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The Boulder Magnetic Observatory



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U.S. Geological Survey

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By Jeffrey J. Love, Carol A. Finn, Kolby L. Pedrie, and Cletus C. Blum

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Abstract

The Boulder magnetic observatory has, since 1963, been operated by the Geomagnetism Program of the U.S. Geological Survey in accordance with Bureau and national priorities. Data from the observatory are used for a wide variety of scientific purposes, both pure and applied. The observatory also supports developmental projects within the Geomagnetism Program and collaborative projects with allied geophysical agencies.

Introduction

The Boulder observatory is one of 14 magnetic observatories operated across the United States and Territories by the Geomagnetism Program of the U.S. Geological Survey (USGS) (Love and others, 2008). Along with the other observatories in the Program's network, the Boulder observatory is operated in accordance with strategic goals for geophysical observation established for the USGS Hazards Mission Area (Holmes and others, 2013), in support of the interagency U.S. National Space Weather Program (NSWP, 2010), and as a service to the scientific community (Love, 2008; Love and Finn, 2011).

Magnetometer data from the USGS observatory network have high time resolution, accuracy, and continuity. These properties mean that the data are useful for a wide variety of research and operational applications (Love, 2008), including (1) analysis and mapping of the main field generated in the Earth's deep interior, (2) analysis and real-time monitoring of magnetic variation generated by dynamic conditions in the Earth's space weather environment, (3) assessment and mitigation of magnetic storm interference and hazards for the activities and infrastructure of our technologically based society (Love and Finn, 2011).

Because the Boulder observatory is relatively close to the USGS Geomagnetism Program headquarters in Golden, Colorado, the site is used by Geomagnetism Program engineers and technical staff to develop, calibrate, and test new sensors, acquisition systems, and operational procedures (for example, Worthington and others, 2009; White and others, 2014). The observatory supports allied geophysical measurement systems, and it is used for training Program staff and visiting technicians. In all of these respects, then, the Boulder observatory plays a critical role in supporting the entire mission of the USGS Geomagnetism Program.

Location

The Boulder observatory is located on what is known as the Table Mountain Field Site, a flat-top butte composed of young Quaternary alluvium north of the city of Boulder, Colorado, just east of the Rocky Mountains (40.1375° N, 105.2372° W), 1,682 meters (m) above sea level (Green, 1992). The land immediately surrounding the observatory is rocky and interspersed with grass and cactus. The climate is semiarid with an average annual temperature of about 11 degrees Celsius. The average annual precipitation is 47 centimeters, often coming in the form of summer thunderstorms and winter snowfall. Although the USGS owns the observatory infrastructure and is responsible for observatory operations within a 1,000-ft (305-m) radius circle centered on the electronics building (discussed below), the land itself is owned by the National Telecommunications and Information Administration (NTIA) of the United States Department of Commerce (DOC).

Operational History

The history of the Boulder observatory can be traced back to September 1960, when the National Bureau of Standards (NBS) of the DOC constructed a nonmagnetic building for data acquisition on its main campus site in the city of Boulder. Magnetic measurement using photographic analog systems commenced in December 1960. At that time, the Coast and Geodetic Survey (C&GS) of the DOC was responsible for the operation of several magnetic observatories in the United States. Under terms of an April 15, 1963 memorandum of understanding, magnetic measurement operations were transferred from NBS (1963) to C&GS. The first reported hourly mean data from the Boulder observatory are in the archives of the World Data Center in Kyoto, Japan. These data were derived from analog magnetograms for April 1963, and, thus, operations at the Boulder observatory commenced in time to contribute to the International Year of the Quiet Sun of 1964. The first published geomagnetic measurements made on the present site of the Boulder observatory, at Table Mountain, were made on July 16, 1964.

On July 13, 1965, the C&GS was consolidated into the Environmental Science Services Administration of the DOC, which, subsequently, became the National Oceanic and Atmospheric Administration (NOAA) on October 3, 1970. A memorandum of understanding effective on May 27, 1973,

transferred ownership and operational responsibility of most U.S. magnetic observatories, including the observatory at Boulder, from NOAA (DOC) to USGS of the Department of the Interior (DOI).

