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Environmental Information Services Working Group (EISWG) Statement on GONG and its Successor Data Source for Space Weather Operations

Submitted to the NOAA Science Advisory Board (SAB) for approval and action

(The EISWG is a Standing Working Group of the SAB)

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GONG and its Successor:
A Vital Data Source for Space Weather Operations

Executive Summary

NOAA's Space Weather Prediction Center (SWPC), one of the nine National Centers for Environmental Prediction (NCEP) of the National Weather Service (NWS), is charged with nowcasting and forecasting space weather conditions. Geomagnetic storms and associated geomagnetic activity are important space weather phenomena that can be hazardous to the nation's infrastructure. Anticipating their onset is one of the major priorities for NOAA SWPC. To provide one- to four-day advanced warning of these storms, NOAA SWPC continuously operates the Wang-Sheeley-Arge-Enlil background solar wind model, with coronal mass ejections from the Sun simulated with the "cone" model, based on white-light coronagraph observations. An essential observational input to the model are global maps of the Sun's surface magnetic field. These maps are created by the National Solar Observatory's (NSO) Global Oscillation Network Group (GONG), a network of six observatories situated around the globe to provide continuous observations of the Sun. GONG was originally built in 1995 for helioseismology research. It is an aging network, and its operation beyond 2030 is considered problematic, and the ability to continue operations beyond 2032 is unlikely. There are no presently available data sources that can replace GONG with longer expected lifetimes. The planned successor to GONG, the next generation Ground-based solar Observing Network (ngGONG), has been discussed for years. An ngGONG proposal was submitted and reviewed under NSF's Mid-Scale Research Infrastructure Program in 2021. It was not selected for funding. The lack of a tangible commitment from an operational agency was perceived to be a major impediment to selection. NSO is submitting a new proposal for the design phase to the NSF Mid-scale R-1 program in May 2023. As the design and construction of ngGONG is expected to take eight years (three years design, five years construction) at minimum, it is imperative that the design phase begin as soon as possible. We recommend that NOAA/NWS financially support the design phase for ngGONG, to insure the initiation of the project.

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1 Introduction: Space Weather

Space Weather refers to the variable conditions on the Sun and in the space environment that can affect humans and technological infrastructure. Space weather encompasses a wide range of phenomena, primarily driven by the Sun and solar activity via plasma and magnetic fields, energetic particles, and electromagnetic radiation interacting with the earth's magnetosphere, ionosphere, and space assets. NOAA's Space Weather Prediction Center (SWPC) is part of the National Weather Service (NWS), and is one of the nine centers that comprise the National Centers for Environmental Prediction (NCEP). They are charged with nowcasting and forecasting space weather conditions. The SWPC Forecast Center is the national and world warning center for disturbances that can affect people and equipment working in the space environment, and is the official source of space weather alerts and warnings for the United States. Space Weather (WRN-SWX) is one of the ten NWS Mission Service Areas (MSAs) supporting a Weather Ready Nation (WRN).

