Open Access Online Journal on Astronomy and Astrophysics

Acta Astrophysica Taurica

www.astrophysicataurica.org

Acta Astrophys. Tau. 1(2) 1–5 (2020)

doi:10.31059/aat.vol1.iss2.pp1-5

Sunspot magnetic fields: a comparison between the CrAO and SDO/HMI data

R.A. Biktimirova[1], V.I. Abramenko[2]

[1] Ural Federal University after the First Russian President B.N. Yeltsin, Ekaterinburg 620026, Sverdlovsk region, Russia
e-mail: bictr97@gmail.com

[2] Crimean Astrophysical Observatory, Nauchny 298409, Crimea
e-mail: vabramenko@gmail.com

Submitted on February 3, 2020

ABSTRACT

We performed a digitization of maximum magnetic field measurements in sunspots. The original data were acquired as drawings at the Crimean Astrophysical Observatory of the Russian Academy of Sciences (CrAO RAS). About 1000 sunspots observed in 2014 have been analyzed. The data were compared to the corresponding measurements from the SDO/HMI instrument (with both the line-of-sight magnetic field $B_z(HMI)$ and the modulus of the magnetic field vector $B(HMI)$). For the same sunspot, the maximum modulus of the magnetic field derived at CrAO was compared to the corresponding value from HMI. The Crimean data and the space-based data (of both types) were found to be in direct proportion to each other. A linear approximation over the entire range of measurements (1–4) kilogauss (kG) shows a Pearson correlation coefficient of 0.71 (with the 95 % confidence boundaries of 0.68–0.74) and a slope of linear regression of 0.65±0.02 for both types of the space-based data. A linear approximation over the range of strong fields $B(CrAO) > 1.8$ kG gives a similar correlation, however the slope of linear regression is far closer to unity and constitutes 0.90 for the relationship ($B_z(HMI)$ vs $B(CrAO)$) and 0.84 for the relationship ($B(HMI)$ vs $B(CrAO)$). In the range of weak fields $B(CrAO) < 1.8$ kG, a non-linear deviation (exceeding) of the space-based data is observed. Non-linearity can be explained, in part, by a specific routine of the magnetic field measurements at CrAO, however further investigations are needed to explore sources of possible non-linearity in the HMI data. The Crimean measurements of the maximum magnetic field in sunspots are concluded to be in good agreement with the corresponding SDO/HMI measurements, and therefore they can be used for scientific purposes.

Key words: Sun, magnetic fields

1 Introduction

The Sun and its emitted energy are a major source of life on the Earth. This raises interest to the solar physics problems. The solar magnetic field is responsible for the solar activity which reveals itself as flares, generating huge mass ejections into the heliosphere and fluxes of accelerated charged particles. These factors affect the space weather in the vicinity of our planet. Owing to these reasons, the solar magnetic field measurements are of great interest. A solar cycle, lasting for about 11 years, manifests itself as a transfer between two global solar magnetic field components: the large-scale magnetic dipole (poloidal magnetic field) and the toroidal magnetic field owing to solar dynamo. Throughout the cycle maximum, active regions often originate, and strong flares are a result of explosive magnetic energy release from the active region. To elaborate effective methods for flare prediction, it is required to know as much as possible about a dynamo process, about both its theoretical background and regularities of its manifestations in the past, and principally about sunspots and a magnetic field in them. In the context of this, of special importance are long time series of homogeneous sunspot magnetic field measurements.

An archive of maximum sunspot magnetic fields[1] has been compiled at the Crimean Astrophysical Observatory since 1956 (about 6 solar cycles). To have a possibility of applying the compiled data, their validation is needed, i.e. by comparing magnetic field values obtained at CrAO and the magnetic fields derived with modern solar instruments, to set up a physical correspondence of the measured values, their measurement accuracy and the presence or absence of systematic deviations.