The first published 1-minute data values from Boulder are for March 1978. These were made using digital acquisition systems. The 1-minute digital data values represent a substantial improvement in temporal resolution over 1-hour analog data values. Boulder observatory data for the year 1991 contributed to the first joint certification and publication of 1-minute data by the international consortium of magnetic observatory institutes known as INTERMAGNET (Love and Chulliat, 2013). Since June 13, 2011, Boulder 1-second data have been reported to INTERMAGNET. Since 1991, data-acquisition operations at Boulder have been maintained with approximately 97 percent continuity.

Facilities

The Boulder observatory consists of several small buildings; these serve a variety of functions, and many of them are made of nonmagnetic material; see figure 1. For magnetic measurement operations, the variations building houses a fluxgate magnetometer and a backup fluxgate magnetometer, each maintained at a stable operating temperature. Near this, an Overhauser proton-precession magnetometer is housed in a small hut. The electronics building contains data display computers, network connections, and office space. For review of observatory instrumentation see Rasson (2007).

The Boulder absolutes building houses a specially designed theodolite made of nonmagnetic material and having a small magnetometer attached to its telescope. This instrument is commonly referred to as a declination-inclination magnetometer (DIM). It is situated on a stable pier that serves as a reference point for the entire observatory. The observatory site has several azimuthal reference markers, also on stable piers, and whose orientation relative to the theodolite pier have been carefully measured using geodetic methods.

A coil system, used for testing and calibrating acquisition systems, is housed in its own dedicated building on the Boulder site (White and others, 2008); a separate building houses modern coil-control electronic systems and power supplies. Two cubical buildings are used for testing new sensor and acquisition systems. A storage building is located about 200 m from the operational and testing buildings.

