Monitoring space weather with the GOES magnetometers

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ABSTRACT

Magnetic field measurements have been made from geosynchronous orbit for more than 20 years. These measurements are important for monitoring "space weather" and for providing a unique data base that can be used for improving our knowledge of the Earth's magnetosphere and solar-terrestrial interactions. This paper will focus on the variety of products and services provided by these measurements - those currently available, and those under consideration for the future. The magnetic field measured at the GOES is presently used to detect synchronous orbit magnetopause crossings and shocks in the solar wind, to assist forecasters in qualitatively assessing the level of geomagnetic disturbance, to interpret changes in energetic particle measurements, to provide data to the National Geophysical Data Center, to support in real-time scientific activities such as rocket launches, and to conduct research for a better understanding of the space environment. One important use of magnetometer data in the Space Environment Center is to alert customers when shocks occur in the solar wind. These shocks have the potential for energizing particles to multi-MeV levels, causing Single Event Upsets (SEU's) in spacecraft electronics, and at lower energy ranges causing deep-dielectric charging that produces spacecraft anomalies. Data from the new GOES-8 and GOES-9 spacecraft will be discussed along with prospects for future products and services.

Keywords: magnetometer, geomagnetic field, geomagnetic storm, geomagnetic substorm, geosynchronous, GOES

1. INTRODUCTION

In 1945, in the British radio journal *Wireless World*, Arthur C. Clarke was the first to propose the use of three satellites, located 22,300 miles above the equator, to provide global TV coverage. As he wrote about this proposal in the early 1960's in the book Profiles of the Future, he noted that preparations were underway by the Hughes Aircraft Company and the United States Army to launch communications satellites into this 24 hour orbit[1]. On July 26, 1963, Syncom 2 was launched, becoming the first communications satellite in geosynchronous orbit. It was only a few years later, in 1966, that the first magnetic field measurements were made in geosynchronous orbit by the ATS-1 (Application Technology Satellite), and operational measurements began with the SMS (Synchronous Meteorological Satellite) in May 1974[2].

Since those early days of the space age, hundreds of satellites valued at billions of dollars have been placed in geosynchronous orbit to provide a multitude of services like improved global communications and weather monitoring. These resources, satellites in other orbits, and many ground-based technological systems are vulnerable to "space weather" effects like those caused by damaging energetic particles and severe geomagnetic disturbances. Consequently there is a need for monitoring, specifying, and predicting conditions in the near-Earth space environment where these systems operate. The Geostationary Operational Environmental Satellite (GOES) magnetometer is one of the instruments that provides these functions, and it is included in the NOAA Space Environment Center Space Environment Monitor (SEM) package that is operational on each GOES. The other instruments in the SEM package, an Energetic Particle Sensor (EPS) and a solar X-ray Sensor (XRS) are described elsewhere. In addition, a new operational instrument to provide Solar X-ray Images (SXI) will be flown on GOES around the year 2000. As described below, the geosynchronous environment is not only an important location for monitoring space weather, but it is also a unique location for providing data that can be used for improving our knowledge of the Earth's magnetosphere and solar-terrestrial interactions.

Following two SMS satellites, the first GOES was launched in October 1975, and they have continued to this day with the currently operational GOES-8 and GOES-9 spacecraft[3]. The magnetic field data, beginning with SMS-1, are used for space weather operations, and are collected and processed by the NOAA Space Environment Center to be archived and distributed through the NOAA National Geophysical Data Center. The continuous record spanning several decades is one of the values of these measurements over measurements made in other orbits over more limited time spans. This paper will describe the magnetometer instrument, the geosynchronous space environment, and operational and scientific uses of the GOES magnetometer data.

2. MAGNETOMETER INSTRUMENT: DESCRIPTION, TESTING, AND OPERATION

The magnetometers on the three-axis stabilized GOES I-M (called GOES 8-12 after launch) series of satellites are three-axis fluxgate magnetometers manufactured by the Schonstedt Instrument Company and integrated on the spacecraft by Space Systems/LORAL. The magnetometer electronics are inside the spacecraft, and the sensors are mounted on a three-meter boom attached at the north west corner of the anti-Earth panel, with the primary sensor at the end of the boom and a second redundant sensor located 0.3 meters inboard of the first. Only one magnetometer may be operated at a time. Each magnetometer axis is measured once a telemetry frame (0.512 seconds), with a 42 millisecond delay between sampling successive axes. To reduce aliasing, each of the three-axis magnetometer outputs is filtered through a five-pole 0.5 Hz Butterworth low-pass filter.

