INVESTIGATION OF THE JOVIAN S-EMISSION DYNAMIC SPECTRUM FEATURES

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Abstract

The Jovian decameter radiation (DAM) is the unique phenomenon due to its still unexplained various peculiarities which appear on the dynamic spectra. Serious investigation of these events remains an actual radio astronomical task, potentially capable to determine characteristic features of the emission and of developing a detailed radiation mechanism which describes a maximum number of observed parameters. The DAM emission basically consists of two types of wide-band noise radio storms, called L-bursts (time scale in seconds) and S-bursts (time scale in milliseconds). Depending on the time resolution achieved in the experiment as well as on the visualization time scale, different features of the radiation spectra can be stressed. Based on observations of the Jovian S-burst radiation which were carried out within the frame of the joint Ukraine-Austria-France-Russia INTAS project with the high-frequency and time resolution equipment of the Digital Spectropolarimeter (DSP) installed into the world-largest decameter band radio telescope UTR–2, a variety of modulation events have been analyzed and ordered. For example, we investigated the behavior of the so called “modulation lanes” which always appear on the scale of minutes when the data time resolution is about 100 ms. As intriguing kind of spectrum modulation was found over the scale of tens of seconds, viz. three separated quasi–harmonic structures of different frequency bands. By processing the data with a millisecond resolution in the wavelet analysis technique we also found a short-pulse content of the individual simple S-burst. Polarization properties of the modulation lanes in the theory of the interference screen have been considered. The obtained results may prove useful for further studies of the still unclear origin of the sporadic Jovian decameter emission

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1 Introduction

Different types of modulation events of the Jovian S-emission were discovered and studied by the several authors [Riihimaa, 1979; Genova et al., 1981; Imai et al., 1997]. For the first time Riihimaa described the so called "modulation lanes", groups of lanes with higher and lower intensity drifting in the time-frequency plane, and representing the element of the "fine" structure of the Jovian dynamic spectrum. He founded that on the spectra these lanes can have positive or negative sign of drift, and, in some cases, their superposition. Genova et al. [1981] depicted a new class of modulations, "high frequency lanes". In the work of [Imai et al., 1997] the so-called "interference screen" model for the modulation lanes origin was developed. The lanes are assumed to be produced by the Jovian decameter radiation scattered from a located near the Jovian satellite Io's orbit grating of field-aligned columns of enhanced plasma density. The column spacing and depth of density modulation in proposed model are adjustable parameters and they are estimated by the comparison between the theoretical and observed dynamic spectra. Progress in electronics, computer and information technologies allows the creation of the effective registration systems with high frequency and temporal resolutions (for example, Digital Signal Processors (DSP), the Waveform Receiver (WFR) and so on). In the case of the using these back-ends in complex with large radio telescope the results can be unique. Some improvements can be also obtained by applying special mathematical methods. These new technologies give the possibility to found and investigate the specific features of the Jovian emission on the higher quality and quantity levels than in the past.

It is obvious that the dynamic spectra image is changing with the time resolution changing as well as with the visualization time scale. In the present work special attention is given to the modulation events which can be presented at the Jovian S-emission dynamic spectra in dependence on the time resolution achieved in the experiment and also on the visualization time scale. In conclusion the some theoretical speculations concerning the polarization properties of the modulation lanes in the theory of the interference screen [Imai et al., 2001] which will be useful for the future experiments are sited.

2 Instrumentations

The wide-band data taken for the present analysis have been obtained with the high frequency and time resolution equipment of a Digital Spectropolarimeter [Kleewein et al., 1997] and a Waveform Receiver [Leitner and Rucker, 2001] installed into the largest decameter band radio telescope UTR-2 [Konovalenko et al., 2001]. The DSP provides the ultimate spectral analysis capability performing real time digital signal processing.

The frequency resolution of DSP is 12.5 kHz, the bandwidth is 12.5 MHz and dynamic range is 70 dB. During the experiments a time resolution was varied from 1ms to 100 ms. The measured linear dynamic range for broadband noise is greater than 60 dB.

