BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD

RECORD 1981/75

MFS-7 FLUXGATE MAGNETOMETER DEVELOPMENT HISTORY

by

K.J. Seers

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Preface

The purpose for writing this Record some years after the event is threefold:

Firstly, it provides historical documentation of the most complex project yet undertaken by BMR's electronic development group and it demonstrates how such projects can generate increased competence in the group.

Secondly, it may assist those involved in equipment development, especially for aircraft or other mobile platforms, because the problems encountered in the MFS-7 development are fairly typical of the problems likely to arise in the development and installation of any sensitive and complex system.

Thirdly, it will give those still involved with the operation and maintenance of the MFS-7 some insight into the evolution of the magnetometer to its final configuration.

Abstract

The BMR-developed MFS-7 fluxgate magnetometer has been BMR's major airborne survey instrument since 1971. For faithful reproduction of magnetic anomalies the instrument was designed to have a bandwidth of 10 Hz; resolution at this bandwidth is 0.2 nT. Backing-off adjustments and supplies were eliminated by a total-field feedback loop. Over the operating range of ± 105 000 nT, accuracy, repeatability, and linearity, are excellent because they depend mainly on precision feedback resistors and the detector coil-constant. Circuits were designed to reduce the detector temperature coefficient to 3 ppm/°C.

Performance of this order demands purity and stability in the sine-wave detector drive. The design of high-power, low-distortion drive amplifiers, together with a tracking filter, a precision level control and a distortion-cancelling bridge, were major challenges.

A three-axis servo system was developed to keep the detector aligned to total field to within 3 minutes of arc.

Problems encountered with the installation in BMR's Twin Otter aircraft resulted in modifications to aircraft wiring and power supplies.

The experience gained from this project resulted in improved construction standards for mobile equipment and in particular for printed circuit boards.

The reasons for in-house development and the aims of the project are stated, and the development history is traced through the prototype, pre-production and production phases. Final performance specifications and a block diagram are included.

1. Introduction

The MFS-7 is a BMR-developed, high-resolution, wide-bandwidth direct-reading, total-feedback, fluxgate magnetometer combining high slew-rate and low noise with unusually high stability and low drift. It is particularly suited to low-level, high-speed aeromagnetic surveying and will operate in either hemisphere over the range 0 to 100 000 nanoteslas (nT). Full performance figures are given in Appendix B; operating and design information appear in the MFS-7 Handbook (BMR Record in preparation).

The MFS-7 project is one of the most challenging yet undertaken by BMR's electronic design group and exemplifies many of the problems encountered in developing complex state-of-the-art equipment for use in high-reliability field systems. When the project was initially proposed, the level of available plant and equipment funds precluded the purchase of a suitable instrument. In this particular case the decision to develop an instrument was also influenced by the experience already accumulated by the group in airborne magnetometer design, even though the need to break new ground introduced some unknowns. In the event, the magnitude of the design tasks and the time required were much greater than had been anticipated. These are constant hazards in development work, other notable organisations being similarly prone to them. The important outcomes, however, apart from a successful survey instrument, are the increased expertise directly applicable to future instrument design or assessment, and the spin-offs in improved design and construction techniques and project organisation which have been applied to subsequent projects.

2. Background

The MFS-7 is the latest, and possibly the last, of a series of airborne fluxgate magnetometers developed within BMR by modifying U.S. Navy airborne submarine-detectors. The first of these was the AN/ASQ-1 modified and installed in VH-BUR (DC-3) in the mid fifties. Next came the AN/ASQ-8, a generally superior instrument which lasted through a number of BMR modification phases, especially those reflecting the advent of solid-state electronic devices in the late fifties and early sixties. This system was installed in VH-MIN (DC-3) and was BMR's major aeromagnetic instrument for many years. Like most systems of that era it was bulky, heavy, power-hungry, subject to sensitivity and baseline drift, and had large temperature coefficients, slow response, arbitrary manual or electro-mechanical baseline setting, non-linearity, and a limited analogue output range.

In 1968, with the imminent replacement of VH-MIN by a lighter aircraft (ultimately VH-BMG, the Twin Otter), and the development of an airborne digital data aquisition system by D. Downie (Downie, 1973), the need for an improved magnetometer became apparent. The Airborne and Geophysical Services Sections of the Geophysical Branch initiated the MFS-7 project.

The aim was to acquire a more recent submarine-detector, the AN/ASQ-10A which was much smaller and lighter than the AN/ASQ-8 (although it too used vacuum tubes), and to modify it to the minimum extent necessary to produce a geophysical instrument meeting the initial specifications set by the Airborne Section (Appendix A). Figures 1 and 2 show the AN/ASQ-10A block diagram and the proposed MFS-7 block diagram. At that time expectations were that modification would be predominantly to the detector channel, to convert it to respond to static fields rather than the rapid time-varying fields (i.e. narrow bandwidth signals) experienced when flying over submarines.

