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The development of optically pumped magnetometer systems and their applications in Australia Part 1

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Introduction

Who remembers when magnetic surveys for mineral exploration required first sending out a surveyor and chain-man to clear lines and peg a grid? The pegs might have been at 5 or 10 chain intervals (100 or 200 m) along lines separated by 40 chains (800 m). The geophysicist would then have carried his magnetometer (in its beautifully made wooden cabinet) and tripod to each grid peg. He would have then set up the tripod, levelled the magnetometer using perpendicular spirit levels and peered down a microscope to read a hairline off a scale. The instrument temperature was recorded with the magnetic field value in a field notebook before the equipment was packed up and moved onto the next grid point. Usually it was a relative measure of the vertical component of the field that was obtained by measuring the torsion on a suspended compass needle and, after temperature compensation, a good operator could resolve down to 2 nT. Less than 100 measurements per day could be acquired with this technology, and this was after the more time-consuming grid pegging was completed.

During the 1950s and 60s the torsion balance, mechanical magnetometers were replaced by electronic flux-gate instruments. Now, a much lighter device could be carried to each grid peg. But this device still needed to be operated while held stationary in a vertical position as determined by a single ‘bulls-eye’ bubble. A relative measure of the vertical component of the field was again hand recorded after reading off an analogue meter. Measurement time was improved at the cost of resolution that, at best, was 5 nT. About 150 measurements per day was typical.

And then, in 1967, in association with Oxford University, the Littlemore Scientific Engineering Company developed the ‘Elsec’ Proton Precession magnetometer. This was a major advance in magnetometer technology as, for the first time, nuclear magnetic resonance enabled the absolute value of the Total Field Intensity to be acquired, not just to 1 nT resolution but in the short time of 3 seconds! Our geophysicist could now occupy a grid station, press a button, wait 3 seconds and then write down a number read off each of five analogue meters graduated in ten steps from 0 to 9. With such measurement speed ‘high resolution’ surveys could be conducted at 1 chain (20 m) intervals. The ‘chain-man’ walked ahead and dragged a ‘chain’ behind, and the instrument operator shouted ‘stop’ each time the end of the chain reached a scrape in the ground indicating an in-fill measurement point. An operator using such an instrument during the ‘Nickel Boom’ of the late 1960s was proud to be able to acquire as many as 750 measurements in a day. But, the day was not yet done. These measurements then had to be hand plotted as profiles and often contoured or, maybe, typed into a card punch and fed into an office mainframe computer. Even in the latter case, while mainframes were connected to a typewriter/printer, how many were connected to a plotter? And, who had software to perform contouring? A well respected archaeological team at Oxford University used alpha-numeric characters on their printer in an attempt to create a ‘grey scale’ image of their magnetic data where a ‘.’ would represent a low value, light grey, and a ‘W’ would use more ink and create a darker impression. Magnetic mapping was still time consuming, with the effort required to determine the location where the measurements were acquired contributing significantly to data acquisition time, and methods for presenting data in an interpretable form were slow and primitive. Moreover, measurements taken no closer than 20 m apart could only be used to properly define target sources deeper than 20 m as shorter wavelength anomaly components arising from shallower sources would be under-sampled and their energy folded back into the profile as noise. This was ‘state of the art’ in the late 1960s.

Establishment of a Geophysics Department at the University of New England, Armidale

In 1967 Ron Green was appointed to the University of New England with the task of establishing a Department of Geophysics. Ron’s vision was for a Department that would specialise in the physics and mathematics that were at the heart of geophysical exploration data acquisition and data analysing technologies. His goal was to produce graduates that were equipped to design and develop the next generation of instruments and data processing technologies, or to go into industry capable of solving the multitude of site-specific problems that were confronting this newly emerging exploration frontier in our challenging, regolith dominated Australian environment. Ron didn’t want to just train exploration practitioners to apply off-the-shelf technologies (developed in Canada or Scandinavia where geological conditions were very different and far more favourable), he wanted to produce problem solvers. Giving priority to physics and maths over geology did not best suit the requirements of all sectors of the industry. But, given that Ron’s graduates from the short, 15 year life of his Department have received 6 of the 14 Grahame Sands Awards given by the ASEG for Innovation in Applied Geoscience, Ron clearly identified an important need in our industry at the time and he fulfilled it admirably.[1]

