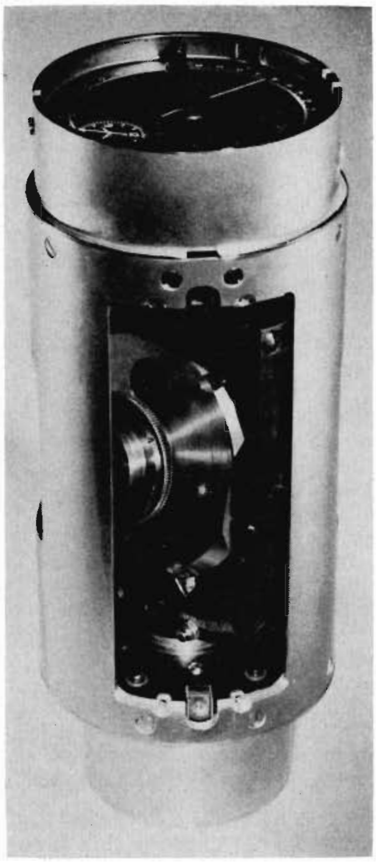

GYRO-COMPASS SURVEYS UNDERGROUND WORKINGS AND BOREHOLES

by EUGENE P. PFLEIDER and OTTO RELLENSMANN

For many years mine surveyors and exploration engineers have sought an accurate means of transferring meridian underground by using the gyro-compass. These efforts have generally failed, either because they were inaccurate or because the size and cost of the unit were prohibitive. During the past ten years, however, great strides have been made. Autonetics in California has developed a comparatively light-weight (100-lb) gyro-theodolite, and the Institute for Mine Surveying at Clausthal Mining Academy in Germany has developed an instrument that is accurate to within 20″ to 30″ of arc. Concurrently, Minneapolis-Honeywell has produced an astounding gyro, the size of a salt shaker, that weighs less than 0.5 lb and compares favorably in performance with the 50-lb gyros of conventional design. This unit, designed for missile guidance, should be adaptable for surveying small boreholes. Given the proper interest and approach from the engineering fraternity, excellent gyro-compasses could probably be available for accurate underground survey work at nominal cost within the next three years.

Principles of the Gyro-Compass: The gyro-compass, used for 50 years as a navigational instrument in ships and aircraft, senses the turning axis of the earth and points out true polar north. It does this by employing the earth's rotation, the force of gravity, and the precession characteristics of a gyro. For further details the reader is referred to several excellent publications[1-3] covering the principles and application of the gyroscope.

The heart of the gyro-compass is the gyroscope, or rapidly spinning wheel, which rigidly maintains its angular orientation in inertial space. Free gyros employ universal joints to allow the wheel axle to maintain its rigid spatial orientation independent of base motion disturbances. Free gyros are independent of the earth's turning and are not north-seeking. Only as they might be initially oriented parallel to the earth's turning axis could any north indication be obtained. In practice, the free gyro tends to drift off its set position and lose its accuracy.

The Sperry-Sun Well Surveying Co. instrument (5½ in. O. D.) is of this free gyro type. It is counterbalanced, however, against the rotational effects of the earth, so that orientation of the spinning axis will be maintained throughout the survey.

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Now, if a force is applied to one end of the spinning axis A-A′ in a direction parallel to C-C′, the primary response is the turning of the wheel assembly about axis C-C′. This effect, called *gyro-precession,* is explained by the mechanics of conservation of angular momentum. Conversely, turning

