

A first rapid synoptic magnetic field map using SDO/HMI and SO/PHI data

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ABSTRACT

Context. Traditionally, the observation time needed to build synoptic maps of the solar magnetic field is bound to the 27 days of a full Carrington rotation due to the single viewpoint from Earth.

Aims. Our aim is to reduce this observation time to 13.5 days by combining magnetograms from two vantage points, 180° apart in longitude in the ideal case.

Methods. We combined observations taken by the Polarimetric and Helioseismic Imager (SO/PHI) during the superior conjunction of the Solar Orbiter in February 2021 with data from the Helioseismic and Magnetic Imager (SDO/HMI) and constructed a synoptic map of the line-of-sight magnetic field of CR 2240.

Results. The result is the first multi-view synoptic map using SDO/HMI and SO/PHI data from an observing period of only 16 days. Comparing the multi-view synoptic map to the standard synoptic map of SDO/HMI shows a significant amount of magnetic evolution between the dates on which the two instruments observed the same solar longitudes. The changed magnetic field was caught by the multi-view synoptic map but would have been missed by a standard synoptic map.

Conclusions. Our results demonstrate that multi-view synoptic maps provide a new method to obtain a more instantaneous map of the magnetic field over the entire solar surface.

Key words. Sun: photosphere – Sun: activity – Sun: magnetic fields

1. Introduction

Synoptic maps of the solar magnetic field are traditionally constructed by placing central meridian slices of continuously observed magnetograms onto a Carrington grid (see e.g. D’Azambuja 1928; Howard et al. 1967; Schatten et al. 1969; Livingston et al. 1970; Harvey et al. 1980; Harvey & Worden 1998; Liu et al. 2017). So far, this process has relied on the solar surface rotating into the field of view of the Earth-bound observer, thus requiring a full Carrington rotation (CR) for the creation of each synoptic map. This corresponds to a fixed synodic solar rotational period of 27.2753 days and is much longer than the typical timescales of magnetic evolution on the solar surface, which changes on the order of hours to days. The result is a single map that shows the magnetic field observed at different times. Up to now, this process has been the only way to acquire global magnetic field maps of the Sun.

Such maps are commonly used to provide the initial conditions for flux transport models (Wang & Sheeley 1994; van Ballegoijen et al. 1998) and the boundary conditions for global magnetic field extrapolations (e.g. Wang & Sheeley 1994;

Wiegmann et al. 2014; Wiegmann & Sakurai 2021), which in turn are used to determine the large-scale coronal and solar wind structure and dynamics (e.g. Wang & Sheeley 1990; Arge & Pizzo 2000). These applications ideally require an instantaneous global snapshot of the magnetic field, which so far has only been available for synoptic maps of coronal structures built from STEREO and SDO/AIA data (Caplan et al. 2016).

The limitation of having to wait for a full solar rotation period in order to construct magnetic synoptic maps has now been overcome with the launch of Solar Orbiter (SO; Müller et al. 2020), which carries the Polarimetric and Helioseismic Imager (SO/PHI; Solanki et al. 2020) and is on an orbit that, for the first time, enables the recording of magnetograms from a vantage point outside the Sun-Earth line. Combining such data with Earth-bound observations can significantly shorten the total observation time for synoptic maps.

In this paper, we introduce the first multi-view synoptic map created from joint observations made by the Helioseismic and Magnetic Imager (SDO/HMI; Schou et al. 2012; Scherrer et al. 2012) and SO/PHI. In order to combine observations from the two instruments, we adapted the SDO/HMI synoptic map

pipeline (Liu et al. 2017) to be compatible with SO/PHI data, which is variable in cadence. In particular, for time-sparse SO/PHI observations, averaging in the same manner as the original SDO/HMI pipeline would result in strong smearing of areas where two slices overlap. To avoid smearing, we used slices with an adaptable width (applying a windowing technique to overlapping areas). A more detailed description of the changes to the pipeline can be found in Loeschl et al. (2023). The result is a new data product that provides the magnetic field over the solar surface within a much-reduced interval of time. Depending on the angular separation between the two instruments, the multi-view synoptic maps can be completed up to 50% faster and thus provide a temporally more consistent magnetic field compared to the classical SDO/HMI synoptic maps.

