# About wavelet methods that can help us to study fine structures of complex radio dynamic spectra

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# OUTLINE

- **Introduction:**
  - ☼ **complex radio flares**

- **Wavelet Separation methods:**
  - ☼ **explanation of the method**
  - ☼ **artificial complex radio data as a test of the method**

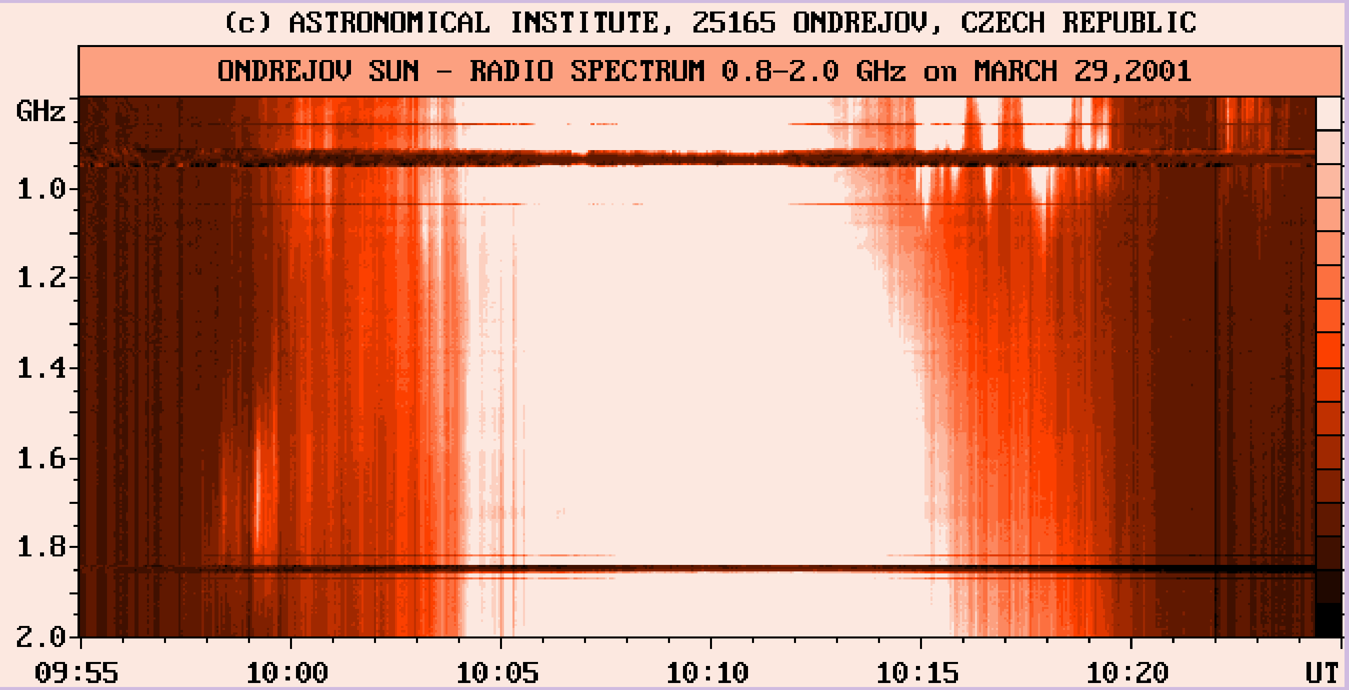
    ***examples in real radio dynamic spectra:***
  - ☼ **separation in time**
  - ☼ **separation in frequency & frequency drift(s)**
  - ☼ **searching for magnetoacoustic waves in time series**

- **Coherence & Phase Differences method**
  - ☼ **explanation of the method**
  - ☼ **artificial complex radio data as a test of the method**

    ***examples in real radio dynamic spectra:***
  - ☼ **searching for differences among individual continua**

- **Conclusions**

# Complex radio fine structures:




- long lasting radio event (about one hour duration)
- observed at many frequencies
- complex central part of event
- strong radio continuum outshining possible fine structures
- difficult for complete radio event analysis in details
- usually we can study fine structures only at the beginning and/or at the end of the event

**Aim:** to separate such a complex radio event into individual more simple radio dynamic spectra that could be analyzed in a simpler way.

## Methods to study complex radio fine structures:

**Separation methods are based on the wavelet analysis technique for the complex radio spectra with many bursts and fine structures:**

- **to divide a radio spectrum into simple bursts and individual fine structures.**
- **to be able to study them in more details**
- **useful for such events when original radio spectrum:**

**(i) consists of a mixture of fine structures/bursts observed at the same frequencies and during the same time interval and therefore individual temporal/frequency components are complicated to recognize them in one 2D radio dynamic spectra (integrated signal of the whole Sun without a spatial resolution);**

**(ii) when weaker fine structures of radio spectrum coincide with strong radio continuum, or with another strong fine structures;**

**(iii) when we want to locate possible sausage magnetoacoustic waves propagating in situ of radio spectrum source.**

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- **artificial data as well as observed radio dynamic spectra**
- **proofs of identity of the separated radio (sub)structures**
- **method limitations**

## Procedure and test of the Separation method:

- building an artificial complex radio dynamic spectrum consisting of individual simple bursts

- method of separation in frequency

- method of separation in time

- proofs of identity of the separated radio sub structures

- method limitations

# **Separation methods:** construction of the artificial radio spectrum

**Mészárosová at al. 2011, A&A 525, A88**

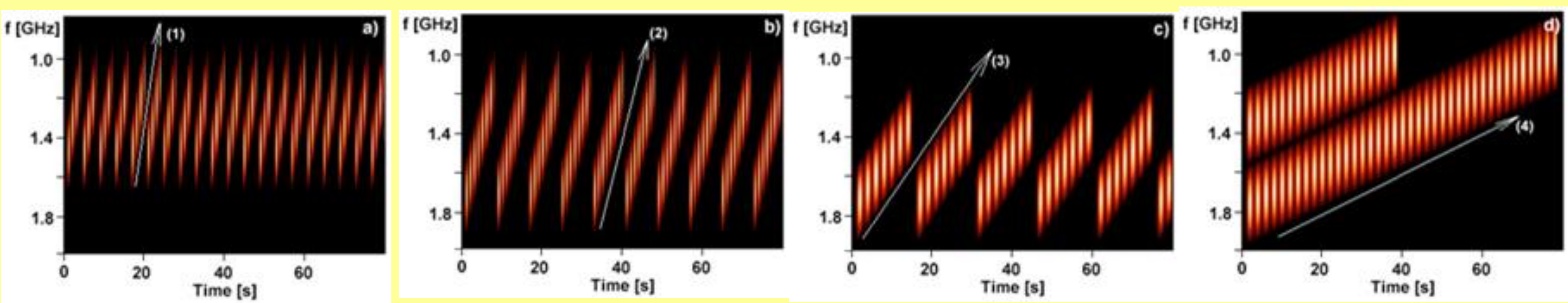
## Parameters of the artificial radio spectrum bursts.

| Spectrum No. | Period *P* [s] | Amplitude *A* [a.u.] | Width *W* [MHz] | Period *RP* [s] | Drift *D* [MHz s$^{-1}$] | Panel |
|---|---|---|---|---|---|---|
| 1 | 2.0 | 600 | 400 | 4 | −120 | a |
| 2 | 2.0 | 500 | 400 | 8 | −80 | b |
| 3 | 2.0 | 400 | 400 | 15 | −30 | c |
| 4 | 2.0 | 400 | 400 | 42 | −10 | d |
| 5 | 0.5 | 50 | 20 | ∞ | 0 | |
| 6 | 2.0 | 300 | 390 | ∞ | 0 | |
| 7 | 2.0 | 200 | 100 | ∞ | 0 | |
| 8 | 2.0 | 200 | 900 | ∞ | 0 | |

**artifical spectrum = sum of artificial**
**four types of pulsations with different frequency drifts *D* of the drifting pulsating structures (DPS, panels *a* − *b*)**

***W* = frequency bandwidth of individual pulsations**
***RP* = repetition period of DPSs**

- **positive & negative parts of amplitudes are in white & black**
- **values more or less about zero are presented in red**




**drift *D* = -120 MHz s$^{-1}$**
**amplitude *A* = 600 a.u.**

**drift *D* = -80 MHz s$^{-1}$**
**amplitude *A* = 500 a.u.**

**drift *D* = -30 MHz s$^{-1}$**
**amplitude *A* = 400 a.u.**

**drift *D* = -10 MHz s$^{-1}$**
**amplitude *A* = 400 a.u.**

**arrows show the global frequency drifts *D***

# Separation methods: construction of the artificial radio spectrum

Mészárosová at al. 2011, A&A 525, A88

**Parameters of the artificial radio spectrum bursts.**

| Spectrum No. | Period $P$ [s] | Amplitude $A$ [a.u.] | Width $W$ [MHz] | Period $RP$ [s] | Drift $D$ [MHz $s^{-1}$] | Panel |
|---|---|---|---|---|---|---|
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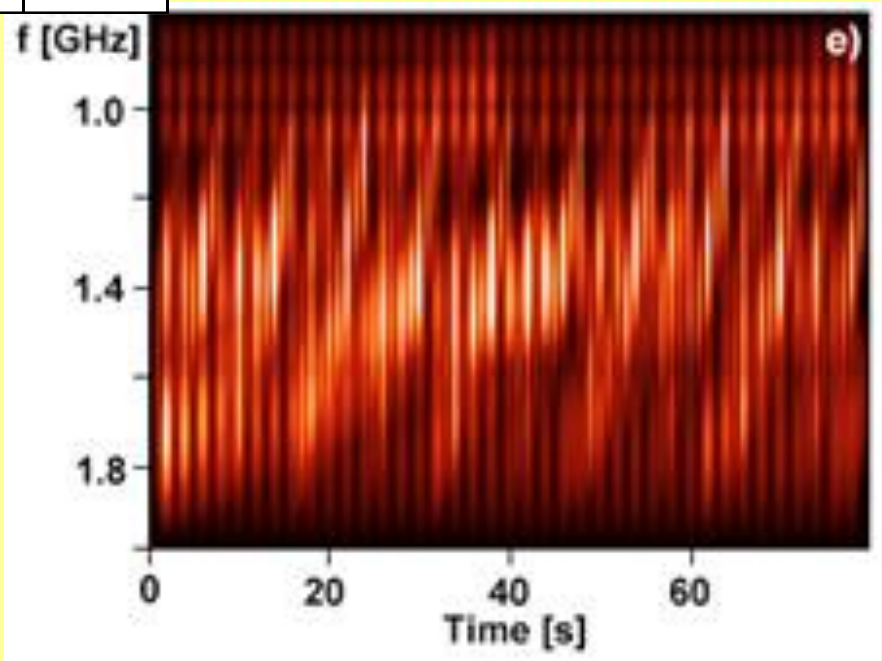
| 4 | 2.0 | 400 | 400 | 42 | −10 | d |
| 5 | 0.5 | 50 | 20 | ∞ | 0 | |
| 6 | 2.0 | 300 | 390 | ∞ | 0 | |
| 7 | 2.0 | 200 | 100 | ∞ | 0 | |
| 8 | 2.0 | 200 | 900 | ∞ | 0 | |

**artificial dynamic spectrum:**
**duration = 80 s**
**frequency range = 0.8−2.0 GHz**



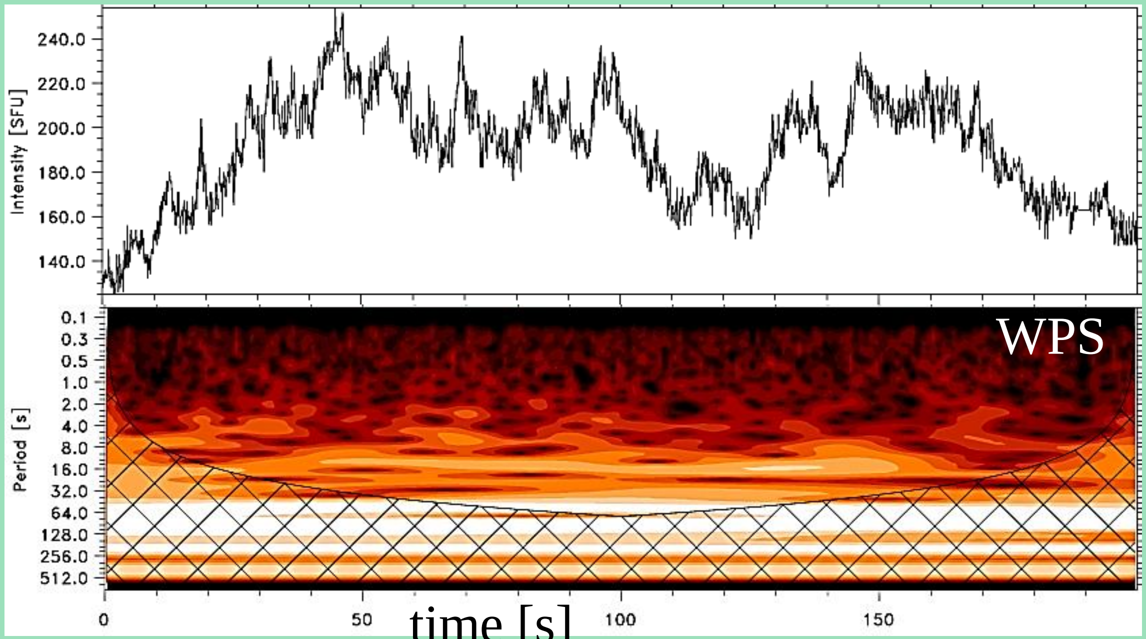

**artificial spectrum = the sum of bursts:**

- **four type of pulsations (DPS, *previous slide*),**
- **three type of pulsations without a frequency drift (*No. 6 − 7 in Table*),**
- **one like-continuum (*No. 8 in Table*)**
- **level of background (quiet sun) with amplitude 50 a.u. (*No. 5 in Table*)**

