WAVELET DECOMPOSITION OF SUBMILLIMETER SOLAR RADIO BURSTS

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Abstract. We present the results of wavelet decomposition of fast-time structures during four solar flares observed by the Solar Submillimeter-wave Telescope at 212 GHz. The result of the analysis shows (1) observational evidence on the existence of submm-emission time variations in the range from a few tens of millisecond up to few seconds during solar flares, and (2) that when a solar flare is in progress the time scales reduce as the bulk of the emission flux time variations is increasing.

1. Introduction

The analysis of the time variations of flare emissions in radio, X-ray, γ-ray, and white-light energy ranges allows us to study the primary energy release and transport processes at the flaring site. Over the last decades sub-second time structures have been found and investigated at microwaves and millimeter flare emission (Kaufmann *et al.*, 1980, 1985, 2000, 2001a; Takakura *et al.*, 1983; Correia and Kaufmann, 1987; Makhmutov *et al.*, 1998; Raulin *et al.*, 1998; Giménez de Castro *et al.*, 2001), as well as X-ray emission from the solar observations obtained by SMM/HXRBS (Kiplinger *et al.*, 1983), CGRO/BATSE (Machado *et al.*, 1993; Aschwanden *et al.*, 1998), GRANAT/PHEBUS (Vilmer *et al.*, 1994), etc. Significant correlation between time structures at microwave, millimeter and hard X-ray, γ-ray domains were found (Takakura *et al.*, 1983; Kaufmann *et al.*, 1985, 2001b). Nevertheless, it has been stressed that 'there is a need for still more detailed studies of hierarchic burst time structures based on extended nonlinear time series analyses...' (Krüger *et al.*, 1994).

In 1999 the Solar Submillimeter Telescope (SST) started solar observations at 212 and 405 GHz at El Leoncito site (Argentinean Andes, altitude of 2550 m) (Kaufmann *et al.*, 2001a) with four beams at 212 GHz (HPBW = 4′) and two beams at 405 GHz (HPBW = 2′). The SST high-sensitivity and high-time-resolution data

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(1 ms) allow one to study the solar radio emission flux variations at various time scales (from a few ms to few minutes).

The first results on the observations of the rapid subsecond submm-pulses during solar flares were reported by Kaufmann *et al.* (2001b, 2002). The goal of this short paper is to present observational results on the time evolution properties of submm-time structures during solar flares using a wavelet decomposition technique.

2. Observational Data and Their Analysis

We selected four solar flares recorded at 212 GHz by the SST in 2001: 6 April, 25 August, 28 November, and 13 December. Using a multiple-beam technique (Giménez de Castro *et al.*, 1999) we determined the solar flux variations at 212 GHz during the events (with the exception of the 13 December event). We do not use the 405 GHz data since only one event was recorded at this frequency.

2.1. Method

A multi-resolution analysis based on wavelet transform is used to define time structures and the time evolution of their characteristics during solar flares. Similar studies at different frequencies and energy domains were presented in the past, (e.g., Kurths and Schwarz, 1994; Aschwanden *et al.*, 1998; Giménez de Castro *et al.*, 2001). In our analysis we used the technique described in Giménez de Castro *et al.* (2001) based on the multi-resolution method proposed by Mallat (1989) and the algorithm developed in Bendjoya, Petit, and Spahn (1993).

