PUBLICATIONS of the EARTH PHYSICS BRANCH

VOLUME 41 – NO. 1

bibliography of fluxgate magnetometers

F. PRIMDAHL

DEPARTMENT OF ENERGY, MINES AND RESOURCES

OTTAWA, CANADA 1970

bibliography of fluxgate magnetometers

F. PRIMDAHL *

The following bibliography lists papers on fluxgate magnetometers and closely related devices, by the name of the first author in the order of the English alphabet. Most of the references include a short description of the contents under the following headings:

1) Type of sensor
2) Theoretical calculations
3) Experimental data
4) Instrument design and description.

The list is not claimed to be complete, but it is believed to cover the major developments in the field from the early 1930s to the present.

Adams, Charles Q. A simple field detector for a dc permeameter. *Rev. Sci Instr.*, 31, pp. 1119-1120, 1960.

1) Two parallel rods.
2) No.
3) Sensitivity 25 μa/moe, range 1 moe – 10 oe.
4) Design data are given for the sensor as well as a simple circuit diagram for the measuring bridge.

Adams, G.D., R.W. Dressel, and F.E. Towsley. A small milligaussmeter. *Rev. Sci. Instr.*, 21, pp. 69-70, 1950.

1) Ring-core with airgap and a single coil.
2) No.
3) Biased and unbiased hysteresis loops are shown together with the corresponding current and voltage waveforms. Calibration curve-sheet for measurements by nulling the field and by using the output voltage directly. Range 10 mgauss to 100 gauss.
4) Design data for the sensor are given and a description of the bridge using a search, and a comparison probe.

Afanas'yev, Yu. V., V.P. Lyulik, and G.D. Alekseyeva. Magnetometric equipment of the Luna-10 and Venera-4 space stations. *Kosmicheskiye Issledovaniya*, 6, pp. 772-781, 1968.

(This paper is quoted in *Foreign Science Bull.*, 5, pp. 84-88, 1969.)

1) Two parallel rods.
2) Short description of the principle.
3) Sensitivity threshold 0.3 γ. Calibration accuracy 0.4 γ. Measuring range ±50 γ. Temperature coefficient less than 0.1 per cent per °C. A graph of the zero offset drift during six days is shown. The zero offset is obtained by comparison with a D-variometer.
4) Detailed descriptions of sensor and electronics are given.

Ageyev, M.V. Approximate theory of magnetically modulated detectors. *Automation and Remote Control*, 17, pp. 827-843, 1956.

1) Two parallel rods.
2) The hysteresis loop is approximated with an average B-H curve and it is shown that the output voltage wave shape is equal to the shape of the derivative $\frac{d\mu}{dt}$, where $\mu = \frac{dB_{eff}}{dH}$ taking the demagnetization into account. B_{eff} is approximated by an arctan curve and from this the output voltage is calculated, the average rectified, and the second harmonic voltage is derived; and formulae for the optimum excitation and for the sensitivity are given. The null output voltage is explained as a "residual transformer" action.
3) From the measured B-H curve is derived $B = \frac{1}{\pi} \times 13000 \arctan 0.42H$ giving optimum sensitivity of 247 mv/oersted for 56.8 ma excitation current; the experimental values were 244 mv/oersted and 55 ma. The sensitivity may be increased by using a certain amount of positive feedback.
4) Design data on the sensor is given together with a description of the electronics.

Aleksanyan, L.M., E.G. Eroshenko, L.N. Zhuzgov, and U.V. Fastovskii. Magnetometric equipment on board the space laboratory "Elektron 2" *Kosmicheskie Issledovaniya,* 4, pp. 302-310, 1966.

*National Research Council postdoctorate fellow, on leave from the Meteorological Institute, Copenhagen, Denmark.

1) Two parallel rods.
2) No.
3) Measuring range ±120 γ for sensitive and ±1200 γ for coarse instrument. Sensitivity without feedback 0.3 – 0.6 v/γ. Measuring threshold 2-3 γ and 20-30 γ respectively. Linearity 2-3 per cent, temp. coeff. 0.2 γ/deg. and 0.7 γ/deg. BW: dc – 0.2 hz and 0.3 hz. Average error on computed total intensity ±2γ and ±20γ respectively. In flight zero corrections 4-12 γ and 35-40 γ (curve sheet). Zero drift per day 2-3 γ (curve sheet).
4) Block diagram and a detailed description of the system is given

Alldredge, L.R. Magnetometer *U.S. Patent, 2,856,581,* Oct. 14, 1958.
1) Tubular ferrite core and ferromagnetic conducting-wire core, both orthogonally gated.
2) A Fourier series describing the output voltage is obtained by assuming the magnetization curve to be a series in odd powers of h, where h is the resultant applied field.
3) No.
4) Detailed descriptions of sensor designs and means of adjustment are given together with a block diagram of a simple magnetometer.

Antranikian, H. Magnetic field direction and intensity finder. *U.S. Patent, 2,047,609,* July 14, 1936.
1) Two rods, parallel or perpendicular to each other, one rod the two halves of which are opposingly magnetized.
2) The operation is explained by assuming that the working point on the common hysteresis curve describing the magnetic state of the two cores splits up into two points when a dc bias field is applied to the sensor.
3) No.
4) Detailed descriptions of the sensors and block diagrams of the electrical circuit is given.

Armstrong, L.D. The use of high permeability materials in magnetometers. *Can. J. Phys.,* 25, *Sec. A,* pp. 124-133, 1947.
1) Two parallel rods.
2) Assuming that the flux variation in a biased transformer contains only fundamental, second harmonic, and third harmonic terms it is shown that the output from the two-core sensor consists of a second harmonic voltage proportional to the bias field. The difference in height of the actual positive and negative output peaks is explained by hysteresis.
3) Waveforms of magnetization circuit core flux, and output voltages are shown. Sensitivity level 10^{-5} gauss.
4) Short description of the sensor design.

Aschenbrenner, H., and G. Gaubau. Eine Anordnung zur Registrierung rascher magnetischer Stoerungen. *Hochfrequenztechnik und Elektroakustik,* 47, pp. 177-181, 1936.
1) Ring-core and two parallel rods.
2) Assuming a magnetization curve of the form $B = a.H - b.H^3$ and a sine wave excitation it is shown that the secondary output is a second harmonic voltage proportional to the applied earth's field.
3) Several recordings with full scale deflection 10γ is shown. The instrument is suited for registration of field variations with periods between 10 min and 1/20 sec. Noise level and reproductibility 1/3 γ.
4) Description of the ring-core sensor and field-gathering devices is given together with electronic circuit diagrams and operation principles of the oscillator and the second harmonic tuned amplifier.

Bailey, Ralph. Canadian aerial magnetic surveys (M.A.D.). *Can. J. Res.,* 26, *Sec. F,* pp. 523-539, 1949.
Description of Canadian use of essentially the same instrument as described by J.R. Balsley.

Balsley, James R. Aeromagnetic surveying. *Advances in Geophysics,* 1, edited by H.E. Landsberg, pp. 313-349, Academic Press, New York, 1952.
1) Single rod and two parallel rods.
2) Short explanation of the principle.
3) No.
4) Block diagrams of second harmonic and of "all even harmonics" magnetometers.

Beck, F.J., and J.M. Kelly. Magnetization in perpendicularly superposed direct and alternating fields. *J. Appl. Phys.,* 19, pp. 551-562, 1948.
For long cylindrical specimens curves are measured of the longitudinal magnetic induction for a steady longitudinal magnetic field vs. transverse magnetic induction from an alternating current through the cylinder.

