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Key Points:
- The Global Oscillation Network Group (GONG) is a ground-based network of instruments that observe the Sun nearly continuously
- Originally developed for helioseismology, GONG now also supplies solar data for space weather forecasting models
- GONG is a good example of research to operations (R2O) providing solar magnetic field, H-α, and far-side data for operations

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The Global Oscillation Network Group Facility—An Example of Research to Operations in Space Weather

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Abstract The Global Oscillation Network Group (GONG) is a system of ground-based solar observing stations distributed geographically so that the Sun is visible nearly continuously at all times. Originally developed to provide data for research into the solar interior via helioseismology, GONG is now also providing data for operational space weather forecasting as a cost-effective and reliable alternative to space missions. The data comprise full-disk magnetograms, H-α intensity images, and helioseismic maps of activity on the solar far side. These data are provided in near real time to the NOAA Space Weather Prediction Center, the US Air Force, and NASA. GONG is a successful example of transitioning a research facility funded by the NSF into an operational asset.

Plain Language Summary GONG is a set of six ground-based solar observing instruments in California, Hawaii, Australia, India, Spain, and Chile. Deployed in 1995, GONG provides data for space weather forecasts in the form of high-cadence magnetograms, H-α images, and helioseismic far-side activity maps.

1. Introduction

GONG, the Global Oscillation Network Group, is a ground-based solar observing system developed to overcome the diurnal cycle of sunrise and sunset at a single location, thereby enabling nearly continuous observations around the clock (Harvey et al., 1996). The requirement for a nearly unbroken long-term (months to years) time series of solar observations arises from the field of helioseismology, the study of the solar interior using the acoustic waves that are trapped below the photosphere. In helioseismology, the prime data set is the frequencies of the waves that are influenced by the structure of and motions within the solar interior. These frequencies need to be measured with a precision of 0.1 μHz, which requires a time series length of at least 115.7 days. In addition, the frequencies change as the activity level evolves so several solar cycles of time series are ultimately required to fully understand the solar interior with helioseismology. Finally, gaps that are periodic in nature produce a substantial number of spurious peaks in the power spectrum of the solar oscillations. The diurnal solar cycle is particularly damaging to helioseismology as many of the spurious peaks are located on top of the actual solar features.

There are only three ways to avoid the gaps inserted into a solar observing time series by the Earth's rotation: (a) observe from Antarctica during the Austral summer to obtain daylight without the Sun setting, (b) place an instrument in space in a fully sunlit orbit (i.e., geosynchronous or at L1), or (c) deploy a geographically separated set of ground-based instruments around the world. Of these strategies, observing in Antarctica has an upper limit of 6 months in length due to the change in seasons. Space-based observations from SOHO and SDO are extensively used in solar physics and helioseismology but are expensive and difficult to maintain. A ground-based network is relatively inexpensive and in principle can be maintained forever, making this choice very attractive for helioseismology.

But it is not just helioseismology that requires continual solar observations. Active phenomena, such as flares, filament eruptions, and CMEs (Coronal Mass Ejections) occur at all times and can be located at almost any position on the Sun. Accurate forecasts of space weather thus require continual solar observing as well. The US Air Force recognized this need, as well as the advantages of a network, and deployed SOON, the Solar Optical Observing Network, in the 1970s. The realization that GONG could be a useful asset for space weather resulted in a reprogramming of GONG priorities, brought disparate funding agencies together, and produced a successful example of research to operations, or R2O. This paper describes GONG and its space-weather related data products and its impact on space weather operational forecasting.

2. Brief History of GONG

GONG was first proposed in 1984 to the NSF as an experiment that would operate for just 3 years to obtain the best possible power spectrum of the solar oscillations. Helioseismology was a new and exciting field at that time, with the unique ability to infer the internal solar physical conditions such as temperature, density, rotation rate, and so forth. At the time helioseismology was considered to be the only path to understanding the solar neutrino problem, which was a major issue in basic physics, only two thirds of the expected neutrinos generated by the fusion processes in the solar core were detectable with the current instruments, calling into question the physics of nuclear fusion and the origin of stellar energy. Led by John Leibacher with Jack Harvey as Instrument Scientist, GONG had substantial support from a broad scientific base that extended beyond solar astronomy to astrophysics and particle physics.

A model of the observing performance of a network using a simple two-parameter seasonal model of weather patterns at a location was developed by Hill and Newkirk (1985). A site survey was started in 1985 to measure the cloud cover percentage and transparency of the sky at 15 sites (Hill et al., 1994). In 1991, the six sites that now comprise GONG were selected on the basis of the overall performance of the network. These sites are:

1. Big Bear Solar Observatory, California, operated by the New Jersey Institute of Technology.
2. Mauna Loa Solar Observatory, Hawaii, operated by the High Altitude Observatory.
3. Learmonth Solar Observatory, Australia, operated by the US Air Force 557th Weather wing.
4. Udaipur Solar Observatory, India, operated by the Physical Research Laboratory.
5. Observatorio del Roque de los Muchachos, Canary Islands, Spain, operated by the Instituto de Astrofísica de Canarias.
6. Cerro Tololo Interamerican Observatory, Chile, operated by the US National Optical Astronomy Observatories.

Figure 1 shows a map of the locations of the sites along with an image of the instrument shelter at each location.

