STUDY OF SED'S EMISSION PARAMETERS

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Abstract

The present research is devoted to the study of parameters of Saturn Electrostatic Discharges (SED) according to the data obtained during the observations of the initial period of storm J (December 2010) or the so-called Great White Spot (GWS). The ground-based detection was provided by the Ukrainian radio telescope UTR-2 at frequencies from 8 to 33 MHz in a wide range of time scales: from the day–to–day SED investigations to the temporal fine structure study up to microseconds. In this paper we describe our methods of data cleaning and the search for Saturn lightning in detail. The sensitivity of the observations allowed us to resolve the temporal micro–structure of lightning discharges. We determined the average signal's dispersion delay for a session equal to $(4.4 \pm 0.8) \cdot 10^{-5}$ pc cm^{-3}. It is close to the predicted value along the ray path from the storm to the radio telescope.

1 Introduction and observations

Ground-based observations of Saturnian lightning became regular after their first successful detection [Konovalenko et al., 2006; 2013] by the UTR-2 radio telescope [Braude et al., 1978] and its confirmation by comparison with Cassini's data [Zakharenko et al., 2011; 2012]. The appearance of the most well-known storm in December 2010 [Fischer et al., 2011; Sayanagi et al., 2013] allowed us to explore this phenomenon with unprecedented temporal resolution due to both the large number and great intensity of the discharges and the advantages of the UTR-2 radio telescope: a high effective area and an upgraded receiver equipment [Konovalenko et al., 2016; Zakharenko et al., 2016]. A complex time structure of the discharges as well as a dispersion delay that characterizes the medium of lightning propagation from the source to the observer were discovered [Mylostna et al., 2013; 2014].

The observations were carried out by the UTR-2 radio telescope from 21 to 27 December 2010 using three different modes of observations:(a) waveform mode, (b) auto-spectrum

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mode with a time resolution of 2 ms, (c) correlation mode with a time resolution of 10 ms. We carried out seven recording sessions during the time of thunderstorm activity on Saturn. The UTR-2 radio telescope has a five beams pattern, each beam spaced by 24 arc minutes (at 25 MHz) in the south–to–north direction. This fact allows us to use the so-called "ON–OFF" mode [Zakharenko et al., 2012; 2016]. This mode is realized when the central beam is aimed at the source ("ON"), and the maximum northern inclination (on an $\approx 1^\circ$ arc) is directed to a reference area of the sky ("OFF"). This mode significantly reduces the effect of interference due to the subtraction of the reference channel ("OFF") from the processed one ("ON"). "ON–OFF" mode was realized by using two DSPZ receivers [Ryabov et al., 2010; Zakharenko et al., 2016], synchronized by a second signal from the rubidium standard. The receivers were operated in correlation mode. This mode is on-line after FFT–processing a data stream with 4 outputs: the auto-correlation spectrum $S_1(f)$ of the "North–South" antenna (Fourier transform of sequence of time samples of the first channel digital receiver), the auto-correlation spectrum $S_2(f)$ of the "West–East" antenna, the real part $\Re(S_1 * S_2)$ of the cross-correlation spectrum of the two antennas, and the imaginary part $\Im(S_1 * S_2)$. A time resolution of 10 ms was chosen for the slow mode when receivers were operated in auto-spectrum mode. The frequency range 16.5–33.0 MHz of the recordings was divided into 4,096 channels each with a width of about 4 kHz.

The recordings in the correlation mode were carried out every night during the time when Saturn was observable using the UTR-2 radio telescope (from about 0:30 to 7:00 UT). Because of the limitations of disk space caused by the high recording rate in the waveform mode (data flow $\approx$ 0.5 TB/hour) the records had a duration of 1.5–2 hours only during the expected storm activity from 21 to 24 December. Results section is based on the observations recorded in this mode. On 25 December a short recording during the time when the estimated position of the storm was located behind the limb of the planet was carried out as a test. Figure 1 shows the schedule of sessions of observations based on the position of Saturn and the storm on its limb. Black rectangles show the time during which Saturn was visible from the UTR-2 radio telescope, orange rectangles show the time intervals when the "head" of the storm was observable from Earth. Blue rectangles (corr) show the time of records that were made by receivers in the correlation mode both from the beams "ON" and "OFF", green rectangles (WF or Sp) show the time of recordings made by the waveform receivers or the receiver in auto-spectrum mode with a resolution of 2 ms. The latter auto-spectrum mode was used once on 27 December 2010. It turned out to be less informative than the waveform mode, because the auto-spectrum mode does not contain information about the fine structure of signals. Figure 1 also indicates the times when the interference level was significantly increased (big light blue rectangles), which is associated with local day time. On 25 December there were three gaps in the recording with a duration of about 25 minutes.

