CGMS-XXX USA-WP-05
Prepared by: NOAA/SEC
Agenda Item: C.2

REPORT ON GOES SPACE ENVIRONMENT MONITOR INSTRUMENTS: OVERVIEW, PLANS AND BENEFITS TO USERS

The GOES Space Environment Monitor (SEM) instruments are used to monitor the Sun and the near-Earth space environment. These instruments include: the Energetic Particle Sensors (EPS), Magnetometer (MAG), Solar X-ray and Extreme Ultraviolet Sensors (XRS and EUV), and the Solar X-ray Imager (SXI). These instruments supply critical data to the NOAA Space Weather Operations (SWO), a multitude of government and private industry users affected by space weather, and the scientific community. The purpose of this paper is to briefly review the history of the GOES SEM instruments, describe what the current instruments measure, changes that are being made for the GOES NO/PQ series, plans for future instruments, examples of some of the GOES products, and how the data from the instruments are used to benefit society.

REPORT ON GOES SPACE ENVIRONMENT MONITOR (SEM) INSTRUMENTS: OVERVIEW, PLANS AND BENEFITS TO USERS

H. J. Singer, S. Hill, T.G. Onsager, R. Viereck

NOAA Space Environment Center
325 Broadway
Boulder, CO 80305

Introduction

The GOES Space Environment Monitor (SEM) consists of several instruments to monitor the Sun and the near-Earth space environment. These instruments include: the Energetic Particle Sensors (EPS), Magnetometer (MAG), Solar X-ray and Extreme Ultraviolet Sensors (XRS and EUV), and the Solar X-ray Imager (SXI). These instruments supply critical data to the NOAA Space Environment Center's (SEC) Space Weather Operations (SWO), a multitude of government and private industry users affected by space weather, and the world scientific community.

One way that the NOAA Space Environment Center communicates current and future space weather conditions, and their possible effects on people and systems, is through the NOAA Space Weather Scales. The scales describe the environmental disturbances for three event types: Geomagnetic Storms, Solar Radiation Storms, and Radio Blackouts. The scales have numbered levels to convey severity, analogous to hurricanes, tornadoes, and earthquakes. They list possible effects at each level. They also indicate the statistical frequency of such events, and give a measure of the intensity of the physical causes. Two of the three scales, Solar Radiation Storms (an indicator of elevated levels of radiation that occur when the numbers of energetic particles increase) and Radio Blackouts (an indicator of disturbances of the ionosphere caused by X-ray emissions from the Sun) depend upon the GOES satellite SEM measurements to determine the occurrence and magnitude of the disturbance.

International collaboration greatly benefits the provision of space weather services and an organization, the International Space Environment Service (ISES), is made up of thirteen space weather forecasting centers around the world. SEC is designated the World Warning Agency of ISES for space weather monitoring and forecasting. Exchange of solar-terrestrial data between the ISES sites occurs several times a day. The GOES SEM data are utilized by these sites to provide space weather services to the geographical regions assigned to them. The GOES SEM sensors are not duplicated on any other spacecraft because of the continuous coverage GOES provides and the quality and calibration of the data. In the future, additional measurements by other nations on their own geosynchronous satellites could complement the measurements made by the United States. For example, to understand solar influences it is necessary to monitor the sun with a variety of imagers that observe at different wavelengths, resolutions, and cadences.

Most of the energetic particle and magnetic field measurements made by GOES depend upon the local time of the observations. Through enhanced international and interagency partnerships, a more complete picture of the space environment could be developed than is now possible.

The purpose of this paper is to briefly review the history of the GOES SEM instruments, describe what the current instruments measure, changes that are being made for the GOES NO/PQ series, plans for future instruments, examples of some of the GOES products, and how the data from the instruments benefit society. The paper is divided into sections covering these issues for each of the SEM instrument packages: EPS, MAG, XRS and EUV, and SXI.

Energetic Particle Sensor (EPS)

The Energetic Particle Sensors (EPS) measure the local energetic particle environment in the immediate vicinity of the GOES spacecraft and include instruments to measure electrons, protons and alpha particles [*Onsager et al., 1996*]. This radiation environment consists of particles trapped within Earth's magnetosphere as well as solar energetic particles arriving directly from the Sun and cosmic rays that have been accelerated deep in space. The GOES energetic particle measurements are the basis for real-time alerts and warnings issued by the NOAA Space Environment Center and are critical for establishing the long-term climatology and short-term variability of the space environment.

The energetic particle sensors obtain the measurements needed to promptly detect hazardous flux levels and to assess the risk to satellites, to astronauts, and to communications systems. Adverse impacts of the radiation environment on satellites include degradation of solar panels and satellite anomalies and/or failure due to single event upsets, deep dielectric charging, and surface charging. The enhanced radiation environment also causes significant modification to the high-latitude ionosphere which impacts, for example, radio communication on airlines. The continuous long-term monitoring of the environment provided by these sensors forms the basis for engineering guidelines for satellite design, for the analysis of satellite failures and anomalous behavior, for risk assessment of human exposure to radiation, and for research leading to improved understanding of the space environment.

The EPS instruments on GOES NO/PQ have been expanded relative to the GOES I-M instruments to provide coverage over a broader energy range and with improved directional resolution. The complete GOES NO/PQ EPS suite consists of two energetic proton, electron, and alpha detectors (EPEADs), a magnetospheric proton detector (MAGPD), a magnetospheric electron detector (MAGED), a high-energy proton and alpha detector (HEPAD), and a DPU that controls the five sensors and interfaces with the spacecraft. The instrument suite on GOES I-M consisted of a single EPEAD and the HEPAD.