An important measure of the effectiveness of a network is its duty cycle, or fraction of clear-sky observing time achieved during some time period such as a day or month with a duty cycle of 1 indicating no missing data in that time period. Figure 2 shows a histogram and a cumulative histogram of the daily duty cycle of GONG from its deployment in 1995 to mid-2017. The median daily duty cycle of GONG is 0.91, which compares favorably with the modeled value of 0.93 for a six-site network obtained by Hill and Newkirk (1985).

After the development of the main instrument, GONG was deployed starting in January 1995 in Spain and finishing in India in October of that year. Shortly after the deployment began, SOHO was launched to L1 carrying the Michelson Doppler Imager, which obtained helioseismology observations similar to those of GONG. Planning for the shutdown of GONG started in 1998 after 3 years of operation, but by this time it was clear that helioseismology inferences needed confirmation from independent instruments and data processing pipelines if they were to be believed. In addition, there was great interest in the solar cycle variations of the frequencies. Consequently, there was substantial pressure from the scientific community to keep GONG operating, to which NSO agreed.

However, in 2006 the NSF carried out a senior review of the Astronomy Division of the Mathematics & Physical Science Directorate, resulting in a recommendation that “GONG be operated for at most one year following successful commissioning of SDO, to allow for intercalibrations. GONG should then be closed, unless international partners or the space weather community agree to take over the majority of the operations costs.” This motivated discussions with a number of potential partners, including the US Air Force Weather Agency (AFWA, now known as the 557th Weather Wing). Fortunately for GONG, at that time AFWA was looking for an observing system to back up the transition between SOON and its replacement, ISOON. An agreement was reached where AFWA funded the installation of the H-α filters and provided substantial operational support as well.

The NSF carried out another division-wide review in 2012, known as the Portfolio review. That report contained recommendation 9.12: “AST and NSO should develop a plan for the NSO Integrated Synoptic Program (NISP) that includes GONG and SOLIS but that limits AST funding to no more than \$2M (FY17) annually. Expanded partnerships for operations should be sought, and the plan should be completed in

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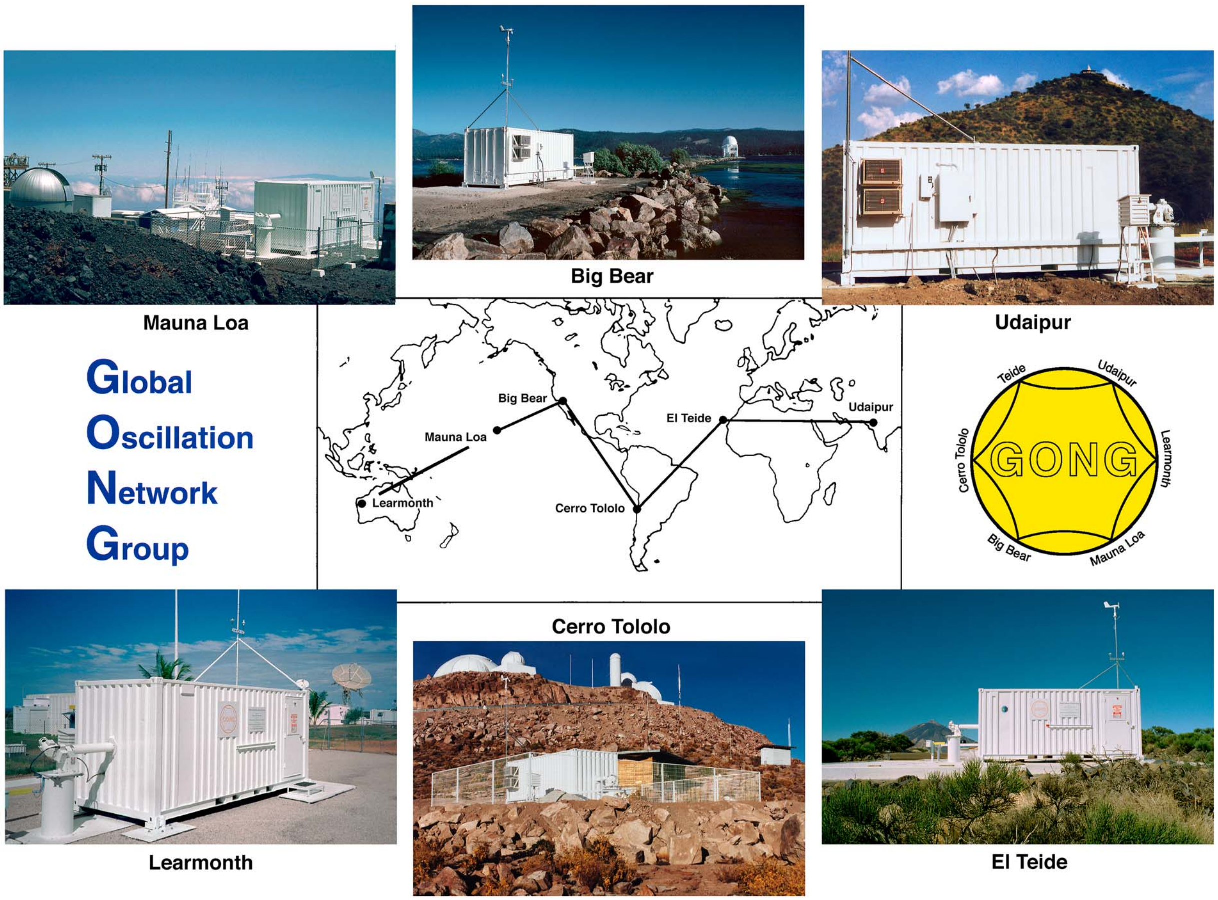