In this work, we show the first ever synoptic map produced by combining magnetograms taken from two vantage points. We describe the intricacies of incorporating real SO/PHI observations from a low-cadence observation campaign during the superior conjunction of Solar Orbiter in Sect. 2. In Sect. 3, we show the first ever multi-view synoptic map and discuss how, thanks to its reduced observation time, the new map suffers less from the effects of magnetic evolution than a standard synoptic map made from data from a single vantage point. Conclusions are presented in Sect. 4.

2. Method

We constructed a synoptic map of the line-of-sight (LOS) component of the magnetic field, B_{LOS} , with the adapted pipeline for multi-view synoptic maps using SO/PHI and SDO/HMI observations (Loeschl et al. 2023). Our aim was to use SO/PHI data from the Full Disc Telescope (FDT) in addition to SDO/HMI magnetograms from the “HMI.M_720s” data series to reduce the combined observation time to a minimum. The selected observations were then ingested into our local clone of the SDO/HMI archive, where the combined data set was processed by the SDO/HMI synoptic map pipeline. This included remapping the observed solar disk to cylindrical equal-area (CEA) coordinates (Thompson 2006) and applying an oversampling-smoothing scheme to suppress possible aliasing (Liu et al. 2017; Sun 2013) before each magnetogram was incorporated into the synoptic map.

Unlike SDO/HMI data, which are averaged over four-hour intervals, SO/PHI observations are not available at a sufficient cadence to do so without smearing out the magnetic evolution. Consequently, SO/PHI data are incorporated as mostly individual magnetogram slices with weighted averages that provide continuous transitions between magnetograms (see Loeschl et al. 2023 for details).

In the particular application presented in this work, we used 18 days of SO/PHI observations from a dedicated synoptic campaign during the superior conjunction of Solar Orbiter in February 2021. A detailed list of the full data set with all employed SO/PHI and SDO/HMI observations is provided in Table 1. A closer look at this table reveals a number of points that need to be considered when combining synoptic data obtained from multiple viewpoints.

Data management. The SDO/HMI magnetogram archive for synoptic maps is organised and queried via the so-called record time T_{REC} , which is a system of predetermined timestamps that refers to the magnetogram observed closest in time (with observation time T_{OBS}). Each T_{REC} can only be associated with a single magnetogram. While this is a reasonable

approach to arrange synoptic data from a single observatory, it can lead to complications once data from multiple instruments at different viewpoints are employed. Using observations of different Carrington longitudes gathered in the same interval of time can lead to simultaneous T_{OBS} between the two observatories and hence to duplicate T_{REC} entries in the database, where the observation of one instrument would be overwritten by the other. Therefore, when producing a synoptic map using data from both instruments, SO/PHI observations are assigned the T_{REC} values of the closest SDO/HMI observation of the respective Carrington longitude. This effectively sorts the combined data set by the observed Carrington longitude and thus avoids conflicts arising from simultaneous observation times.

Carrington rotation. The system of Carrington rotations was originally defined for observations from an Earth perspective. Observing at large orbital separations leads to cases where SO/PHI already sees a given longitude before or after it was visible for SDO/HMI (i.e. in a past or future Carrington rotation). This is also the case for the presented map. Here, SO/PHI observations take place during the period of CR 2240, but it already sees the high longitudes of CR 2241 as observed by SDO/HMI two weeks later. Assigning these longitudes to the closest T_{REC} slots (see previous point) moves them into the processing period for CR 2240.

Observation cadence. Unlike the stable cadence of SDO/HMI observations, the cadence for SO/PHI changes depending on the observation programme and spacecraft telemetry. In this case, it ranges from 2 to 48 h, with the majority of the data being provided at a cadence of one observation every 24 h (see T_{OBS} intervals in Table 1).

Solar rotation. Another complication stems from the constantly changing apparent solar rotation as seen by SO/PHI from the perspective of the highly elliptical orbit of Solar Orbiter. Consequently, a constant observation cadence results in unequally sampled Carrington longitudes. As a result, the temporal spacing of T_{REC} , which is defined for a geocentric observer, is different from that for T_{OBS} .

