Improving Global Solar Magnetic Field Maps: Why Multiple Low- and High-latitude Vantage Points are Necessary

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Synopsis

The solar photosphere supplies the driving boundary data for the solar atmosphere, driving models for the corona and heliosphere, solar wind and radiation (Wiegelmann & Sakurai 2021, Rouillard et al. 2021, Petrie et al. 2021). Key solar physics projects therefore depend acutely on the overall accuracy of solar global magnetic field data, in particular on complete, up-to-date full-surface maps for the photospheric magnetic field. We refer to such maps as synoptic magnetograms or maps. Present-day synoptic maps suffer from a lack of spatio-temporal coverage by magnetographs: until the launch of Solar Orbiter, all solar magnetographs were confined to the Sun-Earth line, a situation only slightly changed by Solar Orbiter because of its lack of sustained observations from any given viewpoint, and the confinement of its orbit to within ±35° heliographic latitude. As far as steady magnetogram sources are concerned, only the Earth-facing hemisphere of the photosphere is observable at any given time, imposing unavoidable limitations upon our synoptic data. Because of the tilt of the solar rotation axis with respect to the ecliptic plane, each pole is unobservable for ≥6-month intervals every year from (near) Earth (Petrie 2015). The more swiftly-evolving active-latitude fields are also unobservable ≥50% of the time, for about two weeks at a time. Moreover, much of what we can observe at any given time is only visible with a large viewing angle, which imposes further limitations on the information available to us. These constraints impose severe limitations on our ability to construct accurate, up-to-date and useful synoptic magnetograms, which is holding back progress on key solar physics projects, including basic science and operations. Since we cannot model unobserved photospheric evolution with the required accuracy, we can only solve these basic, fundamental problems with full-surface observational coverage of the Sun's global magnetic field (see the White Paper on the Firefly mission concept led by Nour Raouafi).