The magnetometer range is ± 1000 nanoTesla (nT), and is measured by a 16 bit analog-to-digital converter providing 0.03 nT sensitivity. With temperature compensation of the sensors and electronics, the accuracy of the instrument is 1 nT. The instruments are monitored for proper operation by adding a series of small fixed currents to a set of auxiliary windings during weekly calibrations and checking for proper magnetometer gains and transient responses.

To insure accurate measurements, the GOES magnetometers are thoroughly tested and calibrated. Prior to launch, the instruments are temperature calibrated, and sensor gains and offsets are determined. Because stray fields, generated by the spacecraft, can severely contaminate the measurement, a stray-fields test program identifies whether or not various spacecraft systems produce magnetic signatures that are likely to be detected in orbit. If there is a detectable signature, it is either reduced to an allowable limit through hardware modifications, or a correction scheme is instituted in the ground-based data processing. Efforts are also made to minimize and control magnetic materials on the spacecraft and boom. An initial calibration of the spacecraft torquer coils is also made prior to launch.

Absolute magnetic field measurements require accurate knowledge of magnetometer offsets that result from the spacecraft and the sensor electronics. A spinning spacecraft continuously provides the opportunity to measure these values for the spin plane sensors; however, on the three-axis stabilized GOES-8 and GOES-9, we must rely on a one time satellite maneuver. In orbit, just after the magnetometer boom deployment, the spacecraft is rotated about 3 axes to determine magnetic offsets that result from a combination of the spacecraft field and the magnetometer sensors. This maneuver cannot be performed again after all spacecraft appendages are deployed and the spacecraft becomes operational. Following the initial offset determination, data comparisons with magnetic field models are used to monitor for any major changes in these offsets.

On GOES-8 and GOES-9, the spacecraft torquer coils are the major system contributing offset fields to the measurements that must be corrected during data processing. The magnetic torquers, along with two momentum wheels, a reaction wheel, the solar panel trim tab and 22 thrusters, maintain the proper attitude of the spacecraft. They are controlled by an attitude and orbit control subsystem. At the launch of GOES-8, the torquers could change current at a 20 minute interval. The currents could change from full scale of one polarity to full scale of the other polarity at one of these steps, could make a small step, or the current might not change at all at one of the possible current change times. A maximum size step can produce as much as a 400 nT magnetic signature at the magnetometer sensors. The control of the torquers has evolved into a small fixed size step in the torquer current at a much faster rate. The current operation of the torquers sets the current change at a level that causes a 1.5 nT magnetometer step at a minimum change interval of 2.56 seconds. In actual operation not every possible change interval has a torquer current change. GOES-8 torquer currents change from 600 to 800 times a day.

A calibration between torquer currents and magnetic field signatures was made both on the ground and in space for correcting the magnetic field measurement; however, on GOES-8, noise in the torquer current telemetry introduced artificial noise in the "corrected" magnetic field at the few nanoTesla level. A correction has been instituted on GOES-8, and will be included on following spacecraft, to allow use of torquer command data for torquer current correction. The problem has been further dealt with on GOES-9, and future spacecraft, by filtering the torquer current telemetry before it is transmitted.

3. THE GEOSYNCHRONOUS MAGNETIC ENVIRONMENT

Geosynchronous magnetic field measurements have proven useful for both operational and scientific purposes, in part because the orbit is in a strategic location for monitoring the effects of the major magnetospheric current systems. Much can be learned about solar-terrestrial interactions from analysis of these data. These currents described below[4], are superimposed on the Earth's internal dipole-like field that has a value of about 110 nT at geosynchronous orbit located at 6.6 Earth radii from the center of the Earth. The Earth's internal magnetic field is modified at this location by perturbations that range from fractions of a nanoTesla to sometimes more than 100 nT, but are more typically on the order of 40 or 50 nT. The variations of concern occur on a wide range of time scales: seconds for solar wind shocks and magnetic pulsations, minutes and hours for substorms, a day for local time variations in magnetospheric structure, days for magnetic storms, and months and years for solar cycle effects.