Bendix Aviation Corporation. Electromagnetic induction device. *British Pat., 592,394,* Sept . 17, 1947.
1) Single rod, two parallel rods, three rods in a triangle, six rods in a star, combination of three orthogonally positioned two-rod sensors.
2) The principle of even harmonics generation in a biased core is explained, and it is claimed that the linearity of the device is poor because of the highly nonlinear B-H curve. However, an improvement is suggested by using a two-rod open core to linearize the B-H curve.
3) Detailed investigations of the magnetic materials and calculations of the expected linearity has been carried out.
4) Detailed descriptions of sensor designs.

Bershtein, I.L. A new type of magnetometer. *Izv. Akademii Nauk, Phys. Series,* 8. No. 4, pp. 189-193, 1944.
Based on the findings by Gorelik *et al.* the author has developed a magnetometer using an orthogonally gated sensor.

Blackett, P.M.S. On a negative experiment relating to magnetism and the earth's rotation. *Phil. Trans. Roy. Soc.*, A **245**, pp. 309-370, 1952.
1) Two parallel rods.
2) No.
3) Noise level 0.1 γ; compensates earth's field to within 0.2γ.
4) No.

Brandstaetter, F. Entwicklung und Anwendung einer magnetischen Feldmessonde zur Untersuchung von Ferromagnetika. *Oesterreichisches Ingenieurarkiv,* **6**, pp. 20-30, 1951, Vienna.
1) Two parallel rods.
2) The operation is explained by the superposition of two biased hysteresis-loops.
3) Several graphs of output voltage vs. ambient field is given with excitation current as a parameter. Range ±80 moe.
4) Design data are given for the sensor as well as for the electronic circuits.

Buckley, O.E. Detection of large magnetic bodies. *U.S. Patent, 2,415,808,* Feb. 18, 1947.
1) Two parallel rods.
2) No.
3) No.
4) Description of the sensor and of the electronics.

Carden, R., *et al.* Final engineering report. Prototype surveyor fluxgate magnetometer, Model ML 125-1. *JPL Contract 950156, ML/TN-2000.70,* Marshall Laboratories, 3530 Torrance Boulevard, Torrance, Calif., U.S.A., 14 June 1962. Clearinghouse Accession No. N65-17213, NASA CR 60762.
1) Two parallel rods.
2) No.
3) Sensitivity 10 $\mu V/\gamma$. 0.25 γ offset after exposure to ±1 oersted. Stability within ± 2γ 25°F to 125°F.
4) Detailed description and circuit diagrams of the magnetometer is given.

Chapman, S. and J. Bartels. Magnetic observations. *Geomagnetism,* **1**, Chap. II, 11, pp. 59-60, Clarendon Press, Oxford, 1940. Quotation of Aschenbrenner's and Goubau's paper. *Hochfrequenztechnik,* **47**, 1936.

Coleman, Paul J. Jr. An analysis of the operation of the fluxgate magnetometer. *Space Technology Laboratories,* Los Angeles 45, Calif., U.S.A., Report No. 7320.2-14, June 20, 1959.
1) Single rod.
2) Using a simplified, parallelogram-shaped, two-zone magnetization curve as a transfer function for the sine wave excitation current the author develops the Fourier series for the distorted output wave, and shows that the second harmonic component depends in amplitude on the ambient DC-field H, the permeability μ, the saturation field H_S, the maximum excitation field H_O, the half-width of the hysteresis loop δ, and on the frequency f. The phase of the second harmonic component depends on H_S, H_O, and δ. A change in H_S or in the shape of the hysteresis curve because of temperature is thus expected to change the phase of the second harmonic.
3) No.
4) No.

Dolginov, S. Sh., L.N. Zhuzgov, and V.A. Selyutin. Magnetometers in the third Soviet earth satellite. *Artificial Earth Satellites,* **2**, pp. 358-396, Plenum Press, New York, 1961.
1) Two parallel rods.
2) The directional sensitivity of the sensor is explained by the difference in demagnetization factors along and perpendicular to the core axis.
3) Mean zero deviation 10 γ /day. Temperature coeff. 2-6 γ/deg.
4) Design data are given for the sensor as well as a complete description of the electronic circuits.

Drozhzhina, V.I., *et al.* The theory of ferro-probes with longitudinal symmetrical excitation. *Fiz. metal. Metalloved.,* **10**, pp. 359-366, 1960. (English translation in *Physics of Metals and Metallography,* **10**, pp. 45-52, 1960.)
If the core is not driven well into the saturation regions by the excitation field it is shown that the superposition of a dc field $H\rho$ on the excitation field causes the working point to follow a minor hysteresis loop slightly different from the loop followed when $H\rho = 0$.
Crossing the apex of the minor hysteresis loop, biased or unbiased, the differential permeability goes through a discontinuity.

Fearon, R.E. Magnetic gradient measurement. *U.S. Patent, 2,520,677,* Aug. 29, 1950.
1) Two parallel rods.
2) The principle of using two different excitation frequencies F_1 and F_2 is explained. One of the modulation products, e.g. $F_1 - F_2$, is used to detect the magnetic field.
3) An accuracy of 0.1 γ is reported.
4) The sensor and the electronical circuits are described.

Felch, E.P., *et al.* Airborne magnetometers for search and survey. *AIEE Trans.,* **66**, pp. 641-651, 1947.

1) Single rod.
2) Neglecting hysteresis by taking a magnetization curve of the form $B = b_1h + b_3h^3 + b_5h^5 + \ldots$ and substituting for h by $H_o \cos pt + H$ where H_o is the max. excitation field and H is the earth's field, the author develops a Fourier series representing the output voltage, where the coefficients to even multiples of pt are odd functions of H. Using a simplified two-zone B-H curve the sensitivity is obtained. A better approximation to the B-H curve, $B = \tan^{-1}(h/a)$, is reported to yield results not much different, and an analysis based on a double characteristic to account for the hysteresis is reported not to affect the foregoing results.
3) Magnetization curve and sensitivity vs. excitation level is shown. Sensitivity 10 $\mu v/\gamma$. Noise 0.25 γ.
4) Design data are given for the sensor as well as block diagrams for the electronics.

——— and **J.L. Potter**. Preliminary development of a magnettor current standard. *AIEE Trans.*, 72 Part 1, pp. 525-531, 1953.
The field from a permanent magnet is cancelled by a constant-current-carrying solenoid using a fluxgate sensor as null-field detector.
The residual second harmonic output in null field is reported to be in quadrature (cosine component) to the field-generated second harmonic (sine component). The quadrature output is dependent on the degree of inhomogeneity of the permanent magnet field.
A stability of ±0.01 per cent for a few days was obtained in constant temperature and for a 30°C temperature change the stability was ±0.05 per cent.

Foerster, F. Ein Messgeraet zur schnellen Bestimmung magnetischer Groessen. *Z. Metallkde,* 32, pp. 184-190, 1940.
This paper describes an instrument developed by the author to investigate magnetic properties of iron samples. The principle used here is very close to the fluxgate principle; but it was only later (autumn 1941) that the modified instrument was used to measure magnetic fields (see F. Foerster, *Z. Metallkde,* **46**, pp. 358-370, 1955).

——— Ein Betriebsgeraet zur schnellen und genauen Messung der Koerzitivkraft sowie ihrer Temperaturabhaengigkeit. *Z. Metallkde.*, **46**, pp. 297-302, 1955.
Description of the use of fluxgates for measuring the coercive force of small samples.

——— Ein verfahren zur Messung von magnetischen Gleichfeldern und Gleichfelddifferenzen und seine Anwendung in der Metallforschung und Technik. *Z. Metallkde,* **46**, pp. 358-370, 1955.
1) Two parallel rods.
2) The operation is explained by the superposition of two biased hysteresis loops. Using a B-H curve made of three straight lines joined by a quarter of a sine wave the author calculates the second harmonic output voltage.
3) Biased and unbiased hysteresis loops are shown.
4) Short descriptions of the sensor and a block diagram of the electronics are given.