2 Technique for measuring magnetic fields

2.1 Measurements and a method for deriving magnetic field vector values at CrAO

A value of the maximum magnetic field and its polarity in a sunspot is measured at CrAO by the technique suggested in (Severnyi, Stepanov, 1956). The technique lies in measuring a splitting of the FeI 6302 Å spectral line affected

[1] https://sun.crao.ru/observations/sunspots-magnetic-field

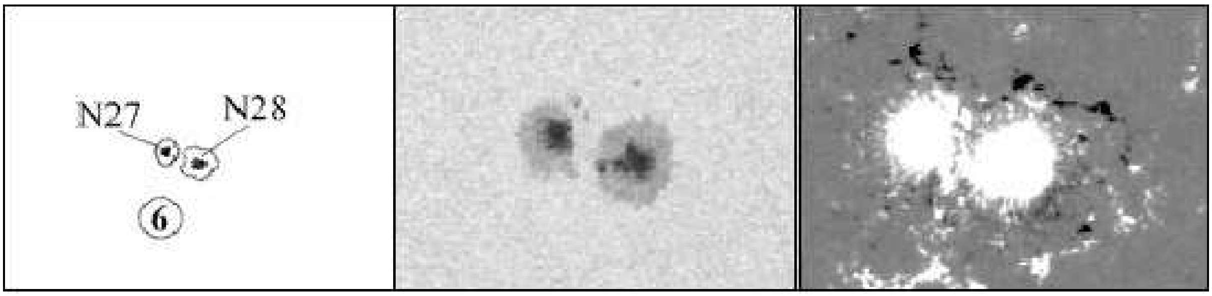

Fig. 1. Example of comparing sunspot magnetic fields. Left: a drawing of sunspot magnetic fields performed at CrAO (the letter denotes polarity, numbers – the field strength in hundreds of Gauss); center: a HMI image of the active region in white light; right: a HMI magnetogram. The maximum longitudinal magnetic field strength from the HMI data in the left (right) spot is 2480 (2270) G, the maximum strength of the modulus of the full magnetic field is 2610 (2530) G

by the magnetic field by means of the polaroid mosaic. The polaroid stripes alternately emanate fluctuations in mutually perpendicular directions. In front of the mosaic there is a quarter-wave plate to transform circular polarization into linear one. The zigzag-shaped image of a line allows one to determine the sign of the field along the line-of-sight. The absolute magnetic field magnitude $|\mathbf{B}|$ in G is derived from the line shift using the formula (Plotnikov, Kutsenko, 2018):

$$\Delta\lambda = g\frac{\lambda^2 e}{4\pi m_e c^2}|\mathbf{B}|, \tag{1}$$

where λ is the spectral line wavelength; B – the magnetic field strength in Gauss; g – the Lande factor; m_e – the electron mass; c – the speed of light (cm/s). Fields with a maximum strength of less than 1000 G cannot be measured this way. But if one considers only fields in spots, then this constraint is insignificant because the magnetic field in pores and spots is typically no less than 1000 G (Steshenko, 1967). The measurement accuracy is 100 G. The measured field values are plotted on drawings in hundreds of Gauss, indicating the polarity, e.g. N27 means +2700 G (see Fig. 1, left).

Table 1. File fragment of comparing magnetic fields

Date	Time, UT	NOAA	$B(CrAO)$, G	$Bz(HMI)$, G	$Bf(HMI)$, G
2014.06.08	07:55	12085	−1000	−1700	−2190
2014.06.08	07:55	12085	−1000	−1780	−2120
2014.06.08	07:55	12085	−1000	−1200	−1200
2014.06.08	07:55	12085	−1900	−2200	−2500
2014.06.08	07:55	12085	−2000	−1920	−2100
2014.06.08	07:55	12085	−1800	−1840	−1880

The results of magnetic field measurements are posted as drawings on the CrAO website. In the following, it is required to enter these magnetic field values into the text table file for further comparing with the SDO/HMI data. A fragment of the text file is represented in Table 1.

2.2 Technique for extracting data from SDO/HMI

For the comparison with magnetic field data acquired at CrAO we used data taken with the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO/HMI, Schou et al., 2012). Magnetic field measurements at the station have been carried out in the FeI 6173 Å line since 2010. For the comparison we took the year 2014 – a year of solar cycle 24 maximum.

To extract the SDO/HMI data, we had to find the corresponding group of sunspots and to download the appropriate magnetogram and the image in white light available on the Joint Science Operations Center (JSOC) website [2]. We used magnetograms of both the longitudinal field component (line-of-sight, hmi.M-720s) and modulus of the full magnetic field vector from SDO/HMI (hmi.sharp-720s) with a spatial resolution of $1''$ (the pixel size is $0.5''$) and a noise level of about 6 G (Liu et al., 2012). Using the method of visual control, each active region on the Sun observed at CrAO was compared to the corresponding active region taken with SDO/HMI based on an image in white light and a magnetogram (Fig. 1). Then for each sunspot recorded at CrAO, using the IDL program, the maximum strength of the longitudinal magnetic field and that of the modulus of the full magnetic field vector was determined in the HMI map. Results were imported into the corresponding column of Table 1. 991 sunspots have totally been processed.

