MAGNETIC MEASUREMENT

MEASURING MAGNETIC FIELDS REQUIRES SPECIALIZED SENSORS AND KNOWLEDGE OF PHYSICS AND ELECTRONICS. YOU CAN USE A VARIETY OF INSTRUMENTS, INCLUDING GAUSSMETERS, TESLAMETERS, FLUXMETERS, AND MAGNETOMETERS, TO MEASURE MAGNETISM, AND PRICES FOR THESE UNITS RANGE FROM PENNIES TO HUNDREDS OF THOUSANDS OF DOLLARS. LEARN WHICH SENSOR FITS YOUR APPLICATION.

BY PAUL RAKO • TECHNICAL EDITOR

In one of the earliest magnetic measurements, primitive mariners used lodestones—magnetized pieces of magnetite—to determine the earth's magnetic field. Today, thousands of applications require the measurement of magnetic fields. Instruments measure the B field, which engineers call magnetic-flux density, whereas physicists call the B field the magnetic field. According to US physicist and Nobel Prize winner Melvin Schwartz, "It is customary to call B the magnetic induction and H the magnetic field strength. We reject this custom inasmuch as B is the truly fundamental field and H is a subsidiary artifact" (**Reference 1**).

"A magnetometer cannot separate out this artificial distinction between the magnetic field, which is just what's produced by a coil, and total magnetic-flux density, which is produced by the coil plus by any internal current circulation inside, say, a piece of steel in the coil," says Bill Lee, PhD, owner of AlphaLab Electromagnetic Instruments, a supplier of diagnostic and laboratory products. "The rotating electrons in the steel produce magnetism there. All any magnetometer can read is the total flux density; it can't distinguish between the amount due to the coil and the amount due to magnetism of the core." Other fundamental issues with magnetic measurements are whether the field you are measuring is a dc or an ac field and whether you are measuring in just one axis or in multiple axes at once.

FROM MEDICAL TO MILITARY

Magnetic measurements find use in a variety of applications. For example, sensors in automobiles use the earth's field to help with navigation, and roadway sensors examine the magnetic signature of vehicles going by, determining the type of vehicle and its direction (**Reference 2** and **Figure 1**). In another application, geologists and earth-science researchers can detect iron-ore and other mineral anomalies by precisely mapping magnetic fields. By examining the latent magnetic field in rocks that have solidified over the ages, geologists can trace the changing location or frequent reversals of the earth's magnetic field (**Reference 3** and **Figure 2**). Some geological surveys use a fluxmeter, a simple coil pickup that connects to an integrator. When researchers pass magnetic materials through the fluxmeter and past a coil, an integrator inside the instrument calculates the dc field.

One of the primary military applications for magnetic-field measurement is detecting submarines. For example, the submarine-hunting Orion P3C military aircraft has a long tail boom to house the magnetometer far away from the engines and other sources of interference. Other military uses for magnetic measurements include instrumentation of small-caliber shells in the development of ranging fuses (**Reference 4**). The instruments inside the shell count the rotations of the shell as it spins through the earth's magnetic field. Because the magnetometer knows the turns ratio of the barrel rifling, a fuse circuit can calculate the distance the shell has traveled, so it can then burst over a target. Methods such as a time delay after firing are less accurate because the bullet speed varies with powder charge and gun condition.

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Countless other applications exist in the industrial, scientific, and medical fields. Industrial customers may simply need to verify the north and south poles on magnets used in motors. Paul Elliot, owner of magnetic-field-sensor-vendor Magnetic Sciences, reports that oil-pipeline installers need to measure the pipes to ensure that no latent magnetism resides in the steel. Many industrial users must measure the field of a magnet to ensure that it has not lost its strength. Another industrial use is to verify whether shipping containers are emitting a magnetic field that is greater than the legal limit.

Scientific uses of magnetic measurements include disk-drive-read-head research. The behavior of material in intense magnetic fields is an area of active study, and it is often necessary to measure the intense field that resistive, room-temperature, and superconducting magnets produce during research.

