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COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

1959/147

Papers on airborne geophysical surveying presented at ECAFE conference Bangkok 1960

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The following papers from Australia were submitted:

"Instrumentation for Airborne Geophysical Surveys with D.C.3 Aircraft"
J.K. Newman

"Problems of Navigation and Position Plotting in Airborne Geophysical Surveys"
R. Carter and I. Mather

"Simultaneous Measurements by Towed and Inboard Scintillographs in Airborne Surveying"
R. Carter

"Radiometric Surveys using Light Aircraft"
B.M.R. Officers

"Electronic Processing of Aeromagnetic Data"
A.J. Barlow and K. Seers

"Reduction of Aeromagnetic Survey Data"
W. Forsyth

"Interpretation of Aeromagnetic Survey Data"
J. Quilty

INSTRUMENTATION FOR AIRBORNE GEOPHYSICAL SURVEYS WITH D.C.3. AIRCRAFT

BY J.K. NEWMAN, BUREAU OF MINERAL RESOURCES, AUSTRALIA.

The Commonwealth Bureau of Mineral Resources conducts aerial magnetometer and scintillograph surveys using a D.C.3. aircraft. This paper describes the equipment installed in the aircraft and that associated with the ground organisation. In addition to the D.C.3. aircraft, the Bureau employs a light aircraft for low-level scintillograph surveys as described in a separate paper - Radiometric Surveys using a Light Aircraft by J.M. MULDER.

PRIMARY EQUIPMENT

MAGNETOMETER

The magnetometer is of the self-orienting fluxgate type. The main detector channel employs a single core fluxgate giving an output of sharp voltage peaks which are detected and amplified by a balanced detector and a differential analyser. Orientation of the detector fluxgate is achieved by means of auxiliary fluxgate channels which operate two servo systems.

The table below summarises the characteristics of the Bureau's airborne magnetometer :-

Response	:	D.C. to 2 c.p.s. (high frequency response to accommodate "backing-off" shift in datum.
Sensitivity (in gammas per full scale deflection on a 10 inch chart)	:	5000, 2000, 1000, 500, 250
Stability and Reproducibility of Calibration	:	0.2% (Calibration can be adjusted to ± 0.1% of nominal value)
"Backing-off" current supply	:	Long term drift is limited to an absolute maximum of 0.1% per hour, but is generally 0.02% after warming-up period.

"Backing-off" steps : Adjustable to 6 inches of chart, ± 0.02 inches, on each sensitivity range. 16 steps automatic in operation.

Stability of calibration is achieved by returning portion of the output current to a feedback coil on the detector fluxgate. The feedback ratio is at least 50 on the 250 gamma range, and 800 on the 200 gamma range, so that the calibration is mainly dependent on the coil and a stable dividing network, and in the stability of a 10 inch Leeds and Northrupp "Speedomax" recorder.

The main portions of the earth's field is annulled by means of a current fed to the main fluxgate drive windings. To simplify calibrations, an additional "backing-off" coil is included. This coil is standardised with respect to the earth's field at an absolute magnetic station and is employed as a secondary standard for sensitivity calibrations to ± 0.01%. This method has been found to be much simpler and more accurate than the use of Helmholtz coils, in that orientation problems are avoided.

The sensitivity ranges of 2000, 1000 and 500 gammas full scale are employed during surveying and are associated with 16 automatic "backing-off" or datum shifting steps of 1200, 600 and 300 gammas respectively. The 5000 gamma range is incorporated for adjustment purposes and for the rare occasions when it is desired to record extremely large anomalies. To date the 250 gamma range has been found useful for making checks on heading error, but has not been employed in routine surveying.

To reduce the effect of aircraft magnetism the magnetometer detector head is installed in a boom extending from the aircraft's tail come. With the detector element positioned 11 feet from the tail cone the total variation in recorded field due to heading error, as the aircraft's heading varies continuously through 360 degrees, is found to be approximately 15 gammas in southern Australia (magnetic latitude 70 degrees) and 35 gammas in northern Australia (magnetic latitude 40 degrees).

The values of the longitudinal and transverse components of permanent magnetisation and the combined effect of longitudinal and transverse induced magnetisation, are checked at the commencement of a survey, by the flying of a small square on the four cardinal headings over an area of low magnetic relief. The track of the aircraft is simultaneously recorded by a vertical strip camera. The square is treated as a minute survey grid in which the misclosures are due solely to heading error. Drift can be neglected and careful inspection of the strip film enables all position error to be removed, if the magnetic relief is not great. A single square (more commonly known as a "cloverleaf" due to the route the aircraft follows in the flight) provides two values for each component of permanent magnetisation, and, effectively, four values for the combined effect of longitudinal and transverse induced magnetisation.

The heading error is reduced to negligible proportions by compensation with two horizontal electromagnets and twin soft irons compensator pods fitted one on each side of the magnetometer boom. The problem of measuring and compensating heading error is simplified by the fact that the magnetometer detector is mounted on an axis of symmetry of the aircraft with respect to the magnetic iron in engines and cables. Thus all but two of the nine coefficients of induced magnetisation can be neglected, and these two can be treated as one, providing it is assumed that the aircraft rotates in azimuth but does not change attitude. A rough correction for the vertical induced and permanent magnetisation to reduce the effect of manoeuvre noise is made by means of a vertical electromagnet. The total vertical magnetisation is most effectively checked by ground tests with a stationary fluxgate magnetometer set up close to the magnetometer boom.

In addition to the 10 inch Speedomax recorder, it has been found convenient to employ a second recorder operating at approximately one quarter of the chart width and chart speed, to produce reduced scale records.

These reduced scale records, when mounted in groups on large sheets, provide a much more convenient guide to the progress of a survey than the large unwieldy full scale records.

For monitoring disturbances in the magnetic field, a single element fluxgate magnetometer is maintained at a ground station and the records from this instrument are used if necessary for applying corrections to the airborne data. As a rather arbitrary criterion, magnetic disturbances of more than 6 gammas in 6 minutes are considered to necessitate correction of the airborne trace. Disturbances greater than 20 gammas in 6 minutes require a reflying of the relevant portion of the airborne survey.

SCINTILLOGRAPHS

Two scintillometers are employed, one mounted inside the aircraft, the other carried in a towed "bird". The inboard scintillometer employes two Chalk River type detector heads, each with two sodium iodide crystals, 2 inches in diameter and 4 inches long, which feed into a single Chalk River ratemeter. The effective time constant of the arrangement is 2 seconds.

The second scintillometer comprises a plastic phosphor 5 inches in diameter and 6 inches long, photo-tube detector, transistorised pre-amplifier and E.H.T. supply built into a "bird" with a total weight of approximately 70 lb. The "bird" is towed at 290 below 360 feet behind the aircraft by a steel cable 1/8inch in diameter, and of 900 lb. breaking strain. The steel sheath of the cable forms the electrical ground and a single central conductor carries a filtered 12 volt D.C. supply down to the bird and returns the amplified scintillation pulses to another inboard Chalk River ratemeter. This has an effective time constant of one second. The output of the two separate ratemeters are recorded by a dual pen Texas Instrument's "Rectiriter" recorder.

NAVIGATION & POSITIONING EQUIPMENT.

Two methods of navigating and recording the flight path of the survey aircraft are currently in use. These methods are described in detail in another paper - Problems of Navigation and Position Plotting. Shoran navigation and the recording of Shoran position co-ordinates are employed when aerial photo-coverage is not available, for example when the area includes a large proportion of water or featureless terrain, or when a very close flight-line spacing is required.

When aerial photography is adequate, the preferred method is to navigate by means of photo-mosaics and to record true position with a vertical camera and Air Position Indicator system. The vertical camera record is used to identify true position at approximately 15 mile intervals or where tie-lines cross flight lines, and the Air Position Indicator provides a fairly rapid means of interpolating between photo identified points.

SHORAN

An AN/APN-84 Shoran transmitter and indicator are installed in the D.C.3. aircraft when required, and are usually operated in conjunction with three AN/CPN-2a ground stations during the survey. The air station transmits 20 KVA peak power at 250 and 230 mc/s.

As is well known, the combination of the Shoran air station plus two ground stations provides two range measurements, which are continuously available for trilateration of the aircraft's position. The principal drawback of the Shoran system is its dependence on an unobstructed line-of-sight between aircraft and beacon. For this reason the average geophysical airborne survey, flown at levels between 500 and 1,500 feet, necessitates the siting of ground stations at a series of high points to provide complete coverage of the survey area. To facilitate the change-over from control by one beacon pair to another, a third ground station is normally moved into a new position while the first two beacons are still in operation. The third beacon serves also a reservoir of spare Shoran units to meet breakdown emergencies.

In operating the airborne Shoran, two sets of signal and marker pulses must be kept in alignment by continuous adjustment of marker pulse delays, the adjustment being controlled by two handwheels. Counters registering from 0.001 to 99.999 are mechanically coupled to the handwheels and translate the marker pulse delays into mileages. As it is almost a physical impossibility for a single operator to continuously adjust the two handwheels and maintain the pulses in alignment for long periods, the Bureau has constructed Aided Layers to a design provided by the Division of Radiophysics of the Commonwealth Scientific and Industrial Research Organisation. This equipment was designed along the lines of gunlaying equipment and is a considerable aid to the Shoran operator in that it removes the constant velocity component from the manual adjustments. Nevertheless, the operator is more or less continuously occupied in maintaining the adjustments required to accommodate changes in the aircraft's speed relative the beacons.

An Automatic Follower, which removes the need for manual alignment of Shoran pulses, is available in the U.S.A., under the designation of Indicator Assembly ID-288D/APA-54a. The Bureau investigated the problem of developing an automatic follower for its own use but decided that the relatively small scale of the Shoran operations would not justify the project. The present method of semi-manual alignment using Aided Layers has proved surprisingly accurate, the error varying from 0.01 to 0.02 miles for an ~~additional~~ individual distance measurement.

In recording Shoran position co-ordinates two methods are used. The first is by photographing repeater mileage counters at intervals of ten seconds with an instrument camera, the main requirement being that the photographic image of the counters on the film should be large enough for reading without magnification.

The second method uses a Straight Line Flight Indicator and Plotter, which has been constructed to the design provided by the Division of Radiophysics of the Commonwealth Scientific and Industrial Research Organisation. The original version of this instrument has been described by Richardson (1959).

The instrument consists of two mechanical linkages which are electrically coupled to the Shoran mileage indicators and automatically indicate the position of the aircraft. One linkage drives an electrical probe, representing the position of the aircraft over an adjustable glass plate coated with a thin layer of metal, through which is engraved a line representing the desired flight path., The probe produces a signal, which is proportioned to the deviation from the line and whose sign depends on the direction of the deviation. The signal operates a left/right position indicator in the cockpit. The second linkage drives a scribe which draws the actual flight path (according to Shoran co-ordinates) on a lacquered glass plate. In both linkages, M-type motors adjust the position of the probe on two lead screws to represent the two Shoran range measurements. The lead screws pivot at points which represent the positions of the two ground stations.

The area over which the Straight Line Flight Indicator and Plotter can be used is restricted by the mechanical characteristics of the instrument. The probe and scribe, which are mounted co-axially and represent the position of the aircraft, cannot cross the baseline between the two lead-screw pivots or approach very close to each pivot. Limitations are also imposed on the range of operation and on the beacon separation.