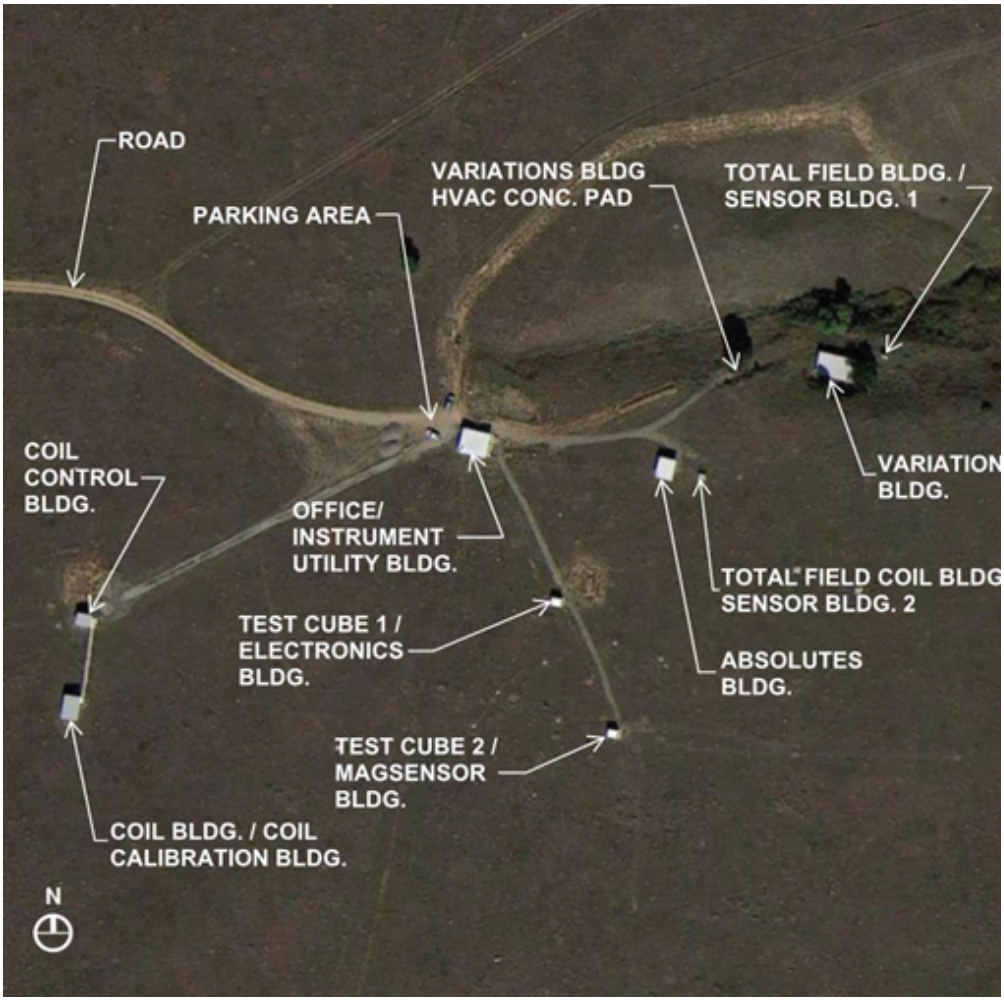


Figure 1. Aerial view of the USGS Boulder magnetic observatory site. (Conc., concrete; Bldg., building)

Data Types

Continuous second-to-second change, or "variation," in the geomagnetic field is measured at the Boulder observatory with a fluxgate magnetometer (for example, Primdal, 1979; Narod and Bennest, 1990). These data are sufficient for many applications, such as monitoring geomagnetic space weather phenomena evolving over timescales of a few hours or less. Variation data are available to the user community in real-time as a preliminary data product from both the USGS Geomagnetism Program and INTERMAGNET.

For many applications, however, magnetic variation needs to be defined relative to an accurate baseline. Two different sensors provide accurate auxiliary data. An Overhauser magnetometer (for example, Hrvoic and Hollyer, 2005) provides continuous absolute magnetic field intensity data, and the DIM instrument is used by an observatory worker twice a week or so to make visual measurements of absolute field direction. These auxiliary data are combined with the variometer data through computer-based processing to produce calibrated data (for example, Jankowski and Sucksdorff, 1996). Promptly processed data, known as "quasi-definitive," are available to the user community within a few months of preliminary data acquisition.

Final "definitive" data, an accurate representation of the Earth's magnetic field at the Boulder site, are reported to INTERMAGNET and made available to the user community on an annual schedule. Long-term archives of definitive observatory data are maintained in the World Data System.

Partners

The USGS Geomagnetism Program collaborates with the University of Washington by supporting the operation of a very low frequency (VLF) (3–30 kilohertz) band antenna on the Boulder observatory site for the World Wide Lightning Location Network (WWLLN; Lay and others 2004). The WWLLN is a collaboration between universities and government labs from around the world for collecting lightning-generated VLF electric field waveform signals. These are used to estimate the location and time of lightning strikes around the world, in real time.

Natural Signals

A long-term view of Boulder observatory magnetic field data is provided in figure 2, for years 1967–2013. Here, annual mean values (green) of horizontal intensity (*H*), declination (*D*), and the vertical component (*Z*) of the magnetic field exhibit a slow secular drift. This variation is global in scale and driven by fluid convection in the Earth's core. Note that in the 46 years of time represented in figure 2, declination has changed by about 4 degrees at Boulder.

Relatively more rapid variation of the Boulder geomagnetic field is seen in figure 2 as the variance of hourly mean values (black) about the slower secular variation. This variation occurs in two distinctively different ways: quiet time variation and magnetic-storm variation. Periodic variation in the geomagnetic field is easily seen in observatory data when magnetic conditions are relatively quiet (for example, Owolabi and others, 2014). Electric currents in the Earth's electrically conducting day-side ionosphere are generated by thermospheric winds that are, themselves, driven by day-night differential solar heating. In figure 3, we show an example of solar-quiet variation recorded in Boulder 1-minute data, November 17–22, 2008; note the prominent quasi-diurnal signal in each of the magnetic field components.

