# IMPROVING SOLAR POLAR FIELD OBSERVATIONS FROM THE GROUND

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## Synopsis

The Sun's polar fields have global influence over coronal and heliospheric structure, and are believed to seed activity cycles. However, they are difficult to measure from (near) Earth. Interplanetary field measurements and heliospheric models tell us that we fail to detect much of the polar fields: magnetogram-based interplanetary field estimates underestimate in situ observations by a factor of two or more. Polar field measurements likely fall short because (1) the polar fields are composed of small flux concentrations with a small filling factor and are weak overall, and (2) the viewing angle is large. Apart from the Daniel K. Inouye Solar Telescope (DKIST) we do not have the instrumentation that can resolve and detect the smallest and weakest concentrations. From near Earth we are forced to observe polar fields mostly in the transverse component, whose Zeeman effect sensitivity is much lower than for the longitudinal component. Full-Stokes spectro-polarimetry for the Sun's polar field is a photon-starved problem that we can and must address with large-aperture telescopes on the ground. Such telescopes observing a judicious choice of magnetically sensitive visible and infrared spectral lines would provide observations of superior spatial and spectral resolution, spectro-polarimetric sensitivity, and multi-wavelength coverage. Thus we could measure the full magnetic vector reliably, resolving the key length scales that have hitherto gone unresolved, at multiple heights in the atmosphere.

## Introduction: Why The Sun's Polar Fields are Important but Difficult to Measure

The Sun's polar magnetic fields dominate the global structure of the corona and heliosphere (Petrie 2015), and the Earth spends most of the solar cycle magnetically connected to the polar coronal holes (Luhmann et al. 2009). However, the polar fields are difficult to observe from (near) Earth (Petrie 2015). Although their magnetic configuration is relatively simple with predominantly near-vertical field lines, this configuration corresponds to predominantly transverse field orientations as seen from Earth, where the polar cap fields are observed with a large (>60-70°) viewing angle. Moreover, the ~kG polar fields that dominate the poles are confined to small facular-scale structures (~5″ across as observed from Earth), and these structures are sparsely distributed such that the overall mean polar field is only of order 5–10 G (Tsuneta et al. 2008). The Zeeman effect makes these transverse signals much harder to observe than the longitudinal ones; typically, sensitivity to transverse fields is one order of magnitude lower (Del Toro Iniesta and Martínez Pillet 2012). This reduced sensitivity renders the polar fields relatively poorly constrained in our current modeling efforts.