VERTICAL CAMERAS.

A photographic record of the track of the aircraft is obtained by a 35 m.m. camera arranged to photograph the terrain vertically below the aircraft. Continuous strip and frame cameras have been used at different times. The continuous strip camera is preferred for the following reasons :-

(a) It is mechanically simpler and more reliable in operation.

(b) The correlation system depending on fiducial marks on recorder charts is more easily applied to the continuous strip film.

(c) It has been found easier for a draftsman to follow and plot the flight path when recorded as a continuous image on strip film rather than on overlapping frames.

Both strip and frame cameras are fitted with wide-angle lenses giving an angle of view of approximately 90°. It is considered that an even wider angle of view could be used to advantage.

During Shoran operations, an F.24 aerial camera, which produces 5½inch square photographs has been used on occasions to fix a Shoran ground station chain with respect to survey trig. points. Shoran controlled F.24 photo-runs have also been employed to provide control for photo-mosaics in inaccessible areas.

AIR POSITION INDICATOR

The Air Position Indicator (A.P.I.) continuously computes air position in terms of nautical miles north-south and east-west of an arbitrary origin. The two counters, which repeat the Shoran mileages and are photographed by an instrument camera during Shoran-controlled surveys can alternatively be elctrically coupled to the A.P.I. to provide a record of position. Recently, the output of the A.P.I. has been coupled to a rectilinear chart recorder in such a manner that the chart's time scale indicates position along a flight line and the pen deflection shows the drift left or right of the planned track. In this manner a continuous record of the computed air position is available for interpolation between photo-identified positions. This replaces the recording of co-ordinates at 10 second intervals by the instrument camera.

The A.P.I. receives distance information from an Air Mileage Unit which integrates air speed information from the standard pitot tube installed in the nose of the aircraft, and receives direction information from a Sperry Gyrosyn compass.

A Ground Position Indicator (G.P.I.) has also been flight tested. This equipment corrects the air position data for wind velocity to produce an estimated ground position. An extra man is needed to operate gyro-stabilised drift meter and to feed wind information to the G.P.I. At the low altitudes common in geophysical surveying, this wind information has never proved sufficiently accurate to justify the extra man, and the G.P.I. has not been adopted for survey use.

RADIO ALTIMETER

A radioaltimeter, type STR 30 supplied by Standard Telephones and Cables is installed in the aircraft. This instrument transmits a 4000 mc/s signal, frequency modulated at 300 cycles, vertically downward. The signal reflected from the ground is mixed with the transmitted signal and the difference frequency becomes a measure of the phase difference, at 300 cycles/sec, of the transmitted and reflected signals, and this is proportional to the altitudes. Two ranges, 1000 feet and 5000 feet full scald, have been found most convenient for survey flights from 500 to 1500 feet above terrain. The altitude indication is displayed on meters in the cockpit and the cabin, is recorded on a Texas Instrument Rectiritár, and also operates limit-lights in the cockpit.

CORRELATION SYSTEM

Depending upon the type of survey, up to seven different records must be synchronised by the correlation system. The various records are :-

Magnetometer

Dual pen scintillograph

Radio altimeter

A.P.I. recorder

Vertical camera

Instrument camera - (for Shoran or A.P.I.)

Shoran position plotter.

Obviously the seven records are not usually required together on one survey, but it is very common to require at least five of them.

In order to avoid the troubles which inevitably occur with a system in which number counters are the sole means of identifying instrument camera frames and strip film positions, and which requires the flight operators to record identifying numbers on the various charts, a coded fiducial system has been adapted. This system depends on a pulse timer which produces single pulses at an interval usually adjusted between 10 and 20 seconds, a double pulse for every tenth interval and a triple pulse for every hundredth interval. The fiducials are recorded as side-pen marks on the charts, as small blanked-off lines across the vertical strip film and as small deflections of the Shoran plotter scribe. In the frame camera the single pulses trigger the shutter and are recorded as frames, the double pulses light a single lamp and the triple pulses light the indicator lamps on the instrument panel.

The use of number counters, photographed by the vertical and instrument cameras, has been continued and operators are required to write an occasional number against the fiducials on the charts. However, the numbers are always checked for agreement and if, for example, number 397 coincides with three fiducials on the vertical strip film, this number is altered to 400. In a similar manner all correlation errors are guarded against as long as the fiducial marker pens on the recorders are adjusted so that there is no parallax between their movements and those of the main pens.

COMMUNICATION EQUIPMENT.

Apart from mandatory communications equipment, an additional BC 348 receiver and a Collins ART 13 transmitter are installed for communication between aircraft and the Shoran ground beacons. Sometimes the same equipment is used for communication with the survey base.

Standard intercommunication equipment is installed for liaison between the flight crew. The pilots have found a loudspeaker installation preferable to earphones and steps are now being takén to fit several loudspeakers in the main cabin.

GENERAL REMARKS

The power required to operate the geophysical equipment in the aircraft is supplied by two 200 amp., 28 volt, D.C. generators. The magnetometer requires 60 amp., the Shoran equipment100 amp. and the winch for the towed bird 90 amp.,. The remainder of the equipment requires approximately 40 amp.

A separate power unit, consiting of a 300 amp., 28 volt, D.C. motor generator mounted on a vehicle trailer, is used for providing power necessary for testing the equipment when the aircraft is on the ground.

The method of installation of the equipment described in this paper is illustrated in a series of photographs which have been made available for display durinb the Seminar.

With regard to the personnel required for operation of the survey equipment in the aircraft, it has been found in practice that two operators are sufficient for both Shoran and photo-controlled magnetometer and scintillograph surveys. During a Shran survey, one operator is fully occupied maintaining alignment of the Shoran signals, while the other supervises the remainder of the equipment from a seat placed in front of the magnetometer recorder. The two operators take turns in attending to the Shoran equipment, in order to avoid excessive fatique, and consequent errors in pulse alignment.

The Bureau has recently completed plans for introducing modifications to the magnetometer instrumentation which will provide for recording of the magnetic data directly in digital form on punched tape and enable reduction of the data to be carried out by an electronic computer.

The possibility of replacing the fluxgate magnetometer by a nuclear resonance magnetometer is being investigated and it is likely that the fluxgate will be replaced eventually by an absolute magnetometer, based on proton precession or possibly rubidium vapour resonance absorption. A magnetometer of this type offers the advantage zero drift which would simplify the problem of reducing the data, and should be more suitable than the fluxgate type for installation in light aircraft.

REFERENCE

A Straight-Line Flight Indicator for the Pilot of a Radar-Equipment Aircraft. By R.C. RICHARDSON.
Australian Journal of Applied Science vol. 2 No. 2. pages 223-234, 1951.

PROBLEMS OF NAVIGATION AND POSITION PLOTTING IN AIRBORNE GEOPHYSICAL SURVEYS.

by

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INTRODUCTION.

The information given in this paper is based mainly on the experience of the Commonwealth Bureau of Mineral Resources in the conduct during recent years, of airborne geophysical surveys on an extensive scale throughout Australia.

In an airborne survey carried out for geophysical purposes, it is essential that reliable methods be used, firstly for flight navigation, to ensure that the aircraft is flown along the pre-determined lines and secondly for the plotting on aerial photographs or maps of the paths actually flown, to enable the geophysical data to be finally presented in map form.

The methods of navigation and plotting most frequently employed in Australia are based on the use of aerial photography. In general, these methods have been found most suitable for aeromagnetic surveys of sedimentary basins and for surveys of a reconnaissance type over metalliferous mining provinces. However, where the surveys extend over off-shore areas or over terrain lacking identifiable features or where very detailed surveys are required as for the investigation of particular mining localities, it is usually preferable to replace the photographic methods by a Shoran radar navigation system. The methods below are used with a D.C.3 type of aircraft, specially equipped for magnetometer and scintillometer surveys.

PHOTOGRAPHIC NAVIGATION.

The aircraft is navigated by visual comparison of ground features with detail on aerial photographs. The photographs are usually on a scale of 1 to 50,000 or 1 to 30,000 and for convenience are assembled into mosaics of suitable size, on which the planned flight lines are drawn. These are usually straight and parallel at separations of $\frac{1}{2}$ or 1 mile, and cover the survey area with a N-S or E-W grid, the direction being governed by geological considerations.

At intervals along each flight line, the pilot marks well-identifiable features on the aerial photographs. The check points so marked are given reference numbers and assist in the subsequent plotting of flight paths from vertical strip film to aerial photographs. The strip ~~plan~~ film is exposed by a 35 mm. camera carried in the aircraft, and arranged to photograph continuously the terrain vertically below the aircraft. The strip film is correlated with the magnetometer and other instrument charts by means of a common fiducial marking system and provides the means whereby the final accurate plotting of the flight path on the aerial photographs is accomplished.

Plotting of the flight paths consists of transferring each check point and intermediate fiducial points from strip film to aerial photographs. The tre-lines are usually plotted first and then the traverse lines. Care must be exercised in plotting the intersections of tie and traverse lines to avoid introducing errors into the subsequent process of reduction of the profiles to a common datum.

The aerial photographs should be of good quality and should give complete coverage of the area to be surveyed. Scarcity or poor definition of topographical features renders navigation difficult and reduces the ease and accuracy of the plotting of the flight paths. The accuracy is reduced because of the lengthening of the intervals between points which can be reliably and accurately transferred from strip film to photo-mosaic or map. The quality of the strip film similarly affects the ease and accuracy of plotting and correct processing of the film is therefore of considerable importance.

In Australia it has been found that extreme diversity of terrain types may occur in an extensive survey area and may result in variability of plotting accuracy. Changes in ground features may occur with passage of time and it is therefore desirable that the aerial photography used should be as recent as possible.

AIR POSITION INDICATOR.

The plotting of flight lines by the method outlined above is, in general, a long and tedious process. It has been found that the time required for this task can be reduced considerably by using an instrument known as an Air Position Indicator (A.P.I.). This is installed in the survey aircraft and is designed to provide a continuous measure of the air position of the aircraft relative to its starting point or other known point, in terms of two co-ordinates. The A.P.I.

integrates air speed and compass heading with time and records a position, which, in the absence of wind, will be the true ground position of the aircraft. The A.P.I. co-ordinates are indicated by mileage counters mounted on a panel and photographed automatically at regular intervals by an instrument camera.

Attempts were made to use a Ground Position Indicator (G.P.I.) in conjunction with the A.P.I. The G.P.I. is designed to compound the A.P.I. data with the wind vector to give the ground position of the aircraft at any instant. However, this method involves the calculation of wind velocity by some separate means such as a drift meter, and was finally discarded in favour of the use of the A.P.I. alone, because of inaccuracy caused by errors in wind measurement and also because the method required an extra air-crew member for drift-meter observations.

The A.P.I. method has been used to reduce effectively the work involved in plotting flight lines. Accurate plotting by transference of points from strip film to aerial photographs is still required for the tie lines, check points and the intersections of tie and traverse lines, the A.P.I. data being used for the portions of traverse lines between check points. The distance between check points over which interpolation by the A.P.I. is satisfactory, varies between 7 and 15 miles depending on the particular conditions of the survey. The flight path between each pair of check points is drawn on an appropriate scale, usually 1 mile to 1 inch from the mileage co-ordinates recorded during flight and is then adjusted proportionately to fit the relevant pair of check points marked on a base map on the same scale. An improvement of the method is under development, whereby the A.P.I. data will be recorded in the aircraft by a pen on a moving chart so as to give a trace representing the position of the aircraft. Transference of the flight path recorded in this way to a planimetric map is facilitated by a specially constructed type of pantograph.

