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Artifacts of SDO/HMI data and long-period oscillations of sunspots

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ABSTRACT

Aims. The artifacts of SDO/HMI magnetograms that may affect the low-frequency power spectrum of sunspot oscillations are analyzed.

Methods. Several examples are given that present false (artificial) harmonics, which are produced by Doppler shifts in the power spectra of long-period oscillations of sunspots. This arises from peculiarities in the orbital movements of SDO.

Results. It was found that those artifacts with periods of 12 and 24 h, as revealed even in variations of weak background magnetic fields, are actually present in SDO/HMI magnetograms. However, the quantitative impact of artifacts remains quite weak and does not change the picture of sunspot oscillations dramatically for as long as the magnetic field in the spot is less than about of 2000 Gauss. When the magnetic field strength is greater than 2000 G, the influence of these artifacts increases sharply to become the dominant factor. One can suggest that the amplification of noise components of these artifacts has a highly nonlinear character with the growth of the magnetic field, and the field strength of about 2000 G then takes on meaning of a threshold value.

Key words. Sun: oscillations – magnetic fields

1. Introduction

In recent years the sunspot properties have been studied on the basis of their long-period oscillations from tens of minutes to tens of hours. These oscillations were detected in the optical range as the time variations of the line-of-sight velocities, magnetic fields and spot areas (Efremov et al. 2007, 2010, 2012). Also, long-period oscillations were revealed in microwave-millimeter radio waves as the time-variations of the radio emission from the sources connected with sunspots (Bakunina et al. 2009; Chorley et al. 2010, 2011; Smirnova et al. 2011). The theoretical interpretation of the phenomenon is given on the base of a "shallow sunspot" model (Solov'ev & Kirichek 2008, 2009).

Such investigations require a long-term homogeneous data series for the possibility of obtaining the physical parameters of sunspots. In this respect, the space-based data obtained with advanced instruments such as the SOlar Heliospheric Observatory/ Michelson Doppler Imager (SOHO/MDI) and Solar Dynamics Observatory/Helioseismic and Magnetic Imager (SDO/HMI) have a huge advantage over the ground-based observations, for which the length of the time series is naturally limited by the daylight.

SDO/HMI provides new wide opportunities for detailed study of the oscillatory processes, not only for a sunspot as a whole but also for the individual points in the umbra or penumbra of a sunspot. Unfortunately, SDO data are distorted by the influence of artifacts that arise at periods of 12 and 24 h owing to the specific features of the orbital motion of the spacecraft. These artifacts do not play a significant role in the study of the relatively high-frequency oscillations with periods up to four to five hours. But they have a significant effect on periods of tens of hours, which is typical of the oscillations of a sunspot as a whole. For this reason, a detailed study of these artifacts and their influence on the real oscillatory apectrum seems to us a definite and important task.

The structure of this paper is as follows. In the second section we present some specific examples of studies of long-period sunspot oscillations on the basis of SDO/HMI data, in which the orbital artifacts manifest themselves in one way or another. In the third section we investigate the spectral composition of the background magnetic field in SDO/HMI magnetograms, and finally in the fourth section we formulate the conclusions of this work.

2. SDO/HMI magnetograms with 45 and 720-s cadence

SDO spacecraft is located in a geosynchronous, inclined (28.5°) orbit, and it completes the orbit in 24 h (Scherrer et al. 2012; Schou & Larson 2011; Schou et al. 2012; Wachter et al. 2012; Couvidat et al. 2012). Also, as seen from the ground the spacecraft traces an "eight" spanning 57 degrees in latitude at an altitude of 36 000 km along the meridian 102° W. Theoretically, it can lead to the emergence of a variable component in the signal with a period of 12 and 24 h due to the Doppler effect.

The artifacts of SDO/HMI are partially investigated in Couvidat et al. (2012) and Liu et al. (2012).

We treated 17 long time series obtained from the magnetograms with a cadence of 45 s and of 720 s. These magnetograms have good spatial resolution (1″), so we expected to use them for a detailed study of long-period oscillations of individual points in sunspots and, in particular, to solve the problem of synchronous oscillations in the sunspot umbra. However, the presence of 12 and 24 h artifacts complicates the investigation of long-period oscillations. We show the real situation with the problem of artifacts in the SDO/HMI data in a number of