**amplitude ≈ artificial intensity of burst: spectrum shows the bursts with the highest intensity**

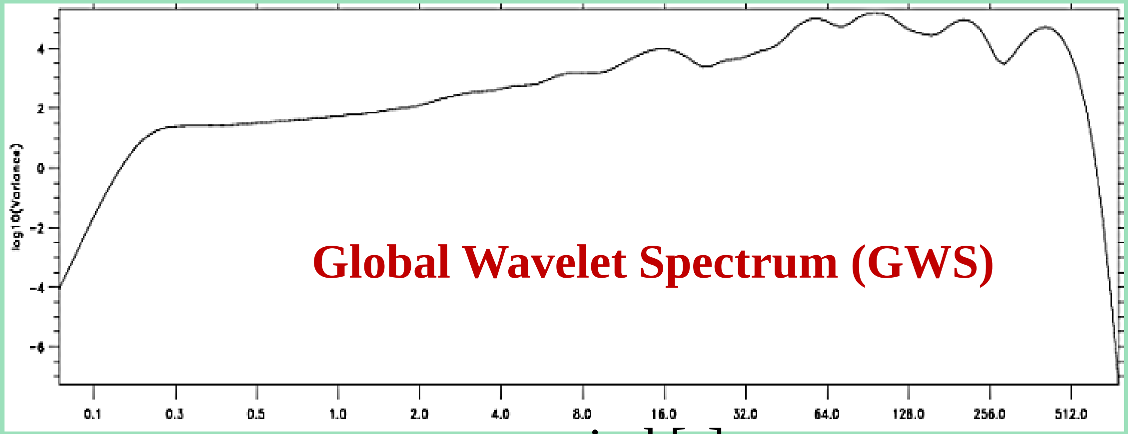
# **Separation methods: construction of the artificial radio spectrum**

**Mészárosová at al. 2011, A&A 525, A88**




**radio time series**
**at frequency 1212 MHz,**
**duration 200 s,**
**time resolution =0.1 s**

**Wavelet Power Spectrum:**
- **smallest periods depend on data time resolution**
- **highest periods depends on the length of time series**

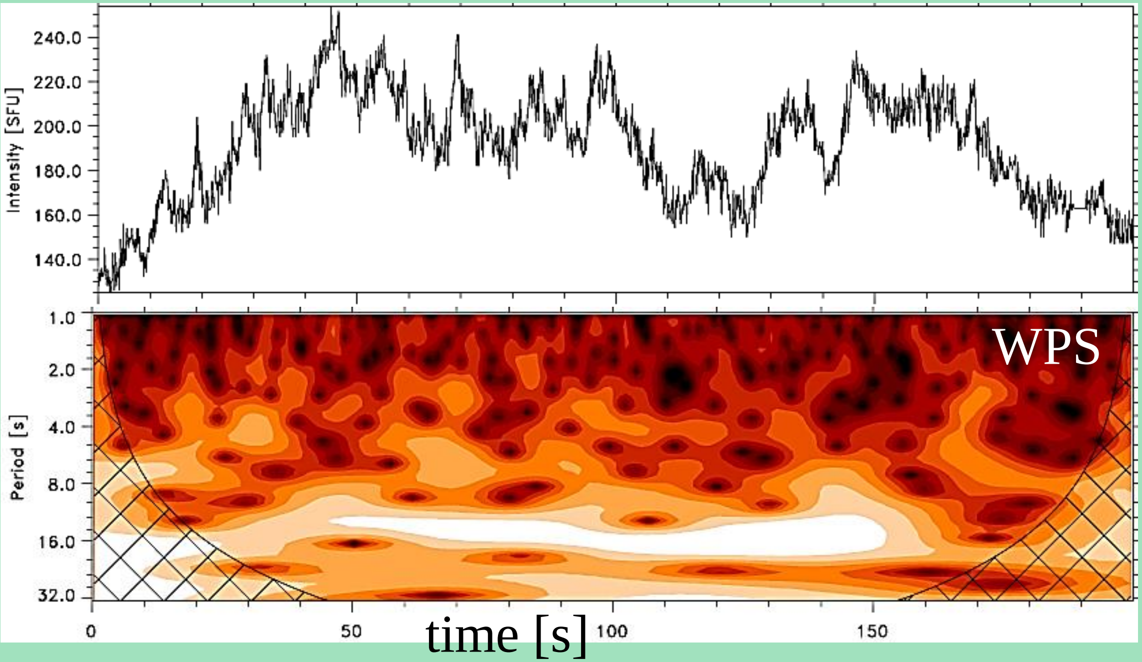



period [s]

**each one point of GWS curve = averaged value of wavelet power (raw) for an individual period**

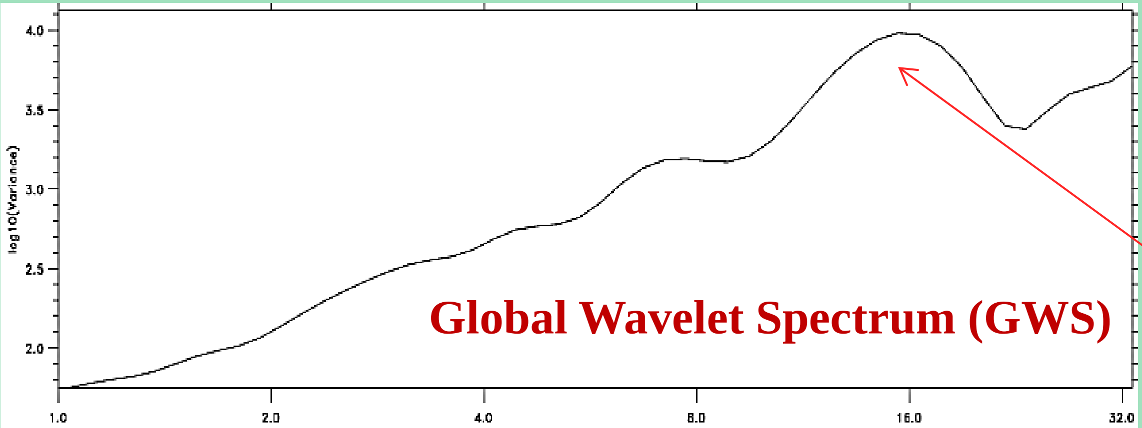
# Separation methods: construction of the artificial radio spectrum

Mészárosová at al. 2011, A&A 525, A88




**radio time series**
**at frequency 1212 MHz,**
**duration 200 s,**
**time resolution =0.1 s**

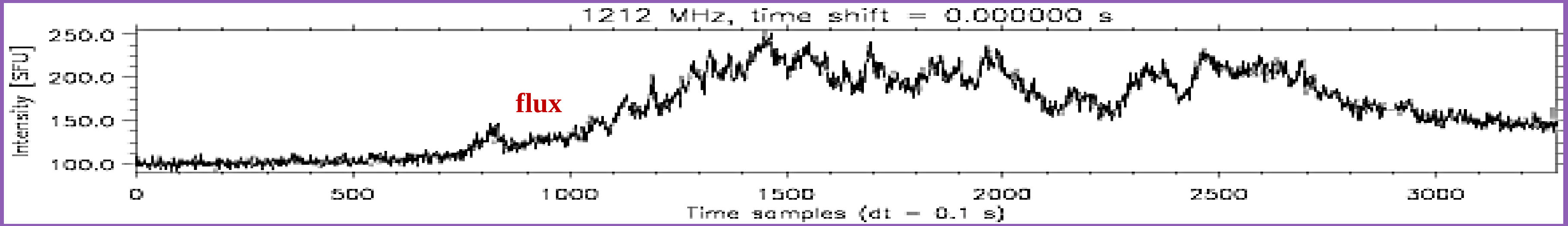
**Wavelet Power Spectrum:**
**for selected period range 1–40 s (highest values are in white, lowest values in black)**




period [s]

**GWS**
**for selected period range with important peak of about period P = 16 s**

**Separation methods: construction of the artificial radio spectrum**
**Mészárosová at al. 2011, A&A 525, A88**




**flux = time series => temporal periods [s]**
**flux = frequency cut at a time moment => frequency widths (bandwidths) [MHz]**
**flux = spatial cut of spatial data map => spatial widths [px/arcsec]**

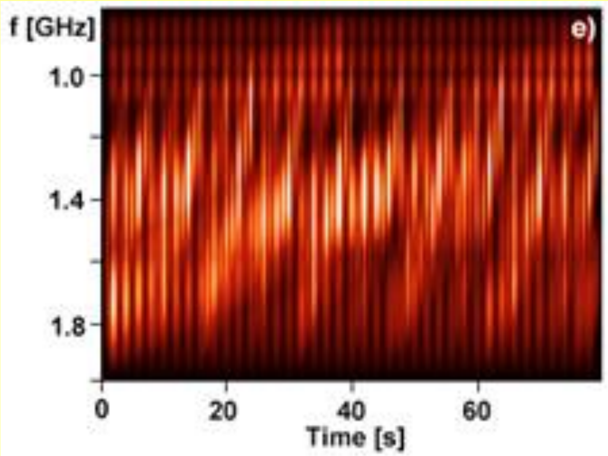
**1) Radio dynamical spectrum consists of fluxes, i.e.:**
**- time series at individual frequencies,**
**- frequency cuts at individual time moments.**
**Wavelet power spectra (Morlet wavelet) are computed for each of these fluxes.**
**We determine 1-D global wavelet spectrum (GWS) for each flux under study.**

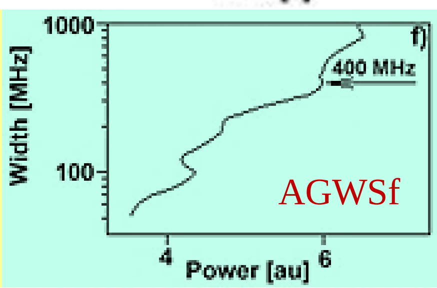
**2) We compute a 1-D averaged global wavelet spectrum (AGWS) by averaging all GWSs.**
**⇒ Information about the characteristic time periods or frequency widths (bandwidths) that are present in the original radio dynamic spectrum.**

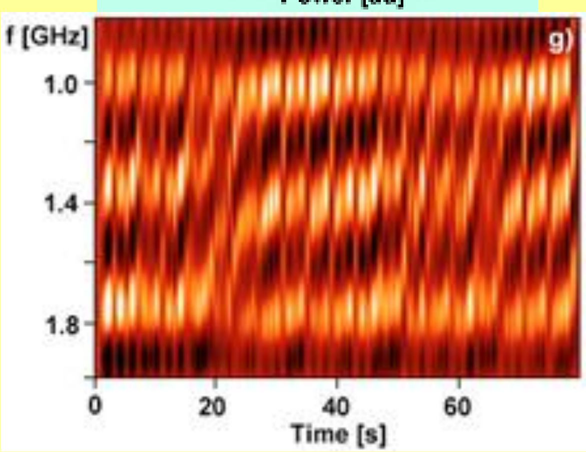
**3) Original radio dynamic spectrum is filtered with respect to these characteristic time period/bandwidth (inverse wavelet analysis, Torrence and Compo, 1998) → one or more new separated radio spectra are calculated. These spectra consist of only those components (bursts) with the required features.**

# Separation methods: construction of the artificial radio spectrum

Mészárosová at al. 2011, A&A 525, A88



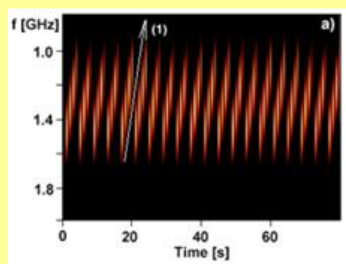



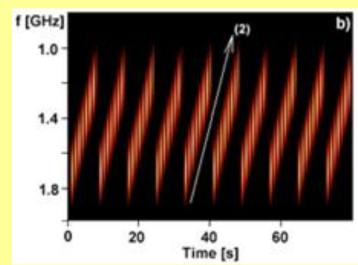

- Wavelet power spectra of are computed for all frequency cuts (*columns in panel e*) of the artificial spectrum at all individual time moments.
- We determine the 1-D global wavelet spectra (GWS) for all f-cuts.
- We compute the 1-D averaged global wavelet spectrum (AGWSf) by averaging all individual GWSs (*curve in panel f*).