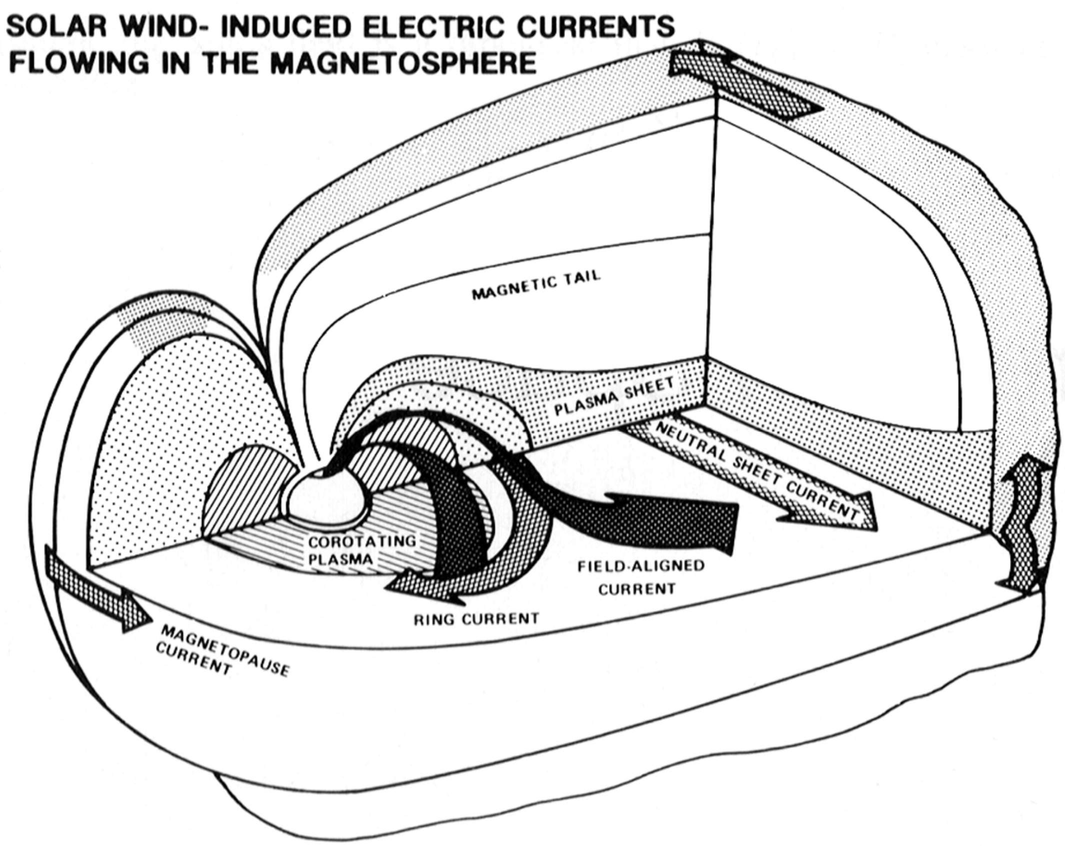

Figure 1: Solar-wind induced electric currents flowing in the magnetosphere. G K Parks, PHYSICS OF SPACE PLASMAS: AN INTRODUCTION, (portion of figure 7.1 from page 224), © 1991 Addison-Wesley Publishing Company Inc. Reprinted by permission of Addison-Wesley Longman Publishing Company, Inc.

As the solar wind streams past the Earth it distorts the Earth's dipole-like magnetic field into a shape that is compressed on the dayside, and drawn out into a geomagnetic tail hundreds of Earth radii long on the nightside (Figure 1). The velocity and density of the solar wind plasma, and the strength and direction of its imbedded magnetic field, influence not only the structure of the magnetic field surrounding the Earth, but also control the processes by which mass, momentum, and energy are transferred from the solar wind to the Earth's magnetosphere-ionosphere system. This interaction between the solar wind and the Earth's magnetic field creates the complex and dynamic magnetosphere which can be monitored by the GOES field and particle instruments.

The perturbations in the Earth's dipole field are caused by current systems external to the Earth that result from the coupling between the time varying solar wind and its interaction with the Earth's magnetic field. The primary current systems affecting geosynchronous observations are the magnetopause current, the ring current, magnetic field-aligned currents, and the neutral sheet or cross-tail current. Figure 1 shows the Earth's magnetosphere and the location of the major current systems in relation to magnetospheric regions and boundaries. Although the boundaries are dynamic, geosynchronous orbit is located in the equatorial region, typically between the plasma sheet and corotating plasma regions.

The magnetopause current system is at the magnetopause boundary that separates the region of space dominated by the Earth's field from the region dominated by the solar wind and its imbedded Interplanetary Magnetic Field (IMF). This interface is typically at about 10 Earth radii upstream of the Earth, between the Earth and Sun, but extends in a long downstream wake that is on the order of 100 Earth radii or more. The magnetopause current on the dayside enhances the field at geosynchronous orbit. The magnetopause boundary is dynamic, and when it is pushed in past the geosynchronous orbit location, satellites operations at that location can be affected.

The ring current is caused by radial gradients in the density and temperature of typically 1 to 200 keV ions that surround the Earth. This current typically maximizes at about 3 to 4 Earth radii, its strength can be asymmetric around the Earth, and its radial location can extend over a distance of several Earth radii. The ring current is a westward current that produces a strong depression in the field in the inner magnetosphere and at the surface of the Earth during geomagnetic storms.

