FIRST SYNOPTIC MAPS OF PHOTOPHERIC VECTOR MAGNETIC FIELD FROM SOLIS/VSM: 
NON-RADIAL MAGNETIC FIELDS AND HEMISPHERIC PATTERN OF HELICITY

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ABSTRACT

We use daily full-disk vector magnetograms from Vector Spectromagnetograph on Synoptic Optical Long-term Investigations of the Sun system to synthesize the first Carrington maps of the photospheric vector magnetic field. We describe these maps and make a comparison of the observed radial field with the radial field estimate from line-of-sight magnetograms. Furthermore, we employ these maps to study the hemispheric pattern of current helicity density, \( H_c \), during the rising phase of solar cycle 24. The longitudinal average over the 23 consecutive solar rotations shows a clear signature of the hemispheric helicity rule, i.e., \( H_c \) is predominantly negative in the north and positive in the south. Although our data include the early phase of cycle 24, there appears to be no evidence for a possible (systematic) reversal of the hemispheric helicity rule at the beginning of the cycle as predicted by some dynamo models. Furthermore, we compute the hemispheric pattern in active region latitudes (\(-30^\circ \leq \theta \leq 30^\circ\)) separately for weak (100 G < |\( B \cdot J \cdot B \) < 500 G) and strong (|\( B \cdot J \cdot B \) > 1000 G) radial magnetic fields. We find that while the current helicity of strong fields follows the well-known hemispheric rule (i.e., \( \theta \cdot H_c < 0 \)), \( H_c \) of weak fields exhibits an inverse hemispheric behavior (i.e., \( \theta \cdot H_c > 0 \)), albeit with large statistical scatter. We discuss two plausible scenarios to explain the opposite hemispheric trend of helicity in weak and strong field regions.

Key words: Sun: dynamo – Sun: interior – Sun: magnetic topology – Sun: photosphere – Sun: surface magnetism

Online-only material: color figures

1. INTRODUCTION

Solar magnetic fields exhibit a hemispheric preference in their sense of twist or helicity. Using chromospheric Hz images, Hale (1927) studied super-penumbra whirls around sunspots. He found that similar to terrestrial hurricanes, sunspot whirls exhibit hemispheric preference in their shape. Later, Richardson (1941) verified the results of Hale (1927) by studying a larger data set and found a hemispheric preference at \(-70\%\) level, although only about one-third of the sunspots showed Hz vortices. The origin of this twist in super-penumbral whirls, initially believed to be due to a Coriolis force acting on plasma flows, is now attributed to the presence of electric currents in sunspot magnetic fields. Later studies established what is now known as the hemispheric helicity rule in various solar features associated with magnetic fields: chromospheric filaments (Rust 1999; Martin et al. 2008), super-penumbral whirls (Balasubramaniam et al. 2004), sheared coronal arcades (Rust & Kumar 1996; Canfield et al. 1997), and interplanetary magnetic field (Smith 1999).

Observations from modern vector magnetographs enabled researchers to carry out a quantitative study of magnetic/current helicity and its sign (chirality; Seehafer 1990; Pevtsov et al. 1995; Abramenko et al. 1996). The chirality from magnetograms is deduced by deriving the quantity \( \alpha = (\nabla \times B) / |B| = J / B \), where \( J \) is the vertical component of the electric current density. This parameter \( \alpha \) is also known as the force-free parameter, following the definition of force-free fields for which the Lorentz force is zero, i.e., \( J \times B = 0 \), which in turn implies \( J = \nabla \times B = \alpha B \). Although the gas pressure and magnetic pressure are comparable at the photosphere, and so photospheric fields are not completely force-free (Priest 1984; Metcalf et al. 1995), such approximations are widely used to extrapolate magnetic fields in the corona using photospheric magnetic field measurements. The observations show a hemispheric preference for the sign of the \( \alpha \) parameter in solar active regions with preferentially negative values in the northern hemisphere and positive values in the southern hemisphere (Seehafer 1990; Pevtsov et al. 1995; Longcope et al. 1998). Similar results are obtained by analyzing the vertical component of the current helicity density \( H_c \), or simply \( H_c \) given by \( H_c = J \cdot B \), whose sign measures the sense of twist of the magnetic field (Abramenko et al. 1996; Bao & Zhang 1998). Here one must bear in mind that only the vertical component of the current helicity density is measured from vector magnetograms observed at a single height; the other two components can, in principle, change the sign of the true current helicity density. However, under the assumption that the sense of flow (parallel or antiparallel) of the vertical component of the electric current, \( J_z \), with respect to \( B_z \), is the same as that of the current vector \( J \) along \( B \), we can treat the vertical component of the current helicity density as a measure of twist. Seehafer (1990) showed that for a cylindrically symmetric flux tube, the magnetic and current helicity have the same sign and increase with each other. Furthermore, it can be shown that \( \alpha \) and \( H_c \) are related to each other: \( H_c = \alpha B_z^2 \) (Hagyard & Pevtsov 1999).

