KEEPING TRACK OF THE EARTH'S MAGNETIC FIELD

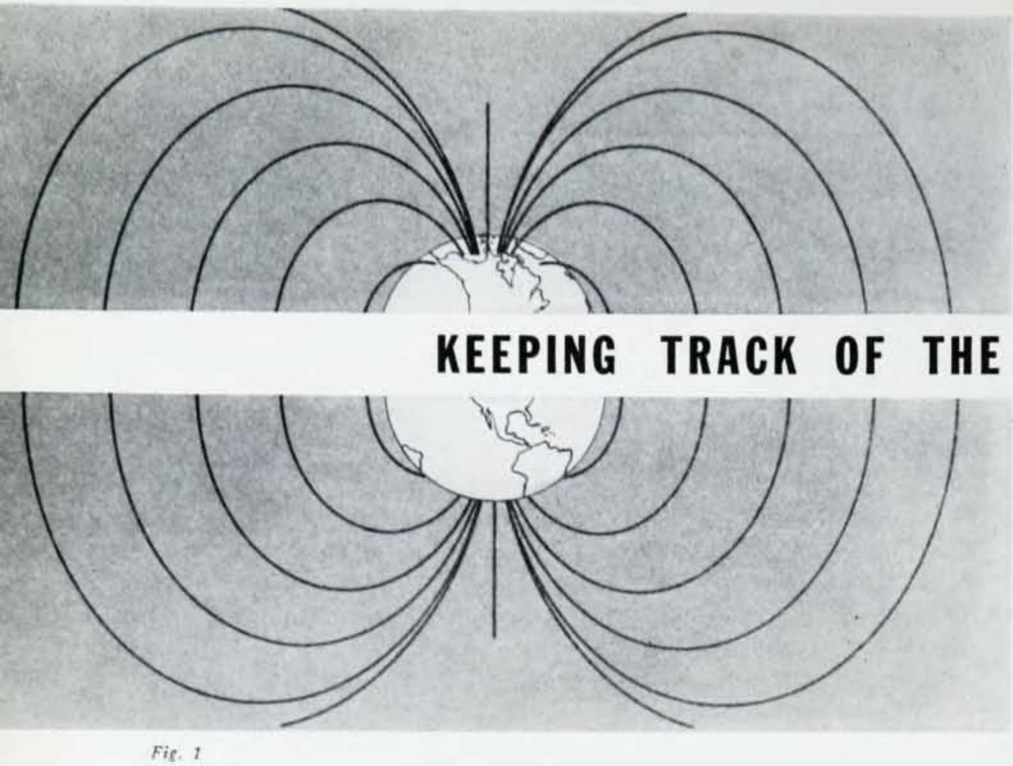

Fig. 1

By L. R. Alldredge

MAN has been studying the magnetic field of the earth for centuries. The existence of this field of force must be deduced by the use of scientific instruments since, unlike gravity, it is not detectable by our human senses. Measurements of the earth's magnetic field have been made from deep down in mines up to nearly one hundred miles above the surface.

The discovery of the magnetic ore magnetite, often called lodestone, paved the way for the development of the magnetic compass, which has been used by navigators since the eleventh century. It was discovered that a piece of lodestone mounted on a block of wood and floated in water always indicated a particular direction at a given location. It was later found that such a compass pointed true north only in certain places. At other localities it would point a little to the east or west of true north. This error with respect to true north has become known as the magnetic declination or variation of the compass. It was not discovered until the 16th century that magnetic forces tended to tip a magnetized needle from the horizontal. The angle between the final position of a magnetized needle free in space and the horizontal plane is called the dip angle or angle of inclination.

The general characteristics of this invisible field of force gradually became known and in the year 1600 William Gilbert published his famous volume *De Magnete* pointing out that the earth itself acts as though it were a great spherical magnet as shown schematically in Fig. 1.

