

S.Kellock¹, P. Austin², A.Balogh¹, B.Gerlach³, R.Marquedant⁴, G.Musmann³, E.Smith⁴, D.Southwood¹, S.Szalai⁵

¹The Blackett Laboratory, Imperial College, London, SW721E!! UK

²Ultra Electronics, Magnetics Division, Hednesford, Staffs, WS125Q7+ UK

³Technische Universität Braunschweig, D-38106 Braunschweig, Germany

⁴Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA91109, USA

⁵KFKI Research Institute for Particle and Nuclear Physics, P.O.Box 49, 11-1525 Budapest, Hungary

ABSTRACT

This paper describes the magnetometer instrument (MAG) to be flown on the Cassini spacecraft. The instrument consists of two magnetometers and an on-board data processing unit. One magnetometer is a Vector Helium device of a type previously flown on Ulysses and several other missions which has been modified to operate in a Scalar mode providing measurements of the magnitude of the local magnetic field with very small absolute error (less than 1nT). This is the first flight of such an instrument. The other magnetometer is a Fluxgate device of similar design to that flown on Ulysses and on many previous missions but with newly developed electronics. Both magnetometers can provide vector measurements of the three components of the magnetic field with a sensitivity of about 10pT. The unique combination of Fluxgate/Scalar or Fluxgate/Vector Helium operation offers increased possibilities for scientific investigation of the magnetic field environment in the Saturnian system. The data processing unit contains dual redundant systems based on the 80C86 microprocessor. It features sophisticated onboard data processing, large internal data storage capability and internal failure detection and recovery, giving the instrument the capability to operate autonomously for extended periods. The MAG instrument development team is drawn from institutes in four countries reflecting the multi-national flavour of the Cassini/Huygens mission.

Keywords: Saturn, Titan, magnetic field, helium magnetometer, fluxgate magnetometer, scalar magnetometer

1. SCIENCE AND OBJECTIVES

The Cassini spacecraft mission will perform a detailed investigation of the Saturn-Titan system, a magnetometer is an essential instrument in any such mission. The existence of an internal Saturn magnetic field, a magnetosphere and a strong plasma interaction between Titan and the Saturn magnetosphere has been shown in previous flyby missions. Our goal is to characterise physically and secularly the dominant processes which maintain the magnetic field and the magnetosphere and we expect to make critical contributions to the understanding of how Titan's outer atmosphere interacts with the plasma surrounding it.

One area of investigation will be the internal field of Saturn. As for other planetary magnetic fields this field is thought to be due to a dynamo motion formed by highly conducting material deep within the interior. In a simple model one would expect that the field would align closely with the rotation axis and resemble a dipole but each planet has been found to exhibit some special feature in its magnetic behaviour and Saturn is no exception. Whilst the field is remarkably symmetric about the planetary rotation axis, compared to other planets, the axis is displaced along the rotation axis from the planetary centre. Planetary internal fields are normally categorised by using harmonic analysis, regarding the source of the field as made up of series of multipoles (labelled by index, n), dipole ($n = 1$), quadrupole ($n = 2$), octupole ($n = 3$), etc., all collocated at the centre of the planet. The radial decay of the field and its variation in latitude and longitude characterises each coefficient. To determine high order coefficients one must measure the field close to the planet and very precisely. The unique scalar measurement capability of this instrument (see below) allows far more precise measurements to be made than in the past. The present description of Saturn goes as far as the octupole coefficient ($n = 3$), we expect to achieve two orders better (i.e. $n = 5$). We will also be able to detect any changes in the planetary field since the Voyager observations. Ultimately, for a more complete picture, we hope to add to the magnetometer measurements, observations made by other Cassini instruments of the planetary radio emissions and the energetic charged particle environment.

The Cassini spacecraft will spend much time in the magnetosphere of Saturn. This is a region of the distant outer atmosphere with a significant amount of ionised material, forming a plasma, where the density is such that collisions between the neutral and ionised components of the gas are relatively infrequent. Here the magnetic field is responsible for any cohesive behaviour, constraining particle motion and transmitting stresses in the medium. As Saturn rotates, material in the magnetosphere far from the planet rotates also. This is due to stresses transmitted via the magnetic field from the ionosphere where collisional coupling takes place between the rotating neutral atmosphere and the ionised component. In the Saturnian system interactions may also occur with the rings and dust should they become electrically charged, large scale current systems are to be expected whose magnetic signatures would be observable with the magnetometer. Current signatures should also be seen due to field aligned currents from the ionosphere to the magnetosphere resulting from the transfer of ionised material into the rotating magnetosphere. This phenomenon is fuelled by the relatively large number of internal plasma sources - neutral hydrogen deep in the magnetosphere, material from Titan around its orbit, Titan itself, the icy satellites, the planetary rings and possibly also material lifted from the ionosphere. To add to these observations we also expect to be able to contribute to other studies of this region, for example analysis of wave activity in the ULF (ultra low frequency) band will provide information on the coupling of different charge species.

The outer regions of the magnetosphere are another area for investigation. The magnetopause, the boundary between the regime where the planetary field controls behaviour and the external solar wind, is of critical interest and similar to the bow shock and the intervening magnetosheath regions contain many important plasma phenomena which help in the understanding of the way in which the planet interacts directly with the surrounding interplanetary material.

Titan observations are a major objective of the Cassini mission. Although not expected to have an internal magnetic field, recent observations of Io and Ganymede have taught us not to rule out such a possibility. Voyager and Pioneer observations have shown strong interaction between Titan, the solar wind and Saturn's magnetosphere. Titan's orbit takes it through a variety of plasma environments - the solar wind, the magnetosheath and the magnetosphere proper - the outer atmosphere interacting with the ambient plasma to form a plasma magnetotail. Magnetometer observations will play a vital part in the understanding of this interaction. Multiple Titan encounters will provide information for a variety of different plasma conditions.

