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The USGS Geomagnetism Program and Its Role in Space Weather Monitoring

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Magnetic storms result from the dynamic interaction of the solar wind with the coupled magnetospheric-ionospheric system. Large storms represent a potential hazard for the activities and infrastructure of a modern, technologically based society [*Baker et al.,* 2008]; they can cause the loss of radio communications, reduce the accuracy of global positioning systems, damage satellite electronics and affect satellite operations, increase pipeline corrosion, and induce voltage surges in electric power grids, causing blackouts. So while space weather starts with the Sun and is driven by the solar wind, it is on, or just above, the surface of the Earth that the practical effects of space weather are realized. Therefore, ground-based sensor networks, including magnetic observatories [*Love,* 2008], play an important role in space weather monitoring.

A Colorful History

In the early nineteenth century the German geographer Alexander von Humboldt, while measuring magnetic declinations at his Berlin observatory, noticed that the field occasionally exhibited "magnetic storms," or periods of rapid, irregular variation that sometimes persisted for several days. A scientific curiosity, magnetic storms were considered to be a nuisance for making global-scale maps of the geomagnetic field needed for compass-based navigation. To better understand storms, to support global mapping efforts, and to improve fundamental understanding of the geomagnetic field, C. F. Gauss and W. E. Weber organized the first campaign for coordinated magnetic field monitoring (1836–1841) with direct visual measurements made simultaneously around the world at predetermined times. The United States participated in this "Magnetischer Verein" ("magnetic society") with observatories at Harvard University, Cambridge, Mass., and Girard College, Philadelphia, Pa. In Alaska, not yet purchased by the United States, Russian scientists operated an observatory at Sitka (1850–1864). Data from these and other observatories

Figure 1. Panoramic view of (a) the Cheltenham, Md., observatory in 1926 and (b) the Fredericksburg, Va., observatory today. Figure 1a courtesy of the Carnegie Institution of Washington, Department of Terrestrial Magnetism.

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revealed, for the first time, the global nature of both semiperiodic, solar quiet magnetic variation and magnetic storms.

In 1878 the Coast and Geodetic Survey (CGS) was established. One of its responsibilities was to operate a magnetic observatory in Los Angeles, Calif. (1882–1889), where continuous analog measurements were made with a photographic magnetogram system. The U.S. Army operated a similar observatory at Barrow, Alaska, during the first International Polar Year (IPY; 1882–1883); the U.S. Navy operated one at its astronomical observatory in Washington, D. C. (1889–1894).

With the start of the twentieth century, and under the leadership of L. A. Bauer and J. A. Fleming, CGS built the foundation of a permanent U.S. observatory network, one that resembles the network that exists today. The Cheltenham, Md., observatory began operating and publishing hourly data in 1901 (Figure 1a). Other observatories were soon installed, notably at Tucson, Ariz.; Honolulu, Hawaii; San Juan, P. R.; and Sitka, not far from the original Russian site. With the second IPY (1932–1933), temporary observatories were operated at Barrow and Fairbanks, Alaska. At the same time, and in coordination with international initiatives, U.S. observatories began to produce 3-hour *K* indices measuring magnetic disturbance, an early data-derived space weather product with which *Bartels et al.* [1939, p. 411] intended to record "the terrestrial effects of solar corpuscular radiation by measuring the intensity of the geomagnetic activity caused by the electric currents produced around the Earth by that radiation"—the notion of what we now call the "magnetosphere" was, at the time, still emerging [e.g., *Chapman and Ferraro,* 1930].

During the International Geophysical Year (IGY; 1957–1958), U.S. observatories were modernized; observatories at Guam and Barrow were opened; numerous temporary observatories were operated; and, with a specific act of Congress, funds were provided to replace the Cheltenham observatory with a new one at Fredericksburg, Va. (Figure 1b). With the IGY also came the development of the storm time disturbance index *Dst* [*Sugiura,* 1964]. Using data from four low-latitude observatories, including those at Honolulu and San Juan, this index indirectly measures the intensity of the magnetospheric ring current. After this came the development of the substorm auroral electrojet index *AE* [*Davis and Sugiura,* 1966], which uses data from high-magnetic-latitude observatories, including those at Barrow and College (Fairbanks, Alaska). In 1970, NOAA was established, and responsibility for the observatories was transferred to the U.S. Geological Survey (USGS), where it remains to this day.