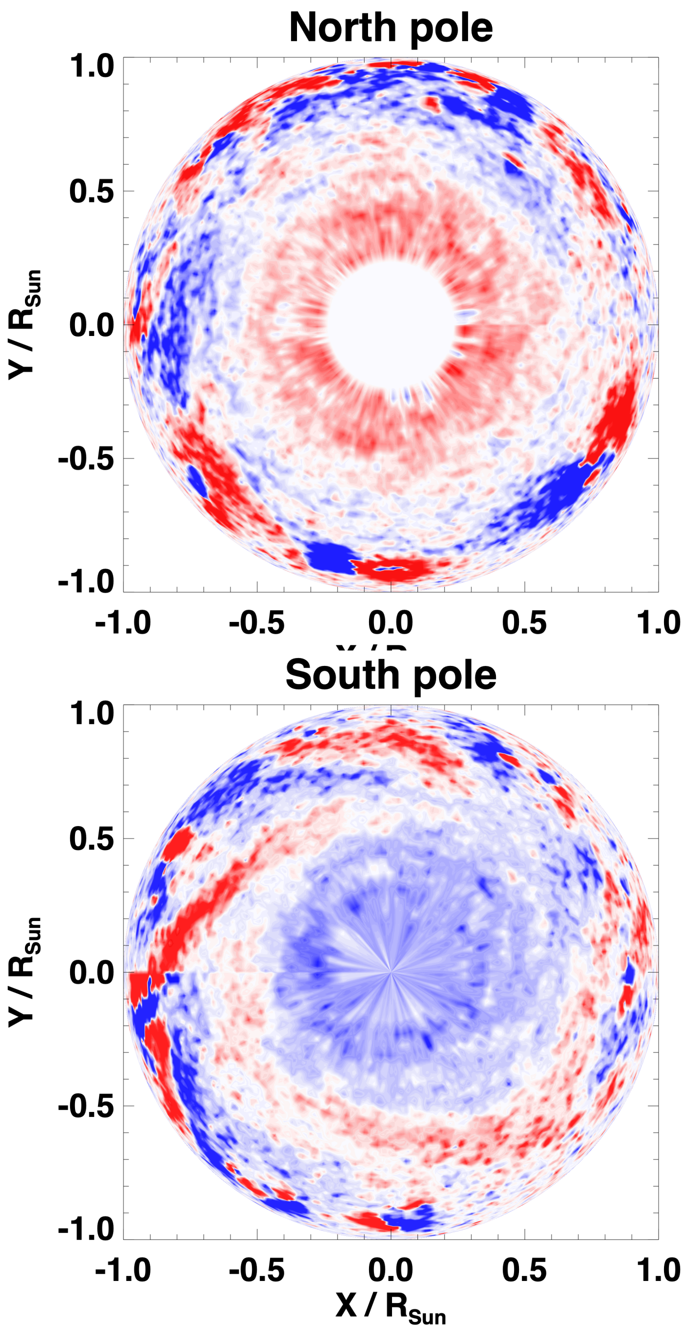

Figure 1: The GONG synoptic map for Carrington rotation 2255 (March 2022) as viewed from above the north (top panel) and south (bottom panel) poles. Positive/negative radial magnetic flux density is represented by red/blue, saturated at +/- 10 G. The data gap at the north pole is due to this pole being tilted away from Earth during this time.

Limitations of Present-Day Synoptic Maps

Observations of the solar photosphere are widely relied upon to supply the driving boundary data for the solar atmosphere, driving models for the corona and heliosphere, solar wind and radiation (Wiegelmann & Sakurai 2021, Rouillard et al. 2021, Petrie et al. 2021). In particular, many key projects depend for their success on complete, up-to-date full-surface maps for the photospheric magnetic field. However, there exist major problems with present-day synoptic magnetograms, due to our limited view of the Sun from our (near-) Earth vantage point

It takes a full solar Carrington (synodic) rotation period of about 27 days to observe all heliographic longitudes from the Sun-Earth line. Up-to-date polar data are yet more difficult to come by: the tilt angle of the solar rotation axis with respect to the ecliptic plane is about 7.25° giving us a view of the north/south pole around September/March each year, albeit with a large viewing angle.

Figure 1 shows an illustrative example of the problems that our limited view of the Sun causes: the GONG synoptic map for Carrington rotation 2255 (March 2022) as viewed from above the north (top panel) and south (bottom panel) poles. Every March/September the south/north pole is tilted towards/away from Earth. In our example, this creates an observational data gap at the north pole, the white gap at the center of the top panel of Figure 1. This gap is usually filled by some form of interpolation whose performance is imperfect (e.g., Sun et al. 2011). In Figure 1, however, we show the original map without pole-filling. At the south pole, visible from Earth at this time, there is no such data gap. However, the map has reduced spatial resolution at this pole compared to the lower latitudes - see the apparent pinwheel pattern at the center of the lower plot. From (near) Earth the pole is observed at a large viewing angle, due to the 7.25 degree tilt angle between the solar rotation axis and the ecliptic plane. Polar observations taken from (near) Earth therefore suffer from major foreshortening of polar field features and reduced effective spatial resolution - see, e.g., Tsuneta et al. (2008). With this in mind, standard synoptic maps are often distributed in longitude-sine(latitude) coordinates, with large latitude bins at the poles to accommodate the low signal/noise ratio there.

Standard ('diachronic') synoptic maps suffer from further artifacts due to our limited view from Earth. They are formed by combining observations collected over a full 27-day Carrington rotation. Therefore the data at the beginning and end of a map are nearly a month apart in age. When plotted on the sphere, as in Figure 1, the beginning and end of the map must meet at a discontinuity. One can see this discontinuity most clearly in the lower panel for the south pole, between $(X,Y)/R_{\mathrm{Sun}}$ = (-1,0) and (0,0) the jump between old (Y<0) and new (Y>0) data is obvious. The corresponding discontinuity in the top panel, between (0,0) and (1,0), is also visible but is less obvious because it fortuitously falls across a quiet region of slowly-evolving widely-spread weak field.

Visibility and Information Density

To demonstrate the fundamental visibility problems imposed by such incomplete spatio-temporal coverage, Figure 2 shows maps of information density in heliographic coordinates for six observing scenarios. We define information density as the number of observed pixels per unit solar surface area. This quantity is proportional to the cosine of the viewing angle because larger viewing angles produce lower effective spatial resolution of the solar surface features. Of course unobserved regions have zero information density. Here the information density is normalized to the disk-center value for a single vantage point. For simplicity, where multiple viewpoints are involved, we combine their information assuming that these viewpoints are equivalent in terms of spatial resolution and distance from the Sun. Although reality would likely deviate from this idealized picture, we only want to illustrate the main problems with limited visibility in this paper.