Protons in the energy range 0.7–900 MeV, alpha particles in the energy range 3.8–500 MeV, and high energy electrons in three energy ranges >0.6, >2, and >4 MeV are measured using two detector sets (EPEADs) mounted on opposite sides of the spacecraft to provide the required equatorial angular coverage. The two EPEADs each contain a telescope assembly to measure the lower energy particles and a dome assembly to measure the higher energy particles. The dome detector also provides the three integral electron flux measurements.

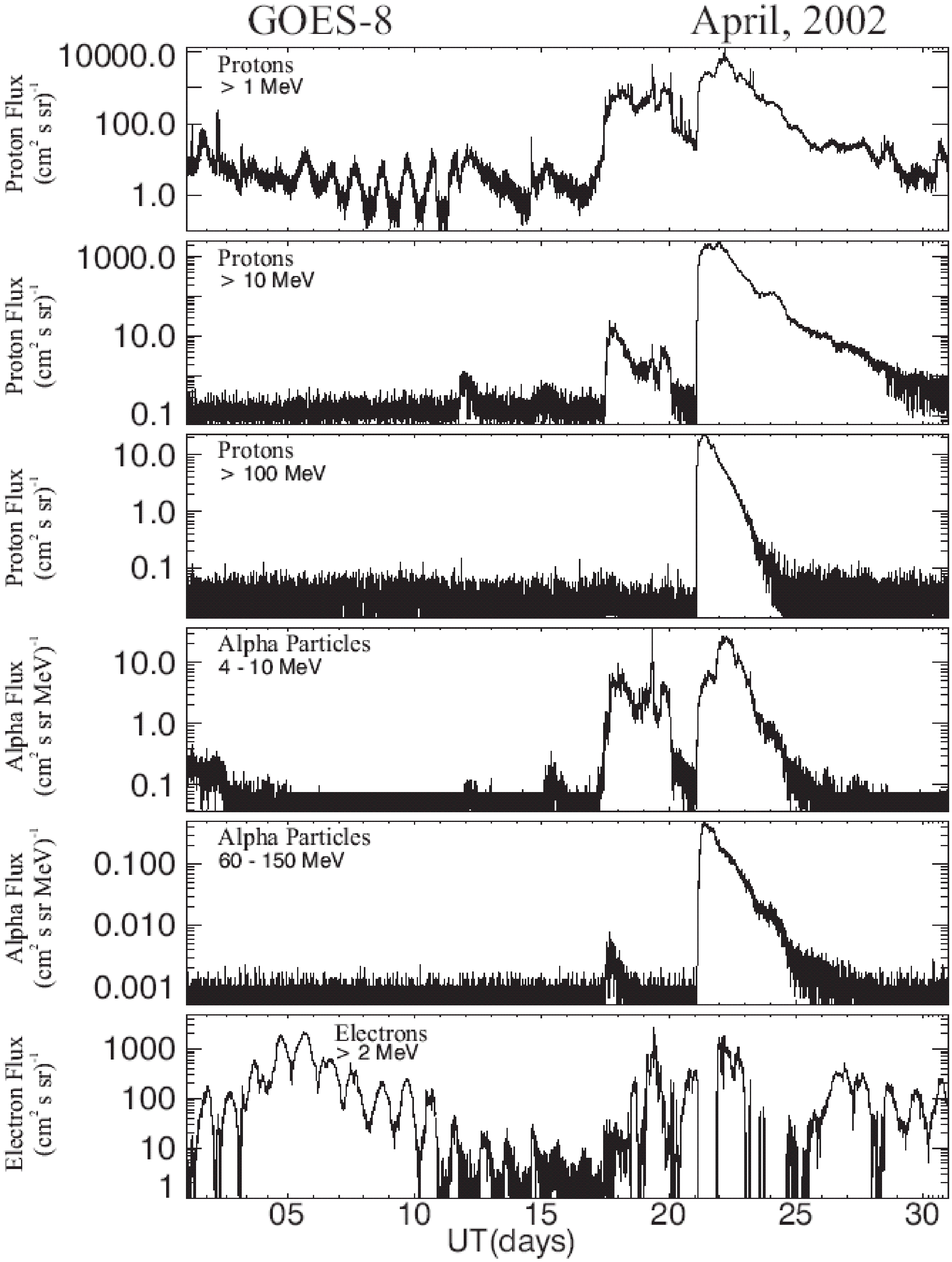

Figure 1: Typical measurements of the energetic particle environment at geostationary orbit during recent solar activity. (See text for details.)

Higher energy particles are measured with the HEPAD, which detects protons at energies above 330 MeV and alpha particles at energies above 2.56 GeV.

Magnetospheric protons and electrons are measured along nine pitch angle directions using two detector sets (MAGPD and MAGED). Protons are measured in five differential energy channels from 80–800 keV, and electrons are measured in five differential energy channels from 30–600 keV. The detector sets are mounted on the anti-earth side of the spacecraft and measure protons or electrons at 0°, ±35°, and ±70° from the anti-Earth direction in both the equatorial and the azimuthal plane.

Typical measurements of the energetic particle environment at geostationary orbit are illustrated in Figure 1. This figure includes data from the proton (upper three panels), alpha particle (fourth and fifth panels from the top), and electron (lower panel) detectors during April 2002. The lowest energy protons (top panel) and the electrons (bottom panel) are trapped within Earth's magnetosphere, and typically show a diurnal variation due to the asymmetric magnetic field, with maximum fluxes occurring near local noon and minimum fluxes near local midnight. The electrons undergo large variations from day to day driven by geomagnetic activity. The higher energy protons and the alpha particles become strongly enhanced during solar energetic particle events, which occurred on April 17 and then continued through the end of the month.