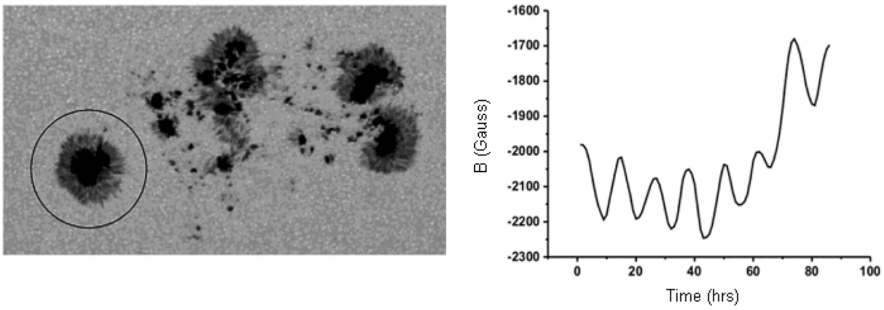

Fig. 1. *Left panel*: HMI intensitygram of the large sunspot (circled) observed in the active region NOAA 11166. The active region field-of-view is [225″ × 125″]. The active region center coordinates are [−230″ × 300″] obtained at 20:00 UT 2011 Mar. 07. *Right panel*: magnetic field strength as a function of time (time series) measured in the sunspot highlighted by the circle (*left panel*). The time series starts at 00:00 UT 2011 Mar. 07.

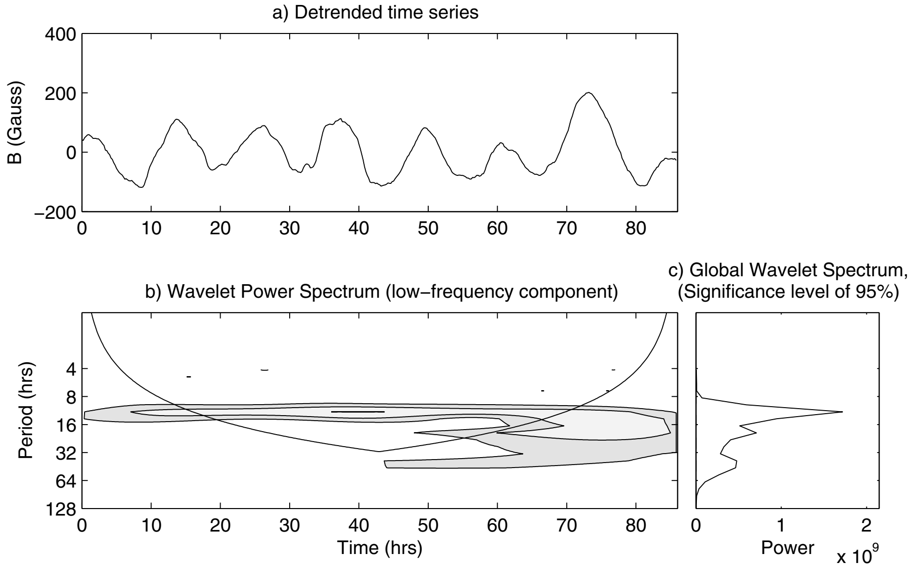

Fig. 2. Panel **a)**: time series of the magnetic field strength variations obtained from the SDO/HMI magnetograms of the sunspot (umbra) in the active region NOAA 11166 (see Fig. 1, right panel). Panel **b)**: wavelet power spectrum of the time series. Panel **c)**: global wavelet spectrum with a significance level of 95%.

examples bellow. We used the technique of the wavelet transform described By Torrence and Compo (Torrence & Compo 1998) to analyze the time series obtained from the magnetograms by the sixth-order wavelet Morlet function.

2.1. Example 1. 12-h artifact

We analyzed the SDO/HMI magnetograms of the large sunspot in the active region NOAA 11166. The SDO/HMI intensitygram presented in the lefthand panel of Fig. 1. The maximum values of the magnetic field strength as a function of time (time series) were obtained during the 86 h with a cadence of 720 s (Fig. 1, right panel). The time series starts at 00:00:00 UT in 2011 Mar. 07.

The absolute mean value of the magnetic field strength in the sunspot during the observations is $B = |2150|$ G. Stable oscillations with a period of 12 h were revealed during the observational session (Fig. 2, panel a). The magnetic field variations have a regular character with a very low noise level. This behavior of the signal is most likely, evidence of its artificial origin. But it is significant that the 24-h harmonic is virtually absent in the wavelet power spectrum (Fig. 2, panels b and c). The bit of 24-h power starts at the end of the time span when the Doppler signal departs more from the being centered on zero (see Fig. 1, right panel).

2.2. Example 2. Single-mode with a period of 39 h

We analyzed SDO/HMI magnetograms of the largest sunspot in the active region NOAA 11232 during 130 h. The averaged values of the magnetic field strength were obtained from the sunspot magnetograms (Fig. 3, panel a). The time series starts at 00:00 UT on 2011 Jun. 05. The absolute mean value of the magnetic field strength measured in the sunspot during the observations is $B = |1750|$ G.

In this case the artificial periods of 12 and 24 h are not found in the wavelet power spectrum (Fig. 3, panels b and c). Distinct mode with a period of 39 h can be identified as a quasi-period of the external exciting force, caused by the perturbed impact of the super-granulation cells that arise and decay near the sunspot (see discussion in Efremov et al. 2012), where the same periods of oscillations were obtained with SOHO/MDI data).