2 Forecasting of Solar Wind Conditions and CME Arrival

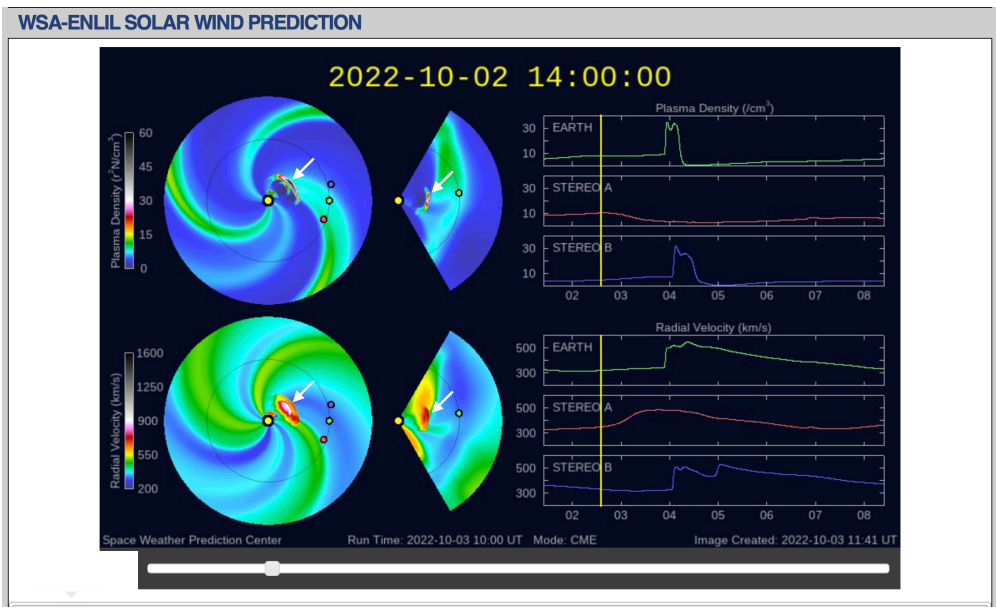

Figure 1: *Snapshot from an animation of the WSA-Enlil solar wind prediction (plasma density and velocity) available at the NOAA SWPC web site. The leftmost part of the frame shows density/velocity in the heliographic plane (close to the ecliptic, the Earth's orbital plane) and a meridional plane. The locations of Earth and the STEREO spacecraft at 1 Astronomical Unit (AU) are also shown. The inner boundary at 0.1 AU is shown in yellow. The enhanced density/velocity region (indicated by white arrows) is a CME, simulated by a cone model velocity perturbation, input at the inner boundary earlier in the calculation. The rightmost part of the frame shows the density/velocity prediction at Earth as a function of time in days.*

Geomagnetic storms and associated geomagnetic activity are an essential aspect of space weather at Earth. They can impact GPS systems, electric power transmission, satellite communications, and satellite drag, and are considered to be hazardous phenomena for the nation's infrastructure. Anticipating their onset is one of the major priorities for NOAA SWPC. The two primary drivers of these storms are fast solar wind streams and coronal mass ejections (CMEs). Solar wind streams arise from the ambient structure of the solar corona and solar wind, frequently reappear at the approximate solar rotation period, and precipitate recurrent geomagnetic activity. CMEs are large-scale coronal eruptions that propel plasma and magnetic fields into the solar wind, and are generally responsible for the most severe storms. To provide one- to four-day advanced warning of these storms, NOAA SWPC continuously operates the Wang-Sheeley-Arge-Enlil background solar wind and cone model, or WSA-Enlil (Pizzo et al., 2011). In this approach, the corona is modeled with a potential field, and the WSA empirical prescription for the solar wind speed based on the magnetic field structure (Arge et al., 2003) is used to specify boundary conditions for the ENLIL magneto-hydrodynamic (MHD) model of the solar wind (Odstrcil, 2003). Fig. 1 shows an example of solar wind predictions from the WSA-Enlil model available at the NOAA SWPC website. Fast and slow streams (green and blue spirals in the heliographic plane in Fig. 1) arise from the structure of the solar magnetic field. The Sun's magnetic field is most reliably measured by telescopes imaging the photosphere (the visible surface) and utilizing the Zeeman effect in spectral lines. Polarization measurements determine the strength and direction of the field. Maps of the solar line-of-sight (LOS) magnetic field are obtained from continuous measurements of the solar surface over the course of the solar rotation. Such maps are the key observational input to the WSA-Enlil solar wind predictions, and they are provided by the National Solar Observatory's (NSO) Global Oscillation Network Group (GONG). NSO is supported by the National Science Foundation (NSF). CMEs are simulated with the "cone" model: launching a velocity perturbation into the modeled ambient solar wind based on white-light images of CMEs in the corona from the Large Angle and Spectrometric Coronagraph (LASCO) aboard the ESA-NASA Solar and Heliospheric Observatory (SOHO).

3 The GONG Network

NOAA SWPC has relied on solar observations from the GONG network since 2010. They are a crucial component of NOAA SWPC's space weather operations. The GONG network utilizes six sites around the world to provide continuous solar observations. Fig. 2 shows an example of GONG full-disk magnetograms from the NSO web site. These ten-minute averaged GONG solar magnetograms are processed into so-called synoptic maps (Fig. 3), which are used to derive the boundary conditions for WSA-Enlil. Additionally, images of the Sun in the Hα spectral line are used for monitoring solar activity such as flares and filament eruptions, and helioseismic imaging of magnetic activity on the Sun's far-side are used to provide warning of large active regions prior to their ro-