One of the most common medical uses of magnetic measurement is to verify the field uniformity in MRI (magnetic-resonance-imaging) machines. The field in the tunnel of an MRI machine must be uniform to parts per million. Sensitive instruments can measure the field at a point, but a sensor array that distributes

24 to 32 sensors on an arc is more useful. Technicians rotate this sensor inside the tunnel of an MRI machine so that sensors sweep out in a sphere. If the magnetic field is uniform at the periphery of a sphere, the uniformity can only improve anywhere inside that sphere. In addition, magnetic sensors around an MRI machine block out the effects of passing cars or elevators. The sensor feeds back the signal to a 3-D Helmholtz coil, a device for producing a region of nearly uniform magnetic field. This coil ensures that outside influences do not affect the field inside the MRI tunnel.

Another area of medical research involves the susceptibility of humans to the magnetic fields that surround us. This area of study is more controversial because power lines and electric cars emit approximately 1-mG (milligauss) fields, whereas the earth's magnetic field is 500 mG. Still, MRI machines can be of concern to health-care workers who operate them. The ICNIRP (International Commission on Nonionizing Radiation Protection) guidelines for occupational static-magnetic fields are 200 mT (millitesla) for continuous exposure; 2000 mT for short-term, whole-body exposure; and 5000 mT for exposure to arms and legs, according to Ian J Walker, vice president of sales for sensor-distributor and -integrator GMW Associates. "These field levels are high and indicate the lack of evidence for biological effects from dc fields," he says (**Reference 5**).

AT A GLANCE

- All magnetometers measure the B field, rather than the H field.
- Different sensors measure ac and dc fields.
- Some instruments measure in only one axis.
- Hall-effect sensors are versatile and have good resolution, but they drift over time and temperature.
- Instruments can cost pennies to hundreds of thousands of dollars.

The use of gaussmeters to measure magnetic fields in homes has uncovered another valuable application. Homes with 60-Hz fields often have wiring errors such that the neutral leg of the dc wiring returns through the ground wire or plumbing. The current conductors are far apart and form a loop, so they generate larger magnetic fields than those in properly operating wiring. Whether the fields themselves could cause injury is debatable, but it is always more desirable to have wall power in the wires and not the pipes of your home.

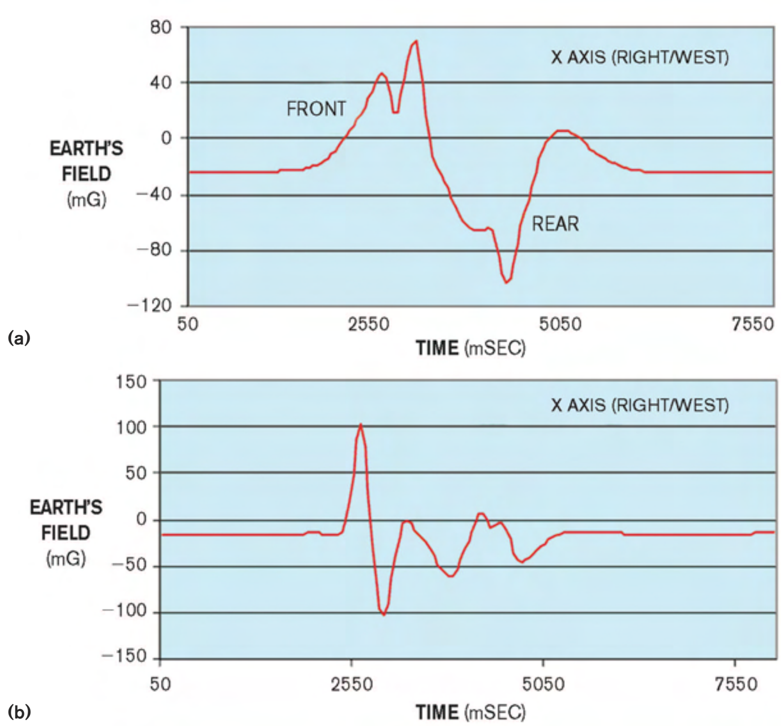

Figure 1 A magnetic sensor in the road can determine vehicle direction and type from a Silhouette van (a) and a Saturn sedan (b) (courtesy Honeywell).