The hemispheric helicity rule is also present in large-scale magnetic fields (LSMFs; Pevtsov & Latsushko 2000; Wang & Zhang 2010). In full-Sun MHD simulations, Yeates et al. (2008) found similar hemispheric preference but only at mid/low latitudes. At higher latitudes they found a reversal of the hemispheric pattern of twist, which is in contrast to the observations which show polar crown filaments having a chirality preference of the same nature as active regions. In addition to the hemispheric helicity rule, the helicity of LSMFs showed evidence of zonal organized bands (Pevtsov & Balasubramaniam 2003) co-spatial with patterns of torsional oscillations (Howe et al. 2000). The sign of helicity in these bands is opposite to the \( H_c \) prevailing for a given hemisphere.

Until recently, the full-disk vector magnetograms were not routinely available, and thus early studies of \( H_c \) in large-scale
fields were based on pseudo-vector derivations. In this method, the components of the LSMF vector are derived from the time sequence of the longitudinal magnetograms under the simple assumption that the field does not change over several days. Even with this assumption, the derivations are limited to only two components (radial and toroidal); the variations in projection are too small to derive the meridional component of the field (however, see Wang & Zhang 2010). The routine observations of full-disk vector magnetic fields by Vector Spectromagnetograph (VSM) on the Synoptic Optical Long-term Investigations of the Sun (SOLIS) system (Keller et al. 2003) and Heliospheric Magnetic Imager (Schou et al. 2012) on the Solar Dynamic Observatory spacecraft allow us for the first time to investigate the current helicity of LSMFs directly without any restrictive assumptions about the nature of these fields.

In this paper, we present the first ever synoptic Carrington maps of the vector magnetic field constructed from VSM/SOLIS daily observations. We contrast the new maps with traditional Carrington charts derived from longitudinal field measurements and find significant differences between true and line-of-sight (LOS)-based radial magnetic fields in areas of active regions and at high latitudes. In Section 2, we briefly describe the SOLIS/VSM instrument and the method of deriving the full-disk vector magnetograms. Then, we describe the synoptic maps of the vector magnetic field and the properties of the radial magnetic field in Sections 3 and 4. In Section 5, we present the analysis of the current helicity density based on new synoptic maps. In Section 6, we study the helicity pattern in strong and weak magnetic field regions separately, and in Section 7 we discuss our findings.

2. OBSERVATIONS AND DATA ANALYSIS

We employ daily observations of vector magnetic fields taken with the VSM—one of three instruments comprising the SOLIS facility for synoptic observations of the Sun in optical wavelengths (Keller et al. 2003; Balasubramaniam & Pevtsov 2011). SOLIS/VSM is a spectrograph-based spectropolarimeter. It takes the full Stokes profiles of the Fe I 630.15–630.25 nm line pair along a slightly curved spectrograph slit that intersects the entire solar disk (from east to west limbs). The full-disk magnetogram is built by scanning the solar image by moving the telescope in the declination. Pixel size in the final magnetogram is about 1 × 1 arcsec². VSM takes about 0.6 s to record all four Stokes parameters for a single scan line, and it takes about 20 minutes to complete a full-disk magnetogram (2048 scan lines).

The Stokes $I$, $Q$, $U$, and $V$ profiles observed in the Fe I 630.15–630.25 nm line pair are sampled in the spectral direction with 2.4 pm pixel⁻¹. The spectra are inverted in a framework of a Milne–Eddington model of stellar atmosphere following an Unno–Rachkovsky formalism (Skumanich & Lites 1987).

Additional details about the instrument and the pipeline reduction steps can be found elsewhere (e.g., Jones et al. 2002; Henney et al. 2006; Balasubramaniam & Pevtsov 2011). Only pixels with a polarization signal above the threshold of 0.1% of continuum intensity, $I_c$, are inverted to obtain the magnetic (field strength, inclination angle, and azimuth angle) and thermodynamic (e.g., Doppler width, Doppler velocity, source function, temperature) parameters. The method also allows us to determine the relative contribution of magnetic and non-magnetic plasma to the line profile for each pixel (filling factor). The threshold of 0.1% of $I_c$ corresponds to the typical noise level in the continuum. Using this threshold avoids fitting profiles buried in the noise. The error in the inferred magnetic field parameter for each pixel is different, as the Stokes signal varies from pixel to pixel. For example, Gosain et al. (2010) used a Hinode vector magnetogram of a sunspot region as a reference field and simulated random errors due to normally distributed photometric noise (0.5% of $I_c$, a 3σ noise level) in Stokes profiles and found that the maximum error in the magnetic field parameters is $\sim$50 G for field strength, $\sim$1.5° for inclination, and $\sim$5° for azimuth angle, respectively. Stokes profiles in regions such as sunspots, plage, network, and decaying regions typically have $S/N \geq 1000$, and so the typical errors are expected to be in this range. The noise levels in the SOLIS magnetograms are estimated to be a few Gauss in the longitudinal and 70 Gauss in the transverse field measurements (Tadesse et al. 2013).