The principal investigator for MAG is Prof. David Southwood of Imperial College. A list of MAG investigators and the science areas in which they were originally allocated primary responsibility is given in table 1.

	institute	Responsibility
D.J.Southwood	Imperial College, UK	Satellite/dust/ring/torus electromagnetic interactions, variation of the Titan-external plasma interaction with orbital phase
E.J. Smith	NASA/JPL, USA	Saturn internal field analysis
A. Balogh	Imperial College, UK	3-D Heliospheric study using cruise phase data
S.W.H. Cowley	Leicester University, UK (formerly Imperial College)	Magnetotail phenomena, reconnection, time variations in magnetospheric phenomena, large scale magnetospheric processes
B. T. Tsurutani	NASA/JPL, USA	Waves and instabilities in Saturn environment+ satellite interactions, Jovian tail and current system
C.T. Russell	UCLA, USA	Wave and boundary structure analysis
G.L. Siscoe	UCLA, USA	Development of a 3-D model of the Saturn magnetosphere, stress analysis of the Saturn magnetospheric system
G. Erdős	KFKI, Hungary	Titan-plasma flow interactions
K.-H. Glassmeier	TUB, Germany	Hydromagnetic wave phenomena in Saturnian and Jovian magnetosphere
F.M. Neubauer	Köln University, Germany	Detailed interpretation/modelling of the Titan plasma environment

Table 1: MAG investigators and their individual prime science responsibilities (as originally allocated)

2. INSTRUMENTATION

2.1 General

The instrument can be conveniently separated into three sub-units: the main electronics, the vector/scalar helium magnetometer (V/SHM) and the fluxgate magnetometer (FGM). The main electronics, which include electronics for each of the magnetometers, are mounted onto two subchassis which are built into the main body of the spacecraft (upper equipment module, bay 4). Both sensors are mounted on a project-provided, deployable, 11 metre boom; the V/SHM at the end and the FGM halfway down the boom. Each sensor uses different, well established, physical principles to measure the three orthogonal components of the magnetic field vector. In addition the V/SHM can operate in a scalar mode (scalar helium magnetometer, SHM) in which it can very accurately measure the magnitude of the magnetic field. In concept the instrument is very similar to the dual magnetometer experiment on the Ulysses spacecraft, which has operated very successfully during that mission's journey around Jupiter and the Sun, the principal difference being the scalar capability of the helium magnetometer. This sensor combination is being flown for a number of reasons: dual vector sensors provide redundancy, improve in-flight calibration and measurement of the residual spacecraft field, the SHM in combination with simultaneous vector measurements using the FGM gives the capability to measure the magnetic field vector to better absolute accuracy (around 1 nT) than that for vector instruments alone. In addition the wide dynamic range capabilities of the FGM are complemented by the low noise, sensitivity of the VHM.

An overall block diagram of the instrument is shown in figure 1.7 this also shows how the hardware responsibilities have been divided between Imperial College London (the principal investigator institute), Jet Propulsion laboratory (JPL) Pasadena and the Technical University of Braunschweig (TUB). The Central Institute for Physics Budapest (KFKI), in conjunction with TUB, are responsible for providing the ground support equipment.

Mass and power figures, measured on the engineering model, are shown in table 2. Prior to delivery the instrument is comprehensively calibrated in several facilities; JPL (VHM), Fredericksburg Virginia (SHM) and TUB (FGM plus cross-calibration of VHM and SHM). In-flight calibration (offset and spacecraft field determination) of the vector magnetometers will be performed using standard techniques developed in previous missions. operation of the SHM at Earth flyby during the spacecraft cruise phase will provide a means to check it's performance in a known magnetic field.

An extensive magnetic cleanliness program has been followed during assembly of the spacecraft. Each instrument and subsystem is subjected to magnetic mapping each time it is delivered for integration, if necessary strong local field sources have been compensated by stable magnets or shielded. In some cases design changes have been made to minimise local fields. The excellent co-operation given by both spacecraft and instrument teams to achieve a magnetically clean spacecraft has been much appreciate by the MAG investigators. The spacecraft field seen at the FGM and V/SHM sensors is expected to be better than 0.6 and 0.2 nT respectively.

	Power (W)	Mass (kg)
V/SHM Sensor plus heaters	2.73	0.93
FGM Sensor plus heaters	1.12	0.42
Sensor and Power Electronics	5.97	5.06
DPU	2.61	2.60
Total	12.43	9.01
Allocation	13.00	9.79

Table 2: instrument mass and power figures measured on the engineering model

2.2 The vector/scalar helium magnetometer (V/SHM)

The V/SHM is an optically pumped magnetometer capable of operating in either a vector mode or a scalar mode. In the vector mode three voltages are generated proportional to the three mutually orthogonal magnetic field vector components whereas in the scalar mode the Larmor frequency proportional to the magnitude of the magnetic field is measured. The

vector fields are measured to an accuracy of better than 0.5% but in the scalar mode the magnitude of the magnetic field is measured to an absolute accuracy of better than 0.01% (1 part out of 10000). The Cassini mission will be the first space mission where one magnetometer having a dual vector or scalar capability will be flown.

Vector and scalar helium magnetometers have a great deal of commonality both in the sensor and the electronics. Only minor modifications are required to change a vector helium sensor into a scalar helium sensor. Similarly the vector helium electronics feedback loop has a number of circuits which are common to the scalar helium electronics feedback loop. As a cost reduction measure the Cassini V/SHM makes use of this commonality by modifying the flight spare Ulysses vector helium magnetometer and using it as the "core" of the Cassini V/SHM flight model. The Ulysses sensor requires only the addition of a 6 turn coil added to the sensor's triaxial helmholtz coil in order to operate the sensor in a scalar mode and the Ulysses vector electronics requires only that the full scale ranges be changed to meet the Cassini vector requirements.