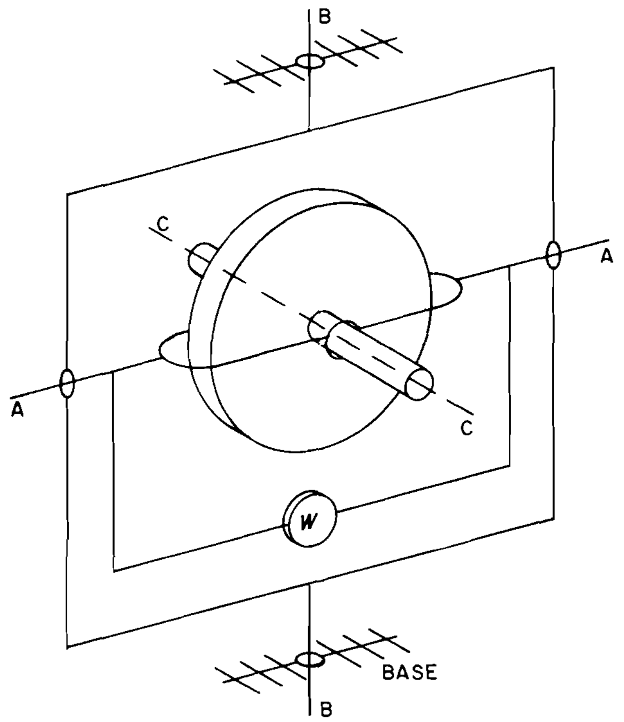

Fig. 1—The three-frame gyroscope with pendulous unbalance added to make it north-seeking. (After Lower).

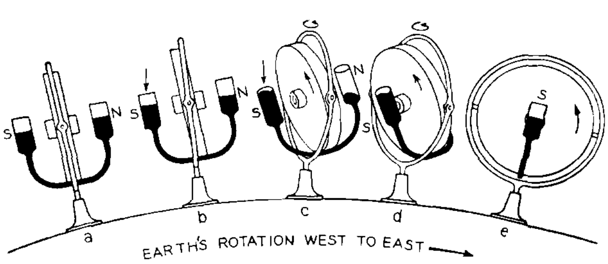

Fig. 2—Gyro-compass, mercury in U-tube. (Lower)

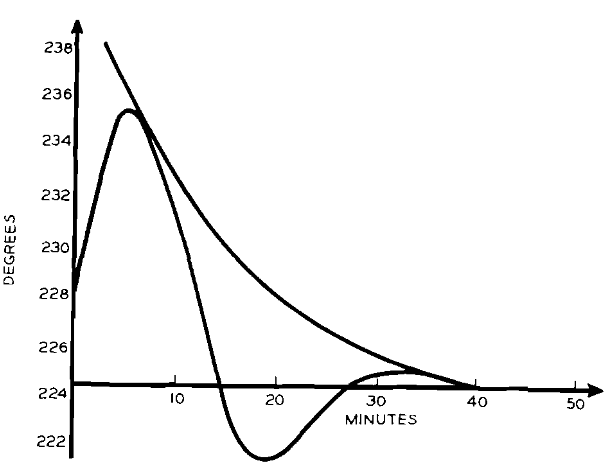

Fig. 3—The dampened swing cycle of the gyro-theodolite is shown on the above graph. (After Ludemann).

rates around vertical axis C-C′ develop a proportional torque and angular deflection around axis B-B′. These angular deflections may be converted into electrical signals by a pick-off device, or a torquer or precession motor can be used to generate control torques on axis C-C′. The Honeywell gyro-compass, described later, employs this technique.

The mechanization of the conventional north-seeking gyro-compass departs from the free gyro concept and couples the earth-turning rate into the gyro. These earth rates precess the gyro and align its axle in a north-south direction. Lower[4] describes the gyro mechanization that will find north. He says, with reference to Fig. 1:

> Assuming the gyro axle to be at a random position off of north as it is started, the gyro rigidity in space will necessitate a tilting about axis A-A as the earth turns. But pendulous weight W tends to maintain the gyro axle in a horizontal orientation. This effect couples a spatial turning rate into the A-A axis and results in a precession of the assembly about axis B-B, in keeping with the basic principles of the gyro. This process will continue until the gyro axle is pointed north; at this unique orientation the earth's turning no longer results in tilting the gyro axle against the restoring pendulum. Fig. 2 serves to illustrate this process of a gyro-compass action using mercury in a U-tube as the pendulum.

The Clausthal gyro-theodolite employs this principle, using lead ballast as the pendulum.

Basic Factors: The accuracy and oscillatory characteristics of a gyro-compass in its seeking and holding of true north depend on several important factors:

1) The extremely low frictional restraint in all movements.

2) The magnitude of the meridian direction moment, R (or the torque developed around the vertical axis in its seeking of north direction).