Figure 1. A map of the locations of the six GONG sites and images of the instruments at each location. Clockwise from the top left: Mauna Loa Solar Observatory, Big Bear Solar Observatory, Udaipur Solar Observatory, Observatorio del Roque de los Muchachos (El Teide), Cerro Tololo Interamerican Observatory, and Learmonth Solar Observatory. GONG = Global Oscillation Network Group.

time for implementation in the FY16 budget. If a partner cannot be found, NISP should be divested entirely." Around the same time, operational support from the US Air Force ended due to the sequestration requirement imposed by Congress. Once again, the space weather community recognized the importance of GONG as an operational solar data provider particularly for the high-cadence magnetic field

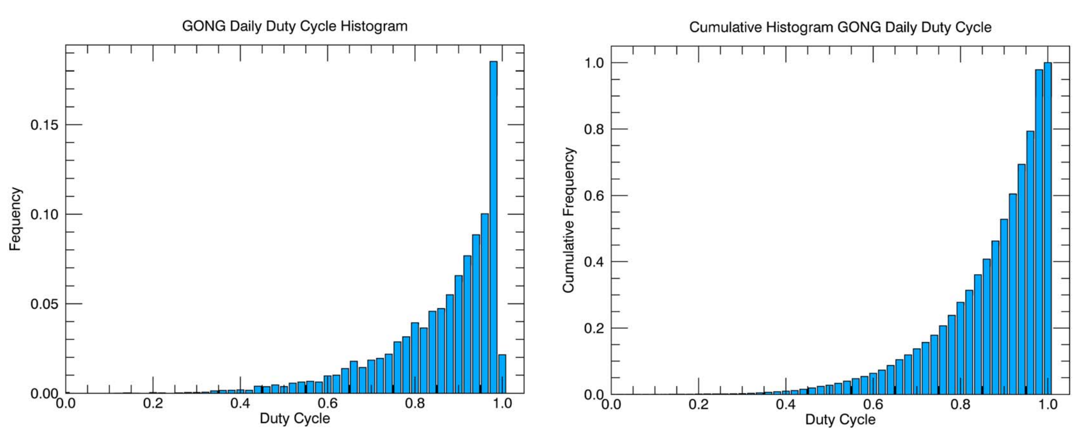

Figure 2. Histogram and cumulative histogram of the daily duty cycle of GONG from May 1995 to July 2017. The median daily duty cycle is 0.91. GONG = Global Oscillation Network Group.

observations to drive geomagnetic storm forecasts. Thus, NOAA agreed to supply funding support for GONG operations in 2016. GONG continues today with a mixture of support primarily from the NSF and NOAA.

3. Instrumentation and Data Products

The main instrument of GONG is known as a Fourier Tachometer (Beckers & Brown, 2013; Brown, 1981; Evans, 1981) that comprises a polarizing Michelson interferometer, narrow-band prefilters, and a rotating half-wave plate that sweeps the interference fringes of the Michelson across the solar spectral line in wavelength. The Doppler shift of the Ni I 6768 Å line used by GONG is determined by comparing the intensity in three segments of the rotation of the waveplate to measure the phase shift of the spectral line, from which the Doppler velocity can be determined. The full-disk 1024×1024 velocity images are the prime helioseismology input data and are also the input for the far-side maps described below. Note that, prior to 2001, charge-coupled device technology of the time limited the GONG camera to a rectangular-pixel format of 244×256 in order to meet the additional requirements of 30 frames per second, deep wells, and high linearity. The camera was upgraded to the current sensor in 2001.

3.1. Magnetograms

A useful aspect of the Fourier Tachometer measurement principle is that magnetograms can be simply created by obtaining the velocity images in two opposite states of circular polarization and then differencing them to produce a line-of-sight full-disk magnetogram. As deployed, the original observational scheme was to obtain a magnetogram once per hour at each site that would then be used to correct the Doppler velocity images for the presence of the magnetic field, which depresses the amplitudes of the oscillations. The optical components available in the late 1980s led to an instrumental design of a nonvariable quarter-wave plate rotated in and out of the beam by a mechanical filter wheel. This arrangement cannot switch polarization states very quickly but was adequate for a cadence of 1 hr.

The installation of the new camera, along with the arrival of liquid-crystal variable retarders (LCVRs) that can switch states very quickly, allowed the deployment in 2006 of the full-time line-of-sight full-disk magnetogram data stream that is now being used for several space weather forecast systems. Both the Doppler velocity and magnetic field images are obtained with a cadence of 1 min. The magnetograms are averaged over 10 min at the remote sites after removal of bad images, and the average and variance of the magnetic field are returned to the Boulder data center shortly after acquisition. These data are then used to create a synoptic map every hour for input into models that produce forecasts of geomagnetic storms. The precision of these near real-time synoptic maps is quite high since they are constructed using roughly 8,000 to 10,000 input full-disk 10-min average magnetograms compared to about 50 input images for maps constructed from daily observations. Figure 3 shows a sample 10-min average magnetogram, while Figure 4 shows a sample hourly synoptic map.