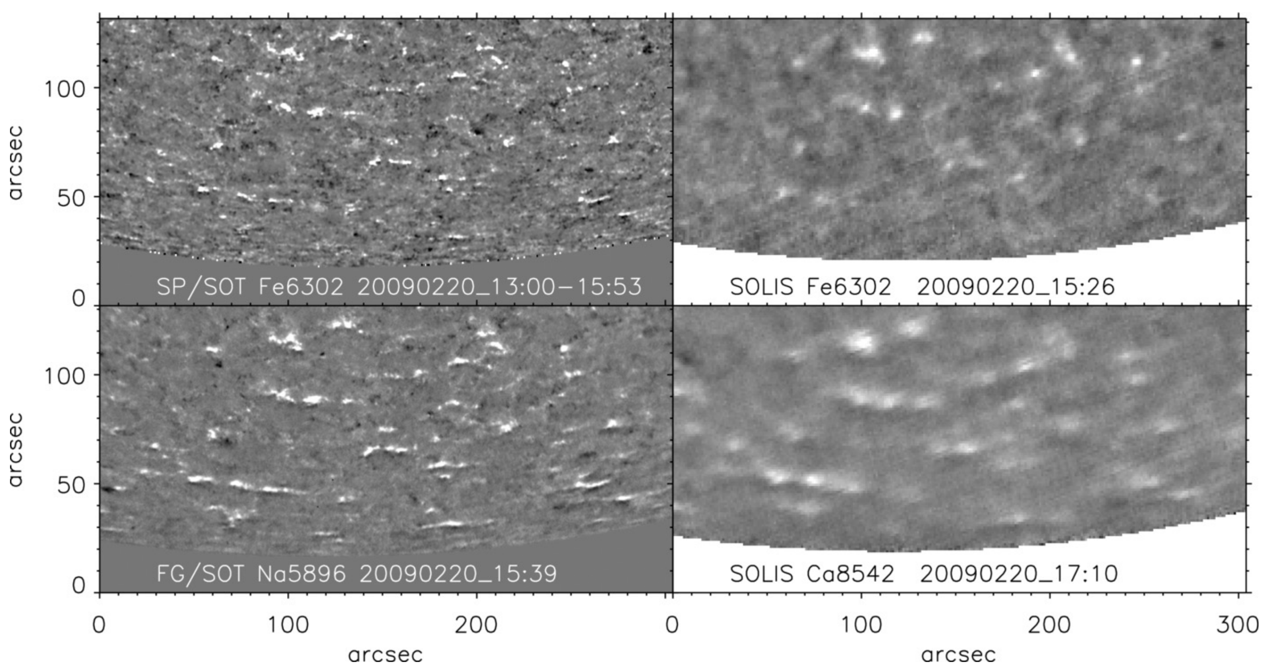


**Figure 1:** Nearly simultaneous south pole line-of-sight field observations with the pole tipped toward Earth by 7°.04. Left: Hinode observations. Right: SOLIS/VSM observations. The top row shows photospheric (630.2 nm) observations, and the bottom row shows low- and mid-chromospheric observations. White represents the positive fields (directed toward the observer) and black negative. The VSM and SOT/SP observations saturate at ±30G, and the SOT/FG observation saturates at ±0.006 IC in circular polarization. From Jin et al. (2013).

## Status of Present-Day Polar Field Observations

The full-disk magnetographs most heavily relied upon by the modeling community are not sensitive enough to meet models' needs, especially at the poles. The NSO's Global Oscillations Network Group (GONG) instrument was initially designed to measure Doppler velocities. Magnetograms were added later using a quarter-wave plate, but the instrument design is not optimal for this application. The instrument has issues with the magnetic zero-point that needs constant monitoring in the reduction pipelines. Moreover, GONG provides only line-of-sight (LOS) fields, unlike the Synoptic Optical Long-term Investigations of the Sun Vector Spectro-Magnetograph (SOLIS/VSM, Keller et al. 2003) and NASA's Solar Dynamics Observatory Helioseismic and Magnetic Imager (SDO/HMI, Scherrer et al. 2012). Increased magnetic sensitivity, resolution, and well-calibrated vector capabilities are mandatory for improved solar wind modeling. This is particularly relevant for the solar polar regions, where all current synoptic data fail to provide satisfactory sensitivity (Hickmann et al. 2015), and for addressing the "open flux problem" (Linker et al. 2017), the persistent underestimation of the radial interplanetary magnetic field by heliospheric models using surface magnetograms. This problem has been linked to issues with polar field data (Riley et al. 2019), although Wallace et al. (2019) found larger discrepancies under solar activity maximum than minimum conditions, indicating that the problems with photospheric magnetic field measurement are not confined to the poles.

## Advantages and Limitations of Existing High-Resolution Polar Field Observations

High-resolution polar vector field measurements are available from the Hinode Solar Optical Telescope Spectro-Polarimeter (SOT/SP) using visible spectral lines (Tsuneta et al. 2008) every March and September, and less frequently from ground-based facilities, e.g., the Tenerife Infrared Polarimeter (TIP II, Collados et al. 2011) at the 70cm Vacuum Tower Telescope (VTT) using the Fe I infrared (IR) lines near 1.56 micron. These IR lines have sensitivities to LOS fields twice that of visible lines used by the VSM, HMI and SOT/SP, and four times higher for transverse fields (Pastor Yabar et al. 2018), besides smaller image disturbances from the Earth's atmosphere. Indeed, Petrie (2017) found some evidence of reduced signal in SOT/SP vector data at the highest latitudes.