This is dependent on the angular momentum of the gyro wheel, the earth's turning rate, and the latitude, as expressed by Eqs. 1-3:

$$K = I \omega \Omega \qquad [1]$$

$$R = \frac{K \cos \phi}{g} \cdot \sin \propto \qquad [2]$$

$$R = \frac{I \omega \Omega \cos \phi}{g} \cdot \sin \propto \qquad [3]$$

Where K = full directional torque developed by gyro at equator, dyne-cm.

R = meridian direction moment at latitude ϕ, gr-cm.

I = moment of inertia of gyro, gm-cm^2.

ω = angular velocity of gyro, radians per sec.

$I \omega$ = angular momentum of gyro, gm-cm^2 per sec.

Ω = angular rate of precession of gyro (or rate of turn) around horizontal axis, due to earth's revolving, radians per sec.

$$\frac{2 \pi}{23.93 \times 60 \times 60} = 0.0000728 \text{ radians per sec.}$$

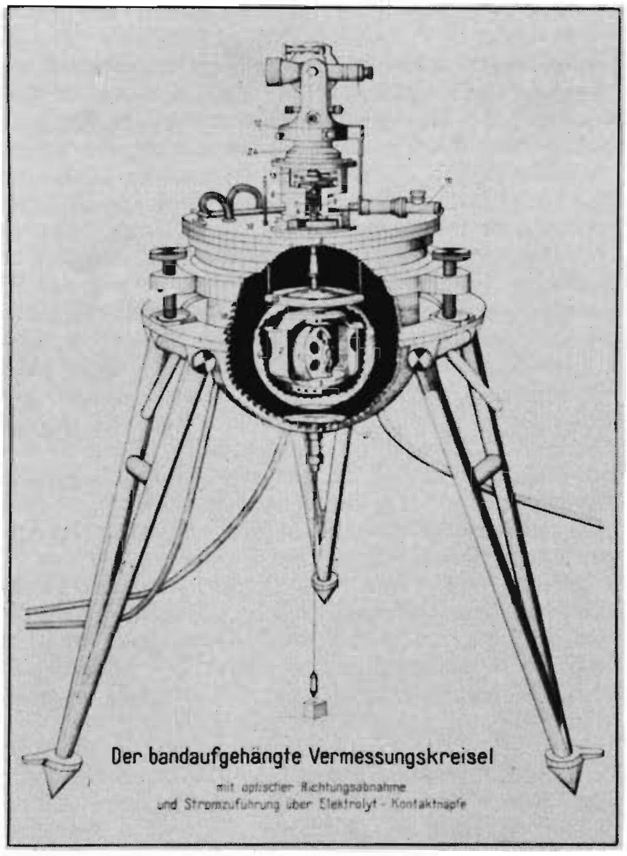

Fig. 4a—Insert shows the suspension of the gyro in earlier model of theodolite developed at Clausthal.

ϕ = latitude of observation, wherein only one half the available torque developed by the gyro would be applied at a latitude of 60° (cos 60° = 0.5).

g = acceleration of gravity, cm per sec^2, dependent on elevation and latitude. Equal to 980 cm per sec^2 at sea level and equator.

α = amplitude of precession from north, degrees.

3) The natural period of the compass, T, i.e., the time it takes to perform a complete oscillation of the gyro-compass about the meridian, as shown in Fig. 3.

This is dependent on the magnitude of the full directional torque, K, the weight of the pendulum, the latitude, and the metacentric height, as expressed by Eq. 4:

$$T = 2\pi \sqrt{\frac{K}{mga\ \Omega \cos \phi}} \qquad [4]$$

T = natural period of gyro-compass, sec

m = mass of pendulum, grams

a = metacentric height equal to distance between point of suspension and center of gravity, cm.

4) The proper damping of the oscillatory swings of the gyro-compass.

Various techniques are used to dampen the oscillatory swings on each side of the meridian. The Clausthal-designed instrument can achieve high accuracy after about 30 min warm-up and 9 reversals of 13.5 min each (for half pendulum time), or a total of 2.5 hr at latitude of Clausthal. Fig. 3 illustrates the damping characteristics of a compass having a 66 pct damping factor, i.e., from 30° to 10° to 3 1/3° to 1 1/9° for the first four half-oscillations.