While precision matters, another data quality parameter, namely the uniformity of the instrumental background, is more important for space weather applications. The synoptic maps obtained in the photosphere provide boundary conditions for various extrapolations of the magnetic field into the corona. Until synoptic observations of the coronal magnetic field are routinely available, these extrapolations will be the only method to produce coronal topology estimates, which are needed as inputs for coronal hole models and subsequent models of the background solar wind, CME propagation trajectories, and geomagnetic storm forecasts. The early GONG magnetograms suffered from background (zero point) variations with amplitudes on the order of 10 G and with substantial differences between sites. This was reduced to 1 G with a software system that compared sites and day-to-day variations. Increased tailoring of the switching voltage waveform controlling the LCVR further lowered the zero-point amplitude to 0.5 G. In order to decrease the influence of the combination of LCVR state switching and seeing in the Earth's atmosphere, the data acquisition system was modified to discard the first 3 (out of 1,200) frames of a 1-min integration. This reduced the zero-point amplitude to its current value of 0.1 G.

The magnetogram in Figure 3 has been zero-point corrected. An example of a coronal field extrapolation via a PFSS model with the source surface at 2.5 solar radii is shown in Figure 5. This particular example, from 26 June 2018 00:14:00 UT, shows the south polar coronal hole extending to very low latitudes near the equator.

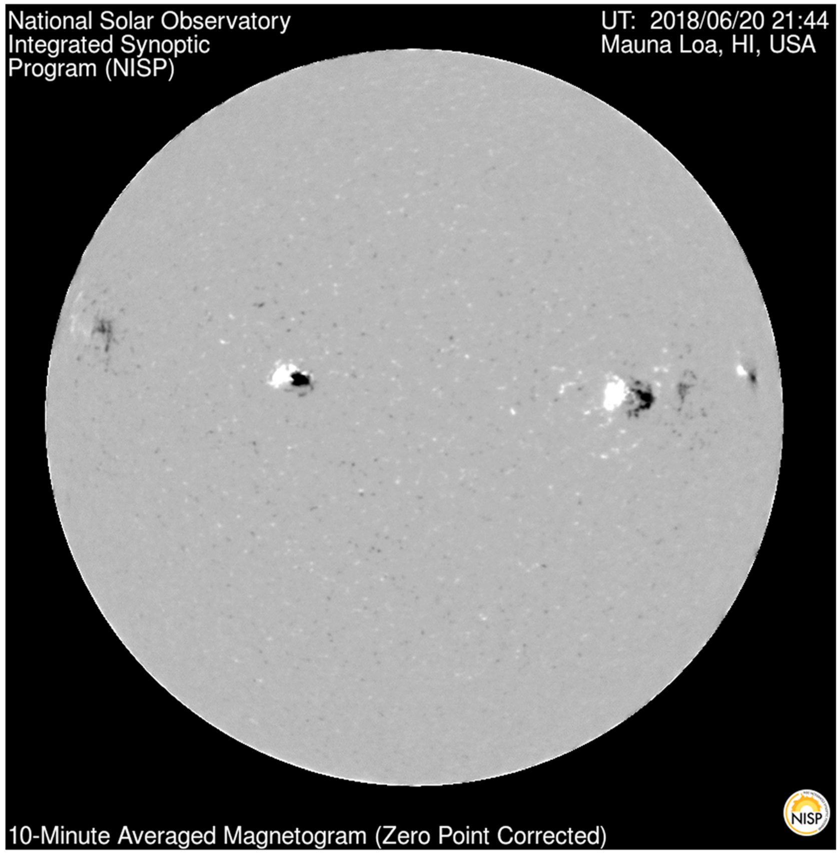

Figure 3. A 10-min average magnetogram from the Mauna Loa Global Oscillation Network Group site at 21:44 UT on 20 June 2018.

3.2. H-α Images

As mentioned earlier, the US Air Force deployed SOON in the 1970s. In 1996, a replacement for SOON, known as Improved SOON or ISOON was started (Neidig et al., 1998). Delays resulting from optical component issues led to a need for a system to back up SOON while ISOON was being developed. Discussions between NSO/GONG and the US Air Force were carried out in 2008 and led to the installation of a system in GONG

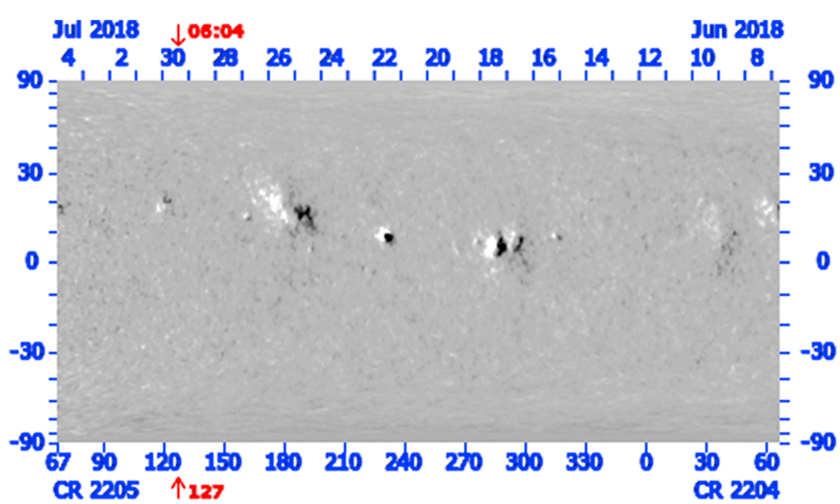

Figure 4. A magnetic field synoptic map from Global Oscillation Network Group data at 06:04 UT on 29 June 2018.

