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On the peculiarities of manifestation of kG magnetic elements in observations of the Sun with low spatial resolution

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Abstract. On the agenda of modern astrophysics is the exploration of not only disk-integrated stellar magnetic fields but surface mapping of them. However, it is hardly possible to expect that spatial resolution better than some dozens or hundreds pixels over stellar disk will be achieved for this goal in the foreseeable future. Among other reasons this fact makes very important observations of the average and large-scale magnetic fields of the Sun, which can be naturally used for testing polarimetric measurements on other stars, especially on solar-type stars. In this study we explore different aspects of observations of solar magnetic fields (SMF) with low spatial resolution, including Sun-as-a-star observations, which are characterized by extremely low magnetic flux densities. Comparison of disk-integrated and spatially resolved Stokes observations of the Sun allow us to demonstrate how Stokes V profiles depend on the distribution of large-scale magnetic fields in the disk center. It is shown that center-to-limb variations of magnetic strength ratios (MSR) and area asymetries, most likely could be interpreted as the manifestation of kG magnetic flux tubes. We have made cross-calibration of the full-disk magnetograms obtained by space-borned SDO/HMI and by the ground-based STOP telescope, and pretty good agreement is found. Finally, the absence of significant systematic time variations of MSRs with solar cycle is demonstrated.

Keywords. Sun, Stokes profiles, Sun-as-a-star, magnetic fields, atmosphere

1. Introduction

One of the most important research line in modern solar physics is the investigation of the fine, small-scale structure of the Sun. And many talks at this conference have showed excelent results in this direction. Namely a study of the fine structure of solar atmosphere is the main reason for building the new 4m class solar telescopes (European Solar Telescope, EST; Daniel K.Inouye Solar Telescope, DKIST) or even larger size facilities (Chinese Giant Solar Telescope, CGST). Most of future instrumentation has the goal of high spatial resolution below 100 km. The construction of such telescopes, connected with use of the most advanced technical and computer facilities, are extremely expensive. But fortunately, there are some tasks where the role of solar telescopes with moderate sizes is still important. As an example, many solar, geophysical and astrophysical problems demand a detailed and regular information about distribution of magnetic fields on the solar disk. Large aperture telescopes with small field of view could not be used for this purpose, and only small aperture telescopes could provide the requested information.

One of such type of instruments is the Solar Telescope for Operative Predictions (STOP) installed at Sayan solar observatory (SSO) (Demidov *et al.* 2002). Two types of regular observations are performed on this instrument: full-disk magnetograms with a spatial resolution about one hundreds arcseconds, and measurements of the magnetic field of the Sun as a star (or solar mean magnetic field, SMMF). Of course, STOP's spatial

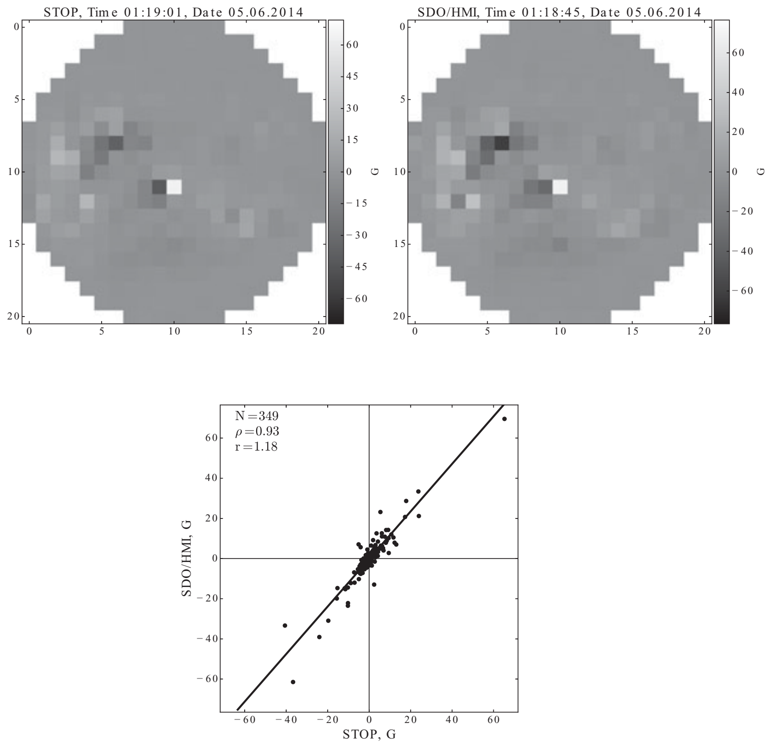

Figure 1. Comparison of longitudinal full-disk magnetograms obtained on 5 June 2014 with the STOP telescope at the SSO and with the SDO/HMI. Top panels show two practically simultaneous magnetograms, where SDO/HMI data (right panel) are smoothed to reach the same spatial resolution which is used at STOP ($\approx 100''$). Bottom panel shows the scatter plot of the corresponding data. N – number pairs of points, ρ – correlation coefficient, r – coefficient of linear regression. SDO data are taken from http://jsoc.stanford.edu/ajax/lookdata.html.