5) The maintenance of a constant rotational speed of gyro and a constant temperature of the liquid in which the gyro sphere is floated.

These points are highlighted in Table I, a comparison of the basic design factors of the Clausthal precision gyro-theodolite, used for accurate surveying underground, and the Miniature Integrating Gyro of Honeywell, considered for borehole surveying.

CLAUSTHAL GYRO-THEODOLITE

The accurate meridian-indicator,[5-7] manufactured by the instrument firm of Otto Fennel-Söhne of Kassel in West Germany, was developed for underground surveying by Otto Rellensmann and his associates at Clausthal Mining Academy. A heavy version of the instrument is illustrated in Fig. 4a and a new smaller version in Fig. 4b. The latter weighs 76 lb: instrument, 28 lb; tripod, 16 lb; transistorized generator, 12 lb; and batteries, 10 lb.

Construction: Design of the instrument utilizes the gyro mounted in a sphere by a bracket. A mast passing through the sphere is attached to the bracket and has a mirror at its upper end. The motion of the mirror, which represents the horizontal pre-

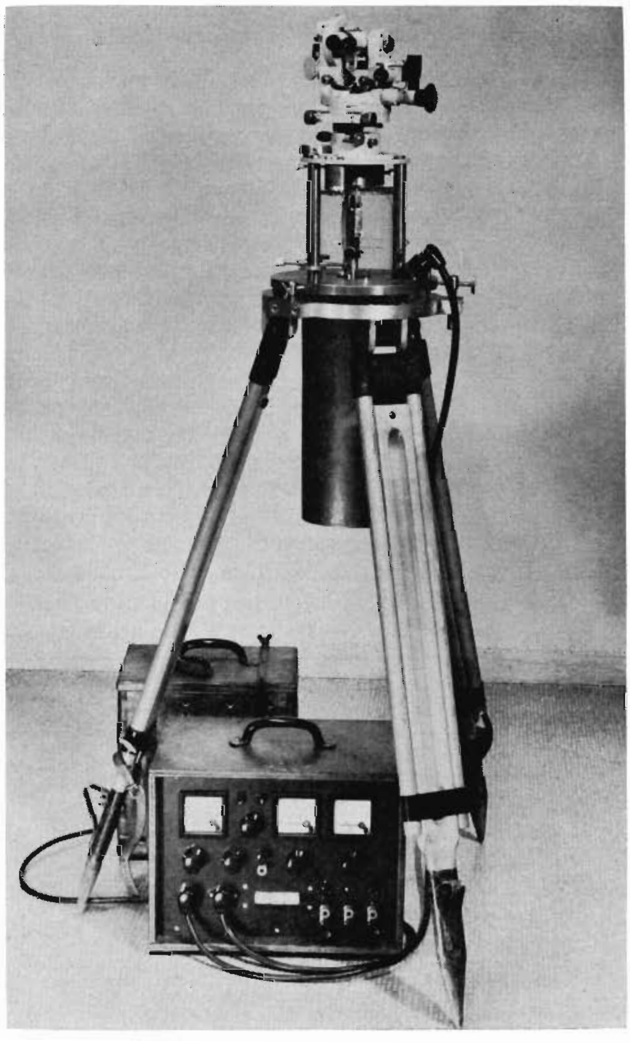

Fig. 4b—The Clausthal Academy KT-1 gyro-theodolite.