To avoid the need for a stable, calibrated, backing-off current source, the MFS-7 was to use total field feedback over its full operating range. Backing-off, if required at all, was to be used only to extend resolution, and was to come from a voltage source in series with the digital voltmeter used to measure the voltage across the feedback resistor. This voltage, being proportional to the feedback current, would, by suitable choice of resistor value, give a direct indication of magnetic field, provided the feedback loop operated with zero error. An integrator was included in the forward path of the feedback loop to ensure zero error in static fields.

Previous work in BMR, on modifying similar systems and in the development of base-station fluxgate magnetometers (Seers, 1971), imparted a high degree of confidence that total field feedback would work provided that the high-Q detector tuning (used in the past) were dispensed with; otherwise there would be stability problems. Without detector tuning, however, there was a possibility of low signal-to-noise ratio (SNR) which would limit resolution. There was no way of assessing SNR at the time; the decision to proceed was influenced by the fact that the AN/ASQ-10A specifications showed a resolution of 0.01 nT, albeit in the narrow bandwidth used for submarine detection. There was, therefore, doubt about meeting the low-noise/high-resolution requirements of the initial specifications.

The AN/ASQ-8 and AN/ASQ-10A systems keep the detector element aligned with the total field vector by an orienting system containing three servo-controlled positioning motors. Two of these are controlled by signals from two auxillary fluxgate elements mounted at right-angles to each other and to the

