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The Automatic Standard Magnetic Observatory

L. R. ALLDREDGE and I. SALDUKAS

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Technical Bulletin No. 31 covers the 1960-1965 research and development project that produced the automatic standard magnetic observatory (ASMO) and automatic standard magnetic observatory-remote (ASMOR). These new systems provide a means of obtaining automatically the statistical output of a standard magnetic observatory, in a form compatible with electronic computer processing. The magnetometers used by the project, the theoretical basis of the ASMO/ASMOR concept, and the progressive advance from initial instrument to ASMOR are described in succeeding sections of this Bulletin.

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The Automatic Standard Magnetic Observatory

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INTRODUCTION

IT HAS been the traditional role of observers at magnetic observatories to act as extensions of the magnetometric sensors. The manual procedures associated with obtaining observatory data, and the time-consuming, hand-scaling of analog records, have left most observers little opportunity to employ the data they collect. The recent emphasis on automatic data processing techniques in data reduction and handling has hardly changed the observer's role; digitization of magnetic data has too often been a matter of manually translating analog records into digital form. Improvements of observatory instruments in recent years--the adoption of electromagnetic standards, rapid-run magnetographs, and nuclear magnetometer sensors--have not materially altered the manner in which geomagnetic data have been processed. Data collection and reduction have remained, literally, in the hands of the observer.

Since the early 1950's, advances in sensor development, digital recording, and data transmission and reduction have opened the way to more constructive alternatives. Ideally, new sensors, whose output is in digital form, could be combined with suitable recorders to obtain *automatically* the principal products of a standard magnetic observatory: Determination of absolute baseline values and the statistical description of mean hourly, daily, monthly, and annual absolute values of the magnetic field components and magnetic activity indices. Such a device would produce data compatible with automatic data processing techniques, would lend itself to remote, telemetered installation, and would transfer the focus of observers from the tedium of manual procedures to productive research activities.

In 1960, Dr. Leroy R. Alldredge of the U.S. Coast and Geodetic Survey described an Automatic Standard Magnetic Observatory (ASMO) and proposed that it be developed.[1] The proposed device used modern quantum electronic instruments to measure the total magnetic field and additional parameters to permit computation of its components, recording data in digital form for high-speed processing by electronic computers.

A program to accomplish the objectives of the Alldredge proposal was undertaken in 1960 by the Coast and Geodetic Survey's Office of Research and Development.[2] The objective of this 5-year project was the conversion of a theoretical possibility into a functioning reality, and the introduction of a new instrumental base for observatory operations.

The research and development phases of that project are now concluded. Four automatic units were developed, fabricated, and put into operation. The first was a Coast and Geodetic Survey "breadboard" system, used primarily to smooth the inevitable roughness between proposal and design. The second and third units were production prototype ASMO's, designed and fabricated to Coast and Geodetic Survey standards by Data Technology Corporation of Mountain View, Calif., and Varian Associates of Palo Alto, Calif. These "prototype" units are now installed at magnetic observatories in Dallas, Tex., and Fredericksburg, Va., and continue to produce useful data on an operational basis.

In November 1965, the fourth unit was accepted from Varian Associates for operation at the cooperative Varian Foundation and Coast and Geodetic Survey magnetic observatory at Castle Rock, Calif. The acceptance of this initial Automatic Standard Magnetic Observatory-Remote (ASMOR) marks the culmination of the 5-year program in research and development. The new instrument, which takes field measurements automatically and telemeters them to several distant receiving and recording stations, is the first of a new generation of magnetic instruments.

This report describes the magnetic sensors whose development made the ASMOR possible, the theoretical basis on which the development

Dr. Alldredge is a research geophysicist with the Institute for Earth Sciences and Mr. Saldukas is a research geophysicist with the Coast and Geodetic Survey. The authors express their appreciation to Mr. Carl A. Posey who synthesized material from various reports for this paper.

[1] L. R. Alldredge, "A Proposed Automatic Standard Magnetic Observatory," *Journal of Geophysical Research, 65*, pp. 3777-3786, 1960.

[2] The formalization of the Environmental Science Services Administration (ESSA), in October 1965, moved the Coast and Geodetic Survey's former Office of Research and Development to ESSA's Institutes for Environmental Research, with the ASMO/ASMOR project under the direction of the Institute for Earth Sciences.

program rested, the progress from breadboard system to ASMOR, and the future role of ASMOR and ASMOR-like units in the search for a better understanding of the earth's magnetic field.

ATOMIC RESONANCE MAGNETOMETERS

On October 21, 1948, R. H. Varian filed application for a patent covering the correlation of nuclear properties of atoms with properties of magnetic fields, and a device which could apply that correlation to the measurement of magnetic fields and related magnetometric operations.[3] Since 1951, when the original patent was granted, a family of magnetometer sensors has evolved that employs the correlation described in the Varian patent.

This family of instruments uses the principle of nuclear precession, a gyromagnetic characteristic exhibited in a constant magnetic field by atomic nuclei having a magnetic moment. When a nucleus is placed in a constant magnetic field, a torque is produced by the interaction between the nuclear magnetic moment and the external magnetic field. Because the magnitude of the nuclear angular momentum (or spin) is fixed, the torquing action produces a change in the orientation of the angular momentum vector, which alters steadily while maintaining a constant angle with the magnetic field (that is, describes the surface of a cone whose axis parallels the magnetic field vector). The principle operating here is similar to that of a gyroscope, which precesses about the axis of the gravity vector at a constant angle to the vertical as long as its angular momentum remains constant. In the nuclear case, the frequency of precession--the Larmor frequency--is directly proportional to the intensity of the magnetic field about whose axis precession occurs. The ratio of the Larmor frequency to the magnetic field intensity, or gyromagnetic ratio, γ_p, is a physical constant; once it has been determined accurately, it can be used to determine magnetic field intensity by measuring a frequency.

In the absence of damping forces, the precession of nuclei would continue indefinitely about the axis established by the magnetic field. In practice, damping forces exist that eventually cause the nuclear magnetic moments to seek a position of least potential energy with respect to the magnetic field. The time required for this suppression, or relaxation time, may vary from microseconds to many minutes.

A variety of methods can be used to obtain coherence in an ensemble of atoms. The degree of coherence is usually quite small because of comparatively large thermal forces operating at the nuclear level. Nevertheless, the effect is large enough that the precessing magnetic moments can induce a usable alternating current in a suitably situated pickup coil, or can be monitored indirectly using optical techniques.

During the 1950's, instruments employing these principles in the measurement of magnetic total intensities became available for observatory applications. In general, these magnetometers offered the advantages of increased accuracy and a data-acquisition rate substantially greater than that obtained with electromechanical/manual instruments; their dependence on atomic constants, rather than gross mechanical effects, and the ease with which their output--a direct or indirect measurement of the Larmor frequency--could be put into digital form, were also strong advantages. The principal disadvantages of nuclear magnetometer sensors lay in the apparent difficulties of using them to obtain component data, and in the apparent complexity of their associated electronics. Neither factor was critical.

Although this class of magnetometers measures directly only total field intensity (*F*), some have been used to measure the horizontal (*H*) and vertical (*Z*) components, as well as *F*, by employing suitable biasing fields. The Coast and Geodetic Survey's proton vector magnetometer[4] uses a proton free-precession sensing head (see below) and polarizing coil positioned inside a vertical, coaxial, four-coil Braunbek system for nulling *Z* during measurement of *H*, and an outer pair of horizontal, coaxial coils for nulling *H* during measurement of *Z*. During measurement of *F*, neither coil is used. This system did not provide for the measurement of the declination (*D*), and was hand operated.

Another system was proposed and tested experimentally by F. W. Bacon in 1955, using bias coils with a proton free-precession sensor to obtain data from which any three orthogonal components could be computed.[5] His method, in modified form, was used at ground stations to monitor the earth's field during the Project Vanguard magnetic experiment.[6,7] In obtaining component data with nuclear magnetometers, the additional expense and work required to provide the necessary auxiliary bias fields is more than compensated by increased accuracy of measurement, and the ability to measure magnetic variations and absolute values with a single apparatus.

It was recognized at the start that the introduction of more electronics into observatories might add reliability and maintenance difficulties; some increase in complexity is natural in any drift

[3] R. H. Varian, *Method and Means for Correlating Nuclear Properties of Atoms and Magnetic Fields*, U.S. Patent Office, Re. 23,769. Original No. 2,561,490 dated July 24, 1951, Serial No. 55,667, October 21, 1948. Reissued January 12, 1954. Much of the language in the following discussion of nuclear precession is borrowed from this document.

[4] L. Hurwitz and J. H. Nelson, "Proton Vector Magnetometer," *Journal of Geophysical Research, 65*, pp. 1759-1765, 1960.

[5] F. W. Bacon, *Adaptation of a Free Precession Magnetometer to Measurements of Declination*, M. S. Thesis, U.S. Naval Postgraduate School, Monterey, Calif., 1955.

[6] J. P. Heppner, J. D. Stolarik, and L. H. Meredith, "A Review of Instrumentation for the Magnetic Field Satellite Experiment," *Annals of the International Geophysical Year, VI*, pp. 323-329, 1958.

[7] I. R. Shapiro, J. D. Stolarik, and J. P. Heppner, "The Vector Field Proton Magnetometer for IGY Satellite Ground Stations," *Journal of Geophysical Research, 65*, pp. 913-920, 1960.

toward automated systems. But the proposed ASMO, when compared with the highly reliable, highly complex systems found in virtually every field of modern science and technology, was electronically very simple.

The nuclear magnetometer sensor appeared to be a necessary element in any ASMO design. Three nuclear magnetometers, operational or under development by 1960, were of particular interest to the beginning ASMO project: the proton free-precession magnetometer; and two optically pumped resonance devices, one using rubidium vapor, the other, metastable helium, as the resonant medium.

Proton Free-Precession Magnetometer

Developed by the Varian Associates Research Laboratory between 1948 and 1954, the proton free-precession magnetometer[8] most closely follows the lines of the Varian invention, and is considered by many to be the simplest and most direct instrument of the new family of nuclear sensors. It was the first magnetometer to come into widespread observatory use that measured the magnitude of the earth's magnetic field in terms of the Larmor frequency of precessing nuclei.

In this instrument, a strong electromagnetic field is applied to a hydrogenous sample (usually water) at approximately right angles to the earth's magnetic field. The applied field polarizes, or orients, a significant percentage of protons (hydrogen nuclei) in the sample along the axis of the polarizing field; when this field is suddenly removed, these protons precess about the axis of the remaining field--in this case, the earth's magnetic field. As has been noted, the Larmor frequency is directly proportional to the intensity of the field about which precession takes place, and the precessing protons can induce a corresponding a.c. signal in a suitably situated pickup coil.

The intrinsic accuracy of the system is quite high, the field intensity being derived entirely from the measured Larmor frequency, and not as a function of signal amplitude. Thus, if the polarizing coil is not perpendicular to the earth's field, the signal is weakened without affecting the accuracy of the measurement as long as a sufficiently high signal-to-noise ratio is retained. Absolute measurements can be made with an accuracy of 0.1 gamma.[9]

In terms of application to the proposed ASMO, the proton free-precession magnetometer had certain critical disadvantages. The instrument required a rather large polarizing field and mechanical relays to switch the polarizing currents. The polarizing coil often became badly overheated when a high data rate was used. The proton unit could make only one field determination per polarizing procedure. Nevertheless, it was the most completely developed nuclear magnetometer sensor available in 1960, and the most accurate; it also provided a direct measurement of the Larmor frequency, which simplified computations of field measurements. At the time of the ASMO proposal, the proton free-precession magnetometer was the most suitable instrument for the ASMO sensor; however, in the interim between the proposal and the construction of the breadboard ASMO, the proton precession instrument was replaced as a candidate sensor.

[8]M. E. Packard and R. H. Varian, "Free Nuclear Induction in the Earth's Magnetic Field," *Physical Review, 93,* p. 941, 1954.

[9]M. E. Packard, "On the Comparison of the Proton and the Rubidium Vapor Magnetometers as an Observatory Standard," presented at the XII Assembly of the International Union of Geodesy and Geophysics, Helsinki, Finland, 1960.

Optically Pumped Magnetometers

A. Kastler, in 1954, described a means of using optical techniques to produce orientation of the magnetic moments of atoms in an absorption cell.[10] This method, called "optical pumping," used resonance radiation to excite vapor cell atoms to higher energy states. In 1957, Kastler showed that the orientations of atoms in optically excited states could be correlated with radio-frequency resonances which corresponded to Zeeman intervals.[11] H. G. Dehmelt, in 1956, reported that paramagnetic resonance could be detected and measured by monitoring the alinement, or orientation, in the optically pumped sample.[12] Zeeman effects in optically pumped samples split pumped energy levels into various sublevels whose separations, or Zeeman intervals, are proportional to the intensity of the ambient magnetic field. In 1957, Dehmelt described a technique of producing and detecting this proportional splitting, making practicable a new class of sensitive and accurate magnetometers.[13] [14]

In general, these instruments consist of a light source producing an intense collimated beam of resonance radiation, an absorption (vapor) cell to be optically pumped, a radio-frequency source to produce resonance signal corresponding with the Zeeman intervals in the pumped vapor, and a photocell to monitor transmission of light through the vapor cell. Most systems incorporate a circular polarizer between the light source and the absorption cell, and some filter the resonance radiation to reduce the spectral effects of fine structure components.

[10]A. Kastler, Les méthodes optiques d'orientation atomique et leurs applications, *Proceedings of the Physical Society, A67,* p. 853, 1954.

[11]A. Kastler, "Optical Methods of Atomic Orientation and of Magnetic Resonance," *Journal of the Optical Society of America, 47,* pp. 460-465, 1957.

[12]H. G. Dehmelt, "Paramagnetic Resonance Reorientation of Atoms and Ions Aligned by Electron Impact," *Physical Review, 103,* pp. 1125-1126, 1956.

[13]H. G. Dehmelt, "Slow Spin Relaxation of Optically Polarized Sodium Atoms," *Physical Review, 105,* pp. 1487-1489, 1957.

[14]H. G. Dehmelt, "Modulation of a Light Beam by Precessing Absorbing Atoms," *Physical Review, 105,* pp. 1924-1925, 1957.

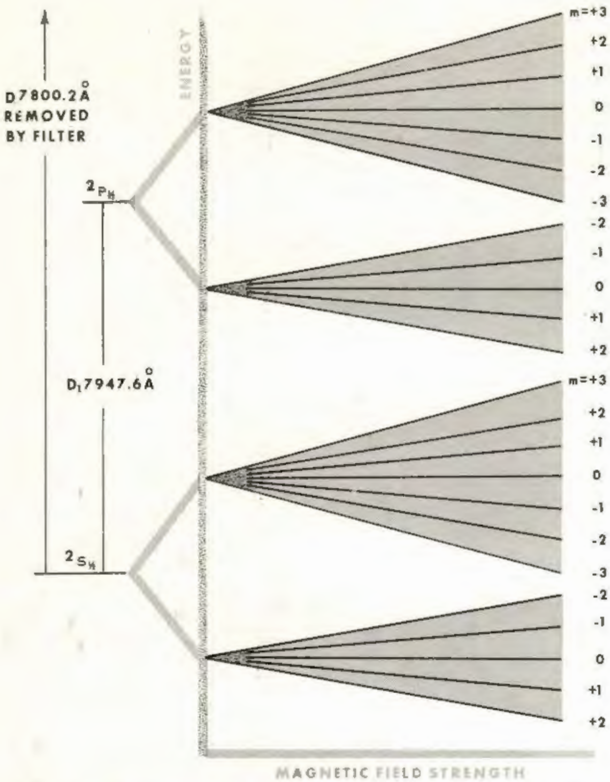

FIG. 1.--Energy levels of rubidium 85. *After Varian Associates diagram.*

Since 1957, optically pumped magnetometers have been designed and operated that use mercury vapor, alkali metal vapors, and metastable helium as the resonant material. Of these, the rubidium vapor and metastable helium instruments are of most interest to this report.

Rubidium Vapor Magnetometer

In the rubidium vapor magnetometer, radiation from a rubidium lamp is interference-filtered to exclude all but the D_1 rubidium line at 7947.6 Å, then circularly polarized, passed through a rubidium vapor absorption cell, and focused on a sensitive photocell. Absorption of photons of this light by rubidium valence electrons causes energy in the vapor cell to be increased from the $^2S_{½}$ ground state to the $^2P_{½}$ state. As excited electrons decay to any of the ground-state sublevels, absorption of D_1 photons is repeated. As a result of the light's circular polarization, the magnitude of the quantum number m associated with each electron so excited is increased by one. This quantum selection means that as absorption and reemission of photons continue, the ground-state population shifts toward the $m = {}^+3$. Because the $^2P_{½}$ state contains no m level above $m = {}^+3$ (fig. 1), transitions out of the $^2S_{½}$, $m = 3$ level are not possible, and electron energies tend to become trapped in this state, leaving the rubidium vapor with a net magnetic moment. Under this condition there can be no further absorption of light, and the vapor becomes transparent. The light flux incident upon the photodetector cell is then at a maximum, and the vapor is said to have been "pumped" into this energy level by the resonance radiation. At this time, the atomic magnetic moments precess about the ambient field at the Larmor precession rate, in the same sense, but with random phase.

The subsequent application of a weak radio-frequency magnetic field perpendicular to the ambient field and varying at the Larmor frequency, which equals the transition frequency between Zeeman sublevels, produces phase coherence of the precessing atomic magnetic moments, and destroys atomic orientation in the vapor cell, redistributing atoms to all m sublevels. For the isotope rubidium 85, this energy separation corresponds to a transition frequency of approximately 4.67 Hz./gamma; for rubidium 87, it is approximately 6.99 Hz./gamma. Once "depumped" from the $m = {}^+3$ sublevel, the electrons are once more capable of absorbing energy from the D_1 photons.

The Larmor frequency in rubidium vapor instruments can be monitored in several ways. Two methods have found most extensive use: The locked-oscillator technique of detecting resonance, and the self-oscillation technique, which detects resonance as a function of modulations of light intensity.

Locked-oscillator systems measure resonance by sweeping the frequency of the radio-frequency field through resonance until maximum absorption in the vapor cell is detected. A servomechanism controlled from the photodetector automatically adjusts the field frequency to the resonant frequency. This method was used in early experiments, but is rather inconvenient for continuous monitoring.

Because changes in orientation of atomic moments in the vapor cell modulate the intensity of the pumping light at the Larmor frequency corresponding to the ambient field value, measurement of light modulation can be used to monitor the magnetic field. Self-oscillating systems detect changes in the transmitted intensity of the component of circularly polarized D_1 light passing through the vapor cell at right angles to the pumping light component. Although the response of the silicon photocells begins to drop at Larmor frequencies of several hundred kilocycles per second (that is, frequencies that correspond to the earth's magnetic field), sufficient light intensity is available for direct detection of modulations. The output from the photodetector is amplified, shifted 90 degrees in phase, and presented as a current to the solenoid which produces the radio-frequency field at the vapor cell. The process of light modulation at the Larmor rate will continue automatically, the frequency of the oscillation changing as the ambient field changes.

