MULTI-HEIGHT MEASUREMENTS OF THE SOLAR VECTOR MAGNETIC FIELD

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Synopsis:

This white paper advocates the importance of multi-height measurements of the vector magnetic field in the solar atmosphere. As briefly described in this document, these measurements are critical for addressing some of the most fundamental questions in solar and heliospheric physics today, including: (1) What is the origin of the magnetic field observed in the solar atmosphere? (2) What is the coupling between magnetic fields and flows throughout the solar atmosphere? Accurate measurements of the photospheric and chromospheric three-dimensional magnetic fields are required for a precise determination of the emergence and evolution of active regions. Newly emerging magnetic flux in pre-existing magnetic regions causes an increase in the topological complexity of the magnetic field, which leads to flares and coronal mass ejections. Measurements of the vector magnetic field constitute also the primary product for space weather operations, research, and modeling of the solar atmosphere and heliosphere.

The proposed next generation Ground-based solar Observing Network Group (ngGONG), a coordinated system of multi-platform instruments, will address these questions and provide large datasets for statistical investigations of solar feature behavior and evolution and continuity in monitoring for space-weather focused endeavors both research and operational. It will also enable sun-as-a-star investigations, crucial as we look toward understanding other planet-hosting stars.

A wide-spread use of full-disk vector magnetic field observations in solar physics research, their increasing importance for understanding many fundamental phenomena, and a growing potential of these data for operational space weather forecast strongly suggest that these type of observations need to be continued as part of long-term (synoptic) program from ground-based and/or space-based facilities. Regular multi-height observations of magnetic fields on the Sun is the next frontier in Solar Physics.

1 Introduction

The Sun dominates the Earth's climate and the space environment throughout the solar system. It provides variable radiative, particle, and magnetic field input to the conditions in the heliosphere which directly influence the Earth's magnetosphere. As a dominant source of electromagnetic energy and energetic particles, we need to understand the Sun's sources of variability. Observations of the solar surface reveal magnetic and velocity fields with complex hierarchical structures, evolving on a wide range of different spatial and temporal scales. These features are the direct manifestation of a hydromagnetic dynamo process operating in the Sun's interior, and leading to the 11 (or 22) -year solar activity cycle (e.g. Charbonneau, 2014). The interaction between flow velocity, the motion of flux tubes through the convection zone, and the generation of magnetic fields are issues which remain open and which are critical to the successful understanding and modeling of the properties of the solar/stellar dynamo that affect the solar atmosphere and active region generation, and the related solar irradiance and heliospheric outflows that ultimately result. Accurate measurements of the photospheric and chromospheric three-dimensional magnetic fields are required for a more precise determination of the emergence and evolution of active regions, wherein newly emerging magnetic flux increases the topological complexity, leading to flares and coronal mass ejections. The challenge is to understand them well enough to be able to predict their occurrence and characteristics.

Due to the availability of full disk vector magnetic field measurements, great progress has been made over the last decade to understand solar variability at different temporal and spatial scales. Because different spectral lines and/or different points along the profile of a single spectral line are formed at different heights in the solar atmosphere, multi-wavelength and spatially-resolved observations of the magnetic field constitute the only tool available today for resolving the 3D structure of the magnetic field in the solar atmosphere. Significant contributions to this effort have been provided by the continuous observations by the Vector Spectro-Magnetograph (VSM/SOLIS, Keller, Harvey, and Giampapa, 2003), the Hinode/SP (e.g. Lites et al., 2013), and later by the Helioseismic and Magnetic Imager (HMI) instrument on the Solar Dynamics Observatory (Hoeksema et al., 2014; Scherrer et al., 2012). The high temporal cadence and continuity of the full-disk HMI vector magnetic field data available since 2010 provides a unique opportunity for a plethora of different studies about our star (e.g. Kazachenko et al., 2022; Lumme et al., 2022), and can be integrated with new technologies such as machine learning (e.g. Higgins et al., 2022). Observations with the HMI instrument are taken at a single layer in the solar photosphere, but studies have shown that measurements of the magnetic field at multiple levels improves data interpretations such as transverse field disambiguation (Leka et al., 2009). They also minimize assumptions that have been used in various models such as non-linear force field model (Wiegelmann et al., 2008) and integral Lorentz force estimations (Petrie, 2019), that provide a better understanding of the morphology and dynamics in the region between the photosphere and chromosphere where both flow and field are equally important (Metcalf et al., 1995). This need also addresses fundamental questions concerning the origin of the magnetic field and helicity observed in the photosphere (deep seated vs. near surface dynamo activity or both), how magnetic helicity is stored in the solar atmosphere and affects the magnetic energy available for solar eruptions, and the coupling between magnetic fields and flows throughout the solar atmosphere, including the sites where the fast and slow solar wind are generated.