The USGS Geomagnetism Program

The USGS Geomagnetism Program monitors the Earth's magnetic field at 14 ground-based observatories that are situated across the United States and its territories (Figure 2). Program staff conduct research on observatory data for purposes of mitigating geomagnetic hazards [*Love et al.,* 2008]. Geomagnetism is funded within the U.S. Geological Survey under a natural hazards mission that includes earthquakes and volcanoes. The program's operations are based out of the Geologic Hazards Science Center in Golden, Colo. The Survey is part of the U.S. government's National Space Weather Program (NSWP; http://www.nswp.gov), which coordinates space weather responsibilities across a diversity of federal agencies, including those of NOAA's Space Weather Prediction Center (SWPC), NASA, the Department of Defense, and the National Science Foundation. The USGS observatory network was identified as a "critical ground-based asset" in a recent review of NSWP [*Lanzerotti et al.,* 2006]. Internationally, the work of the USGS Geomagnetism Program is coordinated with foreign national geomagnetism institutes through the International Real-time Magnetic Observatory Network (INTERMAGNET; http://www.intermagnet.org), a voluntary consortium dedicated to promoting the operation of observatories according to modern standards [*Kerridge,* 2001]. Long-term archives of observatory data are maintained in the World Data Center (WDC) system.

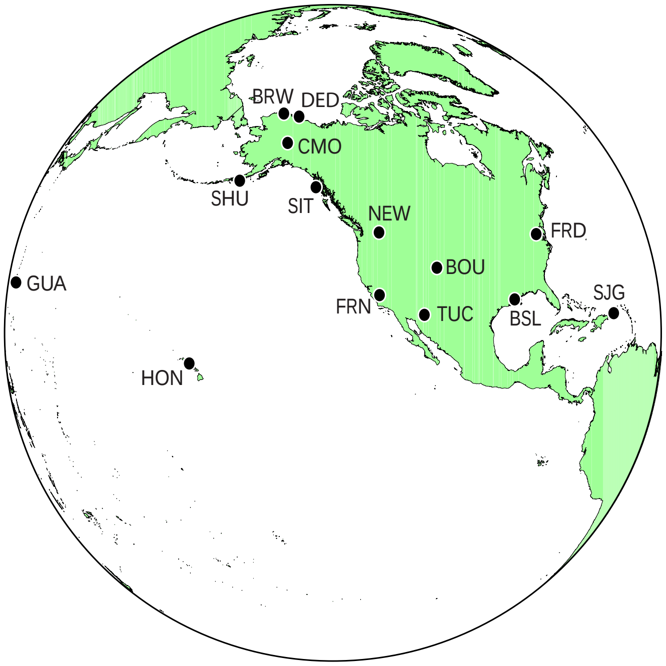

Figure 2. Map showing locations of the 13 U.S. Geological Survey observatories, each indicated by its three-letter International Association of Geomagnetism and Aeronomy code. The joint USGS-Schlumberger observatory at Deadhorse, Alaska (DED), is also shown.

Each USGS magnetic observatory supports the operation of a fluxgate magnetometer, which provides "variometer" measurements of continuous variation of the magnetic vector. For some space weather applications, especially those concerned with resolving magnetic field changes over time scales of a few hours or less, variometer data are sufficient, but for other applications, such as the production of most geomagnetic activity indices and long-term studies of geomagnetic climatology, data defined relative to a stable baseline are required. To meet this need, the instrument response of each observatory's fluxgate is stabilized by maintaining temperature-controlled operating conditions. Additionally, at each USGS observatory an Overhauser magnetometer supplies absolute measurements of magnetic field intensity, and weekly measurements of absolute field direction are made by an observatory worker using a specialized theodolite. These auxiliary data are combined with the variometer data to produce "definitive" data, a product that distinguishes a "magnetic observatory" from a simpler "variometer station" [*Jankowski and Sucksdorff,* 1996].

The USGS Geomagnetism Program first began continuously recording 1-minute-average digital data in 1981, a development that represented a substantial improvement over 1-hour-resolution data measured by hand from analog magnetograms, which do not reveal the detailed temporal evolution of magnetic storms. Today, 1-minute data are the Geomagnetism Program's most important product. Indeed, it is difficult to overstate the impact that 1-minute observatory data have had on the understanding of magnetic storms. Digital 1-minute data enabled coordinated analyses of observatory data with those from high-Earth-orbiting satellites [*Russell and Southwood,* 1982]. One-minute data from USGS observatories were used for detailed minute-by-minute analysis of the deleterious effects of the great magnetic storm of March 1989 [*Allen et al.,* 1989], including the failure of high-voltage transformers in the Canadian Hydro-Québec power grid. The latter resulted in the loss of electric power for more than 6 million people, damaged satellites, and disrupted over-the-horizon telecommunications. More recently, USGS 1-minute data and magnetic indices derived in part from USGS data were used to analyze the effects of the Halloween storm of October 2003 [*Balch et al.,* 2004].

Figure 3. Installation of the Deadhorse, Alaska, observatory, January 2010.

Today, the USGS Geomagnetism Program collects 1-second-average data at all 14 observatories. These data increasingly are being used for a variety of space weather projects. For example, to minimize spatiotemporal aliasing, low-Earth-orbiting magnetic field satellites, such as CHAMP and SWARM [*Matzka et al.,* 2010], produce 1-second data. Therefore, detailed ground-space analyses require 1-second observatory data. And geomagnetic pulsations, with periods of seconds to a few minutes, are observed during substorm onset. This has motivated the development of related space weather monitoring indices derived from 1-second observatory data [*Nosé* et al., 1998]. USGS 1-minute and 1-second data are available to customers in near real time (submit requests to geomagdata@usgs.gov).