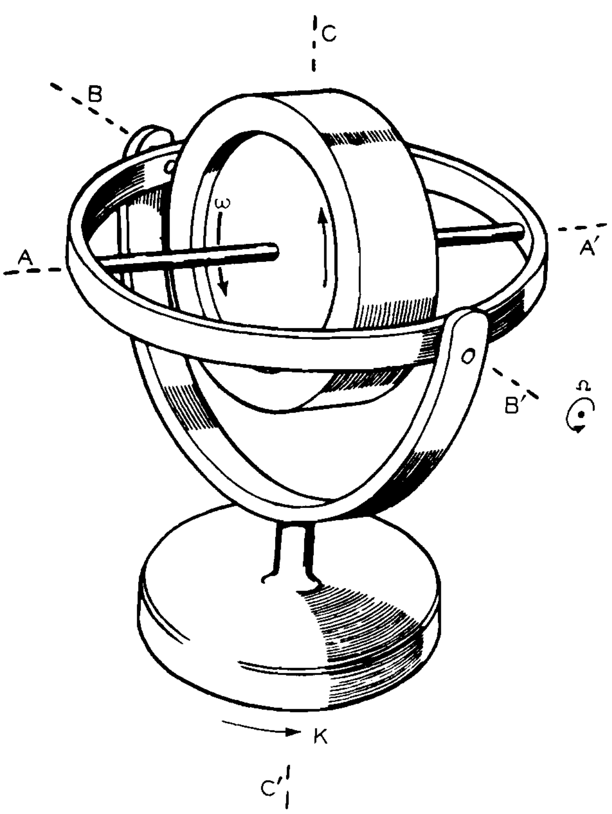

Fig. 5—A two-frame "rate" gyroscope showing relation between angular rate of precession, Ω, and resulting torque, K_p, as applied to gyro-compass. (Richardson).

cession of the gyro, is followed with an auto-collimation telescope attached rigidly to the alidade axis of the theodolite. The gyrosphere is hung by a metal band fastened to the end of the extended alidade axis. To reduce weight on the band to only 200 g, the gyrosphere floats in a water-filled gyro-container, a construction permitting the use of a fine metal band that has minimum torsional resistance to gyro swings. A sphere of Mu-metal on the inside of the container guards the gyro from influences of magnetic fields. The gyro wheel forms the rotor of a three-phase, 333-cycle asynchronous induction motor revolving at 20,000 rpm. Depending on availability or mine safety regulations, the generator providing the driving current may be powered by a 24-v, d-c battery-driven motor; a 220-v, a-c motor; or a compressed-air turbine unit. The instrument is transported in a special spring-mounted frame, with the gyrosphere clamped by two rings.

Table I. Fundamental Properties of the Clausthal Gyro-Theodolite and the Honeywell Miniature Gyro

		Gyro-Theodolite	Miniature Gyro
I =	Moment of inertia, gm-cm²	4.3×10^4	40
ω =	Angular velocity of gyro, rpm	20×10^3	24×10^3
	Angular velocity of gyro, rad./sec	2.1×10^3	2.5×10^3
$I\omega$ =	Angular momentum of gyro, gm per cm²/sec	9×10^7	10^5
K =	Torque, dyne-cm	6.5×10^3	7.5
R =	Meridian direction moment, gm per cm		
	at Clausthal, Germany—latitude 51° 19'	4.9	4.66×10^{-3}
	at Kiruna, Sweden—latitude 67° 42'	2.97	2.82×10^{-3}
T =	Natural period of gyro-compass, minutes		
	at Clausthal	27	
	at Kiruna	34.6	
W =	Weight of gyro assembly, lb	50±	0.5
D =	Diameter of gyro, in.	5.3	
	Diameter of gyro assembly, in.		1.75

Operation: After the instrument is centered and leveled, the swinging of the gyro is followed continuously by observing the mirror through the auto-collimation telescope. At the same time, the torsion moment of the band is compensated by regulating the zero position. In this manner only the direction moment of the gyro is effective. At least three reversing points and probably more, depending on the accuracy desired, are read in order to calculate the north direction. The angle between the calculated north direction and the measured line is corrected by a constant of the instrument, which is determined by checking with the bearing of an accurate base line. If the base line is part of a geodetic system, the convergence of the meridians must be worked out and incorporated into the calculations. Generally, the constant of the instrument is checked by base line measurements both before and after an important series of observations.

Many checks have been made between well established base lines surveyed by astronomic methods and by the gyro-theodolite. The average error of an individual measurement is about 20″ of arc. An order of accuracy of 30″ can be assumed for most work.

Two gyro-theodolites in constant use in the Ruhr coal district are operated under the direction of the Gyro-Measuring Station of the Bochum Mining School at Bochum, Germany. Extensive measurements have also been made at the Kiruna iron mines and the Boliden base metal properties in northern Sweden with good results. Otto Fennel-Söhne manufactures the instruments now in use, copying the prototype developed at Clausthal.

Application: Since the gyro-theodolite measures angles from astronomic north, it is particularly useful for orienting underground surveys. Operating independently of other methods, it provides a check on previous surveys.