Figure 1, from Jin et al. (2013), shows simultaneous line-of-sight field observations of the south pole from the Hinode SOT SP and Filtergraph (FG) instruments and from the SOLIS/VSM. The SOT and VSM data clearly show common solar magnetic features, but the effects of the lower spatial resolution of the VSM are obvious. The SOT data show the common features with much greater sharpness and maximum strength than the VSM data can. Moreover, the SOT data show additional features that don't appear in the VSM data: smaller and weaker structures of either magnetic polarity that did not survive the lower spatial smearing of the VSM data due partly to aperture diffraction (see below) but mostly to atmospheric seeing. Some of the differences between the images are due to the different times of observation and the short lifetimes

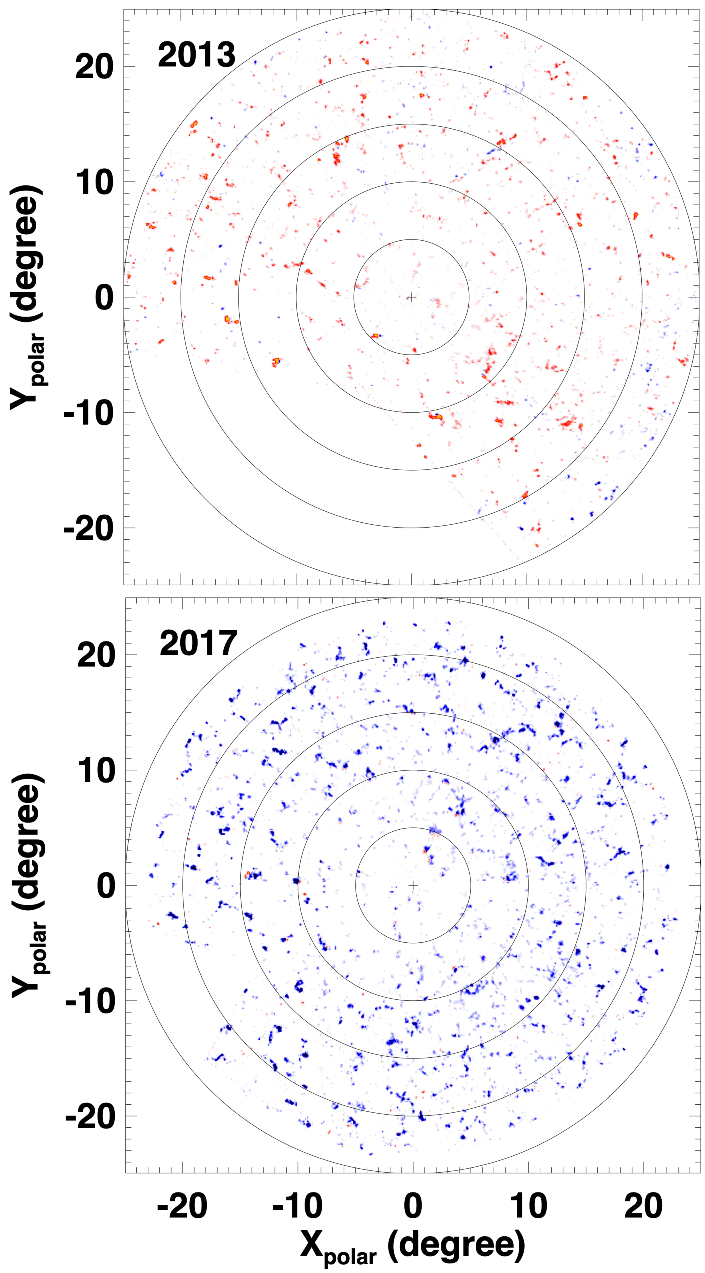


**Figure 2:** Synoptic maps of the south polar radial flux density constructed from Hinode SOT/SP scans for the polar vector magnetic field (data from HAO Community Spectro-polarimetric Analysis Center [https://csac.hao.ucar.edu/sp_data.php](https://csac.hao.ucar.edu/sp_data.php)). Positive/negative flux density is represented by red/blue. The March 2013 map (top) shows an early stage of the polarity reversal from positive to negative. The bottom panel shows the map for March 2018 after the polarity reversal was complete.

of the features, but the typical lifetime of the intense concentrations is about a day, much longer than the differences between the observation times. The differences between the images are therefore likely to be of mostly instrumental origin. The SOT and VSM are fed by primary mirrors of equal size, 0.5m, but the SOT can spend much more time scanning the poles than the VSM can, enhancing the SNR, with a much smaller detector plate scale (0.16 vs. 1 arcsec), and without atmospheric seeing.