The preamplifier in the vector electronics is the only circuit common to the Cassini vector and scalar modes of operation. In the scalar mode the preamplifier drives the input to scalar feedback electronics while the remainder of the vector electronics idles. This is not the most efficient use of power or circuit commonality but is necessitated by the fact that the Ulysses vector Electronics is already in a flight packaged configuration, Even minor modifications which make full use of circuit commonality would impact the flight integrity of the existing hardware and thereby negate the costing saving benefit

The vector mode has two ranges, range 0 covers +/-32 nT and range 1 covers +/-256 nT. The scalar mode range is 256 nT to 16384 nT. The latter range is unusually low for a scalar magnetometer which normally operates in the Earth's field of 30-50,000 nT. It is a consequence of the Cassini orbit which keeps the spacecraft at higher altitude and in weaker fields than is true of Earth Satellites. In the vector mode each range has an in-flight calibrate capability where a calibrated current is injected into each of the three coils in the triaxial helmholtz coil and the response noted in the magnetometer's output. In range 0 and range 1 the in-flight calibrate magnitude is +/-4 nT and +/-32 nT respectively. Switching between ranges is Controlled by the instrument data processing unit (DPU).

2.2.1 Helium magnetometer operating principles

The operation of the helium magnetometer is based on the principles of optically pumped helium in the metastable (triplet) State. The magnetic field is measured by sensing it's effect on the zeeman splitting that occurs in the optically pumped helium. Metm.able helium is generated in a helium absorption cell by a radio frequency discharge. 1.083 μm radiation, circularly polarised and generated in a helium lamp by the same radio frequency discharge, is passed through the helium absorption cell.

The vector mode utilises a rotating magnetic field to vary the optical pumping efficiency which modulates the absorption of the helium cell. The rotating magnetic field is produced by injecting sinusoidal currents into a helmholtz coil that surrounds the helium absorption cell.

In the scalar mode optical radiation at 1.083 μm and an AC magnetic field are simultaneously applied to the absorption cell. The efficiency of optical pumping is minimal and the absorption is greatest when the frequency of the applied AC field is at the Larmor frequency. The Larmor frequency is directly proportional to the ambient magnetic field with a proportionality constant (the gyro magnetic ratio) of 28.023561 Hz/nT for helium.

2.2.2 V/SHM block diagram description

The V/SHM consists basically of three subsystems; vector electronics, scalar electronics and sensor. These are shown in figure 2.

The Ulysses vector electronics are enclosed by a dotted line at the top of the figure. A sweep oscillator produces 2 sinusoids with a 90 degree phase difference. A continuous sinusoid is applied to the set of coils within the helmholtz coil system that is aligned with the sensor's optical axis. Alternate cycles of the 90 degree sinusoid are applied to the remaining two orthogonal sets of the helmholtz coil. The rotating magnetic field therefore commutates between two orthogonal planes of the sensor. Because the pumping efficiency is proportional to $\cos^2(\Theta)$, where Θ is the angle between the magnetic field and the sensor's

optical axis, the helium cell's absorption is modulated at the second harmonic of the sweep frequency. When a steady (or slowly varying) ambient magnetic field is encountered the absorption is modulated at the second harmonic plus the fundamental of the sweep frequency. Synchronously detecting (the fundamental provides the error signal required to null the field at the absorption cell. Having calibrated the sensor's helmholtz coil constants determines the magnetic field, Since the applied sweep field is commutated in two orthogonal planes about the sensor the three vector components of the ambient magnetic field are determined.

The scalar electronics are shown at the bottom of figure 2. These electronics constitute new flight hardware as opposed to the existing vector hardware. The scalar feedback loop is a null sensing control loop as is the vector control loop. The difference is that the scalar electronics must detect and track the Larmor frequency as opposed to the vector electronics that detect and track an error resulting from the addition of the sweep field and the ambient field. Since the Larmor frequency is based on fundamental constants the scalar's absolute accuracy is about 100 times better than that of the vector magnetometer. Tracking the Larmor frequency is accomplished by frequency modulating the AC magnetic field at an audio rate (325 Hz for Cassini). When the control loop is exactly at Larmor frequency only the 2nd harmonic of the audio frequency is detected. The addition of a steady (or slowly varying) magnetic field generates a fundamental of the audio frequency along with the 2nd harmonic. Synchronously detecting the fundamental generates an error signal to draw the control loop back to the Larmor frequency. At turn-on the ambient magnetic field is not known and a search in the form of a linear frequency sweep (30 second period) of the AC magnetic field over the magnetometer's operating range is initiated. As the swept frequency comes in contact with the Larmor frequency an error signal is generated causing the control loop to discontinue the search and to begin it's tracking of the magnetic field.

2.2.3 Sensor

Figure 3 is a sensor schematic. The heart of the sensor is the helium absorption cell. The critical elements to the right of the cell are the circular polariser and helium lamp. Two pie matching networks convert the relatively high lamp and cell impedance (9 and 21 kOhms respectively) to a 50 ohm system. To the left of the cell is an arsenic trisulfide lens and a large area silicon detector. The ignition transformer that is used to initiate the RF discharge is shown at the very end of the sensor.

The sensor can operate over a temperature range of -10 to +40C without any degradation in performance. A 2 W DC heater, proportionally controlled, is used to insure that operation is maintained within this range. This heater consists of Lightly twisted 36 AWG manganin wire. No magnetic interference is detected from the heater.

2.2.4 Calibration

Calibration of the vector mode of the magnetometer is accomplished in the normal manner, The magnetometer is subjected to magnetic fields that are of known magnitude and the resulting output voltage recorded.