The WFR reaches a maximum of the theoretically possible time-frequency resolution. The main concept of the waveform receiver is to store the signal's original waveform.

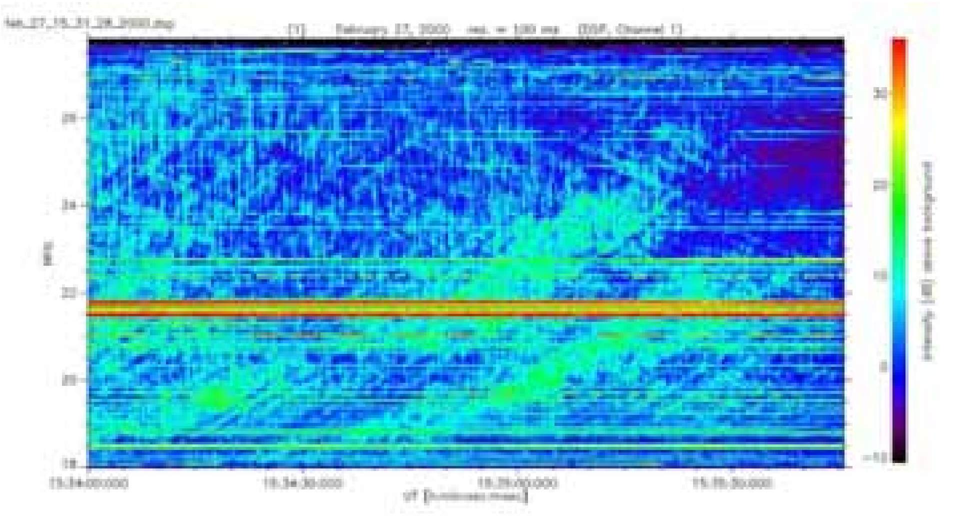

Figure 1: The Jovian DAM (Io-B source) dynamic spectrum with crossed modulation lanes.

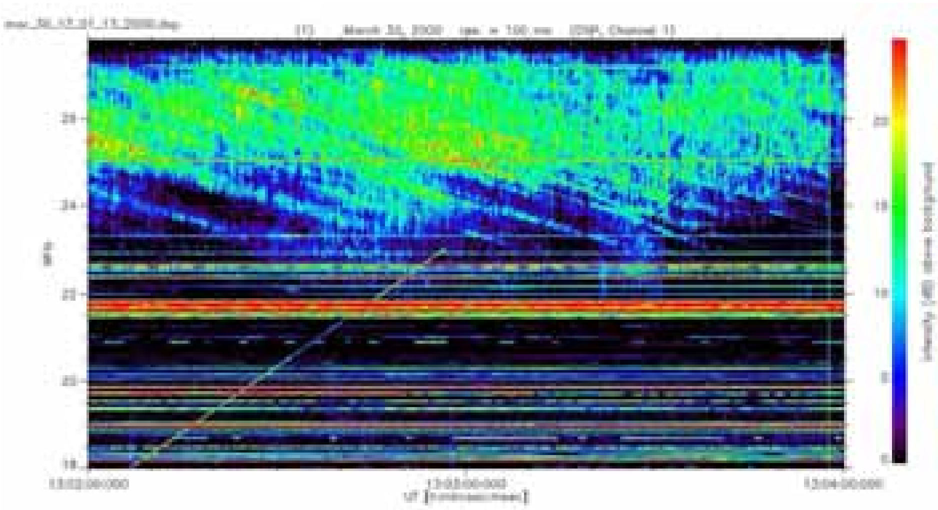

Figure 2: The Jovian DAM (Io-B source) dynamic spectrum with modulation lanes restricted in frequency range.

The dynamic range of the waveform receiver is about 70 dB, the bandwidth in the single channel is 25 MHz.

