TOTAL SOLAR MAGNETIC FLUX: DEPENDENCE ON SPATIAL RESOLUTION OF MAGNETOGRAMS

N. A. Krivova[1,2], S. K. Solanki[1], and M. Fligge[3]

[1]Max-Planck-Institute for Aeronomy, 37191 Katlenburg-Lindau, Germany
[2]On leave from Astronomical Institute, St. Petersburg University, 198504 St. Petersburg, Russia
[3]Institute of Astronomy, ETH Zentrum, CH-8092 Zürich, Switzerland

ABSTRACT

The variability of the solar radiative output is tied to the evolution of the surface magnetic field. Irradiance changes on time-scales of the solar rotation are governed by the varying distribution of the magnetic features and the evolution of sunspots and individual active regions, whereas the total amount of magnetic flux in particular small-scale magnetic elements seems to dominate the irradiance variations on the time scale of the solar cycle. Possibly of even greater relevance for climate on Earth are secular variations of solar irradiance, which are at least partly caused by changes in the quiet-Sun magnetic flux on long time scales. Using NSO/Kitt Peak synoptic charts Harvey (1994) found that the total magnetic flux in active regions at activity maximum is about 3 times higher than the flux at activity minimum. The size of small-scale magnetic elements is, however, far below the resolution of currently obtainable magnetograms. At the same time, their distribution on the solar surface is highly non-uniform, with magnetic elements of opposite polarities often being grouped close together. This leads to an apparent cancellation of the flux within a relatively large pixel of a Kitt Peak synoptic chart and underestimates the total magnetic flux, mainly in the quiet Sun. Using MDI full-disc and high-resolution magnetograms and artificially reducing their spatial resolution by binning several pixels together we study the influence of the resolution on the measured total magnetic flux.

Key words: Sun: activity; Sun: magnetic fields; Sun: variability.

1. INTRODUCTION

Variations in the amount and distribution of the solar surface magnetic field are reflected in the changing output of solar radiation. The distribution and evolution of the active regions on the solar disc defines solar irradiance changes on time-scales of days to months. The evolution of the magnetic flux in sunspots and in small-scale magnetic elements outside active regions leads to the waxing and waning of the total solar irradiance in phase with the magnetic activity cycle, the most prominent manifestation of the irradiance variability. Finally, changes in the quiet-Sun magnetic flux on long time-scales seem, at least partly, to be responsible for secular variations of solar irradiance, which may play an important role in long-term changes of the Earth's global temperature. Thus a fundamental understanding of the distribution and the temporal evolution of the surface magnetic field is necessary to grasp the mechanisms of the solar irradiance variations.

Harvey (1994) analysed synoptic charts constructed from NSO/Kitt Peak (KP) full-disc magnetograms and found that during solar activity maximum the total magnetic flux in active regions, $\Phi_{\rm AR}$, is about a factor of 2–3 higher than the total magnetic flux in the quiet Sun network, $\Phi_{\rm QS}$. However, the magnetic field outside active regions is highly non-uniform, with magnetic elements of opposite polarities often being grouped close together, typically at scales smaller than the size of a pixel in the KP synoptic charts. This causes the flux within a relatively large pixel of a KP synoptic chart to be (apparently) cancelled and, as a result, underestimates the total magnetic flux in the quiet Sun.

Here, we study the influence of the resolution of magnetograms on the measured magnetic flux. We use MDI full-disc and high-resolution magnetograms. To represent lower spatial resolution, we bin several pixels together. We first find the total magnetic flux for the Sun as a whole, as well as for the quiet Sun and active regions individually from the MDI data, and then compare it with the flux obtained with the reduced resolution.

2. FULL DISC MAGNETOGRAMS

As a first step, we take MDI full disc magnetograms and create synoptic charts. Two Carrington Rota-

Proc. SOHO 11 Symposium, 'From Solar Min to Max: Half a Solar Cycle with SOHO', Davos, Switzerland, 11-15 March 2002 (ESA SP-508, June 2002)

Table 1. Magnetic flux, $\Phi_{\rm MDI}$, of synoptic maps (CR 1915 and CR 1975) created from MDI full disc magnetograms, normalised to the flux, which would be measured for these maps with the KP synoptic charts resolution, $\Phi_{\rm KP,\,SC}$. Total flux and flux from quiet Sun (QS) and active regions (AR) are listed separately. The rotation maps were made using original 1-minute magnetograms, as well as 5- and 56-minute averages. Signal below 1σ, 2σ or 3σ was assumed to be noise in the three considered cases, respectively.