3 Results

If we represent data of our table file graphically as a dependence of space-based measurements on ground-based ones and take into account the field sign, then the result of statistical reduction, e.g. the correlation coefficient, turns out to be artificially exaggerated because all the points are grouped in the form of a dumbbell in the first and third quadrants. To gain more objective information on the character of the dependence, it is suggested comparing absolute field magnitudes. Such an approach is justified since for 98 % of cases the field sign coincided on ground-based and space-based data. Spots with divergence in sign were not taken into account.

[2] http://jsoc.stanford.edu

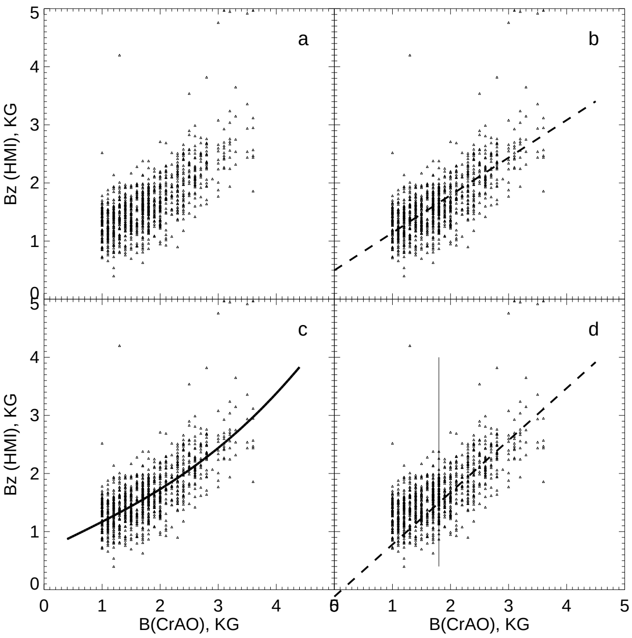

Fig. 2. Diagram of the relation between the magnetic field modulus measured at CrAO and the modulus of the longitudinal magnetic field component measured with SDO/HMI, and various kinds of data approximation: (a) no approximation; (b) linear approximation over the whole variety of data; (c) non-linear approximation using Formula (2); (d) linear approximation using data of $|B(CrAO)| > 1800$ G (vertical line). Axes are in kilogauss (kG). Parameters of linear and non-linear approximations are listed in Table 2 and Table 3, respectively

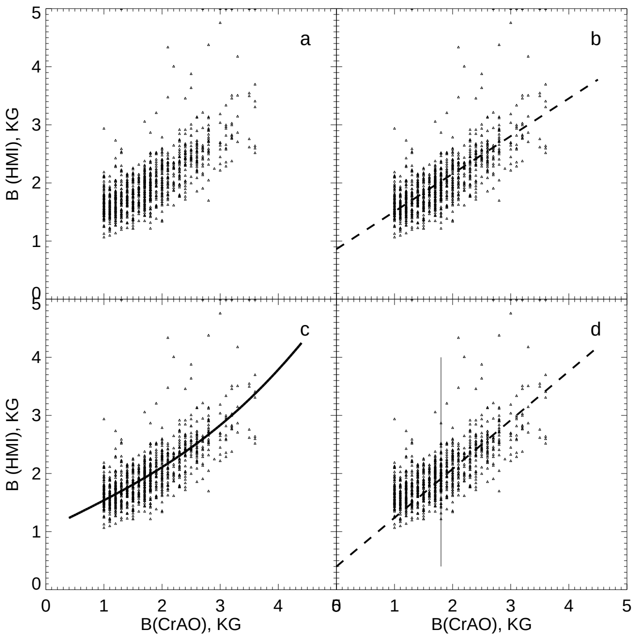

Fig. 3. Diagram of the relation between the magnetic field measured at CrAO and the modulus of the full magnetic field vector measured with SDO/HMI, and various kinds of data approximation: (a) no approximation; (b) linear approximation over the whole variety of data; (c) non-linear approximation using Formula (2); (d) linear approximation using data of $|B(CrAO)| > 1800$ G. Parameters of linear and non-linear approximations are listed in Table 2 and Table 3, respectively