Ron had a small budget to purchase some exploration instruments and he chose to spend this on a 'state-of-the-art' Elsec magnetometer. He also solicited the donation of unrequired equipment from industry, as this would give his students a hands-on introduction to the principles behind the range of methods used at that time for sub-surface exploration. Initially Ron's Department concentrated upon offering a quality Honours year program to graduates strong in physics and either maths or geology. Students with no geology were required to take some geology subjects during their Honours year. He later introduced Masters and Doctorate programs. While he taught geophysics at undergraduate level, his emphasis was on establishing a Post Graduate Department.

John Stanley (the author of this article) and Jim Cull finished Physics Degrees at Monash University in 1968 and chose to join the emerging field of geophysics. They enrolled in Ron Green's Honours program. Both John and Jim had good undergraduate records in the practical components of their degree. In the light of this, Ron proposed that for the major research element of their Honours study they collaborate to apply the principle of 'Optical Pumping' described by Kastler in 1950 to the application of measuring the Earth's magnetic field (Kastler, 1950).

John and Jim soon understood the requirements of their task and knew that at first they would need to devise a very stable, noise free source of spectral light at the D1 wavelength corresponding to the first excited state of the single outer electron of the alkali Cs atom. They would also need an 'absorption cell' containing a vapour of Cs metal. Cs is a liquid at room temperature and its vapour pressure was believed to be sufficient for the purpose. But, Cs is highly reactive, demanding that a silica lamp bulb and absorption cell be completely sterilised of impurities if their life containing free Cs was to be prolonged.

With these components a self-oscillating system was proposed whereby the optical transmission of circular polarised D1 light through the absorption cell could be monitored with a photocell to detect the optically pumped condition (cell transparent). If this signal was amplified and fed back with a suitable phase shift into a coil wound around the absorption cell parallel to the light beam it would cause the cell to 'depump' (making it relatively opaque). With such feedback the pumping/depumping cycle should resonate at the 'Larmor Frequency', known to be proportional to the intensity of the ambient, Earth's magnetic field. Once resonating, the Larmor frequency would be determined and a measure of the Earth's Total Field obtained. It all sounded pretty straightforward!

The attempt to construct an optically pumped Cs, alkali vapour magnetometer in the course of an Honours project proved over ambitious, but two significant achievements were attained. Jim determined that an appropriately stable and noise free source of D1 light should be obtainable from the radio frequency excitation of Cs vapour in an evacuated glass bulb. He successfully constructed a radio valve operated oscillator running at 200 MHz, this being significantly higher than the Larmor resonance frequency of the Cs D1 electron transition in the Earth's field, this being less than 200 kHz. John applied himself to the production of a highly evacuated lamp bulb and absorption cell. These were to contain a trace of free Cs metal and an inert gas to dampen collisions between the Cs vapour and the cell wall. Due to the highly reactive nature of Cs, the major problem of sterilising the quartz glass cell had to be overcome, and it was (Clack and Stanley, 1971). They now had a suitable working lamp and absorption cell, each with a long life expectancy. In fact, a lamp bulb made in 1970 is still producing Cs spectral light in 2016.

The prototype Cs magnetometer

In 1970, John Stanley resumed the task of developing a Cs Vapour magnetometer, now as part of full-time research towards a Doctoral Degree. By the year's end, he had a self-oscillating system working, with the valve driven lamp oscillator now replaced by a transistorised one running at 130 MHz. This achievement had been frustratingly delayed during the winter of 1970 as the importance of heating the Cs to increase its vapour pressure had not yet been appreciated and the research laboratory in Armidale in winter without air-conditioning was very cold!