Frei, E.H., S. Shtrikman, and D. Treves. A transducer using crossed magnetic fields. *Bulletin of the Research Council of Israel,* 3, pp. 443-444, 1953,
1) Tubular, orthogonally gated sensor.
2) No.
3) No.
4) Short description suggesting the use of the principle as a magnetometer.

Fromm, W.E. The magnetic airborne detector. *Advances in Electronics,* 4, pp. 257-299, 1952.
1) Single rod, two parallel rods, ring-core.
2) Qualitative explanation of the principle.
3) No.
4) Descriptions of sensors and of the electronics are given. The paper is primarily intended as an introduction, and a survey over the subject.

Gans, F. Fonctionnement et applications des sondes électromagnétiques. *La Recherche Aéronautique,* 1, pp. 29-39, 1948.
1) Single rod and two parallel rods.
2) The appearance of second harmonic voltages by applying a dc-field is explained by Fourier analysis using the general properties of B-H curves.
3) Spectral distribution of the harmonics of the output voltage from a single rod sensor is shown.
4) A number of theoretical and practical considerations valuable for the sensor design are given.

Gebhardt, R.E. An induction magnetometer, constructions and tests. *Trans. Am. Geophys. Union,* 27, pp. 53-58, 1946.
1) Four parallel rods. The DC excitation current is chopped manually by a snap-switch.
2) No.
3) Mounted on a theodolite for use as an absolute magnetometer, the instrument has a deviation of $+3\gamma$ to -6γ in H and $+9\gamma$ to $+1\gamma$ in Z.
4) Design data are given for the sensor and for the electrical circuit.

Gerard, V.B. A simple, sensitive, saturated-core recording magnetometer. *J. Sci. Instr.*, 32, pp. 164-166, 1955.
1) Two parallel rods.
2) No.
3) Recording shown together with observatory magnetogram. Frequency response 0-20 hz. Max. sensitivity at output 4 γ per ma.

4) Design data of sensor is given. Very detailed description is given of the electronic circuit together with filter frequence response curve and circuit diagrams.

Germain-Jones, D.T. Post-war developments in geophysical instrumentation for oil prospecting. *J. Sci. Instr.*, 34, pp. 1-3, 1957.
1) Two parallel rods.
2) No.
3) Graphs of hysteresis curve and sensor output voltages shown.
4) Simple sketch of sensor is given.

Geyger, W.A. Self-balancing fluxgate magnetometers, *AIEE Trans.*, 77, pp. 213-216, 1958.
1) Two parallel rods and closed core sensor.
2) The principle is explained and the similarity to magnetic amplifiers is emphasized.
3) Linearity error of the order of 0.1 per cent.
4) The principle of the sensor is shown and a magnetometer is constructed using only ring-core magnetic amplifier circuits for amplification, frequency doubling, and signal detection.

———The ring-core magnetometer, a new type of second-harmonic fluxgate magnetometer. *AIEE Trans*, 81, pp. 65-73, 1962.
1) Ring-core.
2) The principle is explained and the similarity to magnetic modulators is emphasized.
3) Oscillograms of excitation current and sensor output voltages are shown. Sensor output current vs. direction of magnetic axis with respect to the applied field is shown. Sensitivity 1 volt per oersted.
4) Design data are given for the sensor as well as simple diagrams of the electronic circuit.

———New type of fluxgate magnetometer. *J. Appl. Phys.*, suppl. to 33, pp. 1280-1281, 1962.
1) Ring-core.
2) A simple explanation of the principle is given.
3) Sensitivity 1 volt per oersted.
4) Design data are given for the sensor together with a simple magnetometer circuit.

———Fluxgate magnetometer uses toroidal core. *Electronics*, 35, pp. 48-52, 1962.
1) Ring-core.
2) A simple explanation of the principle is given.
3) Sensitivity 1 volt per oersted.
4) Design data are given for the sensor together with several simple magnetometer circuits.

Gold, T. Manual for fluxgate ferrite magnetometer. *Report No. CRSR 172,* Center for Radiophysics and Space Research, Cornell Univ., Ithaca, New York, June 1964, Clearinghouse Accession No. N64-28989, NASA CR 58342.
1) Tubular ferrite core. Orthogonally gated.
2) Discussion of design aspects.
3) Typically 40γ offset for 1 per cent sec. harm. in excitation. Sec. harm. of less than 0.01 per cent necessary if drift below 0.4γ is wanted.
4) Sensor and electronics are described.

———Four ferrite core magnetometers. *Final Status Report to NASA, NASA Contract NASr-46,* October 1, 1963 through May 15, 1964, Center for Radiophysics and Space Research, Cornell Univ., Ithaca, New York, Report No. CRSR174, NASA CR 58344, Clearinghouse Accession No. N64-28991.
1) Tubular ferrite core orthogonal sensor.
2) No.
3) Drift and noise within ±0.3γ. Power consumption 0.6–0.9 watts.
4) No.

Gordon, D.I., R.H. Lundsten and R.A. Chiarodo. Factors affecting the sensitivity of gamma-level ring-core magnetometers. *IEEE Trans., Mag.-1*, pp. 330-337, 1965, and *ibid, Mag.*-2, pp. 773-774, 1966
1) Ring-core.
2) Using a simplified, two-zone, parallelogram-shaped magnetization curve the authors derive the transfer function – i.e. induction in the secondary winding vs. excitation field – and use this to obtain the output voltage for constant-current and constant-voltage excitation. The attenuation of the input signal because of demagnetization is emphasized.
3) Experimental curves are given showing sensitivity vs. area and vs. effective length-to-diameter ratio of the cores, and compared to calculated curves. Additionally are given curves of sensitivity vs. dc initial permeability and vs. ac differential permeability.
4) A few design data are given together with suggestions of improvements.

——— and H.H. Helms. A fluxgate sensor of high stability for low field magnetometry. *IEEE Trans. Mag.-4,* pp. 397-401, 1968.
1) Ring-core.
2) No.
3) Stability performance curves are given showing zero-offset vs. time under temperature changes. Offset fluctuations ±0.10 γ in 24 hours at constant temperature and noise 0.10 to 0.20 γ p-p, dc to 10 hz. Difference between offsets at 60°C and −30°C is 0.35γ.
4) Descriptions and design data are given for the sensor.

Gorelik, G., X. Goronina, and I. Joukova. Sur les courbes d'aimantation longitudinale d'un fil ferromagnétique par-

couru par un courant continu. *Comptes Rendus (Doklady) de l'Académie des Sciences de l'URSS,* **44**, pp. 235-237, 1944.

The longitudinal permeability of a ferromagnetic wire carrying a dc current is investigated. When the longitudinal field Hx is small, the corresponding longitudinal induction Bx is expressed by the saturation induction Bs for the material and by Hy the transverse induction in the wire from the dc current,

$$\mu_x = \frac{Bx}{Hx} = \frac{Bs}{Hy} \text{ (Hy > Hs >> Hx).}$$

Graham, R.L., and J.S. Geiger. The application of a fluxgate magnetometer to an automatic electronic degaussing system. *Can. J. Phys.*, **39**, pp. 1357-1368, 1961.

1) Two parallel rods.
2) No.
3) Less than 0.2 per cent harmonic distortion in drive oscillator. Less than 10^{-4} gauss long-term drift. Zero error 5.10^{-5} gauss.
4) Electronic circuit diagrams are given together with a detailed discussion of the possible sources of zero drift and errors.

Greiner, J. Feldmessungen nach dem Oberwellenverfahren, Theoretische Betrachtungen. *Nachrichtentechnik,* **9**, pp. 173-180, 1959.

——— Feldmessungen nach dem Oberwellenverfahren, Methodische Untersuchungen. *Nachrichtentechnik,* **10**, pp. 123-126, 1960.

——— Feldmessungen nach dem Oberwellenverfahren, Sieb- und Differenzsonden. *Nachrichtentechnik,* **10**, pp. 156-162, 1960.