Table 2. Parameters of linear approximation

Parameter	$B(CrAO) - Bz(HMI)$, (1–4) kG interval	$B(CrAO) - Bz(HMI)$, (1.8–4) kG interval	$B(CrAO) - B(HMI)$, (1–4) kG interval	$B(CrAO) - B(HMI)$, (1.8–4) kG interval
N	991	377	991	377
ρ	0.708	0.650	0.712	0.606
95 %(ρ)	0.676–0.737	0.588–0.704	0.680–0.741	0.538–0.666
χ^2	142.7	73.1	140.6	80.8
reduced χ^2	0.144	0.194	0.142	0.214
slope	0.646 ± 0.020	0.897 ± 0.054	0.648 ± 0.020	0.840 ± 0.037
y_{sect}, kG	0.50 ± 0.04	-0.12 ± 0.13	0.86 ± 0.04	0.40 ± 0.08

A diagram of comparing absolute magnitudes of the Crimean data $(B(CrAO))$ and space-based data on the longitudinal field $B_z(HMI)$ is shown in Fig. 2. An analogous diagram of comparing with the full vector $B(HMI)$ is shown in Fig. 3. Panel a demonstrates that there exists a direct proportion between data, however, with a hint at non-linearity. For the longitudinal field, the linear approximation on the whole data set (Panel b) exhibits the correlation coefficient 0.708 and intersection of the regression line with the vertical axis in a point of about 0.5 kG and a slope of less than unity (parameters of linear approximation are listed in Table 2); this provides evidence for some exceeding of the HMI measurements in weak fields and, contrary, some diminishing in strong ones.

In (Pevtsov et al., 2019), through the magnetic field measurement by a method that is similar to what is used at CrAO, the non-linearity was shown to appear associated with using a glass plate for measuring a shift in the dispersion direction. The splitting of sigma components Δx (that is directly proportional to the field, see Expression (1) in Pevtsov et al., 2019) is non-linearly associated with the measured angle of plate's rotation α (Expression (2) in Pevtsov et al., 2019):

$$\Delta x = tsin(\alpha)(1 - \frac{cos(\alpha)}{\sqrt{n^2 - sin^2(\alpha)}}), \quad (2)$$

where t and n are the thickness and refraction coefficient of the plate. If one assumes that Crimean measurements are a proxy of the rotation angle and the space-based measurements are a proxy of the real field, then Formula (2) may be applied for data approximation. Panels c of Figs. 2 and 3 show the result of applying a linear approximation, following the expression:

$$B_z(HMI) = C_0 + C_1\Delta x, B(HMI) = C_0 + C_1\Delta x, \quad (3)$$

where the scaling coefficients C_1 and shifts along the vertical axis C_0 are picked together in such a way that the approximating curve optimally described data (in order the value χ^2 to be at least not higher than that for linear approximation). The approximation parameter values are listed in Table 3.

Table 3. Parameters of non-linear approximation

Parameter	$B(CrAO)$ – $Bz(HMI)$, (1–4) kG interval	$B(CrAO)$ – $B(HMI)$, (1–4) kG interval
N	991	991
C_0, kG	0.68±0.02	1.04±0.02
C_1	1.12±0.04	1.14±0.06
χ^2	138.9	137.4
reduced χ^2	0.140	0.139

Following the criterion χ^2, this approximation is better than the linear one (Panel b), but quite insignificantly. However, there is an important peculiarity which does not allow us to suppose this type of approximation to be best-fit and fully reflecting the reality. Specifically, a non-linearity between the splitting and rotation angle is characterized by the fact that it is quite weak in weak fields and it strengthens in strong ones (Pevtsov et al., 2019). However, the distribution of data shows an inverse picture (see Panel d): linear dependence is better manifested in strong fields, and in weak fields (approximately less than 1.8 kG) there is a visible non-linear exceeding of space-based data. From Fig. 2 (Panel d) it follows that for data of $B(CrAO) > 1.8$ kG, an intersection of the regression line with the vertical axis occurs in a point of about -0.1 kG; this is significantly better than for the linear regression over the whole data (for comparison see Panel b) and provides evidence in favor of the fact that the linearity between the Crimean and HMI data is better in the region of strong fields. An analogous conclusion may be drawn from Fig. 3. Thus, we cannot confidently conclude that the non-linear character of the statistical association between data from HMI and those from CrAO is caused solely by peculiarities of the Crimean measurement technique.

A comparison of Figs. 2 and 3, as well as data in Tables 2 and 3, shows that there is no significant difference in approximation parameters when comparing Crimean data with the longitudinal or full field from HMI. There seems to be a faint hint at better agreement with $B_z(HMI)$ (a slope of the regression line is closer to unity and the intersection point with the vertical line is closer to zero for the pair $B(CrAO)$ – $B_z(HMI)$ than for the pair $B(CrAO)$ – $B(HMI)$). However, this conclusion needs to be further clarified based on larger statistical material.