With a self-oscillating sensor system now working, (Figure 1) it was practical to determine experimentally the cell temperature at which the vapour pressure of Cs in the absorption cell would deliver optimal optical pumping signal. This was found to be 50°C and the sensor was then packaged with a 'zero field' bifilar heating element running at 2 kHz surrounding the absorption cell. The sensor, containing the lamp, heated absorption cell, feedback coil and optics, was then linked by mini-coaxial cables with its control electronics at such a distance as to eliminate magnetic interference from the electronics (1500 mm).

[1]In 1973 Dane Blair, a PhD student under the supervision of Peter Sydenham in Ron Green's Department, set out to develop a laser interferometer strain gauge for use in measuring strain in the Earth's crust from an underground observatory in a disused gold mine at Hillgrove. The use of such a device to detect gravity waves was considered. While Dane's development was an important precursor to this application, it took another 40 years of refinement (by others) before this application was successfully realised.
Andrew Hugill, also under the supervision of Peter Sydenham, set out in 1977 to develop a new transducer to be applied to the measurement of gravity. Andrew delivered a working prototype that he then further developed while employed by Scintrex in Canada. The CG-3 and its later upgrades through to CG-5 have become the industry standard in ground based and borehole exploration using gravity. Andrew's innovations significantly increased the speed with which gravity data could be acquired, thereby reducing the cost of acquiring higher detail in gravity mapping.
Jim Cull, after graduating with Honours in 1970 became exceptionally successful in both industrial and academic environments by applying sound physical principles with innovation and practical application to a diverse range of geophysical instrumentation developments. His achievements culminated in the award of an Order of Australia medal. It was the specific development of an electromagnetic receiver and processor that earned Jim Cull and Duncan Massie the 2006 ASEG Grahame Sands Award for innovation in applied geoscience. Phil Schmidt graduated with Honours in 1972 and after gaining a PhD from ANU in 1976 pursued a research career with CSIRO, always working closely with instrumentation development. Phil Schmidt was recognised with the 2015 ASEG Grahame Sands Award for his development of a 'Q meter', a field portable instrument for measuring the magnetic properties of rock samples, providing information of great practical value in the interpretation of magnetic survey data.
Malcolm Cattach and John Stanley were given the 1988 ASEG Grahame Sands Award for the development of the TM-3 magnetometer and the 1995 ASEG Grahame Sands Award for the development of Sub Audio Magnetics, a method by which both magnetic and electromagnetic data could be simultaneously acquired using a TM-4 magnetometer. Malcolm Cattach, Keith Mathews, Ed Campbell and Symon Bouwman were given the 2013 ASEG Grahame Sands Award for the development of the GeoPak HPTX-70 high power electrical transmitter.
In 2007 John Stanley and Malcolm Cattach were awarded a Comenius University Medal for their contribution to the science of exploration geophysics. Comenius University in Slovakia is where, under the Austro-Hungarian Empire, the first Academy of Mining was established in 1735. This academy later became the first Technical University in the World.

Figure 1. *The prototype Cs vapour magnetometer sensor with discrete component transistorised circuits (1971).*

Attention was next directed to counting the Larmor Frequency and converting this to magnetic field units (Figure 2). By 1971, TTL logic chips had just become available and a fully digital system was envisaged, although a non-volatile digital memory medium was not yet available. Given that the Larmor Frequency varied by 3.49869 Hz per nT, a frequency counter that used a timing gate the reciprocal of this value (0.2858 s) would yield a count numerically equal to the magnetic field in nT. A timing gate 10 times wider (2.858 s) would deliver a count in units of 0.1 nT. While these sample rate and resolution figures were a factor of 10 improved over the Elsec magnetometer, the use of a period counter rather than a frequency counter was recognised as better able to take advantage of the characteristics of the new sensor and deliver a faster measurement rate. By using the Larmor signal to gate a high frequency clock, 0.01 nT resolution could be delivered in approximately a 2.2 s period, 0.1 nT in 220 ms or 1 nT in 22 ms (Stanley et al., 1975). The objective now was to develop applications that would benefit most from these enhanced characteristics.