Magnetic storms are caused by the dynamic interaction of the solar wind with the Earth's magnetosphere. In observatory data, storms are seen as a distinctive transient variation. In figure 4 we show Boulder data recording the Halloween storm of October 29–31, 2003 (for example, Gopalswamy and others, 2005). This storm caused operational stress in the Swedish (Pulkkinen and others, 2005) and Scottish power grids (Thomson and others, 2005). The storm commenced with the arrival at Earth of a coronal mass ejection, which abruptly compressed the magnetopause and generated the positive impulse seen in Boulder *Z* at 06:13 UT on October 29. Complex geomagnetic variation was driven by the arrival of additional coronal mass ejections, solar wind variability, and vigorous magnetospheric convection. What followed was storm main-phase intensification of magnetic activity that lasted for more than 2 days.

Derived Products

Data from the Boulder observatory are used by NOAA's Space Weather Prediction Center (SWPC) for real-time assessment of mid-continental geomagnetic conditions within the United States (for example, Balch and others, 2004). Boulder observatory data contribute to the U.S. Air Force calculation of an American version of the Kp index (Gehred and others, 1995), a traditional measure of global geomagnetic activity that has historically been used for space weather assessment (for example, Mayaud, 1980). The Kyoto World Data Center in Japan uses Boulder data for the calculation of the symmetric (SYM) and asymmetric (ASY) indices (Iyemori and Rao, 1996). These indices represent, respectively, the symmetric and asymmetric parts of the magnetospheric equatorial ring current, both of which are fundamental quantities used for analysis of magnetic storm dynamics. Boulder data are used in the derivation of the International Geomagnetic Reference Field (IGRF), a spherical harmonic model of the main part of the Earth's magnetic field. Widely used for scientific research, navigation, and near-surface magnetic surveys, the