In most self-oscillating rubidium systems, a single source of polarized D_1 light supplies the orthogonal components necessary for the separate processes of pumping and monitoring the Larmor-rate intensity modulation. The light component used to monitor intensity fluctuations vanishes at parallel orientation to the total field vector and becomes unusable within an approximate ± 10-degree polar cone. The pumping component is zero when the light and field vectors are 90 degrees apart, and is unusable over an approximate ± 5-degree equatorial spherical segment. Thus, the instrument is most favorably oriented when the ambient field and the optical axis are 45 degrees apart; it will not oscillate when its optical axis and the magnetic field vector are either parallel or orthogonal.

The rubidium nucleus has a magnetic moment which couples with the magnetic moment of the valence electron to create a multiplicity of closely spaced lines. Although these lines may be resolved in carefully controlled laboratory experiments, they exist in the output of a self-oscillating form as composites, or smears, of several lines. For any particular absorption line in a rubidium detector, ambient field intensity, F, is related to measured frequency, f, with sufficient accuracy by an expression of the form

$$f = aF + bF^2 \qquad (1)$$

The value a = 466,739.3 Hz./gauss for rubidium 85 has been determined by R. L. Driscoll[15] at the National Bureau of Standards, using the Breit-Rabi formula.[16] T. L. Skillman and P. L. Bender have reported the value a = 699,632 Hz./gauss for rubidium 87.[17] These values of a should be constant for all rubidium detectors. The value of b for a self-oscillating system depends to a small degree on the rubidium cell parameters and on details of the electronic circuit, and should be determined for each magnetometer by calibration in a known field. Aging effects for these factors are not yet known in detail, but are not likely to be significant.

Metastable Helium Magnetometer

F. D. Colegrove and P. A. Franken, in 1960, described an optically pumped magnetometer in which triplet metastable helium was used as the resonant material.[18] The metastable state is necessary because helium in its normal ground state has no magnetic moment.

In this device, helium atoms in a discharge tube are excited to the 2^3S_1 triplet metastable state by a weak radio-frequency field before optical pumping begins. The 2^3S_1 metastable level is sufficiently long-lived (about 2×10^{-4} sec. while the discharge is present) to be considered as the ground state of a "new" atom contained in a buffer gas of ground-state helium atoms.

Transitions are induced in the metastable atoms between the 2^3S_1 state and the 2^3P states by the absorption of a group of three helium lines at about 10,830 Å (D_0, D_1, D_2); the excited atoms return to the metastable level by spontaneous emission. As pumping continues, a steady state is reached in which a significant percentage of atoms are in the $^3S_1$ sublevels having the smallest absorption probabilities. This unequal distribution of atoms in the three sublevels constitutes an orientation of the helium atoms. A radio-frequency field applied at right angles to the ambient field destroys this orientation when its frequency approximates the resonant frequency representing the energy separation between sublevels (approximately 2.8 MHz./gauss), and transitions occur which tend to equalize the populations of these sublevels. The number of atoms in the more strongly absorbing sublevels is increased and more of the pumping light is absorbed, diminishing the intensity of light reaching the photodetector. Thus, the resonance signal becomes the difference between the intensity of light absorbed under equilibrium conditions and light absorbed when a radio-frequency field forces equal population of the levels. A locked-oscillator technique of modulating the radio-frequency field across resonance and phase-sensitive detection hold the applied frequency to the center of the resonance line, where the field is directly proportional to the output (Larmor) frequency.

Comparison of Rubidium and Helium Magnetometers

A detailed evaluation of the relative merits of rubidium and helium is not possible at the present time; more experimental work is needed before that comparison can be made. Also, a comparison based on present data would involve considerations of signal-to-noise ratio, line width, line structure, orientation dependence, and associated electronics, which are not pertinent to the present report. For purposes of this discussion, certain general comparisons can be made between the two systems. The reader is referred to a preliminary comparison, reported in 1960 by P. L. Bender, for additional detail.[19]

The helium magnetometer offers the advantage that helium, which has no nuclear magnetic moment, has a much simpler absorption line structure than rubidium 87 and rubidium 85. Because the resonant material in the helium system is a gas, problems of temperature control at the vapor cell are minimized; rubidium must be kept at an elevated temperature to maintain its vapor state.

On the other hand, the helium absorption line is nearly 10 times wider than rubidium lines, and

[15] R. L. Driscoll, private communication, 1963.

[16] J. M. B. Kellogg and S. Millman, "The Molecular Beam Magnetic Resonance Method. The Radio Frequency Spectra of Atoms and Molecules," *Reviews of Modem Physics, 18,* pp. 323-352, 1946.

[17] T. L. Skillman and P. L. Bender, "Measurement of the Earth's Magnetic Field With a Rubidium Vapor Magnetometer," *Journal of Geophysical Research, 63,* pp. 513-515, 1958.

[18] F. D. Colegrove and P. A. Franken, "Optical Pumping of Helium in the $^3S_1$ Metastable State," *Physical Review, 119,* pp. 680-690, 1960.

[19] P. L. Bender, "Measurement of Weak Magnetic Fields by Optical Pumping Methods," *Bulletin Ampère, 9e année,* pp. 621-628, 1960. Much of the following discussion of helium and rubidium magnetometers is borrowed from Dr. Bender's excellent article.

the output frequency of the helium magnetometer is approximately 5 times that of the rubidium instrument. The response time of the helium magnetometer can be quite short as a result of this higher frequency and greater line width; however, the width of the resonance line complicates the design of associated electronics, which must seek the center of the line with high precision to obtain accurate measurements over extended periods of time. The higher frequency of the helium magnetometer is too high for a direct response from the photodetectors. Although the photodetectors can provide control for a servomechanism to drive a local oscillator slaved to the Larmor frequency, this locked-oscillator method is not the best for continuous measurements. The output frequency of the helium system is also too high to permit development of a self-oscillating system at this time.

Both instruments share certain problems. Their frequency outputs are slightly dependent on orientation, and in both systems the output amplitude is reduced to zero for certain unfavorable orientations with respect to the ambient magnetic field. Manufacturers of both instruments have made multi-detector units to avoid these difficulties, with varying success. The output of optically pumped magnetometers is a continuous radio frequency, varying with the ambient field. In some systems this signal is fed directly into a gated counter. If counting is done over successive 1-second periods, the maximum magnetic field frequency response will be limited to a frequency of 0.5 Hz., which corresponds to the Nyquist frequency. Maximum sensitivity under these conditions will be determined by the field corresponding to ± 1 count, or approximately ± 0.2 gamma for rubidium 85, ± 0.14 gamma for rubidium 87, and ± 0.033 gamma for helium. A much higher frequency response can be obtained if the output frequency is mixed with a fixed frequency signal to obtain a low intermediate frequency signal which drives a frequency discriminator and an analog recorder. This method of operation is often used in studying micropulsations. Sensitivities as high as 0.01 gamma have been achieved and frequency responses up to several kHz. could be obtained if desired.

From the standpoint of application to the proposed ASMO, both the rubidium and helium magnetometers appeared in 1960 to require too much additional engineering to be practicable. As noted earlier, the proton free-precession instrument was the strongest candidate for the proposed ASMO in 1960. Between the time of the proposal and the fabrication of the breadboard ASMO, however, substantial advances were made in the development of the optically pumped magnetometers. It was concluded that even quasi-operational units of this type offered advantages which offset the comparative lack of experience in their use.

A metastable helium magnetometer,[20] developed by Texas Instruments, Inc., of Dallas, was obtained for use on the breadboard ASMO; however, the selection of a helium sensor was premature. The inherent disadvantages of the helium magnetometer, as it existed in 1960, generated difficulties during breadboard ASMO tests. The wide line width and high frequency response did not provide a good fit with the rudimentary ASMO design. Since that time, the metastable helium magnetometer has been developed into a practical and operational unit by Texas Instruments, and used in various high-reliability applications.

On the basis of tests with the breadboard system, the two prototype ASMO's and the first ASMOR were equipped with self-oscillating rubidium sensors[21] developed by Varian Associates of Palo Alto. The self-oscillating feature of these instruments is necessary for continuous magnetic field measurement, and the results obtained with the rubidium sensor have been extremely good.

The performance of the rubidium and metastable helium sensors in their ASMO/ASMOR installations is covered in a subsequent section.

THE PROPOSED AUTOMATIC STANDARD MAGNETIC OBSERVATORY

The automatic standard magnetic observatory, proposed by L. R. Alldredge in 1960,[22] was patterned after the plan reported by F. W. Bacon in 1955.[23] As described in an earlier section, Bacon developed a means by which bias fields could be used with atomic resonance magnetometers to obtain absolute measurements of declination and inclination, as well as total field intensity. Bacon's experimental device, called a "declinator," used a proton free-precession sensor centered in a Helmholtz pair of 43-cm.-radius coils. The coils were positioned in such a way that a uniform 6,700-gamma bias field could be applied at right angles across the earth's magnetic field in both the vertical and horizontal planes. Although Bacon's technique included measurement of inclination, the experimental instrument measured only declination and total field intensity, taking two measurements of declination and one of field intensity, every 30 seconds.[24]

The proposed ASMO differed from Bacon's plan in several important respects. It would use a larger (about 15,000-gamma) bias field and a coil reversal procedure, which ensured more accurate absolute inclination and declination data; automatic processing of the magnetometer output would provide the final statistical data typical of standard magnetic observatories.

In describing the proposed system, some averaging of what was proposed and what was developed has been necessary. For example, mathematics presented in 1960 have been refined and simpli-

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[20] L. D. Schearer, *The Metastable Helium Magnetometer*, Texas Instruments, Inc., Dallas, Tex., 1960.

[21] Varian Associates, "V-4938 Rubidium Magnetometer," *Data Sheet*, INS-1495, 1963.

[22] Alldredge, *op. cit.*

[23] Bacon, *op. cit.*

[24] *Ibid.*

fied in subsequent descriptions; such changes are presented in their current form. The intention here has been to preserve the significant features of the 1960 proposal without describing the ASMO in the 1960 terms.

General Description

As designed, the geometrical arrangement of the ASMO corresponded to that shown in figure 2, in which C_i and C_d represent mutually perpendicular Helmholtz coil pairs used respectively to produce bias fields for the determination of inclination and declination. The size of the Helmholtz coil system is dictated by the magnetic gradients which can be tolerated. For a field as large as 50,000 gammas, a Helmholtz coil system 97 cm. in diameter had been shown to be sufficient; for the proposed 15,000-gamma bias field, it was thought that a coil system 75 cm. in diameter would be adequate. Later, with the selection of the rubidium vapor instrument, the coil diameter was reduced to approximately 50 cm., which is convenient for an observatory instrument.

The resonant sample--a water sample in the case of a proton sensor, or a vapor cell when optically pumped sensors are used--is mounted at the center of the coil pair. The rigid coil system can be rotated about the axis *e-f*, which is maintained in the plane of the mean magnetic meridian; the axis *e-f* can be rotated about the magnetic east-west axis *a-b*; and the entire assembly can be rotated in the horizontal plane.

Initially, rotations are made about the vertical axis and the axis *a-b* so that the axis *e-f* coincides as nearly as possible with the mean magnetic field vector, $\mathbf{F}_0$. After this orientation has been completed, the declination, D_0, and inclination, I_0, of the axis *e-f* must be determined accurately. This is accomplished through the use of a mirror, mounted on the coil system, and an external precision theodolite. The mirror is adjusted perpendicular to the axis *e-f* by using the motion of a reflected beam of light for an indicator as the coil system is rotated. The theodolite is then positioned so that the telescope axis coincides with the axis *e-f* by viewing itself in the mirror. The angles I_0 and D_0 are then determined using standard procedures. After the initial hand adjustment of I_0 and D_0, and calibration, the ASMO would operate automatically.

Principles of Operation

Basically, the proposed design called for the determination of the amplitude and direction of the magnetic field vector, $\mathbf{F}$, through the use of two mutually perpendicular auxiliary bias fields. Both fields are perpendicular to the mean magnetic field vector, $\mathbf{F}_0$, and one is in the plane of the mean magnetic meridian. At any given moment, $\mathbf{F}$ may differ from $\mathbf{F}_0$. Differences between the true inclination, I, and the true declination, D, and the values of I_0 and D_0 corresponding to the orientation of the axis *e-f* are determined by use of the auxiliary fields produced by the coils C_i and C_d. If the magnetic axes of the coils were

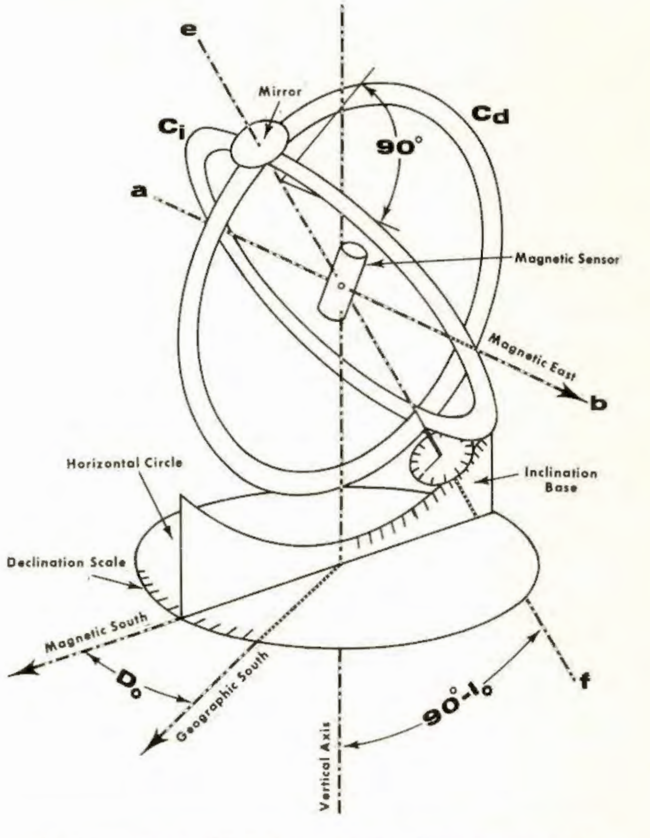

FIG. 2.--Proposed ASMO sensor and coil system, general arrangement.

accurately known, this operation would be straightforward; in practice, the effective axes of the coils must be determined as part of the calibration procedure if accurate values are to be obtained.

Determination of Inclination

The method by which the instantaneous value of I is obtained can best be described in terms of the diagram, shown in figure 3, in which the axis *e-f* is the same as in figure 2 and the axis *g-h* is perpendicular to the axis *e-f* and *a-b* (as shown in fig. 2). The plane defined by the axis *e-f* and *g-h* represents the mean magnetic meridian plane, and the axis *e-f* represents the mean magnetic field vector, $\mathbf{F}_0$. For purposes of discussion, the magnetic field vector, $\mathbf{F}$, is assumed to lie in the plane of figure 3, but inclined with respect to the axis *e-f*. The angle βi represents the departure of I from I_0.

$\mathbf{A}+$ and $\mathbf{A}-$ are equal in amplitude and represent the bias fields created by positive and negative currents, respectively, in coil C_i. $\mathbf{A}'_+$ and $\mathbf{A}'_-$ represent the same bias fields after the coil frame has been rotated 180 degrees about the axis *e-f*. The angle ϵ represents the projection, in the plane of figure 3, of the departure of the bias field from its designed direction along the *g-h* axis.

Before a bias field is applied, the magnetometer will indicate a magnitude F. When a bias field $\mathbf{A}_+$ is applied, the magnetometer will indicate a magnitude F_+, the resultant of **F** and $\mathbf{A}_+$. When the bias field current is reversed, the magnetometer will indicate a magnitude F_-, the resultant of **F** and $\mathbf{A}_-$. $\mathbf{A}_+$ and $\mathbf{A}_-$ are of equal magnitude and are antiparallel. The law of cosines, applied to the two large triangles in figure 3, shows that the approximation

$$\alpha_1 \approx \left(\frac{\pi}{2}\right) + \Delta\alpha_1 \qquad (2)$$

where

$$\Delta\alpha_1 = \frac{F_+^2 - F_-^2}{4AF} \qquad (3)$$

and

$$A = (F_+^2 + F_-^2 - 2F^2)^{1/2}/2^{-1/2} \qquad (4)$$

is accurate to within 1.5 seconds of arc if $\Delta\alpha_1$ does not exceed 2 degrees. In practice this condition will always apply.

The coil frame is then rotated 180 degrees about the axis *e-f* and measurements are made of the quantities F_+' and F_-', which correspond to F_+ and F_- before the coil was rotated. From these measurements, α_2' can be computed from

$$\alpha_2' = \frac{\pi}{2} - \frac{F_+^{2'} - F_-^{2'}}{4AF} \qquad (5)$$

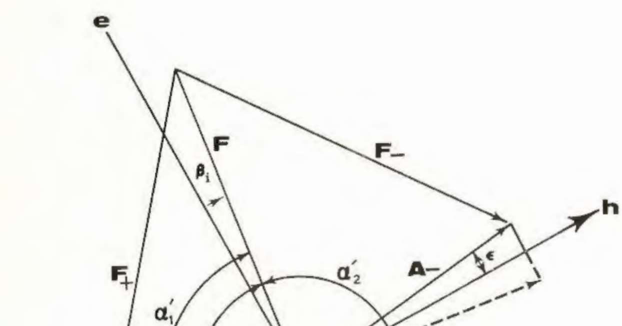

FIG. 3.--Relationships used in determining component values.

It is seen from the geometry that

$$\beta_i = \frac{\alpha_1 - \alpha'_2}{2} \qquad (6)$$

and

$$k_i = \frac{\alpha_1 + \alpha'_2}{2} \qquad (7)$$

Thus,

$$\beta_i + k_i = \alpha_1 \qquad (8)$$

In an automatic system, it would be difficult to rotate the coil mechanically to obtain α_1 and α_2' for each determination of β_i, and it is not necessary to do so. Once β_i and α_1 have been determined at a given instant of time,

$$k_i = \alpha_1 - \beta_i = \frac{\pi}{2} + \varepsilon \qquad (9)$$

which is the angle between the bias field $\mathbf{A}_+$ and the *e-f* axis, will remain constant, requiring only occasional rechecking. During subsequent automatic operation, only α_1 need be determined; the required angle β_i can then be obtained from equation 9. The final value of inclination is given by

$$I = I_0 + \beta_i = I_0 - k_i + \alpha_1 \qquad (10)$$

Determination of Declination

The measurement of declination is essentially the same as that described for inclination. To obtain declination values, the coil C_d is used to create the necessary bias field in a direction perpendicular to the mean magnetic meridian plane. In the process, the coil system must again be rotated initially 180 degrees about the axis *e-f* to obtain the declination value β_d, which corresponds to β_i in the inclination problem. Once k_d is established by an equation analogous to equation 9, β_d can be obtained automatically without further rotation of the coil.

The principal difference between the inclination and declination problems is that β_d must be projected down onto the horizontal plane. Thus, the final value of declination is given by

$$D = D_0 + \frac{\beta_d}{\cos I} = D_0 + \frac{-k_d + \alpha_1}{\cos I} \qquad (11)$$

where α_1 refers to calculations from equation 2 for the case in which bias fields are created by the coil C_d.