SENSE AND "SENSORABILITY"

The availability of such a diverse array of magnetic measurements requires a wide selection of sensors to properly characterize the magnetic field (**Reference 6** and **Figure 3**). One of the most basic is a simple inductive sensor comprising a coil with a magnetic core. It can measure ac fields and may also pick up electric fields. The response of the core material also limits the upper frequency that the sensor can detect. These types of sensors find use in inexpensive gaussmeters, often targeting the health-care market.

The largest drawback of inductive sensors is their inability to measure dc fields. Hall-effect sensors overcome this problem. A Hall-effect sensor yields an output voltage proportional to the magnetic-field strength. Hall-effect sensors work in only one axis, but vendors can mount three devices together for three-axis measurement that provides enough information to detect the earth's magnetic field or, just as useful, to subtract it from the real dc field of interest. The downside of these sensors is that they drift over time and temperature, making accurate measurements difficult.

Flux-gate sensors, which indicate the direction of the earth's magnetic field, can also measure dc fields and can be more sensitive than Hall-effect devices. A flux-gate sensor works by using an ac electric current to sweep a permeable core through its magnetic-saturation curve. The property of the core determines how many ampere-turns—the magnetomotive force developed by a coil through which a current flows—are necessary to achieve saturation. The presence of a dc field in the core reduces the amount of current necessary to achieve saturation in one magnetic direction and increases the current necessary when you try to drive the core in the opposite magnetic direction. It is easy to measure small currents, and, as such, it is possible to measure small fields (**Reference 7**). If you excite the flux gate fast enough, it can easily meas-

Figure 2 This field researcher is using a Grad601 flux-gate gradiometer at an archeological-dig site (courtesy Bartington).

ure 60-Hz fields and other ac fields into the audio range.

Texas Instruments' Burr-Brown division offers the DRV401 chip, which both excites and measures the response of the core in a magnetoinductive magnetometer, similar to a flux gate. By driving the core to a certain current and then reversing, the part establishes a natural oscillation. With no applied magnetic field, the duty cycle of the oscillations is precisely 50%. With an applied external field, the duty cycle changes, showing both the magnitude and the direction of the applied magnetic field. The frequency range of this technique extends to 100 kHz. This chip provides the magnetic sensing in current sensors for magnetic-product manufacturer Vacuumschmelze.

A broad range of magnetic sensors uses the principle of magnetoresistance. A magnetoresistive material changes its resistance in the presence of a magnetic field. Irish physicist and engineer William Thomson, more commonly known as Lord Kelvin, in 1856 discovered the theoretical basis for the phenomenon, and later development of technologies allowing the deposition of thin metallic films popularized these sensors. Because the field directly changes the resistance, this class of sensor can measure both dc and ac fields, and, because the sensors are resistive, you can use them at high frequencies, which accounts for their use in disk drives. These sensors can employ AMR (anisotropic-magnetoresistance), GMR (giant-magnetoresistance), or TMR (tunneling-magnetoresistance) techniques. Japanese physicist Terunobu Miyazaki discovered in 1995 that you can use the TMR technique at room temperature. Since the emergence of that breakthrough, manufacturers of disk-drive-read heads have adopted TMR sensors to reach the fast response and high bit rates that modern drives require. AMR sensors, available from Honeywell and