Spacecraft distance. The elliptical orbit also affects the observed solar disk size, which directly depends on the heliocentric distance from which SO/PHI observes. At certain phases of the orbit, the distance can vary by several tenths of an astronomical unit over the course of a Carrington rotation. In the present case, the data set was obtained during a perihelion approach in the mission’s cruise phase, which led to a fairly constant distance of about 0.5 au. Therefore, the observed solar disk sizes in pixels for SO/PHI are about 28% of the SDO/HMI disk size at 1 au.

We also note that the SO/PHI data used in this work have been treated with preliminary reduction and calibration software. Hence, some artefacts may not have been completely removed.

3. Results

The nominal observation time for CR 2240, as seen by SDO/HMI, lasted from 2021-01-22, 06:31:17 to 2021-02-18, 14:42:57. During this period SDO/HMI observed the full range of longitudes in descending order starting at 360° . About two weeks later, starting on 2021-02-05, 02:30:45, the high longitudes were revisited by SO/PHI, which enabled us to replace data obtained earlier by SDO/HMI. While SO/PHI was observing magnetograms centred on the high longitudes, SDO/HMI was covering the lower longitudes, making SO/PHI’s first observation the starting time for the multi-view synoptic map. The

Table 1. Overview of SO/PHI and SDO/HMI observations used to construct the multi-view synoptic map for CR 2240.

	Index	Observation time [T_OBS]	Record time [T_REC]	Carrington longitude [°]	Carrington rotation	Distance from Sun [au]
PHI 1	1	2021.02.05_02:30:45	2021.01.22_10:23:56	357.89	2241	0.49985
	2	2021.02.05_04:30:46	2021.01.22_12:04:28	356.97	2241	0.49968
	3	2021.02.05_06:30:46	2021.01.22_13:44:43	356.06	2241	0.49952
	4	2021.02.05_08:30:46	2021.01.22_15:24:42	355.14	2241	0.49936
	5	2021.02.05_11:00:45	2021.01.22_17:29:21	353.99	2241	0.49917
	6	2021.02.05_14:30:45	2021.01.22_20:23:38	352.39	2241	0.49890
	7	2021.02.05_16:30:45	2021.01.22_22:03:18	351.48	2241	0.49875
	8	2021.02.05_18:30:45	2021.01.22_23:43:08	350.56	2241	0.49861
	9	2021.02.05_20:00:45	2021.01.23_00:58:10	349.87	2241	0.49850
	10	2021.02.05_22:30:45	2021.01.23_03:03:32	348.73	2241	0.49832
	11	2021.02.06_00:30:45	2021.01.23_04:44:03	347.81	2241	0.49818
	12	2021.02.06_06:30:46	2021.01.23_09:45:58	345.07	2241	0.49778
	13	2021.02.06_12:00:45	2021.01.23_14:21:22	342.55	2241	0.49743
	14	2021.02.07_12:30:46	2021.01.24_10:45:14	331.36	2241	0.49612
	15	2021.02.09_12:30:45	2021.01.26_02:36:34	309.47	2241	0.49468
	16	2021.02.10_12:30:45	2021.01.26_22:32:34	298.54	2241	0.49453
	17	2021.02.11_12:30:45	2021.01.27_18:29:45	287.61	2241	0.49477
	18	2021.02.12_12:30:45	2021.01.28_14:27:20	276.67	2241	0.49539
	19	2021.02.13_12:30:45	2021.01.29_10:24:45	265.72	2241	0.49638
	21	2021.02.14_12:30:45	2021.01.30_06:22:44	254.75	2241	0.49775
	22	2021.02.15_12:30:45	2021.01.31_02:23:08	243.76	2241	0.49949
	23	2021.02.16_12:30:45	2021.01.31_22:27:28	232.75	2241	0.50159
	24	2021.02.17_12:30:46	2021.02.01_18:35:55	221.72	2241	0.50403
	25	2021.02.18_12:30:46	2021.02.02_14:47:43	210.65	2241	0.50682
	26	2021.02.19_12:30:45	2021.02.03_11:02:18	199.54	2241	0.50993
HMI 1		2021.02.02_15:59:53	2021.02.02_16:00:00	209.98	2240	0.98536
		2021.02.02_16:11:53	2021.02.02_16:12:00	209.87	2240	0.98535
		...				
		2021.02.18_14:23:54	2021.02.18_14:24:00	0.19	2240	0.98833
HMI 2		2021.02.18_14:35:54	2021.02.18_14:36:00	0.08	2240	0.98832
		2021.02.03_14:35:53	2021.02.03_14:36:00	197.59	2240	0.98560
		2021.02.03_14:47:53	2021.02.03_14:48:00	197.48	2240	0.98559
		...				
PHI 2		2021.02.15_12:23:54	2021.02.15_12:24:00	40.79	2240	0.98787
		2021.02.15_12:35:54	2021.02.15_12:36:00	40.68	2240	0.98786
	27	2021.02.01_12:30:45	2021.02.15_18:21:59	37.51	2240	0.50918
	28	2021.02.02_12:30:45	2021.02.16_14:36:45	26.41	2240	0.50614
	29	2021.02.03_12:30:45	2021.02.17_10:46:30	15.35	2240	0.50343
	30	2021.02.04_00:30:46	2021.02.17_20:48:46	9.83	2240	0.50221
	31	2021.02.04_06:30:46	2021.02.18_01:49:24	7.07	2240	0.50163
	32	2021.02.04_12:30:45	2021.02.18_06:51:48	4.31	2240	0.50107