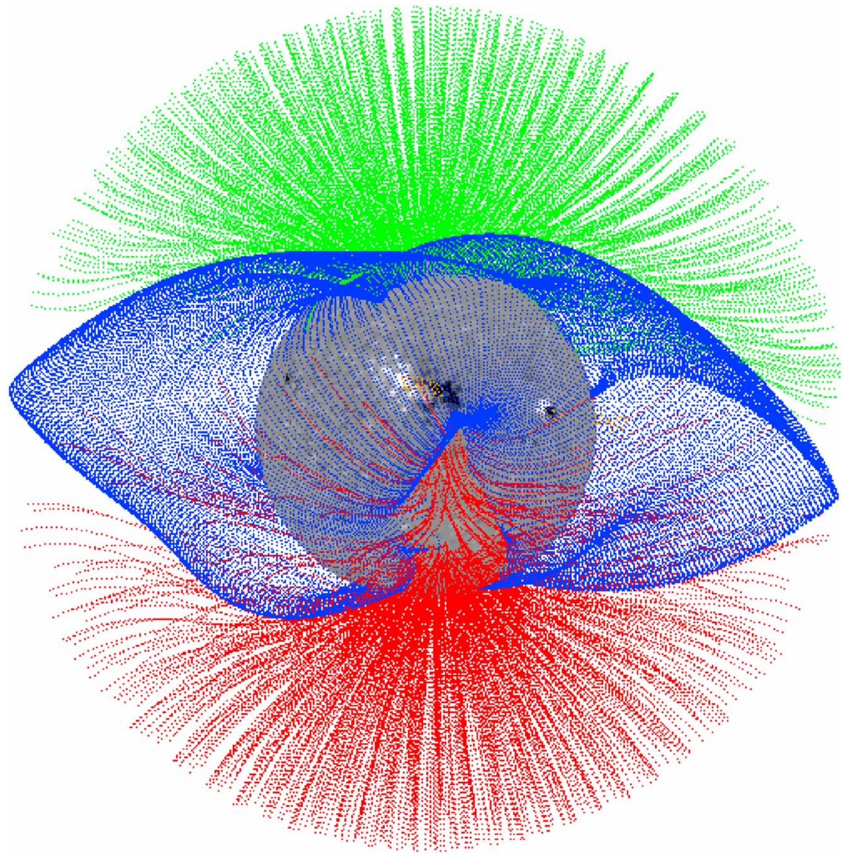

Figure 5. Coronal field PFSS extrapolation at 00:14 UT on 26 June 2018.

to obtain H-α images. The system was deployed in 2010, and provides full-disk 2048 × 2048-pixel H-α intensity images centered on the spectral line with a band pass of about 0.5 Å. The observing cadence at any specific GONG site is 60 s, but the acquisition time is staggered by 20 s at adjacent sites to provide a 20-s cadence network-wide. Each image is returned to the data center and made available within 2 min of acquisition. The data are processed to improve the appearance of the image and rotated to place solar north at the top of the array. Unprocessed data suitable for scientific analysis are also available. Figure 6 shows a sample image.

3.3. Far-Side Activity Maps

Solar activity occurs over the entire surface of the Sun, not just the side that is facing the Earth. Activity on the solar far side will of course be carried on to the Earth-facing near side as the Sun rotates, so advance indications of the location, size, evolution, emergence, or disappearance of far-side active regions are very valuable for space weather forecasts. Except for rare times when a space platform such as STEREO is located at a point where the far side can be directly observed, the only way to obtain information on far-side activity is through helioseismic far-side activity maps. Developed by Lindsey and Braun (1990), these maps are constructed from the phase shift of a group of acoustic waves that can be observed on the near side, come to a focus at a specific point in the far-side photosphere, and then propagate back to the near side. The presence of an active region alters the thermal structure of the layers immediately below the region, which effectively acts to depress the height where the wave reflection occurs. This slightly reduces the travel time of the wave and causes a temporal phase shift. The far-side focal point is spatially shifted by moving the near-side analysis area, building a map of the far-side activity. See Lindsey and Braun (2017) for a thorough discussion of the technique.

GONG produces a far-side map every 12 hr using Doppler velocity data that is reduced in spatial resolution at the sites and returned immediately after acquisition. These data are processed at the data center in Boulder, producing a far-side map. Four consecutive far-side maps are compared to identify persistent features that