2.3. Example 3. Unstable amplitudes of 12 and 24-h oscillations

We analyzed the maximum value variations of the magnetic field strength obtained from the SDO/HMI magnetograms of the large unipolar spot in the active region NOAA 11101 during the 107 h (Fig. 4, panel a). The time series starts at 00:00:00 UT on 2010 Aug. 28. The absolute mean value of the magnetic field strength measured in the sunspot during the observations is $B = |2100|$ G. The harmonics of 12 and 24 h are presented clearly in the wavelet power spectrum (Fig. 4, panels b and c). But the amplitudes of these oscillations are greatly weakened after the 60th hour of the time series. This behavior cannot be typical of the artifacts, which appeared due to the spacecraft movements on the stationary orbit.

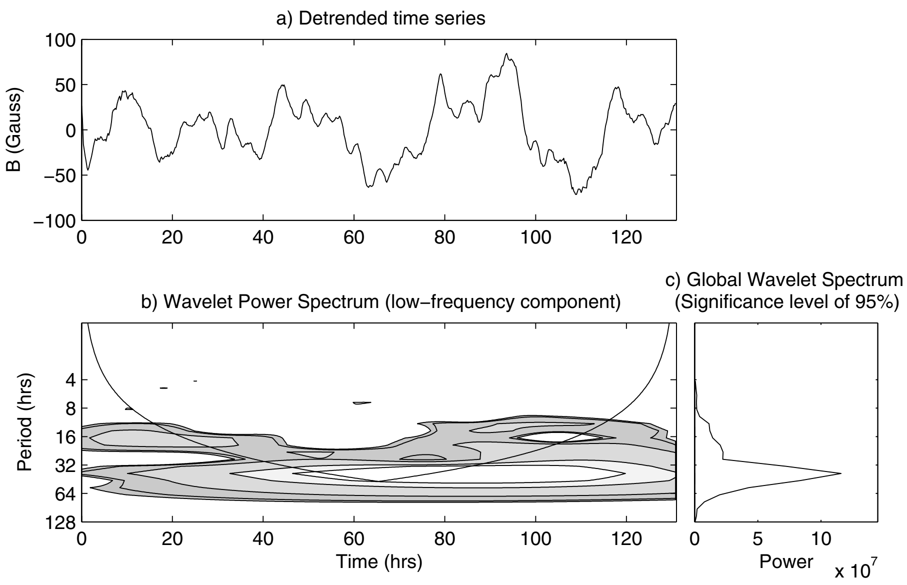

Fig. 3. Panel **a**): time series of the magnetic field strength (maximum values, detrended) obtained from the SDO/HMI magnetograms of the unipolar sunspot in the active region NOAA 11232. The active region field-of-view is [100″ × 125″]. The active region center coordinates is [−334″ × 166″] obtained at 20:00 UT on 2011 Jun. 05. The time series starts at 00:00 UT on 2011 Jun. 05. Panel **b**): wavelet power spectrum of the time series. Panel **c**): global wavelet spectrum with a significance level of 95%.

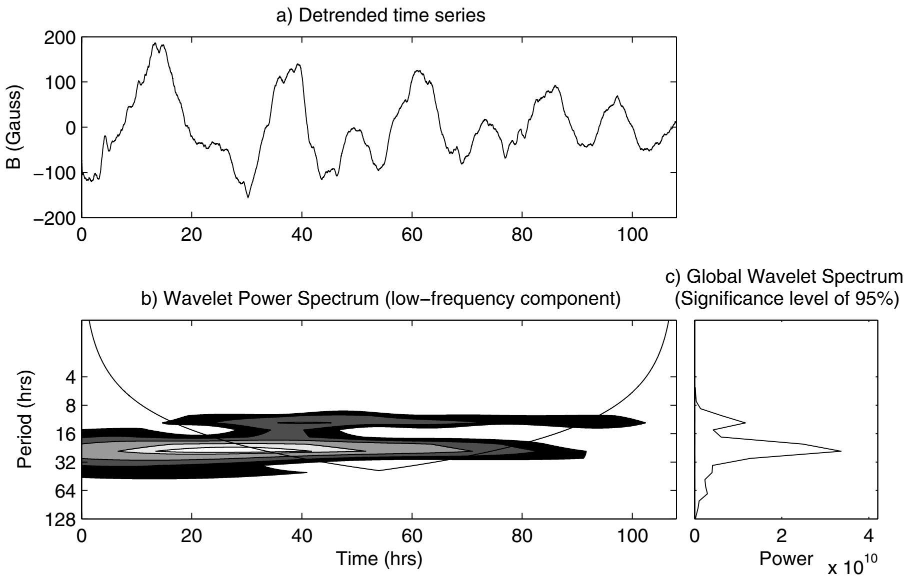

Fig. 4. Panel **a**): time series of the magnetic field strength (maximum values, detrended) obtained from the SDO/HMI magnetograms of the unipolar sunspot in the active region NOAA 11101. The active region field-of-view is [100″ × 100″]. The active region center coordinates are [−319″ × 87″] obtained at 20:00 UT on 2010 Aug. 28. The time series starts at 00:00 UT on 2010 Aug. 28. Panel **b**): wavelet power spectrum of the time series. Panel **c**): global wavelet spectrum with a significance level of 95%.