Operational Partnerships

The U.S. Geological Survey shares facilities and cooperates with NOAA in the operation of observatories at Barrow, Fredericksburg, and Honolulu; with NASA at Stennis, Miss.; and with the University of Alaska at College. Cooperative work with institutes in New Zealand, Switzerland, and Western Samoa is focused on renovating the magnetic observatory at Apia, Samoa, a project that, due to the observatory's unique location, is important for monitoring the magnetospheric ring current. The U.S. Geological Survey recently began a novel public-private cooperative relationship with Schlumberger to install and operate a new observatory near the town of Deadhorse, Prudhoe Bay, Alaska (Figure 3). Data from this observatory will be used to support directional drilling for oil, with magnetic orientation accomplished in situ using magnetometers in the drill string instrument package and simultaneous surface monitoring of the geomagnetic field, which can be very active at high latitudes [*Poedjono et al.,* 2010]. This is an application of data recording space weather effects that is literally "down to Earth"! As a condition of USGS involvement with the Deadhorse observatory project, the data are freely available to the public.

Disturbance Monitoring and Research

In addition to supplying the Kyoto WDC with data for their production of *Dst* and *AE* indices, the USGS Geomagnetism Program supplies *K* index data from Fredericksburg and Sitka to the German GeoForschungsZentrum for their production of the midlatitude planetary disturbance index *Kp* [*Bartels,* 1949]. The U.S. Geological Survey has an ongoing contract with the U.S. Air Force Weather Agency for real-time data from several midlatitude observatories. These are used to produce a U.S. version of *Kp*, which, together with *K* values derived from data from observatories in Boulder, Colo., Fredericksburg, and College, is the basis for SWPC's issuance of geomagnetic storm alerts (http://www.swpc.noaa.gov). USGS data are also used to validate space physics models, such as those being transitioned from research to operations by NASA's Community Coordinated Modeling Center [*Pulkkinen et al.,* 2010]. More generally, in mostly academic contexts, hundreds of peer-reviewed papers are published every year using the *Dst*, *AE*, and *Kp* indices.

Over the past few years, and in preparation for the next solar maximum, research staff in the USGS Geomagnetism Program have developed a new algorithm for calculating the *Dst* index [*Love and Gannon,* 2009; *Gannon and Love,* 2010]. The USGS algorithm exploits modern numerical methods in making a time-frequency-domain separation of the solar quiet signal from the disturbance signal. As such, the USGS *Dst* algorithm is a revision of that presently used by the Kyoto WDC, which was developed more than 50 years ago for the IGY. Thanks, in part, to a cooperative project with Instrument Software Technologies, Inc., Space Environment Technologies, Inc., and the Air Force Research Laboratory, the USGS *Dst* product is now available in real time with 1-hour and 1-minute resolution [*Gannon et al.,* 2011; http://geomag.usgs.gov/dst].

The USGS Geomagnetism Program recently commenced development of real-time *K* and *AE* indices, projects that are parts of a larger effort within the space weather community for developing a coordinated, operational network for monitoring and modeling space weather; for recent comment, see *Tobiska* [2009]. Recent USGS research includes (1) space-time mapping of global, low-latitude, storm time magnetic disturbance, useful for research into ring current dynamics [*Love and Gannon,* 2010], and (2) analysis of long-term change in geomagnetic activity using observatory time series covering the past 13 solar cycles, or 140 years, which has important implications for secular change in solar activity, global climate change, and the prediction of magnetic storm occurrence likelihood [*Love,* 2011].

Looking to the Future

Given the right circumstances and, as always, the availability of resources, the U.S. Geological Survey may, in the future, expand its network of magnetic observatories. Some regionally oriented space weather projects, such as those focused on potential hazards for the domestic electric power grid industry, may benefit from additional observatories in the contiguous United States; directional drilling operations of the oil industry may benefit from additional observatories in Alaska. On the other hand, globally oriented projects, such as those concerned with monitoring and mapping storm time magnetospheric ring current systems, would benefit from better observatory coverage at low geomagnetic latitudes in the Pacific. Auroral and ionospheric polar cap studies would benefit from upgrades of observatory-standard variometers that presently operate at the American base at the South Pole. The U.S. Geological Survey could also expand the time domain of data collection, possibly moving to continuous monitoring at frequencies of 10 hertz or higher, thereby encompassing the broader spectrum of magnetic pulsations. Efficient expansion can also come through collaboration. The Survey will continue to work with the U.S. domestic and international communities to modernize the global network of magnetic observatories; to support long-term, coordinated ground and space-based monitoring; and to pursue space weather research of societal relevance.

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