SHORAN RADAR NAVIGATION SYSTEM.

This system was designed to provide an accurate means of navigating an aircraft and of fixing its position relative to known ground stations. It provides an accurate method of navigation over water or over land areas where suitable aerial photography is not available.

The principle of operation consists in measuring distance in terms of the transit time of a radio signal in the form of a train of pulses, which is transmitted from the aircraft and recived by two fixed ground beacons. The beacons are triggered by the incoming signal and send out a similar train of pulses which is received by the equipment in the aircraft. The transit line for the path from aircraft to beacon and return is measured and converted to a distance expressed in miles. Thus, the master equipment in the aircraft interrogates two beacons established at points fixed by a ground survey, in order to measure the distance from each beacon. The distances are displayed on mileage counters. One pair of counters is photographed automatically at regular intervals by an instrument camera, the other is mounted on the pilot's panel. A trilateral fix of the aircraft's position is therefore made and maintained continuously during flight.

Navigation of the aircraft along pre-determined traverses necessitates the calculation beforehand of the mileage co-ordinates at numerous points along each traverse. The pilot is provided with a list of such co-ordinates and maintains the correct track by continuously comparing the calculated co-ordinates with the changing co-ordinates indicated by the mileage counters.

In some of the surveys carried out by the Bureau it has been possible to simplify the application of the Shoran method by flying arcs instead of straight lines, in which case the aircraft maintains a constant distance from one beacon during each arc traverse. The procedure reduces the work required in calculation of co-ordinates for flight navigation and makes the task of the pilot easier; but, on the other hand may create difficulties in the subsequent reduction of the geophysical data.

A device known as a Straight Line Flight Indicator and Plotter is sometimes used as an adjunct to the Shoran equipment. The device is designed to facilitate the flying along pre-determined straight lines and obviates the need for previous calculation of mileage co-ordinates. The plotter incorporated in the device traces on a lacquered plate, a line representing the track of the aircraft, and gives in effect a plan of the flight lines which is convenient for reference during survey. However, the instrument has not been widely used because of several inherent disadvantages caused by its mechanical limitations.

The positions of the Shoran beacons are accurately fixed prior to the commencement of the survey by triangulation or ground traverse. The flight lines can then be plotted accurately using the known beacon positions and the photographic record of the mileage co-ordinates, (i.e., the distances of the aircraft from each of a pair of beacons) made during the flight. The plotting is done on transverse mercator projection at a scale of one or two miles to an inch.

The process of plotting from the mileage co-ordinates is facilitated by using graticules drawn on transparent sheets and consisting of concentric circles at intervals of 1/10th inch. The graticules are placed so that the centre of the circle system of a graticule coincides with each of the two beacon points. This method of plotting is considerably quicker than the method using vertical strip film and aerial photographs, and has the further advantage that it is very convenient for use by the field party during the course of a survey. In the Bureau's operations it is customary to plot the flight lines on the day following the actual flying so that any omission of lines or excessive departure from the planned flight lines can be detected and rectified in subsequent flights.

As examples of airborne geophysical surveys which required the use of Shoran the following surveys are cited:-

Tennant Creek Mining Field, Northern Territory, where an area of about 2,500 square miles of relatively featureless terrain was surveyed with airborne magnetometer and scintillometer along flight lines spaced 1/5th mile apart. The principal aim of the survey was to delineate magnetic anomalies, which, in the Tennant Creek field are known to be associated with copper and gold ore bodies, and to locate them as accurately as possible in relation to existing mines and mine leases.

Bonaparte Gulf Basin in Western Australia and Northern Territory and Perth Basin in Western Australia. Aeromagnetic surveys were made of these sedimentary basins to assist oil exploration. The use of Shoran was essential to enable the surveys to cover the off-shore extensions of the basins and parts of the land areas where mapping and aerial photography were inadequate.

ACCURACY OF PLOTTING METHODS.

The accuracy of photographic plotting of aircraft position has been estimated taking into account the following possible sources of error:-

Error due to tip or tilt of aircraft of up to 30°, at 1,500 ft. above ground level.	± 80 feet.
Possible error in good slotted template photo-assembly.	± 50 feet.
Personal error in transferring from strip film to photographs.	± 100 feet.

Hence it is estimated that the overall accuracy to be expected in photographic plotting is of the order of ± 230 feet (0.04 mile) or better.

The A.P.I. method was tested over two traverses each 90 miles long and compared with the results using strip film and a reliably controlled slotted template assembly. It was found that the errors introduced by the use of the A.P.I. for interpolation over distances of 90, 30 and 10 miles were ± 0.50, ± 0.25 and ± 0.10 mile, respectively. Similar tests made in a different area indicated errors of ± 0.25 mile for distances of 45 miles and ± 0.1 miles for 30 miles and less. Thus, if interpolation by the A.P.I. is restricted to distances of 15 miles or less the maximum error is unlikely to exceed ± 0.10 mile.

The overall accuracy of plotting using Shoran data and the graticules described above is estimated to be ± 0.02 mile.

HEIGHT MEASUREMENT BY RADIOALTIMETER.

It is normal practice in airborne geophysical surveying to control the height of the aircraft by means of a radioaltimeter, a micro-wave transit-time measuring device which measures the distance between aircraft and ground with an accuracy of ± 3%. In the survey aircraft used by the Bureau, the radioaltimeter indicates the height on a dial mounted on the pilot's panel and also operates warning limit lights which assist the pilot in maintaining the height within the limits imposed by the survey requirements. In addition, the height is continuously recorded on a moving chart in order to provide a permanent record, which is normally required in subsequent analysis of the geophysical data.

COMPARISON OF NAVIGATION METHODS.

The photographic method of navigation and plotting is the one generally preferred and most widely used for airborne geophysical surveys in Australia, both by the Bureau and other operators. Under certain circumstances, for example, over water or over land areas where suitable photography is not available, a radio method such as Shoran has been found to be essential. The Shoran method has certain advantages for general use but these are outweighed by the higher cost of the Shoran operation resulting from the additional personnel required and the necessity of establishing temporary ground beacon stations.

Other systems of navigation have been examined as possible alternatives to Shoran but none has distinct enough advantages to justify the abandonment of the Shoran system. The Raydist system is similar to Shoran in some respects, has greater accuracy, smaller range and is similarly complex. The Doppler Navigator has advantages as regards greater simplicity and less weight, but has a lower overall accuracy due to dependance on a magnetic compass and a range affected by many factors. The Loran system has a high accuracy but is not suitable for short range measurements. The Decca Navigator comprises an airborne unit and three ground stations. It has a shorter range and lower accuracy than the Shoran system while the cost of the equipment and its operation is considerably higher.

SIMULTANEOUS MEASUREMENTS BY TOWED AND INBOARD SCINTILLOGRAPHS IN AIRBORNE SURVEYING. - By [illegible]

BUREAU OF MINERAL RESOURCES, AUSTRALIA

Introduction

The first experiments in the use of aeroradiometric techniques began in 1946. Since then much development of technique and equipment has taken place and the methods have been adopted in many countries. The earliest techniques, using ion chambers or geiger counters, have given place to the use of highly sensitive and efficient scintillation counters.

The airborne scintillograph is designed to produce a continuous record of terrestrial gamma radiation at an altitude of up to 500 feet. The purpose of the aeroradiometric measurements is to locate regions of anomalous radioactivity which might be associated with uranium mineralisation of commercial grade.

Single Altitude recording.

In the interpretation of the scintillograph record, a difficulty arises from the fact that when an anomaly is recorded along a flight line, the track of the aircraft might not have passed through the centre of the source. Thus, a large surface area deposit of low grade with centre close to the track of the aircraft could be confused with a point or small surface area deposit lying further from the track. Further confusion can arise in the differentiation between point and line deposits, and between groups of the former and deposits of large surface area.

A single airborne scintillograph can provide only a single record of gamma radiation intensity: there are three unknown quantities involved in the interpretation of the record.

Surface area of deposit.

Position of deposit (the offset distance of its centre from the track of the aircraft).

Grade of deposit, in effective mass of radioactive material per unit area of surface exposure.

If the offset distance of the deposit be assumed to be zero, then the surface area of the deposit can be estimated from the anomaly width†, and the effective mass of U_3O_8 can be estimated from the anomaly amplitude, for specific values of aircraft altitude and instrumental time constant. Such a procedure would, if followed, give some realistic results, and some would be found confusing and inaccurate upon ground investigation.

To assist in the evaluation of the anomalies one practice has been to classify all anomalies, according to their amplitudes compared with the standard deviation of the statistical variations of the 'background' radiation, assuming that the anomalies are due to deposits at zero offset distance.

The criteria used are somewhat arbitrary, but have the effect of reducing the likelihood of a random variation in counting rate being interpreted as a significant anomaly. However, small deposits of high grade can thus be overlooked while cognisance is taken of those of large area and low grade. This can occur where considerations of anomaly amplitude only are made; the meaning of the anomaly width must be appreciated in order to improve the technique of interpretation.

† Width here and henceforth refers to width at half-maximum amplitude, in units of length.

The amplitude of the anomaly due to a point deposit falls to one-third of its maximum at an offset distance equal to the detector altitude; for a line deposit, the corresponding value is one-half. By regarding the figure of one-third of the maximum amplitude of anomaly for a specific point deposit as the lower limit of resolution, then the effective width of swathe would be, ~~i.e.~~ 1,000 feet for an aircraft altitude of 500 feet.

At 500 feet, a flight-line spacing of 1 mile would therefore result in the surveying of 20% of the overall area, and the probability of detecting a single localised deposit would be 20%.

Simultaneous recording at two altitudes.

From several sources have come suggestions for the obtaining of two records of the surface radioactivity over a specific area or along a specific flight line.

A procedure at first suggested (Godby et al.), and later attempted in Australia by the Bureau, is the reflying of a portion of a flight line, corresponding to a significant anomaly, at a lower altitude. The ratio of the square of the maximum amplitude of the anomaly recorded at the lower altitude to the maximum amplitude of the anomaly recorded at the higher altitude, was found to have a crude relationship to the grade of the deposit, between certain limits of area.

It can be shown that the ratio of the maximum amplitudes of the anomalies recorded at the two altitudes is a function of the deposit area and offset distance: thus, given one it would be possible to calculate the other. Further, on the assumption that the offset distance were zero, one or other of the peak amplitudes can be used to estimate the effective quantity of U_3O_8 in the deposit.

However, it is difficult to refly a line exactly because of navigational difficulties over ill-defined topographical features, particularly so at an altitude of 200 feet and at a ground speed of 130 knots. Therefore the result could be that the anomaly recorded during the second flight would correspond to a different aircraft track. Thus, no further information of the nature of the deposit would be forthcoming.

It will be useful, therefore, to adopt a technique whereby a dual record of the surface radioactivity can be obtained in an aircraft, so that the records correspond to a single aircraft track. The notion of measuring gamma radiation by using two detectors simultaneously at two altitudes was suggested by more than one source (Godby et al.). It was proposed that a single inboard scintillograph be used, and in addition, a similar instrument towed beneath the aircraft, at an altitude difference of about 250 feet.