The observed emission-flux time variation $F(t)$ can be expressed in the form

$$F(t) = \sum_j \sum_k d_{j,k} w_{j,k}(t), \tag{1}$$

where $d_{j,k}$ are the wavelet coefficients and $w_{j,k}$ are the wavelet basis functions evaluated for each time scale from a triangle 'mother wavelet'. We present the results of application of the multi-resolution analysis to the data in terms of *scalograms* $P(t, T)$ and *scalegrams* $S(T)$ corrected by the noise level (e.g., Kurths and Schwarz, 1994; Aschwanden *et al.*, 1998; Giménez de Castro *et al.*, 2001). *Scalograms* show for each time scale T (or TS) the wavelet coefficient ($d_{j,k}$) changes in time, t. *Scalegrams* represent in some way a Fourier power spectral density $P(\nu = 1/T)$ as a function of the frequency ν, averaged during the time interval selected. The power-law slope (β) of the given *scalegram* can be calculated (e.g., Aschwanden *et al.*, 1998). To exclude a noise level of the data from the chosen *scalegrams* we have evaluated a *noise scalegram* with a significance level of 99% level using a Monte-Carlo simulation of 100 000 pseudo-random time series containing 32000 points (for each of the series; for details see Giménez de Castro *et al.*, 2001). In the *scalegrams* plots we present a *noise scalegram* estimated from preflare measurements and *scalegrams* during the events with the subtraction of the noise level as it was proposed by Scargle *et al.* (1993), i.e., $S(T) = S_{\mathrm{event}}(T) - S_{\mathrm{noise}}(T)$.

The details of submillimeter instrumentation in relation to the r.m.s. noise fluctuations of the SST and possible system noise temperature contributions to the result of wavelet decomposition of fast time structures are presented in Raulin *et al.* (2003a). Here we only note that the system noise temperature T_{sys} accounts for the temperature of the receivers T_{rec}, and for all temperatures of sources located along the line of sight: the sky, the quiet Sun, and eventually a localized solar burst. The level of r.m.s. noise fluctuations can be determined from the well-known equation

$$\Delta T = \frac{T_{\mathrm{sys}}}{\sqrt{t \Delta f}}, \tag{2}$$

where T_{sys} is the system noise temperature, Δf is the bandwidth of the receivers ($\Delta f = 1$ GHz), and the time constant is t. The noise r.m.s. fluctuations, due to the different contributions to the system noise temperature, have been estimated during four solar events under consideration. As the result, we found that ΔT increased by a factor ≤ 2 due to the flare emission. This means that the flare emission at 212 GHz did not produce any significant increase of the r.m.s. noise fluctuation level compared to the flux (temperature) fluctuations due to solar burst pulsations, as will be shown later.

2.2. Solar Flare Observations

The solar flare observations at 212 GHz are presented in Figures 1–4, where the upper panels (a) show the flux density (or antenna temperature) time profile. The results of wavelet transform of these time profiles, in terms of *scalograms* and *scalegrams*, are presented in the panels (b) and (c) of the figures. The bottom panels (d) and (e) show the 212 GHz flare emission time profile during sample intervals of 1 s (or 3 s) close to the main phase of the solar bursts. Panels (e) show the corresponding parts of *scalograms* during these intervals. The 3 times the r.m.s. noise fluctuations level ($3\Delta T$) are shown by a vertical thick bar at the left in panels (d).

6 April 2001 X5.6 class solar flare occurred in the active region NOAA 9415 during 19:10–20:29 UT. The comparison of submm-pulses and γ-rays has been presented in Kaufmann *et al.* (2002). Figure 1 presents the 212 GHz solar flux time profile during the event (upper panel; integration time of the data is 10 ms for all events). The gaps in the flare data are due to calibration and opacity measurements. Panel (b) shows the *scalogram* contours. It is seen that close to the peak of the event the shortest time scales of flux variations appeared. To compare the characteristics of subsecond time scales through the flare development we selected nine time intervals with 3-s duration (shown by vertical arrows in Figure 1 top) for which we present the 3-s averaged *scalegrams* panel (c). We define a minimum time scale (T_{min}), with a 99% confidence level, by the intersection of a *noise scalegram* (thick line) and a given *scalegram* for each 3-s interval throughout the event (thin lines). Examination of the *scalegrams* in the panels (c) shows (1) time scales (TS) are $\sim$ 330 ms at the beginning of the event (line 1), then they decrease to about $\sim$ 160 ms (line 3, 4) and became shorter than 100 ms close to the peak of the event (panels (c) and (e)). The power-law slope (β) of the maximum *scalegram* (line 5) is 2.2. During the decay phase of the event the time scale of the variations becomes more prolonged, like that obtained in the ascending phase of the event; (2) the power of all time scales (TS $\leq$ 1 s) is increasing when the flux density increases up to the peak emission.