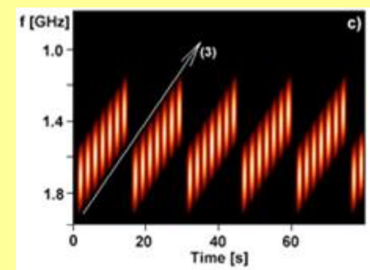
⇒ Information about the characteristic bandwidths that are present in the spectrum, e.g. bandwidth = 400 MHz (*panels a–d*).

- Artificial (= original) radio spectrum is filtered with respect to the selected characteristic bandwidth .
  (inverse wavelet analysis, Torrence and Compo, 1998)

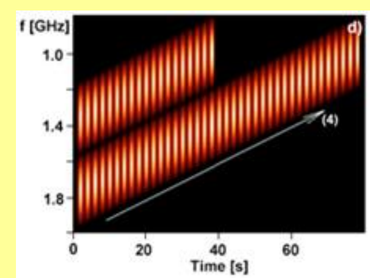
→ new separated spectrum is calculated - it consists of only those components, i.e. of only bursts with bandwidth = 400 MHz (*panel g*).



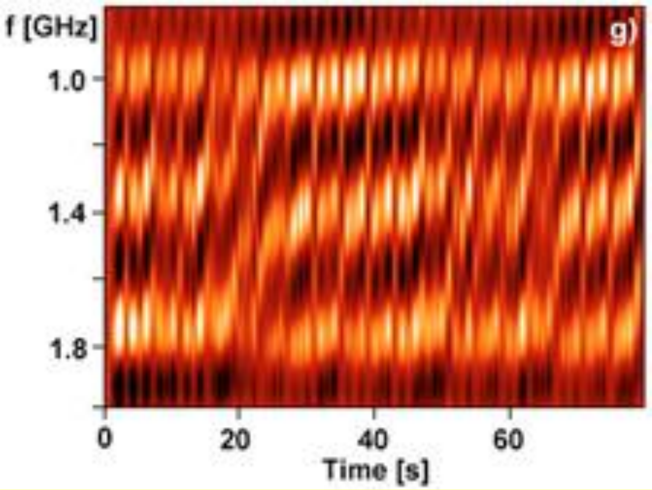



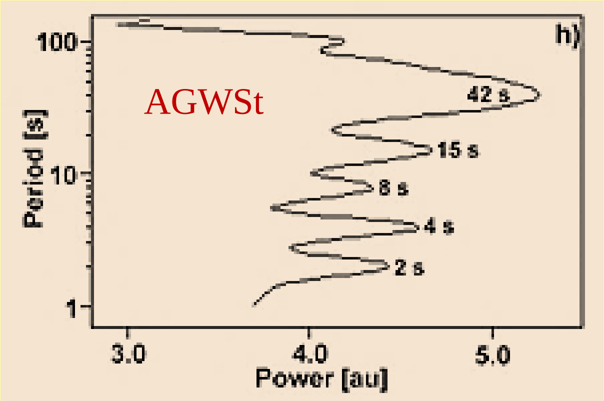

filtered artificial spectrum (*panel g*)
in the bandwidth range 220−500 MHz,
where 220 & 500 MHz are local minima of
the GWASf curve around the 400 MHz peak.



# **Separation methods: construction of the artificial radio spectrum**

**Mészárosová at al. 2011, A&A 525, A88**




**averaged global wavelet spectrum (AGWSt) made from the spectrum in panel g) with peaks for the temporal periods $P = 2, 4, 8, 15$, and 42 s.**

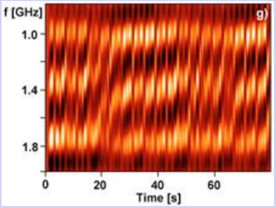
- **Wavelet power spectra are computed for all time series (*rows in panel g*) of the spectrum under study at all individual frequencies.**
- **We determine the 1-D global wavelet spectra (GWS) for all time series.**
- **We compute the 1-D averaged global wavelet spectrum (AGWSt) by averaging the GWSs (*curve in panel h*).**

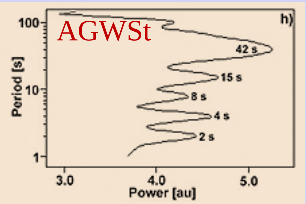
**⇒ Information about the characteristic temporal period that are present in the spectrum under study, i.e. periods $P = 2, 4, 8, 15$, and 42 s (*in panel h*).**

- **Spectrum under study (*panel g*) is filtered with respect to the characteristic temporal periods .**
  **(inverse wavelet analysis, Torrence and Compo, 1998)**
  **→ new separated spectra are calculated - they consist of only those components, i.e. of only bursts with with the demanded characteristic periods .**

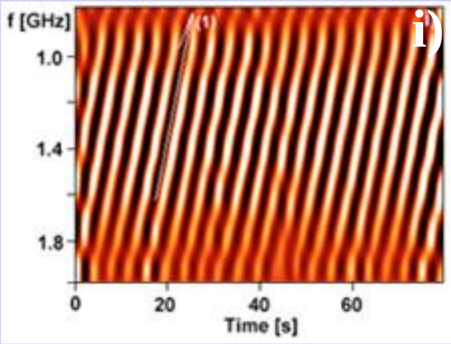
**one characteristic temporal period ↔ one new separated spectrum**

## Separation methods: construction of the artificial radio spectrum (Mészárosová at al. 2011, A&A 525, A88)

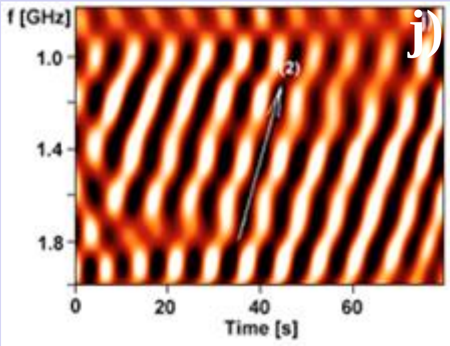


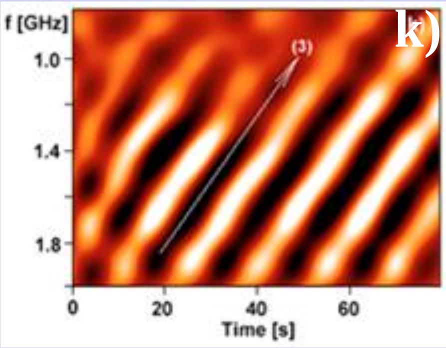

***Panels i−l*** **show the final spectra separated according to individual period ranges (= local minima of the curve AGWSt (*panel h*).**



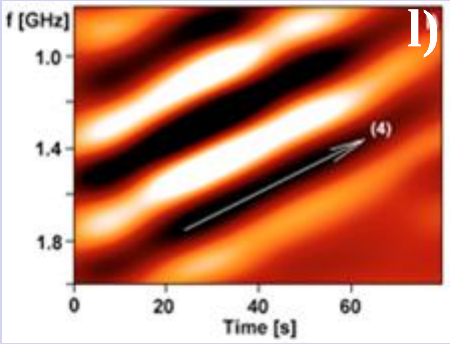

**separated pulsations in the *P*-range 2.9−5.7 s**



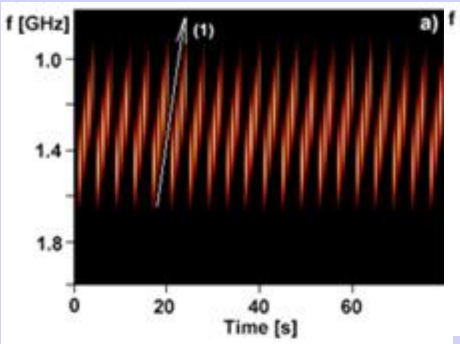

**separated pulsations in the *P*-range 5.7−10.0 s**

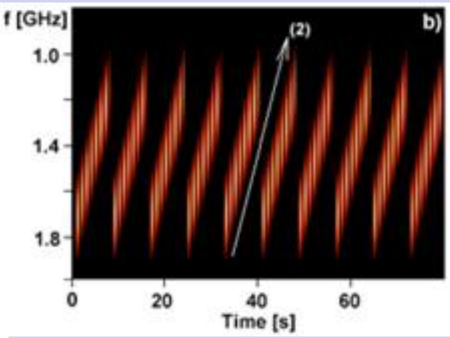


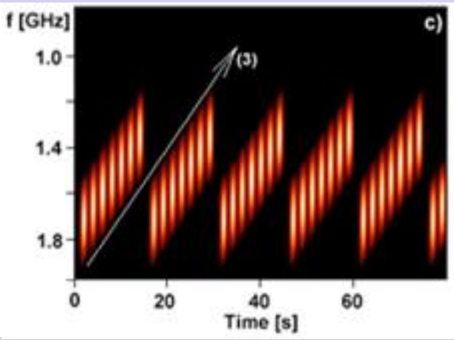

**separated pulsations in the *P*-range 10−24 s**

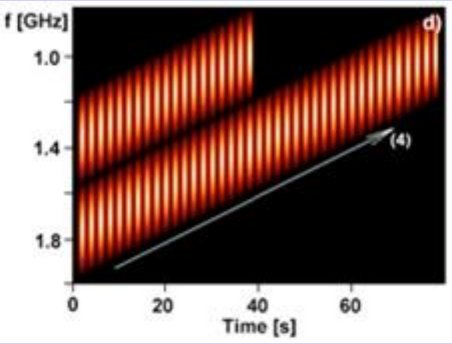



**separated pulsations in the *P*-range 24−90 s**

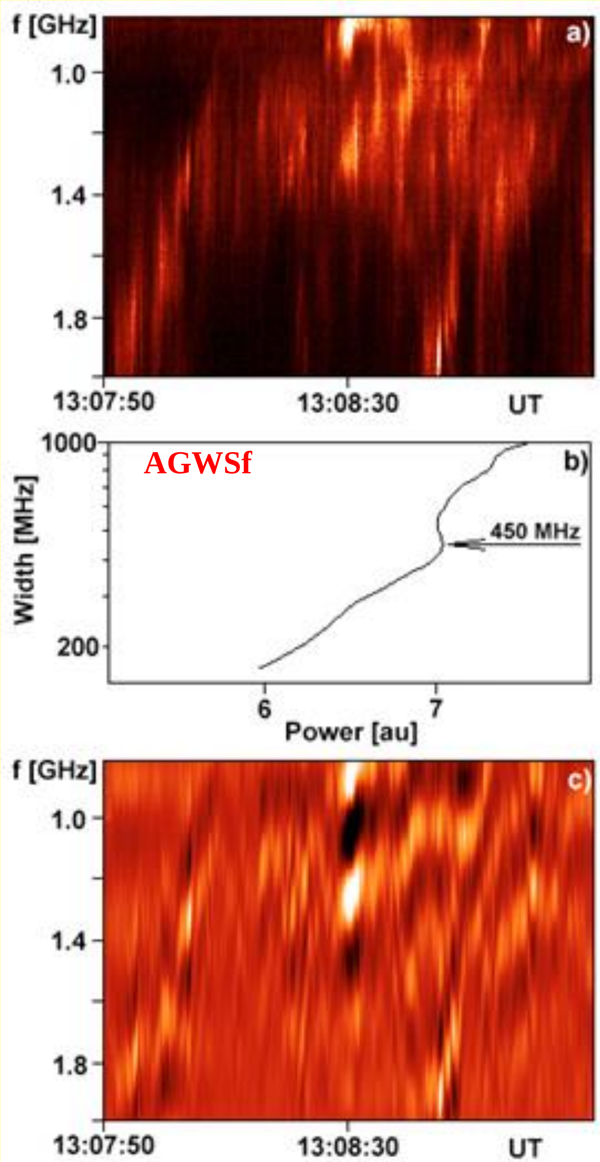


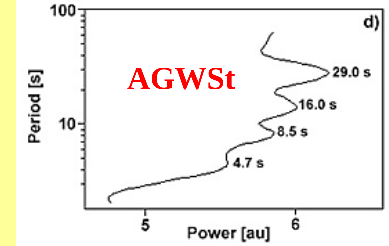

**The final filtered spectra are similar to the original ones (the same number of DPSs & global frequency drift). Some deviations are generated because of the limitations of the wavelet method caused by a finite length of the time and frequency data cuts.**