The reconciliation of the observed evolution of large-scale magnetic helicity and one predicted by current solar dynamo models would require continuous observations of vector magnetic field over the period of solar sunspot or even full magnetic cycle (20+ years). Over the last decade significant advances in computational power, combined with the development of increasingly sophisticated numerical models, have made the full-disk measurements of the solar vector magnetic field especially relevant. When combined into synoptic charts or maps, these measurements are used to drive the most advanced 3-D global numerical simulations (e.g., Bernabé et al., 2022; Li, Feng, and Wei, 2021; Hoeksema et al., 2016). The accurate construction and calibration of these maps establishes both the diagnostic capabilities of the models and their ability to forecast the state of the corona and heliosphere (Wang, Ulrich, and Harvey, 2022; Frost et al., 2022; Riley, 2007; Veselovsky and Ivanov, 2006; Zhao and Hoeksema, 1995). As examples, the 3-D geometry of the magnetic field expansion in the inner corona, from the photosphere out to a few solar radii, plays a fundamental role in determining the density distribution and solar wind speeds in heliospheric models, as the field lines define the flow tubes along which mass and energy flux are conserved. This geometry is directly linked to the global topology of the solar magnetic field, including that on the invisible far-side, and in the polar regions where observations are limited. Multi-height vector magnetic field measurements also play a critical role in addressing this particular issue of the farside and polar observational gaps (Arge et al., 2021; Judge et al., 2021; Hayashi, Wu, and Liou, 2022).

For almost 20 years the Integrated Synoptic Program at the National Solar Observatory has provided to the solar community, through its SOLIS/VSM instrument, unique full-Stokes measurements of the full-disk photospheric magnetic field and more recently full- Stokes chromospheric measurements as well. This achievement is expected to be greatly enhanced by a newly proposed ngGONG (next generation GONG) project, a ground-based global network of highly capable solar observations to study the Sun and its consequences on Earth. Once operational, ngGONG will provide measurements of the processes that drive the activity from the solar interior, the atmosphere, and throughout the heliosphere.

The state-of-the-art magnetohydrodynamic (MHD) coronal models require full disk vector magnetic field information. In the near future, routine well-calibrated and sensitive vector magnetic field measurements in both the photosphere and the chromosphere will be regularly required for modeling space weather, for both research and in support of operational forecasting. Improved performance will enable effective application of the force-free condition adopted by some widely used models for extrapolating magnetic fields into the corona, and addressed the need for a robust approach to the 180-degree ambiguity resolution for the direction of the transverse field (e.g., Valori et al., 2022; Leka et al., 2009). ngGONG will be designed to provide these required vector magnetic field data.