Magnetic field-aligned currents that communicate information and electrically couple the ionosphere and the magnetosphere are quite complicated as a function of latitude, local time, and solar wind conditions. One of the most significant field-aligned currents that is detected at geosynchronous orbit is the current system associated with substorm expansion onsets in the midnight sector. Substorms typically occur every few hours, although their frequency and intensity are quite variable and dependent on solar wind conditions. The perturbations caused by the substorm related field-aligned currents are most notable in the east-west deflections of the geosynchronous magnetic field.

The last current system described, the neutral sheet current, is located in the center of the plasma sheet region and supports the oppositely directed magnetic fields in the tail lobes. Field lines threading the plasma sheet are closed, with one foot in each ionosphere. The foot points form an oval shaped region surrounding the polar cap where the most intense auroral activity occurs in the high latitude ionosphere. When the tail currents are strong the magnetic field at GOES in the midnight region departs from its dipole-like shape and becomes very stretched. When substorm expansions occur, in addition to the field-aligned currents mentioned previously, there is a reduction of the neutral sheet or cross-tail current that causes the field geometry to revert to a more dipole-like shape.

4. USES OF THE GOES MAGNETOMETER DATA

There are a variety of uses of the GOES magnetometer data for both operational and scientific needs. These are outlined in Table 1 and a few examples are discussed in greater detail below.

4.1. Assessing the level of geomagnetic disturbances

The geosynchronous magnetic field data can be used to assist forecasters in qualitatively assessing the level of geomagnetic disturbances. Figure 2 illustrates some of the information that can be learned from the examination of a simple time series of the data; it shows one-minute averages of three components of the magnetic field and the total field measured by GOES-9 for the entire month of January 1996. The three components are: Hp, perpendicular to the satellite orbital plane or parallel to the Earth's spin axis in the case of a zero degree inclination orbit; He, perpendicular to Hp and directed earthwards; and Hn, perpendicular to both Hp and He and directed eastwards. (This is the same coordinate system used for all the GOES magnetic field measurements since GOES-5; prior to GOES-5, Hn was directed westwards.)

4.1.1 Diurnal variations

An obvious feature in the data is the diurnal variation observed in all components and the total field. The diurnal variation is caused by the asymmetry in the Earth's field with respect to the solar direction. Hp (the parallel component) and Ht (the total

OPERATIONAL AND SCIENTIFIC USES OF THE GOES MAGNETOMETER • **Detecting magnetopause crossings** • **Alerting customers to solar wind shocks or sudden impulses** • **Assessing the level of geomagnetic activity** • **Distinguishing among different sources of energetic particle events** • **Developing techniques for new operational applications** • **Providing data to NGDC for archives and the scientific community** • **Real-time data to the US Air Force 50th Weather Squadron** • **Supporting rocket launch decisions and other real-time activities** • **Conducting research for understanding the space environment**

Table 1: Operational and scientific uses of the GOES magnetometer data.

field strength) typically maximize on the dayside near local noon, where the field is compressed by the solar wind pressure. Hp and Ht are reduced near local midnight where the Earth's field is stretched out into a long geomagnetic tail, so the Hp or Ht diurnal variation can be used to quickly assess the local time of the GOES satellite at a particular UT. In this case, during the month of January, GOES-9 was being moved from 115.8 degrees west geographic longitude to its more permanent position at 134.7 degrees. (Typically one GOES satellite is at 75 degrees west geographic longitude and one is at 135 degrees.) At the end of the month the total field (Ht) maximized near 21 UT when the satellite was near local noon and Ht minimized near 09 UT when the satellite was near local midnight.

4.1.2 Solar wind dynamic pressure

Another feature seen in the data, the magnitude of the field strength (Ht) maximum, can be used to infer the solar wind dynamic pressure, since this pressure is one of the factors controlling the compression of the Earth's magnetic field and therefore the strength of the dayside field. During January 1996 the maximum varied by about 35 nT, and during the 4 to 6 hours-per-day when the satellite is within 2 or 3 hours of local noon, these data can be used to monitor the solar wind influence on the magnetosphere. With two satellites separated by about 4 hours local time, as is typical for the GOES satellites, we could have an indicator of solar wind dynamic pressure during about 10 hours each day. These increases in solar wind dynamic pressure can at times be so large as to move the magnetopause inside geosynchronous orbit, causing major changes in the particle and field environment at this location.

