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New Measurements of Magnetic Field of the Sun-as-a-Star: Observations at the Sayan Observatory in 1993-1997

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Abstract. A currently central experimental problem in modern heliophysics is that of measuring global parameters of the Sun. One such parameter, characterizing the Sun as a magnetically variable star, is the mean (general) magnetic field (MMF). Unfortunately, in recent years J.Wilcox Solar Observatory (WSO) at Stanford University has been the only observatory doing regular solar MMF (SMMF) measurements. However, to judge in an unbiased manner the reliability of SMMF observations and results obtained on their basis, it seems appropriate and very useful to compare different observational sequences. Towards this end, an analysis is made of observational data on SMMF obtained with the STOP telescope at Sayan Solar Observatory (SSO) during 1993-1997, or the declining phase of the 22nd activity cycle. During that time interval, after the STOP equipment was step-wise modernized, it was possible to improve significantly the accuracy and reliability of data, as well as to ensure their reasonably high regularity. Correlation and regression analyses of SMMF observations from WSO and SSO showed a very good agreement of the two observational series from 1993 and 1994 and a somewhat poorer agreement for 1995-1997. A certain decrease in correlation is most likely to be caused by a significant fall in SMMF strength during 1995-1997 corresponding to minimum solar activity and, as a consequence, by an increase in the influence of instrumental effects. The paper gives a discussion of some of such effects, as well as of main procedural features of SMMF observations at WSO and SSO.

1. Introduction

A major global parameter that characterizes the Sun as a star is its mean magnetic field (MMF). The solar MMF (SMMF) is the effective longitudinal magnetic field, averaged over the visible hemisphere, which is recorded by the magnetograph in the Sun-as-a-star radiation from the Zeeman splitting of Fraunhoffer lines (usually λ 525.02 nm FeI). In this case an important role in the procedure of physical averaging of local magnetic field performed by the magnetograph is played by different weight functions of solar and instrumental origin (Scherrer 1973).

The current importance of SMMF research derives from several factors. In the first place, such investigations are essential in the problem of solar-stellar analogies. Although the SMMF is significantly weaker as compared with magnetic fields (accessible to observation at present) of other stars, observations of its time variations permit the Sun to be treated as a variable magnetic star. Of vital importance in this context is the study of long-term evolution and magnetic periodicity features (Kotov & Demidov 1980; Kotov & Severny 1983; Rivin & Obridko 1992), the annual variation (Kotov et al. 1981; Rivin 1997), rotation (Kotov & Demidov 1980; Kotov 1987) (including differential rotation (Hejna & Wohl 1993)), and faster changes (Demidov et al. 1990; Demidov 1995). Secondly, since the SMMF is intimately linked with large-scale magnetic fields of the Sun (Scherrer 1973; Kotov et al. 1977) (and is actually determined by them), it is of importance to a better understanding of the origin of solar magnetism, specifically of the peculiarities of the spatial organization of solar activity. And finally, the close association of the SMMF with the sector structure of the interplanetary magnetic field (Severny et al. 1970; Scherrer et al. 1977a,b) determines the important application-oriented and geophysical significance of SMMF observations.

It will be recalled that first SMMF observations were initiated in 1968 at the Crimean astrophysical observatory (CAO) (Severny 1969). Subsequently, in parallel with CAO, regular SMMF measurements were made over a protracted period of time at the Mt. Wilson observatory (MWO) (Scherrer 1973), and since 1975 they have been made at the J.Wilcox Solar observatory (WSO) at Stanford (Scherrer et al. 1977b). Since 1982 such observations have been carried out at the Sayan Solar observatory (SSO) (Grigoryev & Demidov 1987). And there are substantial differences in instruments and techniques of SMMF observation at different observatories.