Figure 2. *The first 'digital alkali vapour magnetometer using integrated circuits'. The release of TTL digital logic integrated circuit devices permitted a magnetometer to be built in 1973 that took the Larmor signal from an optically pumped sensor, and from this determine a digital measure of the Total Magnetic Intensity. A 1 nT resolution could be updated approximately 45 times per second.*

Initial applications of the enhanced magnetometer characteristics

While the high resolution characteristic of the Cs sensor would have application in global geophysics and space science, John recognised the fast sample rate as having the most potential for making sub-surface mapping in geophysical exploration cost and time-efficient. However there was an urgent need to overcome the constraints imposed by conventional survey grid position measurement. Magnetic field values and the location where they were acquired had to be recorded automatically and achieving this became John's priority.

a. Technology for magnetic mapping at an archaeological site scale

An interest in archaeology led John to investigate the feasibility of magnetically detecting pre-historic camp fires through the conversion of less magnetic Fe_2O_3 (haematite) to the more magnetic Fe_3O_4 (magnetite) in the reducing environment of the campfire hearth. To do this, a 26 ft × 14 ft (8 m × 4.25 m) area was to be magnetically mapped before and after a campfire had been lit and let burn for 24 hours (Stanley, 1976).

The Cs sensor was able to be operated from a cable up to 30 m from the counter electronics. A stepper motor was fitted to a chart recorder and this was interfaced to an analogue output port from a D to A converter following the digital period counter in the magnetometer. An odometer was built in which a string from a spool passed around a 318 mm disc which had 100 optical slots at 10 mm intervals around the circumference. The sensor carrier would draw the string out from this odometer as an 8 m length straight line traverse was made across the survey area. As the odometer disc rotated, a light beam was chopped producing trigger pulses to step the chart recorder motor. In this way a scalable record proportional to the distance traversed along a grid line was automatically plotted. At the end of an out-bound survey line, the sensor carrier would move 100 mm across grid, and the recorder operator would then 'wind the string back' as the return grid line was mapped. The 8 x 4 m test area was mapped this way before and after the camp fire was lit. Each coverage automatically logged (in analogue format) effectively 40 000 measurements each to 1 nT resolution. This was achieved in a survey time of just one hour.

How was this data presented? It was an analogue record and individual profiles could be interpreted using the graphical methods of the day. However, by tracing each profile with a small, scaled offset progressively from one edge of the survey area to the other, and with the application of a 'hidden line' where a later profile fell below the topography of a previously traced line, a pseudo 3-D isometric image of the data was generated (Figure 3). It was noticed at the time that this presentation was very effective in enhancing those magnetic features that were continuous between survey lines while supressing the effect of random and temporal noise. This presentation provided a primitive form of image processing and was the precursor of computer generated isometric images that followed soon after.

The success of this experiment led to the use of the odometer system in larger archaeological surveys where areas measuring up to 25 m along line by an unconstrained distance across line were conducted. In this case the 25 m along-line limitation was imposed by the maximum cable length of 30 m permitted between the sensor and its control electronics.

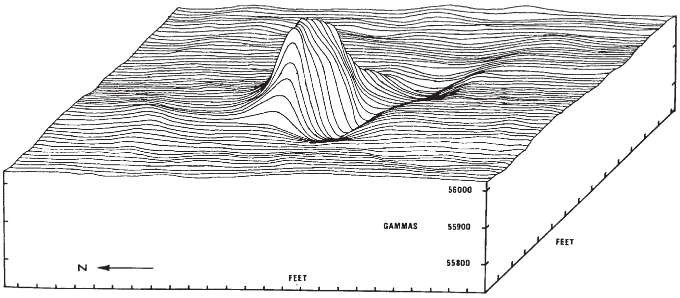

Figure 3. *A pseudo isometric image of the magnetic field recorded over a fire hearth that had been left burning for 24 hours. The image was produced by tracing analogue profiles automatically plotted during data acquisition, each with a scaled offset from the front of the image to the back. (1 gamma = 1 nT).*