3 Some observational results

Figures 1–6 show the examples of the Jovian DAM dynamic spectra of the different time resolutions and recording durations which were obtained with UTR-2 and DSP.

The classical "modulation lanes" events are presented in the Fig. 1–3. Their observed characteristics partly proved the results of the other authors [Riihimaa, 1979; Genova et al., 1981]. For instance, from our experiments we can confirm the following facts marked

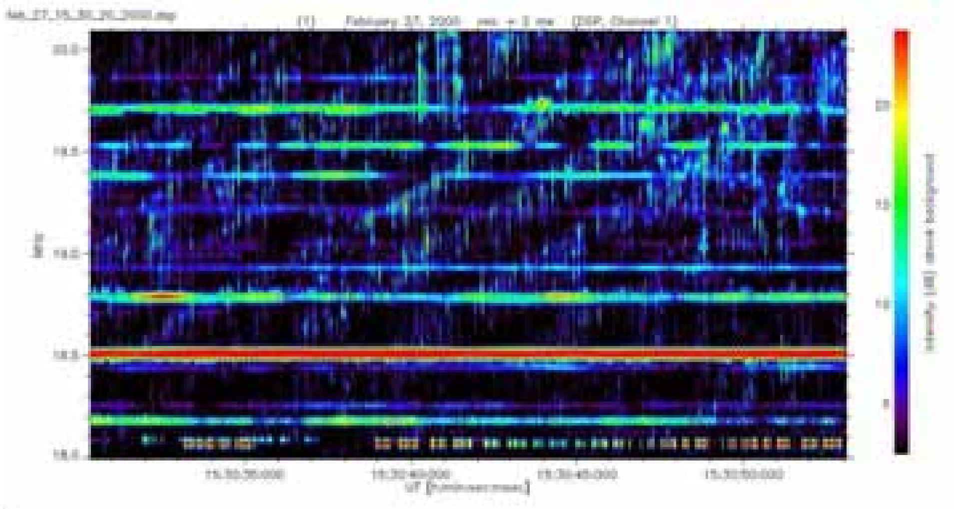

Figure 3: Modulation lanes with positive drift.

by these authors:

1. the modulation lanes generally cover the whole frequency range;
2. they can appear on the dynamic spectra with positive or negative frequency drift, or as result of their superposition;
3. usual frequency spacing is less than 500 kHz;
4. the modulation depth is about few dB.

Due to the high sensitivity of our measurements the modulation lanes were observed practically during the each S–burst storm. This experimental result firstly allows definitely conclude that modulation lanes are always present in the Jovian spectra. We stress that this effect is visible in the spectra image when the registration time is approximately few tens of seconds and the time resolution achieved in the experiment is from 1 to 100 ms. The curvature of positive and negative drifting lanes are differ (Fig.1).

Several kinds of modulation effect were mentioned in the work of [Ryabov, 2001]. He found that the long series of S-bursts are concentrated within spectral sub-bands with 1.5 to 5 MHz width, and the central frequencies of these sub-bands are separated in average by about 3.5 MHz. The sub-bands have a negative or positive drift rate that amount to 17 kHz/s. It was proposed that spectral sub–bands correspond to the Io-tube "bulb" inhomogeneities where the S–burst emitters are probably located. During our experiments the sub-bands are also presented (up to three sub–bands in 12 MHz frequency range), but with more complex structure than was reported. One such example is depicted in Fig. 4. A frequency irregular modulation are visible over the long time interval. Very high correlation of large scale bands structure is evident. The correlation between fine structure of bands is absent.