It should be noted that measuring the SMMF is a very complicated scientific and technical problem. As is known (Stix 1991), in a weak field approximation, the value of the Stokes V parameter in the wings of the λ 525.02 nm FeI line is related to the magnetic field strength H (in μT units) by

$$V \approx 9.6 * 10^{-5} H \tag{1}$$

Since the SMMF strength is usually very small and does not exceed a few hundred μT, and normally it is tens of or even a few μT, the accuracy of polarimetric measurements must be no worse than $10^{-3} - 10^{-4}$. It is understandable that, when recording so small degrees of polarization, results of measurements are affected quite tangibly by numerous instrumental and procedural effects. Therefore, for making unbiased inferences regarding the reliability of SMMF measurements and results derived from them, it is highly important to have and compare data sets obtained with different instruments.

Unfortunately, the only source of regular SMMF observations has been the WSO in recent years. The disadvantages of such a state of affairs are obvious because a major reliability criterion for research results is violated, namely: their reproducibility by different groups of scientists and at different instruments. Furthermore, the availability of observations at different observatories would make it possible to reduce gaps in the data. The intent of this paper is also to address these issues.

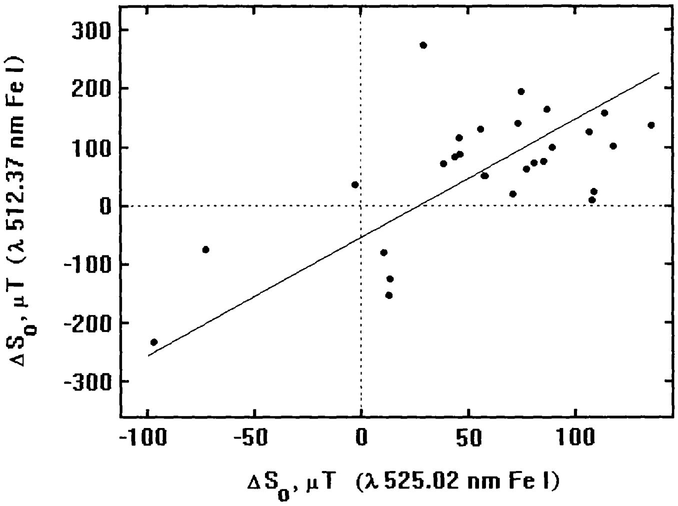

Figure 1. Comparison of the values of zero-level displacements in SMMF observations as measured from recordings in the non-magnetic λ 512.37 nm FeI line and in the λ 525.02 nm FeI line using the $\lambda/2$ phase plate. The slanting solid line shows the linear regression, calculated by RMA method (see equation (2)).

The subject of analysis in this paper includes SMMF observations obtained with the STOP telescope (Grigoryev et al. 1981; Grigoryev & Demidov 1987) at the SSO during 1993 to 1997 (as of June 31). Our choice of this time interval was dictated by the fact that, after STOP was modernized in 1991-1992, it was possible to achieve a higher (than in the preceding years) accuracy and regularity of SMMF observations. For comparison purposes, the corresponding data from the J.Wilcox Solar observatory (WSO) at Stanford were used. Since the method of SMMF measurement at STOP has its own important characteristic properties, first we consider some of them.

2. Some Distinguishing Features Of SMMF Observations at the Sayan Observatory

Since 1992 a new PC-based complex of equipment has been in operation at STOP, which made it possible to make observations on a new, state-of-science level. The computer is employed to final-control the telescope and to collect and pre-treat the data. Measured parameters (brightness, strength, etc.) and equipment status parameters are displayed virtually in real time. This permits the observer to judge promptly the quality of observations. Basic and service information is stored on hard drive files, and after a processing by special processing programs, results are output as observation protocols in tabular and graphic form. A crucial distinguishing feature of the magnetic field observing technique at STOP is the method of monitoring the magnetograph zero-level displacement ΔS_0. It would be remembered that while recordings in the non-magnetic λ 512.37 nm FeI are used for this purpose at the Crimean observatory and at WSO, at STOP we employ recordings with the half-wave ($\lambda/2$) phase plate that