The 180° azimuth ambiguity is resolved using the non-potential field computation method (Georgoulis 2005; Georgoulis et al. 2008). Due to limited memory and CPU speed constraints in the early data reduction pipeline hardware, the 180° disambiguation is parallelized by dividing the solar image into smaller overlapping tiles. The azimuth ambiguity is resolved in each tile independently. For this study, we have also tested a new, faster ambiguity resolution method developed by Rudenko & Anfinogentov (2011). In this method, the direction of the transverse field is determined in accordance with the principle of minimum deviation of net differences of the potential field from those of the defined field. The results presented in this paper are found to be the same with both ambiguity resolution algorithms, which tests the validity and consistency of the new and faster algorithm developed by Rudenko & Anfinogentov (2011).

3. SYNOPTIC MAPS OF THE MAGNETIC FIELD VECTOR

To compute the helicity of magnetic fields over the entire solar disk requires constructing the synoptic maps of the vector field. Until now, no such maps were produced. Here we describe our approach to constructing the vector field synoptic maps and compare these new maps with traditional synoptic maps of the radial field, which are created from LOS magnetograms under a restrictive assumption that magnetic fields are normal to the solar surface.

Traditionally, synoptic (or Carrington) maps are synthesized by combining the daily full-disk magnetograms taken over a period of one solar rotation (~27 days). The maps cover all latitudes (±90°) and longitudes (0°–360°) of the solar surface. Although the purpose of a synoptic map is to represent activity over the entire surface of the Sun, the maps are representative of the activity occurring near the central meridian (CM) of the solar disk at the time of the observations. In earlier times when the angular resolution of data was coarse, a $\cos^4 \phi$ weighting was used (Harvey et al. 1980), where $\phi$ is the longitudinal distance from the CM. With the availability of higher-resolution data, it has been found that such weighting leads to a smearing of small-scale features which evolve substantially from day to day. A Gaussian weighting scheme of the form $W(\phi) = \exp^{-\phi^2/\sigma^2}$ has therefore been implemented (J. W. Harvey 2013, private communication) in order to heavily weight only the regions very close to the CM. Such synoptic maps, therefore, essentially capture a snapshot of activity very close to the CM over the duration of a solar rotation.

Synoptic maps based on the LOS magnetic field of the Sun are widely used to study the evolution of magnetic fields on timescales from a solar rotation to the solar cycle. The maps of the radial field, constructed from LOS magnetograms, are
used as the lower boundary condition for extrapolating the photospheric fields into the corona in a framework of potential field extrapolation (Altschuler & Newkirk 1969). The current-free fields extrapolated to the heights in the corona where they are deemed to become purely radial (potential field source surface, typically between 2.5 and 3.5 \( R_\odot \)) are used in modeling the coronal and heliospheric magnetic fields, the solar wind speed, and the appearance of white-light corona prior to total solar eclipses. The validity of the assumption that the magnetic field is normal to the surface at the photosphere level is largely unknown. Thus, the availability of synoptic maps of the vector magnetic field allows us to verify the assumption of field verticality for the first time.

Below, we describe the steps taken in constructing the vector synoptic maps.

1. After the 180° ambiguity is resolved, the three components of the field in the image plane (\( B_\phi \)—(terrestrial) east–west direction; \( B_\theta \)—(terrestrial) north–south component; and \( B_r \)—vertical) are transformed to a heliographic coordinate system which yields toroidal (\( B_\phi \)), poloidal (\( B_\theta \)), and radial (\( B_r \)) components. The full-disk magnetograms are then re-mapped into heliographic coordinates (longitude: \( \phi \); latitude: \( \theta \)).

2. The individual re-mapped magnetograms are combined in the traditional way with a Gaussian weight of the form \( W(\phi) = \exp(-\theta/\theta)^2 \) given to the data. This results in three synoptic maps (one for each component of vector field) corresponding to one Carrington rotation (CR).

