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Millisecond Radio Spikes in the Decimetric Band

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Abstract We present the results of the analysis of thirteen events consisting of dm-spikes observed in Toruń between 15 March 2000 and 30 October 2001. The events were obtained with a very high time resolution (80 microseconds) radio spectrograph in the 1352 – 1490 MHz range. These data were complemented with observations from the radio spectrograph at Ondřejov in the 0.8 – 2.0 GHz band. We evaluated the basic characteristics of the individual spikes (duration, spectral width, and frequency drifts), as well as their groups and chains, the location of their emission sources, and the temporal correlations of the emissions with various phases of the associated solar flares. We found that the mean duration and spectral width of the radio spikes are equal to 0.036 s and 9.96 MHz, respectively. Distributions of the duration and spectral widths of the spikes have positive skewness for all investigated events. Each spike shows positive or negative frequency drift. The mean negative and positive drifts of the investigated spikes are equal to $-776\ \mathrm{MHz\,s^{-1}}$ and $1608\ \mathrm{MHz\,s^{-1}}$, respectively. The emission sources of the dm-spikes are located mainly at disk center. We have noticed two kinds of chains, with and without frequency drifts. The mean durations of the chains vary between 0.067 s and 0.509 s, while their spectral widths vary between 7.2 MHz and 17.25 MHz. The mean duration of an individual spike observed in a chain was equal to 0.03 s. While we found some agreement between the global characteristics of the groups of spikes recorded with the two instruments located in Toruń and Ondřejov, we did not find any one-to-one relation between individual spikes.

Keywords Solar corona · Flares · Radio bursts

Energy Storage and Release through the Solar Activity Cycle – Models Meet Radio Observations
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1. Introduction

Decimetric radio spikes (hereafter called dm-spikes) are short-lived individual electromagnetic emissions usually of duration not longer than 0.1 s, recorded in a very narrow bandwidth of 0.2 – 2.0% of the center frequency (Benz, 2002). The dm-spikes usually appear in multi-element groups, typically of up to several thousands of individual events each (Benz, 1985). Sometimes one can distinguish columns and chains of spikes on radio spectrograms (Guedel and Benz, 1988; Dąbrowski *et al.*, 2005). A chain of spikes is a series of spikes emitted at about nearly the same frequency. The dm-spikes occur often during DCIM (decimeter, complex, highly structured radio emission) solar events. They can be observed effectively with high time resolution due to their very high flux densities (of the order of 100 solar flux units, $1\ \mathrm{sfu} = 10^{-19}\ \mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$) and very high brightness temperature, greater than $10^{13} - 10^{15}$ K (Benz, 1986, 2002). The intense emission of decimetric radiation is generally considered to originate from nonthermal electron velocity distributions. These distributions can be unstable to maser emission or plasma waves that couple coherently with radio waves (Dąbrowski and Benz, 2009).

The relative spectral widths of the dm-spikes are of the order of a few percent and can vary significantly both from one event to another and within the same event (Benz, 1986; Fleishman and Melnikov, 1999). Csillaghy and Benz (1993) analyzed two events recorded in the 1.08 – 1.6 GHz and 1.0 – 1.35 GHz bands; they found that the average relative spectral width of the spikes was 17 MHz and 49.50 MHz, respectively. Messmer and Benz (2000) observed dm-spikes in the 0.87 – 1.0 GHz band and found that their spectral widths were equal to 7.5 MHz. Table 1 presents a review of the spike durations and spectral widths reported in various papers. Both parameters were evaluated at half height of their maxima, and their mean values were estimated for at least ten or more spikes.

The dm-spikes reveal very fast drifts in frequency, with a wide scatter of the drifts over positive and negative values (a negative drift is defined as the time change of an observed frequency from higher to lower values), but usually the negative drifts dominate. The drifts lie between -1 and $-4\ \mathrm{GHz\,s^{-1}}$ at 770 MHz (Guedel and Benz, 1990), while their absolute drift lies between 2.2 to $4.3\ \mathrm{GHz\,s^{-1}}$ in the 2.7 – 3.8 GHz band (Wang, Yan, and Fu, 2002).

The dm-spikes have the highest association rate with flares (95%) of all coherent radio emissions. By contrast, only 2% of all hard X-ray (HXR) events are associated with dm-spikes (Aschwanden and Guedel, 1992). The emission of the dm-spikes is often correlated in time with the HXR emission recorded during impulsive phases of solar flares (Benz, 1986; Aschwanden and Guedel, 1992; Dąbrowski and Benz, 2009). Unfortunately, due to an insufficient temporal resolution of the presently available X-ray observations, it is not possible to investigate temporal correlations of the individual radio spikes with short-term changes of the HXR flux.

Detailed reviews considering solar dm-spikes can be found in numerous papers, *e.g.*, Benz (1986), Fleishman and Melnikov (1998), and Dąbrowski *et al.* (2005).

In this paper we present an analysis of thirteen events in the dm range observed with the Toruń radio spectrograph having very high time resolution (80 microseconds). Various kinds of co-temporal radio events (two of them with dm-spikes), observed by the Ondřejov radio spectrograph, are also analyzed. The main characteristics of the observed spikes were given in the paper by Dąbrowski *et al.* (2005). Here we present new results concerning their statistical properties and evaluate the physical parameters of their emission sources. We also compare the dm-spikes observed simultaneously by the Toruń and Ondřejov radio spectrographs.

Table 1 Durations and spectral widths of the radio spikes observed in 0.3 GHz to 7.5 GHz band.