Similar analyses were done for other 3 events.

25 August 2001 solar flare. The X5.3 class solar flare occurred in NOAA 9591 during 16:23–17:04 UT. It showed strong high-energy X-ray and γ-ray signal ($E \geq 10$ MeV) as well as strong micro-, submm-wave emissions. A more detailed analysis of this event in relation to the physical processes observed at the flare will be presented in Raulin *et al.* (2003b).

Figure 2 shows the appearance of the fastest-time-scale flux variations close to the maximum of the event (panels (b–e)). They become shorter than 20 ms at about 16:31 UT. Furthermore, the power of all time scales increased significantly, e.g., the power of 125 ms variations changes by a factor $\sim$ 400 in 40 seconds (line 3 and 5 in panel (c)). For the maximum *scalegram* $\beta = 2.0$ (line 5).

28 November 2001 solar flare classified as M6.9 class occurred in NOAA 9715 between 16:26 and 16:41 UT. The duration of this event is about 110 s at 212 GHz and the peak flux value was $\sim$ 150 s.f.u.

Figure 3 shows the time profiles of 212 GHz emissions and seven intervals of 3 seconds which were selected to analyse the temporal evolution of the time scales during the event (upper panel). The time-scale evolution tendency as seen in the *scalegrams* (panel (c) and (e)), shows that closest to the peak of the event the shortest time scales of flux variations are detected.

The minimum time scale at 212 GHz emission during the event maximum is about of 50 ms (line 3 in panel (c)). The power-law slope of the *scalegrams* was in the range from 1.0 to 1.8 during the event. Around the maximum of the event the *scalegrams* are characterized by $\beta = 1.8$ (line 3 in panel (c)).

13 December 2001 X6.2 solar flare occurred in NOAA 9733 between 14:23–14:49 UT. Contrary to the previous events, the flare emission at 212 GHz was less intense and does not show clear bulk (min) emission. However we clearly see the appearance of fast time structures from the original 212 GHz antenna temperature records. Figure 4 shows the antenna temperature time profile as recorded by beam 4 of the SST antenna (upper panel). The *scalograms* obtained during the event are shown in the panel (c) and (e). The evolution of time scales shows the fastest emission variation during the time interval 14:28–14:30 UT, which is close to the maximum of the event as observed by GOES-10. There is a clear indication of the