At any point on or near the earth and at a given instant of time the magnetic field has a definite direction and magnitude. The field points in the direction in which an isolated north magnetic pole would tend to move, and the magnitude of the field is measured by the strength of its force on such a pole. At each point, the magnetic field can be completely described by giving the magnitude, declination, and the inclination, or by giving the vertical and horizontal component of the field and the declination, or by giving the vertical, true north, and true east components.

For the past three hundred years, geomagneticians have been mapping the characteristics of this field with great success. During the same period many investigators have also considered the problem of the origin of the earth's magnetic field, and while several new theories have been proposed which may ultimately lead to a satisfactory explanation the answer still remains obscure.

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Characteristics of the Field

If the earth's magnetic field could be mapped once and these values were to remain unchanged for all future time, the problem would indeed be a rather simple one. A complete, detailed declination survey would result in magnetic navigation maps which could be as appropriately used in the year 2000 as today.

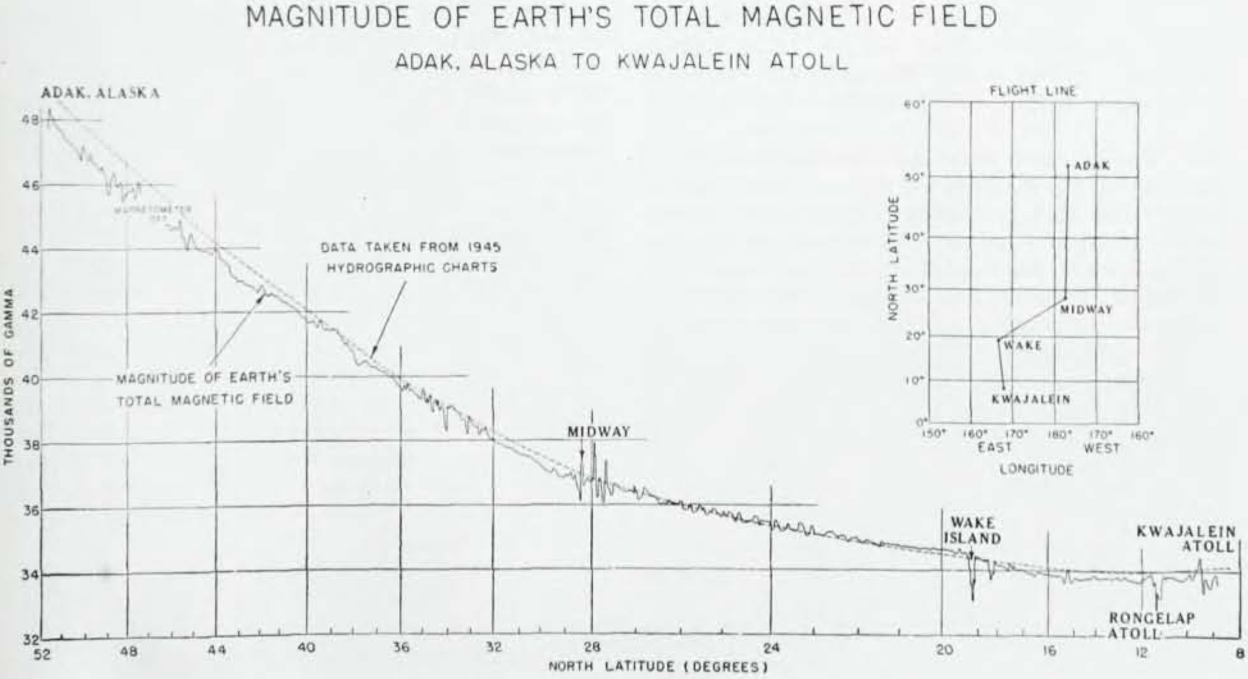
Unfortunately this is not the case. The sparse data which are available near the magnetic poles, where the horizontal component of field is small, indicate that the places where the horizontal component of field is zero, known as the magnetic dip poles, shift slowly in time. This means that in the polar regions large annual changes in declination will occur. It would be quite possible for a compass to reverse its direction during one year at a point near a magnetic dip pole. In some locations quite far removed from the magnetic poles, where more detailed and accurate data are available, the direction in which the compass points changes as much as one quarter of a degree per year. Offhand this may appear to be a rather small rate of change, but it requires that surveys be made regularly in order to maintain the required accuracy of the magnetic navigation charts. These long-period changes are called secular changes.