Freq.[*] [GHz]	Duration [ms]	Time res. [ms]	Width [MHz]	Freq. res. [MHz]	Reference
0.33	–	–	9.9	1 – 10	(Benz, Csillaghy, and Aschwanden, 1996)
0.35	–	–	4.8	1	(Messmer and Benz, 2000)
0.36	–	–	7.32	1	(Csillaghy and Benz, 1993)
0.36	73	2	–	1	(Guedel and Benz, 1990)
0.40[**]	4 – 30	1 & 10	<20	–	(Magdalenić *et al.*, 2006)
0.47	41	0.5	–	3	(Guedel and Benz, 1990)
0.48	–	–	12.6	6	(Csillaghy and Benz, 1993)
0.60	–	100	<2	0.061	(Benz *et al.*, 2009)
0.73	20	10	–	10	(Guedel and Benz, 1990)
0.77	20	2	–	10	(Guedel and Benz, 1990)
0.83	–	–	7.04	1	(Csillaghy and Benz, 1993)
0.87	19	10	–	10	(Guedel and Benz, 1990)
0.94	–	–	7.5	1	(Messmer and Benz, 2000)
1.01	17	10	–	10	(Guedel and Benz, 1990)
1.16	–	–	49.5	14	(Csillaghy and Benz, 1993)
1.34	–	–	17.0	10	(Csillaghy and Benz, 1993)
1.42	2.0	1	–	–	(Wang and Xie, 1999)
1.42	9.0	1 & 10	–	–	(Mészárosová *et al.*, 2003)
1.69	–	–	32.3	10	(Csillaghy and Benz, 1993)
2.00	1.3	1	–	–	(Wang and Xie, 1999)
2.70	5.1	1 & 10	–	–	(Mészárosová *et al.*, 2003)
2.80	–	–	10.8	10	(Csillaghy and Benz, 1993)
2.84	13.2	1	–	–	(Wang and Xie, 1999)
3.20	14	8	–	10	(Chernov *et al.*, 2001)
3.20	42.7	8	117.3	10	(Wang and Xie, 1999)
3.20	8 – 36	8	20 – 110	10	(Wang *et al.*, 2008)
5.25	–	5	~ 30	10	(Rozhansky, Fleishman, and Huang, 2008)
7.30	~ 100	100	120	10	(Benz *et al.*, 1992b)
7.40	–	–	48.7	11	(Csillaghy and Benz, 1993)

[*] Center of the frequency band.

[**] Spike-like structures, observed at 237, 327, 408, 610 MHz and in the range 270 – 450 MHz.

2. Instruments and Observational Data

Thirteen events with dm-spikes were observed in Toruń between 15 March 2000 and 30 October 2001, during nearly 2000 hours of observations (Dąbrowski *et al.*, 2005; Dąbrowski and Kus, 2007) and co-temporal various kinds of radio events were observed in Ondřejov (Table 2).

During the observations of the dm-spikes the 15 m radio telescope in Toruń (located in Piwnice) was connected to the fast multi-channel radio spectrograph Penn State Pulsar Machine II – PSPM II (Cadwell, 1997). Radio spectrograms of the spikes were recorded in

Table 2 Thirteen events of dm-spikes observed in Toruń between 15 March 2000 and 30 October 2001 (some events consisted of two groups of spikes), and corresponding events observed in Ondřejov.

Date	Toruń event Time interval [UT]	Ondřejov event	Class GOES	Position	Flare phase GOES
15.03.2000	12:20:06 – 12:21:08	continuum and spikes	C5.0	S18W19	rise
26.03.2000	10:37:44 – 10:38:04	spikes (800 – 1000 MHz)	C2.0	S18E09	maximum
26.04.2000	14:09:55 – 14:10:35	–	B7.0	S15E10	rise
17.05.2000	15:42:21 – 15:42:26	–	C2.2	N20E20	rise
	15:43:45 – 15:43:52	–	C2.2	N20E20	rise
21.05.2000	09:39:26 – 09:39:31	–	C8.2	S18W47	rise
	09:39:44 – 09:39:45	–	C8.2	S18W47	rise
21.06.2000	09:24:59 – 09:26:05	continuum and weak spikes	M1.3	N24W34	rise
11.07.2000	13:16:03 – 13:16:44	strong continuum	X1.0	N18E27	decay
	13:26:30 – 13:27:37	spikes	X1.0	N18E27 or S17W39	decay
11.07.2000	14:41:10 – 14:48:10	spikes	X1.0	N18E27	decay
11.07.2000	14:57:49 – 15:00:37	–	X1.0	N18E27	decay
22.03.2001	13:10:37 – 13:10:50	–	M1.0	N14E60	rise
	13:11:17 – 13:11:34	pulsations	M1.0	N14E60	rise
23.04.2001	10:09:53 – 10:10:03	continuum	C9.1	N17E26	rise
	10:14:45 – 10:15:05	continuum	C9.1	N17E26	rise
14.05.2001	12:47:25 – 12:47:39	–	C2.3	S15W15	decay
30.10.2001	12:20:14 – 12:20:40	continuum	C7.4	N12E10	maximum

the 1352 – 1490 MHz frequency band split into 46 channels, each 3 MHz wide. The time resolution of the collected data is equal to 80 microseconds (Dąbrowski *et al.*, 2005).

The investigated radio events were also observed by the 10 m radio telescope in Ondřejov with a 0.8 – 2.0 GHz swept-frequency radio spectrograph. The 0.8 – 2.0 GHz band was divided into 256 frequency channels with bandwidths of 3 MHz, set 4.69 MHz apart. The temporal resolution of the radio spectra was equal to 0.1 s (Jiřička *et al.*, 1993; Karlický, Jiřička, and Sobotka, 2000).