As an example, in Figure 1, we show a vector synoptic map for CR 2109. The zoom-in view of a typical active region (Box “1”) and a diffuse bipolar region (Box “2”) along with the overlaid transverse vector is shown in the Figure 2. We find the active region field pattern to be consistent with expectations for dipolar field configuration: the \( B_\phi \) component (Box “1”) between two polarities corresponds to the field lines connecting them, and \( B_\theta \) is in agreement with the group tilt corresponding to Joy’s law (Hale et al. 1919). The patterns for the large-scale field (Box “2”) are similar to those obtained by Pevtsov & Latushko (2000) with the pseudo-vector method for their data during cycle 22. Both foot points of the field in Box “2” show negative \( B_\theta \), which means that the field lines are connected such that the foot points make an obtuse angle with the solar surface, measured from the polarity inversion line (PIL). Furthermore, the transverse field vectors in the diffuse bipolar region (Box “2”) show a north–south component (\( B_\theta \)) such that the field configuration is tilted toward the equator. The reason for the equatorward tilt could be the presence of a filament along the PIL, which would suggest a non-potential field oriented along the PIL, which is oriented roughly along the N–S direction. Furthermore, the period of this observation (2011 April 29) corresponds to the ascending phase of solar cycle 24, so coronal equatorial streamers, which are prominent during solar minima, may also give the large-scale field (reaching high in the corona) a net equatorward tilt. Thus, the derived components of the vector magnetic field in our synoptic maps agree with the expected orientation of magnetic fields on the Sun.

4. OBSERVED RADIAL FIELD VERSUS THE RADIAL FIELD ESTIMATE FROM LONGITUDINAL MAGNETOGRAMS

Assuming that the magnetic field on the Sun is mostly vertical, one can estimate the radial field, \( B_{r(LOS)} \), using the relation

\[ B_{r(LOS)} = B_{\text{LOS}} / \mu, \]

where \( \mu \) is the cosine of the heliocentric angle and \( B_{\text{LOS}} \) is the LOS field. Traditional synoptic maps of the radial field are synthesized using this method, which will work exactly if the field were truly normal to the solar surface. However, in practice, magnetic fields are not normal everywhere. For example, the fields are more horizontal in the sunspot penumbra and near the PIL. Although, in most cases the field in the quiet Sun appears to be more vertical, it is not purely normal to the solar surface (Gosain & Pevtsov 2013). The departure of high-latitude fields from radial expansion at the photospheric level was deduced using a vector field reconstructed from longitudinal magnetograms by Petrie & Patrikeeva (2009).

Now let us compare the radial field reconstructed from longitudinal measurements, \( B_{r(LOS)} \), with the observed radial field component from vector field measurements, \( B_{r(OBS)} \) (or simply \( B_r \) for brevity). For comparison, we compute the difference of the absolute value of the two radial fields, i.e., \( \Delta B_r = |B_r| - |B_{r(LOS)}| \), and plot the signed relative difference, \( \Delta B_r / |B_r| \) (%), as shown in the top panel of Figure 3. This signed difference map is saturated at ±5% to emphasize the latitudinal pattern in the sign of the difference. Black (white) corresponds to the negative (positive) difference, i.e., \( |B_r| < |B_{r(LOS)}| \) and \( |B_r| > |B_{r(LOS)}| \), respectively. We note that in active regions, the differences are large as compared to fields outside the active regions at these latitudes. This is expected due to the presence of fanning fields in active regions.

Furthermore, in the middle panel of Figure 3, we show the longitudinal average of the absolute value of relative difference, \( \Delta B_r / |B_r| \) (in %). We note that the value of the relative difference increases systematically toward higher latitudes. The observations are scanty at higher latitudes, and hence a large scatter is seen, but the systematic increase toward higher latitudes is evident from the profile. To understand the cause of this systematic increase, let us consider a field of strength \( B \) at latitude \( \theta \) having an inclination ±\( \gamma \) in the meridional plane with respect to local vertical. The positive or negative sign corresponds to the case when the field is inclined toward the poles or solar equator. Then the LOS field, \( B_L \), and radial field, \( B_r \), would be given by

\[ B_L = B \cdot \cos(\theta \pm \gamma) \]
\[ B_r = B \cdot \cos(\gamma). \]

When the assumption is made that the field is normal to the solar surface (\( \gamma = 0 \)), \( B_{r(LOS)} \) is derived as \( B_L / \cos(\theta) = B \cos(\theta) / \cos(\theta) \), that is, if the field is not vertical (\( \gamma \neq 0 \)), then this assumption introduces an error. In the latter case, \( B_{r(LOS)} = B \cos(\theta \pm \gamma) / \cos(\theta) \).