2.4. Example 4. Splitting of periods

We analyzed the time series obtained from the SDO/HMI magnetograms of the largest sunspot observed in the active region NOAA 11216 (Fig. 5, panel a). The time series starts at 00:00 UT on 2011 May 20. The duration of observations is 100 h. Here one can see again that the behavior of found periodic components is not typical of the stable artifact: the wavelet spectrum over the observational period looks like a "fork" (Fig. 5, panel b). At the beginning of the analysis the period of 16 h was split into two harmonics with periods of about 12 and 24 h. The absolute mean value of the magnetic field strength measured in the sunspot during the observations is $B = |2150|$ G.

2.5. Example 5. Synchronous oscillations in the bipolar group

We provided the simultaneous analysis of the maximum value variations of the magnetic field strength obtained from two sunspots observed in the bipolar group located in the active region NOAA 11260 (Fig. 6, left panel). Data were obtained during 60 h. It should be noted that the studied group was not stable.

The lefthand panel of Fig. 6 shows the dynamics of the sunspots during the observational period. The origin of the following spot was given by the magnetic element marked in the first frame in the lefthand panel. This magnetic element is very quickly moved away from the leading spot (see frames 2–5), and significantly increased in size. By the end of the observational period, this element represented the basic part of the following spot (frame 6). The locations of maximum values are marked in the frames. In these points the variations of the maximum value of the magnetic field were measured during the observational session. The variations of the of the maximum value of the magnetic field strength in the leading (A) and following (B) spots are shown in the righthand panel of the Fig. 6. These variations are very similar to each other, but the systematic shift takes place. We shifted these curves relative to one another for one hour and calculated the correlation coefficient, which was equal to 0.88. The absolute mean value of the magnetic field strength measured in the sunspot (A) during the observations is $B = |2150|$ G.

It is interesting to note that the changes in the magnetic field of the following sunspot precede the corresponding changes in the leading spot. This is probably because the very rapid spatial movements of the magnetic elements are observed in the region

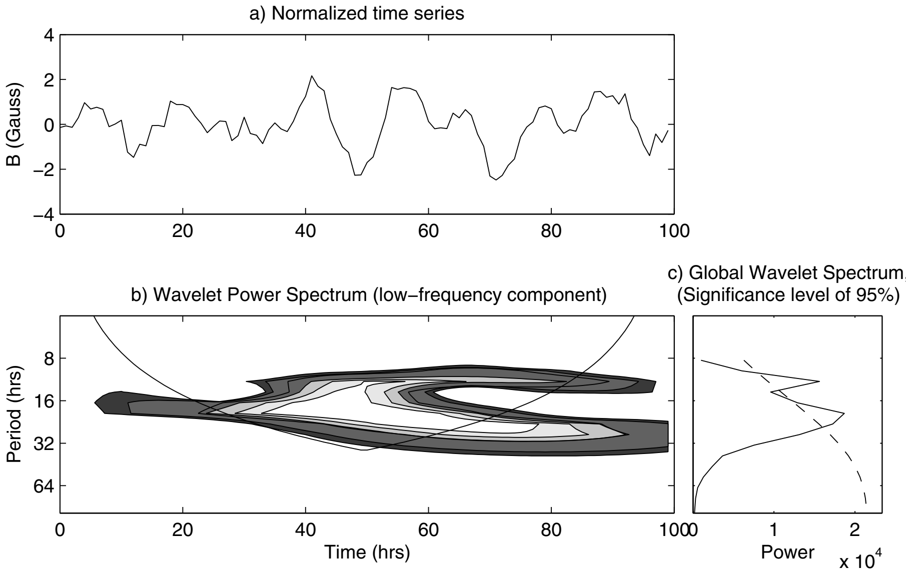

Fig. 5. Panel **a)**: normalized time series of the magnetic field strength (maximum values) obtained from the SDO/HMI magnetograms of the large unipolar sunspot in the active region NOAA 11216. The active region field-of-view is [100″ × 100″]. The active region center coordinates are [−239″ × −198″] obtained at 20:00 UT on 2011 May 20. The time series starts at 00:00 UT on 2011 May 20. Panel **b)**: wavelet power spectrum of the time series. Panel **c)**: global wavelet spectrum with a significance level of 95%.