3. Data Evaluation and Data Analysis Methods

The radio data collected with the radio spectrographs in Toruń and Ondřejov were processed in order to make the sensitivities of the individual channels internally homogeneous, but were not calibrated in absolute flux units or equalized between both telescopes.

For subsequent automatic evaluation of the main observational properties of the individual spikes, we adopted a working definition of a spike as a short-lived increase of the flux with a peak signal more than three times higher than the local background, in accordance with our previous paper (Dąbrowski *et al.*, 2005). The temporal resolution of the data collected in Toruń and Ondřejov was different; then, to compare the spectra, the temporal resolution of the Toruń radio spectrogram was numerically decreased, but the statistical properties of the spikes observed with both instruments were calculated using original data.

Each individual radio spike observed in Toruń was fitted with a two-dimensional elliptical Gaussian (using a nonlinear least-square method), and the basic parameters were measured at an intensity level equal to half of the maximum for duration, spectral width, and frequency drift. All spurious structures (like local peaks) were rejected. A detailed description of this method was given by Dąbrowski *et al.* (2005).

Due to the limited temporal resolution of the data collected with the Ondřejov radio spectrograph, we only analyze the frequency profiles of the individual spikes. An automatic code evaluated the frequency width of the individual spikes by fitting its frequency profile with a one-dimensional Gaussian having four free parameters: height, center frequency, width (standard deviation), and signal level.

4. Results

4.1. Basic Characteristics of the Individual dm-Spikes

We have evaluated the main observational parameters of the 5199 individual dm-spikes (lasting no longer than 0.1 s) observed in Toruń. The mean duration of the spikes was equal to 0.036 s. The measured mean spectral width of the spikes was equal to 9.96 MHz, but this value can be recognized as an upper limit due to the limited spectral resolution of the radio spectrograph, equal to 3 MHz (Benz *et al.*, 2009). For a particular event, the spectral widths of the spikes are usually comparable.

Each spike shows positive (from low to high) or negative (from high to low) frequency drift. The negative drifts range from $-63\ \mathrm{MHz\,s^{-1}}$ to $-13\,600\ \mathrm{MHz\,s^{-1}}$, while the positive ones range from $51\ \mathrm{MHz\,s^{-1}}$ to $13\,400\ \mathrm{MHz\,s^{-1}}$. The mean negative and positive drifts of the investigated spikes are equal to $-776\ \mathrm{MHz\,s^{-1}}$ and $1608\ \mathrm{MHz\,s^{-1}}$, respectively.

Histograms of the basic parameters of the dm-spikes (for all investigated spikes), *i.e.,* duration, spectral width, and frequency drifts, are presented in Figure 1. All investigated parameters have positive skewness distributions (compare with Csillaghy and Benz, 1993).

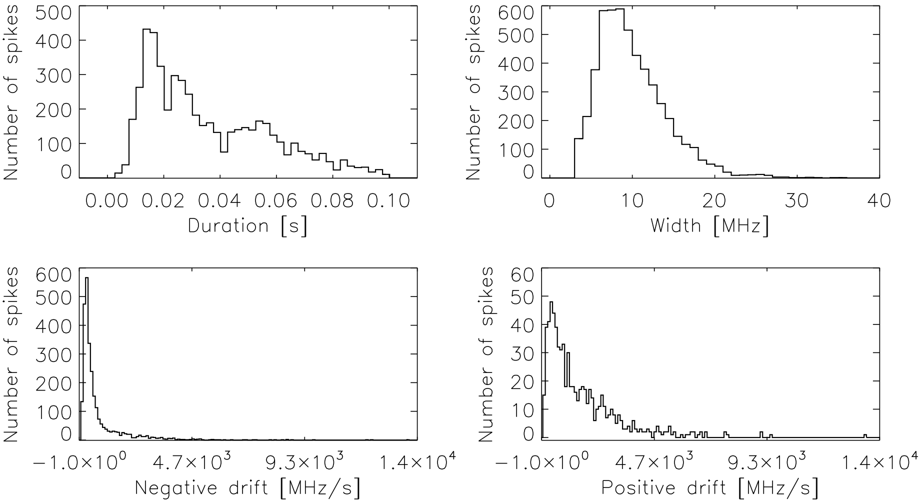

Figure 1 Histograms of the basic parameters of the dm-spikes (for all investigated spikes): duration, spectral width, and frequency drifts.

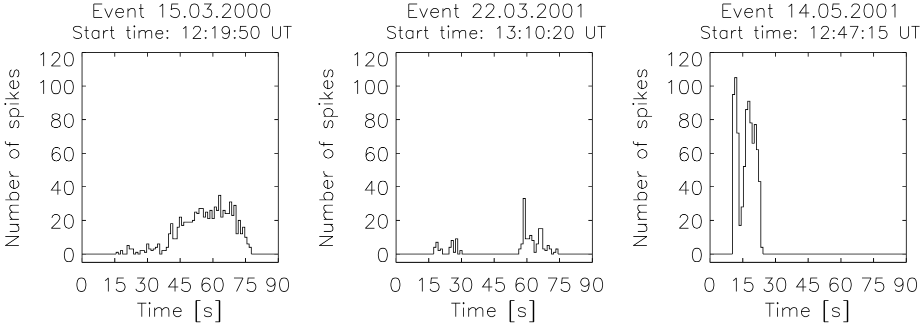

Figure 2 Spike rates (number of spikes per second) in radio events.

4.2. Groups and Rates of dm-Spikes

For the thirteen investigated events we detected eighteen individual groups of dm-spikes (Table 2). The groups of spikes lasted from 1 s up to 420 s; the mean duration was equal to 55.7 s. Each group consists of a dozen or so up to several hundreds of individual spikes.