The data of channels "ON" and "OFF" were cleaned from narrowband and wideband strong interferences (level of broadband noise was obviously higher than the peak intensity of SED radiation) using a procedure similar to the one described in [Zakharenko et al., 2012]. At the same time the procedure calculates an average value of the signal–to–noise ratio in each channel. The timing of each receiver, synchronized by a reference signal from a rubidium standard, allows us to check the time of each spectrum in each channel

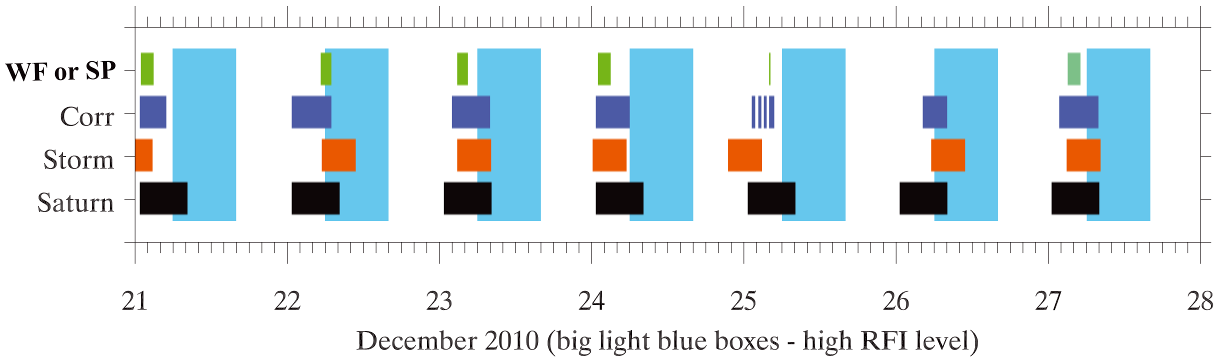

Figure 1: Time diagram of storm observations in December 2010. Saturn visibility (black), head of the storm observable from Earth (red), the recording time in the correlation mode (blue), the recording time in the waveform mode or auto-spectrum mode with a resolution of 2 ms (green). The time when the radio interference level increased significantly is shown by big light blue rectangles.

with a good accuracy and shift channels for further data processing if the time does not coincide. The next step is the subtraction of "OFF" channel from "ON" channel to reduce interference (Figure 2). Parts of recorded data completely corrupted by interferences were deleted in the process of visual inspection. The spectrograms processed in this way were finally re-binned to the desired time and frequency resolution. To increase the sensitivity of records data from 32 bands (each of 4 kHz width) have been accumulated, reaching a frequency resolution of 128 kHz. This stage was conducted simultaneously with additional cleaning from low-intensity interferences.

2 Results

2.1 Low temporal resolution

As a result of the entire session we received thousands of spectra containing lightning signals. The criterion of lightning spectra selection was the exceeding of threshold level equal to 4σ (σ is the standard deviation) simultaneously present at least in 7 sub-bands, which is equal to a 1 MHz frequency band. An example of spectra is shown in Figure 3. The red color shows the lightning flashes in the spectra that meet this selection criterion, whereas blue signals do not meet the criterion. Together with the dynamic spectrum plots we stored text and binary data files containing the following parameters of the detected lightning discharges: time, S/N ratio, average frequency channel, and time from the beginning of a file.