4.1.3 Substorms, field-aligned currents and magnetic field reconfigurations

Substorms include brilliant activation of the aurora, the development of new and enhanced current systems in the ionosphere and magnetosphere, the reconfiguration of the magnetic field geometry in the magnetotail and geosynchronous regions, the injection and energization of particles into geosynchronous altitudes, and the formation of plasmoids that are ejected down the magnetotail. Substorms can be detected in both Hp and Ht and are most noticeable in Figure 2 where magnetic fluctuations

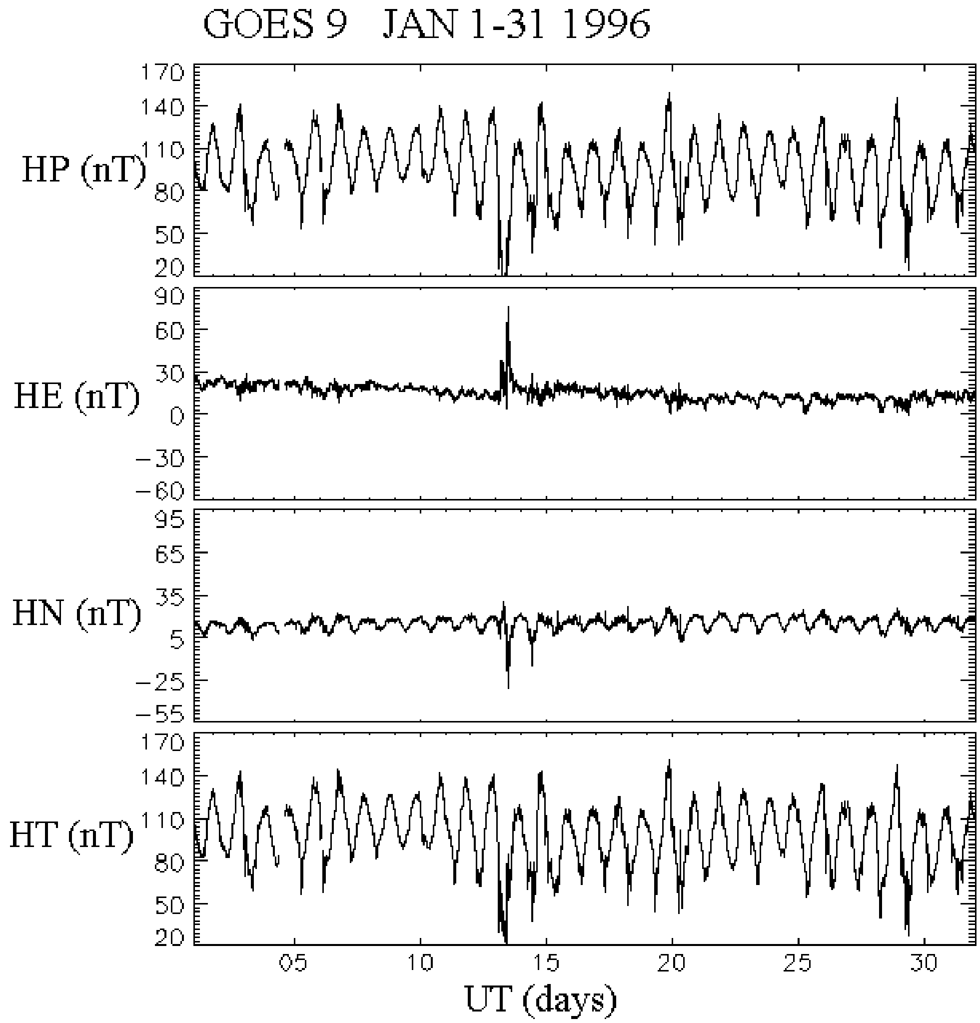

Figure 2: GOES 9 magnetic field data for January 1996.

cause a “hashy” appearance in the display around local midnight; good examples of this are seen on Jan 13, 14, and 15 and again around January 29. The geomagnetic activity index, Kp, indicates that these were the most disturbed days of January 1996.

Just as the Hp component at local noon can be useful for determining how compressed the magnetic field is on the dayside, the Hp component near local midnight can be used to indicate how stretched the field is on the nightside. The more stretched the field the weaker the Hp component near midnight, and as can be seen in the top panel of Figure 2, this component can vary substantially from day to day. Magnetic field stretching in the magnetotail is the result of a complex process that begins with the transfer of energy from the solar wind to the magnetosphere (where energy is stored in the form of increased magnetic flux in the tail lobes of the magnetosphere) enhancing the cross-tail current sheet and causing field-line stretching near geosynchronous orbit. Eventually this energy is released in the substorm process, causing the sudden relaxation, or dipolarization, of the stretched field. The sudden relaxation can be observed as an abrupt increase of the Hp component of the field, as seen on January 20 in Figure 2.