Spike rates (number of spikes per second) are unique for each individual event (Figure 2). There are: *i*) events that have a gradual increase and next an abrupt drop of the numbers of observed spikes, *ii*) events with spikes clustered into well-distinguishable groups of spikes, and *iii*) events with the highest numbers of spikes just at the beginning of the whole event.

4.3. Chains of the dm-Spikes

We have noticed two kinds of well-outlined complex structures formed by numerous individual spikes on the radio spectrograms of the investigated events: columns and chains of spikes. While the columns were studied by Dąbrowski *et al.* (2005), here we analyze the chains in detail. We define a chain of spikes as a group of at least three individual emissions (spikes) having the same (chains without frequency drift) or similar (chains with frequency drift) frequency bands and appearing close in time.

Two kinds of chains, with and without frequency drifts, are presented in Figures 3 and 4, respectively. The chains of spikes were observed during the following events: 15 March 2000, 26 March 2000, 26 April 2000 (only two chains of spikes were observed), and 30 October 2001. We recorded a total of 29 chains of spikes. The mean durations of the chains, evaluated for each individual event separately, vary between 0.067 s and 0.509 s, while their spectral widths vary between 7.2 MHz and 17.25 MHz. The mean duration of an individual spike observed in the chain was 0.03 s. The main parameters of the chains are presented in Table 3. The drift, spectral widths, and durations of the chains were evaluated using the same fitting method as used for individual spikes.

Histograms of the basic parameters of the chains (for all investigated chains), *i.e.*, duration, spectral width, and frequency drifts, are presented in Figure 5.

4.4. Decimetric Spikes *Versus* Phase of the Solar Flare

Emissions of the investigated dm-spikes were observed during various phases of solar flares. Similar results were published by Benz *et al.* (2005). Half of the dm-spike events were recorded during the rise phases of the solar flares (54%). The dm-spikes were emitted mostly (54%) during C-class flares; similar results were published by Jiřička *et al.* (2001), who observed the dm-spikes in the bandwidth 0.8 – 2.0 GHz between 1992 and 2000.

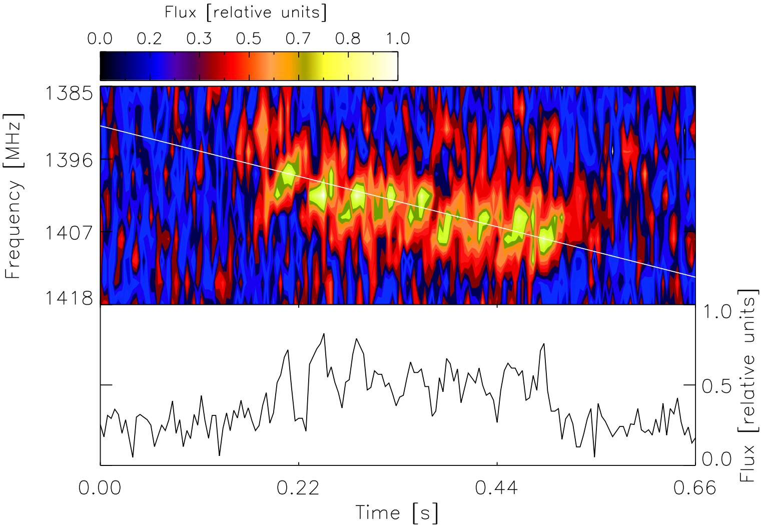

Figure 3 Chain of spikes with a drift in frequency recorded on 26 March 2000 (beginning at 10:38:00.6 UT). The upper panel presents the radio spectrogram. The lower panel shows the changes of signal intensity (along the inclined line in the upper part).

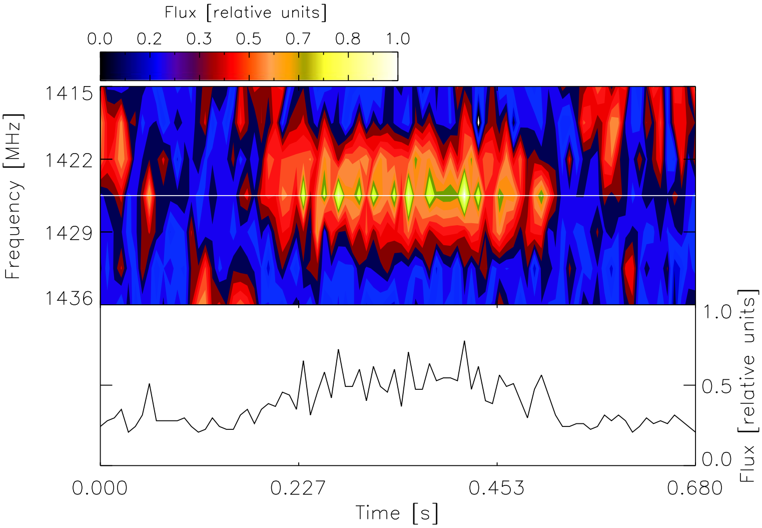

Figure 4 Chain of spikes without a drift in frequency recorded on 26 April 2000 (beginning at 14:10:13.96 UT). The upper panel presents the radio spectrogram. The lower panel shows the changes of signal intensity (at the frequency where we observed the highest signal for this chain of spikes).

4.5. Locations of the Emission Sources of the Radio Spikes

Most of the active regions which host sources of radio spikes (∼ 77%) were located close to the center of the solar disk, inside a circle having a radius of 35° (Figure 6). Due to the low number (thirteen) of dm-spike events observed in Toruń we also analyzed dm-spikes

Table 3 Parameters of the chains of spikes observed in four radio events: 15 March 2000, 26 March 2000, 26 April 2000, and 30 October 2001.