These data provided a number of SED characteristics for the period from 21 to 25 December 2010. For all sessions we established a distribution of SED durations and the corresponding e–folding time (exponential drop in the number of SEDs with increasing duration). We created a "slow" lightning catalogues of SEDs recorded with low temporal resolution. Catalogues of SED radio emissions are formed from the data with a time resolution of 10 ms and 32 μs. The catalogue will be placed on `http:`

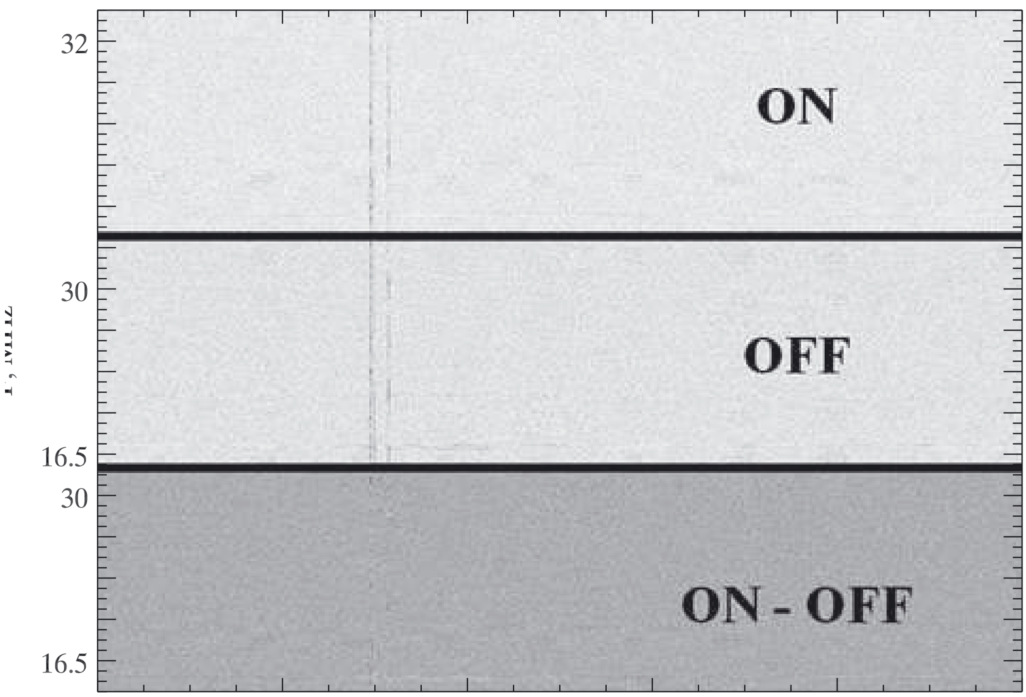

Figure 2: Reduction of interference due to the subtraction of "OFF" from "ON" channel.

//rian.kharkov.ua/decameter/EDC/. The data were used to find the most powerful discharges, which would have a sufficient S/N ratio for a data analysis with high temporal resolution. Our recent study found a sub-millisecond temporal structure: SED signals have sub-pulses with a typical duration of tens and hundreds of microseconds [Mylostna et al., 2013; 2014].

2.2 High temporal resolution

For research with high temporal resolution it is necessary to know the times of SEDs beforehand. As mentioned above, we had an enormous volume of "fast" data (data recorded in the waveform mode). For the search of SEDs in the fast data we used previously found intervals of SED activity, and then apply a new criterion regarding the presence of a dispersion delay (the dispersion measure (DM) should differ from zero). The detection process was made in the following way. The program recorded the value exceeding the at least 4σ level within a band not less than 2 MHz (several channels one by one). An important factor was the detection of a large number of events per time unit. Figure 4 below presents the sample data with plenty of electrostatic discharges and the detection result. In the bottom panel of the figure one can see a dynamic spectrum (intensity of radio waves as a function of time and frequency) that contains the sequence of signals. The data was cleared of noise and is shown after compensation for the dispersion delay. At the top of Figure 4 the profile of lightning is shown. In the middle panel the result of the search is presented. An inspection by eye of the dynamic spectrum reveals more than