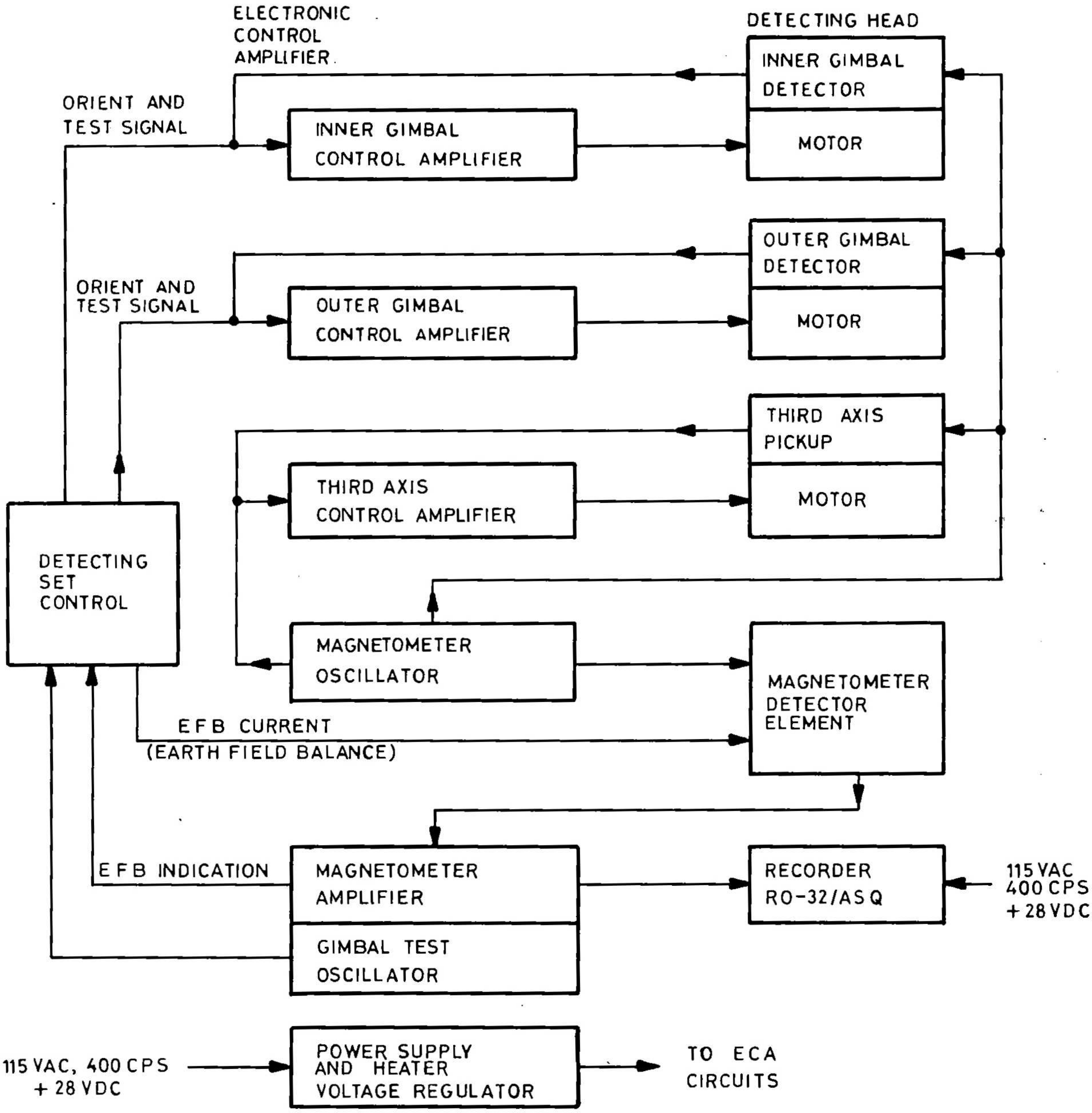

FIGURE 1 MAGNETIC DETECTING SET AN/ASQ-10A, SIMPLIFIED BLOCK DIAGRAM

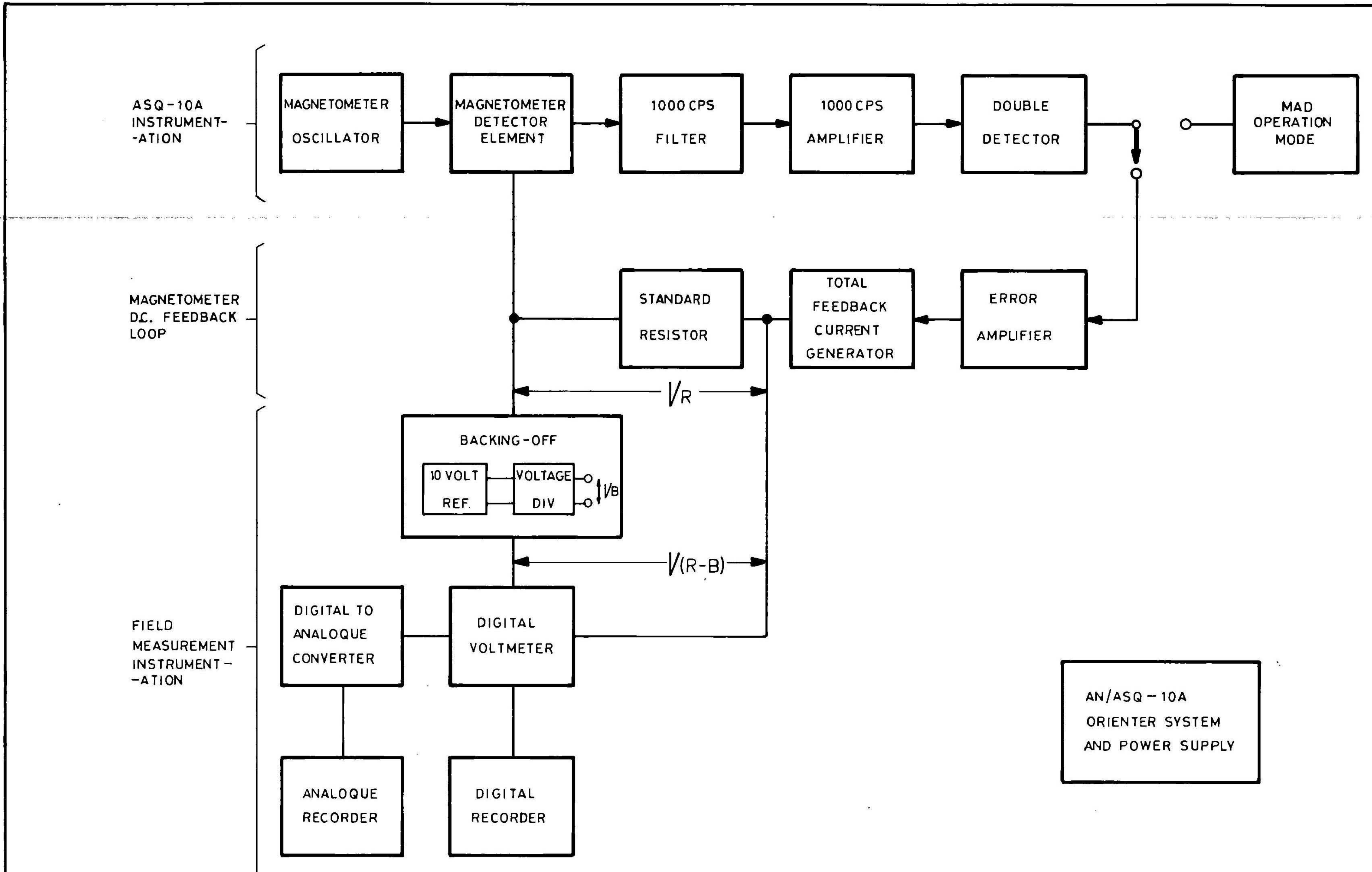

FIGURE 2 BLOCK DIAGRAM OF MFS-7.
(AS PROPOSED IN 1969)