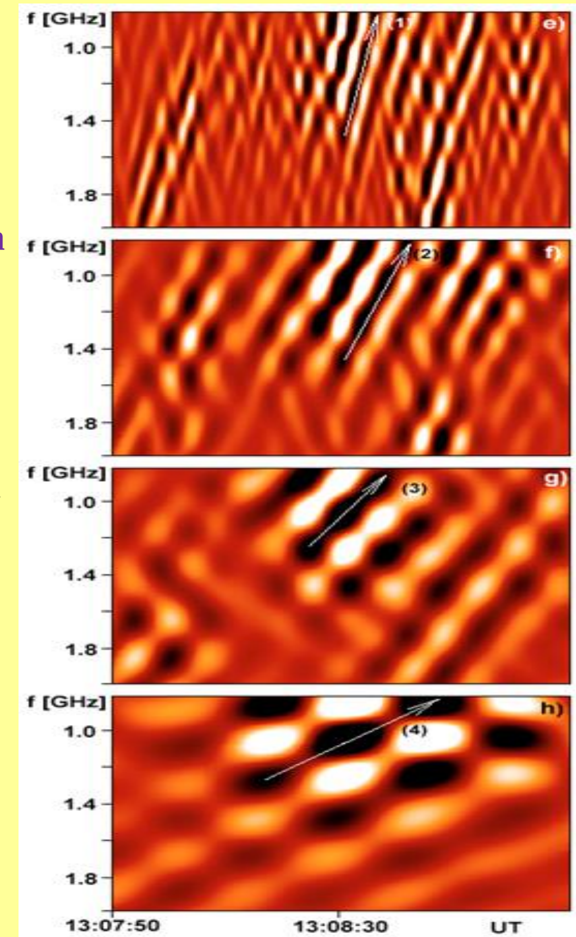



# Separation of real DPSs

**(2001 April 11 radio dynamic spectrum):**

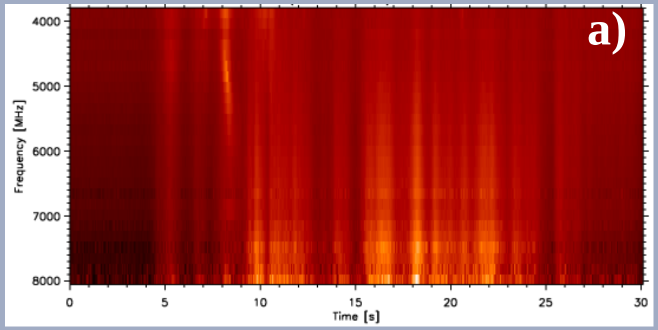
- ***Panel a)* original radio spectrum with drifting pulsation structures (DPSs).**
- ***Panel b)* averaged global wavelet spectrum (AGWSf) with a peak for the frequency width (bandwidth) 450 MHz.**
- ***Panel c)* filtered original radio spectrum in the bandwidth range 290−540 MHz.**
- ***Panel d)* averaged global wavelet spectrum (AGWSt) made from the spectrum in the *panel c)* with peaks for the periods *P* = 4.7, 8.5, 16.0, and 29.0 s.**
- ***Panel e)* separated DPSs in the period range 2.2−5.5 s.**
- ***Panel f)* separated DPSs in the period range 5.5−10.0 s.**
- ***Panel g)* separated DPSs in the period range 10−20 s.**
- ***Panel h)* separated DPSs in the period range 20−44 s.**

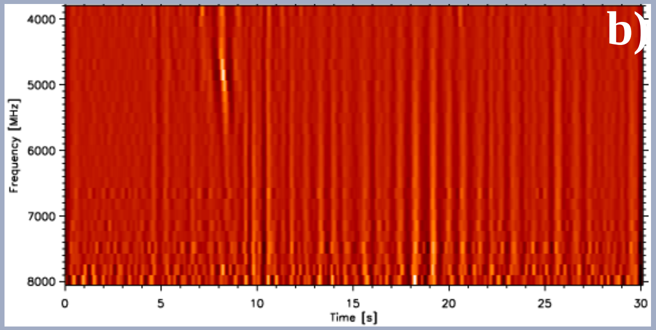


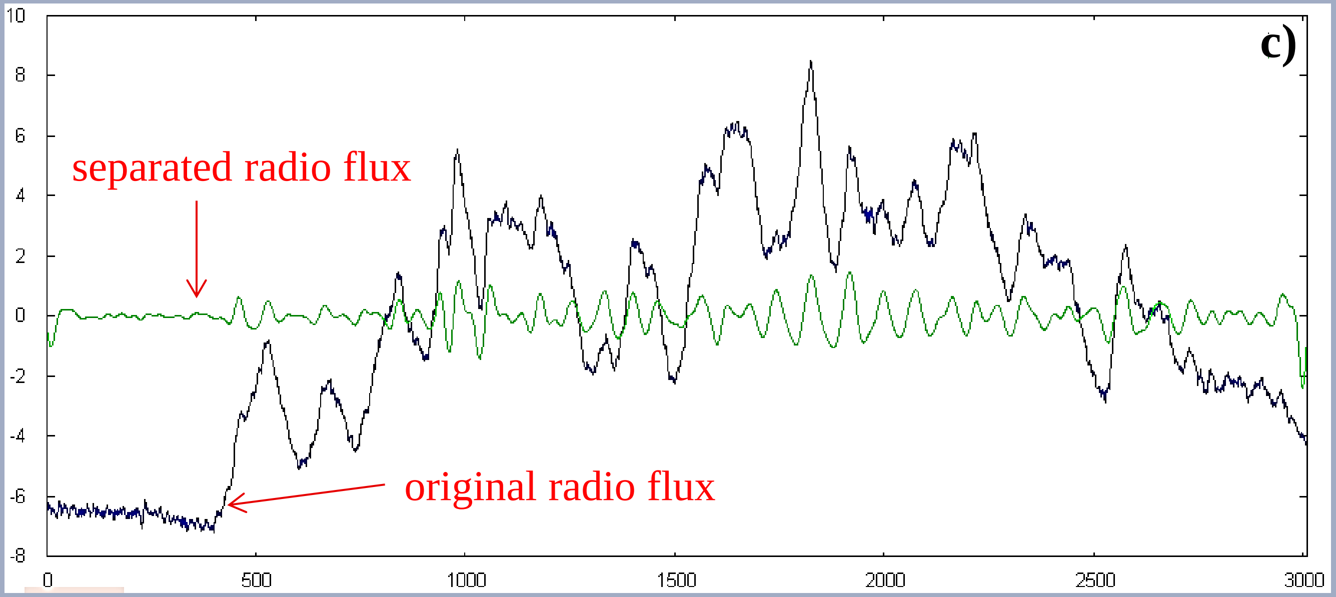

**Arrows in panels show frequency drifts of DPSs.**

# Methods to study complex radio fine structures: Separations



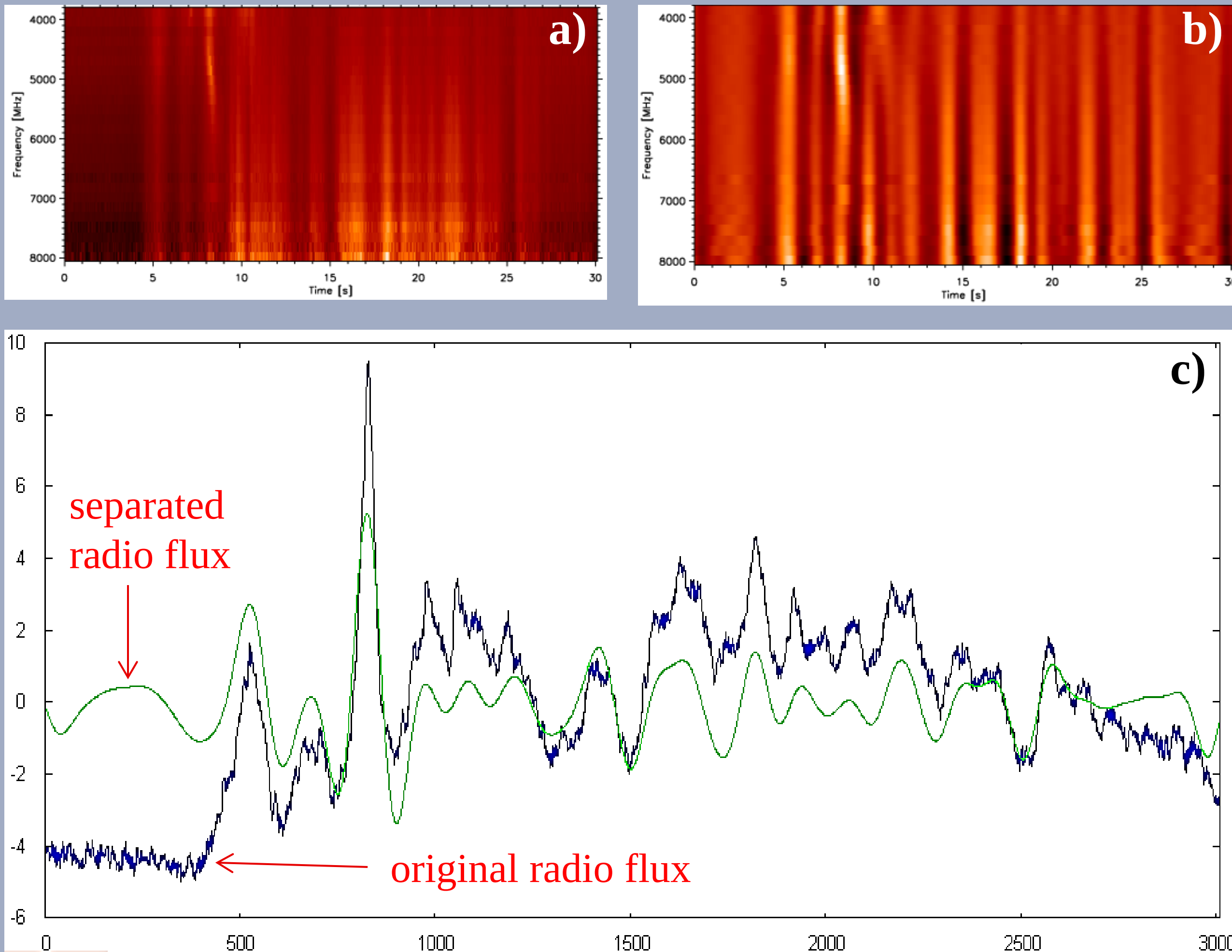

***Panel a)*** **Original radio dynamic spectrum with pulsations superimposed on continuum.**
**duration = 30 s**
**freq. range ≈ 4–8 GHz**




***Panel b)*** **The separated pulsations detected in the period range 0.3–1.0 s. Only fluxes with these periods are included in this new separated radio dynamic spectrum.**
**All separated time series are without underlying continuum (onsets) and without instrument disturbations .**

***Panel c)*** **Original time series at frequency 5398 MHz (in blue). Separated time series at frequency 5398 MHz for the period range 0.3–1.0 s (in green). Separated peaks correspond with peaks of original data.**

# Methods to study complex radio fine structures: Separations

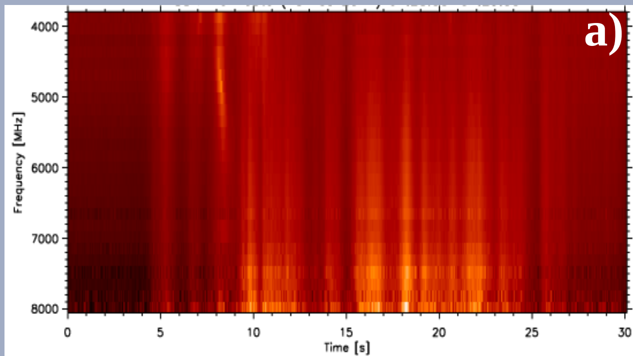


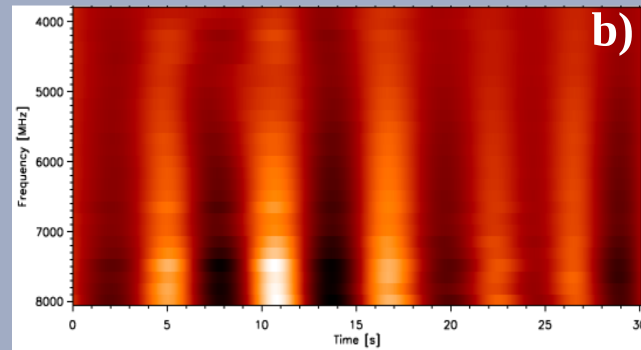

***Panel a)*** **Original radio dynamic spectrum with pulsations superimposed on continuum.**
**duration = 30 s**
**freq. range ≈ 4–8 GHz**

***Panel b)*** **The separated pulsations detected in the period range 1–4 s. Only fluxes with these periods are included in this new separated radio dynamic spectrum.**
**All separated time series are without underlying continum (onsets) and without instrument disturbations .**