Substorm activity and other processes related to energy coupling between the solar wind and the magnetosphere often result in increased field-aligned currents. These currents can cause variations in the east-west (Hn) component of the magnetic field at geosynchronous altitude. A major increase in these currents is seen on January 13 in association with tail stretching and substorm activity. Although these dynamic phenomena have been studied for many years and are among the most fundamental processes in space plasma physics, they are far from understood. They are known, however, to be related to the space weather effects such as spacecraft charging that can affect satellite operations, and ionospheric currents and heating that can effect communication systems that depend on ionospheric properties. In the future, the GOES magnetometer data could be used to develop new substorm indices based on magnetic field stretching, dipolarizations, and the disturbances described above.

4.1.3.1 Magnetic field observations and auroral substorm images

The magnetic field variations observed by GOES magnetometer during substorm expansion onsets, such as tail stretching and dipolarization, are related to a variety of global scale magnetospheric features. Observations from the recently launched NASA Polar satellite provide a new opportunity to explore further the relationship between GOES substorm observations and simultaneous auroral features monitored by imaging the Earth's polar regions in the visible, ultraviolet, and x-ray wavelengths. These comparisons may lead to a better understanding of substorms and to improvements in forecasting and monitoring their effects on ground and space-based systems.

The top portion of Figure 3 shows a gray scale version of an image made by the Polar satellite on May 15, 1996[5]. The entire auroral oval can be seen in this picture, along with a brightening of the aurora on the nightside. This figure, along with many others, are available at the World Wide Web (WWW) site http://www-pi.physics.uiowa.edu/www/vis/. The top portion of Figure 3 is described at this site as, "A sudden, intense bulge in the auroral oval signals the start of an auroral substorm over North America. The bulge can be seen easily over northern United States and southern Canada. A map of the coastal outlines has been superposed on the image. This image has been acquired by the Earth Camera that is one of the three cameras in the Visible Imaging System (VIS) on board the Polar spacecraft. In this mode, an image of Earth can be acquired every 53 seconds with the VIS Earth Camera. This image was taken at 07:13 UT on May 15, 1996. At the time of this image, the Polar spacecraft is located at 82.1° latitude, 74.2° longitude, and is at an altitude of 41,900 km as it approaches apogee. The filter for this image passes ultraviolet emissions that are not directly visible to the human eye. The intensities of this light from atomic oxygen in Earth's atmosphere at altitudes in the range of about 100 to 500 km are color-coded in the image with dark red as lowest intensities and whitish yellow as the brightest intensities."

The bottom portion of Figure 3 shows one-minute averages of the GOES-8 and GOES-9 magnetometer Hp component from 0600 to 0800 UT. While GOES-8 shows little activity, there are two dipolarizations at GOES-9, and the larger second dipolarization at about 0713 UT coincides with the auroral brightening in the Polar image data. On May 15, 1996 GOES-8 was located at 75 degrees west geographic longitude, and GOES-9 was located at 135 degrees west geographic longitude. The foot of the magnetic field line through GOES-9 intercepts the Earth approximately in western Canada just north of the bright aurora, while the GOES-8 field line intercepts the Earth in eastern Canada, far to the east of the bright aurora. These results illustrate how the GOES satellites can be used as a diagnostic of magnetospheric substorms — the two satellites provide information about the substorm expansion onset time and on the strength and spatial extent of the current systems. The high time and spatial resolution Polar images will provide a new opportunity to examine this relationship between the geosynchronous and ionospheric manifestations of the substorm processes.

4.1.4 Magnetopause crossings and shocks

An important operational use of the GOES magnetometer data is related to the need to monitor magnetopause crossings and interplanetary shocks. As described earlier, magnetopause crossings at geosynchronous orbit are caused by increases in solar wind dynamic pressure. The largest increases are often, but not always, associated with shocks in the interplanetary medium and geomagnetic storms. Magnetopause crossings at geosynchronous orbit can have serious effects on those satellites that depend on magnetic torquer coils to adjust for satellite momentum changes caused by solar radiation pressure. Some satellite operators have indicated that they would turn off torquers during these intervals rather than torque against a magnetic field that differs substantially from what is expected[6]. The largest geomagnetic storms often begin with the arrival of a shock in the solar wind[7] and these shocks can cause transient geomagnetic disturbances that affect ground-based electric power systems. In addition, large shocks, such as one on March 24, 1991, can produce new radiation belts of MeV electrons and protons in a matter of seconds[8]. These radiation belts can be long lasting and can damage, destroy, or limit the lifetime of satellite electronics.