	1-min ($\sigma = 20$G)	5-min ($\sigma = 9$G)			56-min ($\sigma = 2.7$G)		
	1σ	1σ	2σ	3σ	1σ	2σ	3σ
CR 1975							
AR+QS	1.38	1.30	1.12	1.05	1.22	1.15	1.10
AR	1.05	1.04	1.03	1.03	1.04	1.04	1.03
QS	1.97	1.75	1.31	1.10	1.50	1.35	1.23
CR 1915							
AR+QS	2.04	1.73	1.16	1.03			
AR	1.00	1.04	1.03	1.03			
QS	2.08	1.77	1.17	1.03			

tions — 1915 (October–November 1996, when the Sun was very quiet) and 1976 (April–May 2001, near the maximum of solar activity) — have been considered.

Next, we remove noise from the signal. The noise has to be treated accurately, since its effect is very similar to that of the signal from small-scale elements: binning pixels with noise of opposite signs leads to an overestimate of the effects of low spatial resolution. The noise (1σ) in an individual magnetogram is typically about 20 G (Scherrer et al. 1995; see Ortiz et al. 2002). To reduce it, we construct averages over 5 and 56 minutes ($\sigma \approx 9$ G and 3 G, respectively). When averaging, we take solar differential rotation into account. The low-noise 56-minute averages can, unfortunately, not be produced for the period of minimum activity, since magnetograms were not recorded regularly enough. Another problem with these low-noise maps is that magnetic features evolve in the course of an hour and the peculiar motion of magnetic features can move them out of a given pixel in this time. This means that in these averaged magnetograms the magnetic signal is smeared and thus also reduced, partly because some of it falls below the noise limit, partly due to cancellation.

If the absolute signal in a pixel is less than 1σ we set it to 0. With this procedure one third of the whole noise is still kept. Therefore, we also use 2σ and 3σ thresholds. In this case, however, more quiet-Sun signal is lost. The maps are also corrected for the foreshortening effect at the limb.

Since active regions are more uniform than the quiet Sun network (in the sense that the former contain larger unipolar patches), the effect of the spatial resolution should be weaker for them. Therefore, we consider not only the Sun as a whole but also the quiet Sun and the active regions separately. To isolate active regions, the technique suggested by Harvey (1994) is used. This includes examination of the amplitude of the variation of the field within subarrays of 20×20 pixels and smoothing of the resulting map to eliminate patchiness.

Now the synoptic charts produced from MDI magnetograms are reduced to the resolution of KP synoptic charts. For this, we bin a number of pixels together (9 and 6 in horizontal and vertical directions, respectively; Harvey 1994; Scherrer et al. 1995). The procedure of isolating active regions is applied to the new maps, too, and the threshold between active and quiet regions is adjusted to give the same active region areas for both resolutions.

The ratios of the total flux obtained for the two resolutions are given in Table 1 (hereafter, index 'KP, SC' refers to maps/magnetograms obtained from MDI data by reducing their spatial resolution to that of the Kitt Peak synoptic charts). The results for different integration times and noise thresholds (1, 2 and 3σ) for the two considered Carrington Rotations are listed. Thresholding at 2σ and 3σ (20 and 40G) for 1-minute maps carries no information, since practically all small-scale magnetic elements become eliminated in this way.

It is immediately obvious that the spatial resolution is rather unimportant for determining the total magnetic flux of active regions: the 'missing' flux (i.e. the flux not seen in the Kitt Peak synoptic charts, but present in the MDI magnetograms) is less than 5%, whereas it is far more important for the quiet Sun. Since with 3σ almost all the noise must have been eliminated, the 56-minute average at 3σ suggests the absolute lower limit for the ratio — at least 20% of the quiet Sun flux is still hidden with the KP synoptic charts resolution.

We believe, however, that this limit is too conservative, and the real ratio is between those obtained

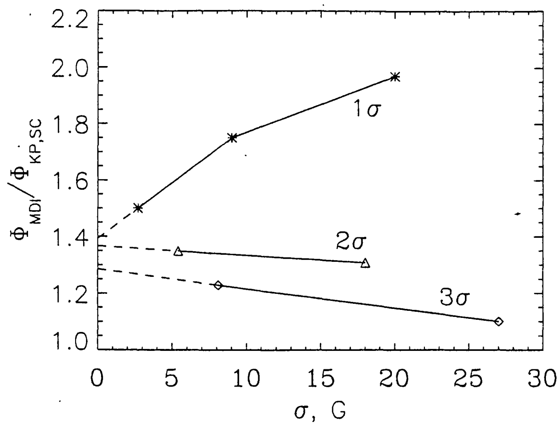

Figure 1. Dependence of the $\Phi_{MDI}/\Phi_{KP,\,SC}$ ratio on the noise level (i.e. total integration time) of magnetograms at 1σ, 2σ and 3σ. Dashed lines are linear extrapolations to the '0'-noise level.