detector element. Mechanical factors limit the angular rotation possible from one of these control axes, so a third-axis control rotates the entire detector frame. Operation is then possible for any combination of field direction and aircraft attitude. The third-axis control signal is partly derived from the alternating field surrounding the detector element as a result of its drive current. This occurs at a frequency of 400 Hz in the AN/ASQ-8 and 504 Hz in the AN/ASQ-10A. Previous modifications used a BMR-designed detector operating from a drive frequency of 5 kHz with the third-axis mechanically clamped and electrically inoperative. There was ample evidence that this caused excessive mechanical stress and wear on the fine orienter gearing during aircraft manoeuvres. To retain third-axis control meant that the AN/ASQ-10A detector and drive frequency also had to be retained, giving rise to further uncertainties: whereas the BMR detector design had been optimised by using separate sets of coils for drive, detection and feedback, the AN/ASQ-10A detector had only one set of coils to serve all functions. Also, though past experience had emphasised the importance of a stable, low-distortion drive source, and, as neither the detector characteristics nor those of the AN/ASQ-10A drive signal were known and could not be measured, at least until the units were purchased, the initial design strategy was to concentrate on the new detector channel known to be necessary, and to perform any further modifications as the need arose. At that early stage no changes to the AN/ASQ-10A orienting system were envisaged; the MFS-7 was to be a hybrid solid-state/vacuum-tube instrument. The caution underlying these strategies resulted in some loss of valuable time, as ultimately the only parts of the AN/ASQ-10A remaining were the detecting head and three small magnetic amplifiers.

3. Development History

3.1 Prototype

E. Muir, the initial project officer, started designing the prototype detector channel in September 1969. A mock-up of this design in November 1969 validated the general concept but was unsatisfactory because of the poor stability and high distortion of the AN/ASQ-10A tuned-plate tuned-grid drive oscillator. Muir designed a Wein-bridge oscillator and tracking filter to be incorporated in the prototype then under construction. Muir resigned in May 1970 before any of his final circuits were tested. For reasons related to AN/ASQ-10A characteristics which were then unknown, none of these circuits survived, but Muir's detector channel block diagram remains unaltered. The use of a tracking filter following the drive oscillator also remains.

K. Seers continued as project officer for the next phase of the project. While the prototype detector channel was under construction, a backing-off voltage supply, including a temperature-controlled cooling chamber (using Peltier cells) for temperature-sensitive components, was designed. This subsequently proved unnecessary as the basic noise level of the MFS-7, when installed in the aircraft, limited resolution to 1 nT; this could be accommodated by a five-digit digital voltmeter (DVM) without backing-off.

The prototype detector channel was completed in October 1970. It showed disappointingly high noise levels and sluggish response. The active RC filters were found to be unstable, so passive LC filters were designed as a temporary measure to enable the remaining circuits to be checked. The amplitude stability and distortion level of the drive output amplifier were then found to be unsatisfactory.

At this time also, VH-BMG was handed over to BMR but was unavailable for installation checks until the necessary wiring and other modifications for BMR systems had been installed.

In November 1970, D. Kerr joined the Instrument Development Group and took over most of the work on the detector and drive channels and, subsequently, on the aircraft installation problems. His first task was the modification of the drive amplifier and power supplies.

The first flight test in March 1971 was unsuccessful because of extremely high noise levels. At first these were thought to be caused by feedback loop instability, but analysis by Seers, using the recently-measured detector coil constant and a 10-Hz bandwidth which had been arbitrarily assigned early in development, indicated ample stability margin. However, the analysis did uncover a fact which had been overlooked: there was a gross impedance mis-match at the detector. This allowed interference to be picked up from the orienter channel. Correcting the mis-match reduced the noise level considerably, but not sufficiently. Over the following four months a long and tedious sequence of magnetometer/installation improvements ensued as an improvement in one area unmasked problems in another:

In April 1971, Kerr discovered that the aircraft installation produced interference; that the detector itself appeared to contribute a long-period warm-up drift; and that drive oscillator components were causing frequency drift.

In May 1971, Kerr worked on the elimination of earth loops in the installation and in the MFS-7; he also designed a notch filter to remove third harmonic signal tending to saturate the detector channel, and an active tracking Butterworth filter to replace the temporary passive one which was both cumbersome and drift-prone. Seers designed a very large LC filter to reduce the effects on the aircraft power supply of 100-Amp spikes from a 50-Hz switching inverter. This filter was used for some months until a 'quieter' sinusoidal inverter could be purchased. Seers also designed a crystal oscillator to be used as a new drive source. A beat in the output voltage, thought to be an aliasing effect with the analogue recorder chopper (there was no digital output then) was removed by an RC filter. The resulting bandwidth restriction (0.4 Hz) could not be tolerated however, and a commercial digital-to-analogue converter was interfaced to the DVM to isolate the recorder from the MFS-7 output.