From our vantage point on the ecliptic plane, one can only build a picture of the full polar cap by combining numerous images collected over a month or so, when one of the poles is tilted towards us. Figure 2 shows synoptic maps of the south polar radial flux density constructed from Hinode SOT/SP scans for the polar vector magnetic field observed in the Fe I line at 630.2 nm, one for March 2013 at an early stage of the polarity reversal from positive to negative, and the other map for March 2018 after the polarity reversal was complete. In these maps the radial flux is concentrated into small features, generally at the vertices of supergranular boundaries, separated by vast areas with much lower flux density. The average flux density over the entire polar cap amounts to only a few gauss, significantly lower than is needed to explain interplanetary field strength measurements. These synoptic maps are based mostly on transverse field measurements because of the approximately radial direction of the fields and the large viewing angle. It seems likely, therefore, that much flux is undetected by the Hinode SOT/SP due to the lower sensitivity of the Zeeman effect to transverse fields compared to longitudinal fields.

The problems illustrated above are due to the difficulty of resolving the small magnetic structures comprising the polar field, and of detecting the Zeeman effect for the weaker features outside the intense flux concentrations. Both of these problems can be solved using the Daniel K. Inouye Solar Telescope (DKIST, Rimmele et al. 2020). The 4m mirror will enable its spectro-polarimeters to resolve facular structures well, at visible and IR wavelengths, all the way to the pole, in the photosphere and chromosphere, albeit with limited spatio-temporal coverage. A large aperture is needed to resolve the fundamental length scales in the solar atmosphere: the photon mean-free path and the pressure scale height. To achieve this, a resolution of 70 km or 0.1 arcsec is required in the photosphere.

## Necessity of a Large Aperture: High Spatial and Spectral Resolution

Due to Fraunhofer diffraction at the circular aperture of a telescope, the observed image of a point source appears as a finite disk, called the Airy disk, surrounded by faint rings. To be resolvable by the telescope, features need to be separated by an angular distance greater than the angular radius $\theta$ of the Airy disk, which has a value of $\theta=1.22\lambda/D$, where $\lambda$ is the wavelength and $D$ is the aperture size. Therefore, one can enhance the spatial resolution diffraction limit by increasing the aperture size, but increasing the wavelength decreases this diffraction limit.

Thus, the spatial resolution of a telescope is limited by its aperture size. Similarly, the high spectral resolution requires high throughput of photons, which in turn requires a large aperture also. Because the quality of spectro-polarimetric magnetic field measurements is so dependent on resolving the details of spectral line profiles with a good SNR, 'photon starvation' is endemic to these measurements, and can ultimately only be solved with a large aperture.

The 3D structure of small-scale magnetic features such as those at the poles is complex, and the density scale height at the photosphere is less than 100 km. We therefore expect much variation of physical structure within the photosphere. We can study these variations along the line of sight with high spectral resolution, by resolving and measuring spectral properties such as line width, bisector shape, Doppler shift, and polarization as functions of depth in a spectral line.

## The Magnetic Resolution of a Spectral Line

The Zeeman splitting of a magnetically sensitive spectral line in the presence of a magnetic field increases quadratically with wavelength $\lambda$. The Doppler broadening of a spectral line due to turbulent velocities increases linearly with $\lambda$. Because magnetic field measurements rely on measuring the shift of line components, such measurements are most reliable if this shift is large compared to the width of the line.

The ratio of the Zeeman splitting and the line width gives a measure of the magnetic resolution of a spectral line, and this ratio is $g_{\rm eff}\,\lambda$, where $g_{\rm eff}$ is the effective Landé $g$-factor for the electron transition forming the spectral line (Penn 2014).

Observations with optimal magnetic sensitivity therefore require large $g_{\rm eff}\,\lambda$ values. Values of $g_{\rm eff}$ generally range between 1.0 and 3.0, and choices of lines are often made based on $g_{\rm eff}$ alone. Spectral lines with both large $g_{\rm eff}$ and long wavelength are clearly the best for making the most sensitive magnetic measurements.