The difference (\( \Delta B_r \)) between true \( B_r \) and the one derived from the assumption that the field is vertical can be expressed as follows:

\[ \frac{\Delta B_r}{B_r} = 1 - \frac{\cos(\theta \pm \gamma)}{\cos(\theta) \cos(\gamma)}. \]

We show that

\[ \frac{\Delta B_r}{B_r} = \frac{\Delta B_r}{|B_r|} = \pm \tan(\theta) \tan(\gamma). \]

The expression for normalized amplitudes of the difference between true \( B_r \) and \( B_{r(LOS)} \) becomes

\[ \frac{\Delta B_r}{|B_r|} = \tan(\theta) \tan(\gamma). \]
Figure 1. Synoptic Carrington map of the vector magnetic field components synthesized using full-disk SOLIS/VSM vector magnetograms is shown for CR-2109. The panels from top to bottom show the distribution of the $B(r)$, $B(\theta)$, and $B(\phi)$ components, respectively. The $B_r$ map is scaled between ±100 G, and the $B_\theta$ and $B_\phi$ maps are scaled to ±20 G. The positive values of $B_r$, $B_\theta$, and $B_\phi$ point, respectively, upward, southward, and to the right (westward). The zoom-in view of the regions marked by rectangles “1” and “2” is shown in Figure 2.

(A color version of this figure is available in the online journal.)
Thus, even if $\gamma = \text{constant}$, $|\Delta B_r|/|B_r|$ will vary as the tangent of latitude ($\theta$). The profile in the middle panel of Figure 3 demonstrates that the effects of the non-verticality of the magnetic field become stronger (and more important) for high latitudes even if the inclination angle does not change systematically.

Furthermore, we note that there is a systematic pattern in the sign of the relative difference, $\Delta B_r/|B_r|$, as described below.

1. Both the active regions as well as the diffuse field outside the active regions show asymmetry in the sign of $\Delta B_r/|B_r|$ along the north-south direction.
2. In both hemispheres, the portion of the active region toward the equator (pole) shows negative (positive) values of $\Delta B_r/|B_r|$.
3. Outside active regions, the diffuse flux in both hemispheres shows an opposite pattern as compared to active regions, i.e., the flux near the equator (pole) shows a positive (negative) value of $\Delta B_r/|B_r|$.

A negative $\Delta B_r/|B_r|$ in high latitudes in the northern and southern hemispheres implies a systematic tilt of the vector magnetic fields toward the equator. The bottom panel of Figure 3 illustrates a schematic of the side view of the portion of the solar disk visible to the observer (labeled LOS) and some example field lines (dashed curved lines). The labels correspond, respectively, as follows: north pole: NP; south pole: SP; equator: EQ; radial direction: R; center of Sun: O; active region: AR; low latitude: LL; and high latitude: HL. It can be seen that in active region (labeled AR), depicted like a sunspot with the field lines fanning out, the equatorward portion of the AR will have field lines oriented in such a way that they deviate from the local solar vertical, inclining toward the equator. Similarly, the poleward portion of the AR will have field lines oriented in such a way that they deviate from the local solar vertical, inclining toward the poles. Then the field inclined toward the equator (pole) will show a negative (positive) sign of $\Delta B_r/|B_r|$, which is what we observe in the top panel of Figure 3. On the other hand, the large-scale field lines (depicted by dashed curved lines) rooted in HL and LL deviate from the local solar vertical, inclining equatorward and poleward, respectively. Thus, we will observe $\Delta B_r/|B_r|$ to be negative in HL regions and positive in LL regions, which is what we observe in the top panel of Figure 3.

These results emphasize the importance of vector field measurements. The quantitative effects arising from replacing the $B_r(\text{LOS})$ synoptic maps by observed $B_r$ on solar wind and coronal field extrapolation are unknown. These effects and a detailed study of the non-radial nature of fields will be a subject for our future study. Here we want to emphasize the importance of vector field measurements and the synoptic maps in deriving the $B_r$, and potentially calibrate the systematic deviation $\Delta B_r/|B_r|$ with latitude.

The systematic pattern shown in the top panel of Figure 3 cannot be a result of random noise. In the Appendix, we show that the random noise in $B_r$ and $B_r(\text{LOS})$ will lead to random noise in the relative difference and not a systematic variation in its sign as shown in the top panel of Figure 3.

5. CURRENT HELICITY DENSITY FROM SYNOPTIC VECTOR MAPS

Given the distribution of the vector magnetic field in the photosphere, one can compute the vertical component of the current helicity density, $H_c$. In spherical coordinates,

$$H_c(\phi, \theta) = B_r(\nabla \times B),$$

$$= \frac{1}{\sin \theta} \left\{ \frac{\partial}{\partial \theta} [\sin \theta B_\theta(\phi, \theta)] - \frac{\partial B_\theta(\phi, \theta)}{\partial \phi} \right\} B_r(\phi, \theta).$$

The distribution of $H_c$ for CR 2109 is shown in Figure 4. The patterns of current helicity density of a mixed sign can be seen in the active region. Such local helicity patterns are well known from previous works (e.g., Pevtsov & Peregod 1990; Pevtsov et al. 1994; Abramenko et al. 1996; Pevtsov & Canfield 1998; Su et al. 2009 and references therein).