Errors in Measurements of I and D

All of the **A** vectors and the axis *e-f* are coplanar; however, because **F** is not usually in the mean magnetic meridian plane, α_1 and α_2' cannot by themselves determine β_i precisely, for a slight interaction is produced between measurements of inclination and declination. Errors resulting from this interaction are not significant in this application. It can be shown that when the series approximations are used for the trigonometric terms and fourth- and higher-order terms are neglected,

$$\beta_i = \frac{\alpha_2' - \alpha_1}{2} - \beta_d\,\delta + \beta_i\left(\frac{\beta_d^2}{2} + \frac{\delta^2}{2}\right) \qquad (12)$$

in which δ is the equivalent for the declination bias field of ε for the inclination bias field, that is, the angular departure from the designed direction along the g-h axis, in their respective planes. If in practice we take the value of β_i expressed by equation 6, the error will be approximately equal to $-\beta_d\delta$. This error is rather small, because β_d seldom exceeds 1 degree even at reasonably high latitudes. This value of β_d would result in an error in β_i of approximately 1 second of arc for each minute of arc for δ. The value of δ cannot be determined by the procedure described here; however, careful adjustment of the coil system limits δ to within a few minutes of arc.

A contribution to the error in the determination of α_1, and hence of I and D, is introduced by the uncertainty of the measurement of the total field values. The error in α_1 decreases as the bias field increases; however, there is a practical limit on the size of the bias field because of power and gradient requirements. By assuming that the values of F, F_+, and F_- can all be measured to an accuracy of $\pm\mu$, the maximum error where F is 50,000 gammas for the simplest case of $F_+ = F_-$ is given approximately by

$$\textit{error in } \alpha_1 = \frac{\pi}{2} - Cos^{-1}\left[\frac{\mu\,(1 + \lambda^2)^{1/2}}{5 \times 10^4\,\lambda}\right] \qquad (13)$$

where λ is the ratio of bias field intensity to total field intensity. The error in α_1 is plotted in figure 4, where it is seen that, for an error in the measurement of ± 0.1 gamma, a bias field of only 0.3 F will keep the error to less than 2 seconds of arc.

Sequence of Operation

The proposed ASMO would be programed automatically to record, once each minute, variables from which one value of F, one value of (F_+, F_-) for inclination, and one value of (F_+, F_-) for declination could be computed. After initial hand adjustments for I_0 and D_0, and coil rotations to determine initial β_i and β_d values, an automatic program would begin, following this sequence of operations:

1. At the start of each minute, the circuit to C_i would close, creating resultant field magnitude F_+;
2. A digital counter at the magnetometer output would be actuated to record the number of cycles, n_+, corresponding to F_+;

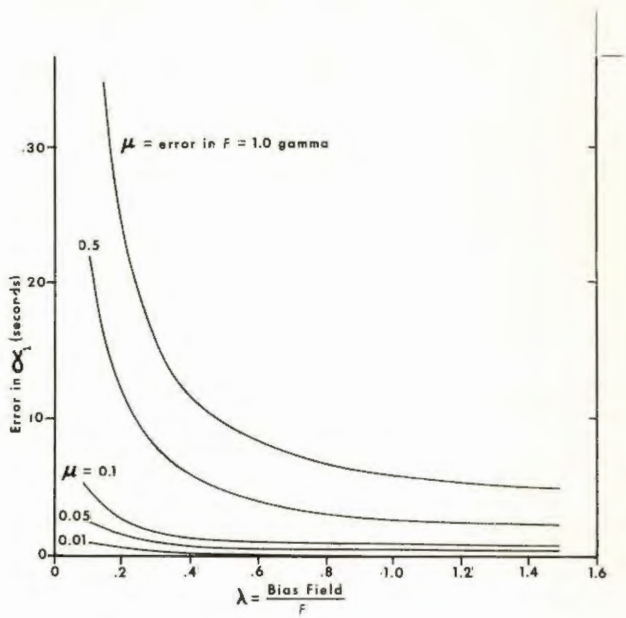

FIG. 4.--Errors in measuring α_1.

3. The bias current in C_i would be reversed, creating resultant field magnitude F_-;
4. Digital counter at the magnetometer output would be actuated to record the number of cycles, n_-, corresponding to F_-;
5. The bias field would be removed;
6. The digital counter would record n corresponding to total field magnitude F;
7. Steps 1 to 4 would be repeated using coil C_d to obtain two additional n_+ and n_- counts for F_+ and F_- fields for declination.

Because of the proposed use of a proton precession magnetometer, an internal subroutine was included in the early design to permit polarization of the proton sample. This feature was discarded as optically pumped magnetometers were incorporated in early ASMO models. It is interesting to note that the requirements shown above--that is, one F, and two each I and D values per minute--are comparatively modest. Later models would take the same measurements six times per minute, providing a complete record of the magnetic field and its components every 10 seconds.

Data Recording

The numbers n corresponding to each magnetic field measured would be recorded to six decimal digits to permit the calculation of the magnetic field values over a range of 60,000 gammas with an accuracy of 0.2 gamma. A digital-to-analog converter was proposed that would obtain voltages, V, proportional to the digital counts n corresponding to field strengths taken during each measurement cycle. Successive values of these analog voltages corresponding to a given variable could then be used to make a visible real-time record of magnetic field changes and could be used to obtain magnetic indices without waiting for the main digital record to be processed.

The above procedure is straightforward when the recorded n is nearly proportional to the magnetic field strength as is the case of the optically pumped magnetometers. A further explanation is required in the case of the proton precession instrument in which the number n usually is the number of cycles from a precision 100 kHz. oscillator which occurs during a predetermined number of proton precessions. This system produces a count n which is inversely proportional to the magnetic field strength. In this case variations in field strength are given by

$$\Delta F = \frac{constant}{V_F^2} \cdot \Delta V_F \qquad (14)$$

and since V_F^2 will not vary by more than 4 percent even for a peak variation of 1,000 gammas, the record of ΔV_F would be taken as a record of ΔF for purposes of determining preliminary magnetic indices.

To obtain variations in inclination, ΔI, V_+, and V_- (corresponding to F_+ and F_- for inclination) would be routinely commuted to a differential amplifier to record an output proportional to $V_+ - V_-$. Using equations 2 and 10, and a Taylor series expansion approximation for any fixed bias field magnitude A,

$$\Delta I = \frac{constant\ \Delta (V_+ - V_-)}{F_0 (F_0^2 + A^2) + y(A^2 - 2F_0^2)} \qquad (15)$$

where y is the component of the magnetic variation along the mean magnetic vector. For y as large as 1,000 gammas, F_0 equal to 50,000 gammas, and A equal to $0.3F_0$, ΔI is proportional to $\Delta (V_+ - V_-)$ to within 3.5 percent. This is sufficiently accurate for use in determination of preliminary K indices from the analog records.

A method of recording ΔD is very similar to that required for ΔI, and is not included here.

Computations and Magnetic Activity Indices

Recorded data would be fed directly into high-speed computers programed to compute minute and hourly average values of each desired magnetic component. In addition, the computer would determine magnetic activity indices as follows:

1. The average value of each component would be determined for each minute over a 3-hour period centered on the minute in question.
2. The difference between the average value and actual value would be determined.
3. The range of deviations between average and actual values would be determined for each 3-hour period (for K indices); and the range of deviations, or the largest single deviation (absolute), whichever is larger, would be determined for each 15-minute period (for Q indices).
4. Predetermined K and Q scales would be used to assign activity indices generally analogous with the well-known K and Q values.

Following computation, digital output would be fed into an automatic plotting machine in which the components would be plotted as magnetograms at a scale suitable for reproduction in observatory publications.

DEVELOPMENT OF AN AUTOMATIC STANDARD MAGNETIC OBSERVATORY

The foregoing material has covered a proposed automatic standard magnetic observatory, and was included to provide a theoretical basis for the subsequent discussion of laboratory and operational units. It also provides an interesting basis for comparison of objectives during the course of the program. Generally speaking, the goals of the proposal were raised during the course of the development project, so that the advanced apparatus described in 1960 seems rather ordinary beside the present ASMOR.

The four ASMO/ASMOR systems developed during the period 1960-1965 are described in the section that follows. Each type of unit--the breadboard, the two prototype ASMO's, and the final ASMOR prototype--is described in terms of developmental timetable, composition, operation, and comparative results. Each successive unit represents a major state-of-the-art advance over its predecessor, and over that which was proposed. The breadboard system somewhat exceeded the proposed system in complexity, but was clearly feasible. The two prototypes are major improvements over the initial laboratory unit. ASMOR is evidence that this project of research and development achieved, and then exceeded, its goals.

The Breadboard ASMO

The project to develop an automatic standard magnetic observatory was begun in the Coast and Geodetic Survey's Geophysics Division in February 1960, and transferred at midyear to the newly created Office of Research and Development. The immediate objectives of the project were the design and fabrication of a laboratory ASMO to test the feasibility of proposed techniques and systems, and the development of associated automatic data processing.[25]

Magnetometer Selection

Initially, a proton free-precession sensor, using auxiliary bias coils for measurement of magnetic field components, was scheduled for the breadboard ASMO. In November 1960, Texas Instruments, Inc., of Dallas responded to the Alldredge proposal with a proposal[26] to supply an optically pumped metastable helium magnetometer for the ASMO. The magnetometer described in Texas Instruments' proposal was a refinement of a laboratory model reported earlier by L. Shearer,[27] which generally followed the work of

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[25] *Cf.* L. R. Alldredge and I. Saldukas, "An Automatic Standard Magnetic Observatory," *Journal of Geophysical Research, 69,* pp. 1963-1970, 1964.

[26] Texas Instruments, Inc., *Proposal to Supply a Metastable Helium Magnetometer for an Automatic Standard Magnetic Observatory,* Dallas, Tex., 1960.

[27] Schearer, *op. cit.*

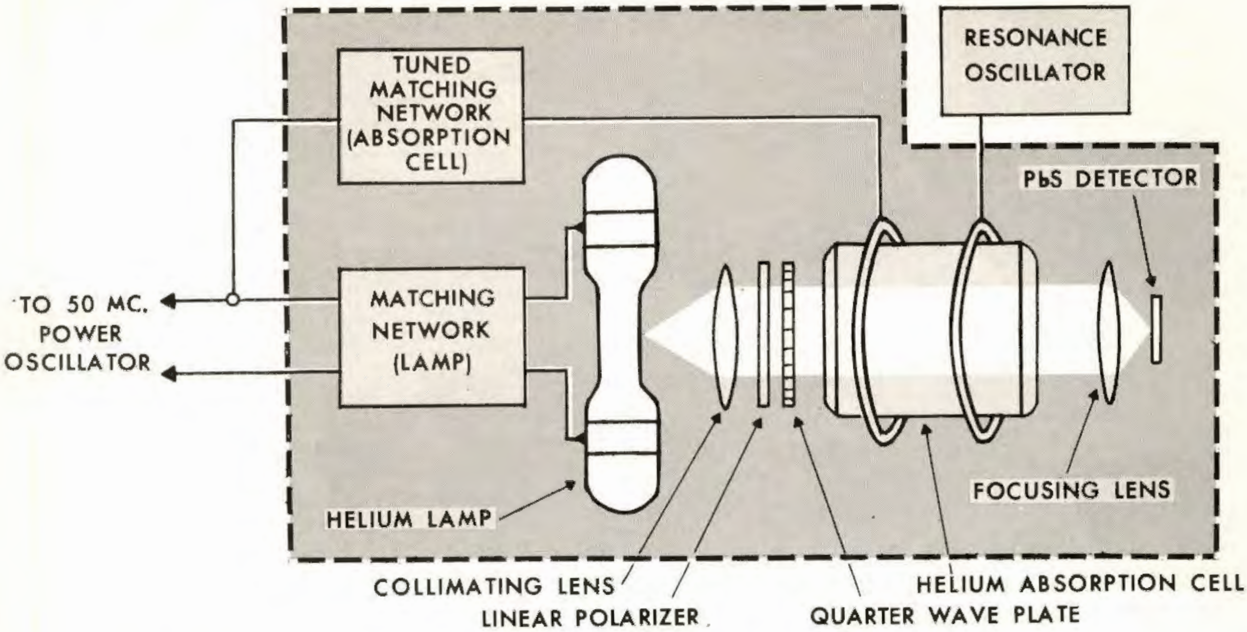

FIG. 5.--Optically pumped, locked-oscillator metastable helium magnetometer, functional arrangement. *After Texas Instruments, Inc., diagram.*

Colegrove and Franken,[28] discussed in an earlier section. The instrument (fig. 5) would consist of a detecting head, including self-starting helium lamp and absorption cell, necessary polarizers and filters, lead sulfide detector cell, matching networks, necessary lenses, and radio-frequency coil; 50-mc. power oscillator to excite the helium lamp; 1.5-mc. resonance oscillator to drive the radio-frequency coil; modulator/phase detector; a.c. preamplifier; amplifier and servomotor; discriminator; and power supply. The unit would cover the range 50,000-65,000 gammas, and have an accuracy of approximately 8 p.p.m. (0.4 gamma in a 50,000-gamma field) for absolute field measurement; increased accuracies would become available as better definition was obtained of the gyromagnetic ratio of the metastable helium atom.

Although this instrument was clearly in an early stage of engineering development, the many advantages of an optically pumped system led ASMO developers to adopt the metastable helium sensor for use in the initial unit. Engineering of the metastable helium magnetometer to preliminary ASMO specifications was conducted jointly by the Coast and Geodetic Survey and Texas Instruments, the first unit becoming available by June 1961. This unit was tested at the Bureau's Beltsville, Md., facility until work was interrupted by exciter malfunction. Familiarization tests were resumed October 9 and 10, 1961. On October 11, the metastable helium sensor was moved to the Fredericksburg Magnetic Observatory and was subjected to a 2-day series of tests against a proton resonance system, to obtain comparable data. Aside from unexpected orientation effects and some residual engineering problems, the helium unit performed satisfactorily.

Breadboard ASMO at Fredericksburg

On December 14, 1961, the breadboard ASMO was installed at the Fredericksburg Magnetic Observatory. This initial unit consisted of an optically pumped metastable helium magnetometer (Texas Instruments Part No. 445770), an electronic counter (Hewlett-Packard Model 524D), a scanner-coupler (Dymec Model DY-5794A-2), a frequency discriminator (General Radio Model 1142A), and a paper-tape punch (Friden Model 2); in addition to the magnetometer power supply, furnished by Texas Instruments, the system included a Harrison Laboratories Model 881-A power supply.

The breadboard ASMO coil system is shown in figure 6. The two vertical outer rings are part of the main frame, which slides on the base to change the inclination setting, I_0, of the axis of the central tube housing the sensor. The base is rotated about the vertical axis to obtain desired declination settings, D_0. The innermost pair of rings produces a 400-Hz. modulation magnetic field required to find the center of the absorption line in a locked-oscillator sensor; this set of coils is not needed when a self-oscillating sensor is used. The two intermediate pairs of rings carry windings in the Helmholtz configuration and provide inclination and declination bias fields. The Helmholtz coil pairs used in the breadboard ASMO had the following characteristics:

[28] Colegrove and Franken, *op. cit.*

FIG. 6.--Breadboard ASMO coil system.

No.	*Radius (cm.)*	*No. of turns/coil*	*Current (ma.)*	*Bias field produced (gammas)*
1	22.8	49	100	19,300
2	21.6	42	100	17,500

The sensor was installed and leveled on an isolated concrete pier, with the control/data console and tape punch situated some 12 meters away in the same building. Orientation of the magnetometer for I_0 was accomplished by adjusting the inclination of the instrument until I_+ and I_- measurements fell within 100 counts of one another. East-west orientation for D_0 was accomplished in a similar manner. The inclination and azimuth of the oriented instrument were determined using a Wild T-2 theodolite equipped with an autocollimating eyepiece.

In this system, microswitches in the master control sequenced bias currents in the Helmholtz pairs and provided signals to the counter and recorder. The microswitches were actuated by cams attached to the shaft of a synchronous motor. The instrument was programed to obtain measurements during 20 seconds of each minute of these frequencies:

1. f_+ corresponding to F_+ for inclination;
2. f_- corresponding to F_- for inclination;
3. f corresponding to F (no bias field used);
4. f_+ corresponding to F_+ for declination;
5. f_- corresponding to F_- for declination.

The counter counted the number of cycles of magnetometer output during a 1-second gating period to determine each frequency; each count was held in the scanner-coupler for subsequent readout and recording on eight-track paper tape. A block diagram of breadboard ASMO components is shown in figure 7.

The breadboard ASMO operated only intermittently until the latter part of February 1962, as developmental answers were worked out to improve system performance. Most of the problems encountered were of the superficial kind anticipated in any breadboard project, and all were resolved by observatory personnel during the testing sequence. At one phase of the testing, a similar helium system was received from the U.S. Navy Hydrographic Office (now U.S. Naval Oceanographic Office) for evaluation, and comparative tests were run with the ASMO and Navy units.

In April 1962, an optically pumped self-oscillating rubidium vapor magnetometer was obtained from the National Bureau of Standards and evaluated in the breadboard ASMO framework. The orientation effects of the rubidium instrument were somewhat more pronounced than those experienced with the helium unit. Calibration of the rubidium magnetometer changes with a change in the orientation of its axis with respect to the field being measured. Errors associated with this effect were avoided by calibrating the breadboard sensor against a proton resonance magnetometer in the same orientation.

As discussed in an earlier section, the signal output of the self-oscillating rubidium instrument is greatest when the light axis is inclined 45 degrees from the ambient magnetic field vector. Bias fields applied perpendicular to **F** are limited in amplitude to 0.3 F, so that the resultant field being measured differs from **F** by no more than

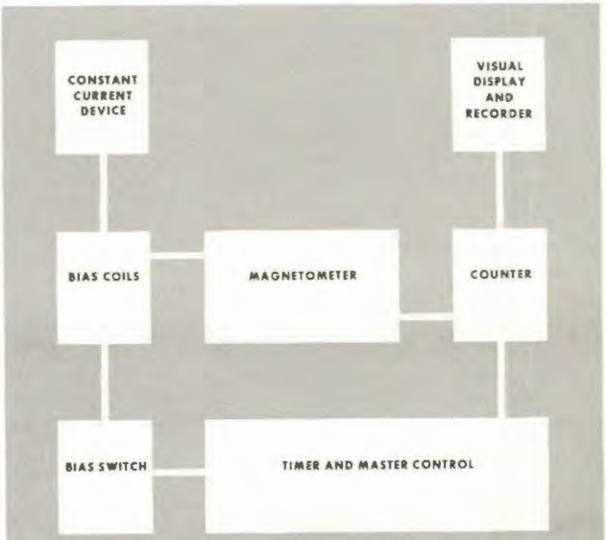

FIG. 7.--ASMO breadboard, general arrangement.

17 degrees, and for this tilt there is still adequate signal output.

Orientation error for the 17-degree variation in orientation which occurs when bias fields are applied would normally amount to a few gammas for a single measurement. It was found, however, that this "error" became part of the calibration constants k_i and k_d, discussed earlier. Measurements taken with bias fields applied are used only in computing angles made by the instantaneous **F** with the mean **F**; because these angles are small and the bias fields are nearly symmetrically arranged about **F**, resulting orientation errors become negligible.