One can define distinct regimes of Zeeman splitting: weak- and strong-field regimes where the splitting is smaller/larger than the line width, and an intermediate regime where the splitting is comparable to the line width. Most visible lines belong in the weak-field regime, whereas the 1.5 micron Fe I line is often fully split.

Figure 3 shows the wavelength separation between the red and blue Stokes V peaks (left panel) and the Stokes V amplitude (right panel) as functions of Zeeman splitting. These quantities are plotted for various Voigt profiles with a 1 kG magnetic field, and for well-known magnetically sensitive visible and IR lines. The IR line is fully split at this magnetic field strength, whereas the visible line is not. The plots therefore demonstrate the advantage of infrared Zeeman observations for making sensitive magnetic field measurements.

Referring to the discussion of spatial resolution above, a major motivation towards large telescope apertures is that near-infrared (NIR) observations of useful spatial resolution require larger apertures than visible ones. For example, 0.1 arcsec angular

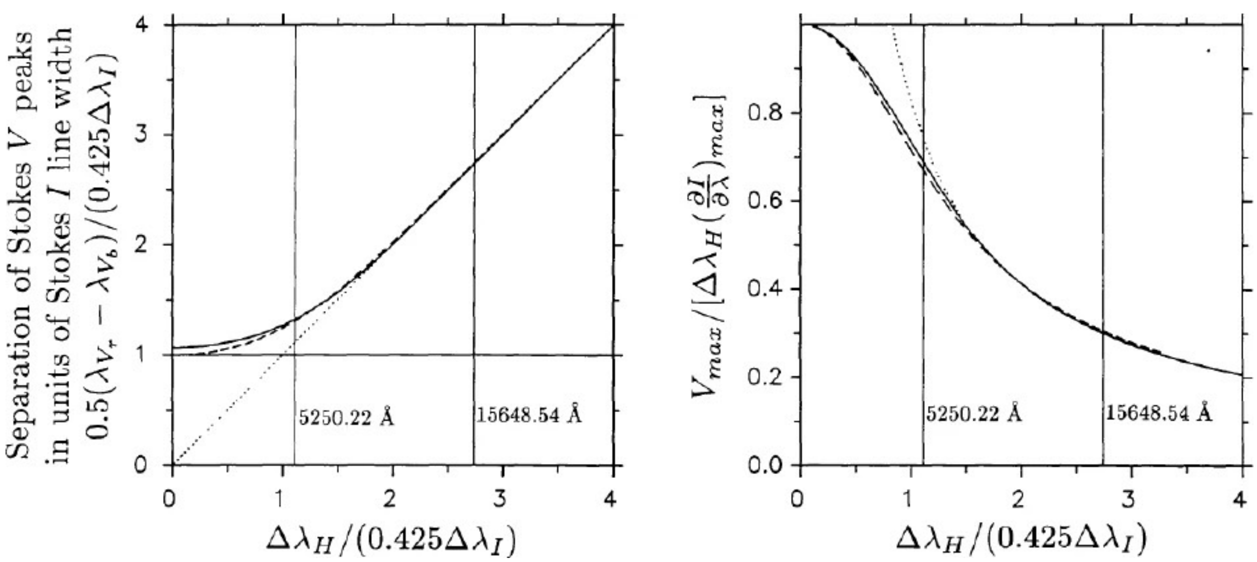


**Figure 3.** The left panel shows the wavelength separation between the red and blue Stokes V peaks as a function of Zeeman splitting. The right panel shows the Stokes V amplitude as a function of Zeeman splitting. Voigt profiles were used for Stokes I, and the solid/dashed lines represent cases with zero and non-zero damping constants. The dotted lines show asymptotic strong-field limits extrapolated to small Zeeman splitting values. The vertical lines locate the disk-center profiles of the visible 5250 A and NIR 1.5 micron Fe I lines for a 1 kG magnetic field (Stenflo, 1994).

resolution at 1.5 micron requires a telescope aperture of 3m, an observation well within the capabilities of the 4m DKIST. Obviously observing with a large aperture is a more practical matter on the ground than in space.