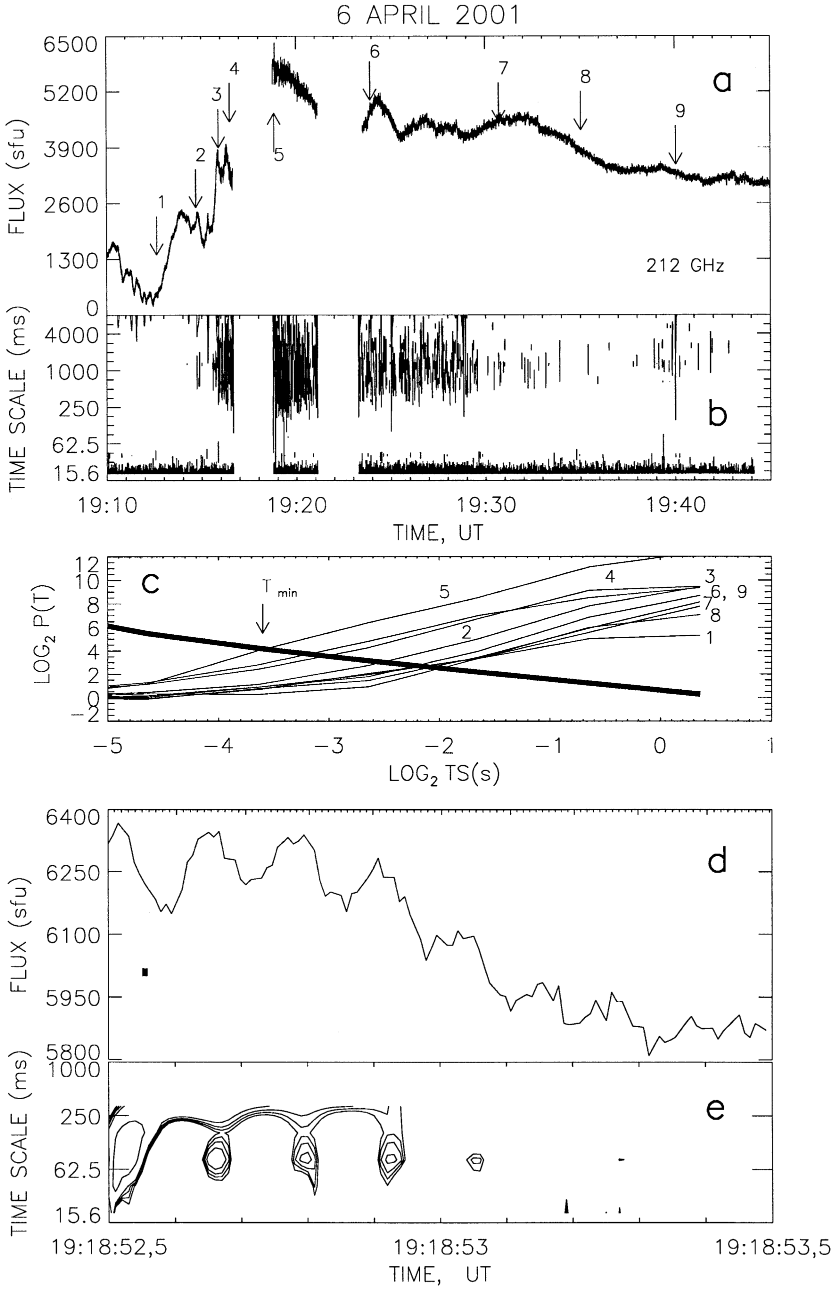

Figure 1. (a) The SST 212 GHz flux time profile during solar flare on 6 April 2001. *Vertical arrows* indicate the 3-s time intervals (from 1 to 9) of the data for which time-averaged *scalegrams* are shown in panel (c). (b) The *scalograms* evaluated from 10-ms SST data during the event. (c) The 3-seconds averaged *scalegrams* obtained during the selected intervals (1–9). The *thick line* is a 'noise' level *scalogram*. Above this line the confidence level of time scales is 99%, i.e., they are significant. The 212 GHz flare-emission time profile during sample interval of 1 s ((d) time constant is 10 ms) and corresponding part of *scalograms* (e) *Vertical thick bar* on the left in (d) corresponds to 3 times the r.m.s. noise fluctuations level.

