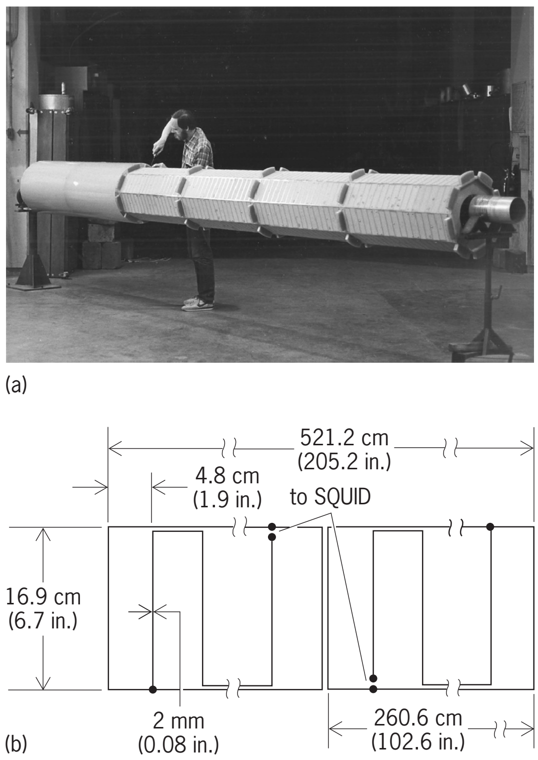


**Fig. 3. Eight-SQUID 1.5-m$^2$ (16-ft$^2$) octagonal detector in operation at Stanford University. (*a*) Detector being adjusted. (*b*) Schematic diagram of detector.**

3000 times lower than the value from the data set that included the original event. Thus the possibility that this event was caused by the passage of a magnetic monopole has been largely discounted.

Another single event was observed in a second-generation detector at Imperial College, London, on August 11, 1985. The possibility of the event having been caused by the passage of a magnetic monopole also has been largely discounted because it was a non-coincident signal observed by only one SQUID, and thus more susceptible to a spurious cause. All other second-generation detectors have used fully coincident multiple-loop detection schemes. *See* SQUID.

Several groups have operated larger third-generation detectors. The detector shown in **Fig. 3**, with a sensing area greater than 1.5 m$^2$ (16 ft$^2$) times $4\pi$ sr, is composed of eight planar superconducting detection coils arranged around a cylinder with an octagonal cross section. Each coil is a gradiometer connected to a high-sensitivity radio-frequency SQUID current sensor.

The gradiometer winding pattern is an important design feature for superconducting monopole detectors. For example, a figure-eight coil couples no net magnetic flux for any change in a uniform applied field. The sensitivity of a gradiometer to external magnetic field changes is substantially reduced over that from a simple coil, whereas the sensitivity to the passage of a magnetic charge remains high since the particle passes through only one element of the gradiometer pattern. A further improvement was achieved by breaking the loop up into a number of separate elements that are connected to one SQUID in parallel, thereby reducing coupling losses to the SQUID.

The monopole flux limit from the combined data of all detectors is below $3 \times 10^{-13}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ (90% confidence limit). Each of the third-generation detectors is capable of surpassing the peak of the mass-dependent Parker bound in 3 years of operation, or convincingly discovering magnetic monopoles in cosmic rays. If magnetic monopoles exist in cosmic rays, they are rare and very large detectors are required to observe them.