Multi-height measurements of the solar vector magnetic field also have important implications for the using of helioseismology as a tool. For example, a study by Schunker and Cally (2006) suggests that the direction of the magnetic field plays an important role in how acoustic waves can be converted into different types of magnetohydrodynamics (MHD) modes. That is, the magnetic field acts as a filter, preferentially allowing through acoustic signal from a narrow range of incident directions. Simultaneous helioseismic and multi-height magnetic observations will improve our understanding of how acoustic wave propagate in the Sun, and help to clarify

the complex plasma structure and dynamics underneath active regions. This has important implications in terms of forecasting the emergence of active regions and subsequent events associated with space weather phenomena (e.g. flares, coronal mass ejection, etc...)
An important area in multi-wavelength studies of the Sun is the development of interpretation tools for such data. Numerical inversion tools that can simultaneously fit multiple spectral lines (forming at different heights) and obtain a physically consistent 3D magnetic and thermodynamic parameters are needed. Machine-learning tools in conjunction with realistic MHD and radiative transfer models can then be used to infer physical parameters in near real-time forecast applications.
However, there are research challenges to be met. Specifically, inversions that return the height-resolved atmosphere, or multi-line inversions that constrain the results even further are still not widely used, although they are being developed actively (del Toro Iniesta and Ruiz Cobo, 2016). In particular, for multi-height disambiguation of the 180° degeneracy and the further interpretation for physics-based inquiry (such as computing the spatially-resolveed Lorentz forces), the mapping from optical depth to physical height is required, and is not straightforward (Pastor Yabar, Borrero, and Ruiz Cobo, 2019; Löptien et al., 2020).

2 ngGONG

The next generation Ground-based solar Observing Network Group (ngGONG), a coordinated World-wide system of multi-platform instruments, will provide a broad range of measurements addressing the needs and goals described above for fundamental research in solar and space physics, and space weather. ngGONG will obtain observations of Doppler velocities in the photosphere, vector field magnetic fields in the photosphere and chromosphere, and full-disk spectrally-resolved scans of polarized light for Doppler velocity. The design of ngGONG is driven by the research interests of the national and international solar and solar-stellar scientific communities, and informed by the requirements of space-weather forecasting agencies. Led by the National Solar Observatory (NSO) in partnership with the National Center for Atmospheric Research (NCAR) High Altitude Observatory (HAO) ngGONG will collect critical observations of solar activity and the Sun's magnetic field over two Hale solar magnetic cycles (about 44 years). ngGONG will provide the information needed to answer some fundamental questions about the nature of the solar magnetic field, including:

- What is the origin of the magnetic field and helicity observed in the photosphere (deep seated vs. near surface dynamo activity or both)?
- How is magnetic helicity stored in the solar atmosphere and how does it affect the amount of available magnetic energy and solar eruptions?
- What is the coupling between magnetic fields and flows throughout the solar atmosphere?
- Where are the the fast and slower solar wind generated?

More details about the design and scientific objectives of ngGONG are provided in the White Paper "ngGONG – Future Ground-based Facilities for Research in Heliophysics and Space Weather Operational Forecast" led by Alexei Pevtsov.

3 A Science Case: Solar Magnetic Helicity

Magnetic helicity is an integral measure of topological properties of the magnetic field (e.g., Pevtsov et al., 2014). Locally, it can be characterized by a number of parameters such as linkage, twist and writhe of the field lines (Berger and Hornig, 2018). In astrophysical dynamos, magnetic helicity is commonly accounted as a nonlinear constraint of turbulent generation of large-scale magnetic field (Brandenburg and Subramanian, 2005). Early studies found that the sign of magnetic helicity in solar active regions follow the hemispheric helicity rule: predominantly negative values in the northern hemisphere and mainly positive values in the southern hemisphere (for review, see Pevtsov et al., 2014). However, recent studies indicate that the evolution of the magnetic helicity density of a large-scale axisymmetric magnetic field is different from what is predicted by dynamo theory (Figure 1). On one hand, the mean large- and small-scale components of magnetic helicity density display the hemispheric helicity rule of opposite signs at the beginning of cycle 24. However, later in the cycle, the two helicities exhibit the same sign, in contrast with theoretical expectations (Pipin et al., 2019).