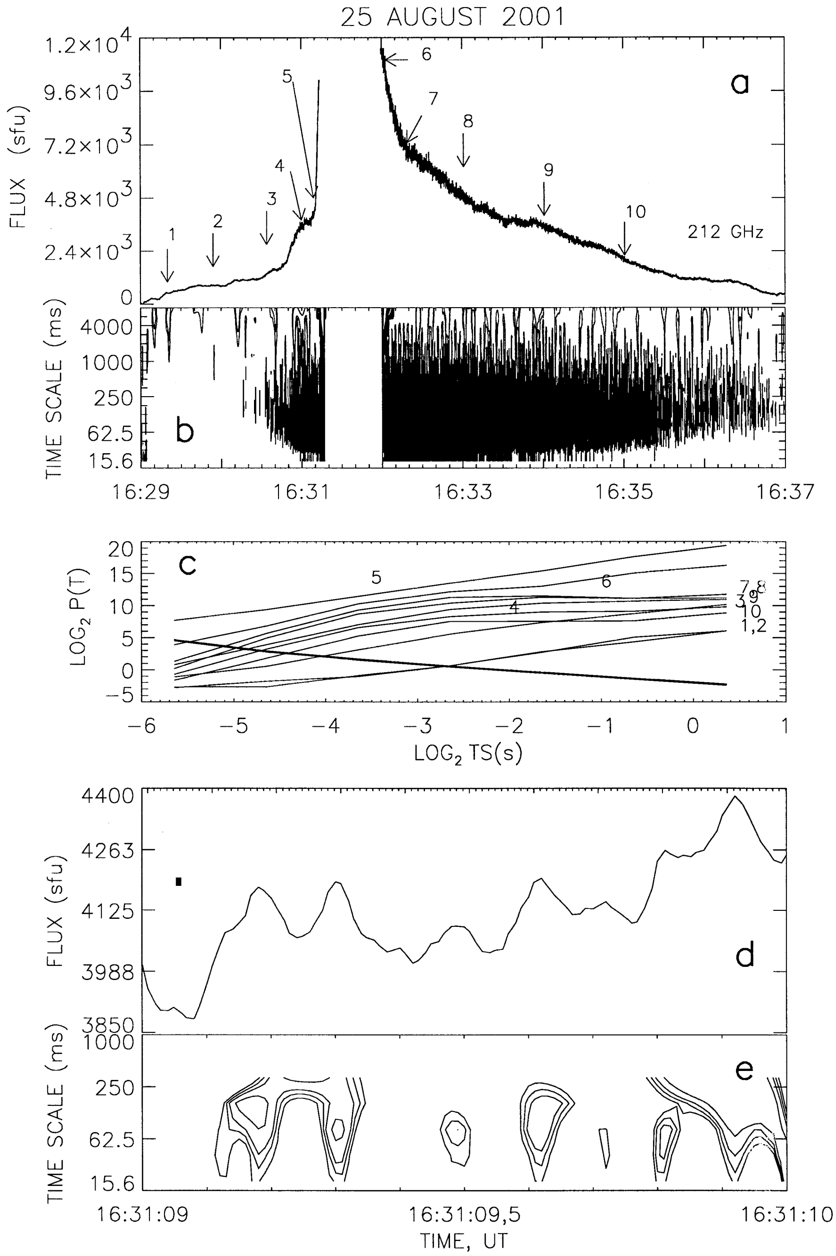

Figure 2. Same as in Figure 1 but for the solar flare on 25 August 2001.