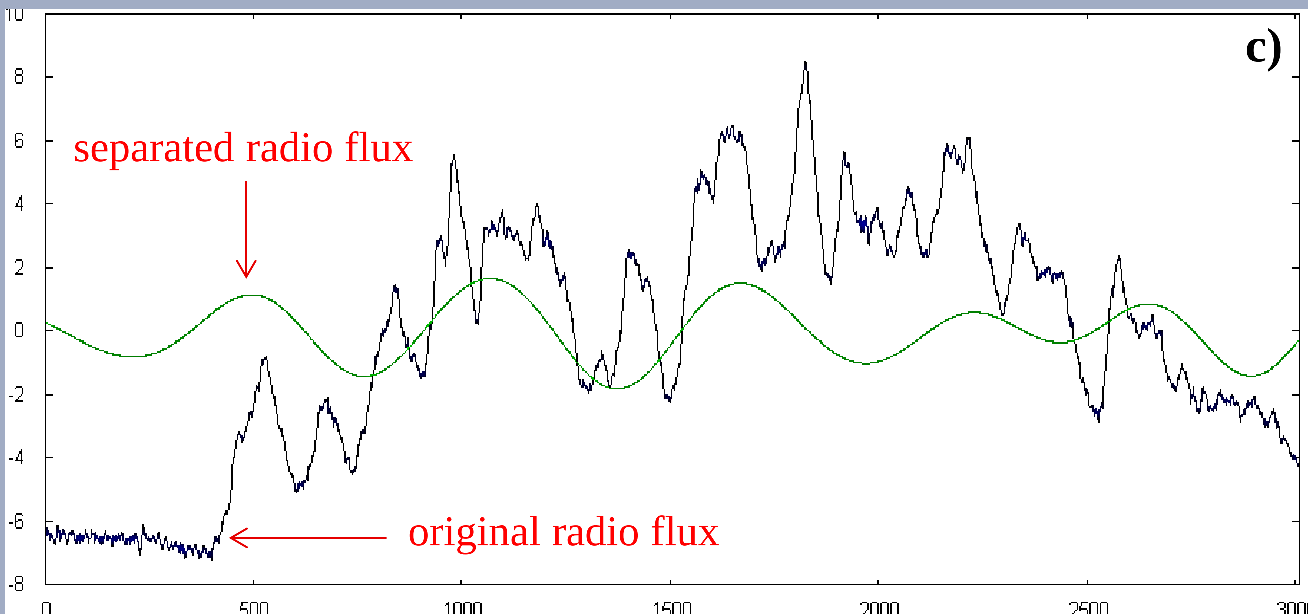
***Panel c)*** **Original time series at frequency 6460 MHz (in blue). Separated time series at frequency 6460 MHz for the period range 1–4 s (in green). Separated peaks correspond with peaks of original data.**

# Methods to study complex radio fine structures: Separations



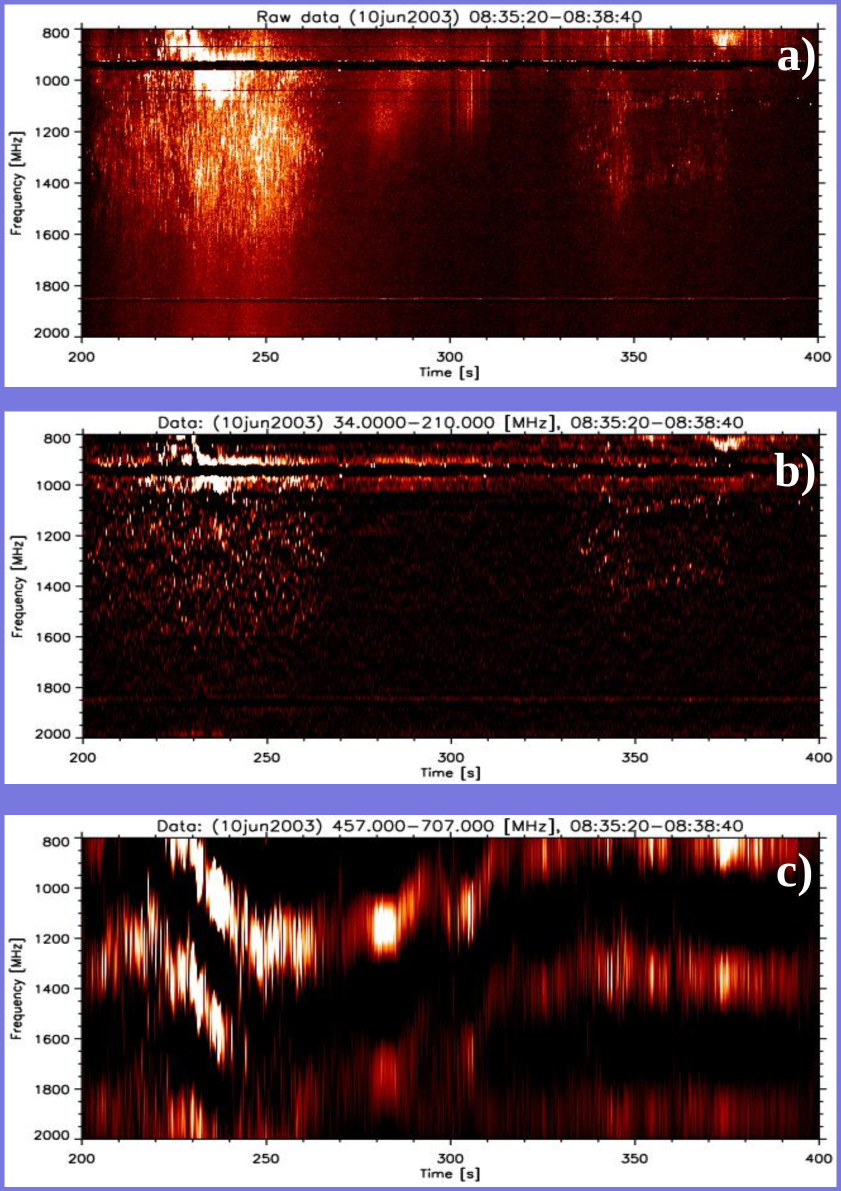

***Panel a)*** **Original radio dynamic spectrum with pulsations superimposed on continuum.**
**duration = 30 s**
**freq. range ≈ 4–8 GHz**




***Panel b)*** **The separated pulsations detected in the period range 4–8 s. Only fluxes with these periods are included in this new separated radio dynamic spectrum.**
**All separated time series are without underlying continuum (onsets) and without instrument disturbances .**

***Panel c)*** **Original time series at frequency 5398 MHz (in blue). Separated time series at frequency 5398 MHz for the period range 4–8 s (in green). Separated peaks correspond with peaks of original data.**

# Methods to study complex radio fine structures: Separations



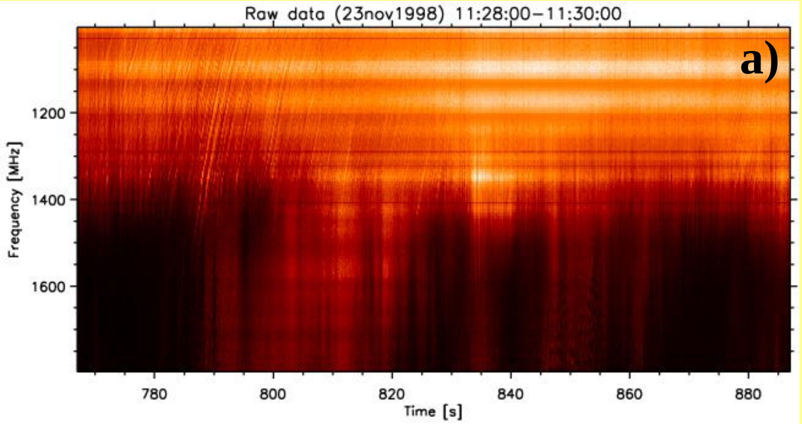

*Panel a)* Original radio dynamic spectrum with narrowband dm-spikes superimposed on continuum.
duration = 200 s, freq. range = 0.8–2 GHz

*Panel b)* Separated dm-spikes detected in the bandwidth range 34–210 MHz. Only frequecny cuts with these bandwidths are included in this new separated radio dynamic spectrum.

*Panel c)* Separated drifting pulsating structures (DPS) detected in the bandwidth range 457–707 MHz. The method allows us to detect hidden structures in a radio dynamic spectrum. They are hidden because of more intense flare structures are present in the original radio spectrum.

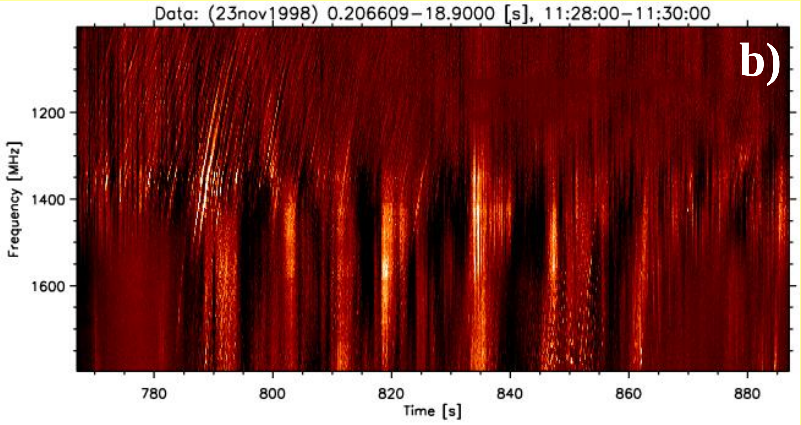
Karlicky at al., 2011:
Spikes and DPS as a radio signature of the fragmented reconnection in solar flares.

# Methods to study complex radio fine structures: Separations

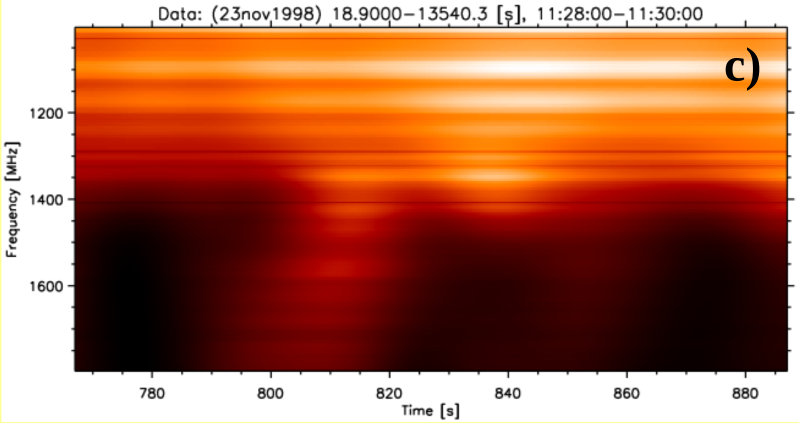



***Panel a)*** **Original radio dynamic spectrum with different fine structures superimposed on underlying continuum:**
**duration = 122 s**
**freq. range = 1.0–1.8 GHz**

**A] separation in temporal period (time series)**

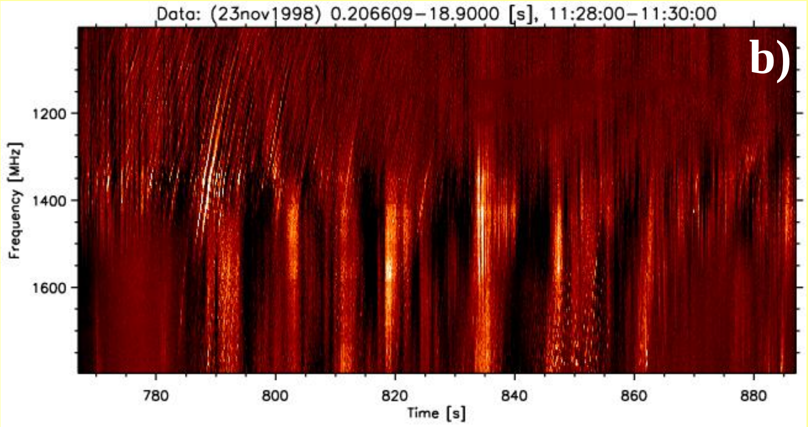


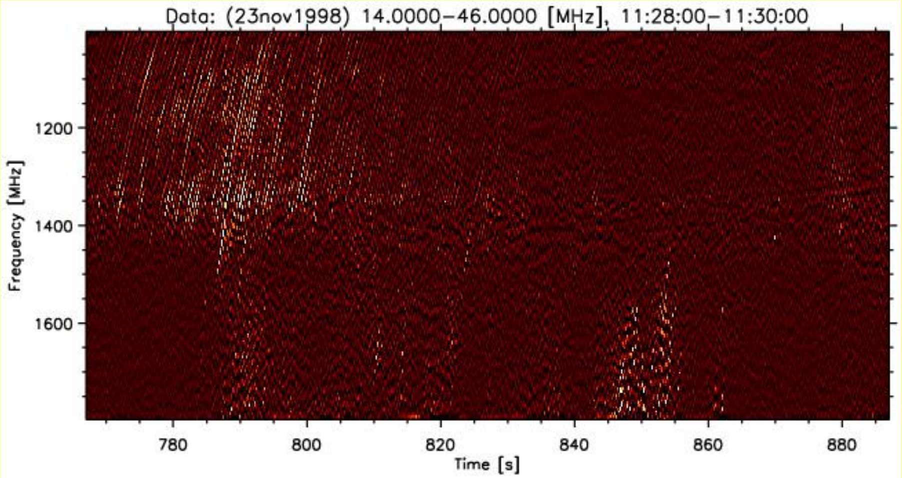

***Panel b)*** **Separated radio spectrum with all fine structures except the continuum. The temporal period range: 0.2–18.9 s.**