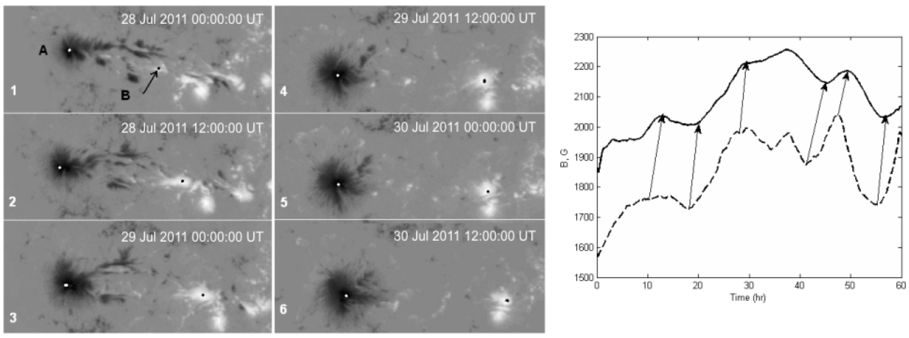

Fig. 6. Sunspot group dynamics during the formation stage. *Left panel*: HMI intensitygrams of the active region NOAA 11260 with two sunspots (A and B). The *XY* coordinates are reverced. The frames obtained in period of 2011 Jul. 28–2011 Jul. 30. The active region field-of-view is [200″ × 100″]. The active region center coordinates are [−278″ × 209″] obtained at 20:00 UT on 2011 Jul. 28. The arrow in the first frame shows the small magnetic element, which is actively developing in time. *Right panel*: time series of the magnetic field strength (absolute maximum values) obtained from the magnetograms of the spot A (solid line) and the spot B (dashed line). Arrows show the quasi-regular delay between the variations. The time series start at 00:00 UT on 2011 Jul. 28.

of the following spot. This powerful dynamical process perturbs the steadies leading spot, which is almost entirely formed. These perturbations propagate in the photosphere with the sound speed of about 10^6 cm/s. Considering that the typical size of the region of the bipolar group formation is about $3–4 \times 10^9$ cm, we find that the characteristic time delay (phase shift between the curves above) is just about one hour. We noted in this case that the artificial harmonics with periods of 12 and 24 h are not clearly revealed.

2.6. Example 6. Independence of oscillations in widely separated sunspots

We analyzed the maximum value variations of the magnetic field strength obtained from the SDO/HMI magnetograms of two sunspots from different active regions observed in one hemisphere. Data were obtained from NOAA 11232 and NOAA 11228 during the 80 h. These sunspots were spaced far enough apart at about 40°. The absolute mean value of the magnetic field strength was about $B = |1800|$ G in both spots. Since the spots were widely separated in space, the start of the observational session was chosen when the NOAA 11228 was in the central meridian. The end of the time series corresponds to the moment when NOAA 11232 was approaching to the central meridian. Temporal changes of the magnetic field at the centers of these sunspots are shown in the lefthand panel. The trends appeared to be the geometrical effect of the magnetic field vector projection on the line-of-sight when the spots move across the disk.

Superposed time series are presented in the righthand panel of Fig. 7. Here one can see two intervals of periods: 22–23 h for the time series NOAA 11232 (S1) and 23–26 h for the time series NOAA 11228 (S2). Even though these periods are close to the artificial harmonic of 24 h, they are not artificial in origin. We suggest that these periods are manifestations of the long-term eigen oscillations of sunspots. Otherwise, when the artifacts dominated, the oscillations in all points of the solar disk would be strictly synchronized.

In general, throughout the observational session, any noticeable synchronization of the two time series is missing. Thus, Example 6 clearly shows that the spatially separated sunspots taken from different active regions oscillate independently. This is how it should be for the two oscillating systems with similar parameters, but without any physical connections.

3. Spectral composition of the background magnetic field in SDO/HMI magnetograms

To complete the investigation of the artifacts we studied the properties of the noise component in the background field.

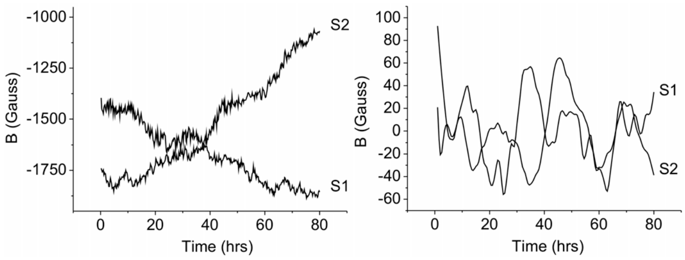

Fig. 7. *Left panel*: simultaneous observations of the magnetic field variations (maximum values) in two sunspots: NOAA 11232 (S1) and NOAA 11228 (S2). The active regions field-of-view is [100″ × 100″]. The S1 center coordinates are [−552″ × 168″], and the S2 coordinates are [110″ × 297″] obtained at 20:00 UT on 2011 Jun. 04. The time series starts at 00:00 UT on 2011 Jun. 04. *Right panel*: detrended and superposed time series. The magnetic field B is the value of the magnetic field strength avareged over the small area near the point of the maximum magnitude inside the umbra. As a rule, this point does not coincide with the geometrical center of the umbra.