resolution is rather low (in comparison to Solar Dynamics Observatory/ Helioseismic and Magnetic Imager, SDO/HMI, for example), but still higher than 3 arcmin resolution of the well known J.M.Wilcox Solar Observatory (WSO). However, this resolution is quite enough for many interesting scientific problems, such as calculations of the magnetic parameters of the heliosphere, or testing the stellar magnetic mapping methods. A big advantage of the STOP data is the fact that they are obtained in the spectropolarimetric mode, where Stokes I and V profiles in many spectral lines are recorded simultaneously with very high accuracy.

The reliability of STOP's data has been shown in some previous studies, where e.g. large-scale magnetic fields (LSMF) (see Demidov *et al.* 2008) or SMMF (Demidov *et al.* 2002) observations are presented. With appearence of the new data sets provided by SDO/HMI it is interesting to compare STOP obseravtions with them. Figure 1 shows the comparison of two magntograms obtained almost simultaneously on these two instruments (obviously the SDO/HMI magnetogram was smoothed to the STOP spatial resolution). It is possible to see that both magnetograms are practically identical, despite using of different spectral lines. It is proved also by the scatter plot of these magnetograms, displayed in the bottom panel of Figure 1. To demonstrate that this day is not an exception and a good agreement is found for other days as well, Figure 2 shows the correlation and regression coefficients for 29 days. It is possible to see that a very good agreement is evident in all magnetograms.

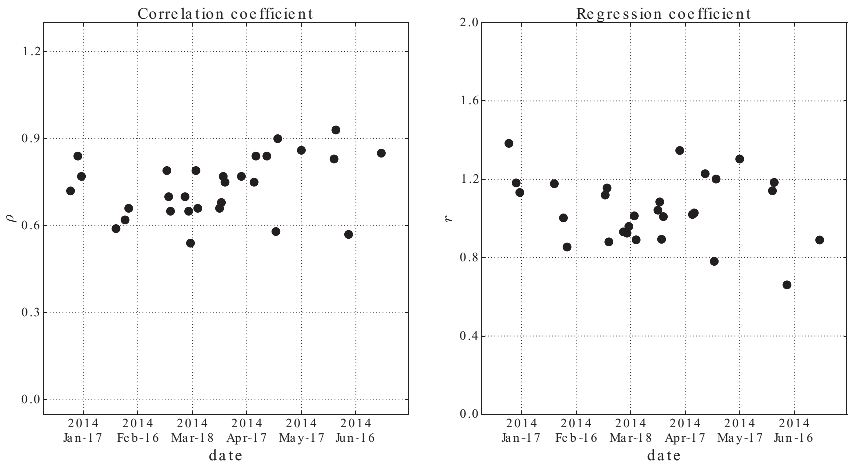

Figure 2. Correlation (left panel) and regression (right panel) analysis of 29 quasi-simultaneous full-disk magnetograms obtained at STOP SSO and SDO/HMI during 6-months, from January 2014 to June 2014. The average value of ρ is equal to 0.7, and $r = 1.04$.

Since the STOP SSO is the only telescope in the world where simultaneous disk-integrated (SMMF) and spatiallly resolved (LSMF) Stokes observations are performed, it gives an unique chance (unfortunately which is not used by stellar astronomers up to now) to attract such observations for testing of methods applied for surface mapping of magnetic fields on the other, especially solar type, stars (Petit *et al.* 2008, Marsden *et al.* 2014). Indeed Figure 3 demonstrates that Stokes V profiles in the SMMF observations (bottom panels) depend on distributions of LSMF across solar disk. We see that when central part of the disk is occupied by magnetic field of one dominant polarity (see right panel), Stokes V have more or less reqular antisymmetric profiles (two lobes), but when we have a mixture of polarities (left panel), as a result we see more asymmetric profiles, in this particular case even with three lobes.

2. Modeling of the Center-to-Limb Variations of Stokes V Profiles Asymetries and Magnetic Field Strength Ratios

It is well known scince the begining of the 70s (Stenflo, 1973), that solar magnetic fields are distributed basically in two components - magnetic flux tubes with kG strength, which contain most of the magnetic flux, and weak fields between such tubes. The correspondence between weak and strong fields depends on the type of surface object under observation, spatial resolution, and magnetic flux density. Important parameters used for the diagnostics of the manifestations of strong small scale elements are magnetic strength ratios (MSR), especially in selected spectral lines, amplitude (δa) and area (δA) asymmetries, as well as zero-crossing shift (V_{zc}) of the Stokes V profiles. If MSR values depend mainly on the strength of hidden flux tubes, Stokes V profiles asymmetries are caused by dynamic processes in the vicinities of them (Grossmann-Doerth *et al.* 1988, Grossmann-Doerth *et al.* 2000).