*Conventional detectors.* These measure the weak ionization of matter expected along the trajectory of a magnetic charge. Particle detectors such as scintillators, which collect the fluorescent light from the ionization, and proportional counters, which collect the electrons produced by the ionization, can be used. The signature of a monopole in these conventional detectors would be that of a massive particle moving a thousand times slower than the speed of light. Such a signature would not directly measure a magnetic charge, but the detection of any massive ionizing particle, whether electrically or magnetically charged, would be highly significant. The primary advantage of conventional detectors over superconducting ones is that sensing areas roughly 10 times larger can be instrumented for the same costs. In addition, the conventional detectors are also sensitive to known particles such as cosmic-ray neutrinos, allowing other experiments to be run simultaneously. *See* IONIZATION CHAMBER; PARTICLE DETECTOR; SCINTILLATION COUNTER. Blas Cabrera

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## Magnetic observatory

A specially designed ground-based facility that provides measurements of the Earth's magnetic field, often with high accuracy and temporal resolution for decades of time or longer. Data from magnetic observatories record a superposition of time-dependent signals related to a fantastic diversity of physical phenomena in the Earth's core, mantle, lithosphere, ocean, ionosphere, magnetosphere, and, even, the Sun and solar wind. Magnetic-observatory data are often used for scientific research, but recently they are also becoming increasingly important for practical applications, space-weather monitoring, and hazard mitigation. Today, magnetic observatories around the world are operated by a variety of government and academic institutions, sometimes in collaboration with private companies. An example of a magnetic observatory is shown in **Fig. 1**. *See* ATMOSPHERE; EARTH INTERIOR; SOLAR WIND; SUN.

In the early eighteenth century, Swedish astronomers Olof Hiorter and Anders Celsius discovered that a compass needle would rapidly swing back and forth at the same time that the aurora was visible at high latitudes. In the early nineteenth

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**Fig. 1. Panoramic view of the San Juan, Puerto Rico geomagnetic observatory (foreground buildings) that is operated by the U.S. Geological Survey.**

century, German geographer, Alexander von Humboldt, called these periods of magnetic disturbance "storms." At first a scientific curiosity, magnetic storms were considered to be a nuisance for making global maps of the geomagnetic field needed for compass-based navigation. To better understand storms, to support global mapping efforts, and to improve the fundamental understanding of the geomagnetic field, Carl Gauss and Wilhelm Weber organized the first international campaign to coordinate magnetic-field monitoring from 1836–1841. Participation came from many countries around the world, with observers making direct simultaneous visual measurements at predetermined times. In 1847, an automatic, analog-photographic method was invented to record magnetic-field variations, thus enabling the efficient and continuous operation of observatories. During the International Geophysical Year (IGY), 1957–1958, an unusual moment of scientific collaboration that came at the dawn of the space age, many new magnetic observatories opened and many existing observatories were modernized. At the same time, the World Data Center system was established to archive geophysical data, including geomagnetic data. In the 1980s, magnetic observatories began the transition from analog acquisition systems to modern digital-acquisition technology, and in 1987, the international consortium of observatory institutes, INTERMAGNET, was formed to establish and promote modern operational standards and to enhance the dissemination of observatory data. *See* AURORA; GEOMAGNETIC VARIATIONS; GEOMAGNETISM.

**Magnetometers.** Today, most magnetic observatories use fluxgate magnetometers, a sensor system that records the time-dependent variation of the geomagnetic vector, usually with either 1-min or 1-sec resolution. The response of a fluxgate instrument is affected by changes in temperature, and this can be somewhat stabilized by maintaining controlled operating conditions. Still, to obtain data accuracy, an INTERMAGNET-standard observatory also includes a proton-precession or Overhauser magnetometer, which provides accurate magnetic-intensity data, and a special pier-mounted theodolite, a surveying instrument with a small fluxgate attached to its telescope (**Fig. 2**). About once a week, an observer visits the observatory site and uses the theodolite to accurately measure the direction of the magnetic field. These different data types are combined through data processing to give a magnetic-field time series that has both high accuracy and high temporal resolution. Since its inception and up to 2011, there have been 125 INTERMAGNET observatories supported by 56 institutes from 41 countries (**Fig. 3**). Some observatories also support search-coil magnetometers, which can measure magnetic-field variations in frequency ranges from about 100 to 0.01 Hz, magnetotelluric electric-field sensors, and other types of geophysical sensors. *See* GEOPHYSICAL EXPLORATION; MAGNETOMETER; SURVEYING INSTRUMENTS.