The scalar mode however is not as straightforward because the scalar can measure field magnitudes to an absolute accuracy better than 1 nT. Thus generating calibration fields for the scalar is extremely difficult. Instead we have measured the offset errors that are known to exist in an optically pumped helium magnetometer in order to correct the data. These errors are on the order of 1 nT and are commonly called lightshift errors. Lightshift errors are constant throughout the Cassini operating range and are caused by a shift in the ground state transition frequency. The shift is proportional to the pumping light intensity. To measure these errors we had to develop special techniques that required a large diameter coil system. We used the coil system at the Geomagnetic Observatory located near Fredericksburg, Virginia. In fields below about 1000 nT, Bloch/Siegert errors are encountered. These occur when the magnitude of the AC magnetic field that depumps the helium becomes around 1% of the ambient magnetic field. The small shift in Larmor frequency that occurs under these circumstances is well characterised theoretically and has been confirmed by careful testing and calibration of the scalar at the Fredericksburg Observatory.

2.3 The fluxgate magnetometer (FGM)

Fluxgate magnetometers have been flown by several investigators, including Imperial College, On many previous missions. The FGM is an improved version of a design used in the past by Imperial College. For a mission such as Cassini the

instrument must exhibit high reliability, a wide dynamic range, low power consumption, very low noise and very low offsets and offset drift. These goals are achieved by the appropriate selection of electronic components and materials and by special measures in the design of the sensor and its electronics. The FGM consists of a boom-mounted sensor and a set of drive/signal processing electronics located in the body of the spacecraft and connected to the sensor by approximately 6.5 metres of cabling. A high efficiency, tuned drive design of the electronics reduces the overall power consumption and the effect of cable loading.

The FGM sensor is composed of three single-axis, high performance fluxgate sensors mounted orthogonally on a block of machinable ceramic. Each fluxgate sensor is a toroidally wound, high permeability ring core inside a rectangular sense winding with its axis in the plane of the ring core. A simplified schematic of the electronics for a single fluxgate sensor is given in figure 4. The ring core is periodically driven into and out of saturation by a 15.625 kHz square wave via the toroidal winding. The component of the external magnetic field which is in the plane of the sense winding is amplitude modulated by the permeability change of the ring core and produces a signal on the sense winding at the second harmonic of the drive frequency. This signal is amplified and synchronously demodulated. The output is passed to the Data Processing Unit (DPU) and is also fed back to the sense winding to create a feedback loop. The toroidal windings of the three sensors are connected in series to reduce cabling and drive circuit complexity. Wale factor and alignment corrections are made electronically by fitting appropriate select 011 test components during set up of the instrument.

The instrument has four fullscale ranges, +/-40 nT, +/-400 nT, +/-10000 nT and +/-44000 nT, which after 14 bit analogue to digital conversion in the DPU give a resolution of 4.9 pT, 48.8 pT, 1.2 nT and 5.4 nT respectively. The highest range is used mainly for pre-launch testing. Range changes are achieved by changing both the feedback path to the sense winding and the amplification of the signal outside the feedback loop. A built in calibration capability has been included in the electronics. When commanded a fixed offset is applied to all three fluxgate sensor outputs, the frequency at which the offset is applied is controlled by command from the DPU.

The complete sensor is contained in a roughly cylindrical fibreglass cover, 100 mm high by 63 mm diameter, which is covered with aluminised mylar tape to satisfy thermal, electrostatic discharge and radiated emissions requirements. All materials used in the sensor construction are non magnetic. Thermal control is assisted by the inclusion of two AC heaters (total power 1W) mounted onto the glass ceramic block with associated control and monitor temperature sensors. These heaters are thermostatically controlled from a controller in the main electronics which provides a 100 kHz square wave, switching on when the temperature is less than 0C and off when the temperature is above 10C. Further thermal input is provided by three spacecraft provided radioactive heater units located on the sensor mounting fixture equidistant around the sensor base.

Performance figures measured during testing of the flight instrument prior to integration with the DPU and full calibration are given in table 3.

	Target	Measured		
		X-Axis	Y-Axis	Z-Axis
Offset	< 1 nT	+0.407	+0.145	-0.682
Noise (at 1 Hz)	<7 pT/√ Hz	3.59	4.89	3.37
Alignment error	< +/-0.1°	-0.018 Xy -0.0s8 XZ,	+0.012 Yx +0.006 Yz	+0.007 Zx +0.060 Zy
Scale factor error	<0.1%	0.066	0.009	0.041
Bandwidth	>75117,	95.25	90.75	95.25

Table 3: FGM flight model performance measured before integration with the DPU versus target specification values.

The FGM sensor and electronics were manufactured under contract by Ultra Electronics of Hednesford, UK.

2.4 The onboard data processing unit (DPU)

The DPU interfaces the magnetometers and the power Management System (PMS) via a project-provided Bus Interface Unit (BIU) to the spacecraft data handling subsystem (see figure 5). The processor system is based on the 80C86 micro processor and operates at 4 MHz. Each of 2 redundant systems (figure 6) contain 32 kByte of PROM, 128 kByte RAM for program, data and snapshot memory. In addition each system contains 16 MByte for multi-snapshot memory.

2.4.1 Telemetry

The MAG instrument transmits science data packets with a data rate of 1976 bits per second (bps) and housekeeping data packets with a data rate of 24 bps. It also transmits ancillary data for other onboard users once per second. About 100 commands control the sensors and the DPU.

2.4.2 Data acquisition

The DPU digitises the 3 analogue signals of the FGM sensor with a default internal sampling rate of 125 vectors per second. The 3 analogue signals of the VHM sensor are digitised with a 125/16 vectors per second sampling rate. All vector components are converted into 14 bit words. The internal sampling rate can be changed by telecommand between 16 and 250 samples per second. Every four seconds the DPU formats 128 FGM and 8 VHM vectors into a science data packet. Fixed window averaging or running averaging can be selected for data compression. The DPU computes the average coefficient in steps of 2^n depending on the sampling and telemetry rate. Thus it adapts to different telemetry rates automatically and tolerates gaps in the science data flow. A magnetic field vector is broadcast once per second to other onboard instruments. A 19 bit magnitude scalar word is obtained once per second from the SHM. An automatic range control sets the FGM and the VHM sensors into the optimum measurement range.