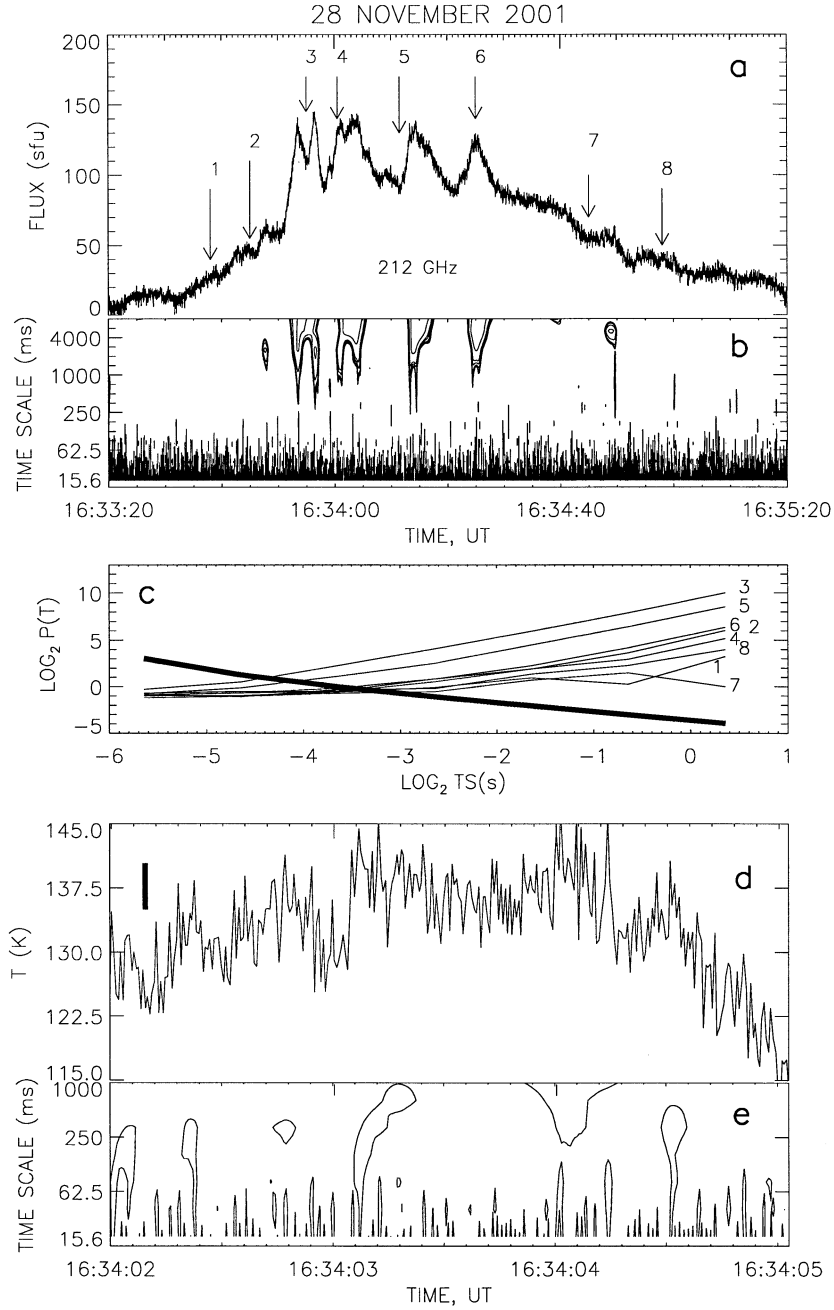

Figure 3. Same as in Figure 1 but for the solar flare on 28 November 2001.