**Discoveries.** Many of the seminal scientific discoveries in geomagnetic science have been made using magnetic-observatory data; we list a few. Secular variation of the geomagnetic field, now known to be caused by convection in the Earth's core, was demonstrated, starting in the sixteenth century, through repeated and systematic measurement of magnetic declination (compass direction) at fixed reference points (an early form of magnetic observatory) in London, England and Paris, France. In 1852, Edward Sabine demonstrated the existence of solar-terrestrial interaction by correlating sunspots with a long time series of observatory data from Toronto, Canada and other observatories recording magnetic storms. In 1889, Arthur Schuster inferred the existence of electric currents above the Earth's surface in what is now known as the ionosphere from daily

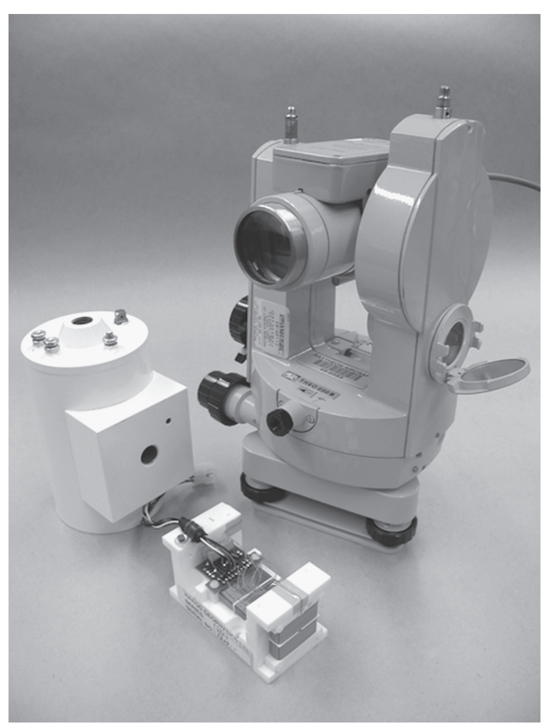

**Fig. 2. A typical magnetic sensor suite at an INTERMAGNET-standard observatory: (front) fluxgate variometer, (left) proton-precession magnetometer, (right) theodolite with small fluxgate attached to telescope.**