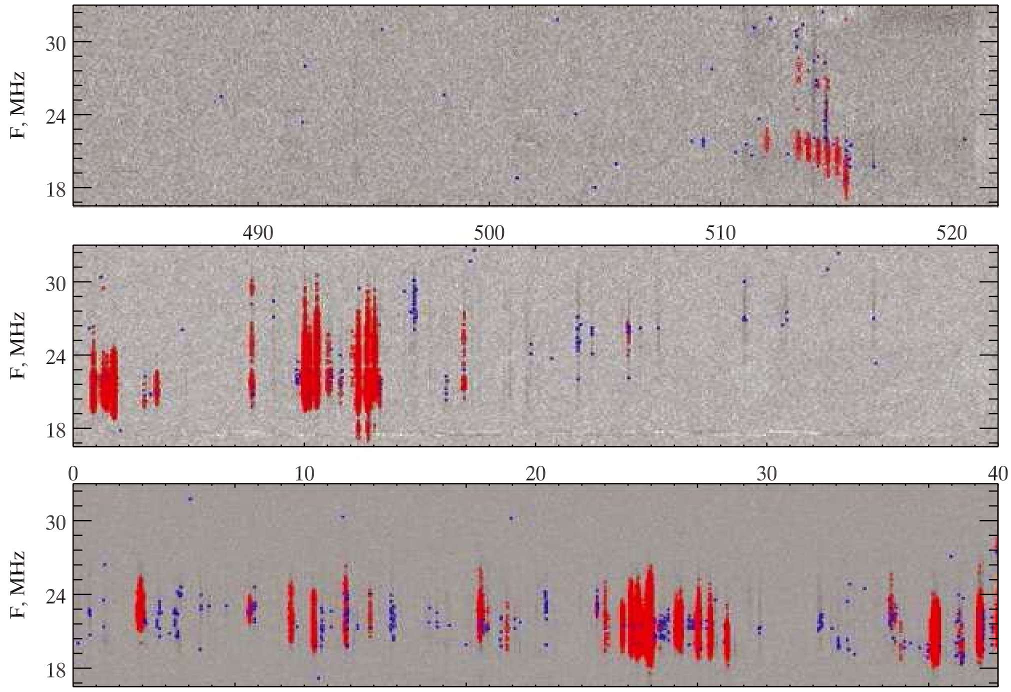

Figure 3: Spectrogram with highlighted lightning positions (red – meet the eligibility criterion, and blue – do not meet the criterion of bandwidth).

20 SEDs. The primary search algorithm revealed only 4, but an "increased attention" automatic search procedure found the 17 lightnings shown in the middle panel of Figure 4.

The study of the fine structure was multi–stage. Step by step we reached the maximum temporal resolution of 0.5 μs. Figure 5 illustrates the fine temporal structure of one SED signal. The top panel (with lower resolution) shows that the SED consists of a series of bursts lasting a fraction of a millisecond. It should be noted that the main property of the registered signals is a dispersion delay at relatively lower frequencies. The dispersion delay is very small (~ 300 μs between 26 and 19 MHz), but it is significant when one uses high temporal resolution. The high temporal resolution allows to determine accurately the dispersion delay. The value for dispersion measure can be obtained with a relatively high accuracy of $3 \cdot 10^{-8}$ pc cm^{-3}. Further increase of accuracy is limited by chosen temporal resolution. To study temporal structure of a signal one should previously compensate for the delay. We used the method of coherent de-dispersion [Hankins, 1971].

To remove a dispersion delay one needs to identify it. The accurate measurement of the DM value was conducted by a procedure that calculates a sequence to improve the DM determination with a gradual increase in the accuracy from 10^{-5} pc cm^{-3} over 10^{-6} pc cm^{-3} to $3 \cdot 10^{-8}$ pc cm^{-3}. In the first phase the DM was determined in the range from 10^{-5} pc cm^{-3} to $7 \cdot 10^{-5}$ pc cm^{-3} with a step size of 10^{-5} pc cm^{-3}. To find the result value we determined the maximum of the frequency–integrated signal in the range of steps. All our steps we can explain using an example. We had a signal with a DM equal to $4553 \cdot 10^{-8}$ pc cm^{-3}. The first step of our procedure will result in a DM value