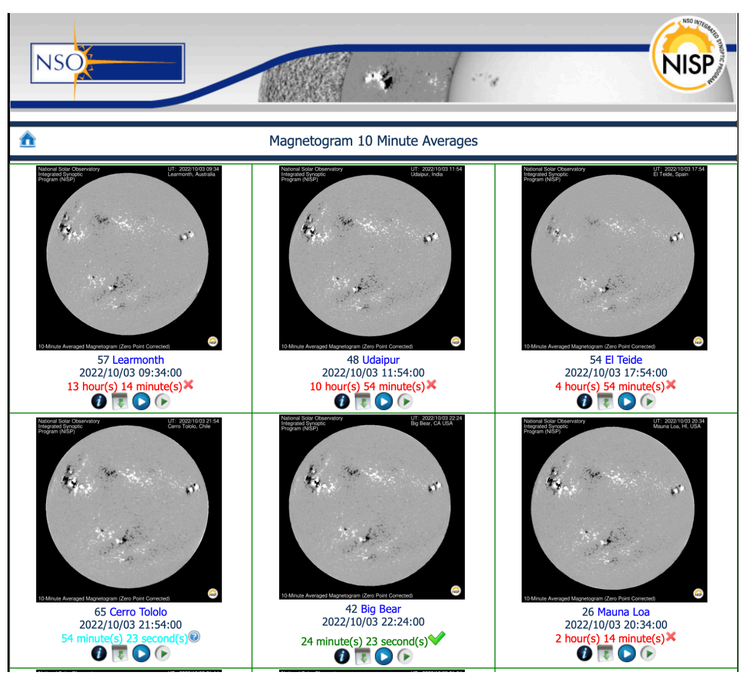

Figure 2: *Full disk magnetograms of the line-of-sight (LOS) magnetic field in the photosphere from the six GONG sites, available every 10 minutes, shown in gray scale. Black indicates negative polarity and white positive polarity.*

tation into view.

GONG was originally built in 1995 for helioseismology research, and has been repurposed to provide crucial space weather data (Hill, 2018). It is an aging network, and many components are not easily maintained or replaced. Recent renovations and maintenance were performed with the goal of extending its lifetime until 2027. Operation of the present network beyond 2030 is considered problematic, and the ability to continue operations beyond 2032 is unlikely. In principle, the NOAA operational pipeline can still function with three working GONG sites; however, if weather or other technical problems prevent observations at one of the three remaining sites, the operational model would cease (an alarm is triggered if there are no observations available for six hours). NOAA presently pays $1.17M per year for GONG maintenance, about 50% of the total cost.

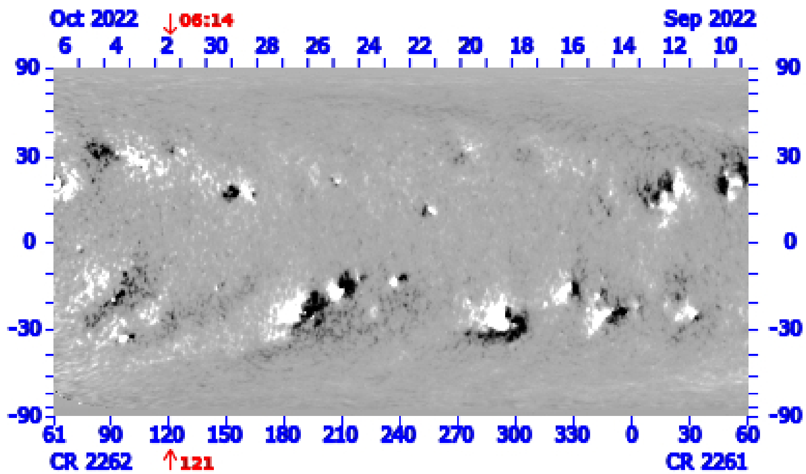

Figure 3: *A synoptic map of the radial photospheric magnetic field (inferred from the the LOS field) as a function of heliographic latitude and Carrington longitude, assembled from LOS magnetograms like those shown in Fig. 2. The map is constructed from the latest magnetograms, together with data observed over the course of the 27 day solar rotation, to cover the entire solar surface. The red arrows indicate the location of disk center at the time of the most recent magnetogram. These maps are provided at an hourly cadence to create the boundary conditions for the WSA-Enlil model shown in Fig. 1.*

4 Maintaining Present Operational Capabilities and Providing for Future Operations

At the present time, there is no operational succession plan for GONG. ngGONG, the most obvious follow-on, is described in the next section. In Sec. 4.2 we describe alternatives if/when GONG halts operations and if the ngGONG project were unable to secure funding.