——— Feldmessungen nach dem Oberwellenverfahren, Winkelsonden. *Nachrichtentechnik,* **10**, pp. 495-498, 1960.

1) Single rod, double rod, and ring-core sensors (parallel gated). Wire, tubular, and plate sensors (orthogonally gated).
2) A qualitative explanation is given based on a two-zone B-H curve and a triangular excitation wave. Quantitative calculations are carried out assuming an arctan shaped B-H curve and a sine wave excitation. The theoretical curves of second harmonic output vs. excitation level are given for parallel as well as for orthogonal gating and it is concluded that there is no significant difference in performance of the various types of sensors.
3) Experimental curves of sensitivity vs. excitation level and vs. excitation frequency as well as of other investigations are given for the six different types of sensors. Mumetal and ferrite is used as core material.
4) Detailed descriptions of the various types of sensors are given.

Hancock, J.D. Engineering report on the evaluation of DLK 101A1 fluxgate magnetometer sensor. *Honeywell,* Boston, Mass., USA, Sept. 9, 1964.

1) No.
2) No.
3) Sensitivity: 15 $\mu v/\gamma$. Drift: ±0.5 γ over 24 hours. Minimum second harmonic output less than 2 γ. Temperature drift 0.18 γ per degree Celcius. Noise less than 0.6 γ p-p for 0.01 hz to 10 hz. Curve sheets are shown from which the quoted and other data are derived.
4) Block diagrams of the test setups are shown.

Hess, H. Aufbau und Theorie eines Geraetes zur Messung der Magnetischen Horizontal-feldstaerke auf See mit der Foerster-sonde. *Deutschen Hydrographischen Zeitschrift,* **16**, pp. 15-43, 1963.

1) Two parallel rods.
2) Short description based on the superposition of two biased two-zone B-H curves.
3) No.
4) Sketch of sensor and a block diagram of the electronics are given.

Hine, A., and H.L. Hitchins. Apparatus for measuring and detecting magnetic fields. *Brit. Patent, 619,525,* March 10, 1949.

1) Two parallel rods.
2) The sensor is modulated by a low frequency alternating field superposed on the dc field to be measured. The demodulated output voltage contains a fundamental component of the modulation frequency proportional to the dc field.
3) No.
4) Block diagrams of the electronical circuits are given.

——— *Magnetic Compasses and Magnetometers,* pp. 47-72, 77, 143-154, 304-316, and 375-388, University of Toronto Press, Toronto, 1968.

This book is a basic source of information on magnetometers. Nearly all types of sensors are treated theoretically, and examples of practical magnetometer circuits are given covering among others peak-detector, second harmonic, and high frequency modulated systems.

Hood, P., and S.H. Ward. Airborne geophysical methods. *Advances in Geophysics,* **13**, pp. 1-41, 1969.

A survey of some Russian, Canadian and American airborne fluxgate magnetometers is given.

Hull, A.W. Magnetic field gradient meter. *U.S. Patent, 2,379,716,* July 3, 1945.

1) Two parallel rods with field gathering devices.
2) Short description of the principle. The unbalance between the two inductors is detected by means of a

nonlinear resistor. ("peak detector" or "fundamental reference" system.)
3) No.
4) Drawing of the sensor and of the electrical circuit is given.

Johnes, J.H. A proposed method of measuring the derivatives of the earth's magnetic field. *Geophysics,* 8, pp. 23-31, 1943.
1) Two parallel rods.
2) Using a sine wave excitation field the core flux vs. time is expressed as a Fourier series and for reasons of symmetry only odd harmonics are generated even when hysteresis is taken into consideration. A small dc field superposed on the excitation is shown to generate even harmonics, and assuming a third degree polynomial approximation to the B-H curve it is estimated that the instrument should be able to detect a field difference of 10^{-7} oersteds.
3) No.
4) Block diagram of the sensor and of the associated electronical equipment is given.

Joukova, I.S. About the EMF-spectrum of transverse induction. *Doklady Akademii Nauk SSSR,* 65, pp. 151-154, 1949.
A ferromagnetic, ac-current-carrying wire surrounded by an axial solenoid is magnetized along the axis by a small dc field Hx. The axial induction Bx is shown to be a dual series in powers of Hx, of the transverse ac-field Hy, and of the stress σ, (established by twisting one end of the wire with respect to the other). The voltage induced in the axial solenoid contains even harmonics proportional to Hx$(1 + a\sigma^2)$ and odd harmonics proportional to $\sigma(1 + bH_x^2)$, where a and b are constants. The results are verified experimentally.

Kato, Y., Z. Abe, and A. Sakurai. The visual magnetic variometer (Tohoku University type) used for the measurement of the effect of 20 June 1955. *Science Reports of the Tohoku Univ., Ser. V, Geophysics, Vol. 7, Suppl.* March 1956, pp. 15-20, Faculty of Science, Tohoku Univ.
1) Two parallel rods.
2) Based on a simplified two-zone B-H curve it is shown that the integrated output from the sensor contains positive and negative pulses of different amplitude with the difference proportional to the applied dc-field.
3) Drift ±1 γ per several days. Noise about 1 γ. Temperature dependency within ±1 γ from 20°C to 40°C. Response time 3 sec. per 10 γ.
4) Design data are given for the sensor together with a block diagram of the electronics.

Kerbnikov, F.I., and M.A. Rozenblat. Magnetic modulators with perpendicularly superposed magnetic fields. *Avtomat. i Telemekh.,* 19, pp. 836-848, 1958. (English translation in *Automation and Remote Control.*)
The principle of orthogonal gating, here used in magnetic modulators, is described theoretically using an arctan shaped B-H curve and the results are shown to fit the experimental data well.

Kerwin, W.J., R.M. Munoz, and M.J. Prucha. An improved magnetometer for deep space use. *IEEE/AIAA National Aerospace Electronics Conf.,* solar wind measurement techniques, Part 1, pp. 73-81, Dayton, Ohio, 1964.
1) Ring-core modified to an elongated toroid.
2) No.
3) Several high sensitivity recordings are shown from which the following data are derived. Noise 0.1 γ p-p, 1 hz BW. Offset after exposure to 2 gauss is less than 0.1 γ. Offset caused by second harmonic content in excitation is less than 0.05 γ.
4) Circuit diagrams and a detailed description of the electronics is given.

Kobayashi, R., *et al.* Mariner A fluxgate magnetometer. Final Engineering Report, Model ML 100-1, *JPL contract 950036, ML/TN-2000.43,* 22 February 1962, Marshall Laboratories, 3530 Torrance Blvd., Torrance, Calif., U.S.A., Clearinghouse Accession No. N65-18096, NASA CR 57081.
1) Two parallel rods.
2) Short description of principle.
3) Sensitivity 10μV/γ.
4) Extensive description of circuits and performance tests are given.

———and D. Sassa. Mariner R fluxgate magnetometer. Final Engineering Report, *JPL contract 950185, ML/TN 2000.47,* 16 March 1962, Marshall Laboratories, 3530 Torrance Blvd., Torrance, Calif., U.S.A., Clearinghouse Accession No. N65-18099, NASA CR 57080.
The report contains detailed technical discussions related to electrical design, test, and calibration process. Sensor analysis (based on a two-zone B-H curve) is presented in an appendix.

Krumhansl, J.A., and R.T. Beyer. Barkhausen noise and magnetic amplifiers. I. Theory of magnetic amplifiers, II. Analysis of the noise. *J. Appl. Phys.,* 20, pp. 432-436, and pp. 582-586, 1949.
It is shown analytically that a magnetic amplifier becomes unstable if the secondary is tuned to an even harmonic and the damping is sufficiently low. The behaviour in the vicinity of the harmonic is analogous to a voltage generator supplying the open-circuit output voltage to a four terminal network whose transfer characteristic is similar to that of a tuned L-C circuit except for an additional negative term in the denominator.