A reconnaissance aeroradiometric survey at high altitude (500 feet), using such a technique, could partially or wholly obviate the geophysical purpose of a lower-level follow-up survey: the flight-line spacing adopted in the former case would be a qualifying factor.

The technique of the simultaneous use of two scintillographs at two altitudes, using one aircraft, has been investigated by the Bureau, and since 1957, experiments have been conducted during airborne reconnaissance surveys in order to develop the method.

Briefly, the instrumentation consists of one scintillograph carried at 500 feet above ground, and another, identical in function, towed at 210 feet above ground.

Interpretation of the dual record of anomalous radioactivity.

The surface exposure of radioactive deposits.

All deposits are assumed to be circular in exposure, and the formulae used in the development of the theory refer also to the limiting case of the point deposit.

However, there are two important exceptions to which other considerations must be given: those are line deposits and groups of small deposits.

A line deposit could be recorded in various forms; as a point deposit, a small circular deposit, or a broad deposit, depending upon the angle between its axis and the track of the aircraft. The adjacent flight-line records might show evidence of the existence of a line deposit by indicating point deposits, the positions of which could be linked up on a map, after a careful study of the local geological formations.

The problem of differentiating between point and line deposits can be partially resolved by consideration of the slope of the resultant anomaly, and by applying the fact that for a point deposit, the anomaly recorded along a line over the deposit falls to 0.3 of its maximum value at a distance from the centre equal to the detector altitude: for a line deposit, the corresponding amplitude is 0.5 of the maximum.

A group of small deposits might be assumed to be a single broad deposit, and adjacent flight-line records might give no additional information. In such a case, greater resolving power must be provided by lower-level flight and/or smaller flight-line spacing.

Superficial deposits.

In natural deposits only the upper layer of thickness 20 centimetres, effectively contributes to the radiation detected above the surface. However, the derivation of formulae relating the detectable radiation intensity, at a point above the ground surface, with the area, position and grade of a deposit, is considerably more complex in the case of a thick deposit than for a superficial one. The curves prepared from the numerical values of the resultant functions differ only slightly for the two types of deposit. Therefore, the simpler mathematical treatment has been used, and all deposits are therefore treated as superficial exposures.

Evaluation of a specific anomaly.

The following families of curves have been prepared :

(1) Anomaly width *versus* deposit radius. Parameters are deposit offset distance, detector altitude and instrumental time constant.

(2) A similar set, with deposit radius and offset distance interchanged as variables.

(3) Recorded count-rate per curie *versus* deposit radius. Parameters are deposit offset distance, detector altitude and instrumental time constant.

(4) A similar set, with deposit radius and offset distance interchanged as before.

(5) Ratio of recorded count-rates per curie at the two altitudes

(5)cont'd.

versus deposit radius. Parameters are offset distance and instrumental time constant.

The anomaly widths at two altitudes can be measured and compared with curves relating anomaly width to deposit radius, at various values of offset distance, at various altitudes. In effect, there are thus two unknown quantities involved, and two simultaneous equations available, by using a family of curves for each altitude. Therefore, approximate values of radius and offset distance can be obtained.

The anomaly widths must be measured as independent of the aircraft air speed, drift, recorder chart speed variations, etc., and therefore they must be expressed as distances equal to those traversed by the aircraft and measured along the ground surface. This can be done by comparing the resultant plotted aircraft track on the photographic mosaics with the recorder chart, correlated by fiducial marks.

One or other of the anomaly amplitudes can then be used in order to estimate the effective mass of U_3O_8 considered as a surface exposure, because the oblique distance from the centre of the deposit to the detector can be calculated.

Ratio of maximum amplitudes for two altitudes.

The ratio of INBOARD/OUTBOARD anomaly amplitudes can be used to calculate the radius of the deposit, after having made due adjustment for difference of detector sensitivities. Such calculations would be based on the assumption that the offset were zero, and therefore could be compared with the result of the use of two width measurements, where the offset had been found to be zero.

Results of dual radiometric record interpretation.

Few concrete results or verifications of the theoretical figures are available as yet because no ground investigations have followed upon the reconnaissance surveys in regard to any specific anomaly. Nevertheless, the method has distinct possibilities in the estimation of the size of a deposit and its position relative to the aircraft track: the calculation of grade is thus made possible.

The accuracy of the method depends upon several factors: signal-noise ratio, detector sensitivity, detector response, recorder mechanical noise, circuit electrical noise, and statistical variations of the counting rate. All of these affect the degree of precision with which the anomaly width and amplitude can be measured; for example, a point deposit at 500 feet gives rise to an anomaly of width 900 feet, using a one-second time constant. For worthwhile results this width must be measured to within 50 feet: the anomaly on the recorder chart must therefore be measured to within 1/50 inch at a chart speed of about 4 inches per minute.

A test of the feasibility of making sufficiently accurate width and amplitude measurements has been made by comparing the values of deposit radius and offset distance, in several idealised cases, determined first by width measurements and then by amplitude ratio measurements, on the appropriate curves in each case. Agreement to within about 5% was obtained.

Some experimental results obtained by measuring the anomalies produced by a test point deposit show agreement to within 10% between the values of radius and offset distance estimated from the width measurements, and the actual configuration: the corresponding anomaly amplitude ratios were in good agreement also.

Finally, some anomalies recorded during a recent airborne survey in Australia were examined and the deposit grades were estimated independently from each of the two records, by using the assigned values of radius and offset distance estimated from the width measurements. The differences between the pairs of values of grade for 5 out of the 6 anomalies examined is within 10%. In the case of the remaining anomaly, the peak was off-scale on one record and was therefore merely estimated.

Instrumentation.

Inboard scintillograph.

The detecting unit consists of a pair of crystal heads, each fitted with a pair of thallium-activated sodium iodide crystals and a single photomultiplier.

The outputs of the detecting heads are combined, amplified and integrated in a Chalk River radiation monitor, to form a D.C. current which energises one channel of a dual-channel Rectiriter recorder.

The recorder pen deflection is thus directly proportional to the intensity of the incident radiation. A sensitivity of 100 c.p.s. full scale is usually used, and the time constant of the integrating circuit is normally 1 second.

Towed or outboard scintillograph.

The detecting unit is contained in a 'towed-bird', which is an aerodynamically-stable fibreglass shell; this can be trailed below the aircraft, suspended by a cable. The upper end of the cable is attached to a hydraulic winch within the aircraft, and during take-off and landing the bird reposes in a cradle structure mounted on the underside of the fuselage.

The airborne shell contains a plastic phosphor detector and a photomultiplier, plus a transistorised preamplifier and battery operated power unit.

The towing cable conveys the electrical output of the detector to a second Chalk River radiation monitor within the aircraft, and the output of this is connected to the second channel of the dual-channel recorder.

A sensitivity of approximately 300 c.p.s. is used, and a time constant of 1 second.

The towed detector, in flight, is normally 290 feet below the aircraft.

Conclusions.

The dual-scintillograph technique described herein has been considered mainly from a theoretical point of view and rests upon several assumptions: however, it is felt that some support or supplementation of the current empirical processes of aeroradiometric data interpretation is necessary.

It is not suggested that ground exploration, ground or airborne follow-up of airborne work, or geological studies of the area in question, will be obviated. It is expected that some reduction in the amount of airborne and ground follow-up work will be made possible by enabling discrimination to be made between broad deposits of low grade and localised deposits of high grade.

It is hoped that the radiometric data resulting from current and near-future airborne surveys in Australia will, on interpretation, establish the technique on a practical basis.

References.

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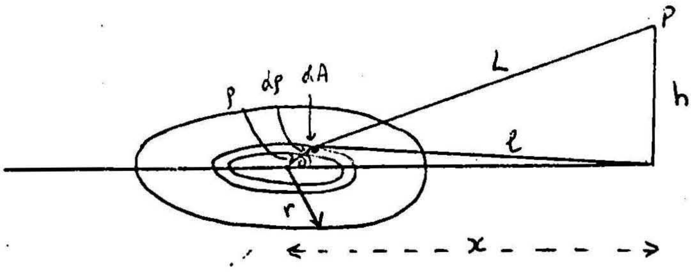
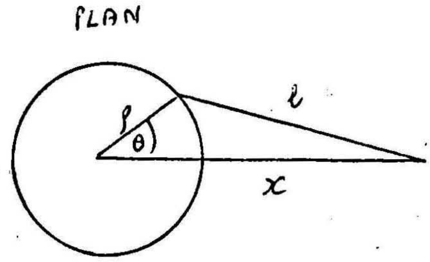
APPENDIX

The following formulae have been derived in order to relate the detectable radiation intensity at a point above the ground surface, to the area, position and grade of a nearby radioactive superficial deposit.

Consider the response at a point P, at a horizontal distance x from the centre of a circular superficial deposit, radius r.





The response due to the element $dA = S(2.95.10^9)^{\dagger}\, g.d\,A.\ \frac{e^{-\mu L}}{L^2}$ counts/second

where g = grade in CURIES†† $/CM^2$

S = crystal area in CM^2

$$= S(2.95.10^9).\ g.\rho\ d\rho\ d\ \theta\ \frac{e^{-\mu\sqrt{h^2 + x^2 + \rho^2 - 2x\rho\cos\theta}}}{h^2 + x^2 + \rho^2 - 2x\rho\cos}$$

The integration of this expression w.r.t. θ, necessary to determine the response due to the annular area, is apparently not feasible without certain restrictions; the absorption factor will therefore be neglected initially.

The response due to the annular ring $= S(2.95.10^9)\ g.\rho\ d\rho \int_0^{\pi} 2.\frac{d\theta}{H^2 - 2x\rho\cos\theta}$

where $H^2 = h^2 + x^2 + \rho^2$

$$= 2S(2.95.10^9)\ g.\rho\ d\rho\ \frac{2}{H^2}\left[\sqrt{\frac{H^2}{H^4 - 4x^2\ {}^2}}\right].\frac{\pi}{2}$$

$$= 2S(2.95.10^9).g\rho\ d\rho\ \pi\left[\sqrt{\frac{1}{(h^2 + x^2 + \rho^2)^2 - 4x^2\rho^2}}\right]$$

∴ The response due to the whole deposit = I =

$$2S(2.95.10^9)\ g.\pi\int_0^r \frac{\rho\ d\rho}{(h^2 + x^2 + \rho^2)^2 - 4x^2\rho^2}$$

$$\therefore\ I = 2S(2.95.10^9)\ g.\pi\int_0^r \frac{1}{2}\ \frac{d(\rho^2 + h^2 - x^2)}{\sqrt{(h^2 + \rho^2 - x^2)^2 + 4h^2x^2}}$$

$$\therefore\ I = 2S(2.95.10^9)g.\pi\left[\frac{1}{2}\operatorname{arcsinh}\frac{h^2 + \rho^2 - x^2}{2hx}\right]_0^r$$

$2.95.10^9 = \frac{3.7.10^{10}}{4}$ and 1 CURIE ~ $3.7.10^{10}$ disintegrations per second.