2.4.3 Snapshot

Transient events such as shocks, discontinuities, angular variations and varying field variances can be captured and stored with the actual sampling rate into 2 snapshot memories. Up to 4 snapshot criteria can be selected for simultaneous computation and for each criterion priority, memory allocation and trigger position can be selected. 10 capture transient events with high time resolution a 64 kByte, Hi Rel, Rad Hard, memory has been selected. One snapshot memory allows storage of about 90 seconds of FGM data sampled at 125 vectors/second. The second 16 MByte multi-snapshot memory consists of state of the art commercial parts and allows storage of 6 hours of data sampled at 125 vectors/second.

2.4.4 Inflight calibration

The DPU provides inflight calibration signals to the sensors. The frequencies of these signals can be selected by command. Onboard ADC test routines compute the spectrum and show noise frequencies. Temperature and radiation drift of the analogue circuitry is monitored by two 16 bit HK channels.

2.4.5 Reliability

Different safety options have been built into the processor system to increase the overall reliability. The DPU is a dual redundant processor system, the only exception being the BIU and a small Common Core. Radiation hard parts (100 kRad) have been used as far as possible. Only the 16 bit ADCs, some Op Amps and the 16MB DRAMs are not radiation hard, these parts are spot shielded with Tantalum. During selection of the 16MB DRAMs, total dose and single event upset measurements were performed. Hamming Single Error Correction and Double Error Detection is applied on all memory devices. Memory scrubbing is used for routine removal of single bit failures. Each processor system contains 4 dual level latch up detectors as flown on GEOTAIL, WIND and SOHO. If an engineering and health status check detects a failure, the watchdog causes a hardware reset. After a reset caused by latch up, watchdog or discrete command, the instrument is automatically reconfigured into its previous mode. If contact is fully or partially lost with the spacecraft data handling system the spacecraft time code and synchronisation signals can be generated artificially by internal timers. The DPU can

automatically adapt the science and housekeeping packet generation to any telemetry rate. The DPU program normally runs in RAM which is loaded from PROM at powerup, this RAM software is modifiable by ground command.

2.4.6 Housekeeping

The DPU digitises 25 analogue housekeeping channels into 8 bit words. Two channels are digitised into 16 bit words to determine the temperature and radiation drift of the analogue circuitry. About 50 error counters are highly subcommutated and monitor anomalies of DPU functions. A maintenance field in the housekeeping data packet can be used for multiple functions: memory dump, calibration, snapshot data, ram check, high time resolution instrument status and analogue housekeeping data.

2.5 The power system

Three main power supplies are used within the instrument. Two cold redundant units, PS 1 and PS2, supply the DPU, FGM, scalar and VHM electronics with thirteen separate power lines. A third unit, PS0, supplies the BIU and common core of the DPU; a dedicated supply was chosen for this task due to the highly variable power demands of the BIU in transmit and idle states. PS0 is always powered whenever the spacecraft has switched power to the instrument. The units are switching power supplies with internal over-voltage shutdown protection, similar in design to ones flown previously by Imperial College. The design ensures that a constant difference of 0.1V is maintained between the supply voltage for the DPU processor and that for the BIU, this is required by the design of the latch up detection circuits of the DPU. The supplies are switched by a 50 kHz clock derived from a 100 kHz signal from the BIU.

Figure 1 shows how power is supplied throughout the instrument. Internal switching of the power lines is achieved using a total of sixteen electronic, non-latching switches rather than by relays. As for the power supplies, the switches are also similar in design to ones flown previously by Imperial College. The switches are controlled by discrete commands either from the DPU or from the BIU and only operate in the presence of the 100 kHz clock signal from the BIU. Each switch has an input current limiter which causes it to switch off whenever the pre-set current level is exceeded.

There is an additional power supply within the VHM electronics unit to supply the VHM electronics. This unit also contains a proportional heater controller for the V/SIM heater. Another heater controller for the FGM is located within the main electronics. The power for both of these is obtained from a single spacecraft power source which is separate to that for the instrument itself.

2.6 Ground data processing and flight operations

The Cassini project has decided on a distributed operations concept for instrument operations during the mission. A secure workstation with a dedicated command and telemetry data line has been installed at the institute of each principal investigator. For MAG this is located at Imperial College. Using this terminal the MAG operations team, based at Imperial College, will be able to produce command files for eventual uplink to the instrument and transfer telemetry held in a central data base at JPL. During downlinks from the spacecraft, telemetry will be available at Imperial College in near-real-time. As part of the distributed operations concept, the MAG team will actively participate in the mission planning cycle, eventually producing detailed command sequences in mnemonic format to be combined and converted into uplink format with other commands for uplink at JPL.

Operational activities during the long, 5 year, cruise phase of the mission are necessarily very limited. For most of this period the instrument will not be powered: the few planned operations being instrument checkout, MAG Boom deployment and scalar operation during Earth flyby, 3 monthly maintenance of the V/SJ IM helium cell. The principal ground activities will be detailed planning for the tour phase in the Saturnian system and preparations for tour operations. During the 4 year tour and the preceding 2 years, instrument science and calibration data will be received at Imperial College, on-line processing will convert to magnetic field values correcting for instrument offsets and spacecraft residual field and the resultant data stored in an instrument data archive. All instrument science investigators will have access to this archive. In-flight operations will be planned to check the instrument calibration and the ground data processing will be updated based on the results.