In June 1971, with much of the noise reduced by the rationalised earth wiring and the 50-Hz filter, Kerr discovered yet further noise sources, continuous and intermittent, caused by aircraft wiring and installation. The more important of these together with others discovered later, are listed:

Trace-shifts and noise on the output record were found to be caused by earth return currents flowing along the wings to the generators. The generator output leads were sufficiently far from these current paths to produce significant magnetic fields which varied with the states of the carbon-pile regulators and generator balancing relay. Although the detector was mounted in a boom aft of the aircraft tail, it was affected by these disturbances. The problem was solved by isolating the generators from the air-frame and by running isolated cable-pairs to the generators.

Excessive capacitance in the cables connecting the MFS-7 to the detector head could not be handled by the drive amplifier. These cables were also microphonic, producing noise from aircraft vibration. Special cables were constructed to remove these effects.

400-Hz rotary inverters in the aircraft nose produced electrical interference and they were replaced by static inverters.

VHF radio transmissions induced spikes on the MFS-7 output. These were reduced by air-frame and rack bonding.

The boom cap fouled the rotation of the detector head. It was replaced by a larger unit with a small observation window.

Solving each of the foregoing problems eliminated some of the noise and trace-shifts but the residue was still too high. The need to temperature-compensate the detector also became apparent at this time and Kerr and Seers both worked on circuits based on a published method (Primdahl 1970).

In July 1971 Kerr found that some of the noise was caused by distortion products and component drift in the detector channel notch filters (fundamental and third-harmonic). After considerable discussion and supporting calculations, a complete change of direction was advocated. The notch filters and some other circuit features were needed only because of imperfections in the drive signal. The new approach was to stop patching up the system and to design an 'ideal' drive channel from scratch. The proposed drive channel was to comprise the crystal oscillator (already designed) and frequency dividers, a method of locking and phase-adjusting the second-harmonic synchronous detector (in the detector channel) to the drive signal, a tracking filter to convert the square-wave divider output to sine-wave, an automatic gain control (AGC) loop to maintain precise amplitude stability, and an anti-phase, closely-matched pair of ultra-linear, low-distortion, wide-bandwidth, capacitively-coupled, solid-state power amplifiers. A new set of power supplies would be required also. This was not a popular proposal because of the delays already experienced and the understandable desire for operational status for the new aircraft as soon as possible; this proposal obviously meant more delays. In hindsight, it should have been adopted earlier, but the pressure to achieve a working system militated against this. As there was little logical alternative, the proposal was adopted.

Kerr had had previous experience in the design of high-power, ultra-linear audio amplifiers; his drive-amplifier design marked a turning-point in the MFS-7 development and was a major contribution to the final excellence of the magnetometer. While Kerr worked on this design and the AGC control amplifier, Seers designed the AGC detector, modified the drive oscillator design to remove intermittent instability, worked on an earthing problem in the detector cable, and devised a new system for setting orienter servo gains - an operation which had relied on the now-abandoned AN/ASQ-10A detector channel.

By October 1971, bench tests of the drive amplifier circuits had given sufficient confidence to start constructing them and their power supplies in AN/ASQ-10A plug-in modules. These were debugged in November. As the tracking filter still contributed some noise it was temporarily replaced with a non-tracking filter. The high precision and low distortion of the new drive amplifiers enabled Kerr to make two further contributions of major significance to noise reduction and performance repeatability. Firstly, he found that the AN/ASQ-10A detector as supplied was wound with neither mechanical nor electrical precision. Careful rewinding reduced the incidence of random trace-shifts and changes in the noise spectrum. Secondly, he developed a bridge input circuit for the detector channel, allowing the effects of residual distortion components in the drive to be eliminated.

The modified prototype was air-tested in February 1972 preparatory to a survey in North-Eastern Victoria in March. Results from this survey were usable but baseline drift and random noise spikes were still present. Kerr continued to work on these problems on an opportunity basis until they were all eliminated (August 1972). During this period he designed a 'soft' turn-on circuit for the drive to avoid excessive current demands on the power supplies, and a precision, noise-free tracking filter for the drive channel which reduced the drift to an acceptable level. Prototype development concluded at this point.

3.2 Production Phase

In March 1972 the difficulties associated with operating and maintaining the much-modified prototype prompted a decision to build two production units (one for a spare) in commercial 'ISEP' chassis. Each MFS-7 was then to comprise five units:

- the detector head
- the DVM
- an 'ISEP' chassis containing detector and drive channels
- an 'ISEP' chassis containing a 28 volt to 400 Hz inverter and power supplies (a separate chasis to avoid interference)
- the AN/ASQ-10A control unit containing the orienter system

The radical layout differences between the production assemblies and the prototype caused further problems with noise and instability. It was necessary to build a pre-production unit to deal with these problems, then to proceed with the production units. As the pre-production unit was forced into service prematurely in March 1973 because of major mal-function in the prototype, further development had to be co-ordinated with operational requirements. This work occupied Kerr for various periods until August 1973. During this time Seers designed the final version of the power supply circuits.