In addition to the slow change with time there are much faster changes which add to the difficulty of making a coherent survey, but which do not result in permanent changes tending to make magnetic charts obsolete. There are more or less regular variations associated with the positions of the sun and moon. There are also irregular variations which occur during magnetic storms. Except for very severe storms, these relatively short period variations have amplitudes which are too small to disturb a navigator using a magnetic compass, but they are large enough to cause difficulty to the geomagnetician gathering data for the construction of magnetic secular change charts.

The irregular variations which occur during magnetic storms may continue for several days. These variations contain energy distributed over a broad frequency range, with the amplitude decreasing at the higher frequencies. Most measurements of this type have failed to record variations which occur faster than one cycle per second. Below this frequency limit the amplitude of disturbances increases with latitude, indicating a dependence upon ionospheric and auroral activity. As an example of magnetic activity of this type, a pulse having a duration of 1 second and an amplitude of 0.1 gamma (1 gamma $= 10^{-5}$ oersteds) occasionally appears superimposed upon the ambient vertical component of approximately 44,000 gamma at Tucson, Arizona.

If sufficiently sensitive detectors are used, it is found that magnetic field variations occur throughout the audio range and up through the radio frequency spectrum. These have been studied extensively as unwanted radio disturbances above 10,000 cycles per second. Very little is known about the natural magnetic field variations in the range from 1 to 10,000 cycles per second. There are several research teams engaged in exploring this region at the present time, so conditions may soon be clarified. It appears that most of the energy in all but the lowest part of this frequency band originates in atmospheric storm centers. Since these centers are concentrated in the equatorial areas, it is expected that

Fig. 2



intensities will fall off rapidly with increased latitude.

It seems certain that the major causes of variations in the magnetic field other than the long period secular changes are external to the earth's crust, whereas the sources of the main part of the earth's field and the causes of the secular changes are deeply rooted within the earth.

In searching for the origin of the main part of the earth's field, much can be learned from the experimental approach of carefully charting the field components over the surface of the earth and studying the secular changes of these components. Magnetic charts of this type showing the declination of the compass are of most interest to navigators. A knowledge of the secular change pattern will permit the extrapolation of present day charts for use in subsequent years. When gathering data to be used in constructing magnetic charts, the short period field variations must be understood so their effects can be eliminated from the resulting charts. The short period fluctuations play only a nuisance role in chart making.

The utility of magnetic declination maps in the science of navigation is obvious, but the practical value of the other elements of the earth's magnetic field (such as its vertical and horizontal components) is not so evident. For a long time, these components were only of academic interest. Later, component measurements were used in geophysical prospecting in the search for magnetic ores or possible oil-bearing substructures. More recently, with the advent of airborne total field magnetometers, total field intensity maps have been used in airborne geophysical surveys. It is conceivable that in the future several of the magnetic field components will be used in routine navigation procedures.

When the amplitudes of any of the magnetic elements are plotted for measurements made on the surface of the earth or at a low altitude, many localized irregularities appear which may be much larger than the time variations mentioned earlier. The amplitude and extent of such space perturbations (anomalies) depend on the magnetic characteristics of the surrounding geology. The degree to which these anomalies are preserved in chart making depends upon the scale and desired use of the resulting chart. In most geophysical surveys where detailed geology is of interest the anomalies are the important parts of the resulting map. Data taken for a small scale navigation chart are purposely smoothed, leaving in only broad regional effects. Fig. 2 shows an example of the degree of smoothing which may occur in compiling world-wide charts. The dotted line was taken from a recent magnetic chart. The solid line is the actual field which was measured during a flight from Adak, Alaska, to Kwajalein using an airborne magnetometer. This flight was made at an average altitude of 1000 feet and the ocean depths ranged from 2000 to 3000 fathoms. The many anomalies which appear would be reduced in amplitude if the flight had been made at a higher altitude. The general divergence between the dotted and solid curves in the vicinity of Adak indicates a need for new data to improve the charts.