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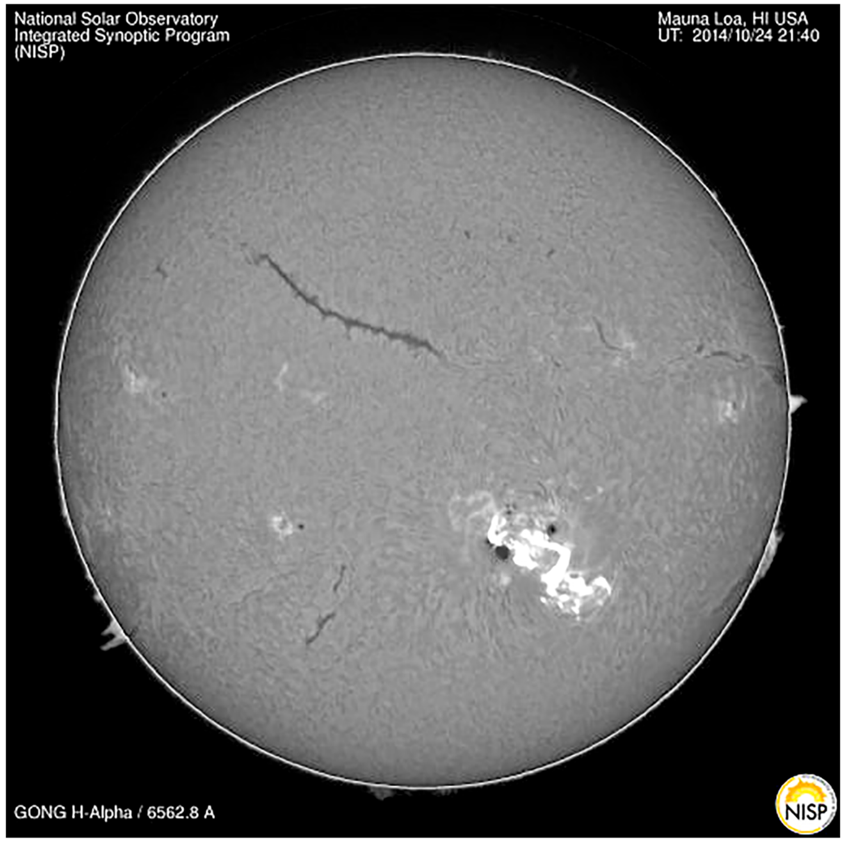

Figure 6. Sample H-α image from Mauna Loa at 21:40 UT on 24 October 2014 catching AR 12192 during a flare.

are also assigned a probability of being an active region depending on the stability of the signal. This reduces transient noise artifacts that may arise from additional phase shifts of the waves as they encounter thermal and magnetic inhomogeneities along their ray path. Figure 7 shows a sequence of maps tracing the far-side passage of AR 12192 during 7 to 21 October 2014. This active region was one of the largest activity complexes ever observed, producing a far-side signal strong enough to distinguish umbra and penumbra. While most sunspots are not as large as AR 12192, the far-side maps are useful for identifying sunspots with areas larger than 100 millionths of the solar hemisphere with a linear relationship between the far-side phase shift strength and the sunspot area (González Hernández et al., 2007). The same paper derives a calibration relation between the far-side signal and the average magnetic field strength in the sunspot. Comparisons with STEREO EUV data (Liewer et al., 2012) show that GONG far-side active region detections agree with the locations of EUV brightness signals for 89% of the cases studied, with 11% false alarms. Thus, the far-side maps provide useful estimates of the characteristics of large, strong, and potentially geo-effective sunspots before they appear on the Earth-facing side of the Sun. The most relevant GONG data products for space weather are summarized in Table 1.

4. Space Weather Applications

The GONG magnetic field observations are now being used in several space weather forecast systems. In particular, the WSA/Enlil model of CME propagation in the presence of the background solar wind uses the GONG synoptic maps as the primary data input for modeling the coronal hole distribution and the resulting background solar wind. This software system is in routine use at the NOAA Space Weather Prediction Center (SWPC) in Boulder and is currently being installed in the UK Met Office space weather center. GONG synoptic maps are also extensively used by NASA's Coordinated Community Modeling Center for inputs into several models. The 10-min average full-disk magnetograms and their variances are remapped into heliographic coordinates and supplied to the AFRL Air Force Data Assimilative Photospheric Flux Transport Model (Arge