1998ASPC..140..271D

is periodically introduced into the light beam ahead of the coelostat. The accumulation time of a single measurement is usually 20 s (irrespective of recordings with or without the plate); a full run of a single measurement of SMMF requires a minimum time of 25-30 min. In this case the R.M.S. of measurements is typically $\approx 20\ \mu$T, and the arithmetic mean error is $\approx 2\ \mu$T. Special measurements were made at STOP in order to compare the values of ΔS_0, determined by the two methods mentioned above. From analysis of results, which are shown in Fig. 1, it follows that using different methods can lead (at least at STOP) to quite considerable differences. For some reasons (Demidov 1996), the method of choice in this case would be through the use of the $\lambda/2$-plate. The correlation coefficient for the Fig. 1 data (the number of pairs of points N = 27) is $\rho = 0.65$, and the equation of linear regression (calculated by the method of reduced major axis (RMA) and shown in the figure as a slanting straight line) has the form:

$$\Delta S_{0\ (\lambda 512.37)} = -56(\pm 49) + 2.0(\pm 0.3) * \Delta S_{0\ (\lambda 525.02)} \qquad (2)$$

Another important feature is the spectrograph illumination technique used at STOP. As is known, at the CAO the slit is illuminated by a parallel light beam directly from the coelostat (Severny 1969). At WSO (Scherrer et al. 1977b) a special lens is employed, which produces on the slit an appropriately de-focused solar image. In this case the image slicer is used to increase the light flux in the spectrograph. STOP uses a technique similar to the Stanford method, but without the image slicer and with different objective lens parameters (a doublet with F = 5 m, and D = 18 cm). To inquire into the question (all the more important because the STOP objective lens has pronounced polarization properties (Demidov 1996)) of the extent to which results depend on the spectrograph illumination system, SMMF observations were made at STOP using two modes: (1) a standard mode, and (2) without the objective lens, i.e., as done at the CAO, in a parallel beam. The results are shown in Fig. 2. In the latter mode, as a consequence of a decrease in light flux, the noise level increased by a factor of three. And it was found that the zero-level position (Fig. 2, left panel) usually changes considerably with removing of the objective. (It should be noted that significant changes of ΔS_0 are caused not only by removing of the objective lens but also by reducing its aperture). The correlation coefficient of ΔS_0 measurements with and without the objective lens was as low as $\rho = 0.42$ (N = 55), and the equation of linear regression calculated by the RMA method, has the form:

$$\Delta S_{0\ (with\ objective)} = -44(\pm 25) + 1.31(\pm 0.16) * \Delta S_{0\ (without\ objective)} \qquad (3)$$

The comparison of the values of SMMF strengths with two observing modes, shown on the right panel in Fig. 2, revealed their reasonably good agreement (systematic), however. Indeed, the correlation coefficient for the data sets presented in Fig. 2 is $\rho = 0.85$ (N = 48), and the equation of linear regression calculated by the RMA method, is of the form:

$$H_{with\ objective} = 5(\pm 4) + 0.88(\pm 0.07) * H_{without\ objective} \qquad (4)$$

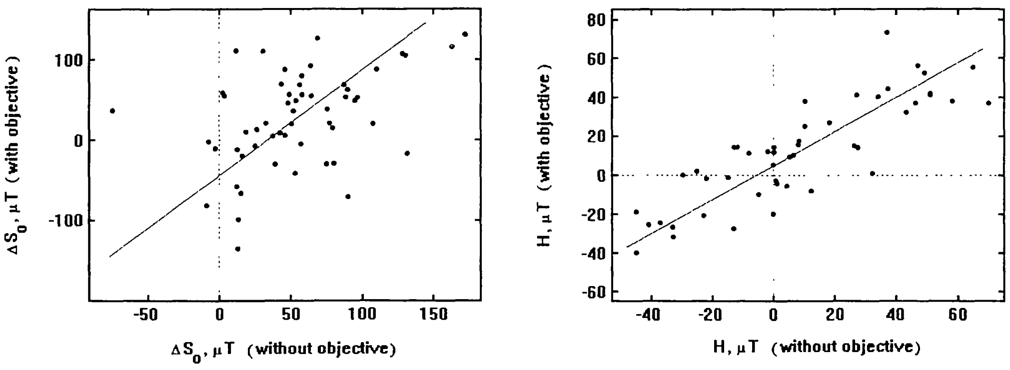

Figure 2. Comparison (in SMMF observations) of the values of zero-level displacements (left panel) and the values of strength (right panel) as measured in the STOP-standard operating mode (with objective) and in a parallel light beam (without objective).