***Panel c)*** **Separated continuum detected in the temporal period range > 18.9 s.**

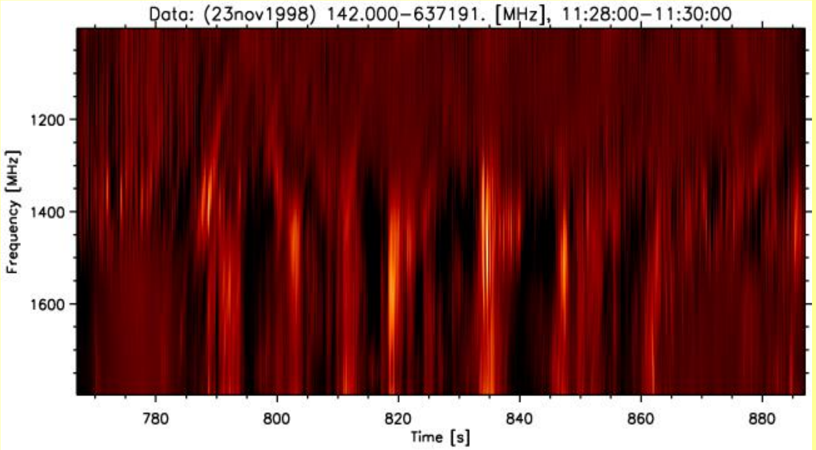
# Methods to study complex radio fine structures: Separations



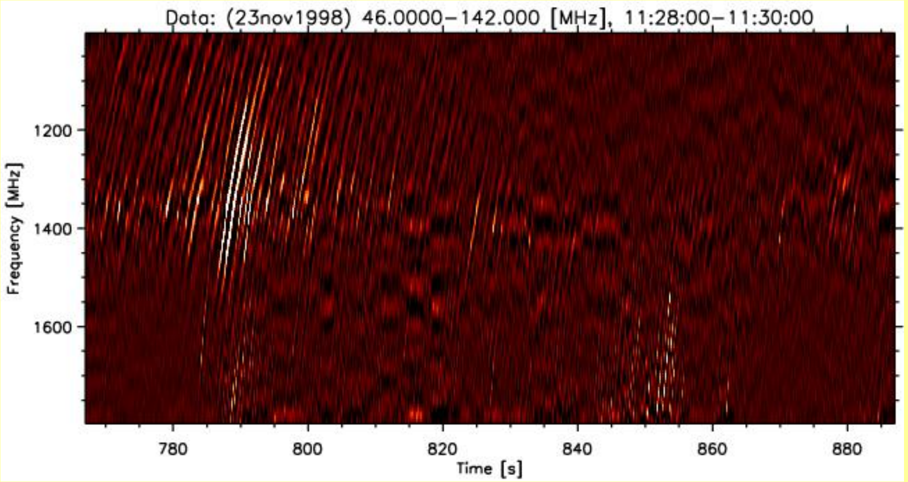




**B] separation in frequency cuts (bandwidths):**

separated bandwidths in frequency range 14-46 MHz: fine zebra patterns

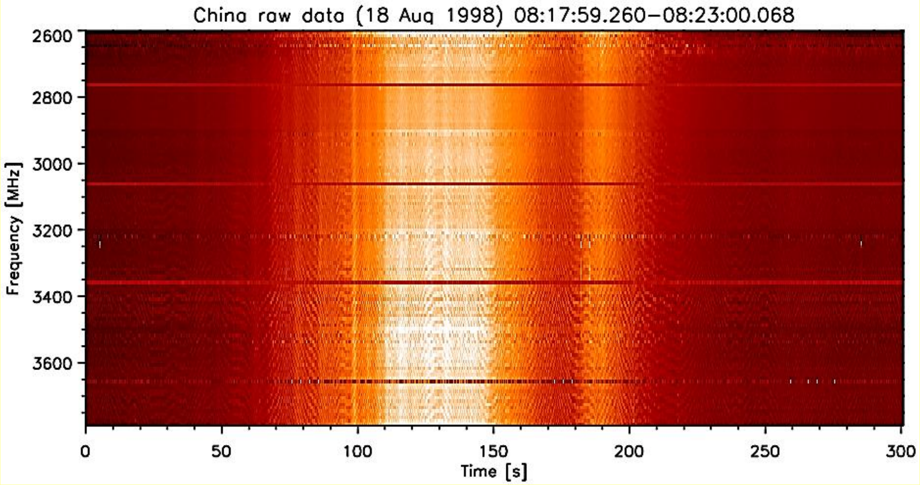



separated bandwidths in frequency range > 142 MHz: pulsations



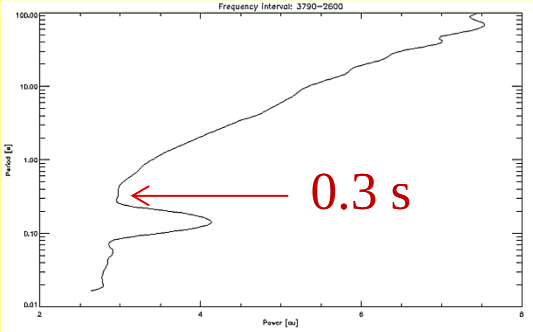

separated bandwidths in frequency range 46-142 MHz: fibers and zebra patterns

# Methods to study complex radio fine structures: Separations

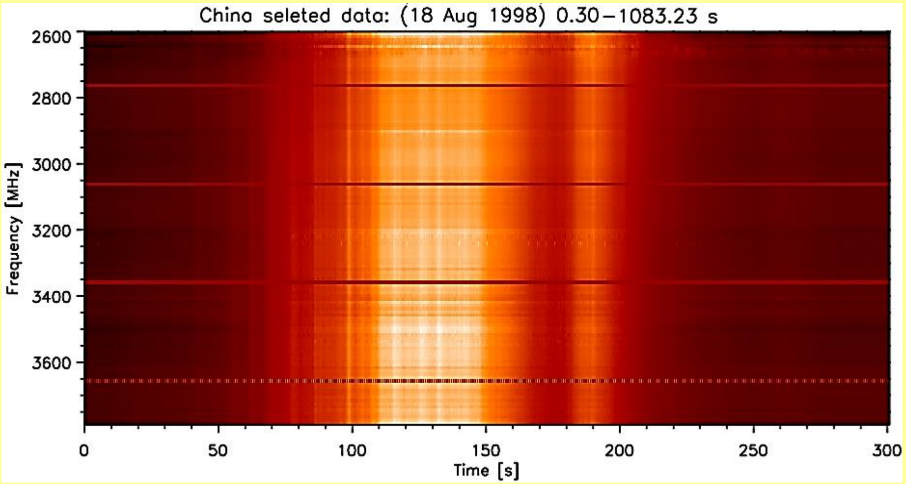



Original radio dynamic spectrum with pulsations, continuum, & superimposed instrumental inteferences.

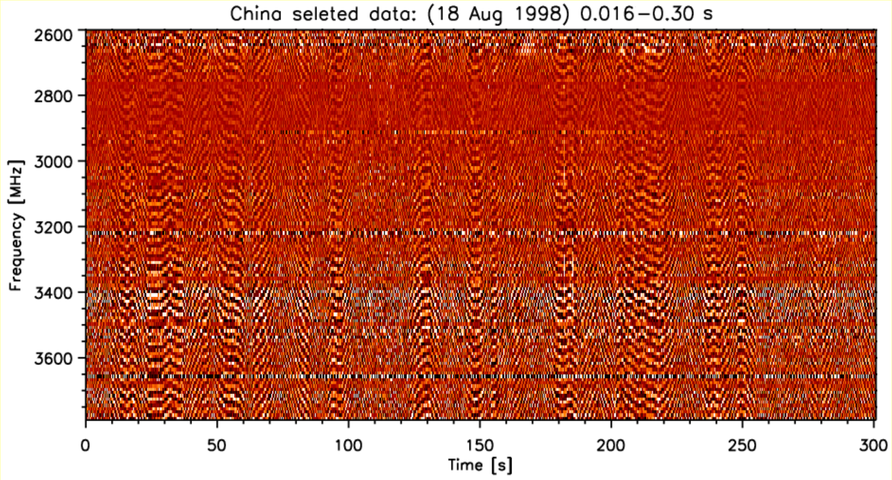
## Separation of instrumental interferences:




Averaged global wavelet spectrum AGWSt with a peak of temporal periods < 0.3 s that reflects instrumental interferences.

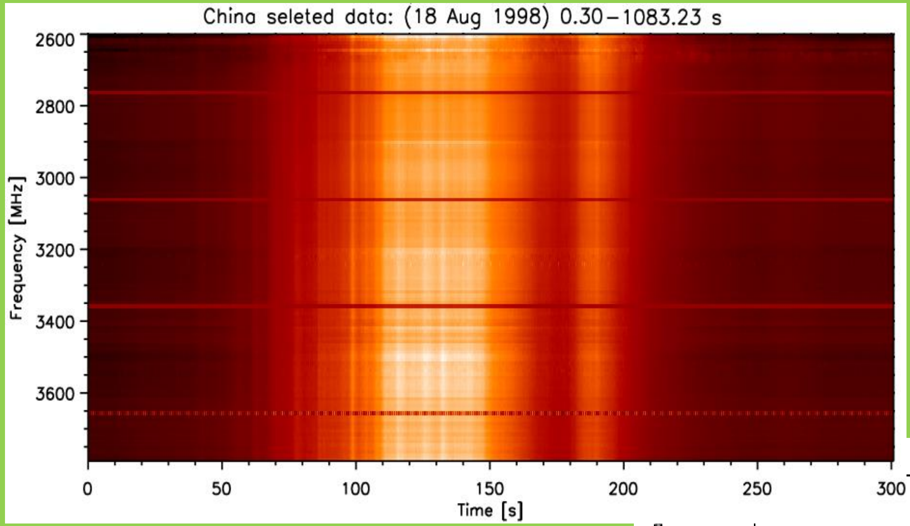



Separated radio dynamic spectrum for temporal periods > 0.3 s with only pulsations & continuum.



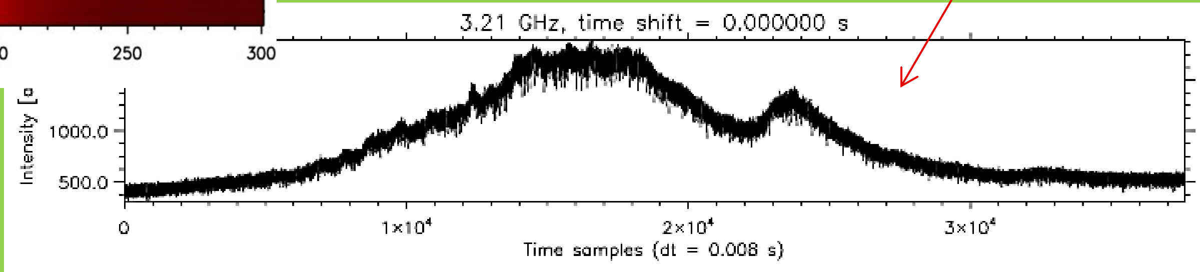

Separated radio dynamic spectrum for temporal periods < 0.3 s with the instrumental interferences only.