Kuehne, R. Magnetfeldmessung mit Eisenkern-Magnetometer nach dem Oberwellenverfahren. *Archiv fuer Technisches Messen, V 392-1,* pp. 175-178, 1952.

1) Single rod, two parallel rods.
2) The second harmonic output voltage vs. excitation level is derived from a simplified two-zone B-H curve.
3) Second harmonic output voltage vs. dc-field is shown for large fields and for very small fields. Sensor sensitivity 1 mv/moe.
4) Design data for the sensor is given together with a block diagram of the electronic circuit.

La Pierre, C.W. Direct current indicator. *U.S. Patent, 2,053,154,* Sept. 1, 1936.

1) Rectangular closed core with field gathering devices.
2) Superposition of any dc flux on the core makes the output wave unsymmetrical and introduces even harmonics.
3) No.
4) Many types of second harmonic fluxmeters with closed core is shown intended for magnetic field measurement or dc current measurement.

Lauche, Hans. Entwicklung einer Apparatur zur digitalen Registrierung erdmagnetischer Variationen. *Diplomarbeit, Institut für Geophysik und Meteorologie der Technischen Hochschule,* Braunschweig, 1967.

A digital feedback system for a fluxgate magnetometer is described.

Lawrence, L.G. Elektronik fuer die Geophysik. *Elektronik, Heft 11,* 5 Messtechnik, Messung nichtelektrischer Groessen, pp. 323-327, 1964.

1) Rectangular closed core, T-shaped core.
2) No.
3) No.
4) Electronic circuit diagrams of a magnetometer with T-sensor is shown together with a block diagram of the general principle.

Ledley, B.G. Magnetometers for space measurements over a wide range of field intensities. *Proc. of the URSI Conf. on Weak Magnetic Fields of Interest in Geophysics and Space,* May 1969, Paris.

A review is given on recent development work on a satellite fluxgate magnetometer. The design goal is to measure field components of up to 60,000 γ in a temperature range of −150°C to +50°C with an accuracy of 0.01 per cent. A highly stable current source has been developed and a pair of coaxial bucking coils with ceramic structure has been constructed to give less gradients over the sensor and less disturbance on the environment.

Ling, S.C. A fluxgate magnetometer for space application. *AIAA Summer Meeting,* Paper No. 63-187, June 27, 1963.

1) Tubular ferrite sensor, orthogonally gated.
2) By expressing the hysteresis loop as a bi-valued function it is shown that the second harmonic output is a linear function of the ambient dc-field. Any stress in the core material will, together with a second harmonic content in the excitation, give a 'false' second harmonic output. Other aspects of the sensor design are treated theoretically as well.
3) The waveforms of excitation field and induction are shown together with apparent permeability and damped output voltage. The axial apparent permeability vs. excitation field strength is shown and compared to the theoretically derived expressions.
4) Detailed sensor design data and electronic circuit diagrams are given.

———Improved magnetometer uses toroidal gating coil. *NASA Tech. Brief, 65-10103,* Goddard Space Flight Center, GSFC – 249, 1965.

1) Tubular sensor, orthogonally gated.
2) No.
3) Detecting level about 0.1 γ. Sensor sensitivity when tuned to second harmonic is 1 mV/γ.
4) A multitude of suggestions to improve the sensor design is given together with detailed descriptions of an actual sensor.

Linlor, W.I., R.M. Munoz, and M.J. Prucha. Stability measurements of fluxgate magnetometers. *Space Magnetic Exploration and Technology, Symp.,* pp. 198-234, University of Nevada, Reno, 1967.

1) Flattened ring-core and ring-core.
2) No.
3) Sensitivity 25 μv/γ. Oscillograms of excitation voltage and current, of induced voltage waveform in the core, and of total null output are shown. Total null output 0.3 volt p-p. Second harmonic feed through is less than 1 γ equivalent with 2.5×10^{-4} sec. harmonic in the excitation. Noise is less than 0.3 γ p-p dc to 10 hz measured for 1 minute. The effect of stress in the core material is investigated. A number of graphs of the offset vs. time under temperature changes are shown. Offsets are from 0.4 γ (18°C to 44°C) to 1.6 γ (−6°C to 20°C).
4) Detailed description of the sensor and a block diagram of the electronics is given.

Lokken, J.E. Instrumentation for receiving electromagnetic noise below 3,000 cps. *Natural Electromagnetic Phenomena below 30 kc/s,* Editor D.F. Bleil, pp. 373-429, Plenum Press, 1964.

A survey of fluxgate magnetometers is given. The operation principle is explained by assuming an odd power series approximation to the B-H curve. Examples of a single rod, two parallel rods, and ring-core sensors are given with block diagrams and detailed descriptions of the electronics. Peak voltage, second harmonic, and saturation time difference systems are described.

Lutz, H. Magnetfeldmessung mit Foerstersonden und Hallgeneratoren. *Elektronik,* 17, pp. 247-250, 1968.
1) Two parallel rods.
2) Short description of the principle based on a simplified two-zone B-H curve.
3) Sensor noise is typically 0.1 γ for 2-20 hz BW. Offset after exposure to 1 oersted is from 0.1 γ to 0.5 γ. Sensor second harmonic null in zero field is 5 to 50 γ equivalent. The temperature coefficient of this offset is about 0.1 $\gamma/^{\circ}$C.
4) Short description of the sensor and a block diagram of the magnetometer is given.

MacNichol, E.F. Jr., *et al.* Servo system employing direct current resolvers. *U.S. Patent, 2,697,808,* Dec. 21, 1954.
1) Two parallel rods.
2) Short description of the principle.
3) No.
4) Detailed description of the sensor with and without feedback, and of the electronics is given.

Mager, A. Ueber ein empfindliches Magnetsfeldmessgeraet nach dem Oberwellenverfahren, *Experim. Techn. Physik,* 1, pp. 109-120, 1953.
1) Ring-core, two parallel rods.
2) Qualitative explanation of the principle based on a two-zone B-H curve, and calculation of the sensitivity vs. excitation level based on an arctan shaped B-H curve.
3) Sensitivity level about 10^{-5} oersted.
4) Design data are given for the sensor as well as a complete circuit diagram for the magnetometer.

Marshall, S.V. An analysis of the ring-core fluxgate. *Proc. Nat'l. Electronics Conf.,* 22, pp. 133-138, 1966.
1) Ring-core.
2) For "constant voltage" excitation is shown that the instantaneous output voltage is proportional to the second derivative of the magnetization curve.
3) The apparent permeability of various ring cores is plotted vs. a normalized geometrical ratio and an empirical formula is given. Oscilloscope photographs of input and output waveforms are shown, together with an experimentally derived curve of the incremental permeability $\Delta B/\Delta H$ vs. dc-bias field.
4) Design data for the ring-core are given.

————An analysis of the fluxgate magnetometer. *U. of Missouri, Columbia,* Ph.D. thesis, 1967, Avail.: University Microfilms, Clearinghouse Accession No. N68-36303.

————An analytic model for the fluxgate magnetometer. *IEEE Trans., Mag-3,* pp. 459-463, 1967.
1) Single rod, two parallel rods, ring-core, and tubular sensor.
2) The even harmonic output from the single rod, the double rod, and the ring-core sensors is shown to be proportional to the second derivative of the B-H curve. For the orthogonally gated tubular sensor it is claimed that the permeabilities orthogonal and parallel to the gating field are equal and thus the same expression as above is valid for the output voltage. However, this is, not in accordance with earlier works (J. Greiner, T.M. Palmer, S.C. Ling).
3) Oscilloscope pictures are shown of output voltage vs. excitation field together with excitation and output voltages for square wave excitation and ramp excitation. An empirical formula for the output voltage vs. excitation field is derived.
4) The construction principle of the various sensors is shown.