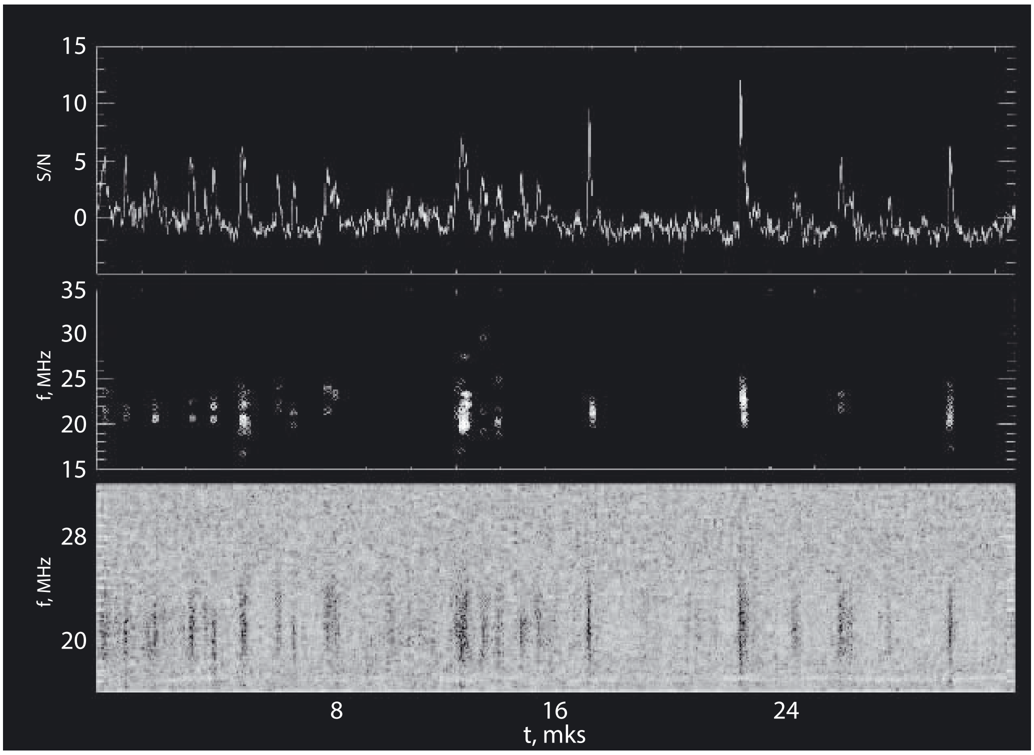

Figure 4: An example of the results of the lightning search. In the top panel a profile of lightning is presented, on the bottom is a dynamic spectrum, and in the middle panel shows the result of the search (17 events have been detected). Time goes over 32 ms.

around $5 \cdot 10^{-5}$ pc cm^{-3}. The next stage was done with a step size of 10^{-6} pc cm^{-3}. The value we found was in the range $46 \cdot 10^{-6}$ pc cm^{-3}. And the last step was made with a step size of $3 \cdot 10^{-8}$ pc cm^{-3}. The fluctuation of the DM can be seen in Figure 5. There are two signals (at 17 and 24 ms, see red marks in Figure 5) separated by 7 ms with a DM difference of $3 \cdot 10^{-6}$ pc cm^{-3}. In the analysis of the "fast" data session from 24 December we have identified a considerable variation in the dispersion measure, much more than for 23 December, but we must build up statistical data for more reliable results. As a result of the fast data processing we made a dataset. For every signal we record the time, frequency characteristics, and the DM value. Table 1 demonstrates all values that are collected in the catalogue. For each spectrum we obtained the S/N ratio, the frequency range, the time of the flash, and the dispersion measure. We emphasize that the obtained result value is close to the theoretical value of $3.7 \cdot 10^{-5}$ pc cm^{-3} [Mylostna et al., 2014], that can be calculated from an interpolation of the total electron density on the line of sight from the source to the observer (mainly in the interplanetary medium). We found that there were no strong signals that have a delay corresponding to a DM less than $2.5 \cdot 10^{-5}$ pc cm^{-3}, the maximum DM does not exceed $6.5 \cdot 10^{-5}$ pc cm^{-3}, and the average DM is $(4.4 \pm 0.8) \cdot 10^{-5}$ pc cm^{-3}. We should mention that minimum and maximum values stand for a very small quantity of events. Moreover, these signals have a longer duration and a lower peak power.