In the some cases the quasi-periodic band modulations were observed (see Fig. 5). In Fig. 6 one can see rather unusual spectrum (time resolution is 2 ms) which consists from

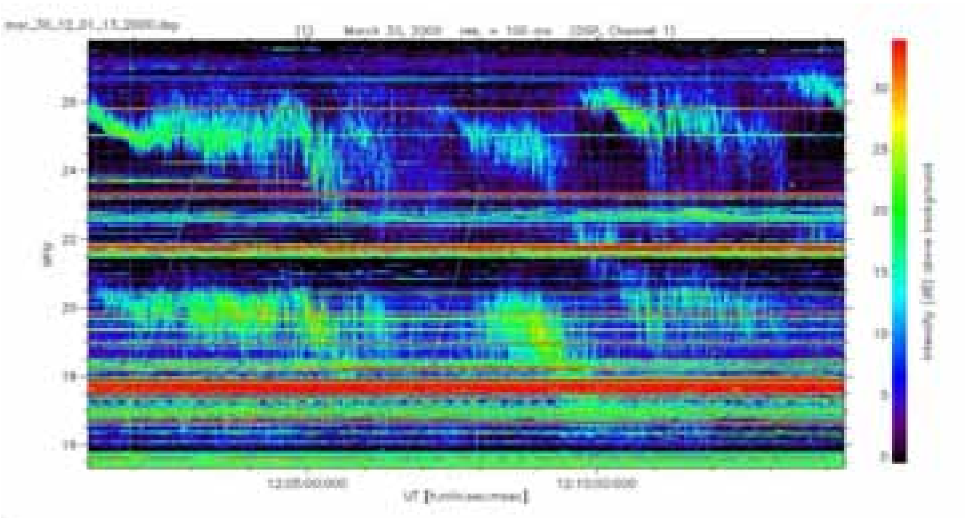

Figure 4: Two sub-bands emission with strong shape correlation.

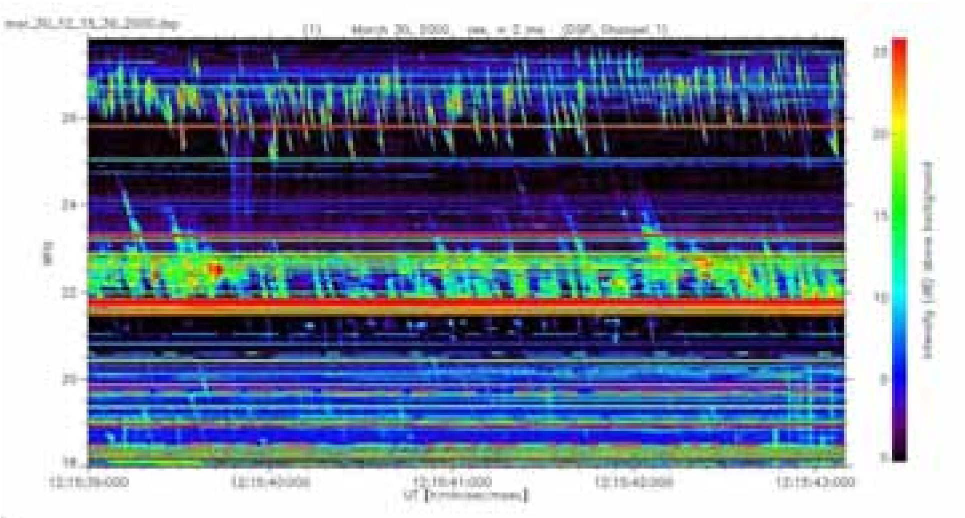

Figure 5: High resolution measurements of two sub-bands emission.

the typical S-bursts in combination with the spot's structure and modulation lanes with the low drift rate.