In the present work, we computed maps of the vertical component of the current helicity density for CR 2109–2131 covering a period from 2011 March to 2012 December. During this time, a total of 453 NOAA numbered active regions crossed the solar disk. The longitudinal average of $H_c$, or ($\langle H_c \rangle$), distribution over all the CR is shown in the top panel of Figure 5. The $\langle H_c \rangle$ profile shows a tendency to be positive in the southern and negative in the northern hemisphere of the Sun, in agreement with the previous results obtained by many researchers for active
Figure 3. Top panel displays the signed relative difference, $\Delta B_r / |B_r| (\%)$, between the absolute values of the observed radial field, $|B_r|$, and the radial field derived from the LOS magnetic field, $|B_{r,LOS}|$, during Carrington rotation 2123. The signed relative difference is saturated between ±5% to emphasize the sign of the difference. The middle panel shows the longitudinal average of the absolute relative difference, $|\Delta B_r| / |B_r| (\%)$. In the bottom panel, we show a schematic model to illustrate the sign pattern observed in the top panel.

(A color version of this figure is available in the online journal.)
Figure 4. Synoptic map of the current helicity density, $H_c$, is shown in the top panel for CR 2109. The rectangular region marked in the map is zoomed and displayed in the lower panel. The amplitude of $H_c$ in the displayed images is scaled between $\pm 2 \times 10^{-3} \text{ G}^2 \text{m}^{-1}$.

(A color version of this figure is available in the online journal.)

regions observed in cycles 22, 23, and even 24 (Abramenko et al. 1996; Bao et al. 2000; Pevtsov et al. 2001; Hao & Zhang 2011).

In Figure 5, the $H_c$ is averaged over regular ARs, ephemeral regions, large-scale bipolar and unipolar magnetic regions, and plages up to high latitudes ($\sim 60^\circ$). In the lower panel of Figure 5, we show the data points confined to the active region belt ($0^\circ$–$30^\circ$) and we fit a straight line to the observed data points to show that the slope of $dH_c/d\theta$ is negative, indicative of a hemispheric sign preference. In computing the average profiles of $H_c$, we used only the pixels above the threshold of 20 G for both radial and transverse fields to filter out the noise.

In the left panel of Figure 6, we construct the time–latitude map of the $\langle H_c \rangle$ during CR 2109–2131. Each column in the map represents the longitudinal average of $H_c$ at all latitudes for the indicated CR number. The blue and red colors represent the negative and positive sign of the $H_c$ where the color scale is saturated between $\pm 2 \times 10^{-4} \text{ G}^2 \text{m}^{-1}$. The hemispheric pattern of $\langle H_c \rangle$ can be seen visually by the dominance of negative (blue) in the northern and positive (red) in the southern hemisphere. The patches of opposite sign are also present in each hemisphere, consistent with previous results that the hemispheric rule is a weak tendency. Nevertheless, on average we find that the hemispheric rule is followed during the studied period which corresponds to the rising phase of the current solar cycle 24.

For large-scale fields, several researchers have used the pseudo-vector reconstruction method (Pevtsov & Latushko 2000; Wang & Zhang 2010) to compute $H_c$ and reported that the hemispheric rule is followed by large-scale fields as well. Here in the middle and right panels of Figure 6, we plot, respectively, the average latitudinal profile (averaged over CR 2109–2131) in the $0^\circ$–$30^\circ$ and $> 30^\circ$ latitude bands. The profile of $H_c$ in the high-latitude band ($> 30^\circ$) is shown separately due to its relatively low amplitude. The error bars show the standard error of the mean. These profiles show that the hemispheric pattern of $\langle H_c \rangle$, namely, negative in the north and positive in the south, is followed in both latitude ranges quite well. Since the latitude range $30^\circ$–$90^\circ$ contains mostly large-scale diffuse fields, we therefore confirm the results of Pevtsov & Latushko (2000) and Wang & Zhang (2010) with observed vector magnetograms for the first time. Another feature that can be noted from these plots
Figure 5. Top panel shows longitudinal averaged profile of $H_c$ over all CRs (2109–2131). The bottom panel shows the same profile between 0° and 30° along with a linear fit with a negative slope.

is that the helicity pattern in the southern hemisphere is much stronger in the sense that we see fewer patches of opposite-signed helicity there, as compared to the northern hemisphere where we see a weaker dominance of negative helicity. It is well known that the north and south hemispheres show an asymmetry in the amplitude and phase of their activity cycle. Here we show evidence for asymmetry in the strength of the hemispheric dominance of the helicity sign. Furthermore, we note signatures of annual $B$-angle variation in the time–latitude plot in Figure 6. Such variation allows us to sample the vector magnetic field at higher latitudes, and therefore study the hemispheric pattern there. We do see fluctuations in the sign of $\langle H_c \rangle$ at high latitudes, however, the average behavior is in agreement with the general hemispheric rule (Pevtsov et al. 1995).