Maxwell, A. III – Electronic recording of the transient variations in the earth's magnetic field. *Ann. IGY,* 4, pp. 281-286, 1957.
1) Two parallel rods.
2) Short description of the principle.
3) Range ± 500 γ, noise 0.1 γ dc 1 hz.
4) Block diagram of the electronics is given.

McCurley, E.P., and C. Blake. Simple null indicating saturable core magnetometer for the detection of static magnetic fields. *Rev. Sci. Instr.,* 31, pp. 440-443, 1960.
1) Single rod.
2) Short description of the principle.
3) Second harmonic content in the excitation is 73 dB below the fundamental. Changes in ambient field of less than 0.1 m oersted is readily observed.
4) Design data of the sensor is given together with a detailed description of the electronics.

McNish, A.G. An induction magnetometer. Principle of operation. *Trans. Am. Geophys. Union,* 27, pp. 49-51, 1946.
1) One long permalloy wire, the two halves of which are magnetized opposingly by the excitation current.
2) The dc-excitation current is chopped manually by a snap-switch and the output pulses are explained by superposing two biased hysteresis loops.
3) No.
4) Block diagram is given of the instrument, which involves no electronics.

Mee, C.D., and R. Street. An improved precision permeameter. *Proc. Instn. Electrical Engrs.,* 101, Part 2, pp. 639-642, 1954.
1) Two parallel rods.

2) No.
3) Noise and stray fields 0.3 × 10^{-3} oersted.
4) Design data of the sensor is given together with a block diagram of the electronics.

Meek, J.H., and F.S. Hector. A recording magnetic variometer. *Can. J. Phys.*, 33, pp. 364-368, 1955.
1) Two parallel rods.
2) No.
3) Noise level less than 0.5 γ. Range 1000 γ. Drift because of nulling field less than 10 γ in 24 hours. Temperature drift less than 10 γ for 5°F.
4) Detailed description of the sensor and of the electronics.

Meyer, O., and D. Voppel. Ein Theodolit zur Messung des erdmagnetischen Feldes mit der Foerstersonde als Nullfeldindikator. *Deutschen Hydrographischen Z.*, 7, pp. 73-77, 1954.
1) Two parallel rods.
2) No.
3) An accuracy of ±0.5′ in D, ±0.2′ in I, and ±1.7 γ in H is obtained.
4) Description of the mounting of the sensor on the theodolite and of the measuring procedure is given.

Mikhailovskii, V.N., and Iu. I. Spektor. Certain problems in the theory of magnetic amplifiers and magneto-modulation probes of the "second harmonic" type. *Automation and Remote Control*, 18, No. 8, pp. 771-777, 1957.
1) Two parallel rods.
2) Based on a parallelogram-shaped hysteresis loop it is shown that the second harmonic output voltage has a quadrature (cosine) component besides the sine component, both dependent on the dc-bias field. The cosine component is proportional to the area of the hysteresis loop. If the field to be measured or the compensation field is inhomogeneous it is shown that simultaneous cancellation of both sine and cosine component is not possible, thus explaining the observed residual quadrature second harmonic output voltage.
3) Measurements of the second harmonic output voltage and phase angle vs. bias field with excitation level as a parameter is shown to fit the theoretical curves well.
4) Description of the sensor is given together with a block diagram of the electronics.

Mocheshnikov, N.I., V.F. Ivanov, and V.V. Petrenko. Adjusting double frequency saturated magnetic probes. *Pribory i Tekhnika Eksperimenta,* 4, pp. 147-148, 1960. (English translation in *Instrum. Exper. Tech.*, 4, pp. 671-672, 1960.)
A simple method of determining the zero offset of a fluxgate is described.

Morris, R.M., and B.O. Pedersen. Design of a second harmonic fluxgate magnetic field gradiometer. *Rev. Sci. Instr.*, 32, pp. 444-448, 1961.
1) Two parallel rods.
2) Short description of the principle.
3) Less than 0.5 per cent second harmonic in the excitation. Differential temperature coefficient 1 γ/°C. A 40-hour stability test showed less than 10 γ drift.
4) Several gradiometer systems are discussed, the construction of the detector mounting is described, and a block diagram of the electronics is given.

Muffley, G. The airborne magnetometer. *Geophysics*, 11, pp. 321-334, 1946.
1) Two parallel rods.
2) Short description of the principle.
3) No.
4) A sketch of the sensor is shown together with a block diagram of the electronics. This paper contains mainly a historical survey of the development of American airborne magnetometers.

Munoz, R. The Ames magnetometer. *Proc. Nat'l. Telemetering Conf.*, Paper AA-3.3, pp. 77-80, 1966.
1) Flattened ring-core.
2) No.
3) Second harmonic distortion in excitation is less than 0.001 per cent. Accuracy ±0.2 γ. Long term stability of ±0.2 γ possible.
4) Description of the sensor is given together with a block diagram of the electronics.

Munoz, Robert M. Computer aided analysis and design of space instrument systems. *Symposium on Space Magnetics Exploration and Technology*, Editor Ernest J. Iufer, pp. 133-154, Reno, Nevada, 1967, Clearinghouse Accession No. N69-33962, CR73350.
As an example of computer aided design the development of the Ames fluxgate magnetometer is described in considerable detail.

Nahrgang, S. Contribution à la théorie du magnétomètre (sonde électromagnétique) à noyau de haute perméabilité alimenté par un courant alternatif. *La Recherche Aéronautique*, No. 16, pp. 11-18, 1950.
1) Single rod.
2) Three approximations to the B-H curve are used. A power series containing only odd powers, the Feldtkeller approximation, i.e. the B-H curve is built up of three straight lines joined by two segments of sine curves, and an approximation by a series of sine curves. If a second alternating field besides the excitation field is imposed on the core it is shown that the output contains only odd harmonics of the excitation field plus all possible combinations of sums and differences

of the fundamental and harmonics of the excitation and of the second alternating field. The cases of an ac or a dc field disturbed by an alternating field is treated and the possibilities for eliminating the disturbance is discussed.
3) No.
4) No.

Ota, M. (Editor). The three component airborne magnetometer. *Report on Aeromagnetic Survey in Japan,* pp. 21-32, World Data Center C2 for Geomagnetism, Kyoto University, Japan, 1966.
1) Single rod.
2) No.
3) Overall error of the system including orientation error of the stabilized platform and residual fields from the aircraft is ±50 γ.
4) Circuit diagram of the electronics is given.

Palmer, T.M. A small sensitive magnetometer. *Proc. Instr. Electrical Engrs.*, **100**, Part II, pp. 545-550, 1953.
1) Ferromagnetic wire carrying the excitation current.
2) Based on the earlier works by Gorelik and by Joukova the author shows, neglecting hysteresis, that for small axial fields the second harmonic output is proportional to the axial field. An expression for large fields is derived too assuming constant saturation of the core by either the axial or the excitation field.
3) Experimental curves of second harmonic output vs. axial dc-field show a close fit to the theoretical curve. Sensor zero offset vs. excitation current after exposure to an axial field of 100 oersteds is given. Fields from less than 5γ has been measured.
4) Detailed description of the sensor design is given together with descriptions of the electronic circuits.

———A battery-operated magnetometer. *Symposium on precision electrical measurements,* Paper No. 9, 17th-20th November, 1954.
1) Ferromagnetic wire carrying the excitation current.
2) Short description of the principle.
3) Wave shape of the excitation current is given together with second harmonic voltage vs. ambient field, sensitivity vs. excitation current, and zero offset vs. excitation current after exposure to large fields. A recording is shown with ±8 γ calibration field and a noise level of about 2γ p-p.
4) Sensor design data and detailed description of the electronics is given.