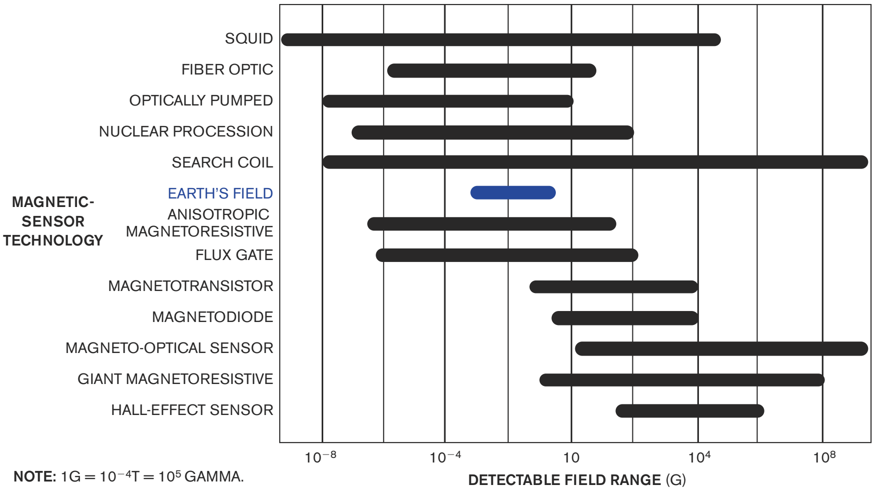

Figure 3 The sensitivity ranges of various magnetic sensors span many orders of magnitude (courtesy Honeywell).

Figure 4 Inductive-sensor instruments can measure only ac fields (courtesy AlphaLab).

Figure 5 The FW Bell model 6010 single-axis dc gaussmeter achieves ±0.25% dc accuracy (courtesy Sypris).

others, find use in anything from compasses to gear-tooth detection.

For example, Maxim offers the 16-bit, RISC-microcontroller-based MAXQ-7665 smart data-acquisition system that interfaces to magnetoresistive sensors; it also integrates an analog front end, a programmable-gain amplifier, and bridge excitation. The device measures the steering angle for yaw and traction control in automotive applications. The microprocessor core has a multiply/accumulate instruction, allowing the device to perform calculations and DSP-type filtering, according to Mike Mellor, staff engineer at Maxim. The device also integrates a CAN (controller-area-network) bus and UART.

Sensors employing NMR (nuclear-magnetic-resonance) technology base their measurement on atomic properties, so they are highly accurate, and you can use them as primary standards. Their resolution approaches one part per billion, and their resonance is based on the spin states of a proton in a hydrogen nucleus. The proton-procession magnetometer subjects water or other hydrogen-rich samples to an intense magnetic field and then allows the field to collapse; a second inductor then measures the weak resonance of the protons. The magnetic field of the earth would result in a resonant frequency of 1.5 kHz. The Overhauser type of NMR sensor excites the hydrogen atoms in water with RF energy of nearly 45 MHz; the sensor absorbs energy at resonance, and this frequency is proportional to the magnetic field. The measurement is precise, has no drift, and measures the three-axis field because the effect is nondirectional. These sensors are more expensive than the other types, however, and have a unique drawback: The water inside freezes in cold climates and ruins the internal vessel, according to Brian Richter, president of GMW Associates. This scenario could happen, for example, if a user leaves the sensor on an airport runway in a frozen climate. NMR sensors also need a uniform field across the measuring vessel, and they work only on dc and slow-ac fields.

The most sensitive magnetometers are SQUIDs (superconducting-quantum-interference devices). "They can easily detect the magnetic field from the nerve impulses in your brain or your heart," says AlphaLab's Lee. "You have to shield them very well since a truck driving by a half-mile away can add more magnetic fields."

WEIGHING YOUR OPTIONS

Selling for less than $300, inductive-measurement devices are the most economical (**Figure 4**). You use them to measure the magnetic fields from ac sources, such as power lines and motors. These instruments can also help find wiring breaks because the magnetic field collapses when it encounters the broken wire. Inductive sensors come in both single-axis and triaxis versions. For example, the FW Bell division of Sypris Test and Measurement offers the series 4100 meters, which can measure ac fields at frequencies higher than 25 Hz in three axes. One unit in the series, the Bell-4180, sells for $324.