Accuracy of a conventional traverse decreases with the length and number of angles measured. The gyro-theodolite can be used to check the direction of any line in the traverse. Even in the case where the underground survey is connected with the surface traverse through two shafts, accuracy depends on distance between the shafts, length of traverse, and number of angles. The methods currently employed for transfer of directions from surface to underground depend on many local conditions, such as condition of shaft, depth, air currents, dripping water, magnetic influences, and hoisting operations. Many of these difficulties can be eliminated by suitable application of the meridian-indicator. Other uses for this instrument include surveys for geographers, cartographers, and geologists and inertial guidance for control of automatic mining machines.

AUTONETICS GYRO-THEODOLITE

A counterpart to the German theodolite has been produced by Autonetics, a division of North American Aviation, under the name of ABLE (Fig. 6). Weighing less than 100 lb, it is powered by either 115 v, single or three-phase current, at 60 or 400 cycles a-c, or by 28 v, d-c, at 125 w. Alignment time is 15 min at 30° latitude and 30 min at 60° to 70° latitude.

The ABLE system[8] consists of a high-quality rate-measuring gyro coupled with an electromechanical arrangement for providing a signal proportional to the space rate of rotation of the gyro about its *input* axis. As the gyro tends to precess, a pick-off device senses a minute displacement and produces an electrical restraint or torque that prevents rotation and also indicates the magnitude of the required restraint. Internal bias torques are compensated for by the technique of completely reversing rotor rotation. Hence the resultant torque supplied by the electrical restraint is the only torque acting. This torque, shown by the indicator, is proportional to the input axis misalignment with respect to east-west.

In operation, the gyro is aligned by increments until the component of the earth rate lying along the gyro input axis is zero. At this point no restraint is required, the indicator shows null, and the north-south baseline is established.

All circuits for operation are transistorized, and plug-in cards provide for easy replacement of individual units. Provisions for rapid circuit checks are included so that marginal operation or malfunction is easily detected. The gyro and mirror assembly, or any of the plug-in cards, can be replaced in the field in a matter of minutes.

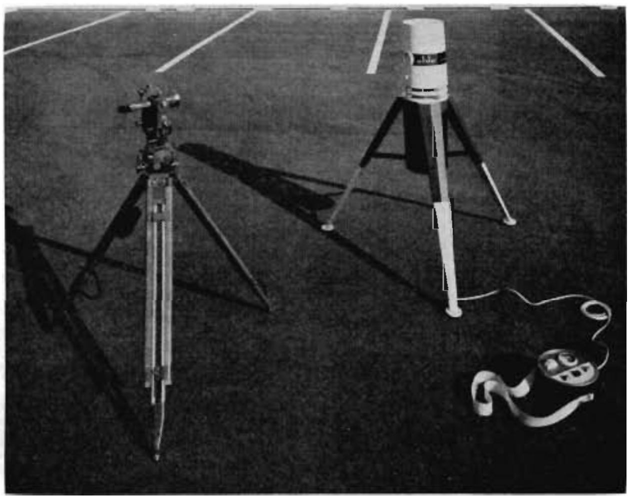

Fig. 6—The ABLE gyro-compass base line equipment.

SURWEL GYRO-COMPASS FOR BOREHOLES

Boreholes having casings of 6⅝ in. O.D. or larger have been surveyed successfully for the past 25 years in both the mining and petroleum industries, using the Surwel well-surveying instrument equipped with a Sperry gyro. The instrument employs the free gyroscope," a plump bob type of angle unit, and a 16-mm camera. The protective casing is 5½ in. O.D. The free gyro is counterbalanced against the rotational effects of the earth, so that orientation of the spinning axis will be maintained throughout the course of the survey.

A gyroscopic direction indicator is attached to the top of the gyro's vertical axis, and a cross-hair plumb bob type of angle unit is mounted directly above the gyro to show the inclination of the hole. Directly under the gyro direction indicator is a tracer watch, which is synchronized with a surface watch. These three essential factors of direction, inclination, and time are superimposed on a background of concentric circles and recorded intermittently, at predetermined time intervals, on 16-mm continuous strip film. By using a time-depth log, the photographic reproduction of the time shown on the tracer watch indicates the depth at which each individual exposure is made. A group of photographic recordings is illustrated in Fig. 7.