The energetic particle sensors that will be flown on GOES NO/PQ provide basic coverage of the conditions in the particle environment which are responsible for economic and human health/safety impacts. In planning for GOES R and beyond, priorities are being assessed for additional measurements or modifications to the current measurements. Of particular interest is the measurement of energetic heavy-ion measurements (up to iron). Heavy ions have been shown to contribute strongly to single event upsets in spacecraft electronics, yet the relative abundances and energy spectra during large solar events is not well known. A long-term baseline of these measurements would be valuable for space system design, and real-time measurements would be used for anomaly resolution as events are occurring. Also of interest to the satellite industry is spacecraft surface charging. Although GOES NO/PQ will provide measurements that characterize in part the electron environment responsible for surface charging, electrons at energies lower than measured by GOES NO/PQ (below 30 keV) are the dominant contributor to surface charging. The priorities among users of GOES data for low energy electron measurements are also being assessed.

Magnetometer (MAG)

Earth's magnetic field varies on time scales from fractions of a second to geologic times. The fast variations are caused primarily by the influence of the changing solar wind (velocity, density and magnetic field) and its interaction with the region of space surrounding Earth called the magnetosphere. The magnetosphere is the region where Earth's magnetic field stands off the blowing solar wind and carves out a highly variable, and often dangerous, region of space that extends to about 10 Earth radii on the dayside and many hundreds of Earth radii on the nightside. It is inside this region, at geosynchronous orbit at 6.6 Earth radii, that the GOES magnetometers measure the magnitude and direction of the ambient magnetic field.

The measurement of the in-situ magnetic field at GOES provides a "roadmap" of the space environment that controls charged particle dynamics in the important outer region of the magnetosphere [*Singer et al., 1996*]. Magnetic field measurements enable forecasters to assess the level of geomagnetic activity and to provide satellite operators with information about magnetopause crossings and other disturbances that can affect satellite attitude and control systems. Shocks in the solar wind that encounter the earth's magnetosphere propagate through the magnetosphere, energizing particle populations that can cause spacecraft anomalies via single event upsets in electronic components and deep dielectric charging. These shocks are detected by geosynchronous magnetometers, thereby providing the opportunity to alert customers. Examination of magnetic field variations enables forecasters to discriminate between solar particle events and other sources of energetic particle events. Magnetic field measurements can provide a remote monitor of solar-wind dynamic pressure and geomagnetic substorms that can be used in space weather forecast and specification models that are used at NOAA Space Weather Operations and DoD Air Force Weather Agency. Magnetic monitoring is also important for geophysical prospectors, rocket launch activities and for developing new space forecast capabilities.

Operational measurements of Earth's magnetic field began with the SMS (Synchronous Meteorological Satellite) in May 1974. Following two SMS satellites, the first GOES (Geostationary Operational Environmental Satellite) was launched in October 1975, and they have continued to this day with the currently operational GOES 8 and 10 spacecraft. Data from these satellites are used for space weather operations and are collected and processed by the NOAA Space Environment Center to be archived and distributed through NOAA's National Geophysical Data Center. The current GOES series (GOES 8-12) have redundant, three-axis, orthogonal magnetometer sensors attached to a boom that places the sensors 3 m and 2.7 m away from the body of the spacecraft. The magnetometers are built by Schonstedt Instrument Company. Only one magnetometer can be operated at a time and the sampling rate is 0.512 second. The magnetometer provides a sensitivity of about 0.1 nanoTesla (nT) while accommodating fields within the range of +/- 1000 nT. The measurement accuracy is 4 nT uncorrected, and 1 nT with temperature correction. A major difference between magnetic field measurements on GOES 8-12 and previous GOES satellites is that the previous satellites were spinners rather than 3-axis stabilized, and the measurements had 3-sec resolution rather than the current 0.512 s resolution.

The GOES NO/PQ satellite series, being built by Boeing Satellite Systems, Inc. will have two magnetometers on each satellite provided by Science Applications International Corporation (SAIC), Inc. The magnetometers can operate independently and simultaneously to measure the magnitude and direction of the magnetic field. One magnetometer is mounted on the end of an 8.5 m AEC-Able Engineering Company, Inc. boom, and the other is 0.8 m closer to the spacecraft. Each magnetometer is a 3-axis fluxgate design and has two ranges: +/-65,535 nT or +/-512 nT. The sensors sampling rate is 0.512 second, and the magnetometer has a sensitivity of about 0.1 nT and accuracy of 1 nT without temperature correction. Magnetic field requirements for the GOES R+ satellite series are unchanged from GOES NO/PQ.

An example of the GOES magnetometer data is shown in Figure 2 from the Space Environment Center's real-time web page. The Hp component of the field is the component that is essentially parallel to Earth's spin axis, which is the axis that is often most closely aligned with Earth's field direction at geosynchronous orbit. The figure illustrates the diurnal variation of the field at geosynchronous orbit and temporal variations, including an interval where Earth's magnetopause crosses geosynchronous orbit on November 24 at the location of GOES 8. It is during such intervals that spacecraft that depend on Earth's magnetic field for orientation knowledge can become confused, and attitude control becomes more difficult.