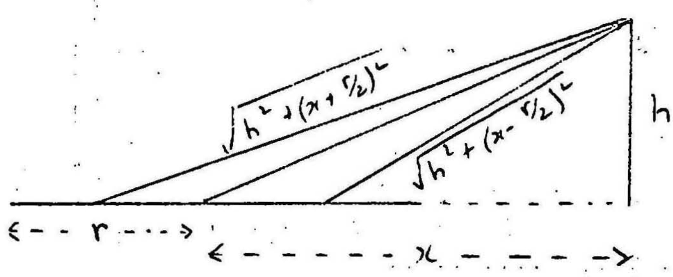
1 CURIE ~ 3000 Kg. Uranium.

$$\therefore \; I = S(2.95.10^9).g.\pi \log \frac{r^2 + h^2 - x^2 + \sqrt{(r^2 + h^2 - x^2)^2 + 4h^2x^2}}{2h^2}$$

And $g\pi r^2 = C$ where C = content of deposit in CURIES

$$\therefore \; \frac{I}{SC} = \frac{2.95.10^9}{r^2} \log \frac{r^2 + h^2 - x^2 + \sqrt{(r^2 + h^2 - x^2)^2 + 4h^2x^2}}{2h^2}$$

It is proposed that an average absorption factor be used for the whole deposit; the resultant count-rate is a very close approximation to that appropriate to the overhead position, where the largest error caused by using a poor approximation would occur.



The absorption factor becomes :

$$e^{-\frac{\mu}{2}\left[\sqrt{h^2 + (x + r/2)^2} + \sqrt{h^2 + (x - r/2)^2}\right]}$$

The complete equation for the response due to the total deposit is -

$$\frac{I}{SC} = \frac{2.95.10^9}{r^2} \log \frac{r^2+h^2-x^2 + \sqrt{(r^2+h^2-x^2)^2 + 4h^2x^2}}{2h^2} \, e^{-\frac{\mu}{2}\left[\sqrt{h^2+(x+r/2)^2} + \sqrt{h^2+(x-r/2)^2}\right]}$$

COUNTS/SEC./CURIE/CM.^{2} OF CRYSTAL.

This expression represents the static response of a detector to the presence of a superficial deposit, radius r, offset x, content C, from an altitude h.

The absorption coefficient μ varies with $L = \sqrt{h^2 + x^2}$ and the relationship suggested by Cook where $\mu = 0.0000594(0.116 + 0.0977 \log 0.0059 h)$ has been used, by substituting L for h.

This expression was postulated ~~by~~ (Cook) for E = 1.8 M.e.v., and it has been found (Berbezier et al.) in experiments using a gamma-ray spectrograph that, for uranium, 1.8 M.e.v. is approximately that at which the absorption of the gamma-radiation by air and soil is least. Also, it has been found (Faul) that the energy distribution of gamma-rays is approximately contant from 0 to 1000 feet above ground.

The increase in scattering by Compton effect because of the oblique path of the radiation through the lower air has been assumed negligible.

This assumption appears to be justified by the results of experiments (Gray, Levin, and White) in which equivalent values for the absorption coefficient for air at altitudes up to 1,000 feet were found to fall far short of the theoretical 'narrow-beam' value for a non-homogeneous medium; in such a medium no photons scattered by the Compton effect reach the detector from a source on the ground.

The average value of μ air from the experiments is 46.10^{-6} cm.$^{-1}$, and the theoretical 'narrow-beam' value is 75.10^{-6} cm.$^{-1}$.

Other experiments (Godby et al.), have produced values for μ air of $37.4.10^{-6}$ cm.$^{-1}$ for altitudes of 0 to 500 feet, and $41.1.10^{-6}$ cm.$^{-1}$ for altitudes of 0 - 1,000 feet.

The conclusions drawn by the writer are :

(a) Compton scattering at altitudes of from 0 to 1,000 feet is smaller than to be expected for a non-homogeneous medium such as the atmosphere.

(b) Its variation with altitude over that range of altitude is negligible because of the degree of homogeneity which exists.

Therefore, an oblique air path of inclination 30°, (the minimum value used in the analysis in this paper, i.e. $x \leq 500'$, $h \geq 200'$) differs only negligibly from a vertical air path of equal length, as regards the scattering of gamma radiation from a source on the ground.

The equation -

$$\frac{I}{SC} = \frac{2.95.10^9}{r^2}.\log \frac{r^2+h^2-x^2+\sqrt{(r^2+h^2-x^2)^2+4h^2x^2}}{2h^2} e^{-\frac{\mu}{2}\left[\sqrt{h^2+(x+r/2)^2}+\sqrt{h^2+(x-r/2)^2}\right]}$$

is applicable for $\begin{cases} r \neq 0 \\ x \neq 0 \end{cases}$

And $$\lim_{r \to 0} \frac{I}{SC} = 2.95.10^9 \frac{e^{-\mu L}}{L^2}$$

is applicable for $\begin{cases} r = 0 \\ x \neq 0 \end{cases}$

And $$\frac{I}{SC}_{x=0} = \frac{2.95.10^9}{r^2} \log \frac{r^2+h^2}{h^2} e^{-\mu\sqrt{h^2+r^2/4}}$$

is applicable for $\begin{cases} r \neq 0 \\ x = 0 \end{cases}$

And $$\lim_{r \to 0} \frac{I}{SC}_{x=0} = 2.95.10^9 \frac{e^{-\mu h}}{h^2}$$

is applicable for $\begin{cases} r = 0 \\ x = 0 \end{cases}$

ANOMALY WIDTH

The two records give rise to two values of anomaly width. The curves relating width to radius and offset distance can be used to find a single solution i.e. one value each of radius and offset which satisfy both the width values.

ANOMALY AMPLITUDE

Using the two records of counting rate, two values of peak amplitude of anomaly can be obtained, by using also the known values of radius and offset distance.

Then the curves relating $\frac{I_d}{SC}$ (in COUNTS/SEC./CURIE/CM^2. OF CRYSTAL), to anomaly radius and offset distance can be used to provide two values for C, of which a mean can be taken.

I_d = peak anomaly amplitude ($d \sim$ dynamic response)
S = detector crystal area (CM^2)
C = content of source (CURIES)

Let $\frac{I_d}{SC}$ = N

From the charts, at altitude h_1, $K_1 = N_1\, S\, C_1$ at a distance L_1 from the source

$$\begin{cases} L_1 = \sqrt{h_1^2 + x^2} \\ K_1 = \text{peak of anomaly.} \end{cases}$$

and at altitude h_2, $K_2 = N_2\, S\, C_2$ at a distance L_2 from the source

$$\begin{cases} L_2 = \sqrt{h_2^2 + x^2} \\ K_2 = \text{peak of anomaly.} \end{cases}$$

From the curves, at altitude h_1, $\frac{I_d}{SC_1} = N_1$, for $r = r$, $x = x$, $h = h_1$, $L_1 = \sqrt{h_1^2 + x^2}$

and at altitude h_2, $\frac{I_d}{SC_2} = N_2$, for $r = r$, $x = x$, $h = h_2$, $L_2 = \sqrt{h_2^2 + x^2}$

$$\therefore \quad \frac{K_1}{\frac{I_d}{SC_1}} \cdot \frac{1}{S} = C_1$$

$$\text{and} \quad \frac{K_2}{\frac{I_d}{SC_2}} \cdot \frac{1}{S} = C_2$$

and $C = \dfrac{C_1 + C_2}{2}$

<u>References.</u>

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5. White, – Phys. Review, 80, 154 (1950).
6. Faul, – Nuclear Geology, p.228.

RADIOMETRIC SURVEYS USING LIGHT AIRCRAFT

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INTRODUCTION

A light aircraft can be used to advantage for airborne radiometric surveying where the terrain is rugged or where the flying of closely spaced lines for detailed surveying is required. High manoeuvreability enables the aircraft to be piloted along valleys and creek beds and along the contours of ridges with a satisfactory maintenance of performance. The ability to use small improvised landing strips enhances the usefulness of light aircraft in the more inaccessible areas. Where detailed surveys are required, maximum economy may be obtained because of the facility with which flight line spacing can be adjusted to suit the geological environment.

The height above ground level normally adopted for survey by light aircraft is 200 feet. This height is well below the maximum at which the search for Uranium can be carried out effectively. At the same time the height is regarded as a minimum safe height for continuous surveying. The aircraft is flown at speeds from 70 to 80 knots.

In 1955 the Commonwealth Bureau of Mineral Resources conducted its first light aircraft survey at low level using a chartered Auster aircraft. The instrumentation was designed solely for radiometric surveys and consisted of a scintillation counter and a chart recorder. Following this survey, others were carried out in many parts of Australia under a variety of climatic conditions.

In 1956 an Auster J5P Autocar was purchased. This aircraft, equipped with improved scintillograph equipment, radio-altimeter and radio transceiver, has since been flown on numerous surveys. Although the Auster's performance was found to be satisfactory over relatively flat country its usefulness was restricted in areas of rugged terrain and under conditions of high density altitude. The Auster has therefore recently been replaced by a

Cessna-180.

EQUIPMENT

During the last ten years scintillation counters have replaced Geiger counters almost entirely for airborne work because of their superior efficiency in gamma-radiation detection. This type of counter contains a phosphor as a detecting element, optically coupled to a photomultiplier tube. Scintillations produced in the phosphor by incident gamma-radiation are reproduced as electrical pulses by the photomultiplier tube. These pulses are fed into a ratemeter, the output of which is a current proportional to the count-rate of the detector. A continuous record of the gamma radiation intensity is provided by coupling a continuously recording meter to the ratemeter output.

The payload of the light aircraft is generally sufficient for the following equipment - a scintillation counter consisting of a detector head and ratemeter, recorder, radio altimeter, an HF and/or VHF transceiver and emergency rations.

Units comprising the survey equipment can be mounted behind the pilot's seat, with the recorder suitably placed so that the observer can inspect it during flight. A remote control unit on the panel in front of the observer carries a milliammeter showing the count-rate, a push button for chart annotation and a switch to operate the recorder.

The transceiver is used by pilot for reporting the position, operating height, etc., at regular intervals during the survey. Emergency rations, canned water, a rifle and a Verey pistol are carried for use in the event of a forced landing.

FIELD OPERATIONS

A survey party engaged in light aircraft operations normally consists of a geophysicist, acting as party leader, a technical assistant, a draftsman, a pilot, a field assistant. With this arrangement of personnel the party leader and his technical assistant fly as observers and the draftsman's work is confined to the plotting of flight lines and results.

Upon arrival in the survey area, reconnaissance flights are made at 2,000 feet to familiarise the pilot and observers with topographical and geological features. Following the reconnaissance flights aerial photographs are examined and the direction and spacing of flight lines is decided. Where possible, the direction of the flight lines is kept at right angles to the strike of geological formations.

The following tests are carried out during each flight to check the survey equipment for satisfactory operation :-

(i) On taking off, the performance of the radio altimeter is compared with the barometric altimeter by flying along the air strip at survey altitude.

(ii) On the flight to the survey area the radiometric equipment is checked at an altitude of 2,000 feet above ground level. At this height terrestrial gamma radiation is effectively reduced to zero and the radiation recorded represents cosmic and contamination background. A small standard source is then placed at a predetermined distance from the detector and the deflection on the record of the gamma radiation intensity is noted.