Events	15.03.2000	26.03.2000	26.04.2000*		30.10.2001
Number of chains	10	9	1st chain	2nd chain	8
Duration [s]					
minimum/maximum	0.048/0.10	0.099/0.34	–	–	0.061/0.159
mean	0.067	0.17	0.275	0.509	0.10
Width [MHz]					
minimum/maximum	5.6/14.4	7.5/15.0	–	–	14.4/25.1
mean	8.27	11.2	7.2	7.8	17.25
Negative drifts [MHz s^{-1}]					
number of chains	7	3	–	–	8
minimum/maximum	180/587	52/340	–	–	59/401
mean	304	179	–	–	218
Positive drifts [MHz s^{-1}]					
number of chains	–	5	–	–	–
minimum/maximum	–	15/267	–	–	–
mean	–	80	–	–	–

*Only two chains of spikes were observed in this event.

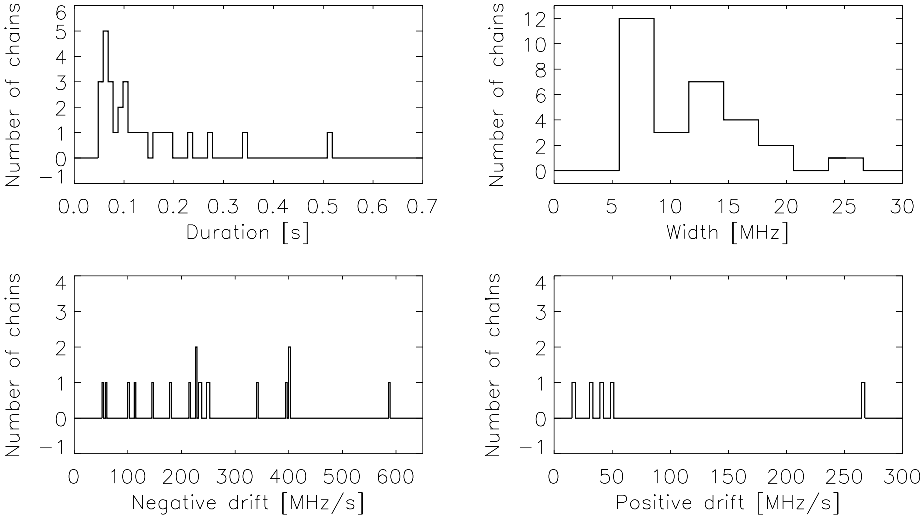

Figure 5 Histograms of the basic parameters of the chains (for all investigated chains): duration, spectral width, and frequency drifts.

observed in Ondřejov in the 0.8 – 2.0 GHz band, which have been described by Karlický, Sobotka, and Jiřička (1996), Karlický, Jiřička, and Sobotka (2000), and Fárník and Karlický (2005). Thus, the total number of dm-spike events having well-established emission sources increased to twenty-one.

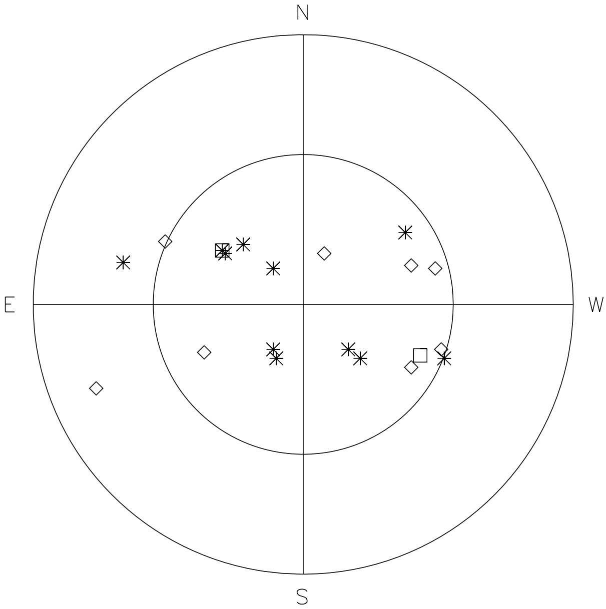

Figure 6 Distribution of active regions associated with the dm-spike emission on the solar disk. Those corresponding to observations from Toruń are marked with asterisks. The event observed on 11 July 2000 in Toruń is marked with a square, but the exact location of the radio source is problematic (two co-temporal solar flares in two distinct active regions were observed). The active regions related with observations from Ondřejov are marked with diamonds. The concentric circles are drawn at 50° and 90° from disk center.

The emission sources of the dm-spikes are determined from Hα, *Yohkoh*, TRACE, and EIT/SOHO observations and are located mainly inside a circle with a radius of 50°. The reasons for this apparent preference in location are unclear, and this topic needs future investigation.

4.6. Radio Events Observed Co-temporal in Toruń and Ondřejov

The radio spectrographs of both observatories have complementary frequency bands (1352 – 1490 MHz in Toruń and 0.8 – 2.0 GHz in Ondřejov), but different time and spectral resolutions.

In Table 2 we present a list of the dm-spike events observed with the Toruń radio telescope and the relevant events observed with the radio telescope in Ondřejov: spikes, continuum emissions, and pulsations. However, for some groups of dm-spikes observed in Toruń there were no specific radio events in Ondřejov. Four dm-spike groups observed in Toruń were simultaneous with events in Ondřejov in the same frequency band, while one dm-spike event observed on 26 March 2000 in Toruń was also observed in Ondřejov, but in a different frequency band (800 – 1000 MHz).

Table 4 presents the main parameters of the spikes observed on 11 July 2000 in the same frequency band in Toruń and Ondřejov (1352 – 1490 MHz). Table 5 presents additional parameters of the dm-spikes observed in Ondřejov in the 0.8 – 2.0 GHz band.