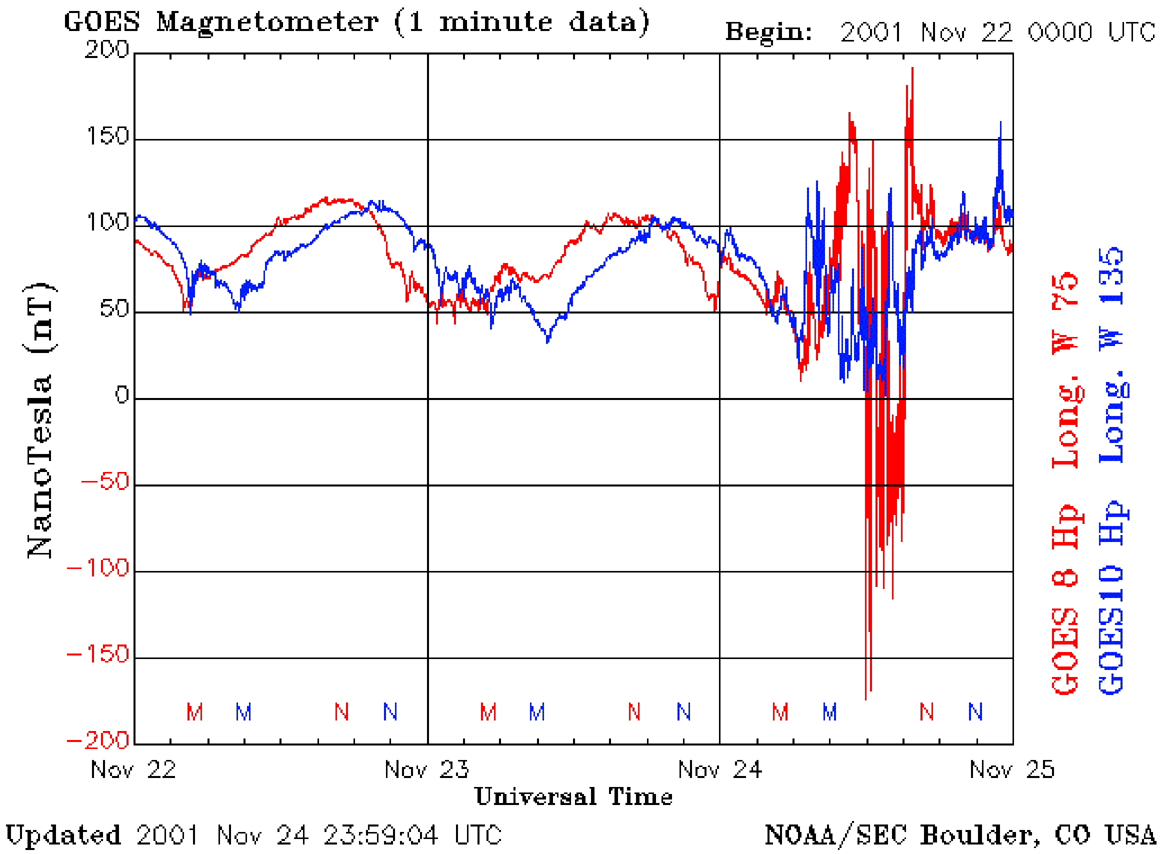

Figure 2: A sample GOES Magnetometer Hp plot containing the 1-minute averaged parallel component of the magnetic field in nanoTeslas (nT), as measured at GOES-8 and GOES-10. The figure illustrates the diurnal variation of the field at geosynchronous orbit and temporal variations, including an interval where Earth's magnetopause crosses geosynchronous orbit on November 24, (identified by negative values of the field) at the location of GOES 8.

Solar X-Ray and Extreme Ultraviolet Sensors (XRS and EUV)

While visible sunlight changes very little over the course of time, (thus the term “solar constant”) the Extreme Ultraviolet emissions (EUV between 1 and 230 nm) can change by factors of two to ten and the X-ray emissions (between 0.05 and 0.8 nm) can change by factors of 1000 in just a few minutes. These solar emissions are absorbed in the upper atmosphere above 80 km and they are one of the main causes of atmospheric variability at these altitudes. These variations in the upper atmosphere affect satellite orbits and high-frequency radio communication and navigation. Sudden increases in solar X-ray emissions associated with a solar flare are also used to predict other geophysical phenomena such as the geomagnetic storms that disrupt radio communication, navigation, and electrical power distribution.

NOAA has been monitoring the solar X-ray flux since 1976 [*Bornmann et al., 1996*]. The GOES X-Ray Sensor (XRS) is the instrument used for identifying the magnitude of solar flares. Figure 3 shows a large X-ray flare as observed in the two channels of the XRS. The GOES XRS measures the entire solar disk-integrated flux of sunlight in two X-ray channels, 0.05 to 0.4 nm and 0.1 to 0.8 nm respectively. These measurements have been made by nearly identical sensors for more than 25 years providing a unique view of the long-term trends in solar variability.