Results obtained in these tests were quite good, and indicated the rubidium sensor might have some advantages. The self-oscillating feature lent itself more readily to continuous observations than the electronic/electromechanical, locked-oscillator method used in the helium unit, and showed greater drift stability. The comparatively narrow line width and comparatively low frequency response of the rubidium instrument were also attractive. Accordingly, the rubidium sensor replaced the helium magnetometer in the breadboard ASMO during the last several months of its test cycle, which ended in December 1962.

Computation and Data Reduction

For the rubidium detector, F is related to the recorded frequency, f, with sufficient accuracy by an expression of the form

$$f = aF + bF^2 \qquad (1)$$

When the quadratic formula is used to express F in terms of f and then expanded, the approximation

$$F = \frac{f}{a} - \frac{bf^2}{a^3} \qquad (16)$$

is obtained. For purposes of machine computation, a linear approximation is used of the form

$$F = c + df \qquad (17)$$

where

$$c = F(f_0) - \left(\frac{\delta F}{\delta f}\right)_{f_0} f_0 = \frac{b}{a^3} f_0^2 \qquad (18)$$

$$d = \left(\frac{\delta F}{\delta f}\right)_{f_0} = \frac{1}{a} - \frac{2b}{a^3} f_0 \qquad (19)$$

and where f_0 is the mean frequency for the observatory location. The value a = 466,739.3 Hz./gauss was determined by R. L. Driscoll[29] at the National Bureau of Standards and should be constant for all rubidium 85 sensors.

Angles that must be computed to determine the direction of **F** and any desired component are given by equations 2 and 3. For routine calculation, equation 3 was simplified by writing

$$\Delta\alpha_1 = e(F_+ - F_-) \qquad (20)$$

where

$$e = \frac{F_+ + F_-}{4AF} \qquad (21)$$

In reducing ASMO data, e was taken as a constant. This approximation resulted in a maximum error of only 2 or 3 seconds of arc in the determination of α_1, which is within acceptable limits.

In determining angles, it was not necessary to compute separate field values from equation 17 before taking the difference called for by equation 20. Because equation 17 is linear in f, the constant term c canceled out and the angle was given by

$$\Delta\alpha_1 = l(f_+ - f_-) \qquad (22)$$

where $l = ed$. This simplification was worthwhile because f values were the recorded variables of an ASMO.

Data taken over a period of several days during the breadboard tests were subsequently processed on a digital computer to obtain D, H, and Z components and simulated K indices. These data were compared with hand-scaled data from normal magnetograms for the same period. Differences in D, H, and Z values are shown in figure 8; differences in K indices are shown in table 1. Table 2 shows the gamma limits used in preparing the K scale for Fredericksburg.

It can be seen that, except for pier differences, the hourly means for the two instruments were very nearly constant. As these data were being processed, every irregularity of a gamma or more in the comparison was traced to errors in hand-scaling the normal magnetogram. This meant that the breadboard ASMO produced hourly mean values which were at least as good as those obtained from the normal instrument. The difference in K indices obtained from the two systems occasionally differed by ±1. Deviations of this

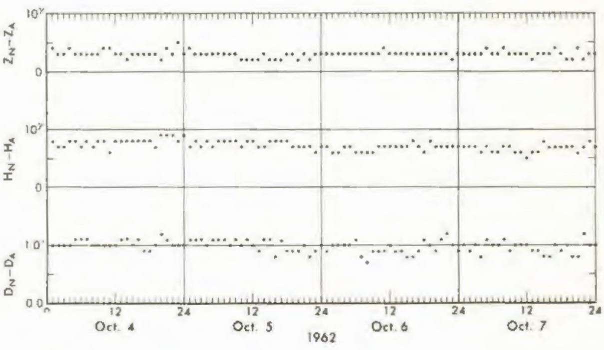

FIG. 8.--Difference between hourly means scaled from normal magnetograms (N) and ASMO data (A).

[29] Driscoll, *op. cit.*

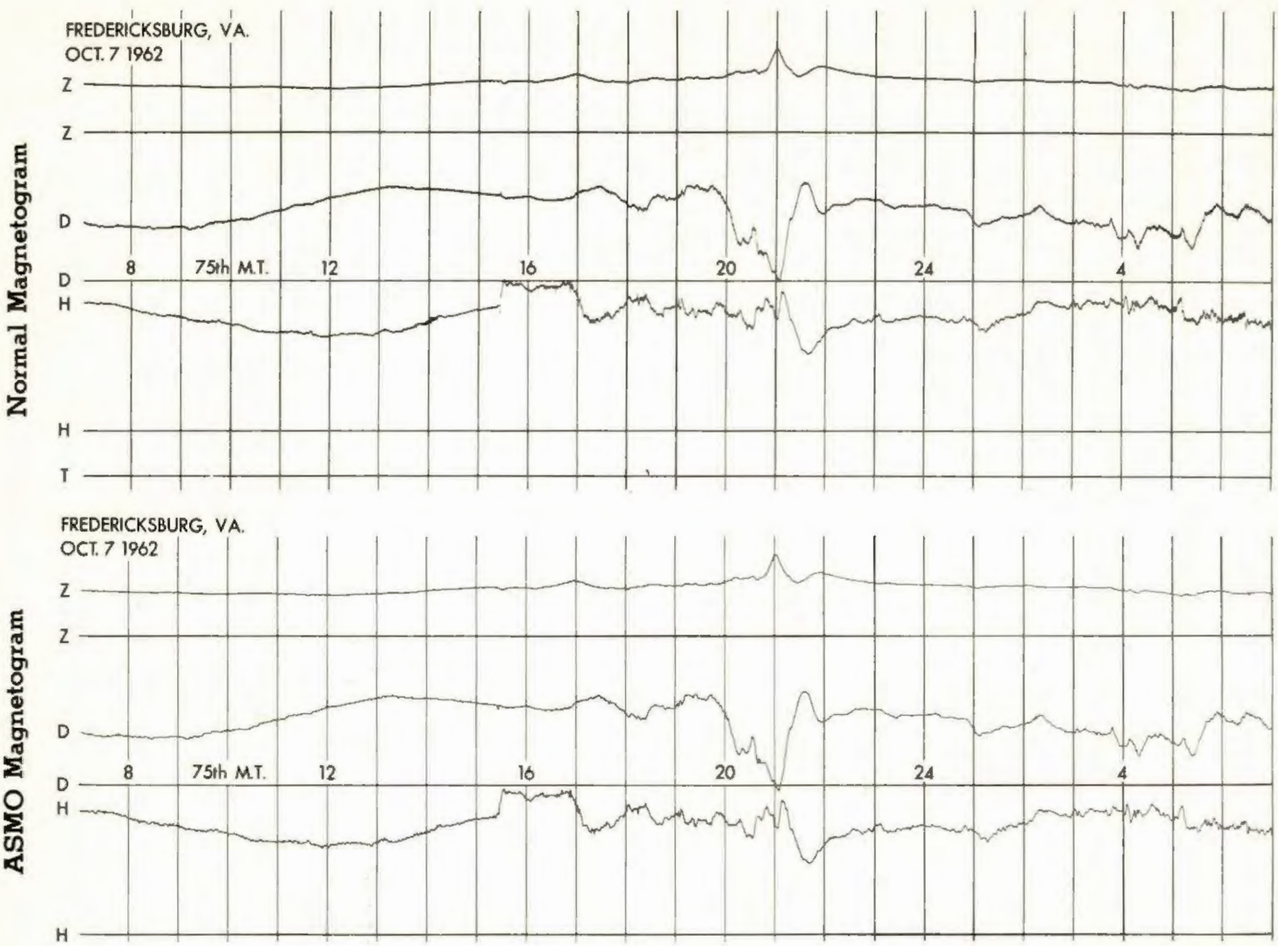

FIG. 9.--Comparison of normal and ASMO magnetograms.

Table 1.--Three-hour-range K indices at Fredericksburg, Va.

Values shown below were scaled from normal magnetograms (N) and calculated from ASMO data (A), and are based on range of differences between recorded values and three-hour averages.

Hour interval	October 1962 (G.m.t.) 4		5		6		7	
	N	A	N	A	N	A	N	A
0-3	2	2	0	1	4	4	2	2
3-6	3	2	2	2	3	3	3	2
6-9	3	3	2	2	3	3	1	1
9-12	2	2	1	2	1	2	2	2
12-15	1	2	1	2	3	3	1	2
15-18	2	2	2	2	2	3	1	2
18-21	1	2	4	4	1	1	3	3
21-24	3	2	3	3	2	2	4	4

magnitude often occur when two observers scale the same magnetogram.

Digital data from the ASMO for October 7, 1962, were plotted automatically by a Calcomp plotter controlled by an IBM 1620 computer. The Calcomp plotter draws an approximately straight line between minute values. In figure 9, a computer-reconstructed magnetogram is compared with a normal magnetogram for the same day. No differences of detail that would result in different statistical results were detected in this comparison.

Table 2.--Gamma limits of the K scale used in Fredericksburg, Va.

Limits of variation (gammas)	K index
0 - 5	0
> 5 - 10	1
> 10 - 20	2
> 20 - 40	3
> 40 - 70	4
> 70 - 120	5
>120 - 200	6
>200 - 330	7
>330 - 500	8
>500	9

Accomplishments

The breadboard ASMO was an assortment of shelf items mated to a new class of magnetometer, and not an integrated apparatus engineered for compatibility between components. During its test cycle, the ASMO left something to be desired in terms of reliability, and knowledge of long-term stability and accuracy. On the other hand, it was estimated that even in the breadboard configuration, individual-derived component values could be obtained with an accuracy of ± 0.2 gamma or less.

The important accomplishment of the test cycle was that the feasibility of the ASMO concept was clearly demonstrated, and guidelines were established by which this feasibility could be translated into a reliable, integrated system. Furthermore, this comparative success at an early stage of ASMO development gave impetus and direction to the overall project.

Specifications for a redesigned ASMO, based on the experience afforded by the breadboard experiment, were completed by mid-1962. Early in 1963, after completion of the initial test program, contracts were let for the design and fabrication of two production prototype units. The advance to follow-on ASMO systems is described in the next section of this report.

ASMO Production Prototypes

Early in 1962, the Bureau's Office of Research and Development began planning for two second-generation experimental ASMO systems to be purchased during fiscal year 1963. These would be fully transistorized, integrated production prototypes, and they would be used to determine the long-term operational characteristics of ASMO-type systems. At a meeting held May 18, 1962, general guidelines were established for ASMO redesign; by July, these guidelines had been translated into specifications.

The new systems would be built around an optically pumped magnetometer, modified by suitable bias coils. During the first 20 seconds of each minute, five frequencies would be measured that corresponded to five magnetic field measurements: F_{+i} with the inclination bias field applied in the positive sense; F_{-i} with the inclination bias field applied in the negative sense; F with no bias field applied; F_{+d} with the declination bias field applied in the positive sense; and F_{-d} with the declination bias field applied in the negative sense. These correspond to parameters recorded by the breadboard ASMO. The redesigned system, however, would record frequencies, augmented by 100,000, which correspond to: F_{+i}; $F_{+i} - F_{-i}$; F; F_{+d}; and $F_{+d} - F_{-d}$. The intent here was to simplify recording and computing by automatically recording the difference between the positive and negative frequencies for component measurements, instead of recording separate positive and negative frequency values for each parameter. The preset 100,000 count was used to preclude the recording of negative values.

Once put into service, the ASMO would be operated continuously, and would compete with magnetometric equipment in which outages of a few minutes per year are considered excessive. Therefore, primary emphasis was placed on reliability in the new design. The ASMO would use every component far below its nominal-rated capacity, and, wherever possible, functional elements would be grouped under common subsystems. No effort was made to identify the functions shown in figure 10 with separate items of equipment, or to design a totally modular unit. On the contrary, it was intended that an integrated system be designed that minimized the number of parts. For example, the precision oscillator, digital clock, program control, and counter would be a single unit employing no more than four or five transistorized card modules. All powered units would be transistorized to use a common battery power supply without inverters or other mechanical devices.

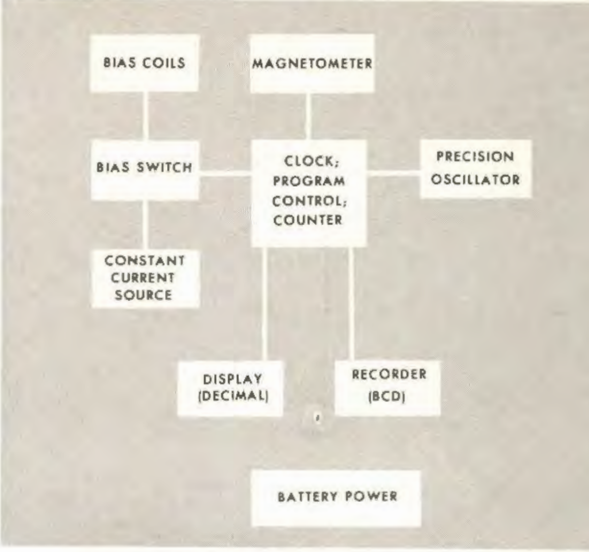

FIG. 10.--ASMO production prototype, proposed functional arrangement.

Contracts were let for final design and production of two ASMO prototypes in the third quarter of fiscal year 1963.[30] Data Technology Corporation (DTC) of Mountain View received a contract to provide the ASMO data and control system. Varian Associates of Palo Alto would furnish an optically pumped, self-oscillating rubidium vapor magnetometer and accessory equipment, excluding bias coils, which would be provided by the Coast and Geodetic Survey. The DTC contract, dated January 24, 1963, was amended during the course of the project to provide for a modified power supply (April 2) and a modified paper-tape punch (May 29), and to alter voltage specifications arising from interfacing problems between the magnetometer and the data system (August 9).

[30] U.S. Department of Commerce, Coast and Geodetic Survey, contract CGS-1019, October 22, 1962, awarded to Data Technology Corp.; and CGS-1119, March 5, 1963, awarded to Varian Associates.

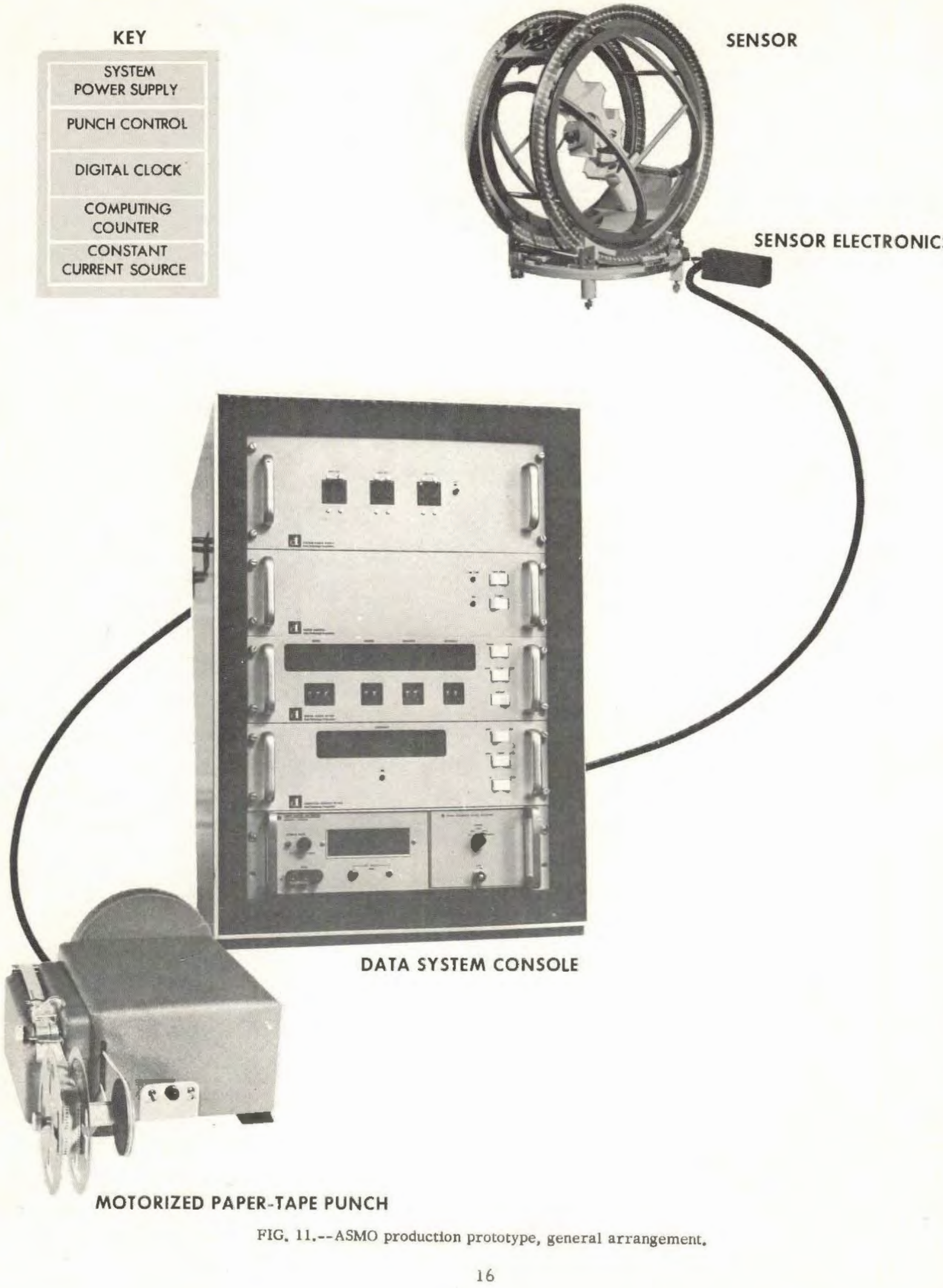

FIG. 11.--ASMO production prototype, general arrangement.