Before the commencement of survey flying, one or two trial runs are made at 200 feet to assess the drift. With the direction of the flight lines known, and the drift estimated, the pilot sets course, and flies by the compass or by landmarks. During survey flight the observer checks and plots the track on aerial photographs, marking the start and end of each line and prominent features along the flight path. These points provide a means of reducing inaccuracies caused by variations in the groundspeed. Starting points, finishing points and prominent features are marked on the chart by means of a side marker, which is operated by the observer when the aircraft is vertically over such points. Flight lines are usually flown parallel to each other, except when circumstances necessitate the contour flying of steep ridges, escarpments or deep river and creek valleys.

Experience has shown that pilot fatigue can be prevented by flights of short duration with the weekly total not exceeding 25 hours. For this reason two survey flights of 2½ to 3 hours are made each day.

INTERPRETATION OF RESULTS

A scintillograph carried in a low-flying aircraft will record a certain background level of gamma radiation originating from the ground, as all rocks and soils are radioactive to some extent since they contain minute quantities of the radioactive minerals, uranium, thorium and potassium. Cosmic radiation and radiation due to aircraft contamination will also contribute to the background radiation.

Variations in the gamma radiation over any area are mostly broad and can often be correlated with the geology. Increases in gamma-ray intensity, which can not be regarded as part of the background radiation, are considered to be anomalies.

For a count-rate to be considered anomalous its amplitude must be several times larger than the standard deviation of the background count-rate. Amplitudes are therefore expressed in term of the standard deviation σ, and a factor 3σ has been accepted as a minimum level of detectability (Peirson & Franklin, 1951).

Not only the amplitude of an anomaly but also its shape is of importance. Whereas, the amplitude depends on the gamma-ray intensity, which varies with the concentration of U_3O_8 on the surface as well as with the distance from the source to the detector, the width depends on the extent of the deposit, the altitude of the aircraft, and the time constant of the scintillograph equipment but is independent of the amplitude.

An airborne scintillograph survey is designed to detect anomalies and to locate their positions accurately, so that investigation by ground parties can be made. Anomalies of most interest in the search for uranium are those due to sources of small ~~aerial~~ areal extent. Such anomalies approximate to a point source anomaly, which has a width at half-rise of about 500 feet, for a survey altitude of 200 feet and a time constant of about 1 second.

The process of interpretation begins with an inspection of the scintillograph record to select the anomalies in gamma-ray intensity which exceed 3σ, and which at the same time satisfy some arbitrary width limitation. These anomalies are then examined to determine whether they arise from a change in altitude or topographical feature. This examination requires an inspection of the radio-altimeter record and may necessitate the study of aerial photographs through a stereoscopic viewer.

Where anomalies are shown to be due to changes in altitude or to topographical features they are discarded. It is the evaluation of the remaining anomalies that forms the most difficult part of interpretation.

The evaluation of anomalies depends to a large extent on the experience and judgment of the interpreter. It is essential to take into consideration all the available geological and geophysical data and the results of his own ground inspection where practicable. These studies lead to the selection of anomalies which could be associated with the occurrence of uraniferous ore. During the course of the survey the anomalies are plotted onto aerial photographs and the photographs made available for public inspection.

For the purpose of publication the results are presented in the form of a planimetric map of the area surveyed, surrounded by copies of aerial photographs showing the position of the anomalies located. The published map is given as wide a distribution as practicable.

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ELECTRONIC PROCESSING OF AEROMAGNETIC DATA

by A.J. BARLOW and K. SEERS

BUREAU OF MINERAL RESOURCES, AUSTRALIA.

INTRODUCTION

Since 1951 the Commonwealth Bureau of Mineral Resources has reduced several hundred thousand line miles of aeromagnetic data using conventional hand reduction methods. In 1958 investigations were commenced on the application of electronic computers for the processing of airborne survey data and towards the middle of 1959 the reduction of a small test survey was carried out in a trial programme run using Sydney University's SILLIAC computer. Good agreement was found to exist between the results of this trial and the results of a hand reduction of the same data.

Electronic data processing offers two main advantages over conventional hand methods of reduction; namely, speed, with consequent reduction in cost, and accuracy. With the exception of the computation of the corrections to be applied at tie and line intersections, the various steps in hand reduction are carried out by computing assistants using a pencil and rule. The process is tedious and subject to human error; it also requires a large team of computing assistants to reduce the records obtained during the course of one field season. The Bureau's investigations so far indicate that a saving of 60% in time and cost would be achieved by the adoption of electronic data processing of digitised aeromagnetic records.

Equipment suitable for operation in the survey aircraft and designed to record the aeromagnetic data in digital form on punched tape is being developed and will undergo trials during the 1960 field season. A description of this equipment is given below following a discussion on computer programming.

COMPUTER PROGRAMMING

In the following discussion it is assumed that the airborne survey is designed to enable a least squares method of reduction to be applied to the aeromagnetic data. A brief description of this type of survey design is discussed elsewhere. (Reduction of Aeromagnetic Survey Data by W.A.L. Forsyth). However a general programme may be designed for any systematic method of data reduction.

A computer programme is contained in two types of punched tape, the programme tape and the parameter tapes. In the process of reduction these tapes operate on the data tape, on which the basic survey information has been recorded during flight. The programme tape carries instructions for the least squares analysis and the instructions for reduction. For surveys over areas of rectangular shape the programme tape remains unchanged from one survey to another. A computer programme can therefore be used repeatedly, with slight modifications for individual surveys being introduced by means of the parameter tapes. For example correction to be applied in distribution of random error can be found from a least squares analysis by means of a table of pre-determined coefficients. These coefficients depend upon the number of lines and ties in the survey area and are fed into the computer on a parameter tape.

The number of parameter tapes vary with the survey design and can be reduced by standardisation of the size of the survey area and of the tie and flight line pattern. The parameter tapes contain information such as :

(a) Line and tie intersections as read from flight line plot.
(b) Direction of each line and tie.
(c) Division of area into major and minor rectangles for a least squares analysis.
(d) Magnetometer sensitivity value.
(e) Least squares coefficients.
(f) Details of systematic error.
(g) Regional gradient correction (if any).
(h) Required datum and contour interval for final map.
(i) Form of output required from electronic computer.

The data tape will contain the series of magnetic field values and correlation data digitally recorded at intervals of one second. Additions or alterations to the data tape can be carried out in an editing process preceding the computer programming. Programme and parameter tapes are prepared as required. These operations are performed by means of a Creed Tape Editing consisting of a keyboard perforator and an automatic tape reader.

The sequence of operations involved in presenting programmed aeromagnetic data to an electronic computer has the following general outline. The data tapes are fed to the computer which stores all data in specified blocks of its memory. Programme and parameter tapes are similarly entered and stored and computation is commenced by operation of a control button. Corrections for systematic effects due to diurnal or instrumental drift and regional gradient are first applied to the magnetic field values, and corrected values returned to the memory. These effects are linear in distribution over suitably chosen intervals, and the computer is capable of distributing the corrections linearly over intermediate values.

The computer proceeds to extract the appropriate magnetic field values at the tie and line intersections listed in the parameter tape, and determines field value differences along each tie and line. By reference to the instruction details of the least squares analysis, the computer selects those lines and ties forming a network of major rectangles, and calculates the misclosures around each rectangle. These misclosures and the table of coefficients previously mentioned are used to determine the corrections to be applied along the sides of the major rectangles to distribute random error. Corrections along ties are distributed proportionately to the segments formed by the intersection of intermediate lines, and adjustments made until all misclosures in the minor rectangles are removed.

When all magnetic field values have been corrected and referred to an arbitrary datum level, each value on a line is tested to determine its level with respect to an integral multiple of the contour interval selected for final presentation of the data. In this manner positions of contour level intersections are determined, by interpolation if necessary, and this information is printed out.

During the computation, various checks can be applied, such as a print-out of the misclosures preceding the least squares analysis to ensure that they lie within reasonable limits. It is envisaged that the complete reduction will not be carried out in a single run, but in several short runs, intermediate print-outs being obtained which can be manually checked for any abnormal results. The final information regarding contour level intersections will be manually transferred to the flight line plot as at present; eventually this process may be carried out automatically.

DIGITAL RECORDING EQUIPMENT

The use of electronic data processing requires that the magnetometer record should be free from "noise" and excessive instrumental drift. A "noisy" graphical record can be smoothed by hand, or excessive instrumental drift corrected in the hand reduction but when electronic data processing is employed, the time taken to correct this inaccurate information outweighs advantages gained by using the computer. The essential information to be recorded on the punched tape consists of magnetic field intensity values at a specified time interval, changes in the "backing-off" field, and fiducial marks for correlation with the strip camera, recorded Shoran coordinates, or other aircraft positioning record.

The equipment required to produce automatically a digital record of the magnetic field comprises a shaft encoding disc, control unit, and punched tape reperforator. The disc and reperforator are available commercially, but because of the special nature of the data to be encoded, the control unit has been designed and built in the Bureau's laboratory.

Shaft encoding disc.

The most convenient method of producing a digital record from a flux-gate magnetometer is to use a shaft encoding disc which will encode the digital information from an analogue recorder. This recorder, a Leeds and Northrup Speedomax recorder, is retained in the system to enable visual checks of the magnetometer record, and spot checks of the encoding system. A shaft encoding disc manufactured by the C.M. Giannini Company was selected, as it can be attached directly to the "Speedomax" recorder. The disc produces a cyclic binary code of 1024 bits, giving a resolution of approximately 0.1% which is somewhat better than the accuracy of the Speedomax recorder. Thus no additional error in the magnetic field readings is introduced by the encoding disc. This disc is designed such that readings can be taken while the disc is rotating.

Control unit.

The control unit has three main sections which perform the following functions :

1. The generation and selection of timing pulses for operating the reperforator and for correlating data.
2. The decoding and storing of instantaneous readings taken from the shaft encoding disc until the reperforator recording operation is complete.
3. Ensuring that the characters, including backing-off, magnetic field data, and correlation data are recorded by the reperforator in the correct sequence.

The control unit is completely transistorized except for three relays providing pulses for external cameras. The timing section consists of a 400-cycle transistorized tuning-fork unit with two binary and five decade counters, which provide pulses at 1 sec., 10 sec., 100 sec. and 1000 second intervals. These pulses are routed to the strip camera, instrumentation camera and analogue recorder and provide fiducial characters on the punched tape.

The decoding section translates the cyclic binary code to the sexadecimal code before recording on the punched tape. This step is useful in that the editing set used for processing the programme and SILLIAC output tapes can then print out portions or all of the data tape in sexadecimal form for checking or other purposes. In addition, this unit uses "flip-flop" circuits which store the instantaneous reading obtained from the shaft encoding disc until a sequence of punching operations is complete.

The third section of the control unit provides the reperforator with the coded data in the correct sequence for punching. This sequence normally comprises one character representing "backing-off" field, followed by three characters representing the magnetic field data. This sequence recurs every second, and after each ten seconds two additional characters are introduced to correspond to a ten-second fiducial mark on the strip camera and analogue records. Similarly, after each 100 seconds, three characters are added. These characters are not included by the computer in the computation of the results but are checked against a total count of the data characters. They also facilitate printing out by the teleprinter-reproducer system. Another function of this section is to provide about twelve inches of delay symbols between each survey line so that the tape can be cut and spliced if necessary.

The operation of the control unit is illustrated by the block diagram in Fig. 1.