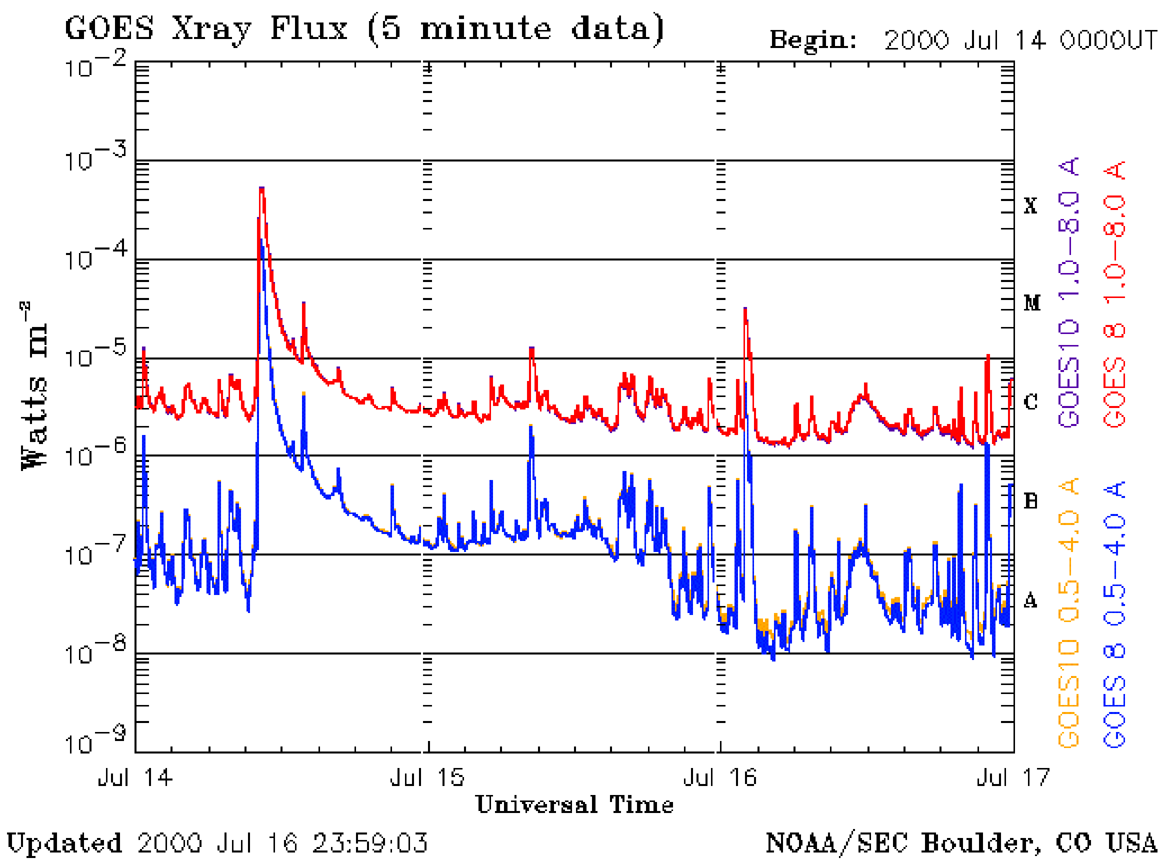

Figure 3. The GOES XRS provides the first indication of an impending space weather event of major proportions.

The GOES EUV sensor is a new instrument. It will perform the task of monitoring the solar EUV flux from 5 to 130 nm in five wavelengths bins. It will establish the baseline for long-term monitoring of the solar EUV flux well into the future. Figure 4 shows how the XRS and EUV sensors fit into the near complete spectral coverage of solar observations made with various instruments on NOAA spacecraft.

The XRS data is sent in real-time to the NOAA Space Environment Center in Boulder Colorado. As soon as the solar X-ray flux reaches specific values, alerts and warnings are broadcast to numerous customers. Products such as the D-Region absorption maps shown in Figure 5 are displayed in real time on the system monitors of the radio operators that provide HF radio communication and navigation to the vast fleets of commercial and private aircraft on transoceanic journeys. The GOES XRS data are the primary input for calculating the "Radio Blackout" NOAA Space Weather Scale. The EUV data will be provided in real-time to the NASA and DOD for use in establishing satellite orbit parameters.

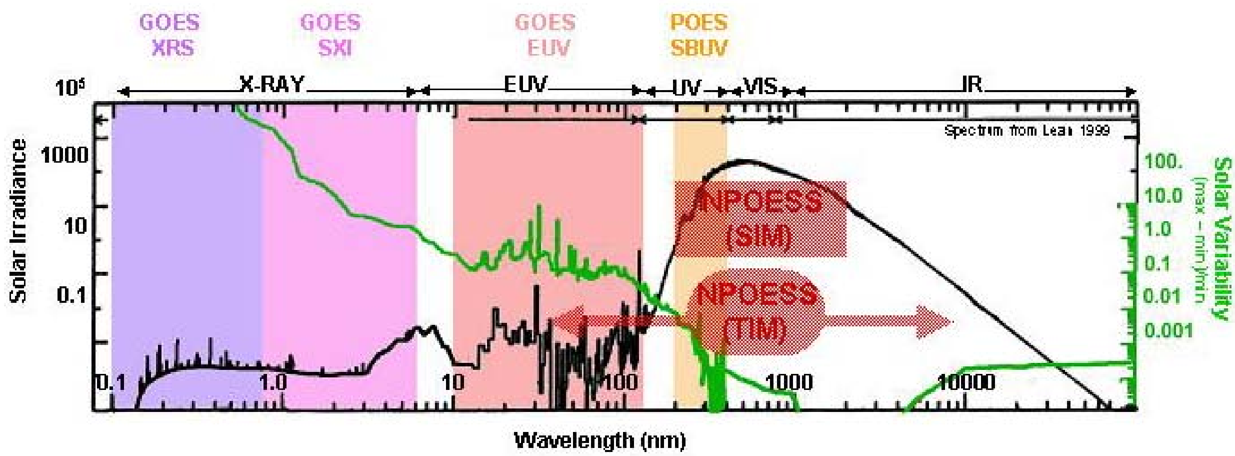

Figure 4. Solar Spectrum (black line) and solar variability (green line). The colored regions show the bands measured (or to be measured) by various NOAA instruments. The GOES XRS and EUV sensors are a critical part of the suite of solar measurements made by NOAA.