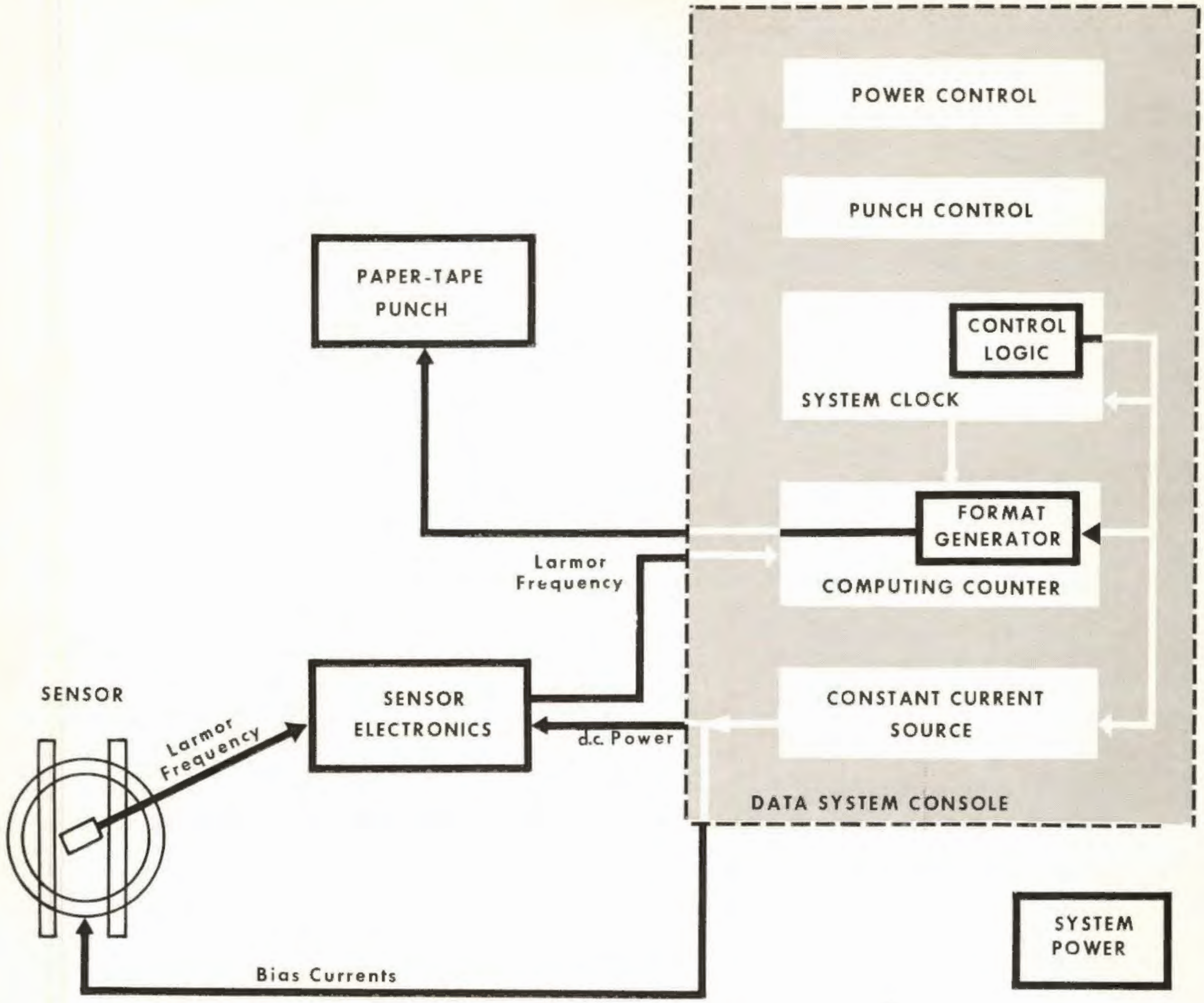

FIG. 12.--ASMO production prototype, functional arrangement.

On July 30, 1963, DTC shipped the first ASMO production prototype to the University of California at Berkeley, where it was displayed for the XIII General Assembly of the International Union of Geodesy and Geophysics (IUGG) during August. Subsequently, this unit was moved to the Fredericksburg Magnetic Observatory and put into essentially continuous operation there.

The second ASMO production prototype--the "Western" ASMO--was shipped to Varian Associates later in the year, and operated intermittently at their Webb Test Facility pending completion of the joint Varian Foundation and Coast and Geodetic Survey magnetic observatory at Castle Rock. The ASMO was installed at the Russell Varian-Castle Rock Magnetic Observatory in September 1964, and continued operation there until July 1965, when it was moved to the Bureau's Dallas Magnetic Observatory, where it continues as an operational system.

General Description

In the DTC-Varian ASMO production prototype, a self-oscillating rubidium vapor magnetometer (Varian Part No. 49-538) operates in conjunction with a separate data system comprising a constant current source (DTC drawing 10939), a computing counter (DTC drawing 11488), a digital clock (DTC drawing 11486), and an externally-mounted, motorized, paper-tape punch (Friden Model 2). The general arrangement of this instrument is shown in figure 11; its functional arrangement is shown in figure 12.

The sensor unit is a cylindrical assembly containing the rubidium lamp, vapor cell, photodetector, optical components, and sensor heater, as shown in figure 13. The housing is constructed of concentric fiberglass cylinders between which are the heater winding, radio-frequency coil, cell-temperature control thermistor, interca-

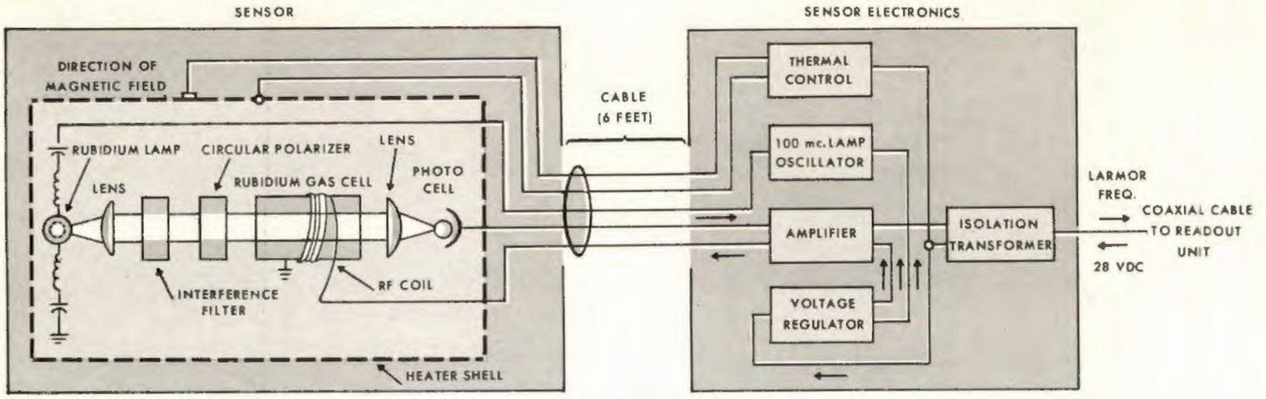

FIG. 13.--Optically pumped, self-oscillating rubidium vapor magnetometer, functional arrangement.
After Varian Associates diagram.

bling, and a Faraday shield. After assembly, this space is filled with low-density acrylic foam for purposes of thermal insulation and mechanical support. A small window penetrates the housing, permitting observation of the rubidium lamp. The inner housing contains the photodetector, rubidium lamp, optical components, and the rubidium vapor cell. Internal sensor temperature is maintained at or near 50° C. automatically by an electric heater controlled through a separate electronics unit by the cell-temperature control thermistor. Sensor power is furnished by the data system constant current source via a coaxial cable, which also carries frequency output to the computing counter; bias coil current is supplied over a separate line. The Varian sensor is positioned within a coil system (nominal 22-cm. radius) furnished by the Coast and Geodetic Survey.

Sensor electronics is provided by a separate unit connected to the sensor by a 3-meter cable, and operated with unregulated +26 to +32 volts d.c. supplied from the data system's constant current source. The electronics package contains three plug-in modules, each of which consists of modular electronic circuit groups. The use of ferromagnetic materials is minimized in the electronics unit to reduce the magnitude of fields produced by direct current loops to the smallest possible values.

The data system digital clock derives a 1-second count from a 1-mc. crystal-controlled oscillator whose accuracy is stable to within a part in 2×10^8 per day. Time is presented on the clock's front panel in a display of nine Nixie [31] tubes showing days, hours, minutes, and seconds. Rotary digiswitches and a preset button provide for selection of any desired starting time; an advance and retard button permits time to be updated after the preselection has been made. Automatic recycle of the clock occurs at 24 hours and 365 days. The digital clock chassis includes the logic for the predetermined sequence of system operation, controlling the constant current source, computer counter, and paper-tape punch.

The constant current source contains the constant current module, which presents its front panel control for output adjustment. A mode select switch provides for the operate mode, in which automatic operation is sequenced by the plot control logic; the null mode, in which the null circuit provides for stability checks on the constant current source; and the external monitor, to which an external meter can be connected into test points on the front panel. The plus and minus inclination and declination direction switches provide for the type of current drive when in the null or external modes. The constant current chassis also contains the mercury relays used to control and sequence constant current output to the Helmholtz coil pairs at the magnetometer sensor.

The computing counter is equipped with a very sensitive Schmitt trigger input capable of detecting sine-wave inputs from ± 0.25 to ±10 volts. The frequency input received by the counter is accrued in six decades of storage and displayed by six Nixie [32] tubes on the front panel. An auto or test mode selector switch on the front panel provides for the automatic sequence as performed by the control logic, or self test of the computing counter alone. A start/stop switch permits resetting and perforation to count in either the automatic or test mode. In the test mode, a green light indicates counts in excess of 1 million, or a negative remainder when count up and down sequences are employed sequentially. The computing counter chassis contains all logic for sequencing and drive to the format generator, also in this chassis, which provides all logic for sequencing and drive to the paper-tape punch.

Data system power uses two 12-amperes regulated power supplies (+12 volts d.c. and - 12 volts d.c. nominal) for operation with a 115-volt a.c. source, and two pairs of 6-volt batteries for operation without the 115-volt a.c. A pair of diode OR gates and two 1-ohm resistors provide the necessary isolation for floating the batteries on the d.c. power lines, and for the charging and maintenance of charge to the batteries. Because

[31]® Burroughs Corp.

[32]® Burroughs Corp.

the entire data system is floated on standby batteries, operation is not impeded by external power failure. Reserve power for 4 hours' operation is available from the battery system.

System output is recorded on paper tape; eight-track paper-tape code is used (fig. 14). Scan positions 1-8 are read out to the recorder only once an hour at the first readout following 00 minutes 00 seconds. Scan position 9 is read out to the recorder only at the first readout following 00 minutes 00 seconds. Scan positions 1, 9, and 16 are fixed; scan positions 2 through 8 are controlled by the clock, and scan positions 10 through 16 are controlled by the computing counter. The motorized paper-tape punch operates at a rate of 20 characters per second.

For automatic operation of the system, the computing counter is reset to 000,000, at which count the automatic sequence commences. Actuation of the computing counter must occur during the period between 30 and 59 seconds of any minute to avoid the recording of partially meaningless data; when the nearest 00 second of system time is reached, the counter begins the automatic sequence shown below. Each step occurs once each minute, except as noted.

1. At 00 minutes 00 seconds (once each hour), system time information in scans 1 through 9 is gated onto the paper tape.

2. At 00 seconds (once each minute except the 00 minute), the carriage return character in scan 9 is gated onto the paper tape.

3. At 00 seconds, current is applied to the inclination coils in the positive sense (increasing downward); a pulse presets the computing counter to 100,000; and a countup signal is sent to the computing counter to ready it for the countup sequence.

4. At 03 seconds, the computing counter gate is opened and a frequency count is obtained.

5. At 04 seconds, the computing counter gate is closed and the frequency count ceases. The count obtained during the interval between 03 and 04 seconds is gated onto the paper tape (scans 10 through 16 for a frequency, augmented by 100,000, which corresponds to F_{+i}). At 04.003 seconds, the drive current to the inclination coil in the positive sense is removed. At 04.011 seconds, the drive current is reversed in the inclination coils to the negative sense. The 3-millisecond time delay described here applies to every operation of the mercury relays, that is, every step in which current is either applied to or removed from the bias coil system. The computing counter retains the frequency count obtained during the interval between 03 and 04 seconds.

6. At 05 seconds, a countdown signal is sent to the computing counter to ready it for the countdown sequence.

7. At 07 seconds, the computing counter gate is opened and a frequency count in the countdown direction is taken. This sequence starts from the count accumulated in the computing counter register during the interval between 03 and 04 seconds.

8. At 08 seconds, the computing counter gate is closed and the frequency count remaining in the computing counter register is gated to the punched paper tape (scans 10 through 16 for a frequency, augmented by 100,000, which corresponds to $F_{+i} - F_{-i}$). At 08.003 seconds, the nega-

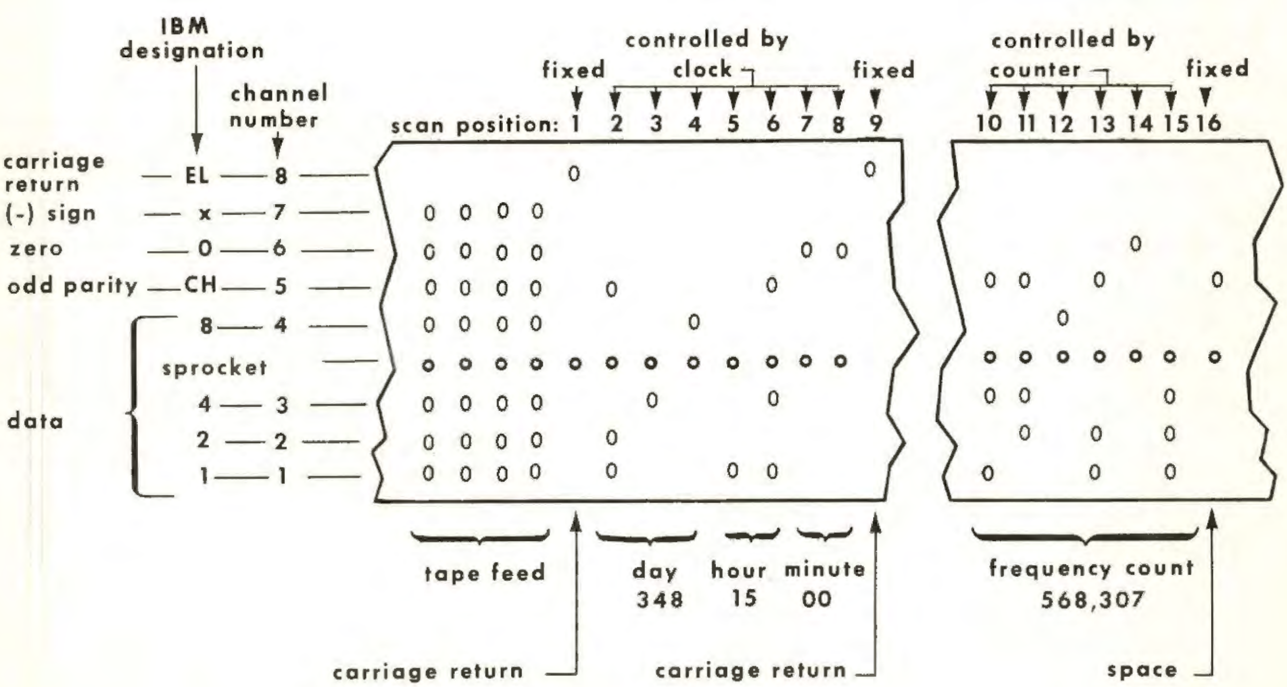

FIG. 14.--ASMO production prototype tape format.

tive drive is removed from the inclination coil. The constant current source is shorted from 08 seconds to 12.003 seconds.

9. At 10 seconds, a pulse presets the computing counter to 100,000.

10. At 11 seconds, the computing counter gate is opened and a frequency count is taken.

11. At 12 seconds, the computing counter gate is closed and the frequency count obtained by the computing counter register is gated on to the paper tape (scans 10 through 16 for a frequency, augmented by 100,000, which corresponds to F). At 12.011 seconds, a 20-millisecond pulse is initiated that places positive (eastward) current drive to the declination coil.

12. At 14 seconds, a pulse presets the computing counter to 100,000.

13. At 15 seconds, the computing counter gate is opened and a frequency count is taken with the computing counter preset to 100,000.

14. At 16 seconds, the computing counter gate is closed and the frequency obtained by the computing counter register is gated onto the paper tape (scans 10 through 16 for a frequency, augmented by 100,000, which corresponds to F_{+d}). At 16.003 seconds, a 20-millisecond pulse removes the positive current drive to the declination coils. At 16.011 seconds, another 20-millisecond pulse is generated which inserts a negative current drive to the declination coils. The computing counter retains the frequency count obtained during the interval between 15 and 16 seconds.

15. At 17 seconds, a minus countdown signal is sent to the computing counter to ready it for the next countdown function.

16. At 19 seconds, the computing counter gate is closed and the frequency count is taken in the countdown direction.

17. At 20 seconds, the computing counter gate is closed and the frequency count obtained by the computing counter register is gated on to the paper tape (scans 10 through 16 for a frequency augmented by 100,000, which corresponds to $F_{+d} - F_{-d}$). At 20.003, a 20-millisecond pulse removes the negative current drive to the declination coil. The computing counter retains the count obtained during the interval between 19 and 20 seconds.

There is a dead period in the interval from 21 seconds through 59 seconds. A system interlock prevents operation in any test mode except during the interval between 30 and 59 seconds of each minute.

Instrument Performance, Fredericksburg ASMO

The first ASMO prototype system was installed at the Fredericksburg Magnetic Observatory in December 1963, following its display and subsequent operation at the University of California at Berkeley, and preliminary tests at the Bureau's Beltsville, Md., facility during November. For the first six months of operation and testing, the Fredericksburg ASMO was plagued with equipment malfunction and failure; operational stability was not achieved until mid-1964. On June 18, 1964, the instrument was put into essentially continuous operation, remaining in this mode until June 30, 1965, when it was disconnected for maintenance and repair, and for installation in a specially constructed building.

The problems encountered on the Fredericksburg ASMO were for the most part traceable to engineering deficiencies and a pattern of component failure under ASMO loadings. The data system's constant current source produced short- and long-term fluctuations above allowable limits. Minor problems were also encountered with the numerical display in the computing counter and with the paper-tape punch. Deterioration of signal level in the impedance coupling network appeared to be the result of the unit's being housed in an unheated building.

The magnetometer gave some trouble in the form of noise from the vapor cell heater and deterioration of sensor tube material. Although the signal-to-noise ratio of the sensor was acceptable, occasional noise bursts from the heater coil disturbed the frequency count. This difficulty, the result of a faulty transformer used to drive the output coaxial cable, was corrected by the manufacturer. Sensor tube deterioration was corrected in subsequent sensor assemblies.

Continuous operation was also delayed by the lack of experience with this totally new instrument, a consideration which applies to both the engineering of the instrument and its operation at the Fredericksburg Magnetic Observatory. Frequent component failure indicated that preliminary estimates of ASMO demands had fallen somewhat below the actual case, although it had been specified that prototype system components were to be used well below their nominal-rated capacity. But only after ASMO had entered its test cycle could there by any real certainty as to what reliable minimum capacities would be. As ASMO experience accrued, however, system malfunctions were corrected by replacing existing components with higher-rated components. Similarly, problems involving system logic were resolved with increasing dexterity as additional ASMO experience was gained.

After a preliminary operational sequence in June and July 1964, the Fredericksburg ASMO was put into essentially continuous operation. Intermittent outage (that is, two 1-day gaps in the first 80 days due to tape malfunction) continued, but no major breakdowns occurred between August 1964 and June 1965.

A typical computer output showing hourly means for one component, *D*, for November 1964, is shown in figure 15 for the Fredericksburg Magnetic Observatory. The declination is 6 degrees West plus the tabular values in tenth-minutes. The day of the month is shown in the first column and the hour of the day is shown in the first row. Daily means are given in the last column; monthly hourly means are given in the last row.

Figures 16 and 17 show typical magnetograms automatically reconstructed from the digital data for the magnetic observatories at Dallas and Castle Rock.