Archaeological surveys very effectively mapped sites of early aboriginal occupation with some fire hearths dated 29 000 years before present being detected. The magnetic disturbance associated with a fire hearth was found to be attributable not only to the reduction of iron oxides in the soil, but also to remnant magnetisation acquired when the hearth temperature cooled after exceeding about 600°C. The very high spatial resolution (high definition) of these surveys also revealed the considerable amount of near-surface geological information that was available and which could now be acquired efficiently. This observation was not forgotten!

b. A vehicle-borne magnetometer system

In 1972 the only practical field portable means for recording rapidly sampled data was using the medium of an analogue chart recorder. Having installed a stepper motor in a chart recorder for the archaeological mapping application, fitting a Hall device switch to the tail shaft of a Land Rover enabled data to be plotted at selectable scales at known distance increments along a driven survey line. Upon mapping the magnetic field around the Land Rover in planes at different elevations above ground, it became apparent that a plane existed approximately through the centre of gravity of the vehicle, in which, just 6 m from the vehicle centre, the contour of uniform interference due to the steel in the vehicle was close to circular. This meant that if the sensor was mounted on a non-magnetic stinger 6 m from the centre of the vehicle the heading error would be minimised (Figure 4). In fact, at this distance, the heading error for a 360 degree rotation was 25 nT peak to peak or approximately 0.07 nT per degree of heading change. As long as the vehicle was driven in a reasonably straight line an acceptable level of heading error would be encountered. Pitch error was found to be similar. A Series 1 short-wheelbase Land Rover was fitted with such a stinger, an odometer switch, power supplies and a chart recorder modified with the inclusion of a stepper motor (Stanley, 1975a). Data could be acquired at 0.25 m intervals while travelling at 40 kph.

Experience with this system in reconnaissance transects across NSW in 1973 resulted in two significant observations. It was noticed that present and prior water courses were frequently associated with a magnetic disturbance due to the concentration of heavy, magnetite rich sands (Stanley, 1975b), and it was documented that many different near surface geological units were characterised by their own, unique 'magnetic signature' (Stanley, 1975a).

c. Portable digital recording

While the first vehicle-borne Cs magnetometer system had (within the limitations of requiring straight line survey transects)

Figure 4. *The vehicle-borne magnetometer in which the Cs magnetometer sensor was mounted in a plane where the contour line of interference from the vehicle's magnetic field was almost circular. The result was a heading error of just 0.07 nT per degree. Magnetic data were automatically logged to scale on a chart recorder triggered from the vehicle odometer. Measurements were acquired at 0.25 m intervals while travelling.*

overcome the problems of automatically assigning a position to each rapidly sampled magnetic measurement, the benefits of digital recording were anticipated, but not as yet available. In 1972, the microprocessor, PC and portable non-volatile memory were still to be invented.

In 1978, the Geophysical Research Institute (GRI) was formed within Ron Green's Department.[2] The objectives of this Institute were three-fold. John, with Ron's support and encouragement argued that:

i. At a time when the exploration industry was confronted with many limitations resulting from the inherent unsuitability of existing geophysical instrumentation for the conductive and magnetic regolith dominating much of our continent, research done in Australia should address identified needs of industry rather than be in pursuit of some purely academic interest.
ii. Research projects that addressed the specified needs of an industry player would benefit from access to current exploration sites, logistical assistance with fieldwork, financial support, and the input of the practical experience of the company's representative. This latter contribution would significantly complement the exploration related project supervision available from Ron and John. At this time the Department had but three academic staff.
iii. A third benefit from involvement with the exploration industry was that the major companies had the latest in equipment and this was mostly outside the resources of a