4 Microsecond structure of the simple S-burst

Signal processing of the Jovian DAM emission is usually based on Fourier analysis which gives important but limited information about the spectrum of the signal. Therefore, it is not really appropriate for treating non-stationary processes like the sporadic DAM radiation. The main drawback of the Fourier method is the impossibility to obtain the simultaneous localization of a signal in the time and frequency domain because of the "uncertainty relation". Recently, several effective mathematical approaches, such as the wavelet transform (e.g. the Wigner-Ville technique), are actively used for the investiga-

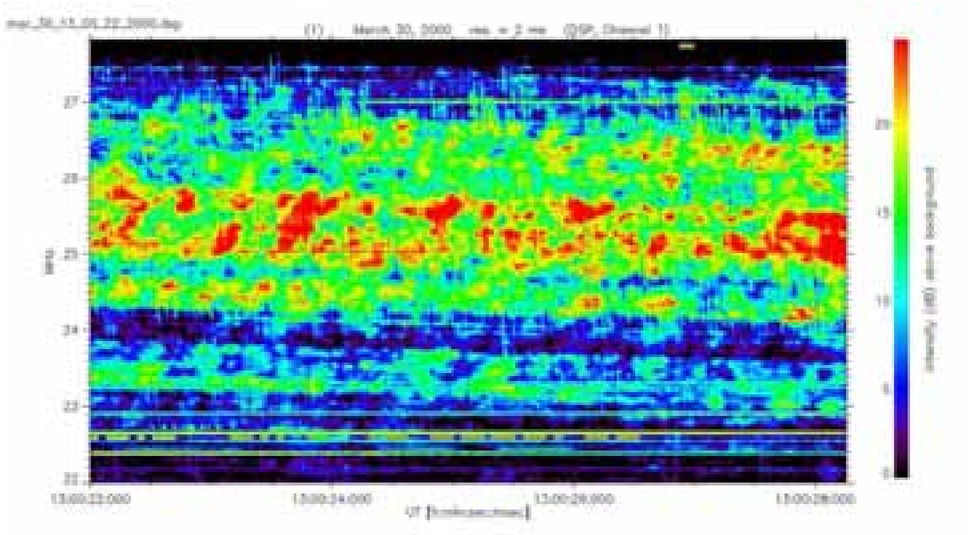

Figure 6: Example of very complex form of the dynamic spectrum obtained with high-temporal resolution.