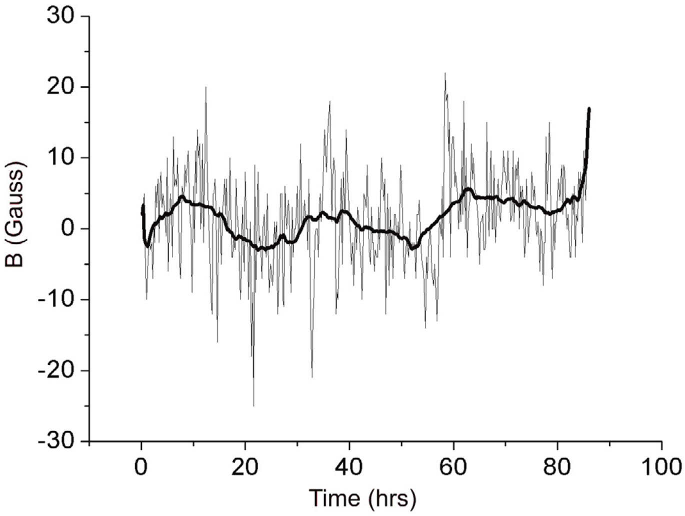

Fig. 8. Time series of the noise obtained from the magnetograms of the point (pixel). The maximum value of the magnetic field strength was measured in the random point. The point was taken outside the active region 11166 (see Fig. 1, left panel). The area field-of-view is [100″ × 300″] including the active region. The point coordinates: [−230″ × 200″] obtained at 20:00 UT on 2011 Mar. 07. Time series starts at 00:00:00 UT on 2011 Mar. 07. Solid-bold line shows the smoothed time series with a window of 2 h.

3.1. Noise in the point

We analyzed SDO/HMI magnetograms of the point outside the active regions. We took one pixel and constructed the time series of the maximum value variations of the magnetic field strength. The pixel was taken near the active region 11166 (see Fig. 1, left panel), but far enough from any active elements in the region. The area field-of-view is [100″ × 300″], including the active region that we need to calibrate the pixel location, so we used the same scenario as for the sunspots to obtain the noise time series. The noise time series is presented in Fig. 8. The time series starts at 00:00:00 UT 2011 Mar. 07. Data were obtained during the 86 h.

At zero value the standard deviation (SD) was about 6 G, which is a good value with the announced accuracy of the instrument (12–15 G). Attention was paid to the presence of a regular long-period component in the time series. The amplitude of the regular part is about 5 G (Fig. 8).

The detrended time series of the niose in the point and its wavelet power spectrum are presented in Fig. 9 (panels a–c). The regular part of the time series is represented by two periods: 12 and 24 h. The 12-h period was unstable, and its amplitude rises in the latter part of the time series.

3.2. Noise in the area

We analyzed different areas on the SDO/HMI magnetograms outside active regions. We selected two boxes with the sizes of 50 × 50 pxls and 100 × 100 pxls near the active region NOAA 11166. The time series were constructed by the same manner as for the point noise, in accordance with the law of the motion of a point on the solar surface. The maximum value of the magnetic field variations were measured from the whole area. The normalized time series obtained from the area of 50×50 pxls, and the wavelet power spectrum is shown in Fig. 10 (panels a and b). We determined that neither the size of the selected areas nor the peculiarities of their movements on the disk do not substantially affect the resulting noise spectrum.

An interesting feature of the noise spatial manifestation: the 12-h periodic component turns out to be small or, in some cases, disappears completely (Fig. 10, panel c). However, the averaging over the some area does not affect the 24-h component, which retains its properties over the entire observational interval.

3.3. Noise and the "useful signal"

The time series of the maximum value variations of the magnetic field strength in the large sunspot in NOAA 11101 during the 107 h is shown in Fig. 11. The time series starts at 00:00 UT on 28 Aug. 2010. The detailed analysis of this time series was presented in Sect. 2.3 (see also Fig. 4).

In Fig. 11 ("Extremum" line) one can see the initial time series where the trend appeared due to the projection effect when the sunspot is moved across the solar disk during the observations. We superposed the time series of the noise in the point (pixel) obtained outside the active region NOAA 11101, far enough from the magnetic elements of the region (Fig. 11). The time series was constructed by the same manner as described in Sect. 3.1. The superposition was done to verify that the obtained noise time series is the real noise. The absence of the projection effect in the noise time series is seen in Fig. 11. This effect takes place due to the disorientation of the magnetic field vector, which is the typical property of the random noise field.