3. ACKNOWLEDGEMENTS

For a complex instrument with a large multi-national team such as MAF3 there will inevitably have been a great number of dedicated people who have made significant contributions to it's development. There is insufficient space hereto do justice to these efforts. At Imperial College T.Beck and M. Malhotra have been involved in most areas of design, development and testing. At the Jet Propulsion Laboratory, L. Wigglesworth, J. van Amersfoort and M. Fong were part of the team who put the V/SHM together. At Technical University Braunschweig, M. Rahm and I. Richter were deeply involved in the instrument calibration, A. Müller made important contributions to the development of the support equipment. There are also a number of people at KFKI who have contributed to development of support equipment, amongst these are I. Szücs and L. Nagy.

We would also like to thank members of the team at Ultra where the FGM was put together, particularly N. Taylor who did much of the work for the FGM. Also the very co-operative group at Rutherford and Appleton Laboratory (RAL), in particular J. Firth and R. Cutler, who helped out in areas of hardware production, environmental testing and design analyses. At UCLA, C. Russell and D. Huddleston have been leading the analysis of the instrument calibration data and B. Snare has been helping with the integration activities on the spacecraft. Much mechanical development of the DPU, including assembly, was made by Martin Pfeil Trawid; our thanks go to D. Pfeil and his father who were responsible for this and who also provided support for testing of the integrated instrument.

As we mentioned in the earlier text, a tremendous effort has been made to try to ensure a magnetically clean spacecraft. our special thanks go to P. Narvaez of JPL and K. Mehlem of ESA for their excellent efforts in this area but also to the Cassini project management who have supported this effort. Over the years we have had a number of engineers assigned at JPL to help our interface with the project team there; our thanks to the most recent of these B. J. Cheney and C. Elliott for their dedication and assistance.

The contributions to this investigation have been supported by the PPARC in the UK, DARA in Germany and by NASA in the US.

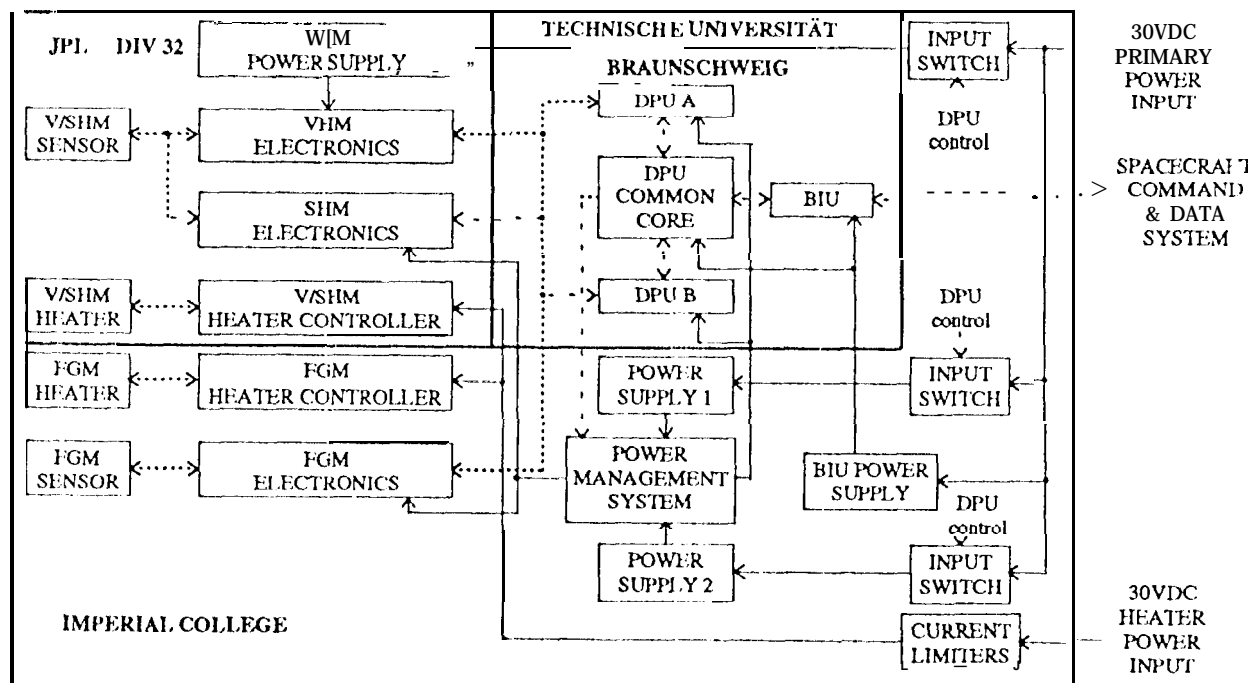


Figure 1: Overall block diagram of the MAG instrument showing also the institutes responsible for the hardware. Command and data interfaces are shown as dotted lines, power interfaces are shown as solid lines.