The fork, scaler, and fiducial pulse selector units produce pulses at 1 sec., 10 sec., 100 sec., and 1000 second intervals. At the start of a survey line, a manually operated press button gates the 1 second operating pulse to the following circuits :

1. Decode and Memory. The pulse triggers "flip-flop" circuits which hold the digital magnetic field information until punching is completed.
2. Sequence. The pulse triggers the first "flip-flop" circuit, which, together with the "and" gates and punch magnet amplifier, sets up the punch magnets for the first character to be punched.
3. Reperforator "on/off". The reperforator starts its cycle of operations by punching the first character. When this character is punched, a synchronising pulse from the reperforator switches off the first "flip-flop" and switches on the second, setting up the next character to be punched.

This sequence of operations is repeated until all characters required are punched. At the end of the sequence, an output pulse from the unit switches off the reperforator and clears the magnetic field data memory circuits to await the next 1 second operating pulse.

At 10 sec., 100 sec., and 1000 second intervals, the tape fiducial unit introduces additional "flip-flops" to the sequence unit so that appropriate fiducial characters are punched. At the end of a survey line, the "line start-finish" button leaves the last sequence "flip-flop" in operation for 10 seconds; thus a series of about 300 delay characters are punched before switching off to await the next survey line.

Punched tape reperforator.

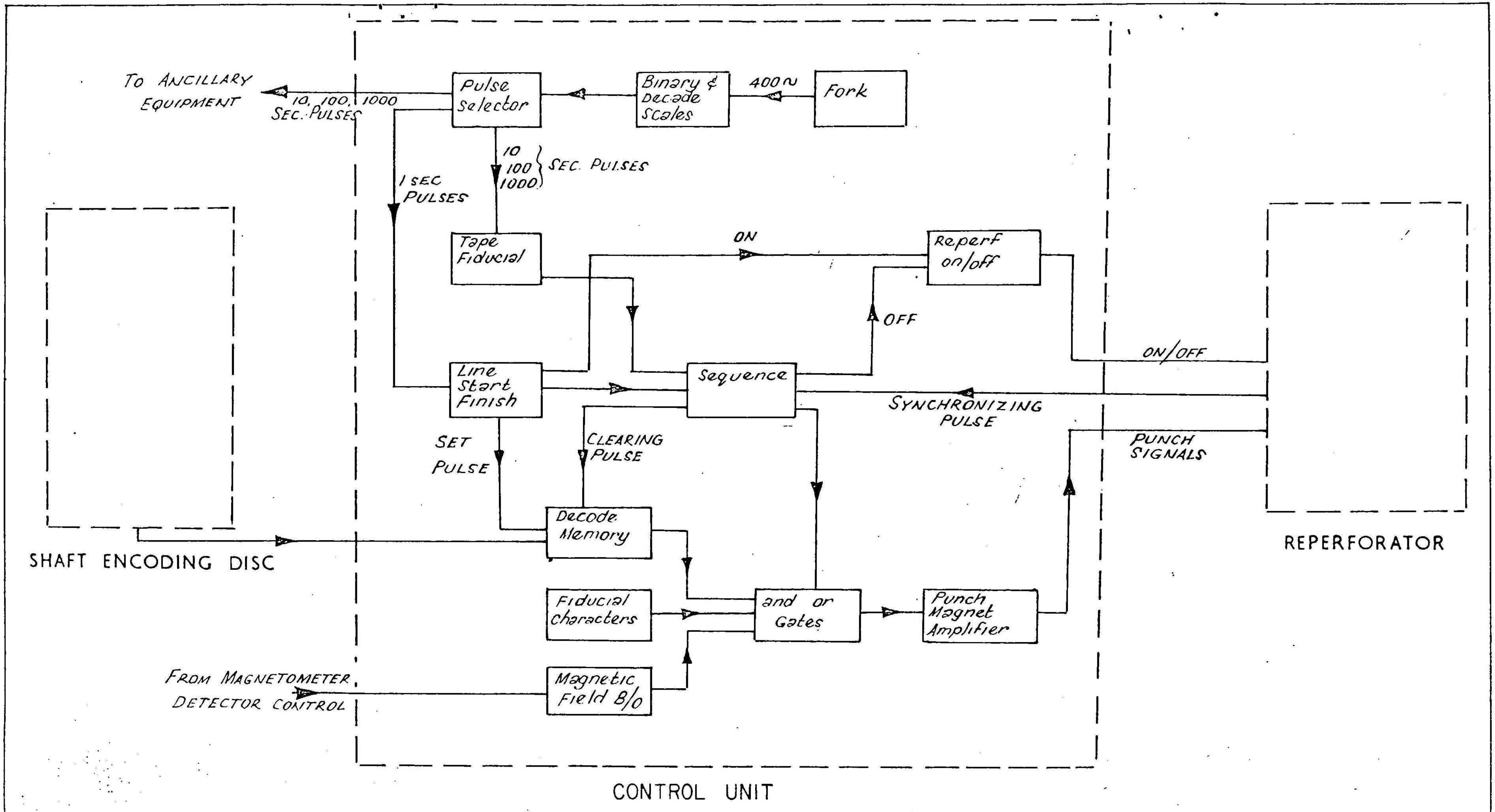
The tape punch used is a standard Creed No. 25 high speed reperforator. The unit will be shockmounted to minimise the effect of aircraft vibration, but it is possible that some trouble might be experienced from aircraft movement under turbulent conditions.

FUTURE DEVELOPMENTS

Some thought is being given to possible developments of this system. The first of these is the use of a nuclear resonance magnetometer instead of the flux-gate type. This would simplify both the aircraft equipment and the electronic computer programming. The nuclear resonance magnetometer has a basically digital output and therefore no analogue-to-digital converter would be required.

The electronic computer offers also great advantages in the processing of the navigational data used in the present photo-plotting system. Basically, the present system entails the plotting of selected check points at approximately 15 mile intervals from the strip camera record to a base photo-mosaic, and the use of an air position indicator to obtain intermediate points by interpolation. If the air position data were recorded digitally, and co-ordinates and fiducials of the check points were fed to the computer interpolation could be carried out automatically and an output tape would show fiducial numbers with their corresponding base map co-ordinates.

The system could be further developed, and at the same time made suitable for use with the Shoran navigation method, by introducing an automatic plotting device which would accept the punched tape output of the electronic computer. The system would then provide a map showing the plotted flight lines and the contour intersection points.



BLOCK DIAGRAM OF AIRBORNE DIGITAL INSTRUMENTATION

THE REDUCTION OF AEROMAGNETIC SURVEY DATA.

by W. A. L. Forsyth,

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INTRODUCTION.

The results of an aeromagnetic survey are initially recorded in the form of continuous profiles representing changes in total geomagnetic field intensity along a system of traverses. Each profile is referred to its own arbitrary datum level, which depends on the magnetometer control settings and other instrumental factors and on diurnal variation of the geomagnetic field. Direct comparison between profiles is therefore possible only after the profiles have been referred to a common datum. The process of reduction consists in adjusting all the profiles from a survey to a common datum level in order to make the individual profiles directly comparable and suitable for the production of contour maps.

CORRECTION FOR SYSTEMATIC EFFECTS.

The main systematic effects which must be taken into account in the reduction process are instrumental drift, diurnal variation and "heading errors" due to magnetism of the aircraft. The influence of diurnal variation upon the recorded profiles is indistinguishable from that of instrumental drift and their combined effect is therefore treated as a single systematic effect. The magnetic field at the magnetometer detector is modified by the resultant field produced by the various magnetic components of the aircraft. It is usual to take precautions to compensate for the magnetism of the aircraft but, in general, small residual effects remain known as "heading errors", which result in a displacement of the profile datum by an amount which is constant for any given aircraft heading but varies with the heading.

It is impossible to detect the presence of systematic effects by examining individual profiles and it is only by use of some suitable form of tie system that they can be measured and corrected for.

TIE SYSTEMS.

The common reference level may be provided by an auxiliary profile along a tie line which intersects all traverses, adjustments being applied to the arbitrary datum of each traverse profile so that the recorded field on the traverse profile is made equal to the recorded field on the tie profile at the intersection of the traverse with the tie line. For the satisfactory correction of errors due to the various systematic effects, it is necessary to use a system of tie lines located at intervals over the survey area.

There are at least two forms of tie system which may be used. These are:-

(a) Double-flown ties, which consist of two closely-spaced parallel lines on reciprocal headings, flown in immediate succession to form a loop. (See Figure 1).

(b) Single-flown ties, which are lines flown across the survey area, successive ties being flown on reciprocal headings. (See Figure 2).

Considerations of diurnal variation and instrumental drift indicate the desirability of orienting the tie lines at right-angles to the traverses and spacing them at distances corresponding to 6 to 8 minutes flying time.

REDUCTION PROCEDURE.

The data required before the results of an aeromagnetic survey may be reduced consist of:-

(a) Profiles. A complete set of profiles of magnetic field intensity, bearing correlation data in the form of a time scale common to all survey records.

(b) Base Map. A map showing a plan view of all traverses and tie lines surveyed, plotted by reference to the common time scale.

(c) Flight Records. Details of instrument control settings and information for the correlation of recorded profiles with positions as plotted on the base map.

The reduction of a set of survey data is carried out in the following stages:-

(a) The times corresponding to all crossover points or intersections of traverses with tie lines, are read off the base map and tabulated.

(b) The crossovers are located on the profiles by reference to the time scale on the recorder charts.

(c) The profile heights at the crossover positions are read off the traverse and tie line charts, and tabulated.

(d) Calculations are made of the corrections to be applied to the datum levels of the traverse profiles at the crossover points in order to make the recorded field intensity on the traverse profile equal to the corresponding recorded intensity on the tie profile.

(e) The corrections are plotted on the traverse charts at the positions corresponding with the crossover points and, on the assumption that the correction varies linearly with time along the traverse profiles between adjacent ties, the plotted correction points are joined by straight base lines. The base lines represent the desired common reference datum and intercomparison between profiles may be made by referring each profile to its corrected baseline.

(f) For the production of magnetic contours, lines representing contour levels are drawn parallel with the baselines and spaced at the selected contour interval.

(g) The contour intercepts are located by reference to the time scale on the edge of recorder chart.

(h) The position and value of each contour intercept is transferred to the base map to provide the data necessary for the drawing of contours.

In drawing the contour map, the contour interval is chosen to be not less than four times the standard deviation of the residual errors in the survey data after correction for systematic effects.

SINGLE FLOWN TIES AND METHOD OF LEAST SQUARES.

Owing to the combination of systematic effects and random errors, the observed increments of field intensity summed cyclically around rectangles formed by adjacent single-flown tie lines and pairs of traverses will, in general, show misclosures. These misclosures may be adjusted by distribution around the sides of the rectangle using the Method of Least Squares, and all profiles referred to a common datum.

The distribution of misclosures may be effected by inspection, using a method such as that described by Smith (1951), or by calculation, using either a table of coefficients or an electronic computer. The last two methods are referred to in a separate Seminar paper by Barlow and Seers (1959).

As the Method of Least Squares presupposes the presence in the data of random error only, it is necessary to ensure that the data is free from systematic effects before deciding to apply this method of reduction.

ERRORS IN REDUCTION.

If misplacement of baselines on traverse profiles charts has taken place through errors in the reduction process, characteristic distortions will be produced in the final contour map and visual examination of the contour pattern may indicate which profiles have been reduced incorrectly.

