Architectures for Space Weather Magnetographs

A Heliophysics 2050 white paper submitted by Neal Hurlburt, *Lockheed Martin Advanced Technology Center* and Tom Berger, *University of Colorado*

The need for magnetograph observations

The ability to accurately measure the magnetic field at the solar surface is a critical space weather requirement as laid out in multiple mission studies. Ideally, space weather modelers and forecasters would have simultaneous knowledge of the field over the entire solar surface in a timely and uniform fashion. However we can currently only measure the field from regular observations gathered on or near the Earth. Both space-borne and ground-based magnetographs have been providing these minimal observations for the past few decades. One challenge has been that solar wind/CME transport models require knowledge of the global coronal magnetic field while solar cycle models require accurate polar field measurements, both of which are unobtainable from our Earth-based viewpoint in the ecliptic. Thus our Earth-based observations have had to be extrapolated to varying degrees of success to provide global-scale, long-duration, estimates of the solar magnetic field.

As we move to the next generation of space weather observing systems, a key driver is the optimal architecture for photospheric (and possibly chromospheric or coronal) field measurements. In particular, should they be acquired from ground-based or space-based instruments, or both? Here we argue that space-based instruments are the best solution, not only due to the well-established fact of their superior data quality, but also to the lesser understood role they play in providing a more cost effective, more flexible and more operationally efficient solution. Using existing operational observing systems as the starting point for our comparison, we project what the next generation of ground- and space-based systems will offer, and compare estimates for their total cost of ownership, system performance, reliability and operational efficiency.

Possible Architectures

The ideal magnetograph observing system would provide reliable and continuous coverage of the magnetic fields over the entire solar sphere (4π steradians). An architecture that achieves this must include instruments at multiple viewpoints in solar longitude and latitude including solar polar orbiting platforms. A single viewpoint, which is all we have had up to now, provides only about 25% coverage due to the combination of foreshortening and other line-of-sight effects encountered when observing beyond about 60 degrees from the Sun center. Currently, the remaining 75% of the surface must be filled in using models or extrapolations that rely on the one-month solar rotation period. Hence all current inputs to space weather models use data that is extrapolated and often outdated due to our limited view. Solar weather models are only as good as the data that drives them, and they have been shown to give significantly different results when driven with data from different magnetographs [1] [2] [3]. Consistent magnetograph calibration and uniform calibration between magnetographs will be critical to provide consistent model inputs. Hence there is a significant benefit gained by using a common design that can be reliably intercalibrated.

Here we present some current and proposed architectures that span the range between these two extremes, i.e., architectures that range from purely ground-based networks to the complete, 4π constellation. We consider the extent of their coverage, the number of platforms re-

Architecture	Ground	LEO	GEO	L1	L1+L5/4/3	Binocular	4π
Surface Coverage %	25	25	25	25	40/60/85	35	100
Number Of Platforms	6	>2	1	1	2/3/4	2	>6
Scales to 4π	No	No	No	Yes	Yes	Yes	Yes
Development Cost	Low	Low	Medium	High	High	High	High
Deployment Cost	Low	Low	Medium	Medium	Medium	High	Very High
Operation Cost	Medium	Low	Low	Low	Medium	Medium	High
Bandwidth Constraints	Low	Low	Low	Moderate	High	Moderate	High

quired, their potential for expansion; expected development, deployment and operating costs; and ease of intercalibration.

Example Instruments

We next consider four magnetographs in various stages of development. These include the ngGONG network of magnetographs proposed by the National Solar Observatory [4], a slightly updated version of the Helioseismic and Magnetic Imager (HMI)[5] on the Solar Dynamics Observatory, a compact magnetograph (CMI) derived from HMI, and MICRO, an ultra-compact magnetograph based on photonic integrated circuits that is currently in development. ngGONG is based a network of six ground-based observatories around the Earth. The other three are designed for deployment in space. After reviewing their performance and resource requirements using a metric evaluation, three candidate architectures emerged.

1. Evolving the Status Quo The ngGONG network is a proposed upgrade to the existing GONG network which is the current data source for operational solar wind forecasting models. The scientific value of this solution is significantly lower than a space-based solution as evidenced by the almost 10:1 citation rate between GONG its space-based equivalents.

2. Maximize Near-term Effectiveness at Minimal Cost Build-to-print duplicates of HMI deployed on the next generation GOES East and West spacecraft provide uninterrupted, distortion-free, coverage with redundancy. The total development and deployment costs would be comparable to the ngGONG network.