A further development phase started in June 1972: Once the pre-production unit was started, difficulties soon arose with the complexity of inter-connections and power supply incompatibilities with the AN/ASQ-10A orienter system. The only practical solution was to convert to a solid-state orienter system which could be integrated with the new chassis and power supplies. Design of this system was constrained by lack of information on the electro-mechanical transfer functions for the detector head. Measuring these would have meant withdrawing one head from service and modifying it extensively. Apart from the risks of immobilising the spare head, the necessary resources were not then available from BMR's mechanical workshops, and in any case, such a course would have contributed long delays. The approach used was to analyse the AN/ASQ-10A orienter circuits stage by stage and then to synthesise the transfer functions with solid-state circuits as simply and accurately as possible. This approach was complicated by the non-linear nature of the original circuits, and some empirical experimentation was necessary for satisfactory operation. This work was started by Seers in June 1972 and a satisfactory system was operating in the pre-production chassis by March 1973 - just in time for the enforced field use of this unit. A small amount of subsequent work provided a system superior to the original, and although the ultimate aim was to simplify this design by a more fundamental approach it is doubtful whether this is necessary or justifiable.

3.3 Compensation

Experience with DC-3 aircraft had shown the importance of magnetically compensating for the various components of permanent and induced field. Anticipating similar problems with the new aircraft, the Airborne Section purchased the ASA-65 9-Term Compensator, an instrument designed for anti-submarine aircraft equipped with the AN/ASQ-10A. Not known at the time of purchase was the need for an input to this unit, having the same amplitude, frequency and phase response as the original AN/ASQ-10A output to enable the compensating fields to be set up as the aircraft performed a prescribed series of manoeuvres. Correspondence with the ASA-65 manufacturer elicited details of the response required and a suggested set of time-constants and gain factors to be applied to the MFS-7 output to emulate this response. Meanwhile, Kerr had provided permanent-field compensation only, by installing the DC-3 compensation coils and driving them with current derived from the MFS-7 power supply via adjusting controls.

In May 1972 Seers started the design of the ASA-65 interfacing filter. The time-constant values supplied did not give the correct theoretical response and the CSIRO CDC 3600 computer was used to determine correct values. The filter was then designed and constructed, but neither it nor the ASA-65 has been used as yet; compensation requirements for VH-BMG proved to be so minor (at least for 1 nT resolution) that three-component permanent-field compensation is adequate. The permanent field compensator driven from the MFS-7 power supply was later replaced with a more stable unit, the MPC-1, designed by Seers and M. Gamlen to specifications supplied by D. Downie.

3.4 Bandwidth

Concern for faithful anomaly reproduction led Kerr to consider the slew-rate, frequency response and phase response necessary in an airborne magnetometer. This investigation started in September 1972, led to a separate BMR Record (Kerr 1975) and validated the 10-Hz bandwidth already chosen for general purpose surveying.

3.5 Later Developments and Modifications (Seers)

In August 1973 Kerr left the Geophysical Branch to join the newly formed ADP Section but continued to make occasional contributions to the MFS-7 project.

By this time S/N 1 and S/N 2 production units were completed, but it had become obvious that the choise of 'ISEP' chassis, while affording rapid construction, was not ideal for operation in the conditions of mechanical shock and vibration experienced in the aircraft. Also, some of the printed circuit board construction techniques used in these units had not been tried previously in BMR equipment and contributed to mechanical unreliability, dry joints, etc. The pre-production unit was subjected to vibration tests and a system of chassis stiffening and component mounting was devised to reduce resonances. Circuit-board standards were also revised. This resulted in S/N 3, a ruggedised version which became operational in March 1975. At the time of writing (1982) S/N 1 and S/N 2 are still operating, but in a rather 'patched-up' condition. As the MFS-7 is expected to be used for some time yet, S/N 4 (ruggedised) is under construction.

As is usual in equipment development a number of design deficiencies appeared after extensive use. Most were minor and easily remedied. Four major ones are listed:

In November 1973 one unit developed large output variations not unlike real magnetic anomalies. These would appear at random or could sometimes be stimulated by surges on the aircraft power supply. The cause was intermittent instability in the detector channel active filter. A detailed circuit analysis had to include second-order effects to show that the design was only marginally stable; an unconditionally stable circuit was designed.