Practically all previous theoretical and experimental studies of the MSR, δa, δA, or V_{zc} were based basically on observations of the Sun with rather high spatial resolution (Grossmann-Doerth *et al.* 1996), because it was interesting to study them for the case of extremely weak magnetic flux densities, which took place in the SMMF and LSMF observations.

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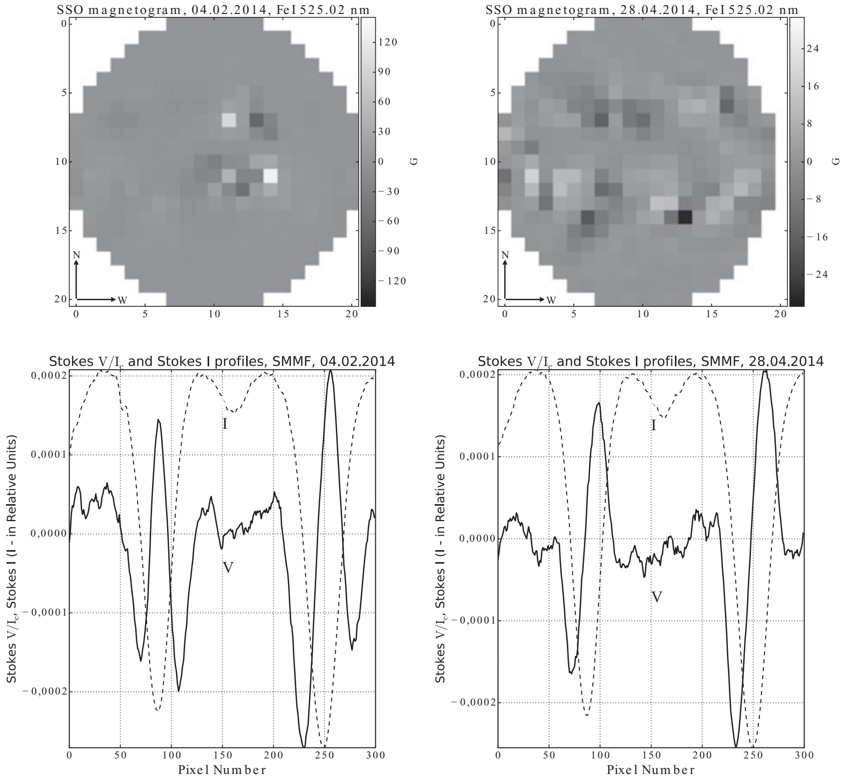

Figure 3. Illustration of dependences of SMMF Stokes V profiles from distributions of large-sale solar magnetic fields across solar disk. Measurements on STOP telescope at Sayan solar observatory for two days observations, February 04, 2014 (left panel) and April 28, 2014 (right panel), are presented. On the bottom panels Stokes I and V profiles for two spectral lines, Fe I 525.02 nm (left strong line) and Fe I 525.06 nm (right line), are presented.

Despite of the fact that, in recent years, several very sophisticated 3D MHD codes, which reproduce many observable phenomena quite well, have appeared, there are some posssibilies to use the old approach for explanation of MSR and assymmetries in a statistical sense. This approach (see e.g. Bünte *et al.* 1993) is based on the assumption of 2-components model (flux tubes and plasma without magnetic field between them). A good example of application of this approach for the explanations of center-to-limb variation (CLV) of the δa for the case of LSMF observations at STOP SSO in spectral line Fe I 525.02 nm is given by Demidov & Veretsky (2003). Concerning the CLV of δA, and MSR (for combinations of spectral lines Fe I 524.71 nm, Fe I 525.02 nm), such models reproduce observable parameters quite well only for the solar disk center, however, it was impossible to achieve a satisfactory fitting for the regions far enough from the center. But because of in the case of LSMF and SMMF measurements we dealt with contribution from different parts of solar disk, including near-limb zones, it is important to study CLV of these parameters for small μ (cosinus of the heliocentric angle) as well. The best results for all range of μ, which are presented in the Figure 4, were obtained recently by combining in the field of view two types of magnetic flux tubes, network (weight 0.9) and plage (weight 0.1) ones. The structures of such tubes have already been modeled (e.g. Solanki 1986). From consideration of the Figure 4 we have to conclude that