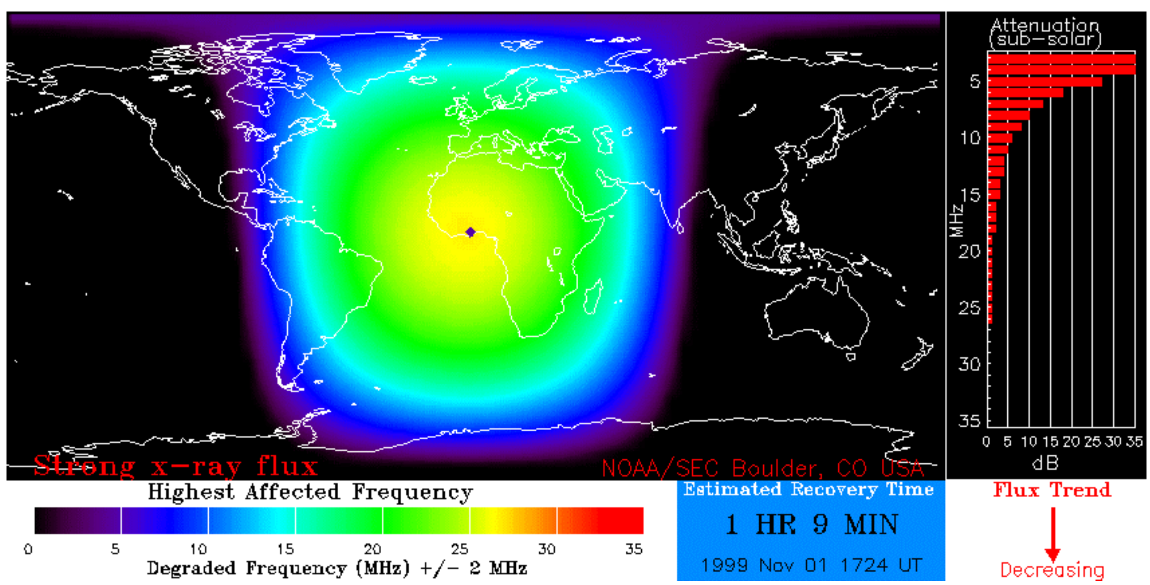

Figure 5. The D-Region absorption map uses GOES XRS data to categorize the severity of the regional degradation of HF communication. This tool is used, for example, by radio operators communicating with commercial and private aircraft on transoceanic flights.

The future plans for the GOES XRS are to continue these measurements with as few changes as possible to the sensor design. In this way, a long-term archive of solar flux data will be acquired. Customer requirements and EUV sensor technologies are being evaluated to determine priorites and specifications for future EUV instruments. A workshop will be held in late October 2002 to consider both of these issues.

Solar X-ray Imager (SXI)

Behind each of the impacts described in the NOAA Space Weather Scales, there is a solar driver. Geomagnetic storms can be initiated by one of two solar sources. Coronal holes, long-lived, large areas of open magnetic field in the solar atmosphere, are the sources of high-speed solar wind that can drive recurring geomagnetic storms. The largest geomagnetic storms occur when a coronal mass ejection (CME) from the Sun throws into the interplanetary medium billions of tons of plasma which envelops Earth's magnetic field. Solar radiation storms originate either in direct association with solar flares or with shocks associated with CMEs. Radio blackouts occur in direct response to the enhanced X-ray radiation from solar flares. Increased satellite drag is associated with longer-term increases in solar EUV flux. These solar drivers lead to specific high-level operational goals for NOAA imaging observations of the Sun:

- Locate coronal holes for forecasts of recurring geomagnetic activity
- Locate flares for forecasts of solar energetic particle events
- Assess active region complexity for flare forecasts
- Monitor active regions beyond the east limb for solar activity ($F_{10.7}$) forecasts, and
- Determine occurrence, *speed, direction, and spatial extent* of coronal mass ejections

The italicized text in the final goal represents the specific improvement that the addition of a white light coronagraph will provide when used in combination with a soft X-ray imager (SXI).

The scientific community has realized the great potential for improved understanding of the solar corona using X-ray imagery for three decades. Early recognition by NOAA of the importance of solar X-ray imaging led to proposals for an operational imager in the late 1960's and ground prototype development in the early 1980's. The prototype SXI built by NASA Marshall Space Flight Center and launched on GOES 12 on 23 July 2001 represents the culmination of NOAA and USAF efforts over a period of 20 years. It is the first of a series of Solar X-ray imagers to fly on upcoming GOES spacecraft. The GOES N/O SXIs are being built by Lockheed Martin and will include a number of enhancements over the prototype instrument. NOAA SEC is now in the process of developing requirements for solar imaging on the GOES R series of spacecraft. Included in the proposed suite of instruments is the addition of a white-light coronagraph to directly detect coronal mass ejections.

The GOES 12 and GOES N/O instruments share many basic features. Both use monolithic, two-reflection, grazing incidence optics to support a bandpass of roughly 0.6-6.0 nm. A set of metallic thin-film filters provides a degree of temperature discrimination among solar features emitting in this bandpass. Metallic thin-film entrance filters provide rejection of IR-Visible-UV solar radiation. A High Accuracy Sun Sensor (HASS) integrated into the instrument provides pointing knowledge. The GOES 12 and N/O instruments both use 512×512 pixel array detectors, but they are of quite different designs. The instruments are operated at basic one-minute image cadences using tables stored in on-board memory.