[2]In 1983, after just 15 years operation, the Geophysics Department was closed and amalgamated with the Geology Department.
In 1984 the GRI became an autonomous, self-funding research entity. John Stanley became its Director in 1985. A private company, Geophysical Technology Pty Ltd, was formed in 1986 by John Stanley and Malcolm Cattach to manufacture instrument developments originating from the GRI. In 1996, through a management buyout, Geophysical Technology acquired the assets and intellectual property of the GRI and commenced trading as G-tek Pty Ltd.
In 2005 John retired and Mal, with key staff, restructured the G-tek business as Gap Geophysics Pty Ltd, now based in Brisbane. Under Mal's leadership Gap has thrived, expanding into a group of businesses addressing a range of applications. These include; manufacture and development, provision globally of ground and airborne exploration services, and the delivery globally of geophysical solutions to environmental problems. Fundamental to this group's success has been their understanding of the underlying science and an on-going commitment to improving their core technologies and to developing new applications. Today all of John and Mal's aspirations for the GRI from the early 1980s have been achieved, and achieved in a manner that has established the line of exploration technologies based upon the Cs magnetometer sensor as universally accepted state-of-the-art.

small department to acquire. If research students could have access to this equipment then research into processing and interpretation of the data acquired, or indeed, research into overcoming the technical deficiencies of this equipment, would be greatly facilitated.

With the formation of the GRI, the vehicle-borne magnetometer system received a major upgrade. The 'home made' Cs sensors that had been used in the pioneering investigations could now be replaced by a military grade product recently released from US classification and now available from Varian Associates 'to friendly allies'. A new product from Sonotek in Canada employed a Z80 microprocessor in a digital data logging and replay capacity with acquisition programs and data logging being interfaced with a digital cassette tape recorder (Figure 5). This 'advanced technology' deserved the suspension and dust free environment of a Range Rover and the University advanced the funds to buy this.

Figure 5. *With the advent of the microprocessor, a digital data logging and replay facility was added to a vehicle mounted survey system. Data acquisition programs and data logging were now interfaced with a digital cassette tape recorder.*

The Range Rover supported digital system rapidly won the favour of key organisations in the minerals exploration industry. By now the highest quality data was preferred, obtained when the sensor was hand-carried some 30 m behind the logging vehicle and connected by a cable. With the 'walker' and 'driver' alternating, 40 km of survey could be acquired in one day with samples logged at 250 mm intervals. The vehicle was soon asked to push survey lines through some extremely rough terrain and heavily vegetated environments. The GRI Range Rover became readily recognisable by its golf ball textured aluminium panels. How could this data acquisition be done better?

In 1978, Honours student Stephen Lee was given the challenge to code the digital count from the Larmor signal using an audio frequency code that could be sent by CB radio back to the base vehicle. Stephen achieved this using 'Frequency Shift Keying' with zeros being represented by a chirp at 1 kHz and ones by a chirp at 2 kHz. At the vehicle, the signal was de-coded and logged on the Sonotek facility as before. Of paramount importance was the inclusion of a hand-carried odometer device to enable the automatic recording of measurements at known intervals along line. The string and pulley principle used in the archaeological investigations was adapted into a system that used a 'lost thread' of biodegradable cotton. This principle was also used in the Hip Chain that became available at the same time. Its advantage over the string system was that survey lines could now be of unlimited length. The system, called a 'Telemetric Magnetometer' model 'TM-1' achieved its objective so long as integrity was maintained in the radio link.

In 1979 Sony released their first 'Sony Walkman', a portable, robust little stereo cassette recorder. A Sony Walkman soon replaced the troublesome CB radio. The position referenced, FSK coded magnetic data were now recorded on one track of the cassette while voice comments were recorded on the other. This latter facility enabled positioned geological observations to be simultaneously recorded. The Walkman tapes then had to be replayed in real time, for logging on the vehicle-borne data acquisition system prior to downloading to a mainframe. The TM-1 was probably the first portable magnetometer with inbuilt memory (Figure 6). It certainly was the first with the capability to automatically record position with each magnetic measurement and to do so in sub-m intervals at traverse speeds faster than the operator could walk.