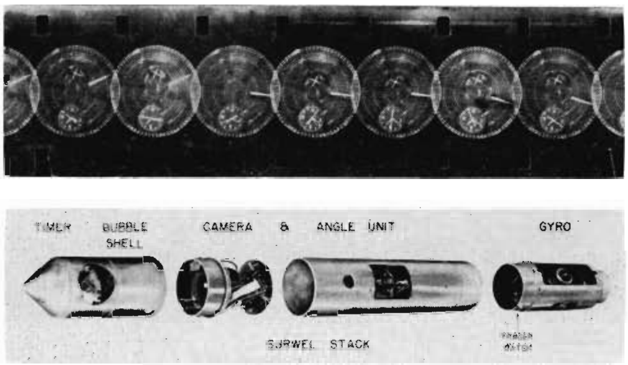

Fig. 7—Camera records of drillhole survey by Surwel. The Surwel multishot instrument is illustrated below.

Since orientation of the gyroscopic direction indicator is determined at the beginning of the survey, and is maintained throughout, the subtented angle between the direction indicator and a line drawn from the center of the inclination circles through the cross hairs gives the true bearing of the hole direction. The Surwel instrument is lowered on a wire line, and stop times of only half a minute are required for each record. Film capacity is sufficient to survey the deepest wells, both in lowering and with a check set of readings upon pulling out of the hole.

As to accuracy, the bottom hole coordinates of two gyroscopic surveys (one made going into the hole and the other coming out) generally will not vary more than 0.1 to 0.2 pct of the depth for the holes inclined less than 10° to 15° from the vertical. Comparable closures for holes of flatter inclination are likely to be greater.

HONEYWELL MINIATURE GYRO-COMPASS

Conventional gyro-compasses employ large gyro wheels, spinning at rapid rates, to obtain the gyro forces and torques required for performance accuracy. Relatively low frictional restraints are obtained by floating the gyro ball and using a system of small torsion wires. The result is an instrument weighing 50 lb or more, one far too large to fit into a small diamond drill hole. Further, the free gyro type of well-surveying equipment,

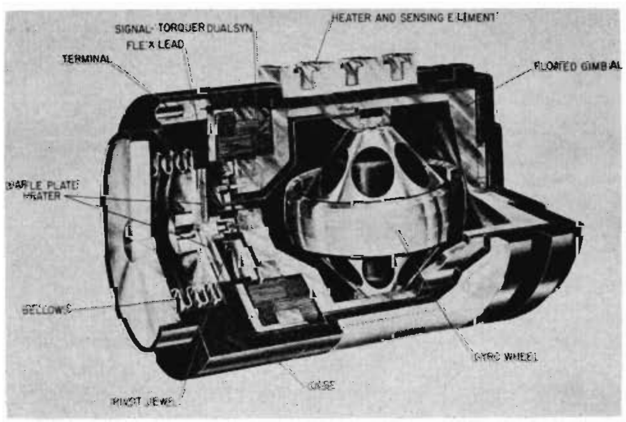

Fig. 8—Honeywell miniature integrating gyro. (Lower).

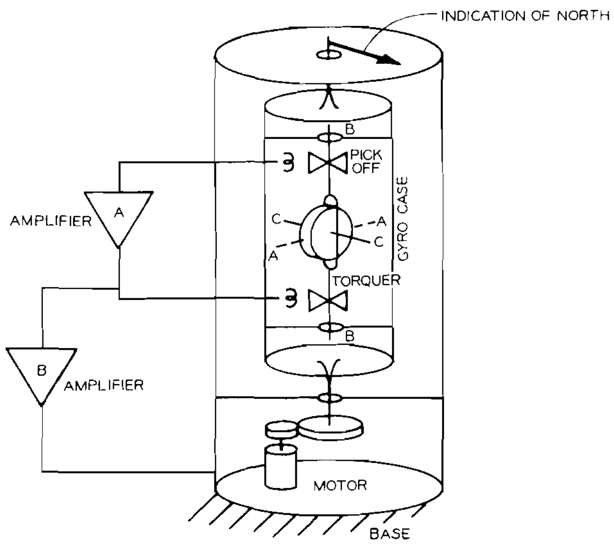

Fig. 9—North-finding method using Honeywell gyro.

such as the Surwel, is too large for use in small boreholes of 2 to 3 in. diam.