4 Conclusion

In the course of implementing the work, the data on the magnetic field $B(CrAO)$ have been digitized from drawings of about 1000 sunspots observed at CrAO in 2014. These data were compared to the SDO/HMI data (magnetic field values of the line-of-sight $B_z(HMI)$ and modulus values of the full magnetic field vector $B(HMI)$). The maximum values of the field modulus were compared in the same sunspots. Results of this comparison may be formulated as follows.

There is a direct proportion between the Crimean data and space-based data of both types.

The linear approximation for the whole interval of field measurements (1–4) kG shows a Pearson correlation coefficient of 0.71 (95 % confidence interval: 0.68–0.74) and a slope of linear regression 0.65 ± 0.02 for both $B_z(HMI)$ and $B(HMI)$.

In diagrams ($B_z(HMI)$ vs $B(CrAO)$) and ($B(HMI)$ vs $B(CrAO)$), a non-linearity of the statistical relation is clearly traced: the statistical dependence is noticeably flatter in the region of weaker fields $B(CrAO) < 1.8$ kG. The linear approximation in the region of strong fields $B(CrAO) > 1.8$ kG shows nearly the same correlation coefficient, but a significantly closer to unity slope of linear regression: 0.90 for ($B_z(HMI)$ vs $B(CrAO)$) and 0.84 for ($B(HMI)$ vs $B(CrAO)$). This fact means that in the region of strong fields the Crimean and HMI data fit each other better than in the region of weak fields.

A non-linear dependence was also tested based on the non-linear relation between the measured rotation angle of the glass plate and magnitude of the recorded field (Pevtsov et al., 2019). This approximation is statistically better than linear, but quite insignificantly. However, the character of this functional non-linearity (quasi-linearity in weak fields and a growth of non-linearity with increasing field) is not consistent with the observed type of non-linearity (non-linear exceeding of the space-based values in weak fields and improvement of linear association in strong ones). There seem to exist other implicit reasons for non-linearity associated with peculiarities of the field measurements with SDO/HMI.

A degree of statistical agreement of the Crimean data with the longitudinal field derived with HMI is approximately the same as with the HMI full vector at rather weak advantage in favor of the longitudinal field. To clarify this conclusion, further studies are presumably needed based on extensive statistical material, moreover at different phases of a solar cycle.

The conclusion was made that the data from magnetic field measurements at CrAO over 2014 exhibit a good agreement with values acquired with such a present-day spacecraft as SDO/HMI, therefore they may be applied for scientific purposes.

Note that the recently carried out comparisons (Pevtsov et al., 2019) of magnetic fields in sunspots based on measurements at different observatories: CrAO, Mount Wilson Observatory (MWO) and with the Vector Stokes Magnetograph (VSM) at the Synoptic Optical Long-term Investigation of the Sun (SOLIS) facility have shown a good agreement of data and, consequently, a possibility of complementing one series with another one without sacrificing reliability of conclusions. Thus, the Crimean data on magnetic field measurements in sunspots still have their scientific importance.

In future we plan to open access to magnetic field data via internet, particularly in the form of collaboration with the Kislovodsk Mountain Astronomical Station GAO. These data may be used for studying regularities of the solar cyclicity regarding next solar cycles and, consequently, space weather in the near-earth space.

Acknowledgements. Authors acknowledge the referee for a number of helpful comments and suggestions which helped to improve the manuscript.

References

Liu Y., Hoeksema J.T., Scherrer P.H., et al., 2012. Solar Phys., vol. 279, pp. 295–316.

Pevtsov A.A., Tlatova K.A., Pevtsov A.A., et al., 2019. Astron. Astrophys., vol. 628, id. A103.

Plotnikov A.A., Kutsenko A.S., 2018. Izv. Krymsk. Astrofiz. Observ., vol. 114, no. 2, pp. 87–96. (In Russ.)

Severnyi A.B., Stepanov V.E., 1956. Izv. Krymsk. Astrofiz. Observ., vol. 16, pp. 3–11. (In Russ.)

Steshenko N.V., 1967. Izv. Krymsk. Astrofiz. Observ., vol. 37, pp. 21–28. (In Russ.)

Schou J., Scherrer P.H., Bush R.I., et al., 2012. Solar Phys., vol. 275, pp. 229–259.