The SXI system produces image data products in two levels of processing, each of which are available in FITS and in browse formats. The Level-0 data consist of raw images assembled from telemetry packets. The Level-1 data have had minimal standard processing applied to the Level-0 data to generate exposure-normalized images mostly free of instrument effects and artifacts.

Because of the operational requirements of SEC's Space Weather Operations Center, the Level-1 data are prepared in real-time and intended to serve as basic source data for research users. Annotated browse images are provided to forecasters in real-time, both for single image display and for movie-loop viewing (Figure 6). These displays allow for qualitative evaluation of dynamic activity on the Sun, including rough flare location, coronal hole location, active region evolution, and CME signature detection. Additionally, the data are stored in a quantitative format for more detailed and precise positional, morphological, and intensity analysis using software tools developed at NOAA/SEC. All of the image products are provided to the National Geophysical Data Center in near real-time for access via the World Wide Web.

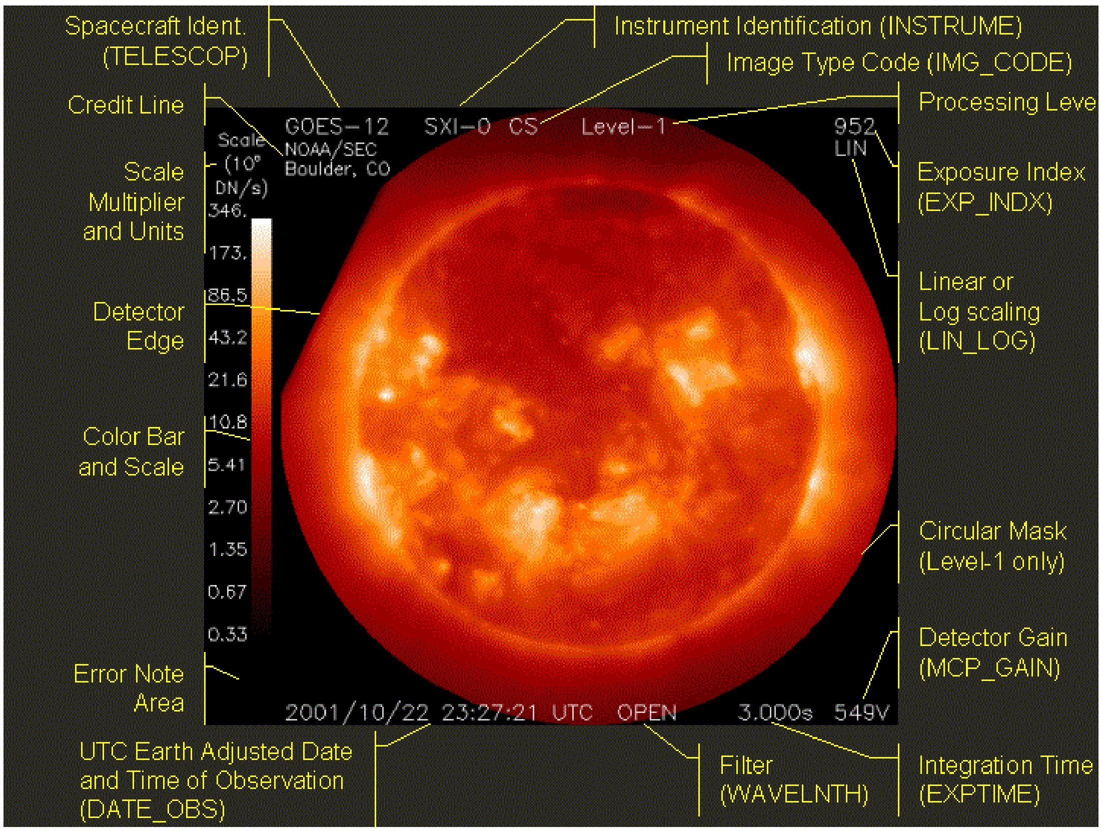

Figure 6: SXI image products for real time display provide basic visual information for interpretation by forecasters and visual characterization of active regions, coronal holes, and other pertinent solar features.

SEC has also developed specialty SXI data products. One example is the automatic location of bright regions on the Sun. In conjunction with temporal detection of flares using GOES XRS data, this allows for automatic location of flares by selecting the single brightest region on the solar disk (Figure 7). Automatic flare location allows quicker determination of the likelihood of a solar radiation storm.

The future of GOES solar imaging is being addressed as part of the planning process for GOES R. A workshop held at SEC in October 2001 identified and prioritized requirements for solar imaging on GOES R. Specifically, the workshop recommended the inclusion of a white-light coronagraph on future spacecraft. Such an instrument would allow for quantitative estimates of the speed, direction, and spatial extent of coronal mass ejections. It would be essential to include both an X-ray imager and a coronagraph, since the benefit from both is more than a simple sum of their capabilities [*Hill and Pizzo, 2002*].