for the 56-min averages at 1 and 2σ. As seen from the Table and from Fig. 1, the ratio $\Phi_{MDI}/\Phi_{KP,\,SC}$ decreases with increasing integration time at 1σ and increases at 2 and 3σ. This is because at 1σ we still keep a significant amount of noise. This becomes clear from a comparison of fluxes obtained for the rotation maps with different integration time (or noise level) and noise threshold. At 1σ, the flux Φ_{MDI} decreases from 1-minute to 56-minute averages, suggesting that there is still a lot of noise in 1- and 5-minute data, which goes down with integration time. Already at 2σ the situation reverses: the flux increases with integration time, which implies that now we see more and more weak features as the noise level is reduced and this effect overrides the decrease in the apparent signal due to lower noise. In Fig. 1 ratios $\Phi_{MDI}/\Phi_{KP,\,SC}$ for the CR 1975 obtained with different thresholds are shown versus the noise level of magnetograms. Linear extrapolations of the curves at 1σ and 2σ to 0 G yield very close values — about 1.35–1.4.

3. HIGH-RESOLUTION DATA

Could it be that even the spatial resolution of the MDI full disc magnetograms is insufficient to avoid apparent cancellation of some flux? To check this to the extent possible, we have also examined 14 MDI high-resolution (HR) magnetograms obtained at different activity levels, from May, 1996 to July, 2001. Each of these has a spatial resolution of 1.2″. Averages over 20 minutes ($\sigma \approx 4.5$ G) were constructed and the noise was treated in the same way as for the synoptic charts.

We first look at the dependence of the total measured flux on the size of a pixel. For this, different numbers of pixels are binned together. Figure 2 shows how the total flux (normalized to the flux for the MDI HR mode, i.e. every pixel represents one bin) depends on the number of pixels that were combined. The 4 magnetograms including active areas are represented by filled symbols. For reference, three of the analysed magnetograms at different activity levels are exhibited in Fig. 3. The dependence on spatial resolution, particularly strong for the quiet Sun, is clearly seen. For the quiet Sun, fluxes above 1σ measured for the MDI full disc are about a factor 1.7–1.8 higher than for the KP synoptic chart resolution, in agreement with Table 1.

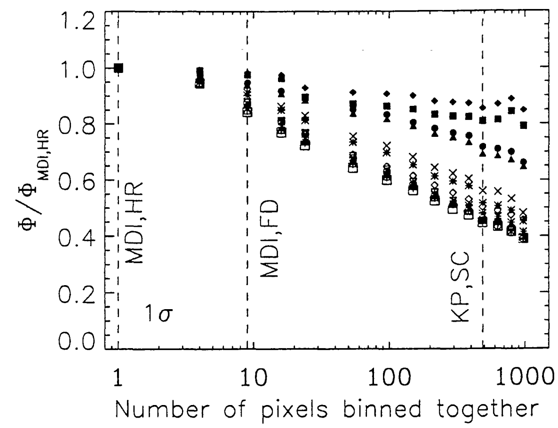

Figure 2. Dependence of the measured magnetic flux on the size of a bin for 14 analysed HR MDI magnetograms. Fluxes are normalized to the flux corresponding to the MDI HR mode. Signal below 1σ is assumed to be noise and has been removed. Filled symbols are used for magnetograms containing active areas. By way of example, magnetograms shown by open squares, filled triangles and filled diamonds are displayed in Fig. 3a, b and c, respectively.

In order to compare more accurately the high-resolution MDI magnetograms with those having the KP synoptic chart resolution, we show in Fig. 4 ratios of the fluxes at the two resolutions as a function of the total flux for a threshold of 1, 2 and 3σ. Every symbol represents one magnetogram. The absolute lower limit for the obtained ratio, i.e. when only flux above 3σ is taken into consideration, during activity minimum is about 1.3. The real value, which we believe corresponds to the case when the threshold is between 1σ and 2σ, is likely to be between 1.6 and 2.2.