While the ASMO was in operation at the Fredericksburg Magnetic Observatory, it was

GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	MEAN
1	572	570	572	573	559	567	572	566	570	570	559	546	549	543	559	584	600	638	640	606	578	585	601	572	577
2	566	570	551	569	595	562	568	557	560	557	558	561	554	555	571	589	599	609	605	589	575	576	571	572	572
3	572	571	564	571	579	578	577	575	566	563	562	559	553	552	561	579	592	599	599	590	580	577	574	570	573
4	568	569	571	555	576	579	576	572	569	566	563	556	555	571	585	588	594	605	607	598	588	580	575	566	576
5	558	567	568	569	573	581	576	571	570	568	565	559	552	572	565	590	608	611	612	613	601	582	569	567	578
6	567	568	570	572	573	572	575	575	566	558	563	558	554	553	560	575	593	606	606	596	585	580	574	570	574
7	567	568	569	571	571	573	574	574	572	569	565	561	550	545	555	572	590	596	592	582	575	575	573	569	571
8	563	562	569	570	570	564	576	583	573	564	561	557	555	567	570	583	596	604	598	591	587	585	577	572	575
9	566	540	524	553	544	560	579	575	590	589	574	578	564	550	557	578	600	606	605	611	606	590	574	544	573
10	562	563	510	566	576	578	577	574	589	575	568	560	549	539	538	555	569	585	595	596	595	585	576	570	569
11	567	568	571	572	579	580	578	574	587	579	560	556	548	545	552	569	592	603	601	590	582	577	578	573	574
12	563	556	559	563	578	609	586	575	572	573	572	570	563	557	557	574	600	612	618	610	598	586	579	572	579
13	569	568	570	574	575	581	611	591	578	569	570	570	565	562	559	572	586	601	611	605	592	583	577	573	580
14	571	571	572	575	577	578	578	580	572	566	564	562	552	545	553	568	589	604	602	590	579	575	574	572	574
15	571	570	571	571	573	575	578	581	569	567	558	555	543	560	589	601	604	605	619	593	579	582	595	564	578
16	561	570	568	575	575	568	578	573	551	544	539	551	541	544	557	583	604	605	602	596	588	580	583	569	571
17	571	569	573	571	572	572	571	571	567	567	566	565	559	554	569	591	601	606	600	587	581	583	579	576	576
18	574	573	570	573	574	574	573	575	574	570	567	565	558	553	559	575	592	601	596	590	582	582	578	574	575
19	572	568	572	571	573	578	578	576	574	571	569	565	558	550	553	569	584	595	595	590	584	581	573	570	574
20	568	568	572	568	573	575	575	574	571	576	570	558	555	554	558	575	591	603	602	595	584	578	575	570	575
21	569	568	567	570	574	578	579	579	576	570	563	563	556	549	552	567	584	599	601	594	581	572	570	564	573
22	564	565	564	572	576	579	578	577	579	566	563	571	562	547	551	572	594	616	619	605	589	579	578	570	577
23	546	557	559	557	544	552	591	589	583	625	621	619	631	587	595	641	633	639	627	614	603	589	577	571	594
24	566	562	567	571	574	581	583	584	578	579	569	565	559	555	558	569	583	597	601	595	588	580	574	572	575
25	569	569	570	572	574	576	577	577	576	574	571	567	563	558	555	568	585	594	602	596	587	580	572	569	575
26	565	565	571	555	568	574	574	578	581	593	588	598	580	602	602	613	624	625	618	611	600	586	580	573	589
27	566	570	572	571	569	573	581	578	577	572	571	568	563	556	549	559	577	592	598	596	594	585	575	570	574
28	570	570	546	567	569	565	575	563	566	562	567	560	559	558	556	569	588	614	609	599	591	579	573	570	573
29	569	569	570	570	574	575	575	573	571	571	565	564	567	566	564	572	581	588	592	585	584	582	578	585	575
30	581	576	572	573	572	557	566	573	571	572	579	571	568	566	563	572	580	582	581	580	579	587	577	586	574
MEAN	567	567	564	569	572	574	578	575	573	572	568	565	560	557	562	579	594	605	605	596	587	581	577	571	00576

FIG. 15.--Fredericksburg ASMO, hourly mean values of declination for November 1964.

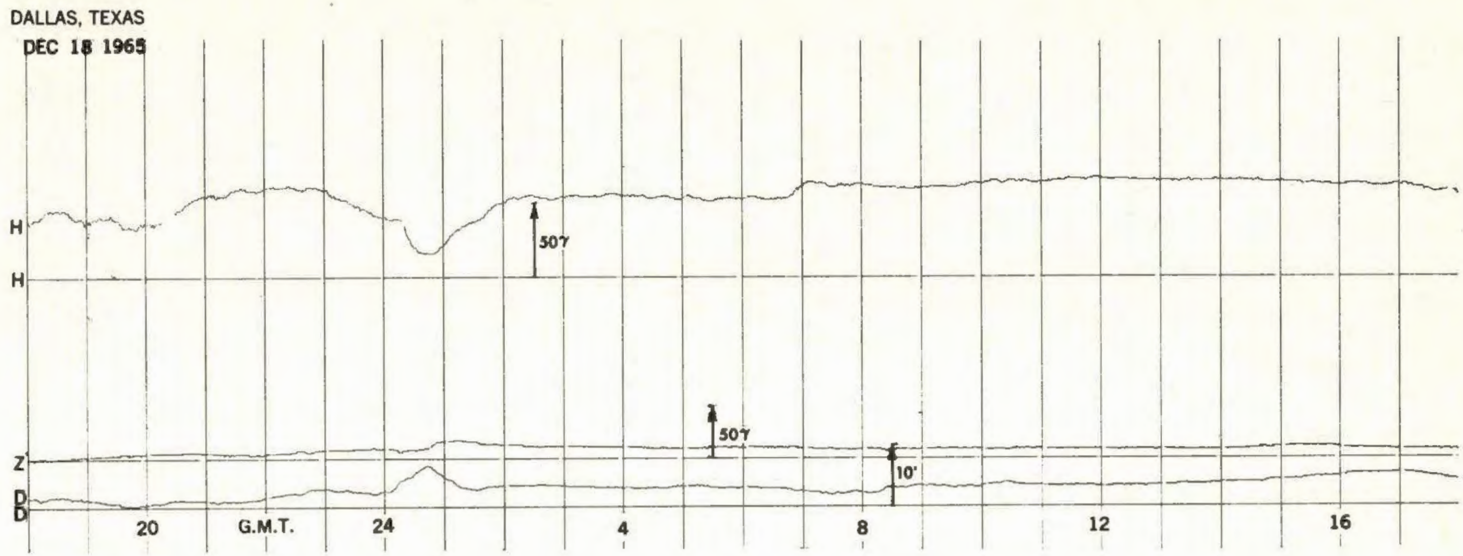

FIG. 16.--Magnetogram for December 18-19, 1965, from the Dallas ASMO.

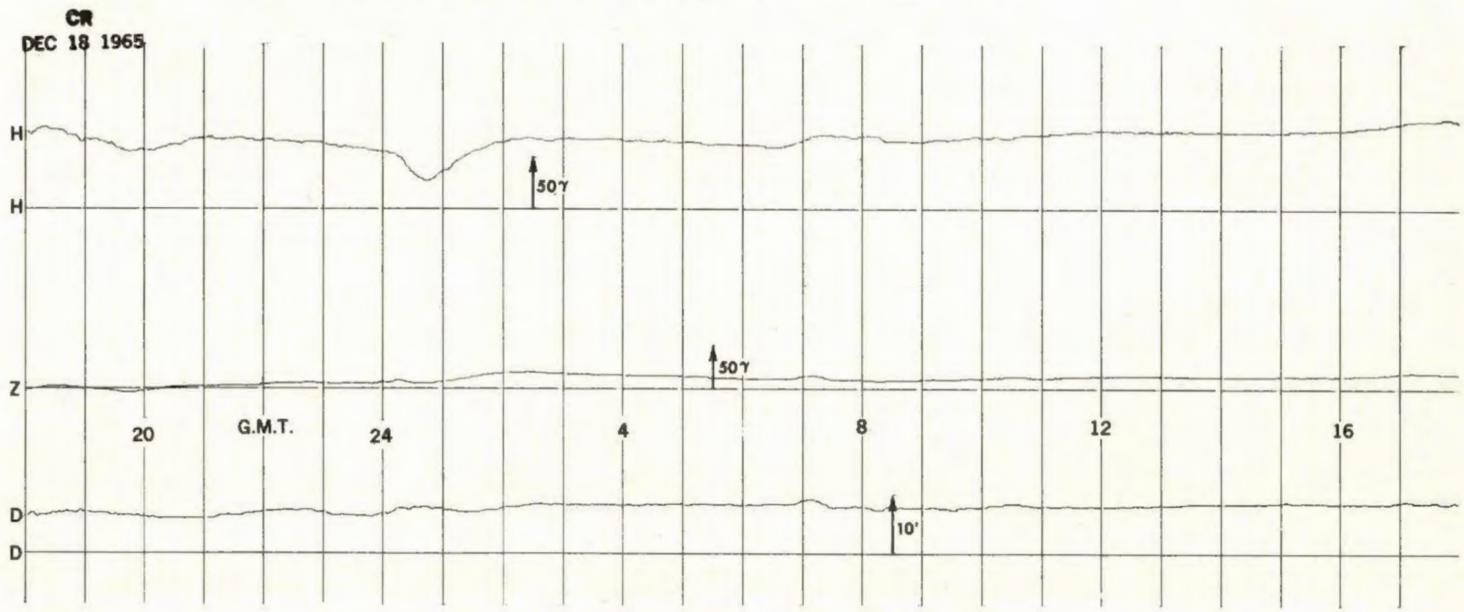

FIG. 17.--Magnetogram for December 18-19, 1965, from the Castle Rock ASMOR.

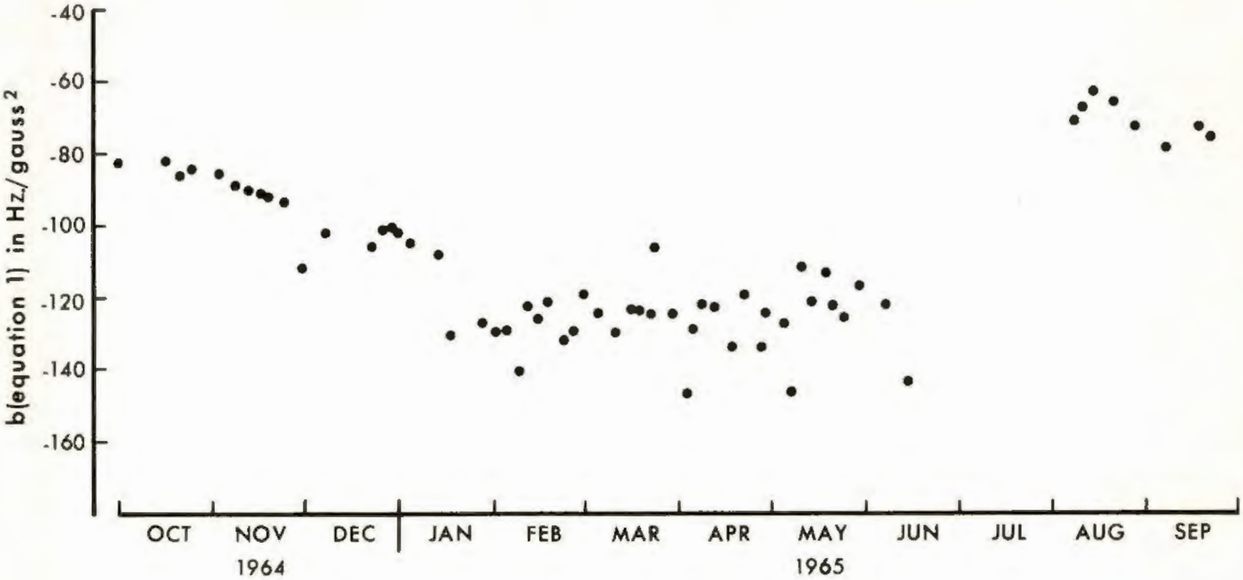

FIG. 18.--Values of *b* (equation 1) obtained during a 1-year's operation of the Fredericksburg ASMO production prototype, October 1964-September 1965.

possible to get ân idea of the stability of the rubidium magnetometer. In particular, the apparent value of *b* in equation 1 was determined by comparing the ASMO results with results from a proton magnetometer. Figure 18 indicates the results of this comparison. The total variation shown for *b* amounts to a total change in calibration for the Rb sensor of nearly 4 gammas. This indicates a need for periodic calibration of the sensor against a proton instrument.

Instrument Performance, Western ASMO

The second ASMO prototype was initially scheduled for installation at the Bureau's Dallas Magnetic Observatory, which began routine operations in July 1963. Prior to delivery, however, a tentative agreement was reached between the Varian Foundation and the Coast and Geodetic Survey to establish a cooperative magnetic observatory in the San Francisco Bay area in memory of Dr. Russell H. Varian. The evolution of this agreement is discussed at length in the section covering the ASMOR--a direct result of the decision to establish a cooperative western magnetic observatory. It was decided that, in the interim between dedication of the Russell Varian-Castle Rock Magnetic Observatory and ASMOR availability, the second ASMO prototype would be installed at the new observatory. Accordingly, this instrument was shipped directly from DTC to Varian Associates.

From August 1963 to September 1964, the so-called Western ASMO operated intermittently at Varian Associates' Webb Test Facility at Stanford University; in July 1964, it was placed in essentially continuous operation. In September 1964, it was moved to the magnetic observatory at Castle Rock, pending availability of the ASMOR in February 1965. The Western ASMO operated concurrently with the ASMOR at the Castle Rock site until July 7, 1965, when it was shipped to the Dallas Magnetic Observatory.

In general, Western ASMO performance paralleled that obtained at the Fredericksburg Magnetic Observatory. Persistent difficulties with the constant current source were not properly resolved until August 1964, and, as a result, the instrument gave only intermittent data. The problem of component failure also persisted, so that over its period of operation at the Dallas Magnetic Observatory, the Western ASMO has been gradually "retransistorized" to support the requirements of continuous operation.

Since July 1964, the Western ASMO has produced essentially continuous data, interrupted principally by movement from installation to installation.

Accomplishments

The ASMO prototypes were the first instruments to measure both total field intensity and components automatically over extended periods, and the first magnetometric systems to permit direct digital computation from a digital output. As such, the prototype instruments satisfied much of the intent of the research and development project. No hand-scaling was involved in computing data acquired by the ASMO prototypes; and, once continuous performance had been achieved, very little active participation by the observer was necessary to sustain operation.

Of more immediate importance, however, was the effectiveness of both systems as test models. The lessons learned during the first 6 months of prototype operation permitted ASMO/ASMOR developers to make *educated* revisions of system standards, and guided the present "retransistorizing" of the two instruments. Once reinforced to these higher standards, the two instruments established a good record of reliability over relatively long periods of continuous operation. They have ceased to be thought of as strictly experimental prototypes; their installations at the magnetic observatories at Fredericksburg and Dallas are permanent.

Principally, the ASMO prototypes contributed experience, both to design engineers and geophysicists involved in the project. Vital experience was also accrued on the data-processing side. The extent to which the lessons of the prototypes were learned, and the degree to which project participants were aided by increased experience, are apparent when considered in the context of ASMOR. That very successful culmination of the research and development project is discussed in the next section.

The Automatic Standard Magnetic Observatory – Remote (ASMOR)

A remotely situated, telemetering ASMO system was an inevitable successor to the prototype instruments. In the case of the present project, development of such a system was given impetus by the establishment of the Russell Varian-Castle Rock Magnetic Observatory (see below), and by the relative success of the prototype systems.

Late in 1962, representatives of the Varian Associates and the Coast and Geodetic Survey began informal discussion to determine whether arrangements could be made for a cooperative geomagnetic observatory in the San Francisco Bay area. As originally conceived, this observatory would be a cooperative effort of the Bureau and one of the area's universities, and would occupy university lands; the initial contact with Varian Associates was made to determine that organization's interest in constructing observatory buildings. This plan was modified as it became apparent that the Varian Foundation and the Bureau would be the parties cooperating in the venture.

On August 29, 1963, in a meeting held at Palo Alto, representatives of the Varian Foundation proposed that the observatory be established within the boundary of Castle Rock State Park, for which the Varian Foundation had been acquiring land to be given to the State of California. Such land as the observatory required would be withheld from the park land. At a subsequent meeting, held in Palo Alto November 7, Varian Associates offered to build observatory structures and to install necessary utilities at the observatory site. The main interest of both Varian Associates and the Varian Foundation was to aid basic research in geomagnetism and to establish a memorial to the late Dr. Russell H. Varian. The establishment of the cooperative observatory, it was hoped, would help revive scientific effort in geomagnetism in the San Francisco Bay area, the benefits of which would be felt by the Coast and Geodetic Survey, Varian Associates, and local universities.

Articles of agreement between the Varian Foundation and the Coast and Geodetic Survey were formulated during November 1963, and endorsed by the cooperating parties in the spring of 1964. The observatory would be a new experimental type, employing only the latest developments in magnetometric instruments. Initially, the Western ASMO would be the instrumental base of the Castle Rock installation; however, the remoteness of the site and the large number of prospective users of Castle Rock data indicated that a telemetering ASMO system would be more attractive here.

In January 1964, the Coast and Geodetic Survey initiated a revision of ASMO specifications to obtain the system needed at the Castle Rock site. Generally, these revisions fell into two categories: Those which had the objective of improving system efficiency and reliability, and those which provided the data-telemetering and remote-recording feature.

The first category of revision involved improvements in the selection and presentation of recorded parameters, and increases in the data-acquisition rate. In the revised system, only frequencies, augmented by 100,000, corresponding to $F_{+i} - F_{-i}$ (designated ΔF_i), F, and $F_{+d} - F_{-d}$ (designated ΔF_d) would be recorded, although all five frequencies formerly recorded would be measured and available on command as a numerical display for calibration purposes. Initially, it was proposed that F values be recorded in analog form during the 40 seconds of each minute not used for digital recording. This feature was subsequently discarded in favor of an increased rate of data acquisition; the revised system would complete a measurement cycle during each 10 seconds of each minute, providing an output approaching that obtained with conventional rapid-run magnetographs. The rate would be adjustable at the operator's option, recording every 10-second period, every other 10-second period, every third 10-second period, or every sixth 10-second period. The new system would employ an incremental drive magnetic-tape recorder instead of a punched paper-tape recorder; 7-track, 1.27-cm. ($\frac{1}{2}$-inch) magnetic tape would be used with reels compatible with IBM 1401 computer operation. An analog recorder containing a digital-to-analog converter would provide a continuous strip-chart record.

Data would be recorded either at the observatory or at remote locations. Four recording stations, one of which would be designated a master recording station, could be served by the observatory, at distances of up to 200 kilometers.[33] Data would be transmitted in digital form over a private, leased standard voice-quality telephone line. Equipment would be packaged to provide separate transmitting and receiving modules, and the instrument would have provisions for direct connection of the digital magnetometer into a recording unit without the addition of intervening equipment. The instrument, without the remoting equipment, would be known as the ASMO; with remoting equipment, the instrument would be known as the ASMOR.

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[33] In practice, there is no distance limitation between sensor and recorder.