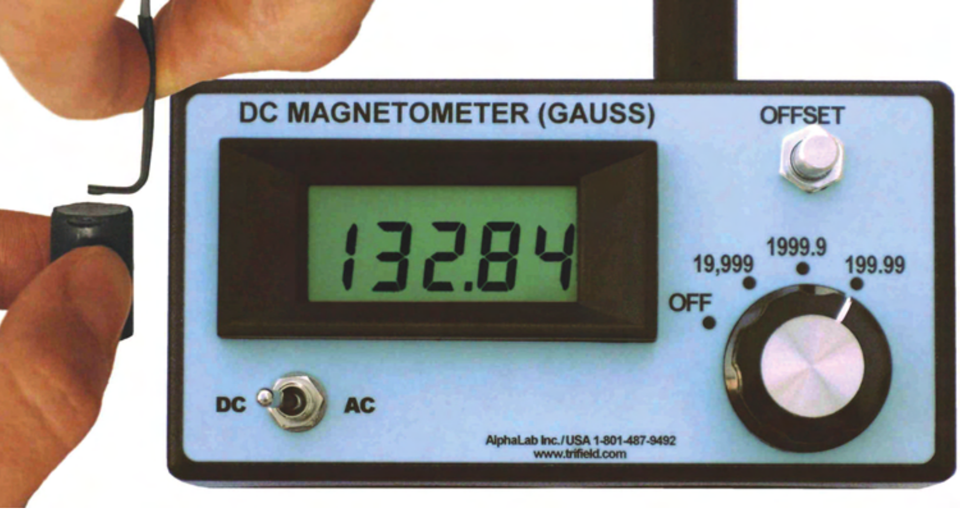

Figure 6 You can bend the sensor for this magnetometer into an L shape or keep it straight. It will withstand 1000 flexures (courtesy AlphaLab).

If high sensitivity is a necessity for your application, you may want to consider a flux-gate sensor. For example, the Mag-03MC flux-gate-magnetometer probe from Bartington Instruments has 70- to 1000-μT sensitivity; this three-axis, dc to 3-kHz instrument has ±0.5% accuracy. The probe, available from GMW Associates, costs $3190 and interfaces with the Mag-03DAM digitizer, which sells for $5750. GMW Associates provides National Instruments LabView drivers for this device and other magnetometers.

Hall-effect sensors are more versatile and their prices—$500 to $800 for a single-axis device and more than $1000 for a three-axis unit—reflect this feature. The FW Bell 5100 series Hall-effect sensor measures dc fields, has 2% accuracy, and can measure frequencies as high as 20 kHz at 1G to 20 kG. The model 5180 has 1.1% accuracy, measures frequencies as high as 30 kHz, and ranges to 30 kG. It also has peak hold, relative mode, and analog and USB outputs. The 5180 costs $1325, and another unit in the series, the 5170, sells for $985. FW Bell also makes two benchtop instruments. The model 6010 Hall-effect gaussmeter sells for $2492, and the 7010 single-channel gaussmeter/teslameter costs $4365 (**Figure 5**). The 7010, with an accuracy of ±0.5% dc ±2%, can simultaneously measure and display flux-density, frequency, temperature, minimum, maximum, peak, and valley parameters. The three-channel model 7030 gaussmeter/teslameter sells for $6864.

You can use AlphaLab's $380, 10,000G DC magnetometer, with overall accuracy of ±2% at 30 to 110°F, for both dc and ac measurements (**Figure 6**). The unit has a pseudo-root-mean-square response, and it operates at 45 to 2000 Hz. A high-stability version is also available. The meter comes with a NIST (National Institute of Standards and Technology)-traceable-calibration certificate. Another line of meters, Hirst Magnetic Instruments' gaussmeters, includes the Hall-effect VGM01, which connects to your PC through an RS-232 interface. Metrolab's $3980 THM1176 sensor integrates three orthogonal Hall-effect elements onto one IC (**Figure 7**). The USB instrument provides a 0 to 20T field range, a dc to 1-kHz passband, a three-axis Hall-effect sensor in a 193.54-mm^3 footprint, and a USB interface that can also interface to an optional $1730 PDA (personal digital assistant). Both the sensor and the PDA include software and are available from GMW Associates.