Notes. The observations are ordered by Carrington longitude for each instrument, which is chronological from the SDO/HMI point of view. This puts the first SO/PHI observation at index 27. Data in HMI blocks 1 (1761 data sets) and 2 (1431 data sets) are provided at a 12 min cadence. They are used for different versions of the synoptic map. All times are given in international atomic time (TAI).

combined observation process concluded when SDO/HMI reached the prime meridian on 2021-02-18, 14:42:57.

The resulting multi-view synoptic map can be seen in Fig. 1. It consists of two zones, with the low longitudes being observed by SDO/HMI $\phi = [0^\circ, \dots, 210^\circ]$ (yellow rectangle, HMI 1 in

Table 1) and the remaining longitudes $\phi = [210^\circ, \dots, 360^\circ]$ being covered by SO/PHI (red rectangle, PHI 1 (1–25) in Table 1). The start and end dates for the observation of each sector are indicated in the lower corners of each coloured box in the figure. This cuts the combined observation time of

Fast SO/PHI & SDO/HMI Multi-view Synoptic Map CR2240

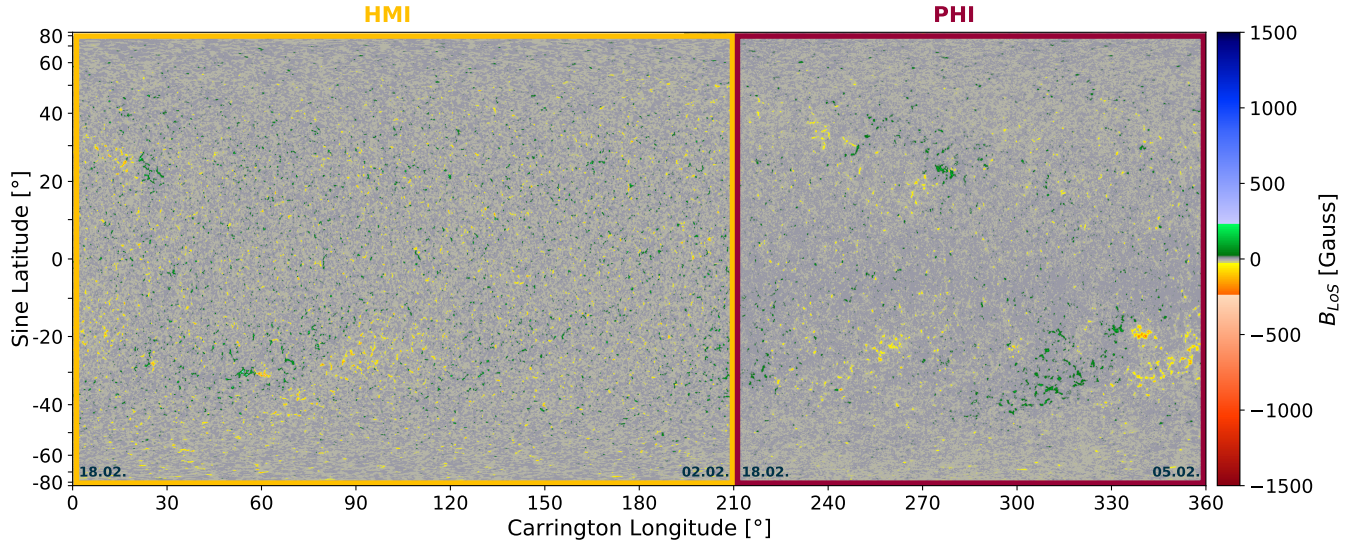


