue conversion. This DAC output is in the range of 0–3.3 V (determined by the IO voltage of the FPGA), and so to provide negative feedback voltages, the signal is passed through a level shift circuit to centre the output on 0 V. A feedback resistor provides the voltage to current conversion, with the value chosen to give 10 pT resolution on a 16 bit field measurement for a $\pm$1.65 V feedback voltage.

The Actel ProAsicPlus evaluation board with APA075 FPGA was used to provide a single axis prototype of the concept.

4. Results

To demonstrate the resolution of the digital magnetometer, the sensor was placed in a three-layer mu-metal can to simulate the low field environment of space. A coil which applied a 100 mHz square wave measuring $\pm$1.5 nT at the sensor was also placed in the can. Figure 4 shows the digital magnetometer resolving the square wave. Here the 976 Hz data from the FPGA is filtered using a Kaiser window FIR low pass filter with a pass-band of 11 Hz and decimated to 22 Hz, the same frequency as the Cluster and Double Star magnetometers in normal mode.

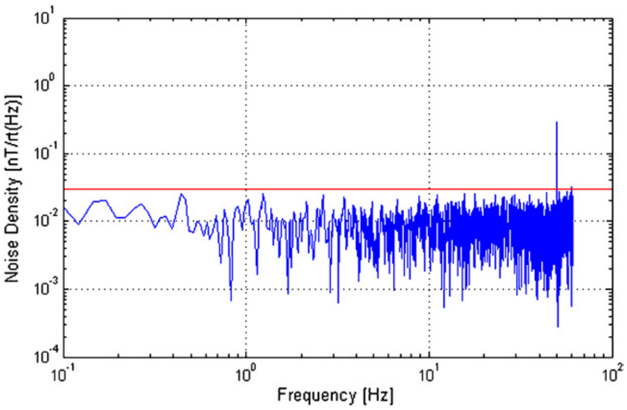

Figure 5. Noise density plot of the FPGA output data filtered and decimated to 122 Hz.

(This figure is in colour only in the electronic version)

To measure the noise performance of the magnetometer, the sensor was placed in the three-layer mu-metal can overnight. Figure 5 shows a spectral density plot of the 976 Hz FPGA data filtered offline and decimated to 122 Hz. A Kaiser window FIR low pass filter with a pass-band frequency of 61 Hz was used to filter the data from the FPGA, which was then decimated to 122 Hz. It shows a noise density of less than 30 pT Hz$^{-1/2}$ (indicated by the solid line) over the range from 0.1 Hz to 61 Hz, and no bandwidth limitations over this range. For a breadboard model, this noise level compares well with the design goal of a noise density less than 10 pT Hz$^{-1/2}$ measured at 1 Hz for a flight instrument. The spike at 50 Hz is due to pick up from the mains supply to other laboratory equipment. A data rate of 122 Hz is representative of the maximum likely frequency required for space-based dc magnetometers. The high-resolution data rate (called burst mode) for the Cluster magnetometers is 67 Hz.

5. Discussion

The results demonstrate that it is possible to migrate the field detection function for a tuned magnetometer sensor to the digital domain. There are a number of key advantages to the digital approach: fewer components mean a lower mass and smaller size and control of the filter design, bandwidth and decimation of the data in the FPGA result in greater flexibility as changes are implemented in software rather than in changing analogue components. The design described here has the additional advantage of using sigma–delta conversion architectures which offer the possibility of an entirely radiation tolerant magnetometer, essential for future space-based applications.

The performance of a $\Sigma\Delta$ ADC is related to its ability to push the quantization noise up to frequencies above the frequency of interest; this noise can then be filtered out by the use of low pass filters (here implemented as a comb filter in the FPGA). This so-called noise shaping is a function of both the over-sampling ratio and the order of the ADC (Candy 1997). In this first iteration of the design, fast commercial parts are used for the $\Sigma\Delta$ ADC (analogue switch, operational amplifiers and comparator) allowing a sampling frequency of 8 MHz (256 times the frequency of interest of 31.25 kHz). Whilst versions of these components radiation tolerant up to a TID of 100 krad do exist, they are not as fast (slower switching times, longer propagation delays) as the commercial parts. This design must be tested with radiation tolerant components. It might be necessary to reduce the sampling frequency and increase the order of the ADC, from a second-order design described here, to maintain the performance of the ADC.

Implementation of the analogue-to-digital conversion prior to the synchronous demodulation stage of the sensor control loop means that the ADC always converts an ac waveform (even when operating in null field mode with no component at $2F_0$, sufficient components at F_0 and $3F_0$ exist to produce an ac signal); consequently, the design does not suffer from pattern noise that may be present in designs sampling dc at the input ADC (Magnes *et al* 2003). Additionally, the noise shaping associated with the ADC is used to push the quantization noise up to frequencies greater than $2F_0$ (31.25 kHz) and does not therefore limit the bandwidth of the magnetometer. The design described here has a bandwidth of 0–60 Hz.