4.6.1. First Event with dm-Spikes on 11 July 2000

The event, which consisted of two groups of spikes, was observed in Toruń between 12:30:10 UT and 13:30:10 UT. The first group of spikes was observed between 13:16:03 UT and 13:16:44 UT, the second one between 13:26:30 UT and 13:27:37 UT. The spikes of both groups were recorded in the entire available frequency range (1352 – 1490 MHz), and no internal structure of the individual spikes was detected.

Table 4 Parameters of the dm-spikes observed on 11 July 2000 in Toruń and Ondřejov in the 1352 – 1490 MHz band.

	Toruń	Ondřejov
Time interval [UT]	13:26:30 – 13:27:37	13:25:40 – 13:27:40
Number of spikes	688	39
Duration [s]		
minimum/maximum	0.01/0.99	–
mean/median	0.03/0.03	–
skewness	1.8	–
Width [MHz]		
minimum/maximum	3.1/31.4	4.8/14.7
mean/median	10.3/9.4	7.6/7.8
skewness	1.1	0.6
Negative drifts [$\mathrm{MHz\,s^{-1}}$]		
minimum/maximum	64/3850	–
mean/median	1153/817	–
skewness	0.8	–
Positive drifts [$\mathrm{MHz\,s^{-1}}$]		
minimum/maximum	149/3853	–
mean/median	1260/1115	–
skewness	1.0	–

Table 5 Parameters of the dm-spikes observed on 11 July 2000 in Ondřejov in the 0.8 – 2.0 GHz band.

	1st event	2nd event
Time interval [UT]	13:25:40 – 13:27:40	14:43:00 – 14:44:00
Number of spikes	261	22
Width [MHz]		
minimum/maximum	4.7/23.9	4.7/15.9
mean/median	7.9/7.1	7.0/6.2
skewness	1.7	1.9

The first group of spikes was associated with strong continuum emission observed in Ondřejov. The second group of spikes was also observed in Ondřejov between 13:25:40 UT and 13:27:40 UT in the frequency band 1.0 – 1.8 GHz. The dm-spikes recorded in Ondřejov were organized into two branches (bandwidth ~ 300 MHz), slowly drifting toward lower frequencies (Karlický *et al.*, 2001) – the bandwidth of the Toruń radio spectrograph is much narrower than the bandwidth of the Ondřejov instrument (Figure 7). The frequency drift of the branches was around $-6\ \mathrm{MHz\,s^{-1}}$. Due to electromagnetic interference the data recorded in Ondřejov in the 1391 – 1278 MHz band were not used. The global spectra of the dm-spikes observed in both locations within the frequency band 1352 MHz to 1490 MHz seem to be similar, but we did not find any one-to-one relation between individual spikes (Figures 8 and 9). The correlation coefficient of the total radio fluxes recorded with both

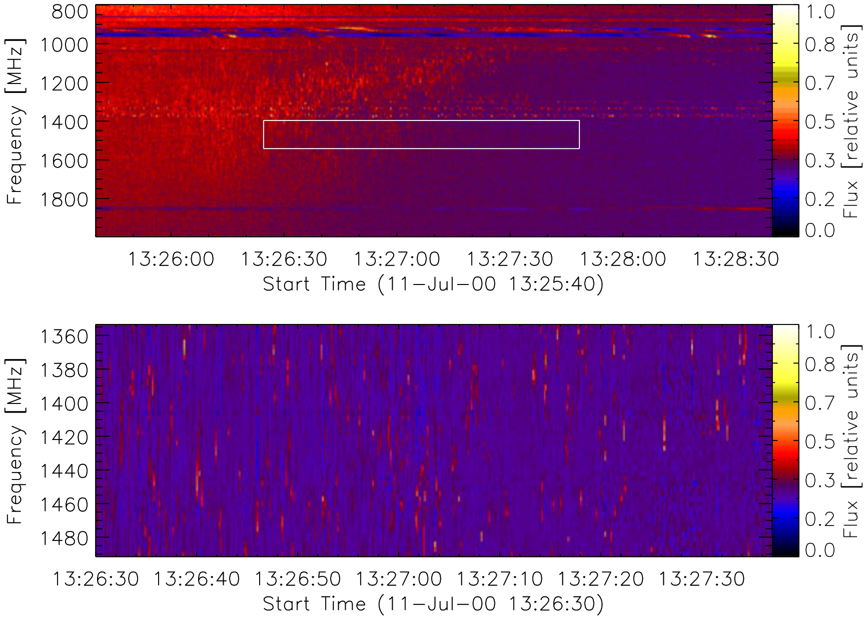

Figure 7 The dm-spikes recorded on 11 July 2000 in Ondřejov (upper panel) and Toruń (lower panel). White rectangle on Ondřejov radio data corresponds to the time and frequency range of Toruń data.

instruments during the same time and frequency range was equal to 0.2 (Figure 8). For two selected sections of the spectra, taken from 13:27:10 to 13:27:12 UT and from 13:27:13 to 13:27:15 UT (Figure 9), the correlation coefficients of the total radio fluxes were equal to 0.45 and 0.02, respectively.

The spikes observed between 13:26:30 UT to 13:27:37 UT in the frequency band 1352 MHz to 1490 MHz have mean spectral widths (FWHM) equal to 10.3 MHz and 7.6 MHz in Toruń and Ondřejov, respectively. Distributions of the spectral widths of the spikes observed in both observatories have positive skewness, in accordance with the results presented by Csillaghy and Benz (1993).