6. HEMISPHERIC PATTERN FOR THE WEAK AND STRONG FIELDS

Next, we study separately the hemispheric pattern for the strong and weak fields in the active region belt 0°–30°. For segregating the strong and weak field regions we used the following criterion: strong fields, $100 \text{ G} < |B_r| < 500 \text{ G}$; and weak fields, $100 \text{ G} < |B_r| < 500 \text{ G}$. Such criterion was used by Zhang (2006) in their study of the hemispheric pattern of helicity in active regions. Thus, adopting the same criterion facilitates a straightforward comparison with their study. The top and bottom panels in Figure 7 show the results for the strong and weak fields, respectively. The panels on the left show the time–latitude plot of $\langle H_c \rangle$ for the active region belt between 0° and 30°. Beyond 30° latitude, only the fields weaker than 500 G remain, so we exclude these regions from comparison. The panels on the right show the latitudinal profile averaged over all 23 CRs (2109–2131) shown in the left panels. We found that the latitudinal profile of $H_c$ for the strong field regions follows the hemispheric tendency and the pattern is similar to the one shown for the 0°–30° belt in Figure 6, for all field strengths. On the other hand, for weak fields the latitudinal profile shows a weak but systematic anti-hemispheric rule, i.e., a preference for the positive sign of $H_c$ in the northern and negative in the southern hemisphere. Thus, our observations, which show that the strong fields obey the hemispheric rule while weak fields show a tendency for the anti-hemispheric rule, disagree with the results of Zhang (2006), who found that weak fields obey the hemispheric rule while strong
fields follow the anti-hemispheric rule. In another related study by Pevtsov & Longcope (2001), it was shown that the helicity of the quiet-Sun flux obeys the hemispheric rule. During their observations, many ARs were present on the Sun and the authors suggest that the helicity pattern of the ARs could be reflected in the quiet-Sun elements simply due to the origin of the quiet-Sun flux from the decayed flux of the ARs.

7. DISCUSSION AND CONCLUSIONS

In this work, we present for the first time synoptic (Carrington) maps of the observed vector magnetic field. These maps provide a representation of magnetic fields without any restrictive assumptions about the topology of the fields, and therefore are expected to improve the outcome of coronal field extrapolation models using synoptic maps as input. A comparison of the radial components derived by the traditional method using LOS magnetograms with the one derived from vector data shows systematic differences in high and low latitudes as well as in active regions. Furthermore, we show that the non-vertical nature of the magnetic field leads to systematic errors in the radial field deduced from LOS observations, $B_{r(LOS)}$. The relative error, $|\Delta B_r|/|B_r|$ (%), varies as a tangent of the latitude, and therefore becomes significant at high latitudes, even if the inclination angle with respect to the vertical direction remains the same. The severity of the differences, when using observed radial field as compared to estimated radial field from LOS measurements, on the extrapolated coronal fields and solar wind derivations is presently unknown and will be a subject of a separate future study.

As the first use for these new synoptic maps, we employed them to study the distribution of the current helicity density on the Sun. We found that the hemispheric pattern of the current helicity density is present during the ascending phase of cycle 24. Although the derived helicity maps do show patterns of opposite helicity present in both hemispheres, there appears to be no indication of a systematic reversal in helicity at the beginning of cycle 24 as predicted by some previous studies (e.g., Choudhuri et al. 2004). Neither do we see the presence of well-defined bands of opposite helicity co-spatial with the pattern of torsional oscillations as was reported for solar cycle 22 (Pevtsov & Balasubramaniam 2003).

We studied the hemispheric pattern for weak and strong fields separately following criterion by Zhang (2006). Our results do show an opposite sign of the hemispheric preference for weak and strong fields. However, opposite to Zhang (2006), we find that the helicity of strong fields follows the hemispheric rule, while the helicity of weak fields exhibits an inverse helicity sign–hemisphere relation. Thus, for strong fields, the product of the helicity and current helicity is negative, in agreement with the hemispheric rule (i.e., $\theta \cdot H_c < 0$). For weak fields, the product of the helicity and current helicity is positive, in agreement with the hemispheric rule (i.e., $\theta \cdot H_c > 0$). The reasons for such a disagreement between our results and those of Zhang (2006) are unknown and need further investigation.