Existing Instruments

Most of the instruments that have been used to measure the relatively higher frequency time variations are of the induction coil type. Such instruments indicate the rate of change of field and their response must be integrated if the field is desired. Various filter and recording circuits are used and no knowledge of the absolute value of the field can be obtained. They are straightforward and are based on well known principles and will not be discussed further here. The instruments used to obtain suitable data for chart making are of more interest and are therefore discussed in more detail.

Nearly all magnetic field measurements before World War II were made using either rotating coils or the deflection and oscillations of small magnets. Many of these instruments are still best for certain types of field measurements.

All magnetic components can be measured very accurately on land with these instruments, and many of them have been adapted for less accurate work at sea in nonmagnetic ships. Ordinary floating and gimbaled compass needles are, of course, in this class and are used in aircraft as well as at sea for very rough measurements. Component-measuring instruments of this type have not been adapted very successfully for use in aircraft, although a few insensitive surveys have been made with their help.

During World War II a new type of magnetometer was developed. The sensitive mechanism in this magnetometer is a thin core of high-permeability material which is driven to saturation by an applied alternating magnetic field. Harmonics of the applied field are developed which are proportional to the magnetic field to be measured along the core axis.

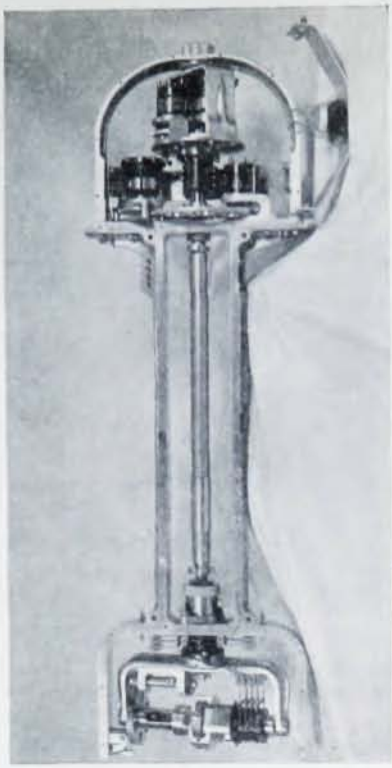
Three of these detecting elements are mounted mutually perpendicular. Two of them (called orienting inductors) control servo motors so that the third one is always maintained with its axis parallel to the direction of the earth's field. Since the magnetometer is stabilized by the earth's magnetic field itself, it is practically independent of the motion of the vehicle carrying it and is readily usable in aircraft. This type of magnetometer has become known as the magnetic airborne detector and is commonly called the MAD. Several different instruments which use this self-orienting saturable reactor principle have been developed by government and private groups.

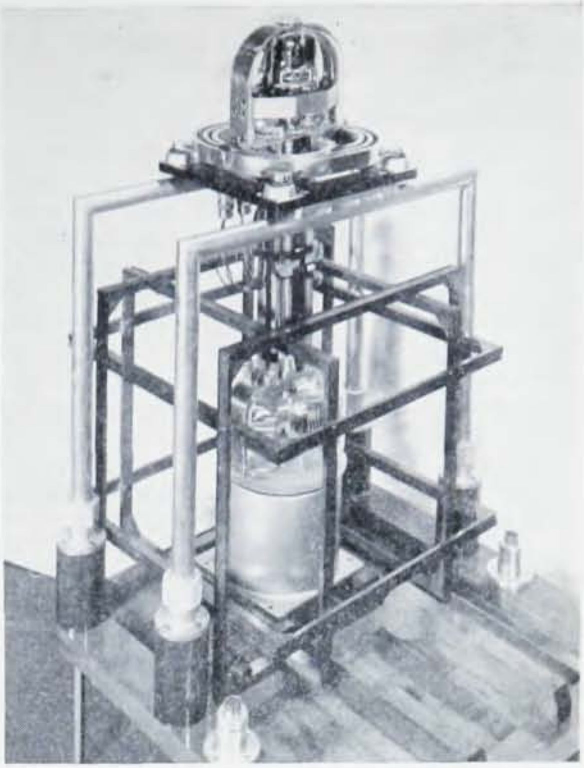
During the war the MAD was used to locate submarines by detecting their magnetic fields. Near the close of hostilities the MAD took its place as an important geophysical survey instrument. Since the war, private industry and government agencies have flown millions of miles to obtain total field intensity contour maps of areas which were of interest because of oil or mineral possibilities.