4.1 ngGONG

In recognition of GONG's finite lifetime, the NSO has planned for the design of a next generation Ground-based solar Observing Network (ngGONG). Discussions between NSO, the Department of Defense, and NOAA have occurred over several years, and proposed observations from ngGONG are envisioned to satisfy key future operational requirements, as well as requirements of the scientific community. These include LOS and vector measurements of the photospheric and chromospheric magnetic field, as well as other observables of operational and scientific interest. As with GONG, six sites distributed around the world to provide continuous observations are planned. ngGONG would not just replace GONG, but provide improved capabilities that will be required to implement more advanced models into operations in the future. One version of ngGONG was outlined in a white paper to the NASA Astrophysics decadal survey (Hill et al., 2019); Pevtsov et al. (2022) describe an updated version in a NASA Heliophysics decadal survey white paper. An ngGONG proposal was submitted and reviewed under NSF's Mid-Scale Research Infrastructure Program in 2021. It received positive reviews but was not funded. This program receives proposals across a wide range of scientific disciplines, and selection is very competitive. While the solar science of ngGONG is highly compelling, NSF must weigh this against many other worthy scientific priorities. Supporting an operational requirement, e.g., serving the NWS mission to protect life and property, can provide the key advantage in such a competition. In conversations with NSF, they indicated that interest from operational agencies has been noted, but the lack of a definitive commitment from either DOD or NOAA was perceived to be a major impediment to selection. NSO is planning a new submittal, with the following features:

1. The design phase is expected to take $\sim$3 years, at a total cost of $17M.
2. Construction is expected to take 5-7 years, with a total cost ranging from $90-$210M.
3. It is nominally planned to last two complete solar cycles ($\sim$44 years).
4. NSO will submit to the Mid-scale Research Infrastructure-1 (Mid-scale R-1) NSF program for the design phase (must be less than $20M). They have submitted a pre-proposal, and have been invited to submit a full proposal, due on 5/5/2023.
5. After the design phase, the construction phase proposal will be submitted to either the Mid-scale Research Infrastructure-2 program (maximum cost $100M) or the Major Research Equipment and Facilities Construction (MREFC) program. Total cost will depend on design decisions and whether cost sharing will be available to reduce the funding from NSF.

The original proposal included a coronagraph. While this instrument is of important scientific interest and is requested by the Air Force, a ground-based coronagraph is not an operational need for NOAA. NOAA/NESDIS is committed to flying coronagraphs on GOES-U and the Space Weather Follow-On (SWFO) missions, with expected launches in 2024 and 2025, respectively. The Compact Coronagraph (CCOR) will replace the aging LASCO coronagraph that is presently relied upon. Removing the coronagraph from ngGONG will simplify design & construction and reduce costs. In October, 2022, the report "Planning for a Collaborative Ground-Based Solar Observing Network" was submitted as National Space Weather Strategy and Action Plan 2.2.5 to the Space Weather Operations, Research, and Mitigation (SWORM) subcommittee. This report, co-authored by scientists and managers from NOAA, DOD, NSF, and NASA, strongly advocates for the multi-agency support for ngGONG. However, it will likely take years for this report to result in tangible budget action. Given the time line for design and construction of ngGONG, it is imperative to begin the design phase as soon as possible. Otherwise, NOAA faces a likely disruption of operational services. The NSF Director of the Division of Astronomical Sciences, Dr. Debra Fischer, indicated that a modest commitment from NOAA for the design (e.g. $1M/year for three years) would greatly increase the chances of ngGONG selection. With the start of the ngGONG design phase, NOAA, NSF and NSO would have time to work out what further monetary support from operations would be available, whether this would just be for maintenance once ngGONG is constructed (as is presently done with GONG), or if there would also be operational funds available to support construction. This could influence the overall design of the system. This would also allow time for multi-agency budget discussions. For example, DOD might then be able to augment construction funds to support their priorities, e.g. coronagraphs.