Shown in the top-left of of Figure 2 is the map for a single magnetograph in the elliptic plane at 1 AU. In this case the rotation axis tilt angle is positive, tilting the north pole towards the observer (and the south pole away) by 6.5°. The disk-center value of 1 is therefore positioned 6.5° north of the equator. There is some information from the north pole, with information density a small fraction of the disk-center value, but not from the south pole. Vast areas of the solar surface are unobservable from a single viewpoint:

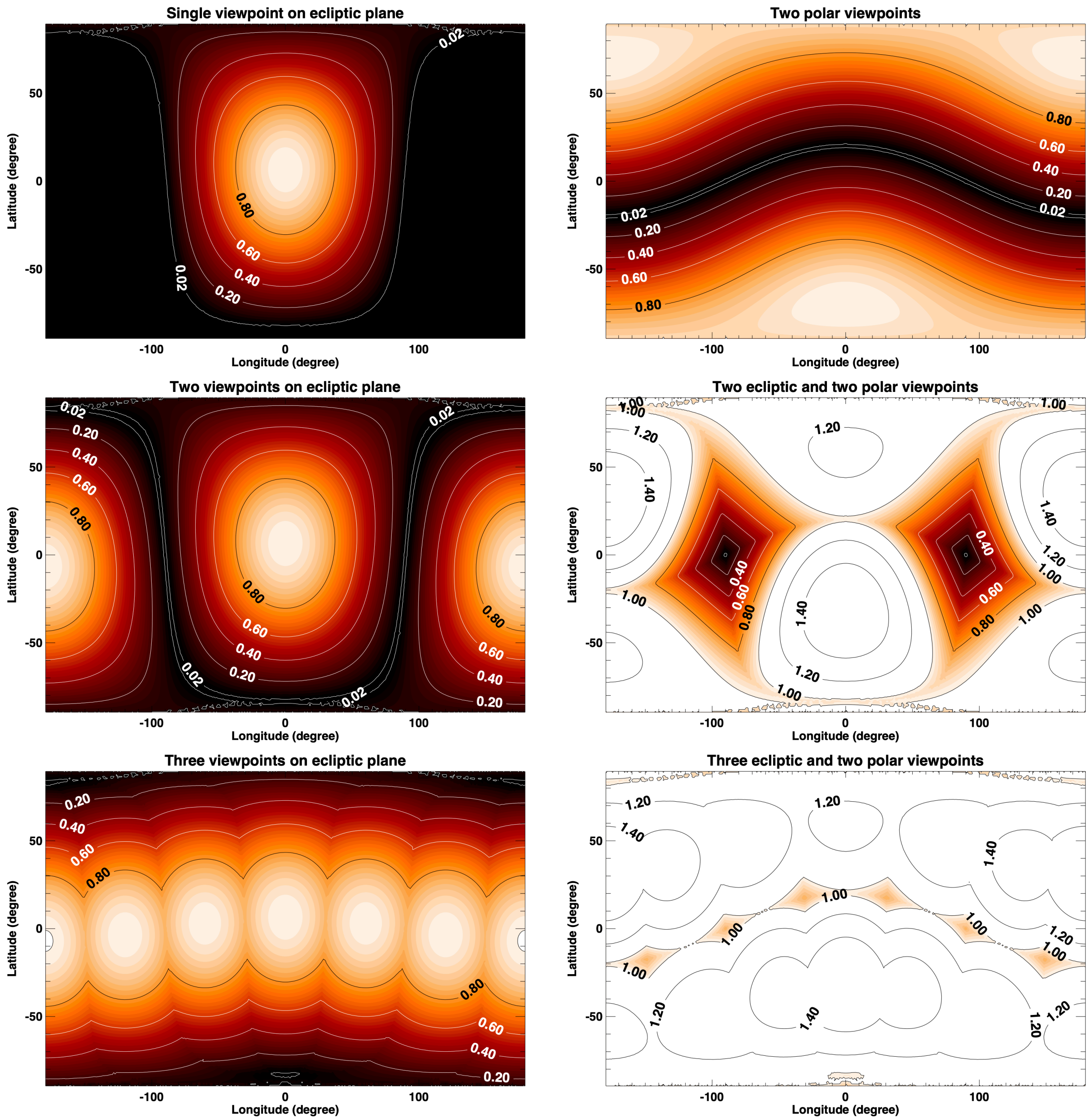

Figure 2: Maps of information density in heliographic coordinates for six observing scenarios, where white/black represents high/low density. The information density is the number of observed pixels per unit solar area, here normalized to the single-magnetograph disk-center value (the color scale is saturated at this value). The left column shows maps for a single magnetograph (top), and two (middle) and three (bottom) magnetographs in the elliptic plane. The right column shows the map for two polar viewpoints at ±70° (top), and maps for these two polar viewpoints combined with the two (middle) and three (bottom) ecliptic viewpoints. See the text for details.

about half is not observable at all, and only a minority of the solar surface is observable with high information density.