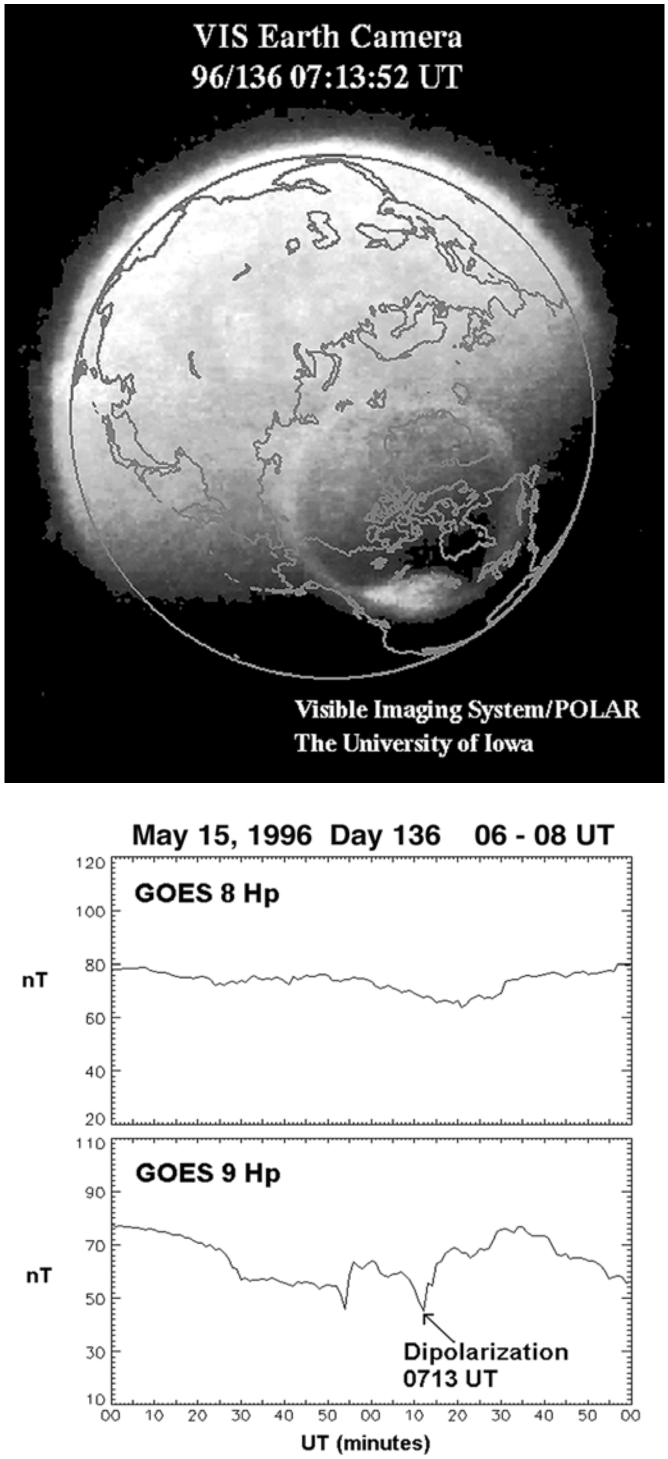

Figure 3: (Top) This image was acquired with the Earth Camera that is one of three cameras in the Visible Imaging System (VIS) which was designed and constructed at The University of Iowa. The VIS is one of twelve instruments on the Polar satellite of the NASA Goddard Space Flight Center. The Principal Investigator is Dr. L. A. Frank and the Instrument Scientist and Manager is Dr. John. B. Sigwarth.

(Courtesy L. Frank) (Bottom) GOES-8 and GOES-9 magnetometer Hp component from 6-8 UT on May 15, 1996.