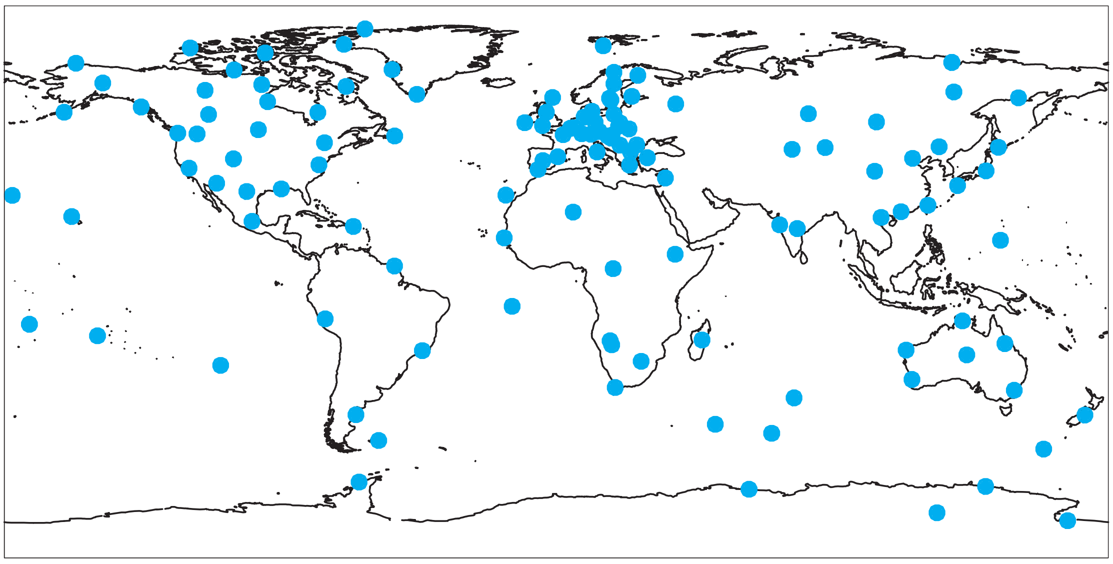

**Fig. 3. Map showing the locations observatories that have been part of the INTERMAGNET consortium 1991–2011.**

semiregular magnetic-field variations recorded at observatories. In 1930, Sydney Chapman and Vincent Ferraro inferred the existence of what we now call the magnetosphere from analysis of the sudden commencements of magnetic storms recorded at many observatories. Considerable research continues on these subjects, and magnetic-observatory data are being used in new subject areas as well, including cosmic rays, oceanic induction, and global-climate change. *See* IONOSPHERE; MAGNETIC STORM; MAGNETOSPHERE; SOLAR MAGNETIC FIELD.

**Applications.** Magnetic-observatory data are routinely used to derive two very different standard but important products. The International Geomagnetic Reference Field (IGRF) is a spherical-harmonic model of the main part of the Earth's magnetic field obtained from satellite and observatories around the world. IGRF models are updated every five years through international collaboration. The IGRF is widely used for navigation, land surveys, and studies of the Earth's deep interior. Magnetic indices record the rapid time-dependent variation of the geomagnetic field, and are widely used for space-weather monitoring and diagnostics. The Kp index measures the average global range of magnetic-field variation and is based on data from Australia, Canada, Denmark, Germany, Great Britain, the Netherlands, New Zealand, Sweden, and the United States. The Dst index measures the strength of the magnetospheric equatorial ring current and is based on data from Japan, South Africa, and the United States. The AE index measures the strength of the auroral-zone electrojet, and it is based on data from Canada, Greenland, Iceland, Russia, Sweden, and the United States.

Large magnetic storms are a potential hazard to the activities and infrastructure of our modern, technologically-based society. By many measures, the great magnetic storm of March 1989 was the largest of the twentieth century. Rapid geomagnetic-field variation during this storm lead to the induction of electric currents in the Earth's crust. These currents found their way through ground connections into the high-voltage Canadian Hydro-Québec power grid, causing transformer failure and resulting in the loss of electric power to more than 6 million people. If a similar storm-induced blackout had occurred in the north-eastern United States, the economic impact could have exceeded $10 billion, not counting the negative impact on emergency services and the reduction in public safety associated with the loss of electric power in large cities. The same storm also damaged satellites and severely disrupted over-the-horizon radio communication. Because these storm effects occur on or just above the Earth's surface, magnetic observatories are an integral part of coordinated ground and space-based "space-weather" projects in several countries. Real-time observatory data feeds are used for up-to-date monitoring. And, after a magnetic storm has passed, observatory data are used for impact assessments. *See* GEOELECTRICITY; VAN ALLEN RADIATION.

Several magnetic observatories are located near the oil and gas fields in the North Sea and Prudhoe, Alaska, where drilling is not just straight down, but, rather, is directed down and horizontally out and away from each drill-rig platform or pad. This technique allows access to multiple reservoirs, reduces drilling costs, and minimizes the impact to the surface ecology. Orientation for directional drilling is accomplished using in situ magnetometers (acting as compasses) in the instrument package that follows the drill bit and, also, simultaneous monitoring of the geomagnetic field at a nearby observatory. This is needed because the magnetic field can be very active at high latitudes, especially during magnetic storms. This interesting application of data recording space-weather effects is literally "down-to-earth."