4.2 Possible Alternatives

4.2.1 SDO

If GONG were to cease operations in the near term, the most likely alternative would be the Helioseisemic and Magnetic Imager (HMI; Scherrer et al., 2012) aboard the NASA's Solar Dynamics Observatory (SDO). SDO is in an inclined geosynchronos orbit, providing continuous observations of the Sun except for eclipse periods of about an hour that occur during several weeks of the year. HMI is a more advanced instrument than the GONG magnetographs, providing vector measurements of the photospheric magnetic field as well as higher resolution. SDO was launched in 2010, and is well past its originally anticipated mission lifetime. While it is expected that NASA will continue to support SDO as long as the mission is viable, the present GONG observatory could well outlive SDO. We also note that adapting the present WSA-Enlil model to a new data stream would require a non-negligible effort on the part of SWPC.

4.2.2 ASO-S

China launched the Advanced Space-based Solar Observatory (ASO-S) in October 2022 (Gan et al., 2022). Included in its instrument payload is the Full Disk Vector Magnetograph (FMG). ASO-S is presently in a commissioning phase, that is stated to last three to six months. It is anticipated to be in a sun-synchronous orbit with near continuous observations of the Sun. On the mission web site, data has been promised to be open access when it becomes available. Data quality, latency, etc., is unknown. Even assuming data quality is good and were available in near-real time, it seems very unlikely that NOAA (or DOD) would accept reliance on this data source for an operational product with National Security implications. The planned nominal lifetime for ASO-S is four years, so this is not anticipated to be a long-term resource.

4.2.3 Other Ground-based Telescopes

There are no other concrete plans for near-continuous observations of the Sun with full-disk magnetographs from Earth's vantage point. The European Solar Physics Research Integrated Network Group (SPRING) under SOLARNET has discussed plans for a GONG-like set of observatories, but there is not yet funding or an envisioned start date. The Synoptic Optical Long-term Investigations of the Sun (SOLIS) facility (supported by NSF and built by NSO) provided solar observations from 2003 to 2017. This included full disk LOS and vector magnetograms (several times a day) from the Vector Spectromagnetograph (VSM) as well as other data from the Full Disk Patrol (FDP). It is planned for SOLIS to be relocated to Big Bear Solar Observatory and to resume operations. There are ground-based telescopes in Russia (Kislovodsk Observatory) and China (Huairou Solar Observing Station) that provide full-disk magnetograms. It is not clear that this data can be provided rapidly in near real time, and again would appear not to be acceptable as an operational resource. The National Astronomical Observatory of Japan (NAOJ) at Mitaka previously produced full-disk magnetograms with the Solar Terrestrial Energy Program (STEP) instrument until 2011. NAOJ's Solar Flare Telescope now regularly provides polarization images in the infrared, but routine magnetograms from this data are not yet available. We note that a single observing site is inadequate for SWPC operations, because the Sun would be observed for only $\sim$12 hours in a given day, and weather or other problems can shut down observations at a single location for days or weeks during the year. Even if disparate sites around the world could be cobbled together, cross-calibration of different instruments is notoriously difficult (e.g. Riley et al., 2014), and building useable magnetic maps from such sources would represent a significant challenge.

4.2.4 National Environmental Satellite, Data, and Information Service (NESDIS)

In principle, NESDIS could fly a magnetograph on a future GOES mission or space weather dedicated satellite. There are no plans at the present time for doing this. The GOES-U launch is planned for 2024, and the Space Weather Follow-On (SWFO) satellite is planned for 2025, with a mission life of five years. The payload for these are set and no magnetograph was ever planned for these missions. While the costs and timeline for this approach cannot be properly estimated without a detailed study, it is instructive to review the history of the CCOR coronagraph and the SWFO mission. Discussions about NOAA flying a coronagraph began in the early 2000's. An initial concept study for CCOR was completed in 2012. Delivery for the version to be integrated with GOES-U delivery occurred in 2022. Studies for SWFO were underway in 2015, and the total cost in 2016 was estimated to be $757M. Based on this experience, we can conclude that a NESDIS dedicated mission to fly a magnetograph would be far more expensive than ngGONG, especially per year (ngGONG has a proposed lifetime of 44 years). The timeline for completion would likely be at least as long as the planned timeline for ngGONG, and probably longer.