But could the artifacts amplitude obtained form the noise time series affect a spot useful signal amplitude? In the sunspot with a field strength of about 2100 Gauss, the standard deviation (SD) of the signal is about 92 G, i.e. 14 times greater than the noise component. The spatial averaging of the noise does not change the phase behavior of the 24-h component; i.e., this is not a local phenomenon. All magnetograms are entirely exposed to this artifact. However, there are numerous examples of uncorrelated oscillations of the magnetic field in widely separated sunspots at different periods.

These facts directly contradict the hypothesis of the global impact of the noise component, which is enhanced by some mechanisms responsible for the signal amplitude. Moreover, such artificial periods in sunspots with B of about 1500–1800 G has not revealed. The components with periods of 12 and 24 h appear in the power spectra of sunspots with B equal to 2000 G and more. This indicates that if there is a strengthening of the

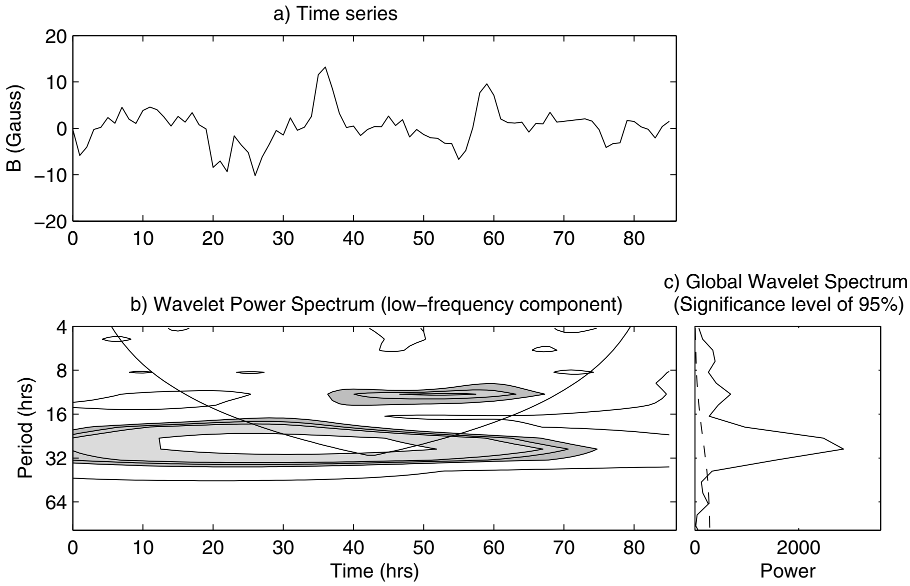

Fig. 9. Panel **a)**: detrended and smoothed time series of the magnetic field variations obtained at the point outside the active region NOAA 11166 (see Fig. 8). Panel **b)**: wavelet power spectrum of the time series. Panel **c)**: global wavelet spectrum with a significance level of 95%.

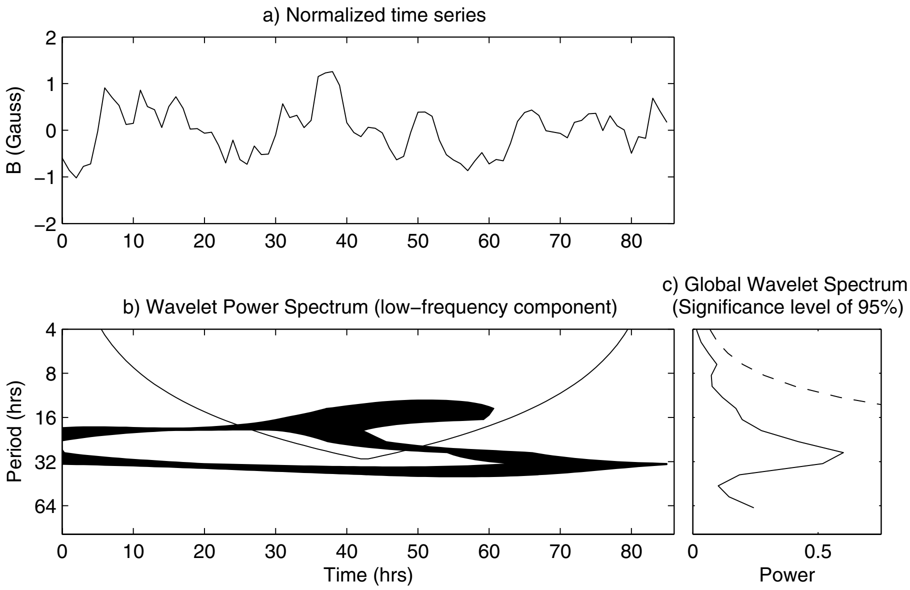

Fig. 10. Panel **a)**: normalized time series of the noise in the area 50×50 pxls, obtained from the SDO/HMI magnetograms near the active region NOAA 11166 during 86 h. The time series starts at 00:00 UT on 2011 Mar. 07. The area center coordinates are [16″ × 200″] obtained at 20:00 UT on 2011 Mar. 07. Panel **b)**: wavelet power spectrum of the time series. Panel **c)**: global wavelet spectrum with a significance level of 95%.

regular noise components to the signal amplitude, it should occur in an extremely complicated nonlinear manner.