Pearlstein, B.A., *et al.* Magnetometer sensor development program. *Honeywell Radiation Center,* Boston, Mass., U.S.A. Final report to NASA, Contract NAS2-2070, December, 1964.
Sensors with 0.2 – 0.3 γ noise in 0-10 hz BW has been produced and the second harmonic feedthrough has been cancelled by a voltage derived from an extra winding of about 30 turns on top of the excitation winding. This is based on the assumption that the sensor null output is due to a residual transformer action (suggested by J.D. Hancock). Several recordings of the sensor noise are shown.

——— **and D.E. Ratcliff.** AIMP-D and E fluxgate magnetometer experiment. *Honeywell Document HRC 67-62, NASA CR 73161,* 153 pp., October, 1967.
Final engineering report on a space magnetometer with test data and complete electronic circuit diagrams. No information is given on the sensor type. Second harmonic feedthrough $< 0.8\ \gamma$, absolute null offset $< 0.7\ \gamma$, noise $< 0.4\ \gamma$, long term drift $< 0.2\ \gamma$, repeatability $< 1.4\ \gamma$, and null change from room temperature to $-40°C < 1.1\ \gamma$, and from room temperature to $+70°C < 1.7\ \gamma$.

Primdahl, F. The fluxgate mechanism. *IEEE Trans. Mag.*, **Mag.-6**, pp. 376-383, 1970.
1) Parallel and orthogonally gated sensors.
2) It is shown that the main difference in gating mechanism between the two sensor types is that parallel gating is due to changes in dB/dH whereas orthogonal gating is due to changes in $B/(H-H_c)$.
3) Gating curves of the two types of sensors are shown.
4) Design data for the experimental sensors are given.

———A ferrite core fluxgate magnetometer. *Publications of the Earth Physics Branch,* **Vol. 40,** No. 1, Department of Energy, Mines & Resources, Ottawa, Canada, 1970.
1) Ferrite tube, orthogonally gated.
2) No.
3) Long term stability ±3.5γ over 60 days in 58,600γ field, time constant 0.3 sec., noise 0.1-0.3γ p-p, sensor zero offset 2-7γ, temperature coefficient in 58,600γ field less than 0.18γ/°C.
4) Detailed description of the sensor and of the electronics is given.

Ringhiopol, I. Un magnétomètre de grande sensibilité avec des applications dans la spectroscopie magnétique nucléaire. *Nuclear Instrum. Methods,* **35**, pp. 309-312, 1965.
1) Two parallel rods.
2) Short explanation of the principle.
3) Sensitivity threshold 2×10^{-5} oersted. Sensitivity 1.4 v/oe. Linearity range 10^{-5} oersted to 10^{-1} oersted. Relative measuring accuracy 0.001 per cent.
4) Detailed descriptions are given of the sensor and the toroidal field nulling coil together with a block diagram of the electronics.

Rose, D.C., and J.N. Bloom. A saturated core recording magnetometer. *Can. J. Res.,* 28, *Sec. A,* pp. 153-163, 1950.
1) Single rod.

2) Using an odd power series approximation to the B-H curve the authors show that the even harmonics generated by the excitation field are proportional to the dc-bias field.
3) Excitation oscillator contains less than 1 per cent second harmonic, which in turn is attenuated 80 dB by filtering. 80 dB + 30 dB attenuation is provided for the fundamental in the second harmonic amplifier. Sensitivity 25 $\mu V/\gamma$ second harmonic. A curve of sensitivity vs. excitation level is shown.
4) Detailed descriptions are given of the sensor and of the electronics.

Rozenblat, M.A. The theory and calculation of a magnetic modulator operating on the second harmonic principle. *Radiotekhnika*, **11**, pp. 36-51, 1956.
Based on an Arctan-shaped B-H curve the output voltage vs. excitation level and the sensitivity of a balanced magnetic modulator is derived. The effect of unbalance, of noise and of zero drift is investigated together with the influence of demagnetization and of inhomogeneous fields.

———Magnetic modulators with second harmonic sine wave output voltage. *Avtomat. i Telemekh.*, 22, pp. 1386-1400, 1961. (English translation in *Automation and Remote Control.*)
For magnetic modulators having parallel or orthogonal gating it is shown that by adjusting the shape of the excitation current wave it is possible to get a pure sine wave second harmonic output which greatly increases the signal-to-noise ratio of the device.

Rumbaugh, L.H., and L.R. Alldredge. Airborne equipment for geomagnetic measurements. *Trans. Am. Geophys. Union*, **30**, pp. 836-849, 1949.
1) Single rod, two parallel rods.
2) Using an odd power series approximation to the B-H curve the authors show that the coefficients of the even harmonics in the output are odd functions of the bias field, and that the odd harmonics are even functions of the bias field.
3) Signal-to-noise ratio of ten at a sensitivity of one gamma for the double rod sensor, and detection of fields less than one gamma with the single rod sensor is reported. A curve of sensitivity vs. excitation level is shown.
4) Description of the sensor principle and a block diagram of the electronics is given. This paper is primarily intended as a survey of airborne magnetometers.

Scearce, C.S. Magnetic field experiment. Pioneers 6, 7 and 8. *Laboratory for Space Sciences*, NASA-Goddard Space flight center, Extraterrestrial Physics Branch Preprint Series, X-616-68-370, September, 1968.
1) Helical core.
2) Short discussion of fluxgate types and possible sources of error.
3) Magnetic noise 0.13 to 0.35 γ. Zero calibration is made in flight by flipping the sensor 180° with an accuracy of ±0.25 γ. Graphs of zero calibration and of frequency response are shown.
4) A description of the helical core sensor is given together with circuit diagrams of the electronics.

Schmitt, O.H. Unbalanced magnetometer. *U.S. Patent, 2,560,132*, July 10, 1951.
1) Two parallel rods.
2) The method of detection described here is of the "peak difference" type. Basically this is a phase sensitive detector using the fundamental of the excitation wave as a reference, instead of the second harmonic. The fundamental reference voltage is here fed to the detector via the sensor by destroying the sensor balance.
3) No.
4) Detailed description of the sensor.

Schonstedt, E.O. Saturable measuring device and magnetic core therefor. *U.S. Patents, 2,981,885* and *2,916,696*, 1961 and 1959.
1) Helical core, single spiral, two parallel spirals, and double spiral.
2) Short explanation of the principle.
3) No.
4) Detailed descriptions of the sensor designs.

Serson, P.H., and W.L.W. Hannaford. A portable electrical magnetometer. *Can. J. Tech.*, **34**, pp. 232-243, 1956.
1) Two parallel rods.
2) Based on a two-zone B-H curve the time varying core-permeability is developed as a Fourier series. The sensor is loaded by a tuning capacitance and a damping resistance, and it is shown that for certain values of the circuit parameters it is possible to obtain large amplification of the second harmonic in the sensor.
3) Used as an absolute magnetometer by mounting the sensor on a theodolite the accuracy is ±0.3′ in declination and ±0.2′ in inclination corresponding to ±3 γ. The probable error of a single observation of the total intensity is from 10 γ to 50 γ.
4) Detailed description is given of the sensor as well as of the electronics.

———An electrical recording magnetometer. *Can. J. Phys.*, 35, pp. 1387-1394, 1957.
1) Two parallel rods.
2) The field at the sensor is nulled by a feedback system. The second order differential equation describing the frequency response is given and from this the system parameters are chosen.

3) Noise and drift tests show 3γ p-p noise dc-1 hz and maximum drift 10 γ in 10 hours.
4) Design data are given for the sensor as well as a complete description of the electronic circuits together with a discussion of the sources of errors.

Snare, R.C., and C.P. Benjamin. A magnetic field instrument for the OGO-E spacecraft. *IEEE Trans.*, **NS-13**, pp. 333-339, 1966.
1) Two parallel rods.
2) Short description of the principle.
3) Telemetry resolution 1/16 γ. Calibration fields of ±8 γ and ±32 are provided during flight.
4) Short description of the sensor and a block diagram of the electronics are given.