The Chen Yang Technologies CYHT-201 measures dc or ac magnetic fields. The instrument has ±2% dc accuracy and ±5% ac accuracy, measures dc to 200-kHz fields, and has a 4½-digit LCD. The company also offers the $350 CYHT-T08A gaussmeter with a Hall-effect probe. Yet another handheld teslameter comes from Tel-Atomic. The TeslaMeter 2000 costs $719 and comes with a transverse probe. The Hall-effect device measures sensitivity to 2T. Accuracy is ±0.5% for dc measurements and ±2% for ac measurements. The company also offers a $150 axial probe and is developing a triaxial probe. Lake Shore Cryotronics offers the $590 Model 410 handheld gaussmeter for field measurements of 0.1G to 20 kG (0.01 mT to 2T). The device displays measurements in gauss or tesla and ac- or dc-magnetic-field values with resolution to 100 mG. Operating functions include maximum hold, filter, relative reading, zero probe, and an audible alarm. Accuracy is ±0.1% full-scale dc and 5% ac, and the frequency response extends to 10 kHz. For users needing a small, inex-

Figure 7 This three-axis Metrolab probe has USB output and comes with an optional PDA (courtesy GMW Associates).

pensive dc gaussmeter, Carlsen Melton offers the $329 GM-200A, which measures to 10,000G with 2% accuracy and resolution of less than 1G. A calibration certificate costs $50.

At the other end of the pricing scale for Hall-effect meters, Group3 Technology's $4390 DTM-151 teslameter has 20-bit resolution and ±0.01% accuracy of full-scale for dc or slow-dc fields. For less demanding applications, the $2380 DTM-133 with digital-linearity correction has 0.03% accuracy, resolution to 10 ppm, and a temperature stability of 100 ppm/°C. Both devices are available from GMW Associates. Because these Hall-effect devices drift more than an NMR unit does, customers sometimes buy one NMR instrument to verify the calibration and drift of several of these less expensive Hall-effect meters.

Micro Magnetics' TMR sensors can investigate extremely small areas. The die measures 1.9×1.9 mm, but the actual area that senses the magnetic field measures only a few microns across, according to Ben Schrag, project manager of metrology at the company. He also notes that you can make an array of sensors on one die and average the result to get better sensitivity. The $325, bipolar, linear-output STJ-020 magnetic microsensor has a field sensitivity of 5 nT. Because the circuit comprises only resistors, the sensor has a frequency response as high as 5 MHz. Sensors with lower resistance have frequency response exceeding 100 MHz.

Metrolab's NMR-type PT 2025 sensor finds extensive use in medical-MRI applications (**Figure 8**). The teslameter achieves 5-ppm absolute accuracy and 0.1-μT (1-mG) resolution for measuring or mapping uniform magnetic fields of 0.043 to 13.7T (430G to 137 kG). Optional probe multiplexers enable readout of as many as 64 probes. The instrument operates in MRI- and spectrometer-magnet mapping, precision field control, and magnetic-sensor calibration. The PT 2025 instrument, for dc or slow, low frequencies, costs $20,650 and is available from GMW Associates. The $31,580 MFC 3045D-32 NMR-probe array, also available from GMW Associates, sweeps a sphere and characterizes the field-strength uniformity for MRI markets.