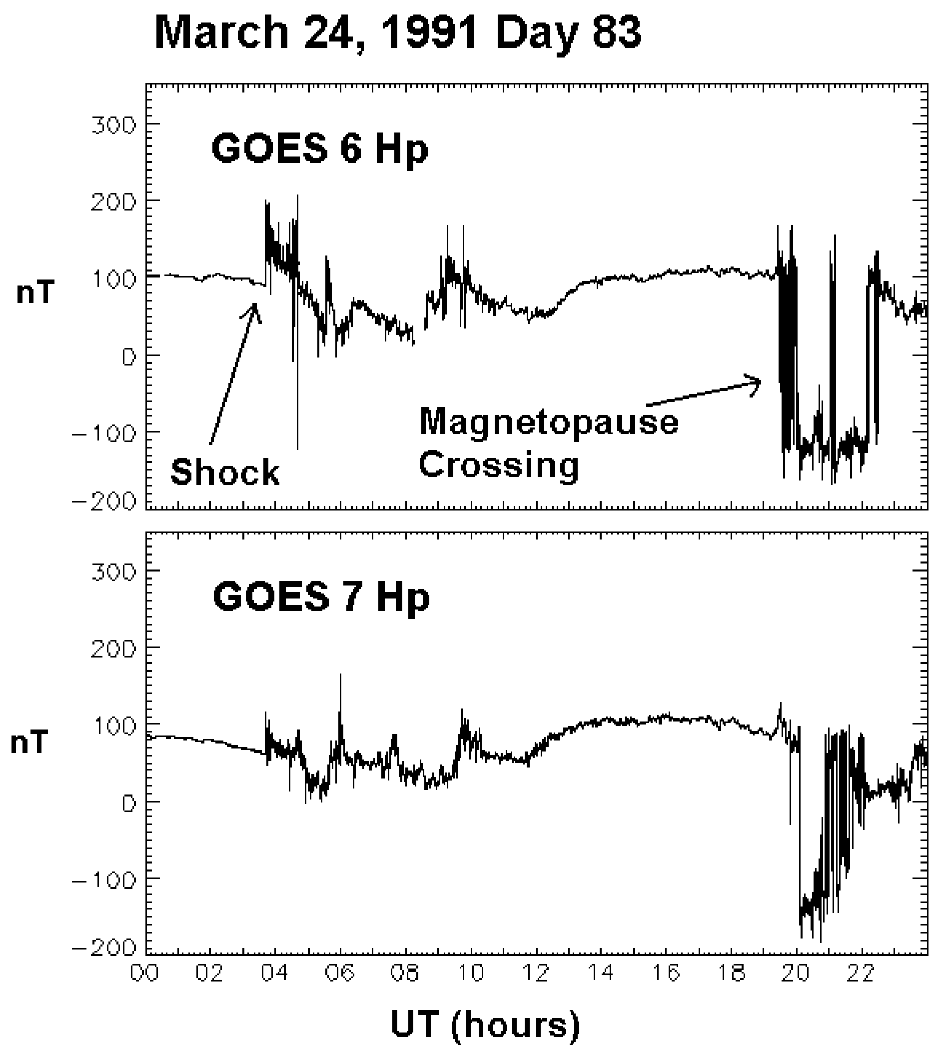

Figure 4: GOES 6 and 7 magnetic field Hp component at the onset of the March 24, 1991 magnetic storm.

The March 24, 1991 geomagnetic storm is one example in the GOES data base that illustrates magnetic field effects during a large storm. These data, from GOES-5 and GOES-6, are shown in Figure 4 as 3.06 second data from the parallel (Hp) component for the entire day. At 3:41 UT a shock in the solar wind encountered the Earth's magnetosphere, compressing the magnetic field to nearly twice its normal value at GOES-6 and slightly less at GOES-7. Later in the day, as indicated in Figure 4, the field normally positive and on the order of 100 nT, reversed sign to a large negative value, indicating a magnetopause crossing. An accurate magnetopause model and solar wind measurements from an upstream monitor, such as the currently operating NASA WIND spacecraft or the future NASA ACE spacecraft, could provide a 30-60 minute forecast of these conditions; current model results, however, are least valid during extreme solar wind conditions, when they are most needed. Therefore, there is a need for improved magnetopause models, the testing of these models under extreme conditions, and monitoring what actually occurs at the geosynchronous location at GOES.

In the Space Weather Operations office at NOAA SEC, an automated computer procedure monitors the GOES spacecraft and the Boulder ground magnetometer for rapid changes in the geomagnetic field. When two out of three of the sensors indicate a rapid change, an alarm is sounded to alert forecasters to a possible sudden impulse or shock, and they can give increased attention to the data, and if necessary, send out an alert to customers.

5. SUMMARY

The GOES magnetometer measurements provide crucial information about the geospace environment that is used to protect military and civilian ground and space-based assets that are vulnerable to space weather effects. In this paper we have briefly described the magnetometer instrument, the environment the instruments monitor, how to interpret the data, and how the data are used to support real-time operations at the NOAA Space Weather Operations and the US Air Force 50th Weather Squadron. The data are archived at the NOAA National Geophysical Data Center. The data are also made available to real-time users through a variety of delivery systems, including the World Wide Web (http://www.sec.noaa.gov), and are archived and used at SEC for anomaly assessments, developing new techniques for operational applications, and for conducting research to better understand the space environment.

6. ACKNOWLEDGMENTS

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