Street, R., J.C. Woolley, and P.B. Smith. Magnetic viscosity under variable field conditions. *Proc. Phys. Soc.*, **B 65**, pp. 679-696, 1952.
1) Two parallel rods.
2) No.
3) With negative feedback the linearity is better than 1/4 per cent.
4) Design data for the sensor is given.

Tenani, M. Nuovo metodo di misura della declinazione e della inclinazione magnetica. *La Ricerca Scientifica*, **20**, pp. 1135-1140, 1941.
1) Closed rectangular core with field-gathering devices.
2) Short explanation of the principle. The sensor is taken from a fluxgate compass and mounted on a theodolite for D and I measurements.
3) The standard deviation on a declination measurement is 5″ (inclination at the site is approx. 60°).
4) Block diagram of the electrical circuit is given.

Thellier, E. Enquête sur les appareils enregistreurs des variations rapides du champ magnétique terrestre. *Ann. IGY*, **4**, Geomagnetism, Part II, pp. 225-280, 1957.
Short description of the fluxgate principle and a discussion of its use as an instrument for recording variations in the earth's magnetic field.

Thomas, H.P. Direction responsive system. *U.S. Patent, 2,016,977*, October 8, 1935.
1) Closed rectangular core and single rod with field-gathering devices.
2) Short explanation of the principle.
3) No.
4) Detailed description of the sensor and the electrical circuit. The even harmonic content is detected by the dc current flowing through a symmetrical nonlinear resistor connected to the output. This is equivalent to the "peak detector" or the "fundamental reference" detector system. The patent was filed in 1931 and is one of the earliest descriptions of fluxgates.

Tolles, W.E. Applications of the saturable-core magnetometer. *Proc. Nat'l. Electronics Conf.*, **3**, pp. 504-513, 1947.
1) Single rod.
2) Short explanation of the principle.
3) Noise level about 0.03 γ dc – 1 hz BW. Sensitivity from 10 μv/γ to 2000 μv/γ. Linear response from zero to 1000 γ or 10,000 γ. Temperature coefficient 0.1 per cent/°C.
4) Some data on sensor design are given. The paper is mainly intended as a survey of development and applications of the fluxgate.

Tucker, J.W. Magnetic amplifier noise limitations. *Naval Research Laboratories*, Washington, Rept. No. 3779, Dec. 29, 1950.
An equivalent input noise of 0.7×10^{-6} volts is reported for 1 hz BW, this corresponds to an input magnetic signal of 0.009 γ.

Vacquier, V.V. Apparatus for responding to magnetic fields. *U.S. Patent, 2,406,870*, Sept. 3, 1946.
1) Two parallel rods.
2) The principle is explained qualitatively from the hysteresis curves of the core material and from the phase difference in the otherwise similar output voltages from the two open core transformers because of the applied dc field.
3) Intensity changes of 20×10^{-5} oersteds are readily detected. Higher sensitivities are obtainable.
4) Detailed descriptions of the sensor and of the electronics are given.

———Apparatus for responding to magnetic fields. *U.S. Patent, 2,407,202*, Sept. 3, 1946.
A gradiometer is described using the invention by the author in *U.S. Patent, 2,406,870.*

Vacquier, V., R.F. Simons, and A.W. Hull. A magnetic airborne detector employing magnetically controlled gyroscopic stabilization. *Rev. Sci. Instr.*, **18**, pp. 483-487, 1947.
1) Two parallel rods, single rod with opposingly magnetized halves.
2) Short description of the principle.
3) Noise level 0.2 γ.
4) Some design data are given of the sensor together with block diagrams of the electronics.

Vasiliu, Gh., N. Calinicenco, and C. Onu. Magnetometru cu sonda de saturatie. *Stud. Cerecetari Stiint., Fiz. Stiint. Tehn.*, **14**, pp. 341-348, 1963. Rumania.
1) Single rod and two parallel rods.

2) Calculation of second harmonic output and sensitivity based on a simplified two-zone B-H curve.
3) No.
4) Description of the sensor and electronic circuit diagram.

Weiner, Melvin M. Magnetostrictive offset and noise in fluxgate magnetometers. *IEEE Trans. Mag.*, Mag.-5, No. 2, pp. 98-105, 1969.
1) Elongated ring-core.
2) Theoretical analysis of the effect of magnetostriction.
3) Second harmonic output (magnetostrictive offset) vs. excitation voltage, and second harmonic output fluctuations (magnetostrictive noise) vs. excitation voltage are shown together with frequency spectra of the offset and noise.

Whitham, K. Measurements of the geomagnetic elements. *Methods and Techniques in Geophysics,* 1, editor S.K. Runcorn, pp. 134-147 and 165-167, Interscience, London, 1960.
This book contains a survey of saturable core magnetometers with information on core designs, performance data, theoretical analysis, and descriptions of the different types of electronical magnetometer circuits.

Williams, F.C., and S.V. Noble. The fundamental limitations of the second harmonic type of magnetic modulator as applied to the amplification of small dc signals. *Proc. Inst. Electrical Engrs., II 97,* pp. 445-459, 1950.
The theoretical and experimental results given in this paper are in most cases applicable to fluxgate devices. The noise which is attributed to Barkhausen jumps is equivalent to an input signal of 10^{-3} γ, the zero drift is $\pm 5 \times 10^{-3}$ γ. These results are valid for a closed magnetic path; in applying them to an open core device as the fluxgate the input attenuation because of demagnetization will mean an increase in noise and drift of the order of 10^2.

Wurm, M. Beitraege zur Theorie und Praxis des Feldstaerkedifferenzmessers fuer magnetische Felder nach Foerster. *Z. Agew. Phys.*, 2, pp. 210-219, 1950.
1) Two parallel rods.
2) A qualitative explanation of the principle is given, based on a simplified two-zone B-H curve. Based on the actual hysteresis-loop for the core it is shown that, compared to a B-H curve without hysteresis, a phase shift of the second harmonic is introduced. This phase shift is proportional to the area of the hysteresis loop. Theoretical curves of second harmonic vs. excitation level are given and the possibilities of balancing the sensor by external impedances are investigated.
3) Balancing impedances are plotted for a number of cores compared to a standard core, and a null-field output of 5 γ to 20 γ, not further reducible, is reported. By using selected cores instead of external balancing, null-field outputs of less than 2 γ was obtained.
4) Some design data of the sensors are given.

Wyckoff, R.D. The Gulf airborne magnetometer. *Geophysics,* 13, pp. 182-308, 1948.
1) Two parallel rods, rectangular closed core.
2) No.
3) Many oscilloscope photographs explaining the operation of the sensor are shown.
4) A sketch of the sensor principle is shown together with a circuit diagram of the differential peak detector. This paper is intended as a survey of the airborne magnetometer development.

Yanus, R.I. Theory of ferro-probe magnetometers for non-uniform magnetic fields. *Fiz. Metal. Metalloved.*, 14, pp. 336-373, 1962. (English translation in *Phys. Metals Metallography,* 14, pp. 41-46, 1962.)
It is shown analytically that a fluxgate sensor in an inhomogenous field will measure the average field over its length.

Zatsepin, N.N., *et al.* Problem of the measurement of non-uniform magnetic fields by means of ferroprobes. *Fiz. Metal. Metalloved.*, 14, pp. 30-34, 1962. (English translation in *Physics of Metals and Metallography,* 14, pp. 29-32, 1962.)
In moderately inhomogenous fields it has been found that the fluxgate measures the average field along the sensor length. In highly non-uniform fields there is a considerable difference between the magnetometer indications and the average field, the magnitude and sign of which is dependent on the position of the sensor in the field.