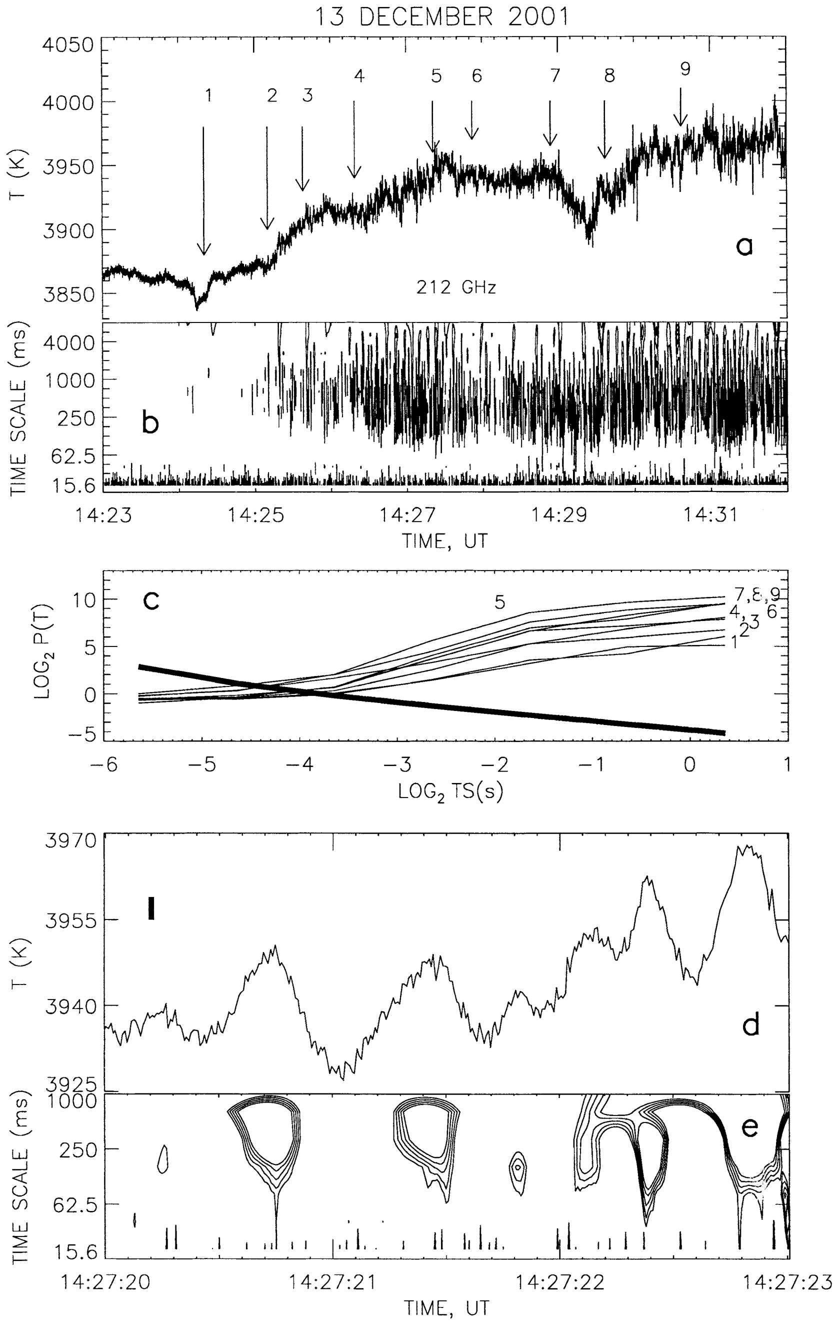

Figure 4. Same as in Figure 1 but for the solar flare on 13 December 2001. The *upper panel* shows the antenna temperature time profile during the event.

existence of time scales down to 50 ms in submm emission (panel (c) and (e)). The maximum β value during the event is equal to 2.2.

3. Conclusions

We presented the results of the analysis of observations of four solar flares on 6 April 2001, 25 August 2001, 28 November 2001, and 13 December 2001 provided by the multiple-beam Solar Submillimeter Telescope at 212 GHz. We used a multi-resolution time analysis based on wavelet transform to define the solar radioemission time structures and their evolution during the events. All four examples have shown (1) observational evidence of the existence of subsecond time scales at 212 GHz; (2) the evolution of the subsecond time structures during the flare shows that the time scale decreases down to 20–100 ms close to the peak of the event; (3) the power of all time scales ($\leq$ 1 s) significantly increases around the maximum of the event and (4) the power-law slope (β) of the *scalegrams* around solar flare maximum changes in the range 1.8–2.2. This is in accordance with the estimations of β during strong impulsive X-ray flares (Aschwanden *et al.*, 1998) as well as that obtained at 37 GHz (Schwarz *et al.*, 1998) and 48 GHz (Giménez de Castro *et al.*, 2001) during the main phase of solar flares. The detailed analysis of the origin of these fast time structures is out of the scope of this paper. Nevertheless, we note: (1) the 25 August 2001 solar flare shows that the more energetic and very fast increase of solar radio-, X-ray, and γ-ray emissions were related in time to the appearance of very compact sources ($5''$–$7''$) in soft X-rays according to *Yohkoh*/SXT and TRACE observations (Raulin *et al.*, 2003b). At this moment the time scales of 212 GHz emission are the shortest (see the *scalegram* 5 in panel (c) of Figure 2). Assuming a very simple relation between $T_{\rm min}$ and the loop size r in the form $T_{\rm min}({\rm s}) \approx 0.5r({\rm cm})\times 10^{-9}$ (Aschwanden *et al.*, 1998), with $r \approx 6\times 10^7$ cm we get $T_{\rm min} \approx 20$ ms; (2) the fast time structures observed at microwave, submm-wave emission might be consistent with the coalescence model of flare energy release (Pritchett and Wu, 1979; Tajima *et al.*, 1987, etc.) assuming a small size for the energy release region ($l \leq 10^{7-8}$ cm).

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