Fig. 1. Synoptic map covering CR 2240 based on SO/PHI observations 1–25 and SDO/HMI block 1 (Table 1). The coloured sectors show the SO/PHI (red) and SDO/HMI (yellow) contributions at different longitudes. The dates (DD.MM) in the corners of the marked SO/PHI and SDO/HMI contributions indicate the start (right) and end (left) dates of each sector.

SO/PHI & SDO/HMI Multi-view Synoptic Map CR2240

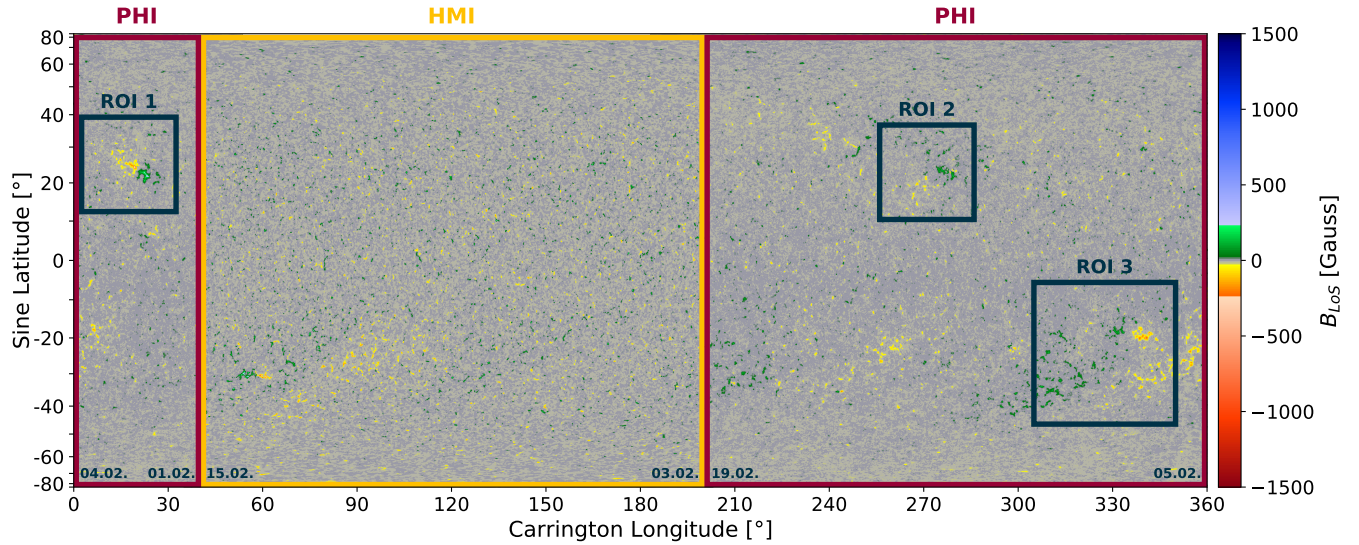


Fig. 2. Annotated synoptic map covering CR 2240 from SO/PHI observations 1–32 and SDO/HMI block 2 (Table 1). The coloured sectors show the SO/PHI (red) and SDO/HMI (yellow) contributions at different longitudes. Three regions of interest (ROI) are marked, which are displayed individually in Fig. 3. The dates (DD.MM) in the corners of the marked SO/PHI and SDO/HMI contributions indicate the start (right) and end (left) dates of each sector.

SO/PHI and SDO/HMI down to 16 days, which is about 60% of the full 27-day Carrington rotation required for a standard synoptic map. Consequently, the intrinsic magnetic evolution that is usually present over the 27 days is also significantly reduced.