## Better Ground-Based Polar Field Observations

Precise measurement of the magnetic Stokes vectors is needed to deduce the solar vector magnetic field accurately. To obtain the necessary signal-to-noise ratio at a given spatial resolution, the required aperture is larger than required by diffraction alone. Because solar magnetic features on the 0.1 arcsec scale evolve within 30s, we need an aperture of at least 3m to achieve a good SNR within 30s at 0.1 arcsec resolution, and even larger to measure the smaller magnetic features which have been predicted by theory. An accurate measurement in a visible spectral line of the vector magnetic field at 0.1 arcsec resolution and 5-second integration time requires a 4m aperture.

DKIST/ViSP will measure well-known spectral lines at visible wavelengths observed by, e.g., SOLIS/VSM, GONG, SDO/HMI, Hinode/SOT/SP). DKIST DL-NIRSP will also measure near-infrared wavelengths. The near-infrared spectrum around 1.5 micron has many advantages, particularly for magnetic field studies, including greater magnetic sensitivity and smaller image disturbances from the Earth's atmosphere. An aperture of 4m is needed to clearly resolve features at 0.1 arcsec in the near infrared.

While DKIST will resolve the fine features of the polar features as never before, global and heliospheric models require continuous, full-disk coverage with high spectro-polarimetric sensitivity. To achieve this from the ground, we would need a new network of synoptic full-disk magnetographs to replace GONG (e.g., next-generation GONG, or ngGONG). To improve polar field observation with such a ground-based network, we estimate that a telescope with a 0.5m aperture is required to collect enough photons to achieve the necessary ($10^{-4}$) polarization sensitivity, and to measure the line-of-sight field with a sensitivity of 1 G per 0.5″ pixel, with ground-layer adaptive optics to achieve 1″ spatial resolution with stable image quality. A full-disk spectro-magnetograph similar to the SOLIS/VSM observing the Fe I line at 1564.8 nm and a chromospheric line like the He I line at 1083.0 nm, could give multi-height coverage with the required sensitivity.

A network of such telescopes would produce data essential to the security and reliability of the nation's technology vulnerable to space weather, complement other ground-based solar physics facilities such as DKIST, and improve real-time modeling of the heliosphere, which is also crucial for encounter, multi-messenger missions such as Parker Solar Probe and Solar Orbiter. Magnetogram data products combining the advantages of both DKIST and ngGONG, such as cross-calibrated magnetograms and hybrid synoptic maps, would support further improvements in the photospheric flux transport (Arge et al. 2010) and global heliospheric modeling. For operational space weather purposes we need to maintain continuous round-the-clock ground-based capabilities to ensure long-term real-time observation of the Sun's polar fields.

# Recommendations

The limitations of present-day polar magnetic field measurements are holding back numerous key solar physics projects and are preventing fundamental questions from being adequately addressed. The widespread demand for more sensitive and reliable polar field measurements can only be answered from the ground, where large-aperture telescopes can be built and maintained. A combination of observing campaigns at the highest resolution during March/September from DKIST, and continuous round-the-clock observations from a network of spectro-magnetographs similar to the SOLIS/VSM, observing an optimal set of visible and NIR spectral lines, would ensure the most sensitive possible measurements of the Sun's polar field, long-term and near-real-time.

- How the WP links to the statement of task:
  - The structure of the Sun and the properties of its outer layers in their static and active states
  - The characteristics and physics of the interplanetary medium from the surface of the Sun to interstellar space beyond the boundary of the heliosphere
  - The space weather pipeline from basic research to applications to operations, including the research-to-operations-to-research loop that strengthens forecasting and other predictive capabilities.

- Describe the highest-priority science goals to be addressed in the period of the survey.
  - Obtain regular and usable polar magnetic field data from the photosphere and chromosphere.

- Develop a comprehensive ranked research strategy that provides an ambitious but realistic approach to address these goals that include ground- and space-based research investigations as well as data and computing infrastructure to support the research strategy
  - Continue the synoptic polar observations with Hinode, start one with DKIST
  - Ingest synoptic polar data into models
  - Ensure requirements flow into ngGONG

Category: Basic Research
Primary topic: Solar Physics
Secondary Topic: Space Weather Research to Operations to Research Loop

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