NOAA Space Operations Facility has a well proven operations group. In GOES-13,14,15 operations, the space weather related instruments were managed by three equivalent personnel with an additional two NASA equivalent personnel and 2 equivalent vendor personnel over the mission life of the instruments. The ground personnel allocated for GOES-16 and 17 follows the same trend. HMI is currently operating, collecting and processing data with even lower levels of support.

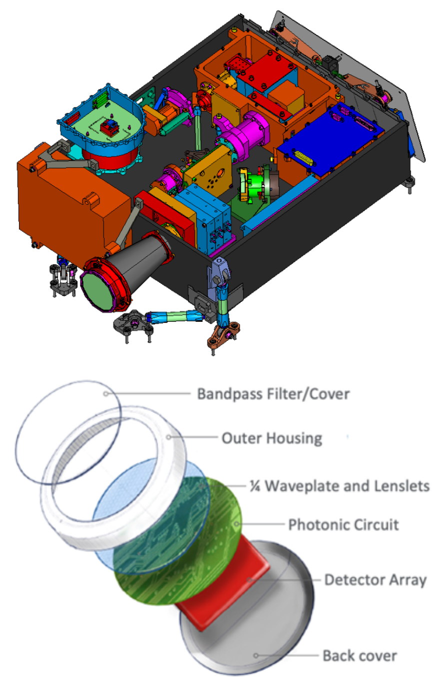
Staffing could be reduced even further by integrating with NOAA systems and automating standard operations. In that case calibrations would be performed regularly using a scheduler with pre-defined APID structure for required the calibration data. The calibration data would be ingested by the analysis pipeline to automatically produce calibrations, instrument trends, and auto-generate the trend and calibration reports.

HMI has a dedicated downlink bandwidth of 55Mbps which is used to downlink images used for both magnetograms and dopplergrams for helioseismology. Data products could also be generated on board (as is done on Solar Orbiter) to reduce the bandwidth requirements by a factor of 5 or more, and would maintain existing HMI capabilities with a ~10Mbps downlink.

3. Optimize for Long-term Performance and Effectiveness To approach the ultimate requirement of 4π coverage, new instruments are necessary, primarily to reduce their size and weight and enable deep-space deployment on existing launch vehicles. This will require investments to develop them for flight which increases the up-front development cost, but would reduce cost in the long run by producing a common instrument that could be used from GEO to deep-space. This has the added value of improving reliability and simplifying data operations, intercalibration and processing.

Instruments derived from the existing HMI design, such as LMATC's Compact Magnetic Imager (CMI), would require relatively modest investments to prepare for flight. The average unit cost for CMI instruments is comparable or perhaps lower than that required for HMI clones. Operations costs are also similar.

Disruptive solutions, such as MICRO, require a similar investment in development but would result in dramatically reduced unit costs since major components would be printed using standard lithographic techniques rather than assembled. The similarly dramatic reduction in mass would enable deployment on virtually any platform, including out of the ecliptic missions, or as a hosted instrument on planetary or other deep-space missions.



Magnetographs tailored for space weather observations, such as the CMI (top) and MICRO (bottom), offer optimal performance at dramatically lower cost.

Conclusion

Magnetograph constellations in space offer superior data products at comparable or reduced costs when compared with ground-based network alternatives. The lowest-cost and highest performance (in terms of duty cycle, data volume, and quality) solution considered would be to place HMI clones on the next generation of GOES spacecraft. Constellations starting at L1 and then forming the "string of pearls" around the ecliptic are promising but require new instruments such as the Compact Magnetic Imager or MICRO. Truly complete measurement of the solar magnetic field for optimal solar wind forecasting will require solar polar orbiting missions.

References

1	C. Gressl, et al. Sol. Phys, vol. 281, p. 1783–1801, 2014
2	C. Gressl, et al. Sol. Phys, vol. 281, p. 1783–1801, 2014
3	P. MacNeice, et al, " Space Weather, vol. 16, pp. 1644-1667, 2018
4	F. Hill 2018, Space Weather 16, 1488.
5	J. Schou, et al. Solar Physics, pp. 229-259, 2012.
6	H. Hammel et al., 2019. https://arxiv.org/ftp/arxiv/papers/1903/1903.06944.pdf
7	https://www.nso.edu/telescopes/nisp/gong/nisp-tech-docs/