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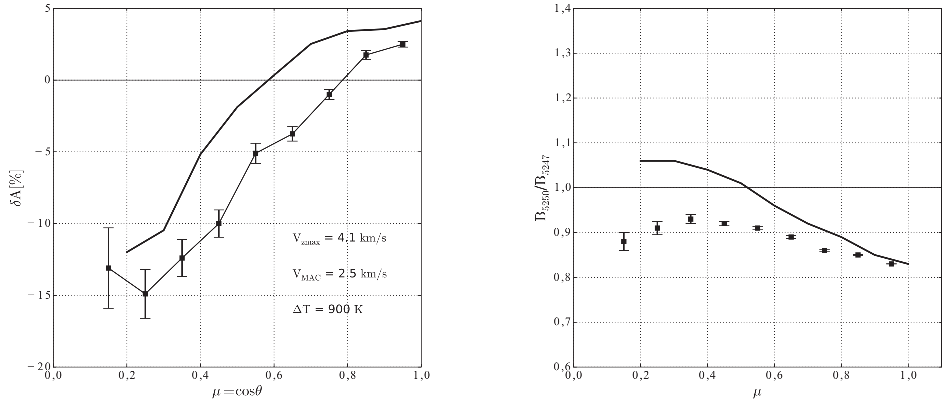

Figure 4. Modeling results (solid lines) and experimental data (points with error bars) of the CLV of arrea assymetry δA for the line $Fe\,I$ 525.02 nm (left panel), and magnetic strength ratios (MSR) for lines Fe I 524.71 nm and Fe I 525.02 nm.

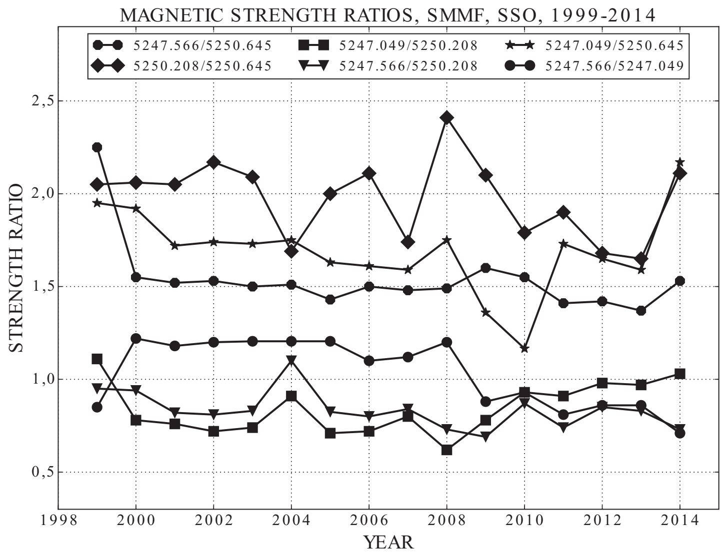

Figure 5. Magnetic strength ratios for all combinations of four spectral lines in the vicinity of Fe I 525.02 nm. SMMF observations at STOP telescope during 1999 – 2014 years are used to plot these graphics.

interpretation of magnetic measurements in the places on the big distances from solar disk center is still an open question (see also Frutiger *et al.* 2003).

3. On the Time Variations of Magnetic Strength Ratios

The next interesting issue that should be considered in the context of this study is a temporal variation of MSRs for the case of SMMF observations. Indeed, it is known (see e.g. Stenflo & Harvey, 1985; Stenflo *et al.* 2013) that MSRs depend on the value of the strength itself (magnetic flux density). So because of SMMF strength is changing with solar cycle, it is posible to expect variations of MSR with time. Figure 5 shows MSRs for all combinations of four spectral lines in the vicinity of Fe I 525.02 nm for a 15-years period, which partly covers two cycles of solar activity. It is possible to see

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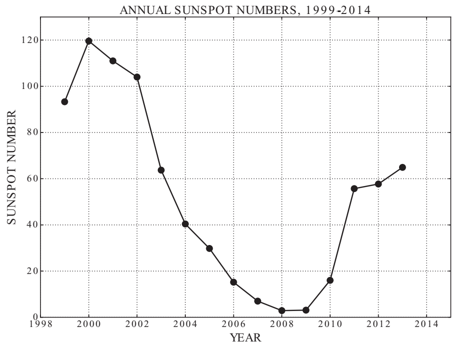

Figure 6. Sunspot number for the same time interval than the one of Figure 5.

that althoug surface magnetic flux (a good proxy of which is the sunspot number) has changed significantly (see Figure 6), there are no systematic variations of the MSRs for all combinations of lines. Seaching of reasons for such non-trivial result must be the issue for future investigations.

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