The advent of these successful airborne magnetometers brought clearly into focus the desirability of making world-wide magnetic surveys from the air rather than in slow-moving surface craft. This need was fur-

Fig. 3. Universal magnetometer orienting detector mechanism

Fig. 4. Orienting detector mechanism pendulously suspended





ther emphasized by the fact that long-range planes could quickly cover large ocean areas which had never been covered before or at best were last surveyed before 1929 when the last nonmagnetic ship "Carnegie" was destroyed by explosion in Samoa.

The MAD measured only the magnitude of the earth's total field. This single bit of information about the earth's field is valuable and has been used extensively for geophysical prospecting. It is not, however, adequate for making world magnetic charts. The way in which the data are taken does not permit the calculation of inclination, declination, or any of the component magnetic intensities.

Improved Instruments

Recently a new instrument has been completed which will permit the continuous recording during flight of all the data required for complete magnetic mapping. Basically an orienting saturable reactor magnetometer like the MAD instruments, it is built in such a way that the orientation angles of the detector coil, when it is slaved to point along the field vector, can be recorded automatically. In this way the entire field vector, amplitude and direction, is determined so that all of the desired components can be computed. This instrument is called a universal airborne magnetometer.

Fig. 3 is a photograph of the orienting detector mechanism. The three mutually perpendicular saturable reactor units are contained in the roughly cylindrically shaped part at the very bottom of the picture. This cylindrical part is gimbally mounted so that it can be rotated about its own axis and about a second axis parallel to the center line of the entire mechanism. Servo motors located at the top portion of the mechanism are connected through reduction gearing to concentric shafts on the center line of the mechanism to turn the cylinder about these gimbal axes. The servo motors are controlled by the outputs of the two orienting inductors in the cylindrical part to orient the third inductor parallel with the earth's field. Synchro transmitters located adjacent to the servo motors are geared to the gimbal axes to permit measuring the instantaneous direction of the earth's field with respect to the mechanism.

The entire orienting detector mechanism is pendulously suspended, as shown in Fig. 4, to provide its own vertical reference. The pendulum is damped by means of a baffle immersed in a viscous silicone oil. Orientation of the mechanism with respect to geographic meridians is determined by means of astral observations. The three-dimensional Helmholtz coil system which is centered on the saturable inductor elements is used to compensate for permanent magnetism in the aircraft. The position of the aircraft over the surface of the earth is determined by various combinations of dead reckoning, celestial observations, Radar, Loran, Shoran, visual observation, and terrestrial photography.

The instrument just described is now being flight tested and there are already assurances that the resulting airborne measurements will attain approximately the same accuracy obtainable by the older point-by-point methods used in nonmagnetic ships. Components should be accurate to within 100 gamma except in the general vicinity of the earth's magnetic poles.