Due to the large magnetic Reynolds number, the magnetic helicity originating from the solar interior can be carried away through the photosphere into the corona. In addition, the kinetic helicity of subphotospheric flows is also a critical ingredient of the solar dynamo as it plays a role in future flare activity of active regions after they crossed the visible solar surface. A deep-seated dynamo, which generates strong magnetic fields below the photosphere, is likely to be helical, while a near surface dynamo may not contain a net-helicity on a large scale. Comparing the kinetic helicity of subphotospheric flows with the magnetic field helicity provides invaluable information about flow of helicity through the solar atmosphere, and its eventual removal from the Sun - a key process for understanding the internal workings of solar dynamo. Currently there are two methods to estimate helicity in active regions. One is to integrate over time the helicity flux that ejects into the corona (e.g. Liu and Schuck, 2012); the other is to calculate the helicity using modeled magnetic field in the active regions (e.g. Valori et al., 2016). The limitation for the former is that for many active regions, observation may not be available to catch the entire process of emergence and development so that the accumulated helicity calculated in this way may only contain a fraction of the total helicity in the regions; the latter depends on the modeled field in the volume of the active regions that might not precisely represent the real field. More recently, Fisher et al. (2020) and Hoeksema et al. (2020) have shown that full-disk vector magnetic field observations can be used to derive the changing electric field in the solar photosphere over active-region scales. Once the electric fields have been computed, it can be

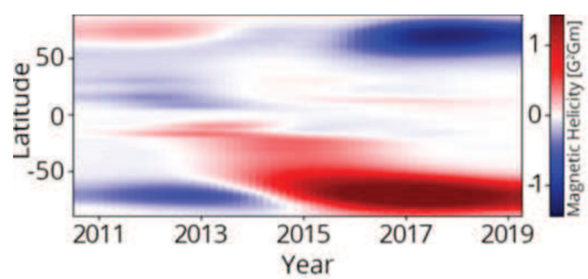

Figure 1: Puzzling sign-reversal of large-scale magnetic helicity in cycle 24 derived using vector magnetic field observations from SDO/HMI. During same period, small-scale helicity (not shown) exhibits “regular” hemispheric asymmetry without sign reversal as in the large-scale helicity. Adopted from Pipin et al. (2019).

use them to estimate the Poynting flux of energy in the radial direction and the helicity injection rate contribution function. However, because we do not have a sufficient amount of information, particularly on the vertical gradients of the magnetic field around the photosphere, assumptions have to be made (Hayashi et al., 2018).
However, the relationship between the accumulated magnetic helicity flux through the photosphere and the magnetic helicity in the corona is still unclear. Computation of magnetic helicity on the Sun requires knowledge of the vector magnetic field in a 3-D region. Measurements of the vector magnetic field at different heights in the solar atmosphere are critical for a proper derivation of magnetic helicity on the Sun. Current observations are usually taken in a shallow layer of the solar atmosphere, typically in the photosphere, and a force-free parameter α is commonly used as a proxy of magnetic helicity. To address this important limitation, ngGONG will provide measurements of the magnetic vector field both in the photosphere and chromosphere.
The reconciliation of the observed evolution of large-scale magnetic helicity and one predicted by current solar dynamo models would require continuous observations of vector magnetic field over the period of solar sunspot or even full magnetic cycle (20+ years).