The synoptic map shown in Fig. 1 covers a fairly quiet period at the start of solar cycle 25. In order to better show the magnetic field evolution and the difference that having two vantage points makes, we included additional data with more activity from the beginning of the SO/PHI observation campaign (see Fig. 2). As a result, the SO/PHI observations entering the synoptic map start four days earlier, on 2021-02-01, 2:30:45, so they now also

cover the low longitudes between $\phi = 0^\circ$ and 40° (PHI 2 in Table 1). Soon afterwards, SO/PHI crossed the prime meridian and thus covered high longitudes. We replaced the SDO/HMI data obtained earlier by these SO/PHI data (PHI 1 in Table 1), as was previously done for the map shown in Fig. 1. The observation process for this version concludes with the last SO/PHI data on 2021-02-19, 12:30:45, which results in a combined synoptic map that is completed in 18 days.

For the analysis of this synoptic map, we identified three regions of interest (ROI), tracking the active regions NOAA 12799 (ROI1), NOAA 12803 (ROI2), and NOAA 12797 and 12798 (ROI3). They are indicated by the dark blue squares in

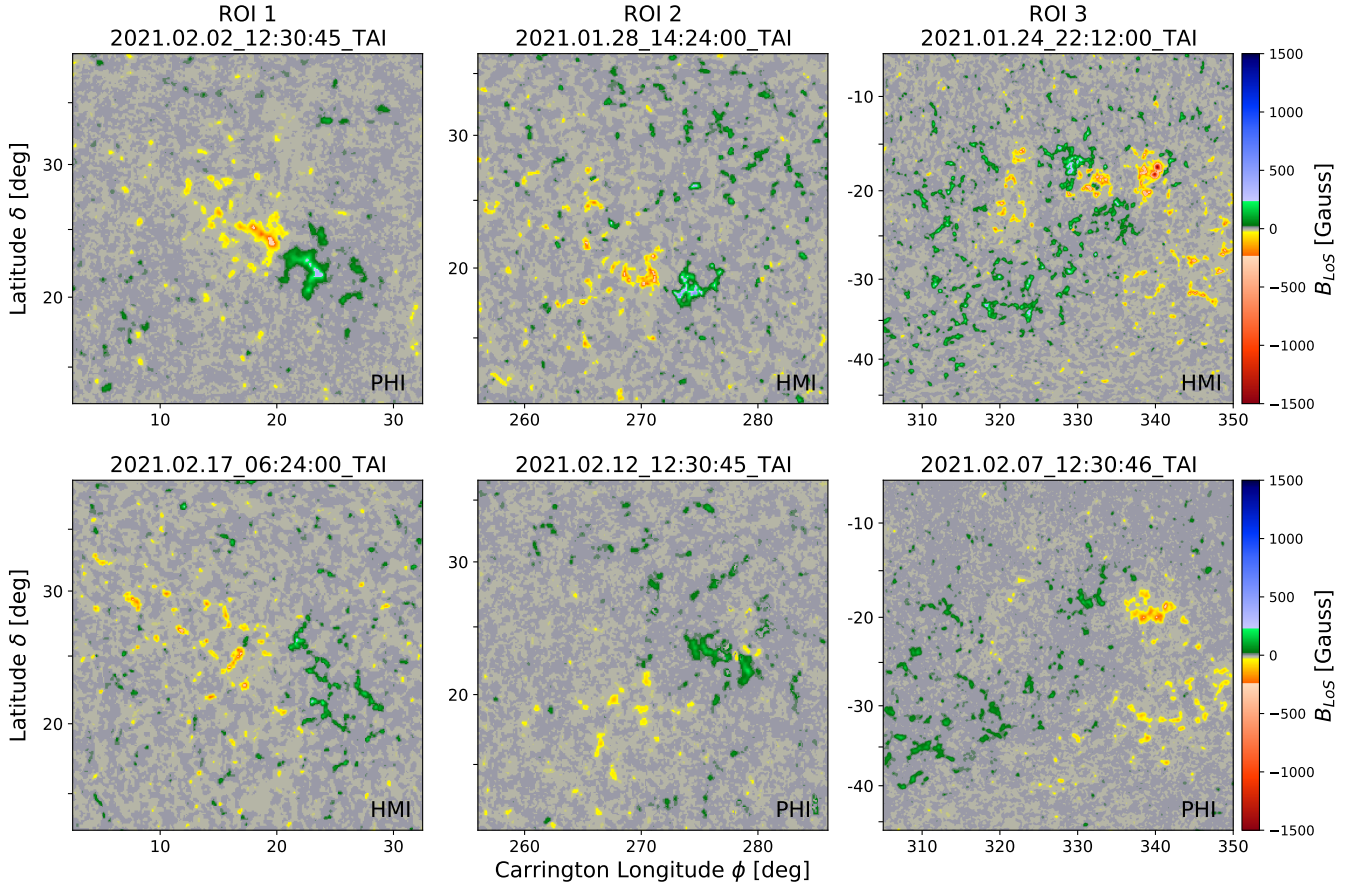


Fig. 3. Three regions of interest showing significant magnetic evolution between the SO/PHI and SDO/HMI observations. The panels in each column show the same region as observed at different times, with the top row showing the earlier observation. Regions 2 (NOAA 12803) and 3 (NOAA 12797 and 12798) were first observed by SDO/HMI and were observed about two weeks later by SO/PHI (see dates and times above the panels). Region 1 (NOAA 12799) was observed in reverse order, first by SDO/HMI and then by SO/PHI.

Fig. 2. A detailed view is provided in Fig. 3, which includes both SO/PHI and SDO/HMI views of the ROIs.

ROI1 was first observed by SO/PHI, whereas ROI2 and ROI3 were first seen by SDO/HMI. The time between visits by the two instruments for each ROI is about 14 days. The overall field configuration was largely maintained over these roughly two weeks, with the patches of a given polarity remaining at approximately the same position. On smaller scales, however, the regions differ significantly. Each of them shows a decay and dispersal of the line-of-sight flux over time (see Fig. 3), with denser and larger magnetic structures in the earlier snapshot and a more dispersed magnetic field in the later snapshot. Consequently, the synoptic map plotted in Fig. 1 is not only the fastest possible based on the available two data sets, but it also gives a temporally more consistent state. Capturing the magnetic evolution at this reduced timescale is expected to bring significant improvements to solar wind speed prediction (Pevtsov et al. 2020), as delaying the observation by even a single active region for only five days