4. Conclusions

Based on the examples shown above we can make the following general conclusions. Periods of 12 and 24 h are not always clearly visible in the test series. Often, the oscillations with periods of 12 and 24 h, if they appear in the power spectrum at all, have the character inherent to real physical signals; i.e., they exhibit the variations in the amplitude, frequency drift, fork splitting, merging of periods, etc.

Typically, periods of low-frequency oscillations in sunspots are observed in a wide range from 0.5 h up to 40 h. The lowest mode of these oscillations lies in the interval of periods 12 to 32 h (Efremov et al. 2012) depending on the magnetic field strength. As a result, artificial frequencies included in this interval and their existence greatly complicates the study of long-period oscillations. However, in some cases the artifacts do not remarkably affect the pattern of physical processes in sunspots. In particular, as shown in Example 6, one can obtain the important result concerning the independence of long-term oscillations in widely separated sunspots. In this case artifacts were not visible and the magnetic field did not exceed 2000 G.

Another case of this kind is Example 5, where we are dealing with a dynamical process of sunspots formation in the bipolar group. Here there was a high time synchronization in the behavior of magnetic field variations in the leading and following spots. The phase shift between two curves revealed in this example (Fig. 6) has a clear physical meaning as a time delay required for propogating perturbations from a region with spots that are developing dynamically. There was no observed manifestation of artifacts.

The influence level of the artifacts in dependence on the magnetic field strength can be seen more clearly from Table 1. It shows that the artifacts are sharply expressed in cases where the magnetic field strength in a sunspot (in its position on the central meridian) is greater then 2000 G. Example 5 is an exception because it is a dynamic process, not a well-established pattern of oscillations. The first column presents the number of the example. The absolute mean value of the magnetic field strength taken from the time series is shown in the second column. The

Table 1. Summary of the examples.

Example number	Magnetic field (Gauss, absolute mean value)	Status of artifacts
1	2150	Strong
2	1750	Not visible
3	2100	Strong
4	2150	Strong
5	A: 2150	Not visible (spots in the formation stage)
6	S1: 1750; S2: 1850	Not visible

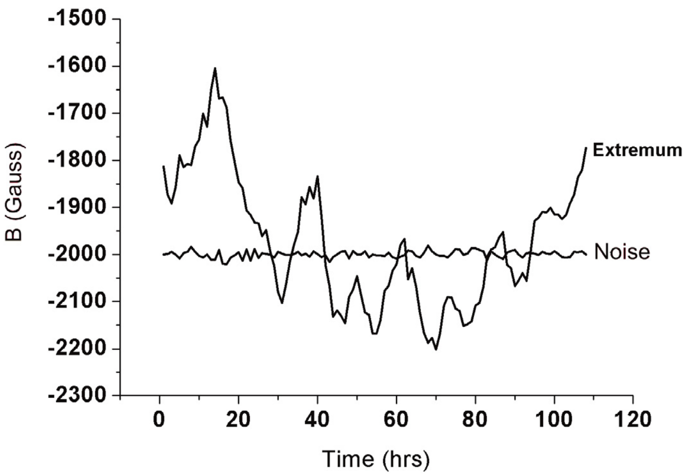

Fig. 11. Superposition of the initial time series obtained from the magnetograms of the active region NOAA 11101 and the noise time series obtained from the magnetograms of the point located outside the active region. The value of the noise time series was increased by the 2000 Gauss over its initial value. The active region field-of-view is $[100'' \times 100'']$. The active region center coordinates are $[-319'' \times 87'']$ obtained at 20:00:08 UT on 2010 Aug. 28. The point coordinates are $[-319'' \times -125'']$ taken at the same time as the sunspot coordinates. The time series starts at 00:00 UT on 2010 Aug. 28.

third column represents the status of 12 and 24 h artifacts, i.e., whether it is visible or not clearly defined.

Considering that the artifacts are even present in the noisy component of the magnetic field, all the above suggests that the function of the artifact amplification has a threshold character with the growth of the magnetic field. As long as the magnetic field strength is less than 2000 G (absolute value), the impact of artifacts is relatively small and does not significantly distort the power spectrum of real oscillations. When the magnetic field strength is greater than 2000 G, the influence of artifacts becomes dominant, and study of long-period oscillations of sunspots turns out to be impossible.

An independent analysis of the cases we have examined has been conducted by Scherrer (priv. comm.). He confirms that HMI does have such errors. The risk of 12 h and 24 h artifacts can be estimated by adding the Doppler signal to the magnetic signal: $2.16 * B$. If this total "equivalent velocity" is close to or exceeds 6500 m/s, the modulation of the 12/24 h harmonics appears.

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