4.6.2. *Second Event with dm-Spikes on 11 July 2000*

The radio event was observed in Toruń between 14:34:50 UT and 14:51:30 UT. During the event a single group of spikes was identified between 14:41:10 UT and 14:48:10 UT in the frequency band 1352 – 1490 MHz. The spikes were recorded in the entire available frequency range; no internal structure of the individual spikes was detected. The dm-spikes were also observed in Ondřejov between 14:36:10 UT and 14:44:50 UT in the frequency band 0.8 – 1.8 GHz. For statistical analysis, we selected a one minute long period from 14:43:00 UT to 14:44:00 UT; this period consisted of 22 spikes (Table 5). As in the previous case, no one-to-one correlation between the individual spikes observed in Toruń and Ondřejov was found.

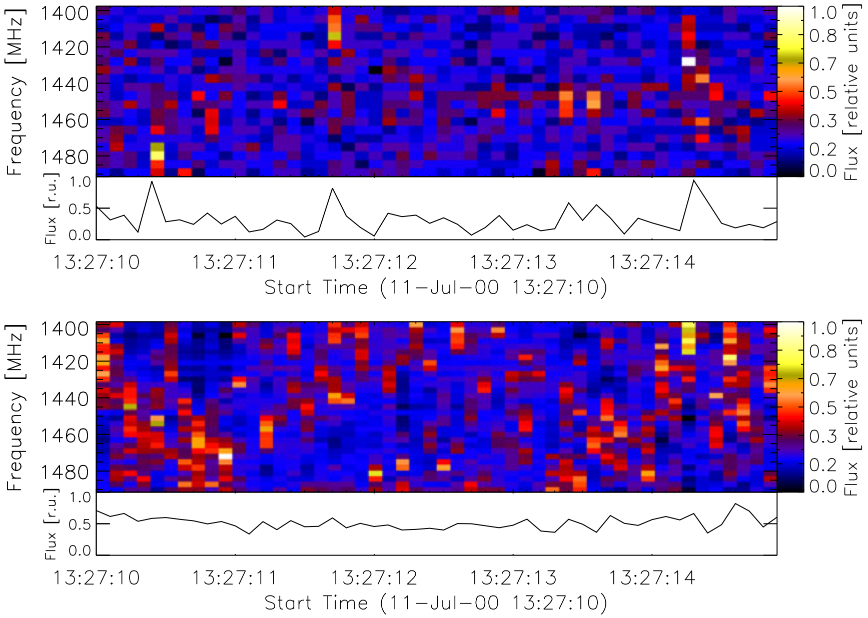

Figure 8 The dm-spikes recorded on 11 July 2000, between 13:27:10 UT and 13:27:15 UT in the band 1400 – 1490 MHz with 0.1 s time resolution in Ondřejov (upper panel) and Toruń (lower panel). Total radio fluxes (in relative units) are presented below the corresponding radio spectrogram. The correlation coefficient of the total radio fluxes is equal to 0.2.

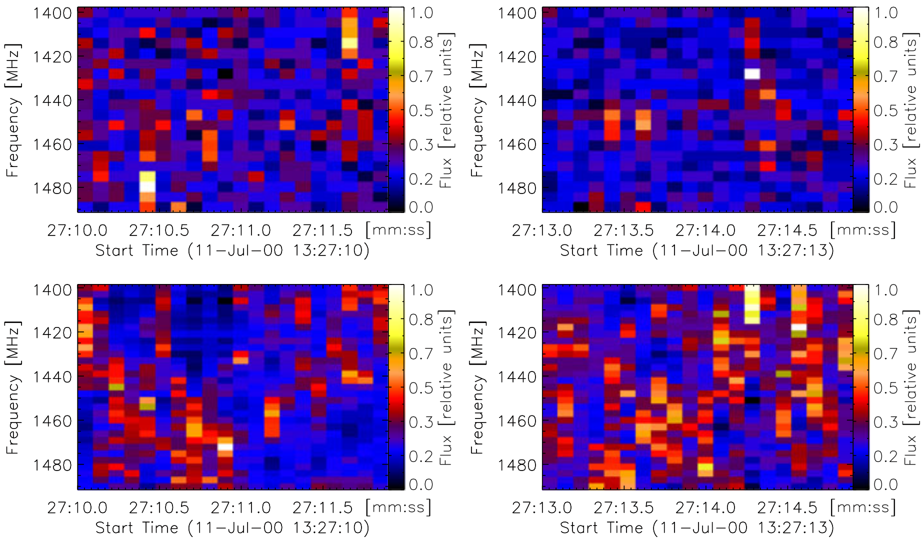

Figure 9 Enlarged sections of the radio spectrograms presented in Figure 8. Upper panels: dm-spikes recorded in Ondřejov. Lower panels: dm-spikes recorded in Toruń. The correlation coefficients of the total radio fluxes of the spectra are equal to 0.45 and 0.02 for left and right columns, respectively.

5. Discussion and Conclusions

We investigated thirteen events having dm-spikes observed in Toruń between 15 March 2000 and 30 October 2001, and complementary radio events observed in Ondřejov: spikes, continuum emissions, and pulsations.

The mean spectral width of the spikes observed in the 1352 – 1490 MHz band was equal to 9.96 MHz; this is nearly three times smaller than the spectral width (32.2 MHz) estimated by Csillaghy and Benz (1993) for spikes observed in the 1400 – 1970 MHz band. However, the mean spectral width measured at half height of the maximum intensity in 1420 MHz using the relation presented in the paper by Csillaghy and Benz (1993) is equal to 13.9 MHz. This value is similar to the one that we obtained. Distributions of the spectral widths of the spikes have positive skewness for all investigated events, in accordance with the results obtained by Csillaghy and Benz (1993). For a particular event the spectral widths of the spikes are usually comparable. This could be attributed to stable or marginally variable conditions in the emission source, but it could also be an observational artifact due to the narrow frequency band of the observations (138 MHz).