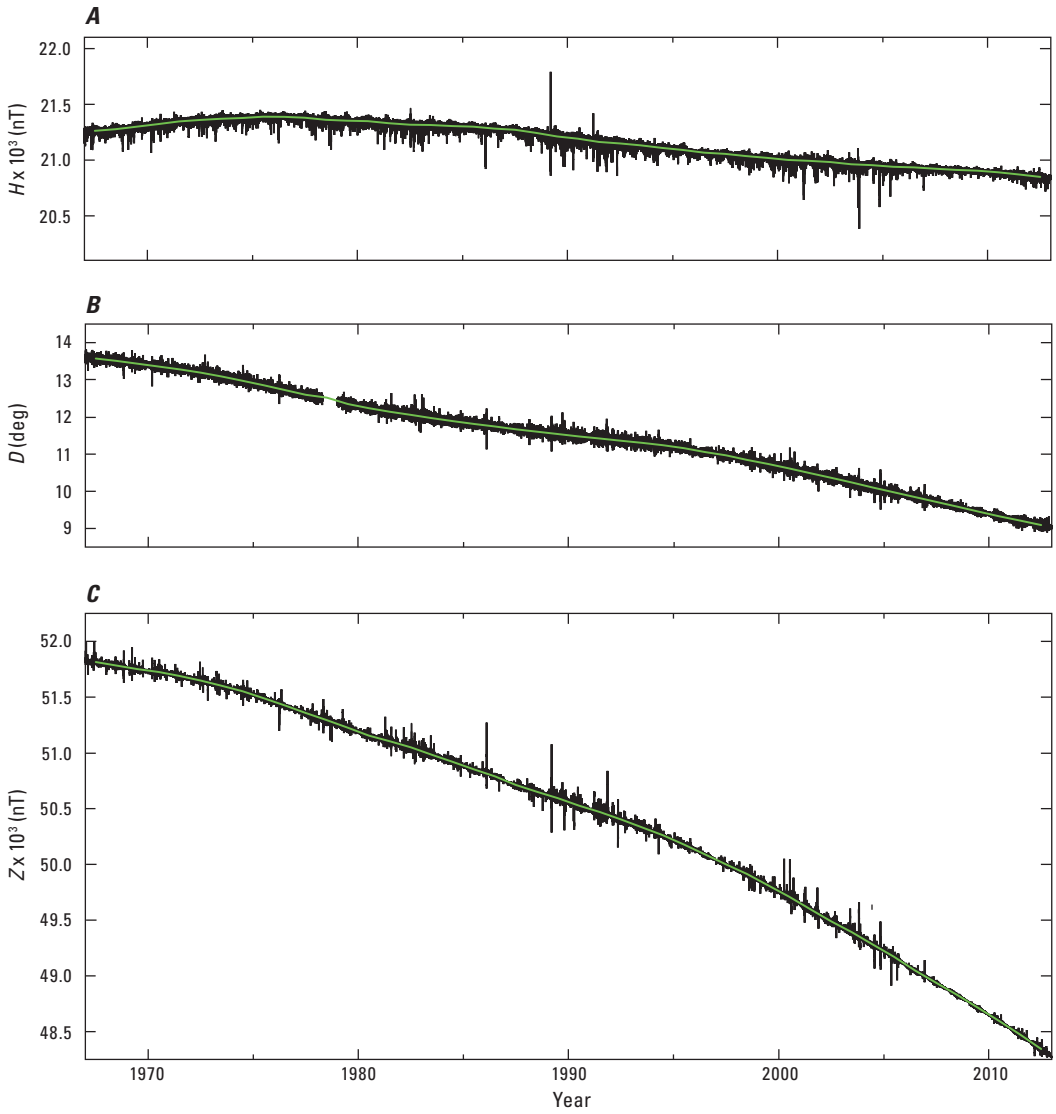


Figure 2. Boulder geomagnetic data for years 1967–2013, hourly values (black) and annual mean variation (green): *A*, horizontal intensity (*H*); *B*, declination (*D*); and *C*, vertical component (*Z*). (deg, degrees; nT, nanoTesla)

IGRF is constructed using a combination of data from satellites, ground surveys, and magnetic observatories—including data from the Boulder observatory (for example, Finlay and others, 2010).

Workshop

The 13th biennial International Association of Geomagnetism and Aeronomy (IAGA) Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing was hosted by the USGS Geomagnetism Program, June 9–18, 2008. This was the first time this important workshop was held in the United States. More than 100 participants, representing many different institutions came from 36 countries and 6 continents. In preparation for the workshop, several new absolutes piers were installed at the Boulder observatory to facilitate simultaneous measurement of the absolute direction and intensity of the geomagnetic field (Berarducci and Woods, 2009; White, 2009). Results of the measurement session and the presentations given during the scientific session are presented in the Workshop's proceedings (Love, 2009).

Induction Hazards: Future Developments

The Boulder observatory has recently become a focal point for the USGS Geomagnetism Program and its support of a multiagency project for studying, monitoring, and evaluating magnetic storm hazards (Love and others, 2014; NSTC, 2015). Of concern is the storm-time induction of geoelectric