This prototype single axis design takes up 81% of a 75000 gate FPGA device and would take up less than 8% of a radiation tolerant Actel RTAX1000S FPGA. Thus all three axes of a vector fluxgate magnetometer can be sampled simultaneously on the same FPGA eliminating the need for dedicated ADC and DAC chips for each sensor axis or complicated multiplexer arrangements (Glassmeier *et al* 2007). In addition, there is the potential of combining components of the magnetometer instrument design which traditionally reside on a central digital processing unit into the same FPGA as the digital magnetometer electronics, further reducing the component count of the overall design. Alternatively, several magnetometer sensors could be run from one FPGA again reducing the component count required. Many missions house two magnetometers on a boom to allow the monitoring and removal of the field from the spacecraft (Carr *et al* 2005). Part of the requirement for such dual magnetometer modes is the simultaneous sampling of the field at both locations; this could be easily facilitated with the use of one FPGA for both sensors.

6. Conclusions

This work demonstrates the feasibility of reducing the component count and increasing the design flexibility of a tuned fluxgate magnetometer by moving the field measurement extraction and feedback generation to the digital domain inside an FPGA. This has significant advantages of reducing the mass of designs for space applications as well as offering the possibility of a flight design that can be fully implemented using radiation hardened components. The capacity of modern radiation hardened FPGA chips further offers the opportunity of migrating processing electronics onto the same chip as the magnetometer electronics and combining the electronics from several magnetometer sensors onto the same chip further reducing the component count and facilitating simultaneous measurements from two or more sensors.

7. Future work

The described instrument performance was obtained with a rather simple prototype set-up (commercial components, minimal consideration to grounding and layout, flying wires, etc) and so to really prove that the concept can get to the noise performance demanded by scientific missions ($<$10 pT Hz$^{-1/2}$ at 1 Hz, 10 pT resolution) further work is required to produce a more representative flight prototype. Some missions will require a larger range than the current design ($\pm$327 nT), and to achieve the required linearity across that larger range, a more involved DAC design may be required, such as a combined pulse-width modulation and sigma–delta modulation design (Forslund *et al* 2007). Further optimization of the ADC, DAC and field extraction algorithms may also be required to accommodate radiation tolerant components.

References

Acuña M H 1974 Fluxgate magnetometer for outer planets exploration *IEEE Trans. Magn.* **10** 519–23

Acuña M H 2002 Space-based magnetometers *Rev. Sci. Instrum.* **73** 3717–36

Auster H U, Lichopoj A, Rustenbach J, Bitterlich H, Fornacon K-H, Hillenmaier O, Krause R, Schenk S and Auster V 1995 Concept and first results of a digital fluxgate magnetometer *Meas. Sci. Technol.* **6** 477–81

Balogh A, Beek T J, Forsyth R J, Hedgecock P C, Marquedant R J, Smith E J, Southwood D J and Tsurutani B T 1992 The magnetic field investigation on the Ulysses mission: instrumentation and preliminary scientific results *Astron. Astrophys. Suppl. Ser.* **92** 221–36

Balogh A *et al* 2001 The cluster magnetic field investigation: overview of in-flight performance and initial results *Ann. Geophys.* **19** 1207–17

Candy J C 1997 An overview of basic concepts *Delta-Sigma Data Converters: Theory, Design and Simulation* ed S R Norsworthy, R Schreier and G C Temes (Piscataway, NJ: IEEE) pp 1–41

Carr C *et al* 2005 The Double Star magnetic field investigation: instrument design, performance and highlights of the first year's observations *Ann. Geophys.* **23** 2713–32

Cerman A, Kuna A, Ripka P and Merayo J M G 2005 Digitalization of highly precise fluxgate magnetometers *Sensors Actuators* A **121** 421–9

Dougherty M K *et al* 2004 The Cassini magnetic field investigation *Space Sci. Rev.* **114** 331–83

Forslund Å, Belyayev S, Ivchenko N, Olsson G, Edberg T and Marusenkov A 2007 Miniaturized digital fluxgate magnetometer for small spacecraft applications *Meas. Sci. Technol.* submitted

Glassmeier K-H *et al* 2007 RPC-MAG the fluxgate magnetometer in the ROSETTA plasma consortium *Space Sci. Rev.* **128** 649–70

Hapgood M A, Eckersley S, Lundin R and Kluge M 2005 Nano-satellite beacons for space weather monitoring *Proc. 5th ESA Round Table on Micro/Nano Technologies for Space (ESTEC, Noordwijk, The Netherlands, 3–5 Oct. 2005)*

Henriksen J P, Merayo J M G, Nielsen O V, Petersen H, Raagaard Petersen J and Primdahl F 1996 Digital detection and feedback magnetometer *Meas. Sci. Technol.* **7** 897–903

Hogenauer E B 1981 An economical class of digital filters for decimation and interpolation *IEEE Trans. Acoust. Speech Signal Process.* **29** 155–62

Magnes W, Pierce D, Valavanoglou A, Means J, Baumjohann W, Russell C T, Schwingenschuh K and Graber G 2003 A sigma–delta fluxgate magnetometer for space applications *Meas. Sci. Technol.* **14** 1003–12

Primdahl F, Hernando B, Petersen J R and Nielsen O V 1994 Digital detection of the flux-gate sensor output signal *Meas. Sci. Technol.* **5** 359–62

Valavanoglou A, Oberst M, Magnes W, Hauer H, Neubauer H, Baumjohann W and Falkner P 2007 Magnetometer front-end ASIC (MFA) *EGU General Assembly (Vienna, Austria, 15–20 April 2007)* EGU2007-A-06089

Zhang T L *et al* 2006 Magnetic field investigation of the Venus plasma environment: expected new results from Venus Express *Planet. Space Sci.* **54** 1336–43