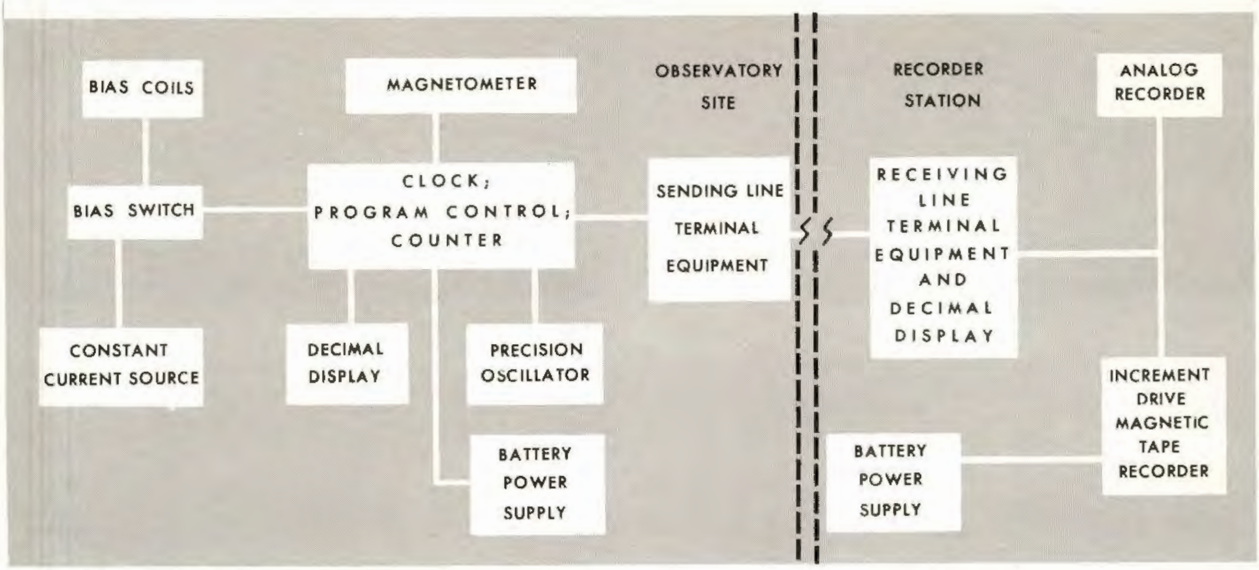

FIG. 19.--ASMOR system, proposed functional arrangement.

Superficially, the ASMO prototypes and proposed ASMOR seem to be variations on a single design; reliability specifications, components (except remoting equipment), and principles of operation are similar. The differences between systems are the product of experience gained on the ASMO prototypes, and they are sufficient in number and magnitude to make the proposed ASMOR a new, rather than a modified, instrument. As proposed, the ASMOR would carry the project into its truly operational phase, performing somewhat above the comparatively modest requirements of the 1960 proposal. The proposed functional arrangement of the ASMOR system is shown in figure 19.

In the last quarter of fiscal year 1964, Varian Associates was awarded the contract[34] to design, manufacture, test, and furnish one ASMOR system. Delivery of this unit was made to the Russell Varian-Castle Rock Magnetic Observatory facility on February 19, 1965, when acceptance tests were begun. The ASMOR has operated continuously since that date, and, following the correction of minor problems, was accepted by the Coast and Geodetic Survey during November 1965.

General Description[35]

In the ASMOR system, a self-oscillating rubidium vapor magnetometer and coil assembly operate in conjunction with three other major units of equipment: the data transmitter, data receiver, and recorder section. The sensor assembly is mounted on a massive concrete pedestal in a small building at the magnetic observatory at the Castle Rock site. The data transmitter is located in an instrument building more than 250 meters from the sensor, far enough away to prevent disturbance of the measured magnetic field by electronic equipment, vehicles, and human activity around the observatory. The main data receiver and recorder are located in the Hearst Memorial Mining Building at Berkeley for use by the academic community. Up to the present time, one additional receiving and recording station is located at the Ames Research Center in Mountain View. The general arrangement of ASMOR equipment blocks is shown in figure 20.

The magnetometer sensor used in the ASMOR system is essentially the same as that installed in the ASMO prototypes, although some modifications to the basic system were made for the ASMOR application. As in the ASMO prototype sensor, an electronics package is permanently fixed to the sensor with a short length of cable, and contains the lamp driver, sensor-temperature control thermistor, and a signal amplifier to drive the 250-meter cable connecting the magnetometer to the data transmitter. The Larmor frequency signal and the d.c. power required by the electronics package are conveyed over a single coaxial cable, transformers at each end decoupling the two. A separate cable carries the coil bias current from the data transmitter to the Helmholtz coils. The bias coils used with the ASMOR sensor have a nominal 28-cm. radius and consist of two mutually perpendicular aluminum frames, each wound with 42 turns of copper wire. A maximum bias field of 26,000 gammas can be obtained with this coil assembly. The coils are mounted in such a way that they can be adjusted in azimuth and inclination, and are leveled by means of three jacks and sensitive bubble levels.

[34]U.S. Department of Commerce, Coast and Geodetic Survey, contract CGS-1296, June 19, 1964, awarded to Varian Associates.

[35]John Blesch, "An Automatic Magnetic Observatory," *Geophysics Technical Memorandum No. 21,* Varian Associates, INS-1574, 1965. Much of the following description of the ASMOR system was borrowed from this copyrighted document.

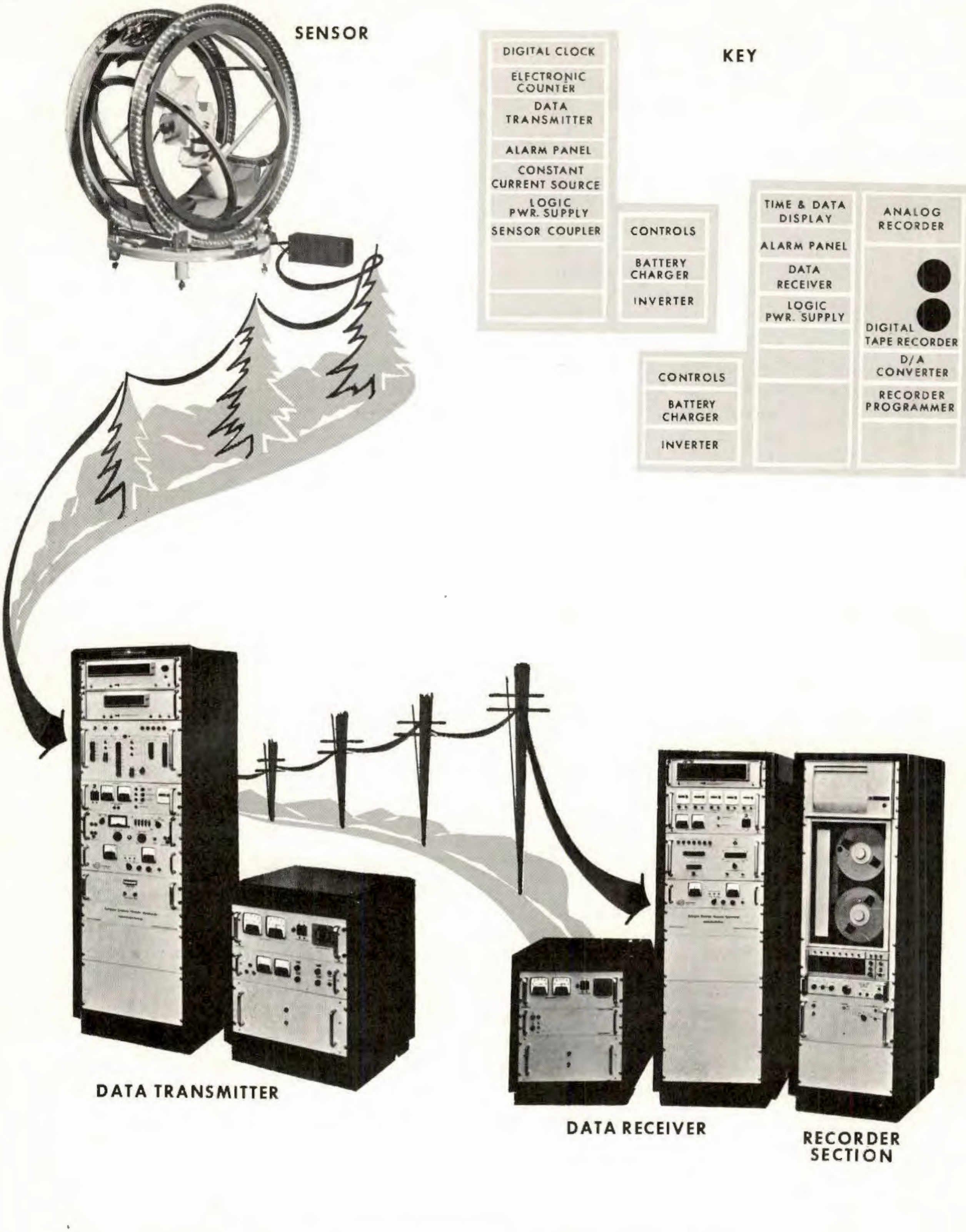

FIG. 20.--ASMOR, general arrangement. *After Varian Associates diagram.*

The data transmitter equipment group includes the magnetometer sensor coupler, bidirectional electronic counter, digital clock, and data transmitter. The magnetometer sensor coupler separates the incoming Larmor frequency from the d.c. current going to the sensor, and amplifies it for input to the electronic counter. The counter counts the Larmor frequency on command for a 1-second gate time, thereby providing a digital measurement of magnetometer output frequency. The counter is a solid-state, externally-controlled bidirectional totalizer. Input signals are passed through the input amplifiers and are converted into pulses of uniform amplitude and rise time. The output of the input amplifier is applied in a continuous train to a cascade of six bidirectional decade counting units. Counter display is independent of counting action, occurring only on command from the system programer. This feature permits the operator to select the display of any one or all five parameters being measured.

The digital clock is a solid-state timing instrument that measures elapsed time in units of days, hours, minutes, and seconds. Time reference is supplied by a 1-MHz. crystal oscillator whose output frequency is divided in five decade steps to 10 Hz. In normal operating mode, this 10-Hz. signal is applied continuously to a cascade of 10 counting units, and is totalized. Elapsed time is displayed numerically on the front panel with a resolution of 1 second, and is terminated in digital form on a rear panel connector with a resolution of 0.1 second. The following pulse outputs are provided at rear panel connectors:

1. 1×10^6 p.p.s., for monitoring timing-oscillator stability;
2. 1×10^3 p.p.s., used by data transmitter to develop serial clock for 202D Dataphone; [36]
3. 100 p.p.s., for bidirectional counter time base;
4. 1 p.p.s., not used;
5. 1 p.p.m., for timing data transmitter operations occurring once per minute;
6. 1 p.p.h., for timing data transmitter operations occurring once per hour.

This time information, once decoded, generates commands which operate the other components. As a result, the ASMOR system operates in synchronism with the clock. Each measurement cycle begins at the same instant of each minute of each hour of the day. This pattern of operation provides unique advantages when recording natural phenomena by facilitating correlation with other sources of data.

The data transmitter contains the digital logic which sequences and actuates the system, initiating specific operations at specific times as decoded from the digital clock. Signals are generated that command the electronic computer to reset and to count at the proper time, and to actuate the relays which control the bias currents to the Helmholtz coils. The system is designed to operate automatically in a program synchronized with the digital clock; however, sufficient controls are provided on the front panel to allow manual operation for system checkout and test. A 36-bit shift register in the data transmitter accepts data in parallel form, then shifts them serially, along with address and keying bits, through a pulse-width modulator and into a Bell System Dataphone[37] for transmission via telephone line. This shift register provides the ASMOR system with its remote transmitting capability. Five different types of data are handled by the shift register and sent to the receiving station:

1. Frequency count of the electronic counter transmitted every two seconds;
2. Minute and second as generated and indicated by the digital clock, transmitted every second;
3. Day-of-the-year and hour as indicated by the digital clock, transmitted every hour for continuous display at the receiving station;
4. Supervisory and alarm, transmitted every second, to give an indication at the receiving station in the event of observatory power failure, manual operation, dangerous over-temperatures, or unauthorized entry into observatory buildings;
5. Time and address symbols: # transmitted every minute; d, h, @, once per hour; end of record (EOR) gap, once per hour.

The relays and power supplies required by the alarm circuits, together with circuit breakers and power control equipment for the complete ASMOR system, are located in the alarm panel. Here also are located the relays which switch current to the bias coils on command from the digital logic. A bias coil current of exceptionally high stability is supplied by the constant current source.

The standby power supply is a completely separate system into which the a.c. line cord of the ASMOR may be plugged to obtain uninterrupted power. The standby power supply consists of a set of high quality lead-acid storage batteries, a battery charger to keep the batteries fully charged between periods of power failure, a static inverter which operates on battery current and produces 120-volt, 60-cycle power for the ASMOR system, and a control section containing relays to switch the ASMOR system from line power to standby power in the event of commercial power failure. It will be noted that the ASMOR is not floated on a battery power supply, and does not receive its power through this standby system. This was an important lesson learned from operation of the ASMO prototypes.

The receiving station includes two major equipment blocks, the data receiver, and the recorder section. If the telephone link is not used between the data-gathering and recording functions, the recording equipment can be plugged directly into the data transmitter; the data receiver is required, however, to accept information from the Dataphone at the receiving terminal and to convert it to parallel form for the recorders. The standby power system for the receiving terminal is the same as that used for the transmitting terminal, except for a small difference in capacity.

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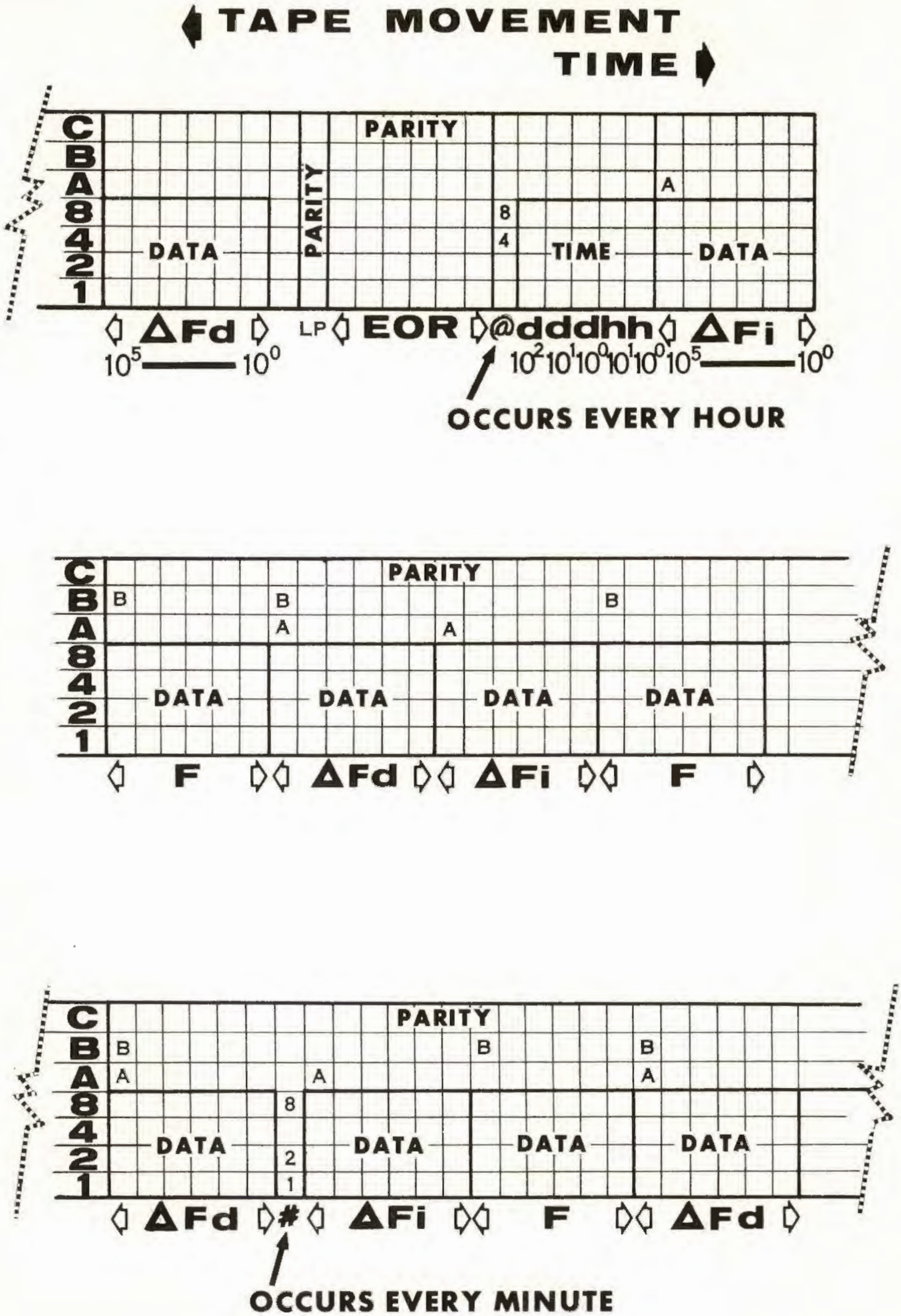

FIG. 21.--ASMOR magnetic tape format. *After Varian Associates diagram.*

The data receiver is equipped with a 36-bit shift register identical to that located in the data transmitter. This shift register accepts data from the telephone line in serial form, and is supplied in parallel form for display and recording. The frequency count and time information are stored and displayed in the display unit at the data receiver, permitting the same visible display at the receiving terminal as is displayed at the transmitting terminal. The alarm panel indicates the status of the three transmitting terminal alarm circuits. Panel lights indicate when an alarm condition has occurred and remain lighted until manually reset. Elapsed time meters indicate the duration of alarm conditions.

The recorder section contains equipment required to record data and time on digital magnetic tape and to produce a visual analog record of this information. The recorder programer controls this function, presenting the data to the recorders in the proper form and providing the command signals properly timed to actuate the equipment. An incremental drive magnetic-tape recorder records observatory data in digital form ready for direct processing by a high-speed digital computer. Time information is entered on the magnetic tape every minute with field data; the day-of-the-year and hour are recorded every hour. With time information recorded on the tape with field data, the exact time of occurrence of any unusual field activity can be readily determined. The tape format used in the ASMOR system is shown in figure 21.

A digital-to-analog converter in the recorder section accepts parallel digital data and converts them to a voltage level which can be recorded on the strip-chart recorder. Data are presented in separate tracks which indicate variations in total field intensity, declination, and inclination. Once each hour, a time mark is recorded on the chart to permit quick, visual correlation of ASMOR data with data obtained from other sources. A segment of the ASMOR analog record is shown in figure 22. The top trace shows the changes in declination, the bottom trace gives the changes in inclination, and the center trace shows the changes in total field intensity. The breaks in the traces are caused by a resetting when the trace goes off scale. ASMOR system specifications are shown in table 3.

Table 3.--ASMO equipment specifications.
[*After Varian Associates table.*]

Sensor

Type: Optically pumped rubidium vapor.
Measurement range: 15,000 to 80,000 gammas.
Sensor sensitivity: ±0.001 gamma.
System sensitivity: ±0.2 gamma (due to counter least count uncertainity).

Clock

Time-base stability: ±3 parts in 10^7 per month over ambient temperature range.
Time display: Day-of-year, hours, minutes, and seconds.