A new Honeywell miniature gyro with associated electro-mechanical equipment finds north by a technique somewhat different from that used in the conventional gyro-compass. As a consequence, it has promise of size reduction to 3 in. diam or less and may be a candidate for diamond drill hole exploration. The instrument, as described in detail by Lower,[4] is shown in Fig. 8. Although it is only 1.75 in. diam and 0.5 lb in weight, its sensitivity permits finding north to a fraction of a degree in most latitudes. This gyro sensitivity results from the greatly reduced frictional restraints realized by floating the gyro's moving element in a special heavy viscous fluid called Fluorolube. The gyro wheel (Fig. 8) spins in an inert gas within the floated gimbal, which is positioned by watchmaker-type pivots and jewels. Friction levels of about 0.01 dyne-cm are achieved. Since the gyro wheel momentum is 10^5 gm-cm^2 per sec, about 7.5 dyne-cm torque is developed for the earth's turning rates of 15° per hr. Hence high gyro-compass sensitivity has been made practical in a very small package. Furthermore, the distributed support afforded by the fluid makes for a very rugged instrument, capable of taking shocks and field use.

Fig. 9 illustrates the method of finding north. Any component of the earth's rate coupled into axis A-A will develop a torque about B-B and start to displace axis B-B relative to the gyro case. Such displacement causes the pick-off to generate a signal that is amplified by amplifier A to drive the torquer. Electrical input to the torquer is a measure of the earth's turning rate into axis A-A; when such rates are zero, axis A-A must have a unique east-west orientation. A second amplifier, B, would actuate a motor and gear train to turn the gyro case, thereby automatically making this rate settle out to zero. At this condition, the gyro case will be indicating polar north.

To log the direction and inclination of the drillhole, it will be necessary to correlate data from a pendulum or plumb-bob device to the gyro-compass data. Various solutions to this general problem are now in use, such as punching a disk by a plumb-bob tip. Possibly newer methods may be required to complement the miniature gyro-compass approach.

Accuracies to be expected from this new approach can only be surmised. As with the Surwel unit, it seems clear that the closures of surveys would be inversely proportional to departure of the hole from the vertical.

Summary: The gyro-compass is being perfected in accuracy, as well as miniaturized, to a point where mining and civil engineers should consider its application for certain phases of underground surveying. The gyro-theodolite, as developed at Clausthal Academy and now available both in Germany and the U. S., can determine or check bearings of lines to approximately 30″ of true direction when related to polar north. This is generally better than the accuracies obtained when bearings are taken underground by conventional wire methods through single shafts. Unfortunately the cost of the instrument is high, and only major companies operating several groups of underground mines could justify the purchase. In order that the smaller operator may have access to such a method for checking important surveys, it is suggested that the U. S. Bureau of Mines, or some mining supply or service company, have several gyro-theodolites available throughout the U. S. on a rental basis.

Relative to gyro well-surveying equipment, the Sperry-Sun Surwel unit has been doing a commendable job for years in both the oil and mining industries. However, the drillhole must have a casing size of 6⅝ in. O. D. or greater. This excludes the unit in surveys of diamond drill holes as used in mining, for which the NX hole at about 3 in. O.D. is the largest size employed. The magnetic compass is satisfactory for determining the direction of inclination if the hole is not cased or if rocks are non-magnetic. Where this condition does not obtain, there is no satisfactory method of determining bottom coordinates, and there has been much interest in developing a gyro-compass package of 2 to 3 in. diam. The new Honeywell miniaturized gyro offers hope that a practical gyro-compass for small boreholes will be available.

Full development and use of these new surveying methods, employing the gyro-compass principle, are directly dependent on the interest of the world's mining and exploration drilling industries.

The authors thank Sperry-Sun Well Surveying Co., Autonetics, and particularly J. W. Lower, gyro section chief of Minneapolis-Honeywell, for their valuable contributions and permission to publish data on their respective instruments.

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