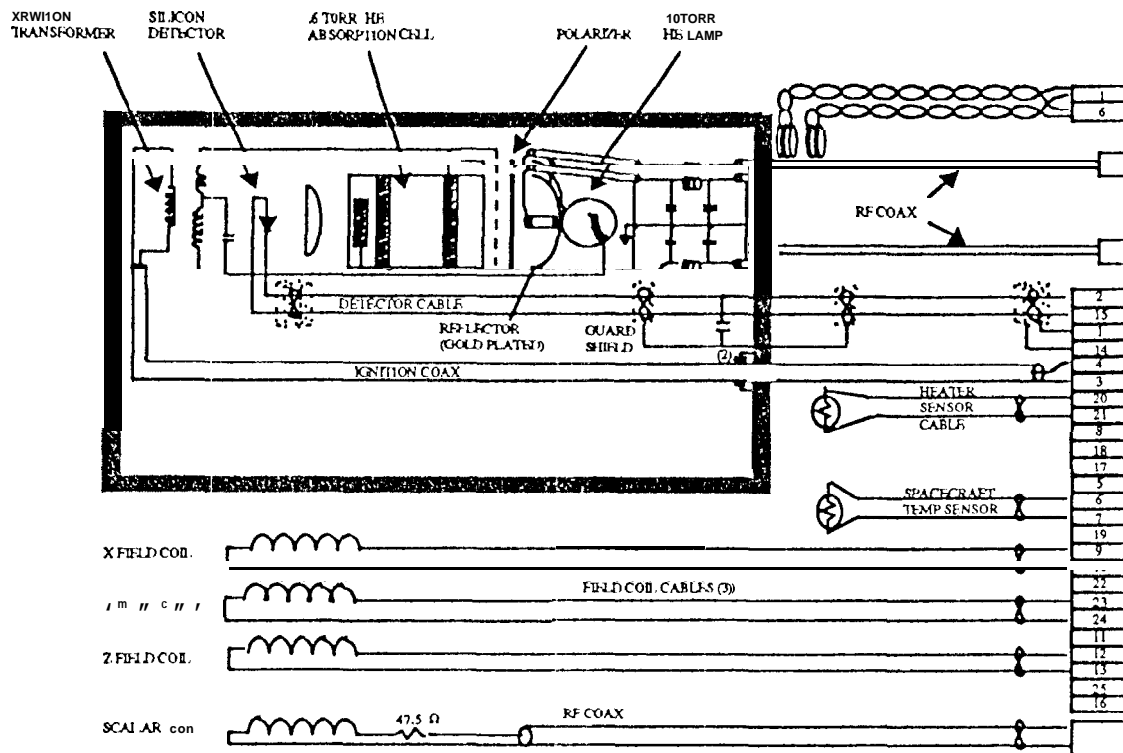


Figure 2: Cassini V/SIM sensor schematic

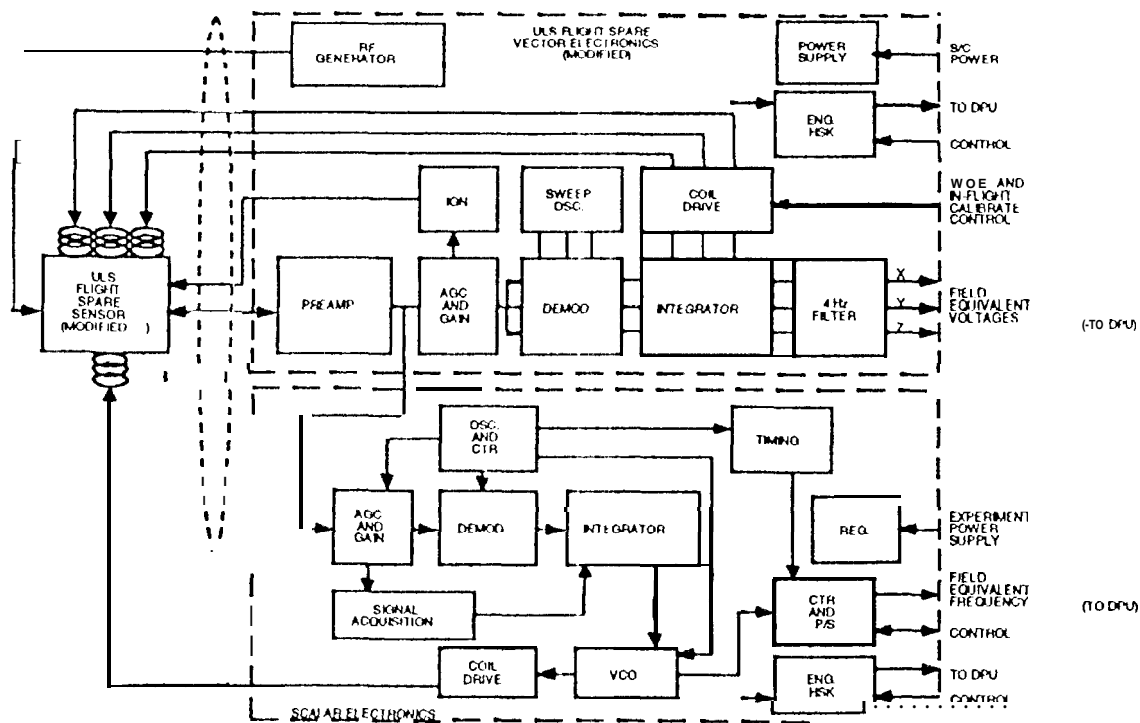


Figure 3: Cassini V/SIM block diagram

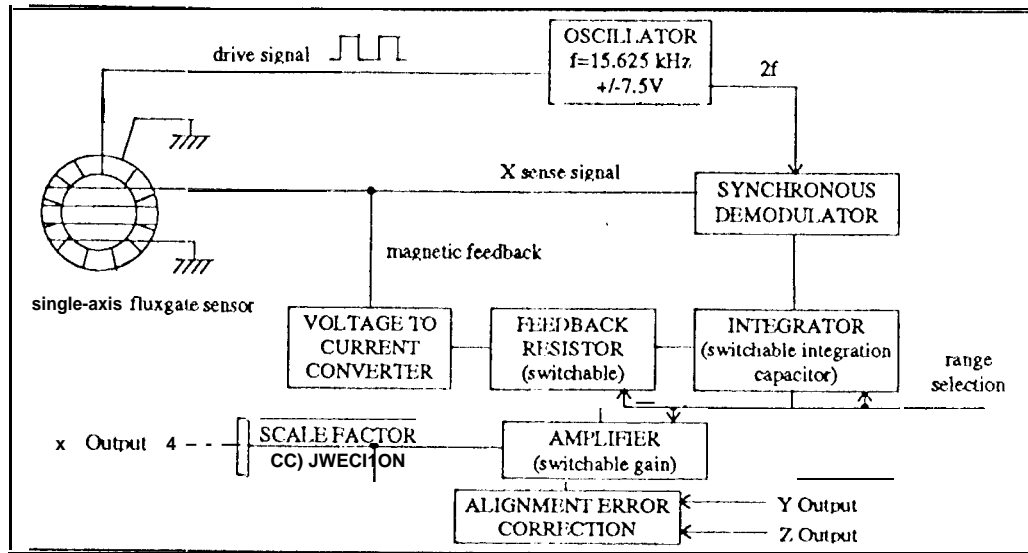


Figure 4: Simplified schematic of the electronics for one single-axis fluxgate sensor. Shown for the X-axis sensor.