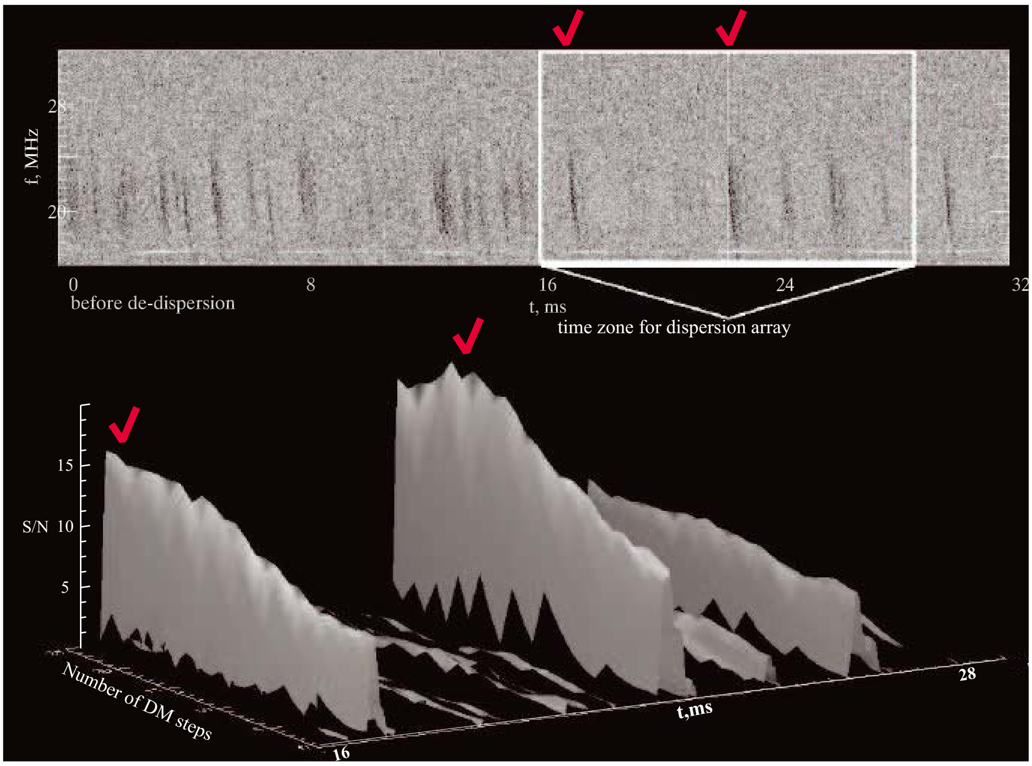

Figure 5: An example of the results of the dispersion measure search. In the top panel cleaned data is presented as a dynamic spectrum. The lower 3D diagram shows changes of values of the signal–to–noise ratio due to various measured dispersions.

Table 1: Data for one SED spectrum from the observational session of 24 December 2010.

Name	Frequency channel 1	Frequency channel 2	Frequency channel 3	Frequency channel 4	Frequency channel 5
S/N	4.6725380	4.3681969	4.3488375	4.6372279	4.6625492
Frequency, MHz	18.3047	19.0781	19.3359	19.5938	30.6797
Time in seconds from the start of the file: 10.617298					
Number of spectrum from the start of the file: 342159.00					
DM = $5.16 \cdot 10^{-5}$ pc cm^{-3}					

3 Perspectives and discussion

SED research with high temporal resolution reveals the dispersion delay and allows to estimate the propagation effects in interplanetary space. As one can see from the figures above, the precise definition of the dispersion measure is very difficult because of the low S/N ratio (up to 20) in the fast data. This reduced intensity of the signal is obvious because the S/N ratio becomes less with the increase of temporal resolution. For the first time we measured the dispersion delays of thousands of bursts that occurred during several days. The next observations may allow one to obtain more accurate values of the DM up to 10^{-8} pc cm^{-3}. At this stage, the accuracy of DM determination is still not good enough for meaningful studies of the DM parameter versus time at short intervals. The created database can serve as a basis for further research of SED parameters. A proper consideration of the dispersion delay will be necessary for the analysis of temporal and spectral characteristics down to short time scales. We measured flux densities up to 5000 Jy and burst durations from a few microseconds to hundreds of milliseconds. We will pay special attention to the search of regularities of SED fine structures and analysis of dispersion measure variations. The study of the latter is a unique probe of the interplanetary medium. As a result we expect to determine its characteristic and variations in time. We determined the basic parameters of Saturn's Electrostatic Discharges, and the results might have significant implications for further lightning studies of other planets.

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