Magnetoresistive sensors measure weak-dc fields in AlphaLab's dc milligauss magnetometer. The instrument has a resolution of 0.01 mG (1 nT) and a range of ±2000 mG (200 mT). At fixed temperature, reproducibility is ±0.01 mG (1 nT), and the temperature coefficients of the offset and of the gain are less than 0.01 mG/°C and less than 0.0015%/°C, respectively. The $490 device has a gain accuracy of ±0.5%, and the meter offset is ±0.5 mG. The $4.95 CY-MVF555 magnetic-field viewer from Chen Yang requires no electricity and allows you to directly view a magnetic field (**Figure 9**). This ability can expose multiple poles in a magnetic assembly or indicate the field uniformity or fringing around a magnet.

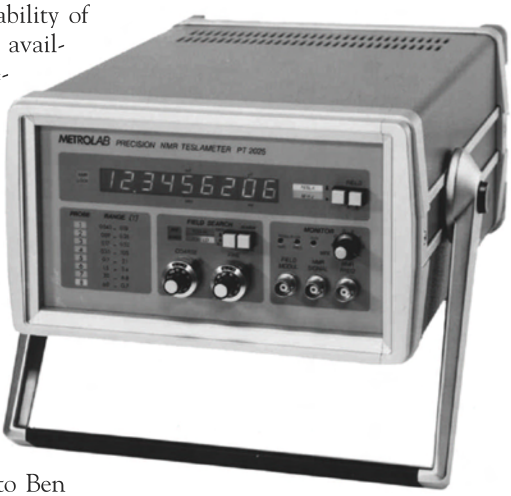

Figure 8 This NMR gaussmeter offers 5-ppm accuracy but can measure only dc or very-slow-ac fields (courtesy Metrolab) and comes with an optional PDA (courtesy GMW Associates).

Magnetic measurements are important if you are finding the North Pole or looking for submarines underwater. Instruments to measure magnetism can detect a dozen orders of magnitude of field strength. Understanding whether you need to measure ac or dc fields, along with the limitations of single- versus three-axis measurements, will help you do the job. If you realize the limitations of the various sensors and instrument types, you can ensure that you get an accurate measurement in the most cost-effective way.

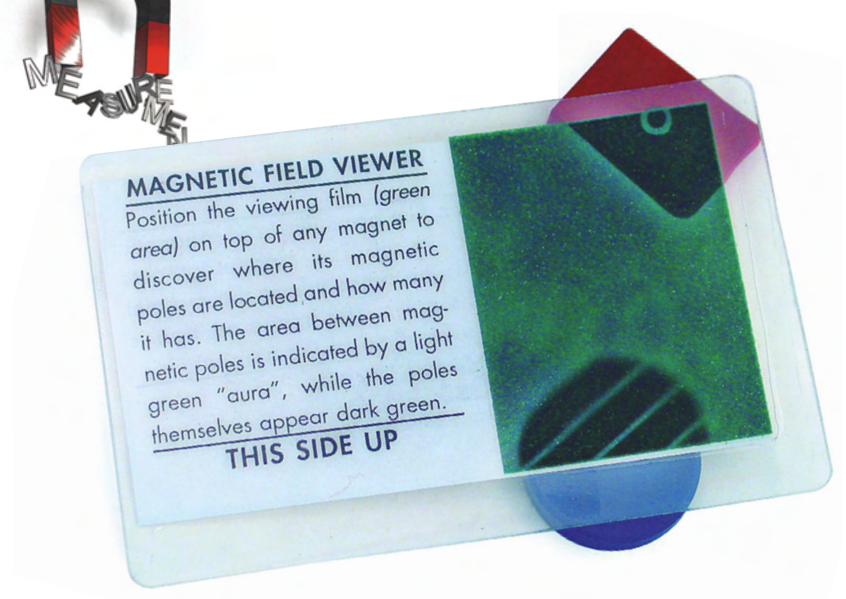

Figure 9 This viewer can directly display the presence of magnetic poles (courtesy Chen Yang).

No matter whether your instrument costs $50 or $50,000, it represents a beautiful collaboration of the regimes of physics, electronics, and even optics. EDN

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You can reach Technical Editor Paul Rako at 1-408-745-1994 and paul.rako@edn.com.