On considering the influence, upon results of SMMF measurements, of some factors of a single instrument, we now make a comparative analysis of the data from different telescopes. Specifically, in the next section we report basic information about the SMMF observations at SSO and results derived by comparing them with the WSO data.

3. Observational Data and Analysis

Basic statistical information about SMMF observations at SSO for the time interval being analyzed is presented in Table 1. One can see that SMMF parameters undergo quite considerable changes. While for the first two years the (amplitude-) averaged SMMF strength was reasonably high ($\geq$ 30 μT), for the subsequent years corresponding virtually to the minimum of solar activity, it became significantly weaker (almost by a factor of two) to be comparable with

Table 1. Basic information about observations of magnetic field of the Sun-as-a-star at the Sayan Solar observatory during 1993-1997

Year	Number of days with obser.	Minim. value	Maxim. value	Mean value	Mean value error	R.M.S.	R.M.S. error
1993	53	-55	88	7.3	4.6	33.6	10.5
1994	151	-63	84	7.7	2.5	30.9	7.4
1995	125	-42	67	7.2	1.8	20.6	5.2
1996	177	-53	49	1.0	1.4	18.7	4.3
1997	106	-36	40	-2.0	1.3	13.6	3.6

instrumental noise. Of course, this inevitably and adversely affected the accuracy of data and, as a consequence, the degree of matching between the Sayan and Stanford data sets.

Results of correlation and regression analyses of SMMF observations at SSO and WSO are listed in Table 2. The regression of the WSO data (set Y) to the SSO data (set X) was calculated, as usually done in this paper, by the RMA method. When analyzing the table, one can see a very accurate agreement (both in amplitude and in the degree of correlation) of two sets of measurements in 1993 and in 1994. Since the WSO observations undoubtedly are most accurate at present, this fact may be regarded as a sound proof for the reliability of the Sayan data. During 1995-1997 the agreement of the two data sets, as would be expected, became poorer. A summary comparison of the SMMF observations from the two observatories for the entire time interval being analyzed (N = 487) is shown in Fig. 3. The slanting straight line shows the linear regression calculated by the RMA method, the parameters of the equation of which are given in the last row of Table 2.

Table 2. Results of correlation and regression analyses of SMMF observations at SSO and WSO during 1993-1997. Parameters of the equation of linear regression $H_{WSO} = A(\pm\Delta A) + B(\pm\Delta B) * H_{SSO}$ are calculated by the method of RMA

Year	Number of observ.	Correl. coeff.	A	ΔA	B	ΔB
1993	50	0.83	-14	6	1.04	0.08
1994	125	0.84	-6	3	0.99	0.05
1995	95	0.63	-7	3	0.85	0.07
1996	127	0.34	-3	2	0.58	0.05
1997	90	0.31	-0.5	2.2	0.78	0.08
1993- -1997	487	0.71	-5.4	1.4	0.91	0.03

4. Discussion and Conclusion

Research into SMMF is an important problem in heliophysics (and in related branches of science) where the role of regular, synoptic observations is especially high. Since the spectrum of SMMF time variations is quite varied (from a few minutes to tens of years), such measurements permit reliable results to be obtained. Also, for checking data obtained, and also for reducing the number of gaps in data sets, it is very important to have and compare observations from different observatories. On earlier occasions, such comparisons for different combinations of observatories (CAO, WSO, MWO , and SSO) were made in (Kotov & Severny 1983; Scherrer et al. 1977a; Grigoryev & Demidov 1987), and