**Outlook.** In the future, we can expect to see a gradual expansion of the modern global magnetic-observatory network, either by installing new observatories, or, more efficiently, by renovating and upgrading the existing observatories, especially those in economically emergent countries. We also expect that data collection will expand in the time domain, with many observatories now transitioning from collecting basic 1-min data to 1-sec and, even, higher-resolution data. Since the Earth's magnetic field is global in scale, international collaboration among magnetic-observatory institutes is essential, and the expected improvements in global coverage and data resolution will yield new insights into details of our planet's geomagnetic field. Jeffrey J. Love

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## Magnetic reception (biology)

Sensitivity to magnetic stimuli. For more than a century, biologists have speculated whether any living organism can detect magnetic stimuli, especially the very weak ones occurring naturally in the environment (the intensity of the Earth's magnetic field, the geomagnetic field, is roughly 0.5 gauss). A great variety of biological effects resulting from exposure to fields many thousands of times more intense than Earth's have been reported. Among these are changes in plant growth rates, retardation of embryo development, changes in enzyme activity, alterations of tumor growth, and other indications of stress. While the evidence for some of the reported effects is not very convincing, it does seem likely that, under certain conditions, such intense fields can indeed produce stress effects in living tissues similar to the effects of factors such as extremes of heat, cold, or starvation. This article is primarily concerned with sensory detection, not with stress effects, and focuses primarily on fields of geomagnetic intensities.

**Invertebrates.** Most of the evidence for magnetic detection comes from experiments performed during the 1960s and 1970s. During the first half of this period, most of the experiments were performed by F. A. Brown and colleagues, who reported turning or orientational responses to weak magnetic fields in a variety of invertebrates, including protozoa, flatworms, and snails.

In the late 1960s and early 1970s, a number of other laboratories began to find evidence of responses to weak magnetic fields. Attracting special attention were experiments on insects and on birds (and later, on fish and on bacteria). In 1968, Martin Lindauer and Herman Martin first published extensive data showing that the geomagnetic field influences the orientation of the waggle-run dance by which a scout honeybee communicates the distance and direction of a food source to the forager bees. Later, Lindauer and Martin showed that honeybees are so sensitive to magnetic stimuli that fluctuations of less than $10^{-4}$ gauss (roughly 1/10,000 of the Earth's field) can influence their behavior. Other investigators found evidence of magnetic detection in other kinds of insects, including termites, beetles, and fruit flies (*Drosophila*).

**Birds.** Most of the evidence for magnetic detection by birds has come from studies of their migratory and homing behavior. Experiments on birds exhibiting oriented migratory restlessness in circular test cages and experiments on the initial orientation of homing pigeons have yielded results strongly suggesting that birds possess a magnetic compass, that is, they can determine compass bearings from the geomagnetic field. Evidence indicates that birds' sensitivity to magnetic stimuli is roughly similar to the honeybees'; they too can probably detect fluctuations of less than $10^{-4}$ gauss. It appears that the tiny fluctuations in the Earth's magnetic field caused by solar flares and other solar disturbances have a detectable effect on birds' navigation.

Although behavioral effects of magnetic stimuli have been found in many kinds of animals, no one has yet succeeded in conditioning an animal to a magnetic stimulus in the laboratory. There is abundant evidence that the detection process is not quick, usually taking 15 min or more; hence, the flash stimuli presented in most classical conditioning attempts may be undetectable.

It appears that birds do not read the magnetic compass from its horizontal component the way people do. Rather, they probably rely on the angle between gravity and the magnetic total vector (which points north and down in the Northern Hemisphere); for a bird in the Northern Hemisphere, north is apparently that direction in which the gravity and magnetic vectors form the most acute angle. Only the magnetic vector itself, not its polarity, is important. Moreover, the detection system probably has a narrow range of sensitivity; magnetic fields much stronger or weaker than the Earth's probably cannot be detected. *See* MIGRATORY BEHAVIOR.

**Mechanisms.** The physical mechanism for magnetic detection by living organisms is unknown, though a variety of possibilities have been put forward, such as an induced electromotive force (emf) as a result of motion through the magnetic field; deflection of moving charges by means of the Hall effect; distortions of molecular bond angles; nuclear magnetic resonance effects; direct deflection of ferromagnetic particles; and many others. But the evidence is still so scanty that any choice between