In June 1974 it was noticed that the field readings obtained at turn-on in a constant field varied. There was sometimes drift for about twenty minutes until the correct reading was reached. It was known that there were no warm-up effects remaining in the electronics and the phenomenon was traced to the detector head itself. The problem could be rectified by applying greater than normal drive current to the detector (and orienter fluxgates) for a short time after turn-on. A circuit was incorporated to do this automatically. No explanation has been found for this effect to date; detector remanence and hysteresis are unlikely because of saturation of the detector cores in opposite directions on each half-cycle of the drive current. One possibility, not yet investigated, is weakly magnetic material near the detector which adopts some magnetisation at turn-off and, at turn-on, is slowly de-gaussed by the drive field.

In July 1974 it was found that earth currents from the 400-Hz inverter in the power supply chassis were interfering with the detector signal and causing a variable frequency beat voltage corresponding to several nT in amplitude at the MFS-7 output. The chassis wiring of the production units had inadvertently included a number of earth loops; removing these greatly reduced the effect but did not eliminate it completely. In practice it is avoided by precise detuning of the inverter frequency.

In June 1976 the temperature compensation circuit was re-designed to remedy inadequate drive signal filtering and adjustment coarseness.

Figure 3 shows the final form of the MFS-7 block diagram.

3.6 Detecting-Head Maintenance

During development there were problems associated with mechanical wear and adjustments in the detector head servo-system. Although a range of mechanical spares had been purchased, the BMR mechanical workshops did not have the capacity to undertake routine maintenance (still less emergency repairs) particularly as they were not equipped with the special purpose test jigs etc. recommended for this purpose by the U.S. Navy. Fortunately the Australian Navy still uses the AN/ASQ-10A in its tracker aircraft, and as BMR modifications were minimal (detector re-wound, capacitor across detector), arrangements were made early in 1975 to have the three BMR units serviced by HMAS 'Albatross', the Naval Air Station at Nowra. These arrangements worked very well and have been extended to include two new detecting-heads purchased from the U.S. Navy - one for S/N 4, the other for a spare.