In 1980 the TM-1 prototype, modified to use a cassette tape recorder instead of a CB radio link, was upgraded. Use was now made of the Varian module that supplied power to the sensor, that had its own inbuilt frequency counter with serial output port (0.1 nT at 10 Hz), and a digital display. The Varian module also provided an audio tone proportional to the Larmor Frequency.

Figure 6. *The 'telemetric magnetometer' TM-1 encoded digital data in an audio code suitable for transmitting by CB radio to the vehicle-borne digital data acquisition system. With the advent of the Sony Walkman cassette recorder in 1979, the troublesome CB link was replaced. The instrument shown here was the first portable magnetometer with inbuilt memory and a data positioning device.*

This latter feature not only alerted the operator to magnetic anomalies being traversed, but it also provided a valuable monitor should the orientation of the sensor drop out of its operating zone. Data from a serial port on the Varian module was FSK encoded as was done in the prototype and then recorded in real time using one of the two stereo tape tracks. As with its predecessor, the second tape track was used to record voice notes of observations relevant to the interpretation of the magnetic data. The TM-2 was a robust and compact little unit that performed many thousands of survey km (Figure 7).

Figure 7. *In 1980 the TM-1 prototype was upgraded using facilities available in the Varian sensor controller/frequency counter module. Digital data and voice notes were recorded in real time at sample intervals automatically determined by a cotton thread type odometer. Positioned measurements at sub-metre intervals could be acquired at survey speeds faster than the operator could walk.*

d. Technology for explosive ordnance detection

After the successful detection and mapping of pre-historic campfire sites, curators of the world's largest public collection of Thai ceramics held at the Adelaide Museum of Fine Arts asked if the TM-2 could be made available to search for buried pottery kilns at the site of an archaeological study in Thailand (Hein, 2001). Their problem was that all visible kilns had been plundered for the tourist trade, destroying their originality and

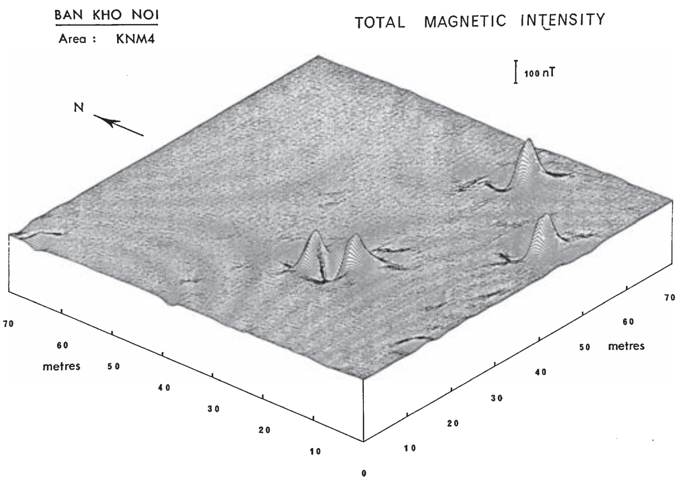

Figure 8. *The magnetic field mapped in Thailand in 1984 with a TM-2 magnetometer. The four anomalies visible indicate the location of four pottery kilns from the Sukhothai period of 1250 to 1500 AD.*