# Methods to study complex radio fine structures: Separations

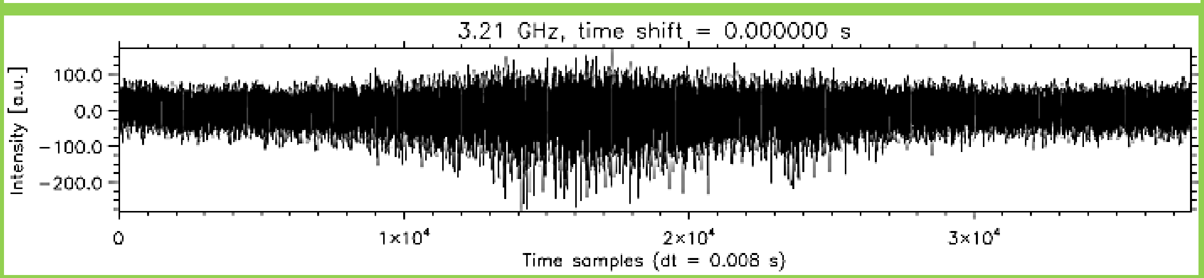



## Separation of instrumental interferences:

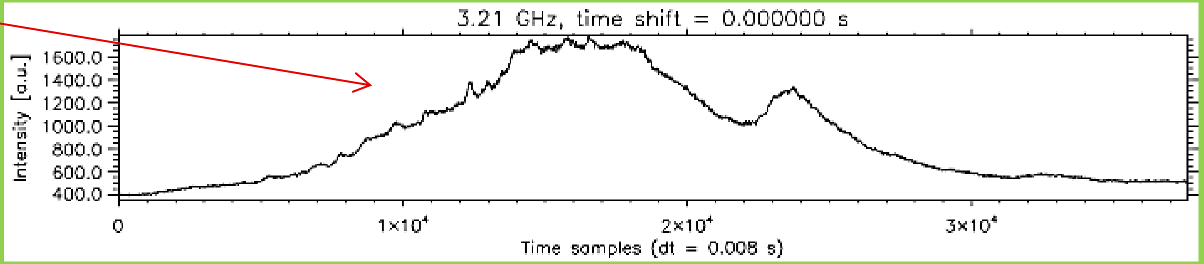
**Example of original time series at 3.21 GHz with instrumental interferences.**



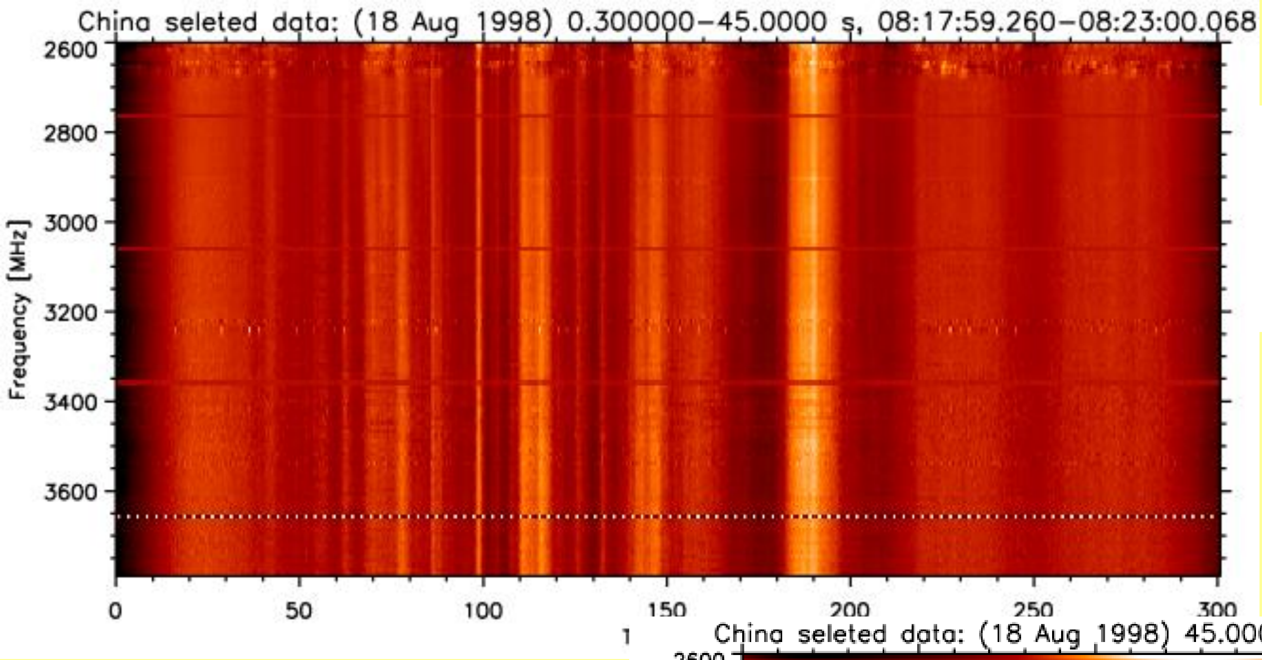

**Separated instrumental interferences at 3.21 GHz time series**



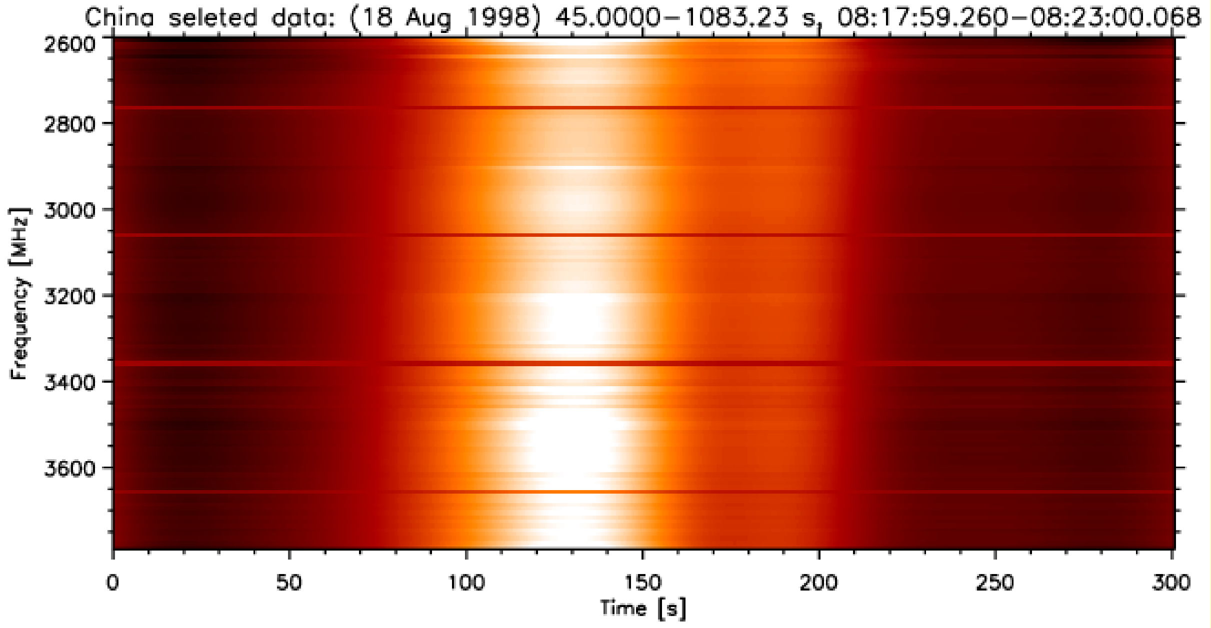

**All pulsation peaks at 3.21 GHz time series are saved (no smoothing).**
**For a study the quasi-periodic pulsations we need to have them without the underlying onsets.**



# Methods to study complex radio fine structures: Separations

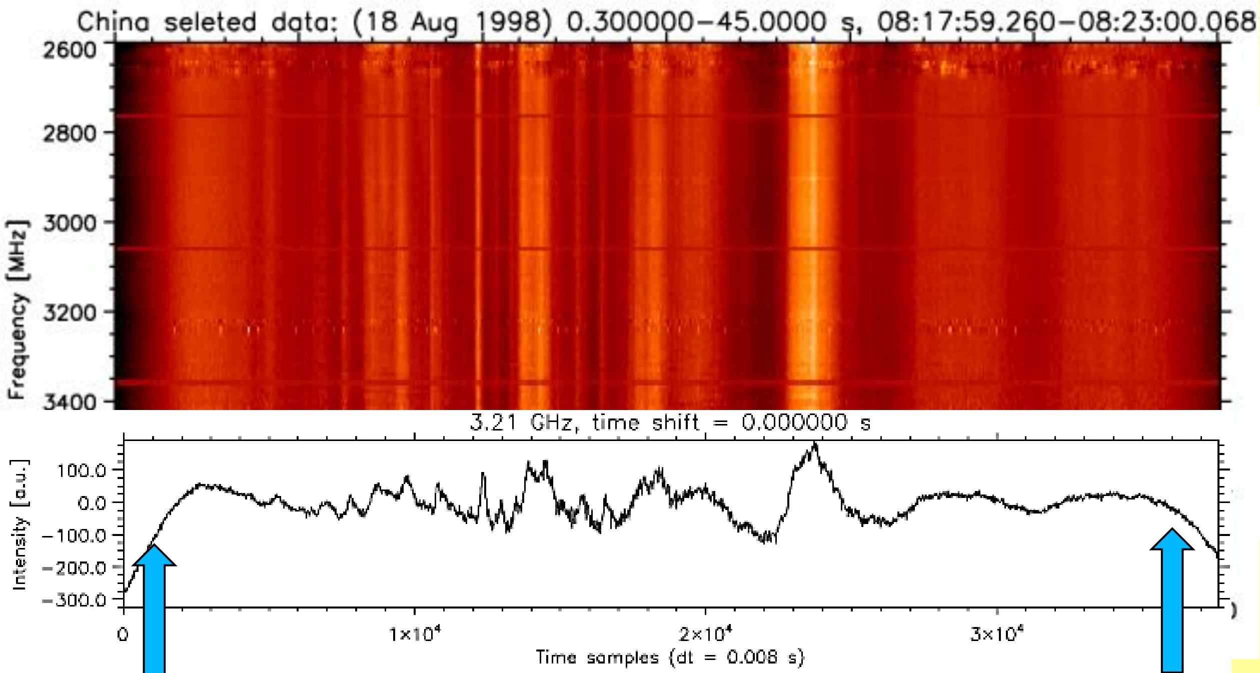



**Separated radio dynamic spectrum for temporal periods 0.3-45 s with only pulsations.**




**Separated radio dynamic spectrum for temporal periods > 45 s with only continuum.**

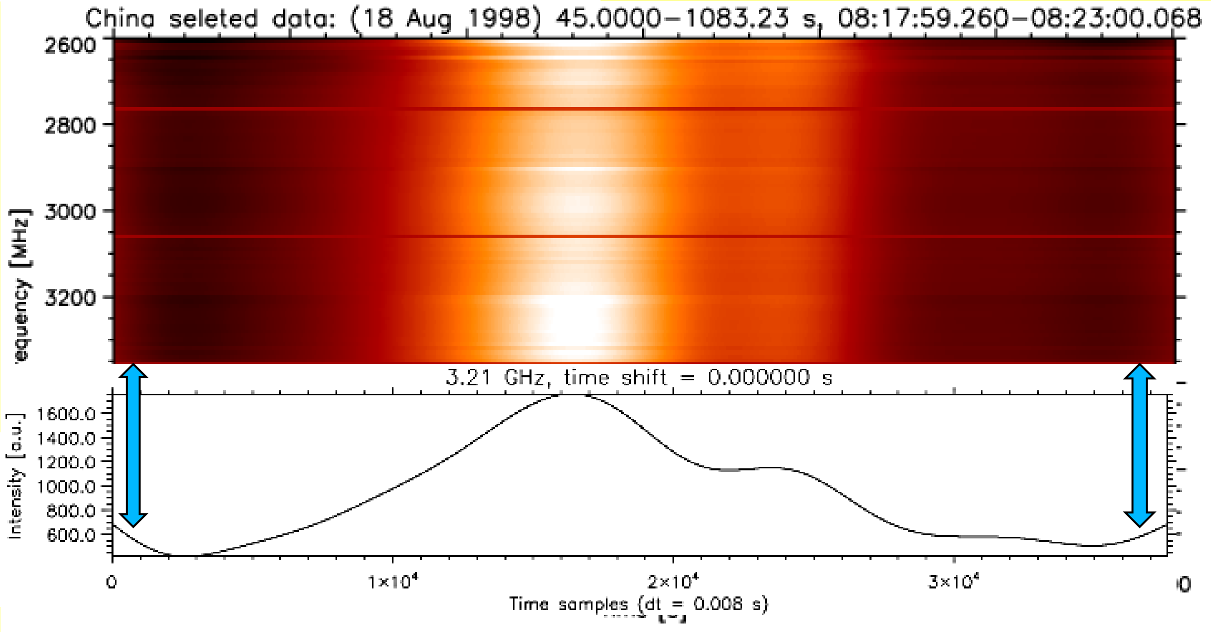
# Methods to study complex radio fine structures: Separations




**Separated radio dynamic spectrum for temporal periods 0.3-45 s with only pulsations.**

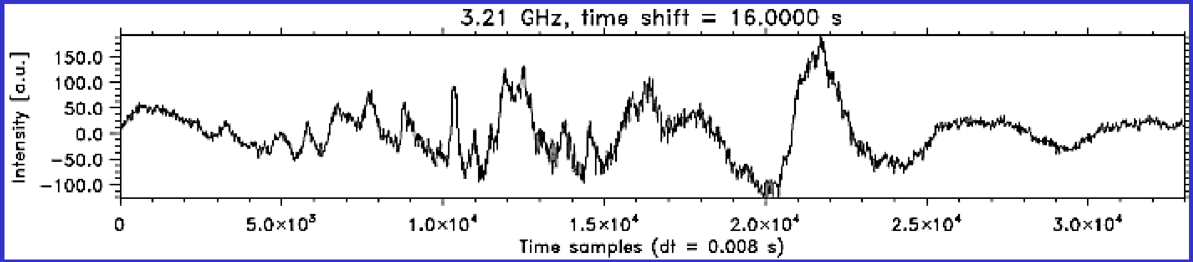
**Example of time series at 3.21 GHz with only pulsation peaks.**

**Arrows in blue: areas with deviations that are generated because of the limitations of the wavelet method caused by a finite length of the time data cuts.**