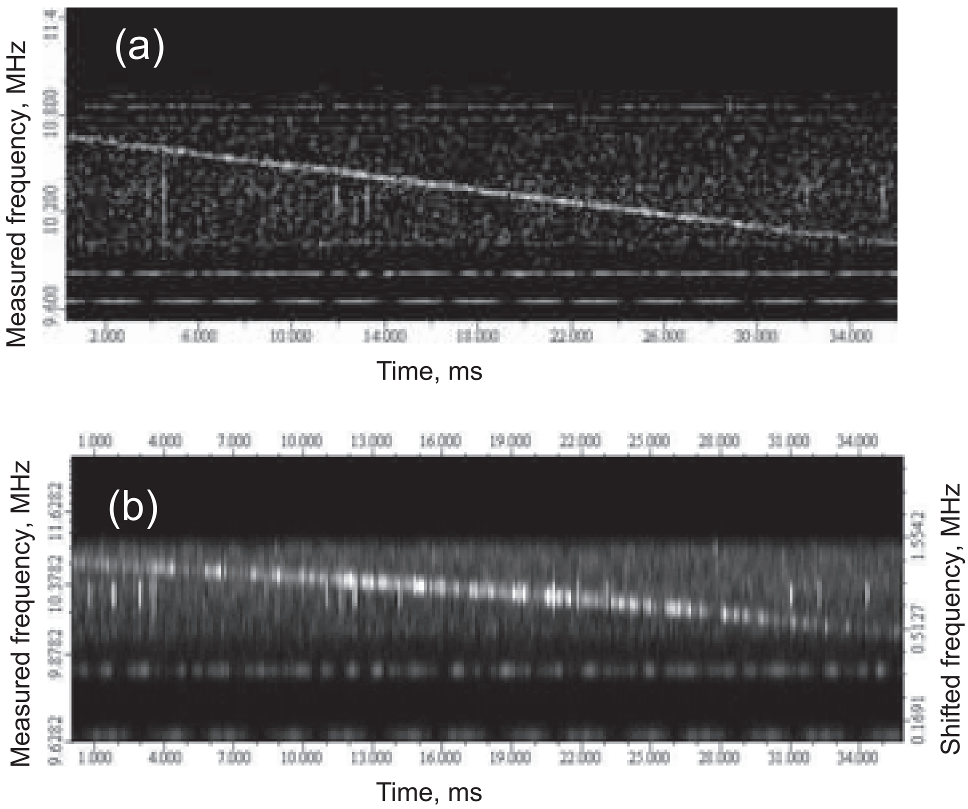

Figure 7: Fourier spectrum of the single S-burst, Io-C event, February 2000 (a); Wavelet spectrum of the same burst (b).

tions of non-stationary and non-linear processes. The wavelet transform is able to "zoom in" on very short-lived high frequency phenomena [Daubechies, 1988)]. In Fig. 7 a characteristic example of processed S-burst emission data is shown [Litvinenko et al., 2004].

In the top panel the simple linear-drift S-burst (a segment of about 35 ms, with an initial data sampling rate of 50 MHz) dynamic spectrum is presented. This spectrum shows that the burst looks like a continuous chirp signal with rather constant characteristics through the time-frequency plane. Wavelet spectrum (bottom panel) performs a very intriguing time structure of simple S-bursts. To obtained this result the continuous wavelet transform (CWT) was used,

$$W(a,t) = \int_{-\infty}^{+\infty} s(t')\psi_{a,t}(t')dt', \tag{1}$$

where

$$\psi_{a,t}(t') = \frac{1}{\sqrt{a}}\Psi_0\left(\frac{t'-t}{a}\right)$$

is the family of wavelet functions (base functions) which are constructed from the "mother-wavelet" function $\Psi(t)$ by transformations and shifts (the scale index is $a = 1/\omega$, t is the shift index). For forming the orthogonal basis the complex Morlet wavelet with a limited definition field was choose as the basis mother wavelet function. The Morlet wavelet is defined as [Grossman et al., 1989]

$$\Psi(t) = e^{-t^2/2}(\cos\omega_0 t + \imath \sin\omega_0 t), \tag{2}$$

where ω_0 is the central frequency of the wavelet.

The wavelet spectrum was obtained with a sample rate of 14.3 kHz due to averaging and resampling applied to the initial data set (initial sample rate 50 MHz divided by 3500). It can clearly be seen that an internal structure consists of very narrow pulses (μs-duration) which possibly can be produced by some kind of modulation process in the emitting source region.

5 Some theoretical study of the "modulation lanes" polarization properties

Use of the wavelet technique for the analysis of the Jovian decameter radiation allows us to obtained a new information about the emission source and the propagation properties. As one of example we consider the "interference screen" model of [Imai et al., 1997] which was proposed for the explanation of the modulation lanes origin. According to this model the modulation lanes are the result of Jovian DAM emission propagation through the interference screen deposited in the Io plasma torus. In the Io plasma torus the elliptically polarized Jovian radiation propagate as two independent coherent modes, ordinary (o-mode) and extraordinary (e-mode), with approximately equivalent intensities. So, two waves with the circular polarization and different plane-of-polarization rotation fall to the interference screen which consists from enhanced plasma density field-aligned columns. The difference between the refraction indexes of these two waves is small value:

$$\Delta n = |n_\mathrm{e} - n_\mathrm{o}| \simeq \frac{f_p^2 f_B}{f^3}\cos\phi \tag{3}$$

where $n_{\rm e}$ and $n_{\rm e}$ are the refraction indexes for extraordinary (e) and ordinary (o) modes, respectively, $f_{\rm Pe}$ is the plasma frequency, $f_{\rm Be}$ is the gyrofrequency, f is an emission frequency, ϕ is the angle between the emission path and the planetary magnetic field lines. In according to the diffraction theory the intensity of ordinary and extraordinary wave passing through the diffraction screen is the maximum in the following directions:

$$\sin\theta_{\rm e}^{l} = \frac{c}{n_{\rm e}d}l, \qquad \sin\theta_{\rm o}^{l} = \frac{c}{n_{\rm o}d}l, \tag{4}$$

where d is a characteristic size of plasma irregularity, $l = 0, 1, 2\ldots$, $\theta_{\rm e}^{l}$ and $\theta_{\rm o}^{l}$ are the angels between the perpendicular to the screen plane and the direction to the intensity maximum of order l for e and o modes, respectively. The difference between $\theta_{\rm e}^{l}$ and $\theta_{\rm o}^{l}$ angles is

$$|\Delta\theta_l| \simeq \frac{f_p^2 f_B}{f^3}\cos\phi\tan\theta_l. \tag{5}$$

At the point of observation the diffractive fringes of extraordinary and ordinary emission components shift each other by a spatial distance

$$\Delta x_l \simeq R \times \Delta\theta_l \tag{6}$$

where R is the distance between the phase screen and the observer. This spatial displacement of the diffractive fringes can be seen as a temporal displacement of the modulation lanes on the dynamic spectra obtained due to antennae with opposite sense of the circular polarization. The value of the temporal displacement can be estimated as

$$\Delta t_l \simeq \frac{\Delta x_l}{V_\perp} \tag{7}$$

where $V_\perp$ is the component of the Jupiter-observer relative velocity which is perpendicular to the line of sight. It is seen from (5) and (6) that the relative shift of the diffraction fringes Δx_l depends on the diffraction angle $\Delta\theta_l$ and increases with its increasing. Assuming the plasma frequency in Io plasma torus (diffracting screen) $f_p \simeq 4.5\times10^5$ Hz, the electron gyrofrequency $f_B \simeq 6\times10^4$ Hz and emission frequency $f \simeq 20$ MHz, $\cos\phi \sim 1$, $\tan\theta_l \sim 1$, $R = R_{JE} \simeq 7.5\times10^{13}$ cm, and $V_{JE} \simeq 3\times10^6$ cm/s. Here R_{JE} is the distance between Jupiter and the Earth, V_{JE} is the Jupiter-Earth relative velocity. Obtained results are

$$\Delta\theta_l \simeq 1.5\times10^{-6}\ \text{rad}, \qquad \Delta x_l \simeq 10^8\ \text{cm}, \qquad \Delta t_l \simeq 30\ \text{s}. \tag{8}$$

It should be note here that the observations of modulation lanes [Riihimaa, 1975, 1976; Genova et al., 1981] showed the absence of marked qualitative difference between the right-hand and left-hand circular polarizations. No quantitative measurements could be done at the time of the observations. However, as it is seen from our estimations the modulation lanes with the opposite polarization can be evidently shifted relatively each other, provided the reason of the modulation lanes is the diffraction scattering. The using of the wavelet analysis method will allow to investigate the fine structure of modulation lanes, to identify the left and right polarized emissions in the modulation lanes, and, as result, to evaluate the parameters of an interference screen in Io's plasma torus.

6 Conclusions

Large amount of experimental data was accumulated during 50 years of Jupiter decameter radio emission investigations. It needs to be pointed out that not full set of data has a quality physical explanation. So, it is important to carry out new observations with essential improved sensitivity, time and frequency resolution. During the period 1999–2002 the extensive observation of Jupiter DAM emission was organized on the based of UTR-2 Telescope and new back-end facilities. In the present time the obtained data (approx. 100 GB) has the best combination of sensitivity parameter (antenna effective area is near 100 000 m^2), frequency resolution (12 kHz), and time resolution (less than 1 ms). New emission features were determined. It includes as particularities of the simple set of S-bursts and also the effects of modulations on various time and frequency scales. Some theoretical speculation which seems to be useful for the future polarization measurements of the modulation lanes in the Jovian decameter emission was given. For the future investigations of the Jovian radio emission features it is important to continue the detail observations using the more effective instruments as well as an applying the appropriate mathematical methods for the further data processing.

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