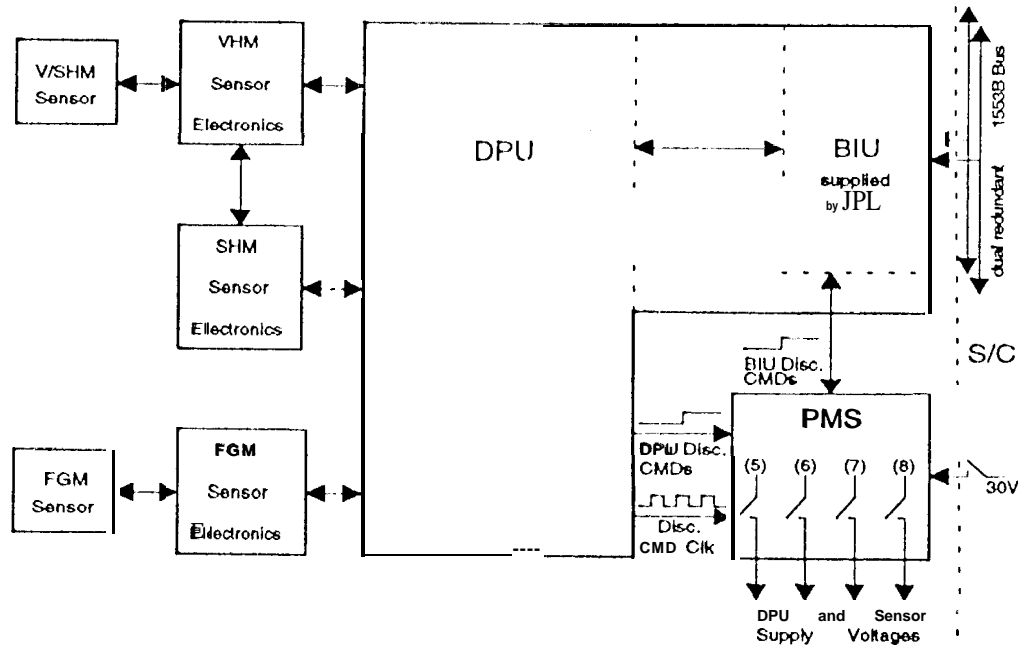


Figure 5: Instrument and spacecraft command and telemetry interfaces to the DPU. PMS is the instrument power management system containing the secondary power switches and the power distribution network.

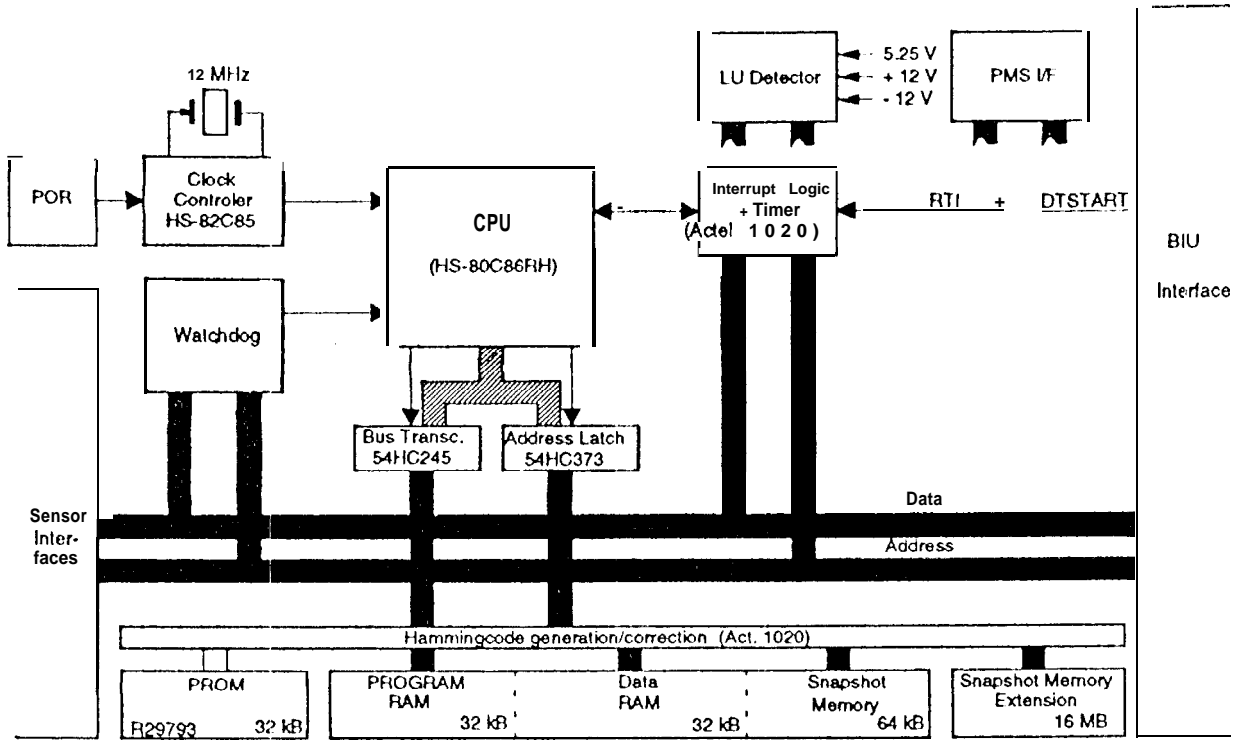


Figure 6: Block diagram of one of the two, cold-redundant, DPU 80C86 microprocessor systems.