4. CONCLUSIONS

The influence of the spatial resolution of magnetograms on the measured total magnetic flux has been studied. The MDI full disc and high-resolution magnetograms were used and compared to the resolution of KP synoptic charts. The analysis has been

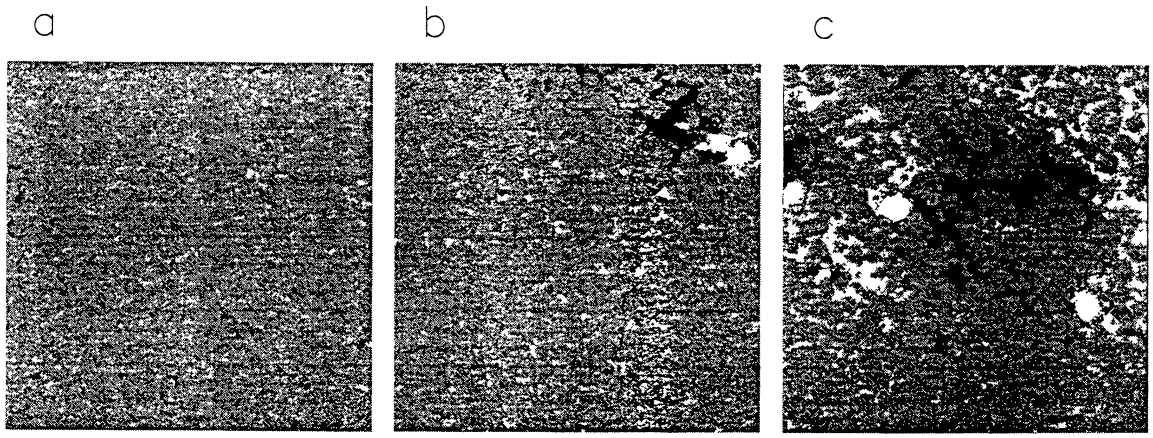

Figure 3. *Examples of high-resolution magnetograms.* **a**: *quiet Sun (08.05.1996, shown by open squares in Fig. 4).* **b**: *small active region (06.11.1997, filled triangles in Fig. 4).* **c**: *active Sun (17.07.2001, filled diamonds in Fig. 4).*

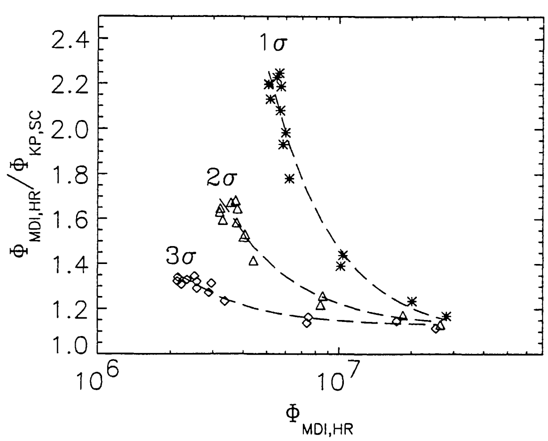

Figure 4. *Ratio of magnetic fluxes obtained for the MDI HR and KP synoptic chart resolutions as a function of the total flux. Three cases, with the threshold being* 1σ, 2σ *and* 3σ, *respectively, are shown.*

carried out separately for the Sun as a whole, quiet Sun and active regions. Whereas for active regions, the effect of the spatial resolution is rather unimportant, significant magnetic flux contained in small-scale magnetic elements goes uncounted because opposite polarities are present within a single resolution element of the Kitt Peak synoptic charts.

Compared to the full disc resolution of MDI, between 20% and 50% of the total flux must have escaped notice in KP synoptic charts, with the most probable value being 35–40%. However, even with this resolution there is still some flux going unnoticed, which becomes evident from the analysis of MDI magnetograms obtained in the HR mode. Employment of these high-resolution data leads to a factor of 1.4–2.2 with respect to the KP synoptic charts.

ACKNOWLEDGMENTS

We thank R. Bush for useful discussions.

REFERENCES

Harvey K.L., 1994, In: Pap J.M., Fröhlich C., Hudson H.S., Solanki S.K. (eds.) IAU Coll. 143: The Sun as a Variable Star: Solar and Stellar Irradiance Variations, 217–225, Cambridge: Cambridge Univ. Press

Ortiz A., Solanki S.K., Domingo V., Fligge M., Sanahuja B., 2002, Astron. Astrophys., submitted

Scherrer P.H., Bogart R.S., Bush R.I., et al., 1995, Solar Physics, 162, 129