Estimating the cost of flying a magnetograph on a GOES satellite or future Space Weather mission would require a detailed study, but the additional cost of adding a magnetograph to the payload of a planned mission would certainly be much less than a stand-alone mission. The NESDIS Director of the Office of Projects, Planning, and Analysis, Dr. Elsayed Talaat, indicated that NESDIS could investigate a magnetograph for future missions: there are several pros and cons to flight hardware versus ground-based telescopes that would have to be explored. Costs would strongly depend on the instrument requirements. A touchpoint is the HMI magnetograph that was launched by NASA as part of SDO, with proposed costs of ∼$70M in 2002[1]. If no ground-based alternative materializes, it seems that this approach would be necessitated. The timeline would depend not only on the instrument development time but the availability of a satellite, and would appear to be, at minimum, at least as long as ngGONG. This approach would commit NOAA/NESDIS to continuously flying magnetographs to maintain operational capabilities.

5 Impacts

There has been an increasing recognition that Space Weather events, such as geomagnetic activity, can pose a significant threat to our technological infrastructure. Estimates of the possible economic impact of severe geomagnetic activity have been performed in several studies and have varied widely. Eastwood et al. (2018) explored different possible scenarios for Europe and characterized them by (1) no forecast (present forecasting capabilities not available); (2) present forecasts; and (3) improved forecasts. For one of the extreme scenarios, they estimated global losses at 5.8-8.3 trillion euros for case (1), 0.79-1.1 trillion euros for (2), and 190-270 billion euros for (3). With the enactment of PROSWIFT in 2020, it is recognized that to protect vital national interests, the US needs to not just maintain present capabilities, but to improve them.

If/when GONG ceases to operate and if there is no replacement of the data source, we can expect the following outcomes:

- The WSA-Enlil model will not operate in its present form. Forecasting for solar wind conditions by NOAA/SWPC will likely return to a state prior to 2011.
- NOAA has invested in flying coronagraphs on upcoming missions to ensure continuity of CME observations. The model for which these observations are used as input will no longer

[1] http://hmi.stanford.edu/proposal_April_2002/HMI_merge_proposal_public.pdf

be operating, negating some of the utility of these observations.

- The present modeling pipeline is based on simpler, older models. Newer, more advanced models may eventually improve forecasts. All such models require, at minimum, observations of the solar magnetic field, and will not be possible without a replacement for GONG.
- If the envisioned ngGONG is constructed and brought into operations, it will provide a foundation for Earth-based solar observations for the next four decades. As a ground-based resource, it can be maintained and improved.
- Proposed new capabilities of ngGONG (e.g. vector magnetograms at photospheric and chromospheric heights) may lead to improved models and forecasts.

6 Conclusions

6.1 Findings:

- The GONG network is a crucial resource for present Space Weather Operations. It is 28 years old, and approaching its end of life. If GONG ceases operations without a replacement, an important operational capability will be lost. This will compromise the NWS's ability to forecast potentially hazardous space weather phenomena.
- ngGONG is the most obvious replacement for GONG. ngGONG is a long-term solution that will not only replace current measurements, but provide more advanced capabilities that will allow more sophisticated models to move into operations in the future.
- Design and construction of ngGONG will take a minimum of 8 years (probably longer). It is imperative that this begin as soon as possible, to avoid a disruption to operations.
- ngGONG was unsuccessful in obtaining NSF funding in 2021. While the project was recognized to have high merit, the lack of tangible support from any operational agency was seen as an important factor in the declination.
- NSO is submitting a new proposal for the design phase to the NSF Mid-scale R-1 program in May 2023. A relatively small commitment (e.g. $1M/year for three years) would greatly enhance the chances of success.
- If ngGONG is not constructed, the only viable alternative to continue operations would appear to be for NESDIS to fly a magnetograph on a GOES or space weather dedicated satellite, and to continue such missions into the future. Cost for this approach is unknown, but likely to be expensive. The timeline to operations for such an instrument would be also be many years. If this approach were not initiated rapidly, a disruption of operational services is likely.

6.2 Recommendation:

- GONG provides a vital data source for space weather operations, and it is nearing end of life. The ngGONG project is the most straightforward replacement. It will maintain present operational capabilities, and provide observations for future requirements. The time window to complete ngGONG prior to the demise of GONG is closing. We recommend that NOAA/NWS financially support the design phase for ngGONG, to insure the initiation of the project.

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