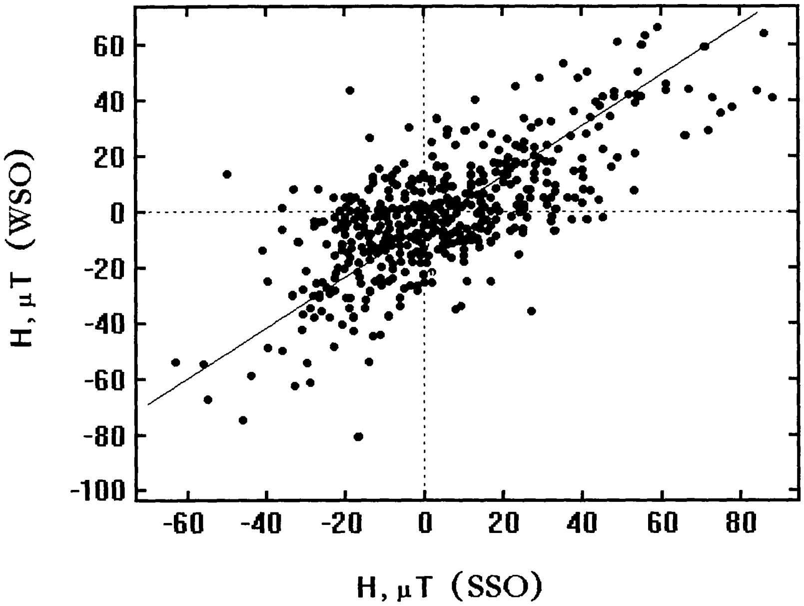

Figure 3. Scatter plot of all same-day pairs of SMMF observations ($N = 487$) for the WSO and SSO observatories for 1993 through middle 1997. The equation of linear regression calculated by the RMA method has the form: $H_{WSO} = -5(\pm 1) + 0.91(\pm 0.03) * H_{SSO}$.

quite significant random and systematic (by factors of 1.5-2) differences were revealed. This paper is devoted to the analysis of the SMMF observations from the SSO observatory for the time interval 1993-1997, and to their comparison with corresponding data from the WSO observatory. It should be recognized that an absolute day-to-day agreement of SMMF observations from different observatories does not seem to be the case because there are a large number of factors which lead (or can contribute) to their difference: a different time of measurement (for example, the difference of the SSO and WSO longitudes is 9.14 hours), differences in procedures of calibration and zero-level monitoring, differences in instrumental weight functions and in parameters of photometer exit slits, etc. Therefore, it is safe to reason that the results reported in this paper reflect the objective reality and betoken a high reliability of the observations, both from WSO and from SSO. Especially representative are the data for the first two years of the time interval being analyzed when, with a very high correlation coefficient, an almost total coincidence of amplitudes occurs. A change in the situation in comparison with that reported in (Grigoryev & Demidov 1987) appears to be caused by a modernization made at STOP in 1991-1992 when the photometer slit parameters were substantially modified. Thus, the availability of a new set of SMMF observations as demonstrated in this paper enhances considerably our knowledge of this important parameter and forms the basis for future investigations planned by these authors with the use of new observations from SSO and WSO, as well as observational data from CAO and MWO.

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Group Discussion

J. Harvey: Do you check the zero point of your sun-as-a-star magnetic measurements by using a $g = 0$ spectrum line?

Demidov: For the routine observations the answer will be: No! For this aim we use quite a different method – observations with half-wave ($\lambda/2$) plate which is periodically introduced into the light beam ahead of the coelostat. The $\lambda/2$ plate changes the sign of the V-Stokes parameter and as a consequence the sign of magnetic field strength. So the zero-level position is $\Delta S_o = (H + H_{\lambda/2})/2$, where H-measurement without $\lambda/2$ plate, and $H_{\lambda/2}$ is with the $\lambda/2$ plate. But sometimes we make measurements of ΔS_o using g=0 spectral line (FeI 5123.7Å), as well. Some aspects of zero-level problem are discussed at the poster by Demidov and Grigoryev (these proceedings) and in the paper by Demidov, published in Solar Physics (1996, 164, 381)