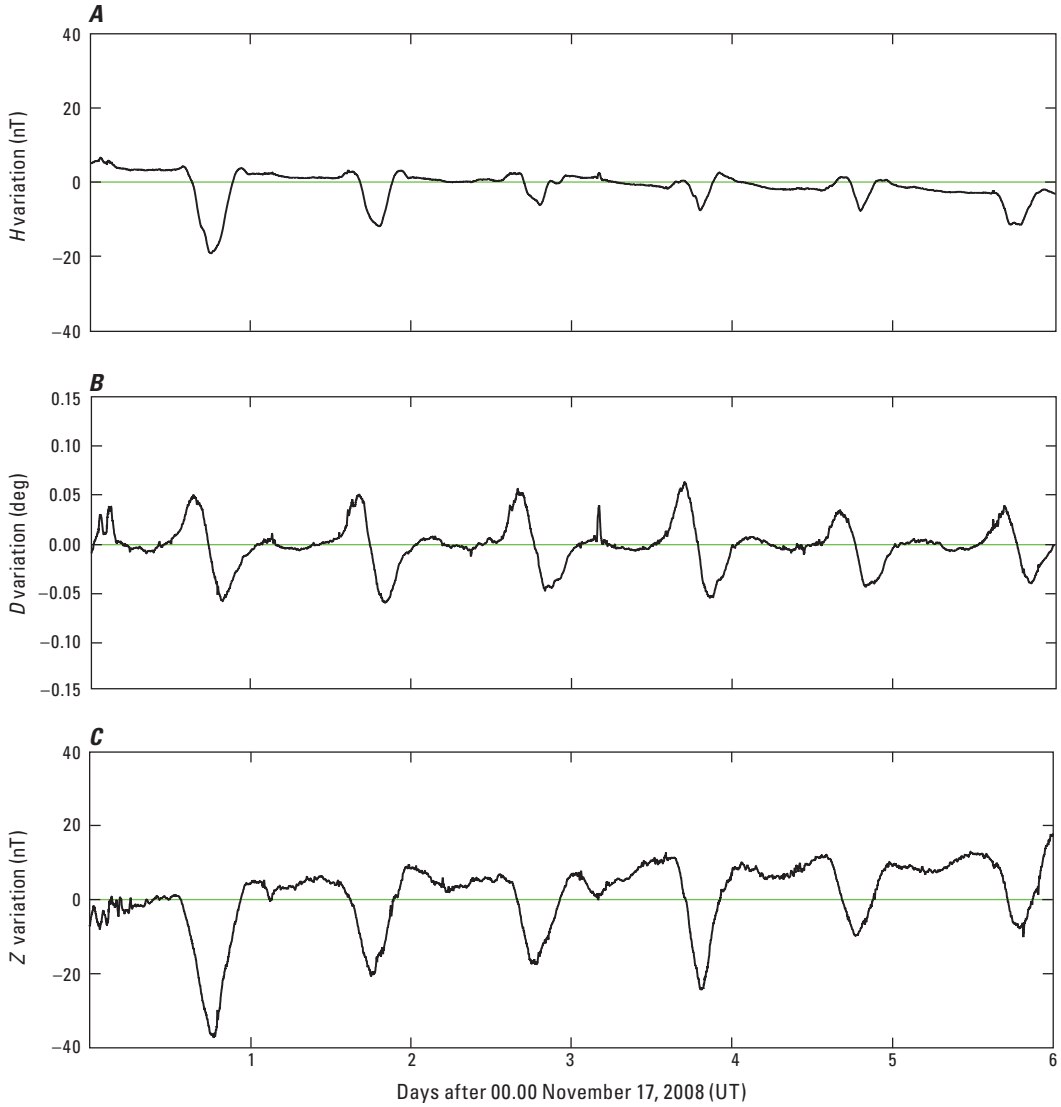


Figure 3. Quiet time Boulder geomagnetic variation for November 17–22, 2008, minute values (black) relative to absolute baseline (green): *A*, horizontal intensity (*H*); *B*, declination (*D*); and *C*, vertical component (*Z*). (deg, degrees; nT, nanoTesla)

fields in the Earth's electrically conducting lithosphere. Corresponding voltage differentials can find their way into electric-power grids through ground connections, driving uncontrolled electric currents that interfere with grid operation, sometimes causing blackouts (for example, Boteler and others, 1998).

One part of this induction-hazard project is focused on real-time mapping of storm-time magnetic disturbance across North America using data from the USGS and Canadian observatory networks (Pulkkinen and others, 2003; Rigler and others, 2014). For this, magnetic data from the Boulder observatory, with its location in the continental interior, will play an important role in constructing such maps and validating their accuracy. Another part of the project is focused on estimating the storm-time induction of geoelectric fields, and, as a check of such estimates, the geoelectric field will be directly monitored at the Boulder observatory site.

Other possible operational opportunities for the Boulder observatory include testing electromagnetic crustal exploration systems, and development of a joint U.S.–Canadian calibration facility. In the coming years, the Boulder magnetic observatory will certainly remain an important site for operations and developments within the USGS Geomagnetism Program.