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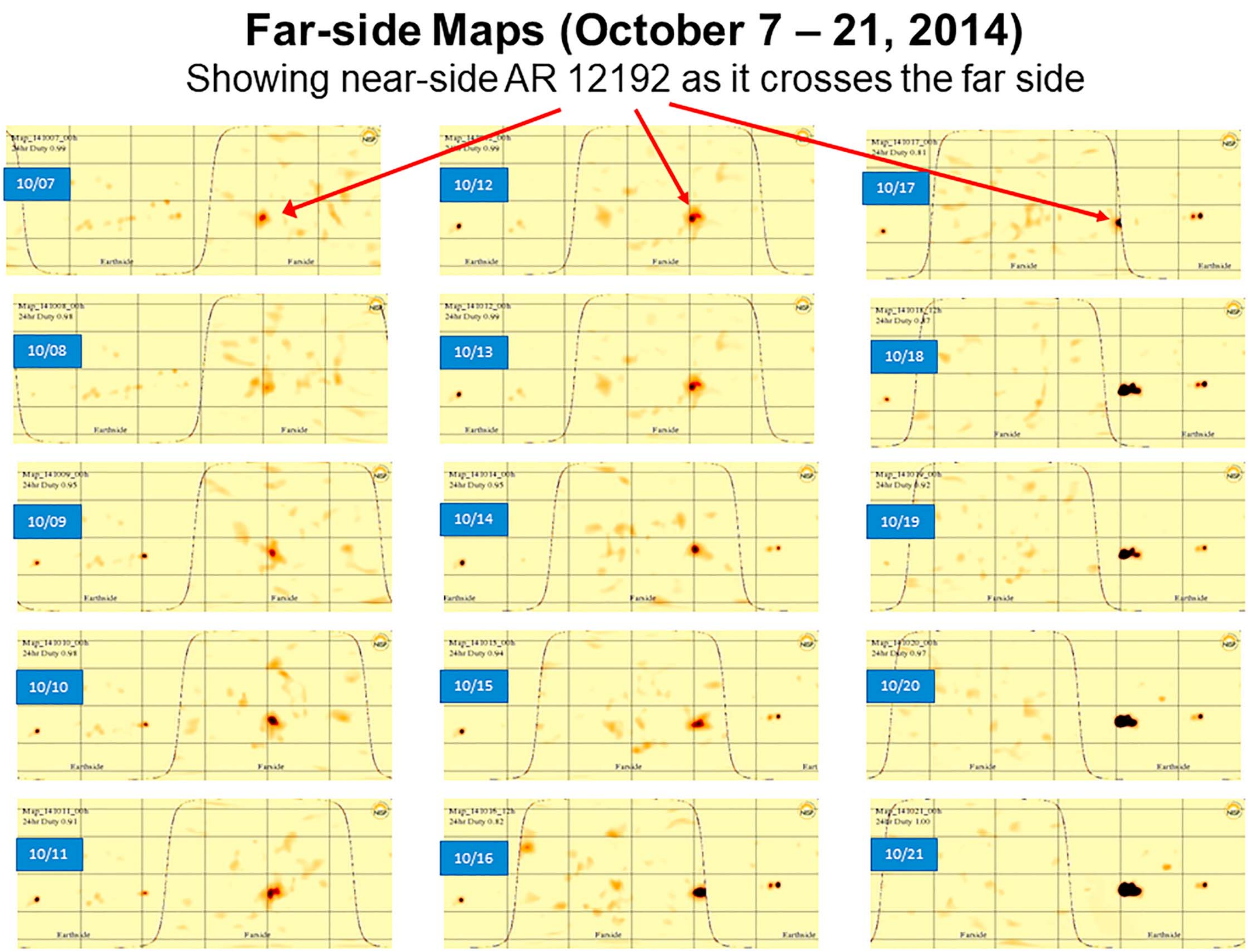

Figure 7. A sequence of far-side maps showing AR 12192 as solar rotation carries it across the far side. The boundary between the far- and near-sides is shown as a thin gray line.

Table 1
Global Oscillation Network Group Data Space Weather Products

Data product	Spatial resolution	Image format	Temporal cadence	Space weather uses
Line-of-sight magnetic field	5 arcsec	Full-disk, 1024 × 1024 pixels	60 s, 10-min average and variance returned in near real time	Coronal field extrapolations
Line-of-sight magnetic field	1°	Synoptic map, 180 × 360 pixels	1 hr	Coronal field extrapolations, coronal hole extrapolations, background solar wind forecasts
H-α intensity	2 arcsec	Full-disk, 2048 × 2048 pixels	60 s at a specific site, 20 s around the network	Flare and filament detection
Helioseismic far-side activity maps	1°	Synoptic map, 180 × 360 pixels	12 hr	Monitoring of active region emergence and evolution; correction of synoptic maps