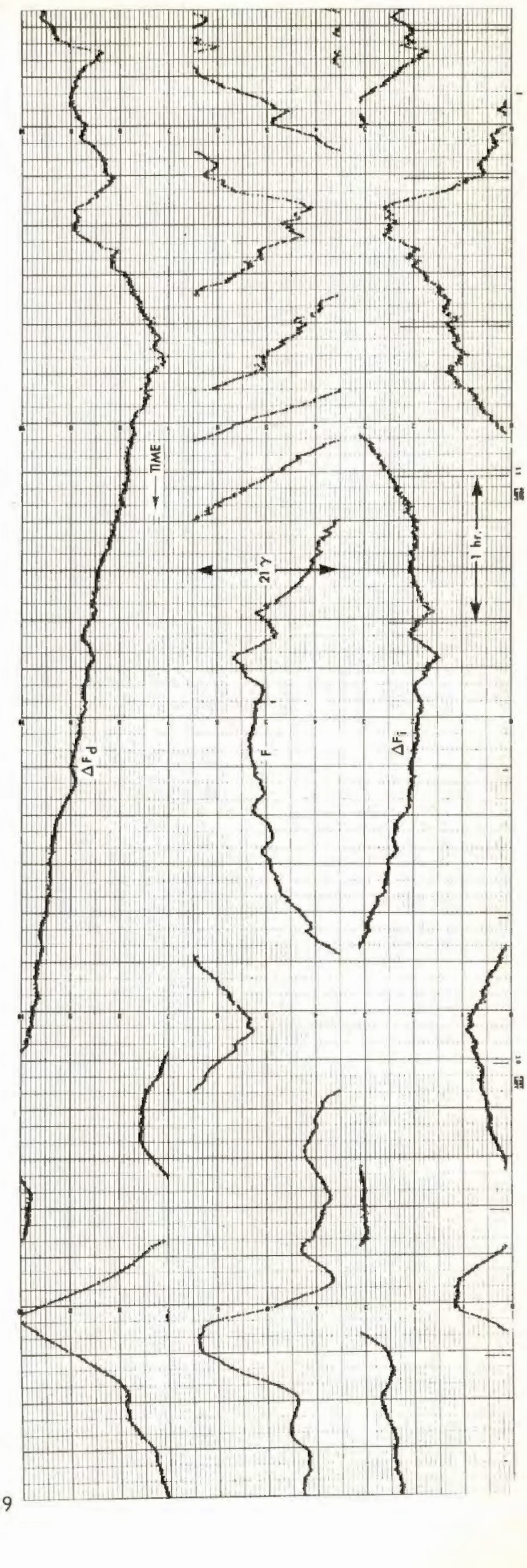

FIG. 22.--Castle Rock ASMOR analog record showing magnetic bay.

Table 3.--ASMO equipment specifications.--Cont.

Counter

Reference oscillator: Uses 1 Mc./sec. time-base oscillator (in clock).
Type: Bidirectional, resets to 100,000.
Operating cycle: Repeated every 10 seconds.
Measured parameters: Frequencies, augmented by 100,000, which corresponds to:
1. F_{+i}
2. $F_{+i} - F_{-i}$
3. F
4. F_{+d}
5. $F_{+d} - F_{-d}$

Gate time: 1 second, fixed: a count is made every odd second.
Display: Six decades.
Operator select: Operator can select any one or all five parameters for display.

Constant Current Source

Range: 10 to 200 ma.
Stability: ±5 parts in 10^6 per minute.
±1 part in 10^5 per day.
±1 part in 10^4 per month.
Accuracy: ±0.02 percent.

Recorders

Location: Transmitting and/or receiving site.
Parameters: TIME: Day-of-year and hour.
DATA: Frequeucies, augmented by 100,000, corresponding to:
1. $F_{+i} - F_{-i}$
2. F
3. $F_{+d} - F_{-d}$

Recording cycle: TIME: Every hour on the hour.
DATA: Selectable to 1, 2, 3, or 6 times per minute.
Digital magnetic tape: Incremental, 200 characters per inch, 7 channel, ½-inch 1.5 mil. tape, 2,400-foot reels, IBM compatible.
Analog strip chart: 10-inch-wide strip chart, speeds 1, 2, 3, or 6 inches per hour.

Bias Coil

Type: Two orthogonal Helmholtz pairs.
Diameter: Nominal 22-inch diameter.
Turns: 42 turns per bobbin.
Constant: Nominal 130 gamma/ma.

Logic

Type: All solid state, 100 Kp.p.s. modules.
Power supplies: All solid state, regulation ±0.1 percent.

Power

Input: 105-125 volts a.c., 50-60 cycles.
Standby power supplies: Provide 500 volt-amperes at 115 volts a.c., 60 cycles, for 4 hours minimum.

Automatic operation of the ASMOR is similar in sequence to that described for the ASMO prototypes. The principal differences are that the measurement cycle occurs once every 10 seconds in the ASMOR, whereas in the ASMO phototype, the measurement cycle is 20 seconds long and occurs only once each minute; and the recording of only three parameters in the ASMOR (ΔF_i, F, ΔF_d), versus five parameters in the ASMO. The functional relationship of ASMOR components is shown in figure 23. Figure 24 shows ASMOR program timing for one 10-second cycle.

Instrument Performance

On February 16 and 17, 1965, representatives of the Coast and Geodetic Survey witnessed such acceptance tests of the ASMOR system as could be conducted at the Varian Associates plant in Palo Alto. The sensing and transmitting units were moved to the magnetic observatory at Castle Rock, and the receiving and recording units to the University of California at Berkeley on February 18. On February 19, the ASMOR system was placed in operation for a four-hour test run. In general, these preliminary operations were satisfactory, although some modifications were indicated. During the next 9 months, the ASMOR produced usable data, despite the persistence of certain problems.

Difficulty was experienced with the analog-strip chart recorder. This unit is a critical element in the ASMOR system, for its use is essential to data gathering, trouble diagnosis, and data display; even short periods of imperfect operation are sufficient to bring the reliability of the entire system into question. By August, the malfunctioning components of the recorder had been modified to prevent recurrence of what amounted to minor failures.

An early failure of a constant-voltage battery charger power supply to regulate its output voltage within set limits caused failure of the static inverter at the observatory. When inverter failures persisted after repairs had been made, corrective action was taken in the form of system modifications and qualitative upgrading of certain components. This potential source of malfunction appears to have been eliminated.

The major difficulty encountered with the Dataphone[38] equipment was a prohibitively high incidence of false alarm signals, which garbled data. The Pacific Telephone Company adjusted its equipment, and the rate of false alarm signals fell within acceptably low levels.

The most elusive and potentially most serious problem encountered with the ASMOR involved an irregular variation in the output of the frequency counter that did not appear to correlate with normal temporal variations of the geomagnetic field. As experienced at the magnetic observatory at Castle Rock, this data scatter generally produced points at a maximum of about 20 Hz. from the apparent mean value of the component being measured. On several occasions, this phenomenon completely obscured the mean value of recorded components as seen on the analog record. The scatter could be either subtractive or additive in measurements of D and I, but was always subtractive in measurements of F. In the course of troubleshooting this problem, an impressive variety of prospective remedies was applied. The system's rubidium sensor was replaced by another Varian 49-538 sensor, with no significant effect on data scatter. Increasing the signal-to-noise ratio of the instrument from 5 to 18 eliminated imprecise counts, but had no apparent effect on data scatter. Operation of the system with no bias currents

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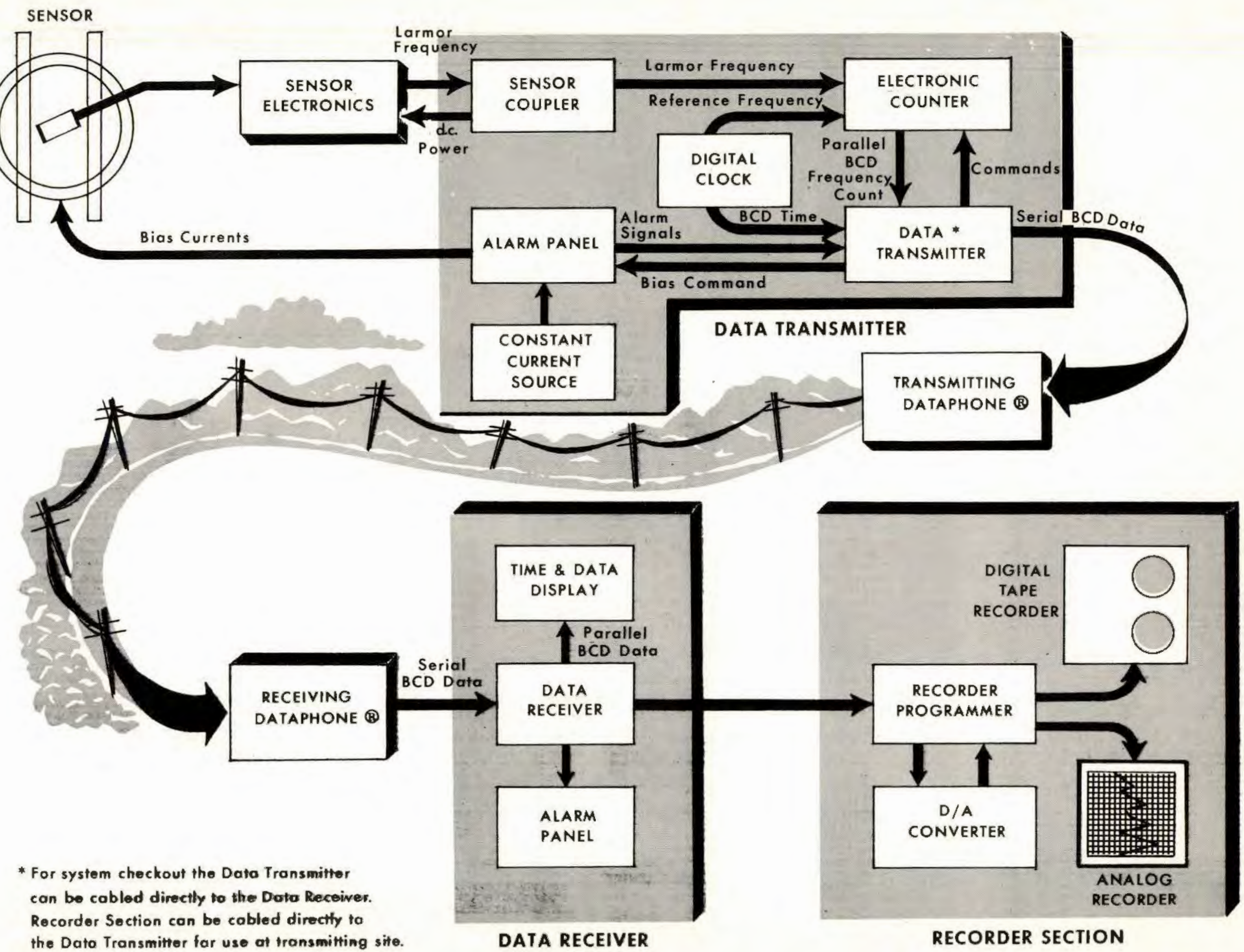

FIG. 23.--ASMOR, functional arrangement. *After Varian Associates diagram.*

FIG. 24.--ASMOR program timing for one 10-second cycle.
After Varian Associates diagram.

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=*99946L38754A00042*99944L38754A00042*99945L38754A00043*99945L38753A00042*99945L38752A00044*99947L38752A00043
=*99945L38752A00043*99947L38752A00043*99946L38752A00044*99945L38752A00043*99945L38752A00044*99946L38752A00043
=*99947L38752A00044*99946L38752A00043*99944L38752A00042*99945L38753A00044*99945L38754A00044*99947L38754A00044
=*99945L38753A00042*99945L38752A00044*99945L38753A00043*99947L38753A00043*99945L38752A00042*99945L38752A00043
=*99945L38753A00044*99945L38752A00043*99945L38752A00043*99945L38752A00043*99945L38752A00042*99946L38752A00044
=*99946L38752A00044*99947L38752A00043*99946L38753A00043*99945L38752A00045*99946L38751A00045*99944L38752A00043
=*99945L38752A00042*99945L38752A00043*99945L38752A00042*99946L38751A00043*99945L38751A00043*99947L38751A00043
=*99945L38751A00043*99945L38751A00044*99945L38751A00043*99945L38751A00043*99944L38752A00043*99945L38752A00044
=*99945L38752A00042*99944L38752A00044*99946L38752A00043*99945L38752A00043*99944L38752A00043*99945L38752A00043
=*99944L38752A00042*99944L38751A00042*99945L38751A00042*99944L38752A00043*99946L38752A00042*99945L38752A00043
=*99943L38752A00042*99944L38752A00042*99945L38752A00042*99944L38752A00044*99946L38753A00044*99945L38752A00042
=*99945L38752A00043*99945L38753A00043*99944L38753A00043*99945L38753A00042*99944L38752A00044*99945L38752A00043
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FIG. 25.--Castle Rock ASMOR, output data for one hour (20th hour, December 6, 1965).

applied (that is, continuous measurement of F); occupation of different sensor positions around the observatory site, using paper-tape punch concurrently with magnetic tape recording; and persistent investigation of power supply, component performance, data transmission, and thermal effects produced no significant reduction of scatter, and gave no substantial clues to the origin of the scatter. At one juncture, it appeared the scatter might be the result of seismic activity, but this was not substantiated.

Substitution of a quartz crystal oscillator as a signal source for the ASMOR system produced a record free of data scatter. Subsequently, a cesium sensor was substituted for the rubidium instrument, and no data scatter was observed; when the cesium detector was replaced with the rubidium sensor, data scatter began almost immediately. Although earlier tests had indicated that the trouble did not lie in the rubidium sensor, it was decided to replace the ASMOR sensor with a new rubidium unit. On October 25, a new, updated version of the original sensor was installed. No data scatter was observed when the system was placed in operation. The originally furnished sensor was returned to Varian Associates for tests, and was found to be faulty.

As noted earlier, the ASMOR data recorded since February 1965 constitute a geophysically useful body of material. Since October, this record has improved and is not being obtained on a reliable, routine basis. ASMOR output for one hour (20th hour, December 6, 1965, the 340th day of the year) is shown in figure 25.

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C5340200 473 315 494 473 316 494 472 316 494 472 316 494 472 316 494 472 316 494
C5340201 471 316 494 471 316 494 471 316 494 471 316 493 471 316 493 471 315 494
C5340202 470 315 494 470 315 493 470 315 493 470 315 493 470 315 493 470 315 493
C5340203 470 315 493 469 315 493 469 315 493 469 315 493 469 315 493 469 315 493
C5340204 469 315 493 469 315 493 469 315 493 469 315 493 469 315 493 469 315 493
C5340205 468 315 493 468 315 493 468 315 493 467 315 493 468 315 493 467 315 493
C5340206 467 315 493 467 315 493 468 315 493 468 315 493 468 315 494 467 315 493
C5340207 467 315 494 467 315 494 468 315 494 467 315 494 467 315 494 467 314 494
C5340208 467 314 494 467 314 493 467 314 493 467 314 493 467 314 493 467 314 493
C5340209 467 314 493 467 314 493 467 315 493 467 314 493 467 315 493 467 315 493
C534021 16 469   24315   44993
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FIG. 26.--Castle Rock ASMOR, computer sample for 20th hour, December 6, 1965.

There is one line of data per minute. The first 18 digits in each line give data on ΔF_i, F, and ΔF_d as indicated in figure 21. There are six such observations per minute (line). The equal sign at the start of each line indicates the start of a new minute, and the odd characters shown as the first of each six characters are a result of the flagging procedure indicated in the format of figure 21.

Figure 26 shows a computer output for the same hour. In this printout, there is one line each 6 minutes giving D, H, and Z in sequence; and one value each minute minus a base value, evident from the hourly means given in the last line, which are $D = 16° 46.9'$ East, $H = 24{,}315$ gammas, and $Z = 44{,}993$ gammas. The C stands for Castle Rock, which is followed by a 5 for 1965, followed by 340 for the day of the year, followed by 20 for the hour of the day, followed by a number 1-9 for the card number within the hour.

Accomplishments

In general, ASMOR performance must be considered a notable success, for it is an instance in which a new system provided substantially greater reliability than its less complex predecessors. Operation of the ASMOR system at the Russell Varian-Castle Rock Magnetic Observatory established that component failure need not be a recurrent, intrinsic penalty of using ASMO-type instruments. It also established that the magnetic observer can be freed to pursue constructive research programs. The observer-in-charge at the Russell Varian-Castle Rock Magnetic Observatory was concurrently enrolled in a graduate program at the University of California, where ASMOR data were recorded. Five years ago, the establishment of an unattended magnetic observatory at Castle Rock--or at any limited-access site--would have been impossible. Not until the advent of the ASMOR has the magnetic observer been able to work in less isolation than his instruments.

The success of ASMOR somewhat exceeds the comparatively modest requirements of the 1960 proposal. The data rate is greater, the advantages of remote recording have been realized, and the ASMOR has attained a satisfactory reliability. The establishment of a new instrumental base for magnetic observatories was the chief objective of the research and development project begun in 1960. That objective was achieved with the acceptance of ASMOR for operation at the Russell Varian-Castle Rock Magnetic Observatory.

THE ASMO/ASMOR POTENTIAL

At present, two operational ASMO production prototypes are installed at Coast and Geodetic Survey magnetic observatories in Fredericksburg and Dallas; the single ASMOR system is installed at Castle Rock. Refinements of those second- and third-generation designs have already begun; for example, Spectra-Physics of Mountain View is developing fully miniaturized ASMO components. Other refinements are on the way. The potential of present and future systems of the ASMO/ASMOR type is great.

The economy of automatic observatory systems was demonstrated emphatically during operation of the ASMO prototypes and the Castle Rock ASMOR. Data from those three instruments were received and processed by one man; extrapolations of time required for such work indicate that one man can handle the data for five automatic observatories. Economies in the form of scientist-utility are also evident when an observer's time is spent working in his geophysical field rather than as an instrument technician, and when he is not forced into isolation by his instruments. Automatic observatory systems would also tend to reduce observatory costs; it has been estimated that an ASMO with 90 percent reliability would reduce station-hour costs by nearly 80 percent, even assuming 100 percent reliability in existing magnetic instruments.

Distribution of instruments of the ASMOR type would permit the establishment of permanent geomagnetic observatories in areas of limited accessibility. Such installations would be a big help to geophysical research in this country. For less-favored nations, ASMOR-type observatories would be an important step toward the geophysical foundation needed for economic and social development.

But the future of these new instruments is less clear than their potential. Procurement of follow-on systems, remote or otherwise, was not a positive objective at the end of 1965. It may be that automatic systems of the ASMO type will not be used in standard observatories, but that ASMOR's will be installed in locations like Castle Rock. It may be also that the Castle Rock ASMOR is the first and last of its kind, and will be replaced by something similar or something better.

Whether these automatic systems are used widely or are merely precursors to more advanced equipment, it is clear that the technology of magnetic measurement has passed a major milestone. From the research and development project begun in 1960, something more than new equipment has been gained! The ASMOR, and systems of its type, have broadened the technological base from which all new developments in magnetometric instrumentation must begin.