can lead to persistent differences in the open magnetic flux as well as in the location of open magnetic foot points on the solar surface (Weinzierl et al. 2016). Unfortunately, the preliminary nature of the SO/PHI-FDT calibration does not yet allow for such extrapolations with sufficient accuracy to permit a detailed comparison with results based on the classical SDO/HMI synoptic maps. We plan to follow up on this work as soon as data of suitable quality becomes available. This also includes the addition of SO/PHI far side magnetograms to the SDO/HMI synchronic map, resulting

in synchronic maps with similar coverage, as seen in the EUV counterparts from STEREO (Caplan et al. 2016). In addition, a more quantitative analysis of the magnetic field evolution of the active regions is to be presented by Strecker et al. (in prep.).

4. Conclusions

We present the first ever synoptic map of the solar magnetic field from multi-view observations based on SO/PHI and SDO/HMI data. Thanks to the nearly optimal orbital alignment of the two spacecraft, we were able to produce a synoptic map of CR 2240 from data gathered over only 16 days (i.e. only 60% of the time normally required). This constitutes a significant reduction of the time lag between the newest and oldest magnetic information in the map and, hence, the highest degree of temporal consistency attained so far. A comparison with a synoptic map based on a single viewpoint (SDO/HMI) showed clear signs of evolution in all three of the largest bipolar magnetic regions present during CR 2240. Consequently, a purely SDO/HMI-based synoptic map would visibly suffer from the considerably longer time needed to construct it.

Going forward, the presented result provides a strong case for using multi-view synoptic maps (if available) in any applications that would ideally require a global snapshot of the solar magnetic field. Such maps are also a viable supplement to global maps created with helioseismic holography (Lindsey & Braun 2000; Chen et al. 2022; Yang et al. 2023a,b), which come with

the advantage of being more instantaneous, though they lack in resolutions and do not provide information on the magnetic polarity.

The disadvantage of Solar Orbiter’s orbit for this purpose is that it is behind the Sun only for a short amount of time, so multi-view synoptic charts will generally require more time to be made than the ideal 13.5-day minimum. A magnetograph at a fixed third vantage point, such as the Photospheric Magnetic Field Imager (PMI; Staub et al. 2020) onboard ESA’s Vigil mission at the Lagrange L5 point, would enable a constant stream of data to make multi-viewpoint synoptic maps of the magnetic field, although with a smaller gain in time than what Solar Orbiter occasionally allows.

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