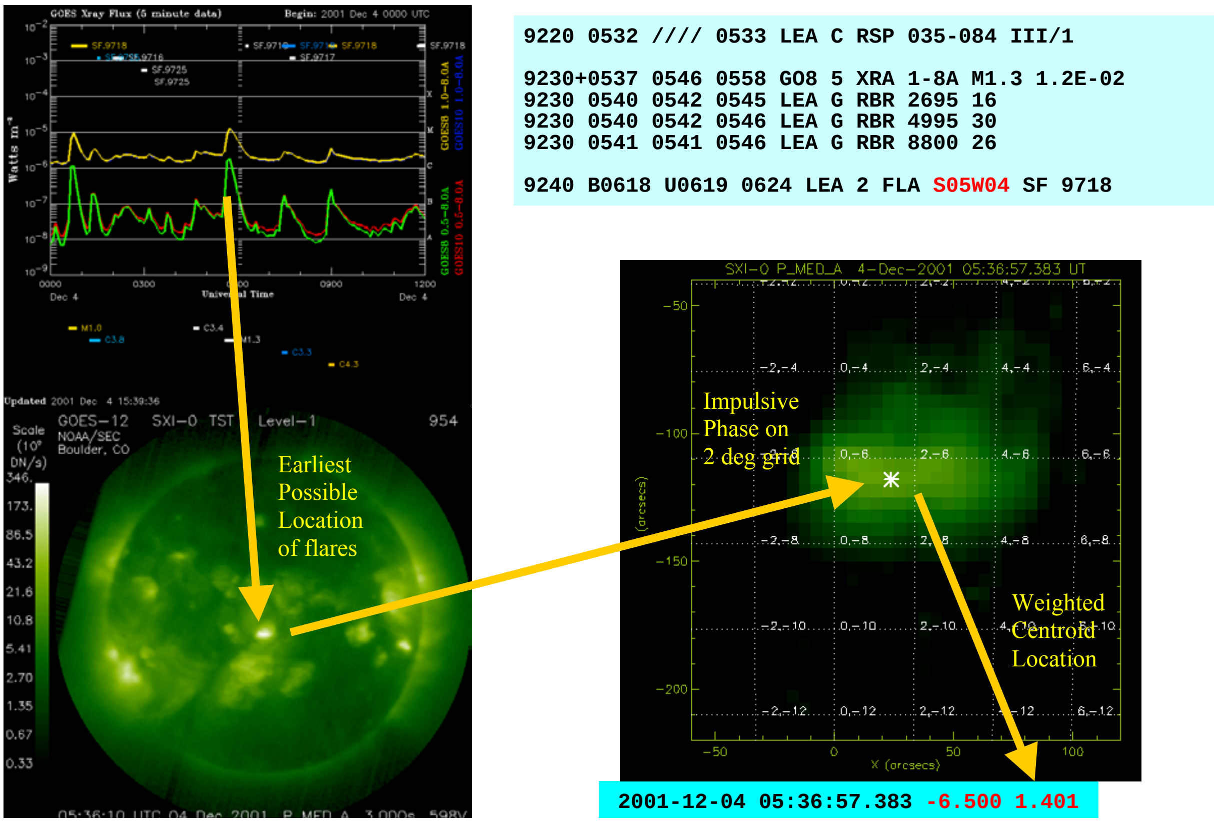

Figure 7: Automated bright region identification has been implemented for the GOES 12 SXI. In conjunction with flare event identification from XRS, SXI provides real-time automate flare location.

Summary

The GOES Space Environment Monitor instruments have a long history of measuring the dynamic conditions at the Sun and in Earth's space environment. These measurements provide critical real-time alerts and warnings for industry and government activities that are impacted by space weather, and they provide a continuous record of the long-term variability of the environment for scientific research and climatological models. As technology and our understanding of space have improved, the measurement capabilities have grown to give an increasingly comprehensive view of space weather. This report has provided an overview of the space environment measurements made by GOES and plans for future instrumentation that will continue to serve our current and growing list of space weather customers.

References

Bornmann, P.L., D. Speich, J. Hirman, L. Matheson, R.N. Grubb, H.A. Garcia, and R. Viereck, The GOES X-Ray Sensor and it Use in Predicting Solar-Terrestrial Disturbances, *SPIE Conference Proceedings,* Vol. 2812, p. 291-298, GOES-8 and Beyond, Edward R. Washwell, ed., 1996.

Hill, S. M. and V. J. Pizzo, Advanced Solar Imaging from the GOES R Spacecraft, *SPIE Conference Proceedings*, Vol. 4853, Innovative Telescopes and Instrumentation for Solar Astrophysics, in press, 2002.

GOES I-M Databook, Space Systems/Loral, Palo Alto, CA, 1992.

GOES PRODUCTS AND SERVICES CATALOG (Third Edition), Frances C. Holt and Steven R. Olson, OAA/NESDIS/ARAD, Research and Data Systems Corporation, Camp Springs, MD 20746, Greenbelt, MD 20770-3211 (See Chapter XII. SPACE ENVIRONMENT MONITOR by Speich and Singer, http://orbit35i.nesdis.noaa.gov/arad/fpdt/goescat/).

Onsager, T.G., R. Grubb, J. Kunches, L. Matheson, D. Speich, R. Zwickl, and H. Sauer, Operational Uses of the GOES Energetic Particle Detectors, *SPIE Conference Proceedings,* Vol. 2812, p. 281-290, GOES-8 and Beyond, Edward R. Washwell, ed., 1996.

Singer, H.J., S. Hill, T. Onsager, R. Viereck, and V. Pizzo, Geostationary Operational Environmental Satellites (GOES R+), Operational Requirements Document Version 2.00, NOAA Space Environment Center (SEC), 325 Broadway, Boulder, CO 80305, 5 February 2002.

Singer, H.J., L. Matheson, R. Grubb, A. Newman and S.D. Bouwer, Monitoring Space Weather with the GOES Magnetometers, *SPIE Conference Proceedings,* Vol. 2812, p. 299-308, GOES-8 and Beyond, Edward R. Washwell, ed., 1996.