Despite these differences, an important question remains: why is different hemispheric behavior for weak and strong fields seen? The models of helicity generation in solar magnetic fields must be confronted with observational results. Mean field dynamo models based on the $\alpha$-effect (Steenbeck et al. 1966; Seehafer 1996) show two helicities, the one in the mean field and another in the fluctuations. Furthermore, both have similar magnitude but opposite sign, such that the sign of helicity in the mean and fluctuating fields is shown to be of positive and negative signs, respectively, in the northern hemisphere and vice versa in the southern. In the mean field dynamo, the active regions are thought of as fluctuations and not as the mean field. Thus, we get the same hemispheric preference for the sign of the observed current helicity as ARs as we get in mean field dynamo models for the fluctuating field. What about the observational counterpart for the helicity of the mean field? Could the mean latitudinal profile of the helicity for weak fields, which shows an anti-hemispheric rule, as shown in the right panel of Figure 7, represent the helicity of the mean field from dynamo models, since they have the same sign preference?

Another plausible explanation could be that the current helicity observed in the strong and weak magnetic fields is a result of two different processes. For example, helicity in the strong fields of active regions could be created by the
Figure 7. Left top (bottom) panels show the time–latitude plot of current helicity density, $H_c$, for strong (weak) fields over $0^\circ$–$30^\circ$ latitude belt. Each column corresponds to the longitude average of $H_c$ for the Carrington rotation as labeled. The blue (red) color represents the negative (positive) sign of $H_c$. The magnitude of $H_c$ is scaled between $\pm 5 \times 10^{-4} \text{ G}^2 \text{ m}^{-1}$. The right panels (both the top and bottom rows) show the mean latitudinal profile of $H_c$, derived from respective time–latitude plots on the left. The error bars show the standard error of the average $H_c$ value.

The twist can be induced in the magnetic flux due to the vorticity of the (near) surface flows (e.g., supergranular flow; see Duvall & Gizon 2000). The (near) surface flows (from surface to a depth of about 16 Mm) were studied using the ring-diagram technique by Komm et al. (2007) as a function of the magnetic flux. They found that on average, quiet regions show weakly divergent horizontal flows with small anticyclonic vorticity (clockwise in the northern hemisphere), while locations of high activity show convergent horizontal flows with cyclonic vorticity (counterclockwise in the northern hemisphere). Consider an untwisted flux tube embedded vertically in photospheric layers and subject to clockwise horizontal flows. It can be seen that a clockwise flow will induce positive twist in the magnetic flux tube and a counterclockwise flow will induce negative twist. Thus, the flow patterns from local helioseismology (Komm et al. 2007) would tend to induce positive current helicity in the magnetic flux rooted in quiet regions and a negative current helicity in the magnetic flux rooted in strong field regions in the northern hemisphere. Such a pattern is similar to what we see in our present observations, namely, a positive helicity in weak field regions and negative helicity in strong field regions in the northern hemisphere. Thus, the observed behavior of current helicity in strong and weak fields could be explained in the framework of mean field dynamo models, or alternatively due to the interaction of magnetic flux tubes with turbulent plasma flows in the convection zone.

However, more observations are needed to improve the statistics further. Synoptic maps of the vector magnetic field presented here appear to be useful tools for such statistical studies. Accumulation of more vector synoptic maps during the entire solar cycle 24 and beyond would be useful to establish patterns of helicity on the Sun and will also help in testing the validity of various physical mechanism(s) that have been proposed in order to explain the hemispheric preference of magnetic twist, its associated statistical dispersion, and variation with solar cycle.
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Facility: SOLIS (VSM)

APPENDIX

EFFECT OF NOISE ON $\Delta B_r / |B_r|$  

Let us assume that $B_r$ and $B_r(\text{LOS})$ (or simply $B_r$) have the same sign (say positive), and the noise $\sigma$ is small compared to the magnitude of the radial field (both $B_r$ and $B_l$).

Then,
\[
\frac{\Delta B_r}{|B_r|} = \frac{|B_r \pm \sigma| - |B_l \pm \sigma|}{|B_r \pm \sigma|} = \frac{(B_r \pm \sigma) - (B_l \pm \sigma)}{B_r \pm \sigma} = \frac{(B_r - B_l) \pm \sigma}{B_r \pm \sigma}.
\]

If $\sigma \ll B_r$ and $B_r \approx B_l$, then we can rewrite the above as
\[
\frac{(B_r - B_l) \pm \sigma}{B_r \pm \sigma} \approx \frac{\pm \sigma}{B_r}.
\]

Thus, as noise $\sigma$ increases, the scatter in the relative difference, $|\Delta B_r / |B_r||$, also increases proportionally. A systematic latitudinal pattern in the sign of relative difference, $\Delta B_r / |B_r|$, as seen in the top panel of Figure 3 is not expected from random noise in $B_r$ and $B_l$.

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