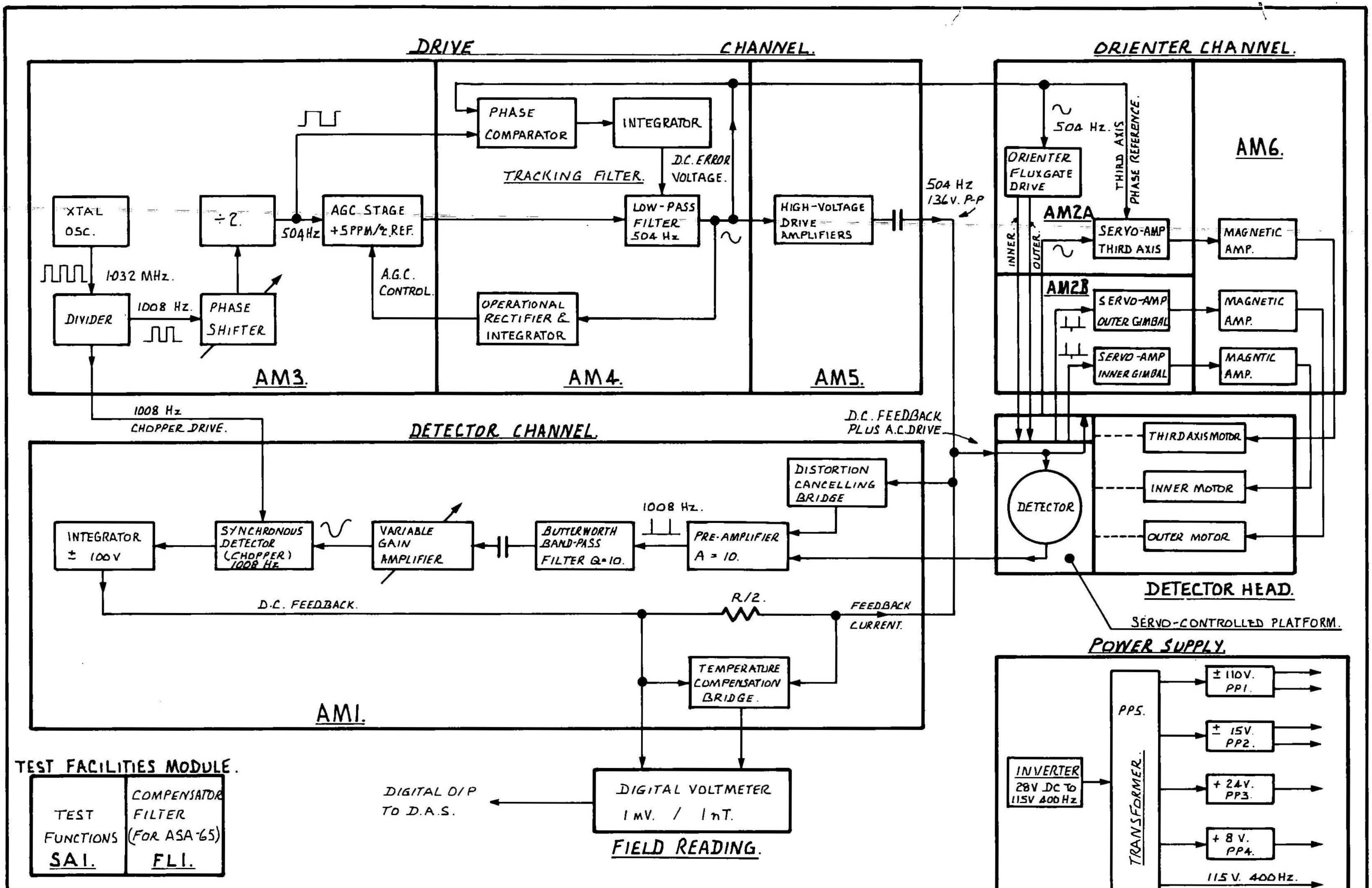

FIGURE 3 MFS-7 FLUXGATE MAGNETOMETER: BLOCK DIAGRAM.

4. Concluding Remarks and Acknowledgements

In spite of development difficulties, the MFS-7 is now a very successful survey instrument used routinely in the Twin-Otter (VH-BMG) and on occasion in the Aerocommander (VH-BMR). It has flown well over half a million survey line-kilometers. There are also moves to use it as a vehicle-borne magnetometer for metalliferous studies and as a down-hole single-component magnetometer.

The foregoing development history is in fact no more than a summary of major events; as in most development projects, particularly those at state-of-the-art frontiers, there were many day-to-day problems which would be too tedious to document but which nevertheless had to be worked through. The project could not have been brought to a successful conclusion without the dedication of all staff involved. Many worked after hours or in their own time at weekends to take advantage of periods free from magnetic disturbances, or to reduce survey down-time. Many man-hours were spent in temperature extremes in cramped conditions in the aircraft performing ground tests or installation check-outs, and in enduring the six degrees of motional freedom while air-testing.

In addition to the professional officers already mentioned, the following officers played a key role in the project:

Laboratory technical officers W. Greenwood and H. Leuzinger.

Airborne technical staff R. Curtis and K. Mort.

Electronic draftsmen R. Gan, F. Clements and P. Bryan.

Mechanical technical officer D. Stevens.

Model maker G. Lockwood.

Finally, acknowledgement is due to the co-operation and understanding of the geophysicists in the Airborne Section, notably R. Wells and D. Downie; their patience must have been sorely tried during the prolonged gestation of the MFS-7.

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APPENDIX A

ORIGINAL PERFORMANCE SPECIFICATION REQUESTED BY AIRBORNE SECTION (1968)

1 Resolution

Analogue and digital recording on any one of three selected ranges with the resolutions shown:

Range 1 : 10 nT f.s.d. (analogue) with 0.01 nT resolution
Range 2 : 100 nT f.s.d. (analogue) with 0.1 nT resolution
Range 3 : 1000 nT f.s.d. (analogue) with 1.0 nT resolution

2 Noise

Range 1 : ± 0.01 nT
Range 2 : ± 0.1 nT
Range 3 : less than ± 1nT (not resolvable)

Additional noise from aircraft installation to be less than 0.05 nT

3 Measurement Range

20 000 to 70 000 nT with display capability of 100 times f.s.d.

4 Stability

Better than 1 to 2 nT/hr from all sources after 30-minute warm-up

5 Configuration

Total feedback with manual backing-off for DVM

6 Physical

To use as much of AN/ASQ-10A as possible with minimal modification. Additional hardware to be off-the-shelf where possible.

APPENDIX B

MFS-7 PERFORMANCE SPECIFICATIONS

Measurement Range	:	-1.05×10^5 to $+ 1.05 \times 10^5$ nT
3dB bandwidth	:	Adjustable to 50 Hz. 10 Hz recommended
Phase Response	:	-63.5° at 10 Hz B.W.
	:	-179° at 50 Hz B.W.
Slew-Rate (10 Hz B.W.)	:	1.8×10^5 nT/s
Total Noise (10 Hz B.W.)	:	Less than 0.2 nT p-p
Accuracy	:	$\pm$ 0.005% of reading after 35 minutes
Resolution	:	Limited by noise (see above)
Electronic Drift	:	0.2 nT/hr, 0.25 nT/°C after 20 minutes
Detector Tempco		
Uncompensated	:	Approx. 0.003% of field per degree Celsius
Compensated	:	Approx. 0.0003% of field per degree Celsius i.e. 0.15 nT/°C in 50 000 nT
Linearity	:	1 nT or better over the range
Outputs		
Analogue	:	1 Volt per 1000 nT
Digital	:	BCD from DVM. Reading rate and resolution depend on DVM, but at least 5 per second at 1 nT
Power Supply	:	+ 26 to + 30 V dc (28 V nom. at 8 Amps)
Operating Temperature Range	:	0°C to + 50°C