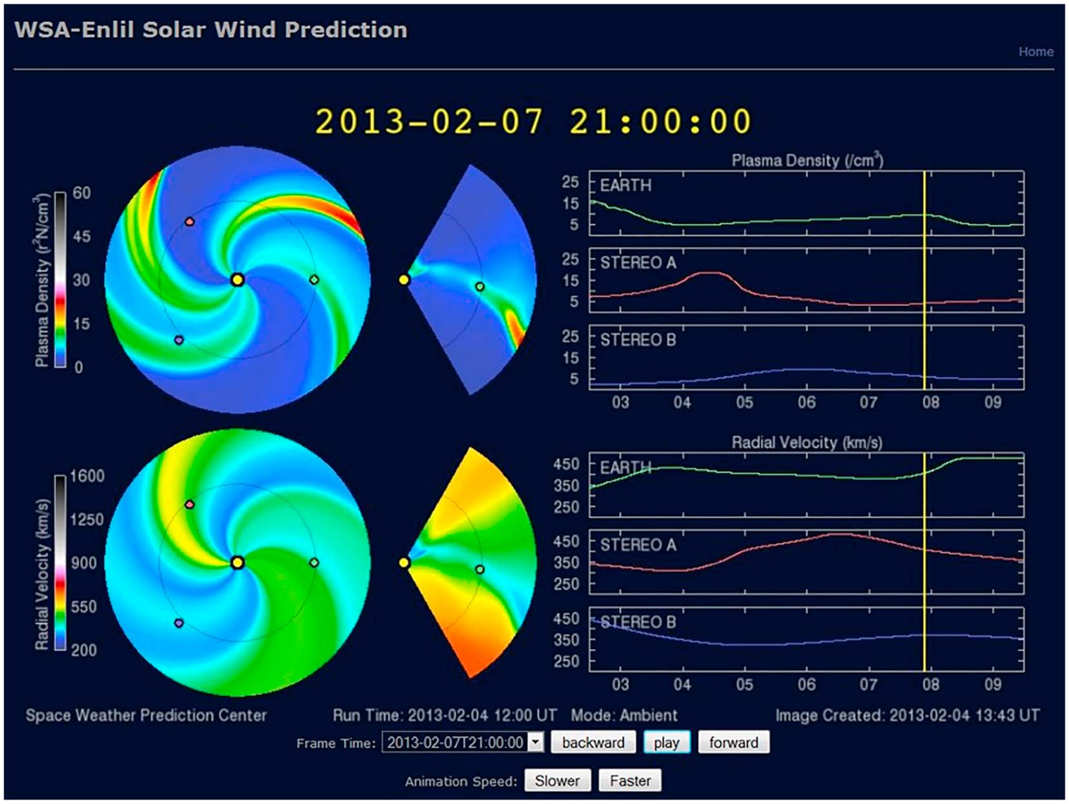

Figure 8. An example Space Weather Prediction Center forecast of geomagnetic activity using Global Oscillation Network Group data as input to the WSA/Enlil CME propagation model.

et al., 2010). Figure 8 shows an example geomagnetic storm forecast from SWPC using GONG data as input to the WSA/Enlil prediction system.

The H-α observations are supplied directly to SWPC, and the USAF 557th Weather wing, where they are used to locate flaring regions and filaments. Flare strengths are estimated from the H-α intensity and the area of the flare. Far-side maps are used by SWPC and the Air Force for awareness of new active regions that have emerged on the far side, the disappearance of older active regions, and possible rapid changes in the active region areas. Far-side maps are also useful for improving synoptic maps when a newly emerged region rotates onto the near side for the first time. Since synoptic maps are constructed from data that can be as much as 30 days old, a region that has emerged on the far side since the construction of the map will suddenly appear on the east limb, producing a spurious sharp change in the extrapolated coronal field. Inclusion of far-side information in data assimilation methods can markedly reduce the effect of these unexpected active regions (Arge et al., 2013).

5. Conclusions and Future Paths

Ground-based observing networks offer some advantages over space missions as sources of solar data for space weather. Compared to space missions, networks are inexpensive, and the hardware is physically accessible so in principle, networks can be maintained and upgraded forever. In addition, ground-based assets are less vulnerable to the effects of space weather itself. Of course, ground-based observations do not enjoy the space-mission advantages provided by being outside the Earth's turbulent and light-absorbing atmosphere, but the impact of seeing on the observations can be reduced.

GONG is currently undergoing a refurbishment project that will replace the aging cameras, upgrade the LCVRs, install a system to monitor the zero point of the magnetic field, replace all of the computers with modern hardware, and upgrade the air conditioners and weather stations at the sites. The most significant development will be the installation of a tunable H-α filter system to provide additional observations in the red and blue wings of the spectral line. This capability will supply measurements of the Doppler shifts of erupting filaments that can be used to identify potential CME sites. The refurbishments will ensure that GONG continues to supply space weather data for the next 10 to 15 years. After that time, a new ground-based network known as SPRING (Solar Physics Research Integrated Network Group) could be operational. SPRING (Gosain et al., 2018; Hill et al., 2013) would provide multiwavelength observations of the Doppler velocity and vector magnetic field as well as intensity images. Using a pointing platform capable of carrying several instruments, SPRING would offer a very flexible system that could be tailored to specific operational and scientific needs. SPRING would replace both GONG and SOLIS (which is another NSO instrument) adding nearly continual vector magnetic field measurements at multiple heights in the solar atmosphere capable of observing the complicated field structure at the polarity inversion line where energetic events frequent originate. These observations would improve studies of the origin of space weather.

The transformation of GONG from a purely research-oriented facility to one that also supplies operational data is a successful example of research to operations, or R2O. It has been a pathfinder for multiagency cooperation, bringing together the NSF, NOAA, US Air Force, and NASA, and represents a cost-effective and efficient approach to the extended use of scientific research facilities as operational assets.

Acknowledgments
GONG is the result of the efforts of hundreds of dedicated people around the world. In particular, John Leibacher as the original GONG Director, Jack Harvey as the GONG Instrument Scientist, and Juri Toomre from the University of Colorado were key in establishing GONG as a helioseismology facility. The transformation of GONG into a space weather operational asset was greatly facilitated by Michael Bonadonna at the Office of the Federal Coordinator for Meteorology; Fred Lewis and Ralph Stoffler of the US Air Force 557th Weather Wing; Rodney Viereck, Brent Gordon, and Tom Berger at NOAA/SWPC; Dave Boboltz at the NSF; Michael Starks, Nick Arge, and Carl Henney at the AFRL (Air Force Research Laboratory); Janet Luhmann at the University of California, Berkeley; and Peter MacNeice at NASA's CCMC. This work utilizes GONG data obtained by the NSO Integrated Synoptic Program (NISP), managed by the National Solar Observatory, the Association of Universities for Research in Astronomy (AURA), Inc. under a cooperative agreement with the National Science Foundation. The data were acquired by instruments operated by the Big Bear Solar Observatory, High Altitude Observatory, Learmonth Solar Observatory, Udaipur Solar Observatory, Instituto de Astrofísica de Canarias, and Cerro Tololo Interamerican Observatory. All GONG data are available at https://gong2.nso.edu/products/mainView/table.php?configFile=configs/mainView.cfg.

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