4 Modeling: Space Weather Research and Operations

It is clear that Space Weather research and operations will increasingly depend on the accuracy and availability of the synoptic maps derived from magnetic field measurements that are the main drivers of coronal and heliospheric models.
There many factors that can affect the quality and diagnostic value of these maps. These include high-noise level in the measured magnetic field, calibration of the magnetic field, low-Zeeman polarimetric sensitivity, and difficulty in in representing the true orientation of the solar magnetic fields with weaker polarization signals. For the specific case of full-Stokes measurements, the adopted inversion technique and disambiguation method (Pevtsov et al., 2021; Valori et al., 2022; Leka et al., 2022) will also affect the derived vector magnetic field.
However, one of the most critical limitations is represented by how poorly the polar regions of the Sun are observed. Polar field measurements are extremely important for several reasons: 1) they dominate the coronal structure over much of the solar cycle (except when the polar fields reverse), 2) polar magnetic flux plays a role in determining the properties/evolution of the heliospheric magnetic field, 3) the polar magnetic fields are thought to be the direct manifestation of the Sun's interior global poloidal fields which serve as seed fields for the global dynamo that produces the toroidal fields responsible for active regions and sunspots, and 4) the polar regions, and their midlatitude extensions, are the source of some of the fastest solar wind streams (Petrie, 2015).
Unfortunately, measuring the polar field is difficult due to foreshortening effects at the solar limb as well as the intrinsic weakness of the field near the poles, and interpretation of these measurements is complicated by a number of factors including the complexity of the polar magnetic landscape. Hinode observations of the polar regions have revealed patches of magnetic field with different spatial extent and distribution. While some are isolated, others form patterns like chains of islands. Many of these patches are coherently unipolar and have field strengths reaching above 1 kG (Tsuneta et al., 2008). Their size tends to increase with latitude, up to about 5×5 arcseconds. All of the large patches have fields that are predominantly verti-

cal relative to the local surface, while those of the smaller patches tend to be horizontal. If a typical radial correction is applied to line-of-sight magnetograms, then the horizontal fields are incorrectly amplified with a strongly varying radial function.

Depending on the distribution of the horizontal fields this may lead to a sign bias and inaccurate flux on any given day. Furthermore, for a given latitude, these effects will change with the B0 angle. Because of projection effects, polar measurements obtained at favorable B0 angle (around March/September for the southern/northern solar hemisphere) will be less noisy than other periods of the year. The sensitivity of the magnetic field measurement is also a significant factor, and seeing plays a role in ground-based observations. The impact of all of these factors is expected to be greater during solar minimum, when the strength of the poloidal field is stronger.

There are different ways to improve the quality of synoptic magnetic maps used in coronal and heliospheric models. From an observational point of view, better polarimetric sensitivity (better signal-to-noise ratio) in measuring the transverse component of the solar vector magnetic field (Stokes Q and U) will improve the calculation of the three components of the vector field. This is particularly important for identifying the morphology of the magnetic field in regions away from the solar disk center, where the transverse field is the dominant component of quiet/weak field regions. This includes the very important highest latitude regions located above approximately ±60 degrees latitudes. One of the major objectives of ngGONG is to produce such measurements.

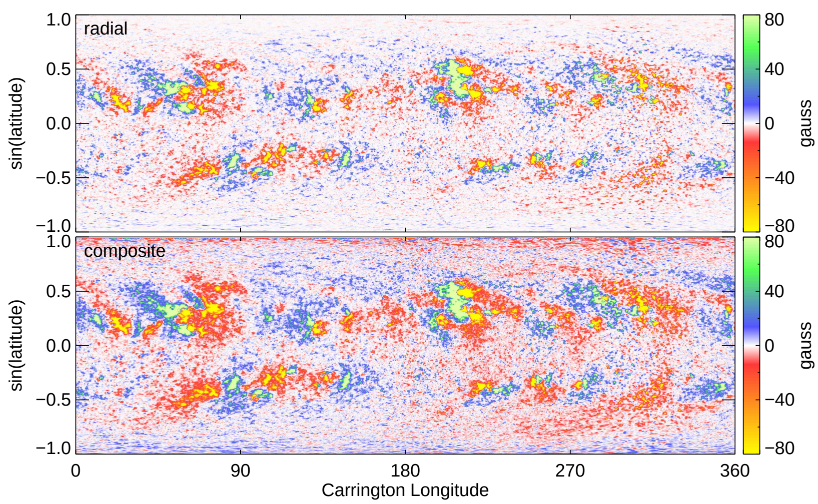

Figure 2: Comparison between radial (top) and composite synoptic charts (bottom) derived from SOLIS/VSM FeI $\lambda 630.2$ nm vector and longitudinal magnetic field observations for Carrington rotation 2119 (Jan-Feb 2012). Note the enhanced weak magnetic field in the composite chart.