The top-right map of Figure 2 shows the case including only information from two polar vantage points, at (0°,-70°) and (180°,+70°). With these two polar vantage points the polar field coverage is excellent, and unsurprisingly much improved from the cases without polar vantage points: the information density is over 60% of the disk-center value all the way down to ±60° latitude.

The middle-left map of Figure 2 represents two viewpoints in the elliptic plane separated by 180° in longitude, at (0°,+6.5°) and (180°,-6.5°). One of these two ecliptic vantage points may be assumed to be (near) Earth and the other near the L_2 Lagrange point. Unsurprisingly these two low-latitude information sources cover the low latitudes about twice as fully as the case with only a single viewpoint in the ecliptic, but there remain regions of low information density around the two longitudes ±90°. As for the polar fields, there is some low-density information from the north pole around 0° longitude, and from the south pole around ±180°, so at least some information is available from each pole unlike in the single-viewpoint case above.

The middle-right map of Figure 2 shows the case with these two ecliptic vantage points combined with the same two polar vantage points as above. These four vantage points together provide much better coverage of the photospheric surface, but there remain two equatorial blind spots around the two longitudes ±90°.

The bottom-left map of Figure 2 represents three viewpoints in the elliptic plane separated by 120° in longitude, at (0°,+6.5°) and (±120°,-3.5°). (The sixfold fluted pattern is created by the six limb edges of the three overlapping information density profiles.) In this case one of the three ecliptic vantage points may be assumed to be (near) Earth. These three low-latitude information sources comprehensively cover the low latitudes, eliminating the poorly-observed regions of the cases with one or two low-latitude vantage points.

Finally Figure 2 bottom-right shows the case with these three ecliptic vantage points combined with the same two polar vantage points as above. These five vantage points together provide excellent coverage over all of the photospheric surface.

The Globally-Influential Poles: How Large Viewing Angles Hold Us Back

Adding vantage points would clearly transform our knowledge of the global solar field, but spatial coverage is only a part of the story. Large viewing angles pose further problems that are holding us back, particularly with observing the polar fields. Several major branches of solar physics feature the polar fields as key physical participants, and rely heavily on good polar field measurements. The polar fields have a dominant influence over the global structure of the corona and heliosphere, and they seed activity cycles in realistic solar dynamo models (Petrie 2015). Observing the polar fields well is therefore of primary importance, but they are difficult to measure from the ecliptic, or any vantage point with a large viewing angle. From the ecliptic the viewing angle is large (>80°): because of the 7.25° rotation axis tilt angle with respect to the ecliptic. Until the launch of Solar Orbiter all solar magnetographs were confined to the ecliptic plane. Solar Orbiter's orbit will reach about 35° latitude around 2030, for a relatively short time and one pole at a time, leaving a viewing angle of about 55°.

Large viewing angles pose particular problems for observing the polar fields. Although the polar fields feature facular structures whose field strength may exceed a kilogauss, such structures are small (about 5″ as observed from 1 AU), and sparsely distributed: the mean flux density of the polar fields is only of order 5-10 gauss at full strength (Tsuneta et al. 2008, Petrie 2015). Furthermore, although the polar field structure is generally quite simple with mostly unipolar and nearly-radially-directed fields, the large viewing angles for the polar fields force us to observe them mostly in the transverse component. It is well known that Zeeman sensitivity to transverse fields is an order of magnitude lower for transverse fields than for line-of-sight fields (Del Toro Iniesta & Martinez Pillet 2012). With a large viewing angle one therefore has to detect an overall-weak field mostly in the transverse component, which poses a difficult detection problem.

Another major problem with near-limb magnetogram observations, such as polar observations from (near) Earth, is that they have significantly lower signal/noise ratio than disk-center observations because of limb-darkening. Near disk-center the signal is dominated by hotter, denser, brighter layers of the photosphere/chromosphere than is the case near the limb, where opacity effects cause the signal to be dominated by higher, cooler, dimmer layers.