A specimen positive magnetic anomaly oriented at right angles to the traverse direction is illustrated in Figure 3a. The effect of an upward displacement of the baseline for the profile of traverse 3 is shown in Figure 3b and that of a downward displacement in Figure 3c. The distortion of contours resulting from alternate upward and downward displacement of baselines for successive profiles is depicted in Figure 3d.

Another form of distortion of contours results from a parallax effect on the profile charts, caused by a displacement between the reference time scale on the chart and corresponding points on the profile. This effect is illustrated in figure 3e.

It will be realised that accurate reduction of aeromagnetic data depends, to a large extent, on correct performance of the airborne equipment and the use of a reliable fiducial marking system. It is important to recognise the various sources of error and to ensure that the survey incorporates a suitable tie system which will enable the errors to be reduced to a minimum.

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ABSTRACT

This paper deals with the aims and methods used in interpreting aeromagnetic surveys. It outlines practical problems experienced in the interpretation of data recorded over metalliferous regions and sedimentary basins.

Examples are given in maps of metalliferous regions within Australia. Methods used by the Bureau of Mineral Resources in interpreting maps of sedimentary basins are described, with a discussion of their merits.

THE INTERPRETATION OF AEROMAGNETIC SURVEY DATA

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The recorded aeromagnetic data, after reduction to a common datum, is normally presented on a base map as contours of total magnetic intensity, or as reduced-scale magnetic profiles, using the plotted flight traverses as baselines. The Bureau of Mineral Resources uses contour presentation for all broad reconnaissance surveys.

Interpretation of the aeromagnetic map consists basically of determining the form and estimating the depth of magnetised bodies which satisfy the parameters of the observed magnetic anomalies and are consistent with the known or assumed geological conditions of the area. By applying the principles of magnetic potential theory, the interpreter attempts to distinguish the magnetic effects of bodies varying in shape, size, susceptibility, polarization direction and depth of burial below the surface. The task is complicated by the bipolar properties of magnetism and the measurement of the total field anomaly by the magnetometer. The postulated bodies must be geologically feasible in the area under consideration.

The potential problem has unfortunately an infinity of solutions. Ambiguities can be resolved by making use of external control in the form of known geological structure, borehole data or direct measuring geophysical methods (e.g. seismic). However, in the absence of such control, approximate solutions can be produced by making reasonable assumptions as to shape, size or depth of magnetised bodies. For simple forms, maximum depth limits can be determined by measurement of horizontal extent of anomaly gradients.

A valuable reference in practical interpretation is a set of standard curves representing the anomalies due to many types of magnetised bodies are shown graphically. This data is obtainable by model experiments or calculation using potential formulae. The latter was done in the Bureau. By the use of the surface integral for homogeneously magnetised bodies after Gulatee (1938), the anomalies in total field anomaly and those in the vertical and horizontal components, were calculated and drawn for elongated bodies resembling dykes, blocks, slabs, faults, contacts etc. for ranges of size, strike, depth, and for different values of magnetic inclination. Single pole and dipole fields were also calculated and drawn. This data, with the profiles of vertical and horizontal field components for various bodies published by Gulatee (1938) and the total magnetic field anomalies by Vacquier et al (1951) have comprised the standard source material. Experience in the composition and use of such data allows the interpreter to interpolate for departures of observed anomalies from those calculated.

Aeromagnetic maps of metalliferous regions present different practical problems of interpretation from those of sedimentary basins. The magnetic patterns of the former reflect the presence of magnetic orebodies, or associated rocks and structures. The magnetised bodies often lie at shallow depths and show marked susceptibility contrast with neighboring materials, resulting in sharply defined anomalies on the map. The interpreter's work is to correlate magnetic data with known geology, and to determine the form and estimate the depth of bodies lying probably within a few hundred feet of the ground surface. The aeromagnetic maps of sedimentary basins show anomalies arising from magnetic contrasts at basement rock level, which may be overlain by thousands of feet of non-magnetic sediments. This separation between source and observation level and the possibility of low susceptibility contrasts in the basement rock may result in ill-defined anomalies of low intensity and broad horizontal extent. The aim is to determine basement depth and topography from measurements on these anomalies or specially calculated functions of them, such as second vertical derivatives, downward continuations, etc.

The correlation of aeromagnetic data with known geology is an essential process in interpretation. Its value is well illustrated in aeromagnetic contour maps of the Kalgoorlie gold-fields region in the state of Western Australia. This region is part of the west Australian Plateau within the Pre-cambrian crystalline complex of the continental shield. Metamorphosed sedimentary rocks (Whitestone Series) and igneous rocks (Greenstone Series) are interspersed through the main-mass of granite and allied acidic rocks. Intense anomalies on the aeromagnetic map correspond with banded iron formations which are characteristic of the Greenstones and Whitestones, whereas the acidic rocks show little magnetic disturbance. A more detailed correlation, between magnetic anomalies and the rock types present may be made as geological mapping proceeds. The aeromagnetic data will assist in geological mapping of this region particularly in areas covered by sand and soil.

The Tennant Creek gold-field of the Northern Territory is an example of an area in which the aeromagnetic map has delineated structural elements which evidently control ore deposition. Many of the existing gold-bearing hematite mines were found by subsequent aerial survey to be located on the flanks of east-west trending elongated anomalies; these anomalies are believed to be due to strongly folded and overturned beds impregnated with iron solutions. Drilling has disclosed the existence of magnetite at depths in one of the mines. Other apparently similar structures, of which there was no surface indication, have been detected by aeromagnetic survey, and are being investigated in detail by ground magnetometer surveys. As an example of direct location of magnetic ore deposits, the map of the Rocky River - Rio Tinto district on the rugged western coast of Tasmania shows intense elongated anomalies indicating the position and horizontal dimensions of iron ore deposits. The major bodies are estimated to lie less than 300 feet below the ground surface, from measurements of the horizontal extent of maximum gradients on selected east-west anomaly profiles.

The results of extensive aeromagnetic surveys at one-mile flight line separation of Australian sedimentary basins are presented by the Bureau in the form of contours, such as in the Perth and Carnarvon coastal basins of Western Australia, and the Gippsland basin of Victoria. The survey areas are usually extended beyond the basin margins to investigate the magnetic characteristics of basement rock outcrops. The information obtained is of great assistance in the subsequent interpretation.

Data from broad reconnaissance traverses over, for example, the Great Artesian basin of eastern Australia and the Eucla basin of southern Australia, is shown as profiles along plotted flight traverses. Such profiles are interpreted qualitatively in the first instance, relative depths of basement rock being estimated by degree of magnetic disturbance and sharpness of individual anomalies. This relationship can be made quantitative when basement rock depths are known at control points throughout the area. Such a method was used to determine approximate thickness of sediments in the Eucla basin. Estimates of basement depth from individual anomalies recorded on single traverses require assumptions being made as to possible configuration of the magnetised body, because its horizontal dimensions are not outlined by the available data. Estimates of this type were made in the interpretation of the Great Artesian basin reconnaissance survey.

The aeromagnetic contour maps over sedimentary basins may be interpreted by several methods. Basement depths are estimated at all points where well-defined anomalies occur. The depths may be estimated by comparing the anomaly parameters such as horizontal extent of maximum gradients, anomaly maximum to minimum, or between maximum and half-maximum with those of standard anomalies. Preliminary examination of anomalies recorded over basement outcrops adjacent to the basin show which parameters are most reliable indicators. The method of Peters (1949), in which the horizontal distance between the two points at which the slope of the curve equals half the maximum slope is divided by a factor of 1.6 to give approximate depth to surface of structures with vertical boundaries, is an empirical one based on vertical magnetization but may be used to a limited extent on total field anomalies. If sufficient depth estimates can be made, approximate basement contours may be drawn from the aeromagnetic data. Basement topography is deduced from a series of individual depth estimates, there being no direct means of distinguishing anomalies due to topographic features from those due to intra-basement susceptibility contrasts.

Second vertical derivative maps are constructed in the Bureau's interpretation of certain areas to provide a greater degree of resolution of, individual anomalies than is apparent in the total field intensity contours. A square grid with line spacing equal to the average basement rock depth (determined by the above methods) is superimposed on the contours. Field values at the grid corners are interpolated and tabulated, and the second vertical derivative calculated by an appropriate formula. Vacquier et al (1951) have shown empirically that the lines of zero curvature correspond approximately with the horizontal dimensions of the magnetised bodies, and that certain parameters of the second vertical derivative anomalies are reliable indices for depth estimates.

The method of upward continuation of the total field data recorded at one level to higher levels by grid calculations, after Henderson and Zietz (1949), was carried out by the Bureau over a test area of basement outcrops, and the results were found to be in good agreement with actual recordings of the field at the higher level. Upward continuation of data observed over typical basement structures adjacent to a sedimentary basin allows a comparison between anomalies calculated for various heights and those recorded over the basin. Curves showing anomaly parameter measurements versus height can be compiled for depth estimation, but in practice the results do not differ substantially from those obtained by reference to standard source data.

Downward continuation of the aeromagnetic field data, as described by Peters (1949), reproduces the aeromagnetic data at lower levels as accurately as the original record and the calculation method permit. Individual anomalies are resolved and sharpened from the broad patterns recorded over deep sedimentary basins. Downward continuation of observed fields and the construction of vertical derivative maps probably constitute the most useful approach to the practical problem of interpreting anomalies due to deep-seated magnetised bodies. The former technique has not yet been used by the Bureau; electrode data processing techniques under investigation may be adopted for the time-consuming calculations involved.

An examination was made of Baranov's (1957) proposed method of transforming total intensity anomalies into pseudo-gravimetric anomalies, based on vertical polarization conditions. Coefficients published in Baranov's paper could not be reconciled with the derived formulae. Using these coefficients, transformations were shown to be reasonably satisfactory on anomalies due to simple magnetised bodies for dip angles of 60 degrees or greater. Even if other satisfactory transformations were possible, the usefulness of such maps in practical interpretation is considered doubtful.

Great accuracy in depth estimation cannot be expected in interpreting aeromagnetic maps, considering the departure of actual geological conditions from the simplified bodies on which calculations are based. The estimates are naturally less accurate in measurements on magnetic patterns from deep-seated basement rocks, where individual anomalies are merged at the observation level. Homogeneous magnetisation and constancy of magnetising vector assumed in calculation are not realised in natural rock masses. Nevertheless, results often confirm the validity of the methods of measurement, accuracies within ±20% in favorable areas being reported in geophysical literature. The complexity of natural magnetised structures also indicates that calculations based on elaborate shapes of magnetised bodies will not necessarily assist practical interpretation.

Aeromagnetic detection of probable ore bodies is normally followed in Australian exploration by ground magnetometer survey, drilling targets being selected on the more detailed indications of the latter method. In sedimentary basins, the role of aeromagnetic, and gravimetric, survey is usually one of primary investigation, followed by direct seismic measurements over favorable structures outlined by these potential field measuring methods. However, in certain sedimentary areas, localities for stratigraphic drilling have been selected solely on the interpretation of aeromagnetic and gravimetric maps. Drilling has commenced on several of these sites. Confirmation is to hand on one site in a shallow part of the Canning basin where basement rock was penetrated at approximately 2000 feet midway between two points of measurement indicating 1000 feet and 3000 feet respectively.

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