Solar Orbiter, an international cooperative mission between ESA (the European Space Agency) and NASA, will observe the Sun's atmosphere up close, with high spatial resolution telescopes. Thanks to its unique orbit, Solar Orbiter will also view the poles from solar latitudes higher than 30 degrees (compared with $\sim$7 degrees from the Earth) and will provide an unprecedented picture of the magnetic environment in the Sun's polar regions. These data will provide a unique opportunity to address one of the major limitations in building current synoptic maps of the solar magnetic field. Since these maps need to be fully filled with data, whenever one of the polar regions are not observable from Earth some sort of extrapolation of the field at lower latitudes is adopted in order to account for the missing data. Different techniques have been proposed, but there is no consensus on which one is more reliable. Using these new data to first determine an optimum extrapolation from statistics of real polar measurements, and then later routinely apply it to ngGONG maps, will reduce this ambiguity.

Merging observations taken from different instruments, however, is not a trivial task. It requires a carefully analysis of the properties of the individual data sets and a proper cross-calibration scheme. A similar approach has been developed at NSO to merge together photospheric vector and longitudinal measurements taken by the SOLIS/VSM instrument. The main purpose was to exploit the better sensitivity to the weak magnetic field provided by the longitudinal measurement with the more reliable determination of the vector field derived from the full-Stokes measurements. As illustrated in the bottom panel of Figure 2, the result is a hybrid synoptic maps of the radial component of the magnetic field showing an enhanced morphology of the field outside active regions. Further research is needed, however, to account for varying formation heights, the potential for multi-vantage-point and multi-line data, and determining the most appropriate representation for full 4π boundary condition inputs for global models.

Growing sophistication in our knowledge, available (and possible) observations, and computational tools have together fundamentally changed the way heliophysics is done, and how it fits into the broader scope of NASA's and other agency programs. In particular, both researchers and others interested and/or invested in areas involving our space environment have become increasingly aware of, and in many cases, users of, models. While empirical models have historically been a mainstay of applications such as space weather event forecasting, there are new generations of these inspired by improved understanding of underlying physics and processes. For example, modern flare and CME forecast models now often rely on combinations of magnetograms and sometimes images to assess the likelihood of a major x-ray outburst and/or a material eruption (e.g. Falconer et al., 2011; Goodman et al., 2020; Leka, Barnes, and Wagner, 2018; Leka et al., 2019). These approaches now can routinely make use of HMI images of active region vector fields combined with chromospheric magnetic field observations and related modeling to reconstruct the field geometry (e.g. Korsós et al., 2020). At the same time there is a long-standing modeling community goal toward driving global models of the corona that include these active regions in their large scale context (e.g. the review by Wiegelmann, Petrie, and Riley, 2017). Such a model would break through a critical barrier to understanding how the solar activity cycle changes the character of the heliosphere 22 years, how it is connected to the interior dynamo processes, and how coronal eruptive processes fit into the overall dynamics of the entire coupled interior-to-heliopause system. The modeling work is moreover increasingly shared through outlets such as the CCMC at GSFC, where a PFSS coronal field model is readily available, together with several coronal and heliospheric MHD models, all currently based on synoptic photospheric magnetograms-but capable in some of the latter cases of ingesting more detailed active region field data even today (e.g. Gombosi, Tamas I. et al., 2021). It is important to recognize that all of these increasingly essential modeling efforts rely on the availability and completeness of solar magnetic field observations, without which heliophysics would not be progressing.

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