Figure 9. *A shallow, 15th century, Thai pottery kiln measuring about 5 m x 3 m during excavation after being detected with a TM-2 magnetometer in 1984.*

making them unsuitable for research into the kiln technology itself. Finding kilns that had been buried by the regular deposits of river flood alluvium over the last 1000 years was desired. In 1983 and 1984 John used a TM-2 to map many hectares of river flood plain at a data density of 50 000 positioned measurements per ha (Figure 8). By virtue of great luck, one of the first kilns discovered was found to have collapsed during firing and had been abandoned. These kilns measured some 5 m in length and 3 m width (Figure 9). During firing, these kilns are maintained at approximately 1200°C. So, when a kiln collapsed it was easier to move on and build another. But this kiln had collapsed late in the firing process and inside were hundreds of almost perfectly glazed items. Some were large water urns that at 1200°C were quite plastic and had become deformed (Figure 10). Inside and well protected there were also dozens of beautiful lamps and vases in perfect condition. As a second incidence of luck, the BBC were passing through the area at the time, documenting the footsteps of Reginald le May, an early British official who had reported signs of a significant pottery industry. Here before their cameras was a pristine example! The film crew were also impressed by, and gave credit to, the role that new magnetometer technology was playing in this project.

The day following the BBC documentary going to air in 1984, John got a call from a representative of the RAAF. He said: 'If

Figure 10. *Excavation of a kiln that had collapsed during firing in the 14th Century. Visible are two large water urns. Inside these were many undamaged oil lamps and vases. The BBC cameraman can be seen scoping the angles for filming.*

you can find 1000 year old pottery kilns then surely you can detect 1000 lb bombs – and we have lost a few'. The TM-2 was then contracted in 1985 to map an 80 ha dis-used bombing range area in Darwin for the purpose of detecting unexploded ordnance (UXO), prior to making the area available for civil use as the municipal garbage dump. The particular problem confronting the RAAF in Darwin was the high incidence of magnetite in the lateritic hill-top target area. Conventional metal detector systems failed to resolve between signal and noise from the geology. With digital data, appropriate filtering and discrimination provided visually from isometric images, UXO were detectable amongst the background interference. The success of this project led the Australian Department of Defence in 1986 to contract Geophysical Technology, a spin-off from the GRI, to build and supply a system for unexploded ordnance detection. This system had to include both robust hardware and a data processing stream implementable on a PC that would provide an audit trail for quality assurance purposes. Prior to this development an operator using an analogue detector might be assessed by what he had found each day, but no-one had any idea what he might have missed. In reality the operator may have had the instrument turned off and no one would know! Little was it appreciated at the time that the quality processes developed at the GRI for the RAAF would have a global impact just a few years later when the Iron Curtain fell and world-wide there emerged a need to clean up former Defence sites so that land could be handed back to the public with a reasonable certificate of assurance that the ground was safe.

Critical to the success of this contract was the contribution that Malcolm Cattach made in developing operational and data analysis software, the latter able to be run on a PC. The new 'TM-3' had an inbuilt Z80 microprocessor based data acquisition system using now available solid state memory, input and counters for 2 Cs sensors and a cotton thread type odometer (Figure 11). Software running on the system had the facility to calculate a linear correction for cotton thread stretch using known control points along line. Positional error along line was now reduced to approximately 0.2% of the distance between control points, or 100 mm when control lines were set at 50 m intervals. Data stored in memory could be output via a serial port. One ha could be mapped by two operators with 100 000 positioned measurements in under four hours. The era of the PC had now arrived and Mal developed data imaging software involving colour mapping and isometric plotting, the benefits of which in signal recognition from background noise had already been appreciated. Three-dimensional data inversion over identified targets permitted the position, depth and approximate size of items requiring investigation to be defined and recorded for quality process purposes.

The contribution of the TM-3 to the expanding application of magnetic mapping was recognised by the ASEG in 1988 when John and Mal became the recipients of the first Grahame Sands Award for Innovation in Applied Geoscience.

Figure 11. *The TM-3 magnetometer with microprocessor controlled survey management aids, inbuilt odometer and digital recording from up to two optically pumped sensors.*

Editor's note: John Stanley's fascinating account of the development of optically pumped magnetometer systems and their applications in Australia will continue in the next issue of *Preview*, in which John will describe the diversification in the applications of optically pumped magnetometers and development of SAM and SAMSON.

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