In order to make magnetic measurements from ships, the initial expenditure for equipment is large. Special nonmagnetic ships, such as the "Carnegie" and the "Research", which has been constructed in England but is not yet fitted out, must be built. Fortunately, modern airplanes are constructed principally of aluminum, which is nonmagnetic, although there are many parts of an airplane such as motors and steel torque tubes which can cause difficulty with magnetic measurements. Many modern military planes with their armor and dc-operated motors with ground return are unfit to carry a sensitive magnetometer. Some aircraft can, however, without great difficulty, be modified into suitable vehicles for magnetic work. In a few cases it has been possible to install the magnetometer detector in a plywood extension of the tail-cone section of the aircraft or on a wing-tip. An early MAD tail cone installation is shown in Fig. 5. The new instrument is, however, much larger than the wartime MAD and because of its pendulum mounting has required a carefully compensated inboard installation. The new instrument has recently been installed in a Navy P2V air craft in which it is now being tested. An earlier model was installed in a B-29 aircraft and has been used successfully for nearly 3 years.

Comparison of Survey Methods

A nonmagnetic ship using conventional magnetic instruments normally obtains data at stations separated by 200 or 300 miles. The "Carnegie" occupied 6000 declination stations during seventeen years of service. Because of the secular changes occurring during this period the problem of reducing all of the data to a common time base was an extremely burdensome task. Several cooperating airplanes could complete a world-wide survey rapidly enough to avoid this time-consuming problem. The airborne techniques which are being developed will give continuous data along a flight line. Furthermore, airborne measurements can be made over any part of the earth and at various altitudes.

Because of the differences in the type of data obtained by nonmagnetic ships and by proposed airborne techniques, it is impossible to make an accurate comparison of costs for the two methods.

Taking into account the difference in the speeds of the ship and plane and the time required for maintenance and bad weather delays, assuming that each is equipped with the same instruments, it is estimated that from ten to fifteen ships would be required to obtain as much data as a single plane. Cost estimates for the two methods would also greatly favor the airborne measurements.

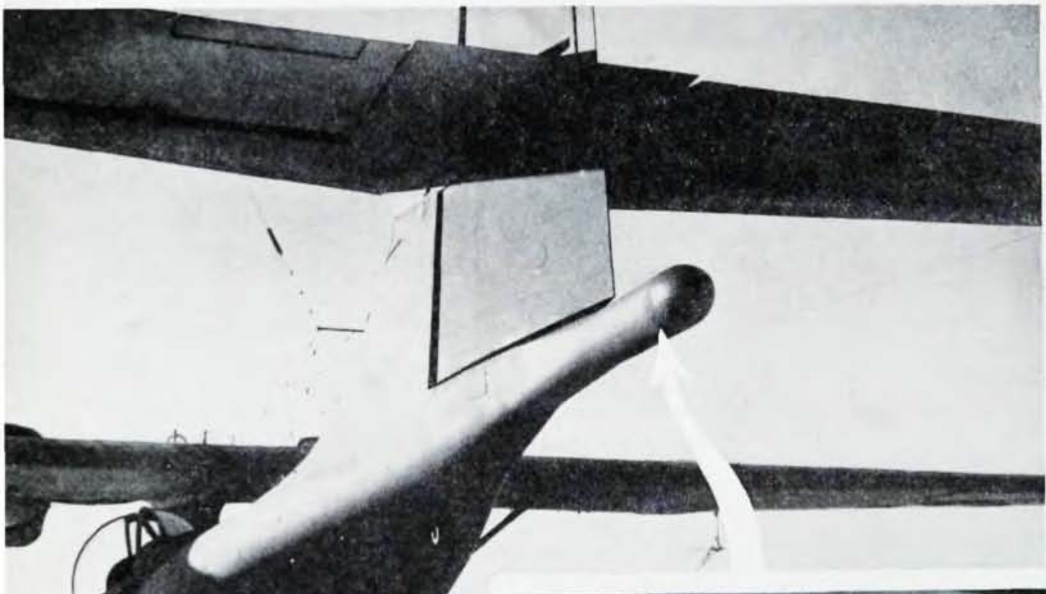


Fig. 5. PBY with tail cone housing for magnetometer (*all figures courtesy Naval Ordnance Laboratory*)