One can try to circumvent the problems of detecting weak transverse field signals by using line-of-sight measurements alone. One can estimate the polar flux using the so-called radial field assumption, where the predominantly near-vertical photospheric field allows one to estimate the strength of the polar field vector from the longitudinal measurement alone by dividing it by the cosine of the viewing angle. This is standard procedure in global synoptic magnetogram construction and coronal field modeling (Hill 2018). Although synoptic full-disk vector data have been available for years, the majority of coronal and heliospheric models, especially the key operational pipelines, rely on this radial field approximation for line-of-sight data. Bearing in mind the relatively low signal/noise ratio of near-limb observations, the problems with applying the radial field assumption to noisy measurements taken near the limb, dividing through by the cosine of a large viewing angle, are obvious.

Continuous and reliable synoptic observations of the polar field from a polar vantage point would eliminate these major problems associated with large viewing angles, and therefore transform our current situation. Only by adopting polar vantage points will we capture the polar field strength across the full polar cap in the line-of-sight Zeeman measurement. See the White Paper 'Revealing the Sun’s Polar Magnetic Fields: The Key to Unlocking the Solar Activity Cycle', led by Lisa Upton, for further discussion. Another White Paper, ‘Improving Solar Polar Field Observations from the Ground’, led by the present author, describes how ground-based larger-aperture telescopes should provide accurate high-resolution full-Stokes polar vector field measurements, complementary to the continuous full-surface data described here.

The Magnetic Change We Miss at High and Low Latitudes: The Necessity of Full 4π Steradian Coverage

Problems associated with our limited view of the Sun arise with observations of both high and low latitudes. Constructing full-surface synoptic magnetograms for the global photospheric field necessarily involves merging multiple images taken at different times and/or from different viewpoints. Synoptic magnetograms may be divided into two basic classes: diachronic and synchronic. Diachronic maps, such as the GONG map shown in Figure 1, are constructed by merging images taken at different times, usually over a full solar rotation from a single point of view on or near Earth. This involves combining observations taken up to about a month apart in time, neglecting the physical evolution of the fields during this time. Data gaps occur at unobserved locations, such as the pole tilted away from the observer, and are artificially filled by either interpolation based on observational data for neighboring locations that were observed (e.g., Sun et al. 2011). Though helpful as a historical record of the global photospheric field, such maps have obvious drawbacks as lower-boundary data for near-real-time coronal and heliospheric modeling.

Synchronic maps represent an attempt to address these problems by offering a snapshot of the entire global photospheric field, using a flux-transport model to include unobserved changes. Such models are generally based on the well-known Babcock-Leighton (Babcock 1961, Leighton 1969) phenomenological model for the solar activity cycle (Arge et al. 2010, Worden & Harvey 2000, Schrijver & Derosa 2003, Upton & Hathaway 2014). Assimilating magnetograms over a rotation or more, these models represent the unobserved field evolution by modeling the flux transport due to the canonical near-surface flows: supergranular diffusion, differential rotation, and meridional flow (Wang et al. 1989).

These models capture in simplified fashion the decay and transport of active-region fields by these canonical flows, but they cannot offer full physical realism. Despite their relative simplicity, flux-transport models have numerous free parameters that are not tightly and uniquely constrained by observations, such as the meridional flow speed and diffusivity, which likely must vary as functions of space, time, and magnetic field strength. If the flux-transport velocities or sunspot umbral field strengths or Joy's law tilts are not accurately captured in the model at all times, then significant errors can build up. Furthermore, important aspects of photospheric flux evolution are not accurately represented in flux-transport models, such as meridional flow variations and active region rotation, which can significantly change the subsequent impact of the flux transport on the polar and global field.

One can try to address the lack of magnetogram coverage of far-side flux emergence using non-magnetogram data, which has been found to improve model performance in a small number of cases (e.g., Arge et al. 2013). However, such methods are not an adequate substitute for accurate and detailed magnetogram observations. Flux-transport models are simple representations of generic solar behavior, and not satisfactory substitutes for good empirical coverage of the complex and unpredictable global photospheric field.

Recommendation

Key solar physics projects are being held back because global solar magnetic field maps of all types unavoidably contain out-of-date or otherwise inaccurate information. These problems cannot reliably be solved without greatly extending our observational coverage, necessarily involving multiple viewpoints including from polar latitudes. A combination of vantage points in the ecliptic plane and in polar orbits would transform this situation dramatically. A multi-satellite mission that would provide such vantage points is described in the White Paper on the Firefly mission concept led by Nour Raouafi.

- 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 full-surface (low-latitude and polar) magnetic field data for the photosphere.

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

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