The knowledge of the frequency drifts allows us to estimate the bulk velocities of the electron beams exciting the dm-spikes as proposed by Benz *et al.* (1992a). Assuming plasma emission at the fundamental plasma frequency for a $-776\ \mathrm{MHz\,s^{-1}}$ drift (the mean value for all dm-spikes with negative drifts observed in Toruń), the relevant velocity is $\vartheta_{\mathrm{b}} = 1.1 \times 10^{9}\ \mathrm{cm\,s^{-1}}$, and the kinetic energy of the electrons is equal to 0.344 keV. For a drift of $1608\ \mathrm{MHz\,s^{-1}}$ (the mean value for all dm-spikes with positive drifts observed in Toruń), the bulk velocity is $\vartheta_{\mathrm{b}} = 2.3 \times 10^{9}\ \mathrm{cm\,s^{-1}}$, and the kinetic energy of the electrons is equal to 1.504 keV, assuming a density scale length of $\sim 10^{9}$ cm (Benz, 2002) and an emission frequency $\nu = 1420$ MHz. We did not find any correlation between the emission frequency and the frequency drift. However, in some cases the frequency drift was equal or nearly equal for various emission frequencies. In such cases, the electron beams traveled with constant velocities through the whole observed region.

The frequency drifts of the spikes are scattered in a broad range. In the entire set of investigated emissions, we have found some having very low negative and positive frequency drifts. We found eighteen spikes (0.3% of the whole population) with negative drifts lower than $-100\ \mathrm{MHz\,s^{-1}}$ and four spikes (0.08%) with positive drifts lower than $100\ \mathrm{MHz\,s^{-1}}$, respectively. These values of the frequency drifts are much lower than the average for all spikes and the average for type III bursts. Assuming that all the spikes are generated by electron beams, such a broad scattering of their frequency drifts can be explained by a broad range of density gradients in their sources. Namely, the travel distances of these beams are of the order of 1000 km due to the very short duration of the spikes. The density gradients on such short spatial scales can differ essentially from gradients in the mean solar atmosphere, especially in turbulent reconnection outflows, which were proposed as sources of the spikes by Bárta and Karlický (2001).

The spikes are spread uniformly across the radio spectrograms. The only exception consists of chains and columns of spikes, but their number is relatively low. This means that the individual spikes are emitted from various altitudes.

In some events (for example, on 17 May 2000) there are no spikes between the groups of spikes.

The main parameters of the spikes emitted in groups for a single event are stable. It is very likely that the emissions of the whole group occurred in a single region with stable physical conditions. The sizes of the emission sources of the investigated spikes were estimated using the relations described by Benz (2002). Assuming the plasma mechanism of emission, the mean diameters of the emission sources are of the order of 100 km.

For the dm-spikes emitted in 1420 MHz, the relevant electron density is equal to 2.5×10^{10} cm^{-3} (from the relation of the plasma frequency and electron density). According to the solar corona model evaluated by Aschwanden (2002), a resulting density of 2.5×10^{10} cm^{-3} must be present at an altitude of $\sim 10^4$ km above the solar surface. Assuming an active region mean magnetic field of the order of 200 G (Aschwanden, 2004) and a magnetic dipole depth of 3.5×10^4 km (Takakura and Scalise, 1970), the emission source observed at a gyromagnetic frequency of 1420 MHz (central frequency of the analyzed band of frequencies) will be located at an altitude of 5.7×10^3 km (Zhao, 1995). This altitude corresponds to the lower solar corona.

We have found chains of spikes in the analyzed spectrograms. Assuming the plasma emission mechanism, the chains of spikes could be excited by MHD shock waves similarly to the case of the chain of type I radio bursts (Spicer, Benz, and Huba, 1981). These chains thus support the idea that dm-spikes are generated in the turbulent reconnection plasma outflows (Bárta and Karlický, 2001).

While we found some agreement between global characteristics of the groups of spikes recorded with the two instruments located in Toruń and Ondřejov, we did not find any one-to-one relation between individual spikes (Figures 7 – 9). To explain this finding, we considered two possibilities: *i*) high directivity of spike emission and *ii*) differences in measurements at Toruń and Ondřejov. Concerning the first possibility, for the distance between Toruń and Ondřejov observatories (450 km), the angle of the directivity emission cone, explaining this low correlation, should be lower than ~ 1 arcsec. This is much lower than the one (1 arcmin) estimated for spikes by Fleishman (private communication). Therefore, we decided to check the second possibility by making the following test. We generated a one minute artificial spectrum covering the frequency range from 1400 MHz to 1700 MHz; then, we added 1000 spikes randomly distributed in this spectrum. The duration and bandwidth of individual spikes were selected in the observed ranges. Considering the parameters of the radio spectrographs at Toruń and Ondřejov, we generated matrixes that mimic real observations. Then, we computed "radio fluxes" at the grid points of these matrixes. Thus, we obtained two records of the same set of spikes, which represented the spectra from Toruń and Ondřejov. For comparison, we smoothed these spectra to the same time and frequency resolution and then computed their correlation coefficient. We made several computations for different values of the duration and spectral width of spikes. We found that the correlation coefficient increases with the increase of these parameters. For a duration of individual spikes of 0.2 s (the mean value) and a bandwidth of 2 MHz (the value estimated as the real one by Benz *et al.*, 2009), the correlation coefficient was 0.4. Based on these tests, we think that the low correlation between individual spikes observed at Toruń and Ondřejov is due to differences in time and spectral resolutions, and the sensitivity of both instruments.

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