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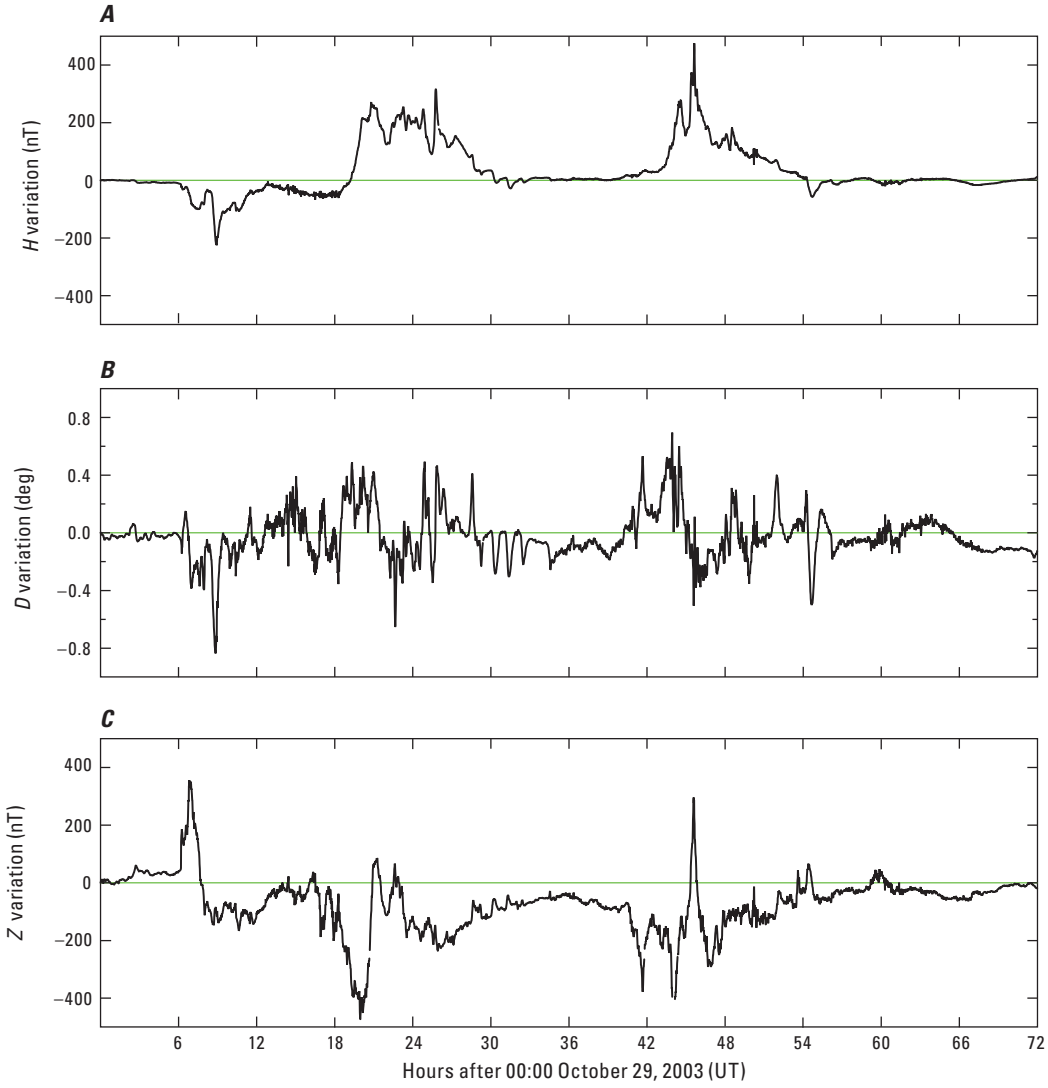


Figure 4. Magnetic storm Boulder geomagnetic variation for October 29–31, 2003, minute values (black) relative to absolute baseline (green): *A*, horizontal intensity (*H*); *B*, declination (*D*); and *C*, vertical component (*Z*). (deg, degrees; nT, nanoTesla)

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