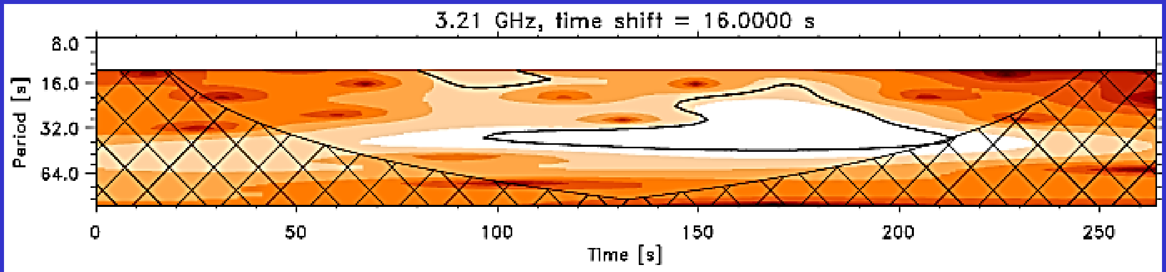



**Example of time series at 3.21 GHz with only continuum peaks.**

# Methods to study complex radio fine structures: Separations



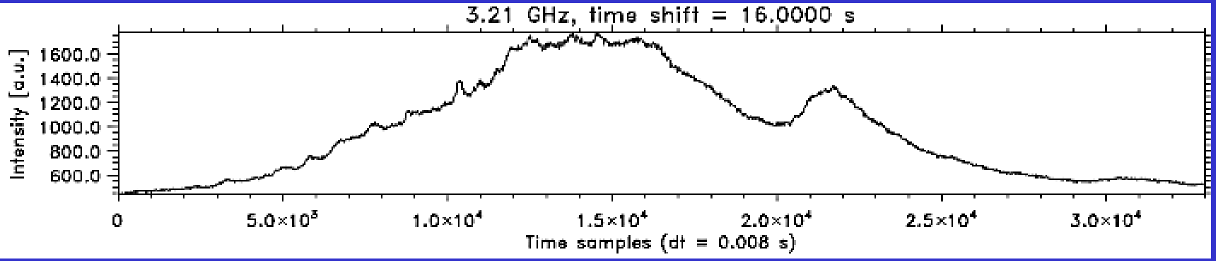

Valid area of time series at 3.21 GHz (separated pulsations).



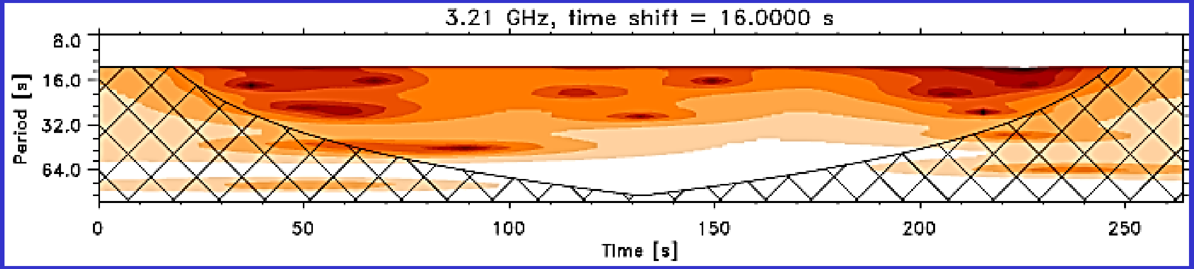

Wavelet power spectrum of the time series above with a ‘tadpole’ pattern.

Cross-hatched regions are the COIs. The contours overlaid are the same 95% confidence level.

Valid area of the original time series at 3.21 GHz but without instrumental interferences.



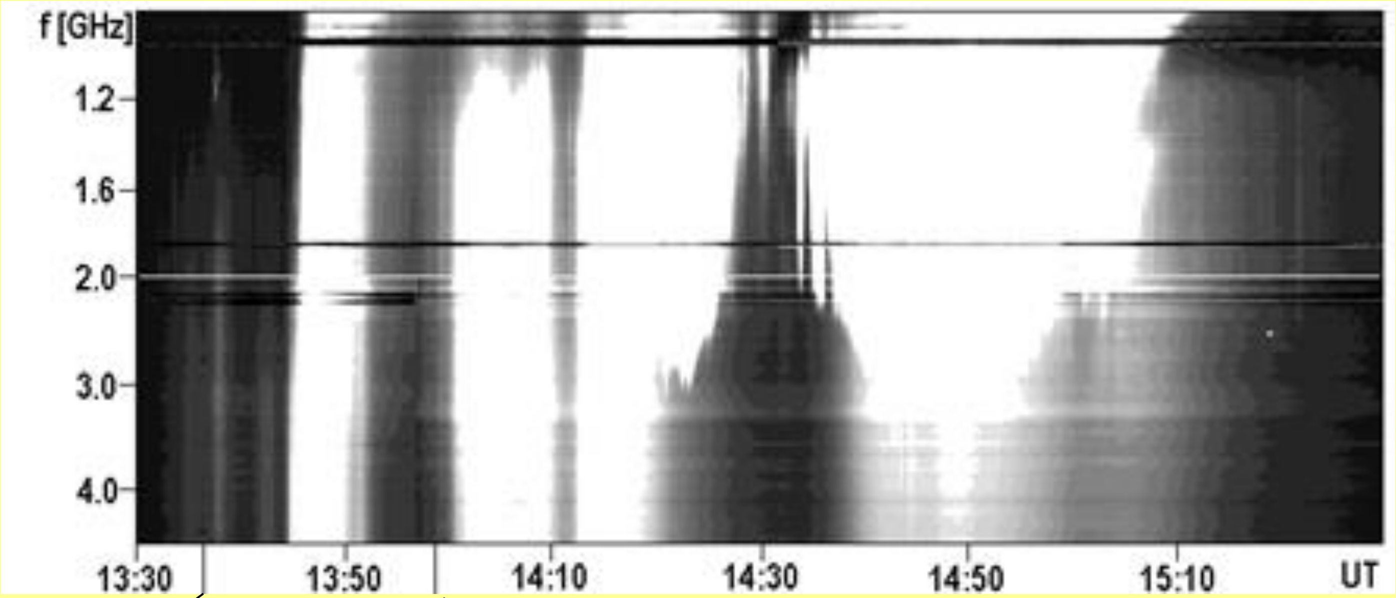

Wavelet power spectrum of the time series above: Continuum onsets have predominant influences.

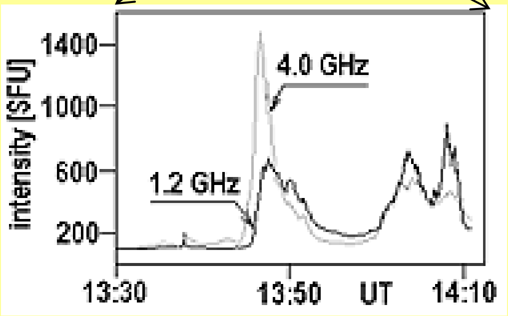


# Methods to study complex radio fine structures: Coherence, phase differences

Mészárosová at al. 2006, A&A 460, 865

The 0.8−4.5 GHz radio spectrum of the April 15, 2001 flare
(Ondřejov radiospectrograph)




Radio fluxes at 1.2 and 4.0 GHz
(Ondřejov radiospectrographs).

emission mechanism of individual continua:

- plasma radio emission?
- gyrosynchotron emission?

estimations:

at frequencies < about 2000 GHz ⟺ plasma radio emission

at frequencies > about 2000 GHz ⟺ gyro-synchrotron emission

# Methods to study complex radio fine structures: Coherence, phase differences

Mészárosová at al. 2006, A&A 460, 865

**To understand the global relationship between radio fluxes on low and high frequencies (0.8–4.5 GHz range) and to recognize different emission mechanisms, we can made the cross-correlation of the radio fluxes at different frequencies. In our case we found high cross-correlations in whole frequency range.**

**For more detailed analysis we used other methods (Bloomfield et al. 2004) regarding the Mean wavelet coherence and Phase differences of dominant periods between two wavelet power spectra of two individual time series. This method uses the phase information residing within the Morlet transform.**

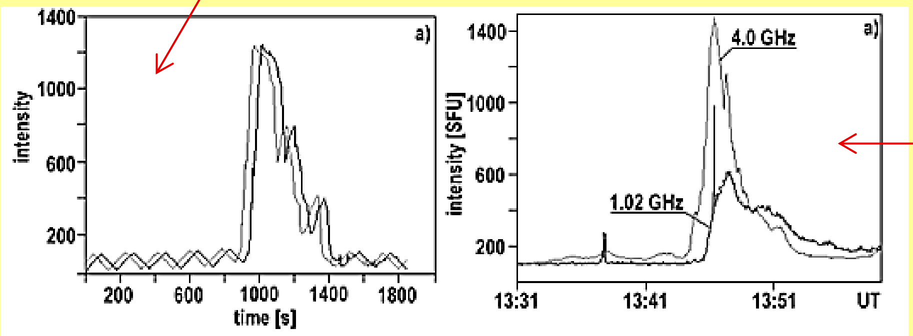
**While a wavelet power spectrum shows the variance of a time series, the cross-wavelet power of two time series shows the coherence between these time series. Thus the cross-wavelet power can be used as an indication of the similarity of periods.**

**Measurements of the phase difference between two time series yield information on the phase delay between oscillations in the time series as a function of periods.**

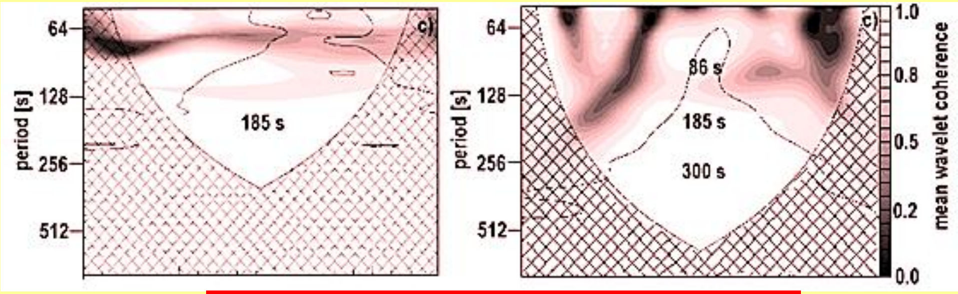
# Methods to study complex radio fine structures: Coherence, phase differences

**Mészárosová at al. 2006, A&A 460, 865**

**Two artificial identical time series, but the 2nd  one is shifted by 90° compared to the 1st one.  Temporal period is 185 s.**




**Two observed time series at 1.02 and 4.0 GHz (April 15, 2001 event).**




**Mean wavelet coherence.**

***Bottom panels:***

**The most significant range in the mean wavelet coherence are in white:**

***Left panel*: both artificial time series  are the same with a dominant period 185 s.**

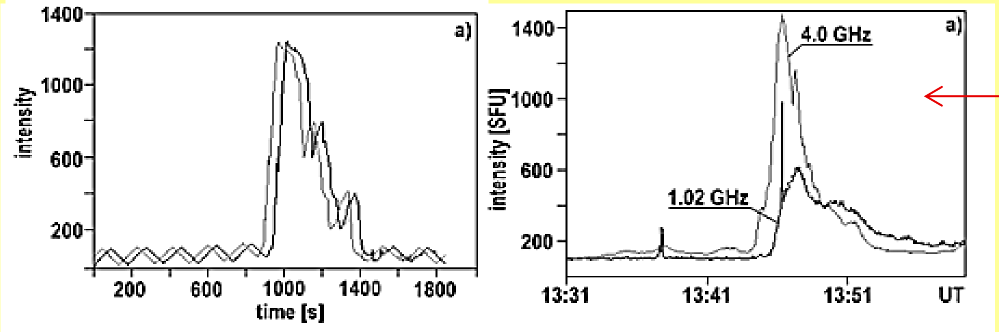
***Right panel*: both 1.02  and 4.0 GHz frequencies have the dominant periods 86, 185, and 300 s.**

# Methods to study complex radio fine structures: Coherence, phase differences

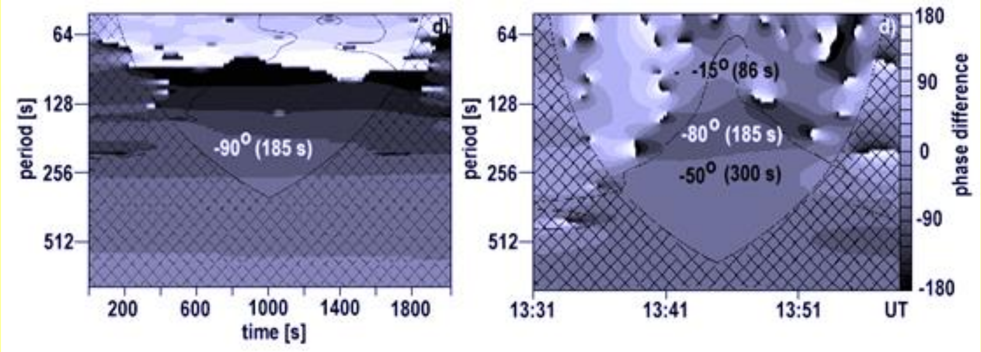
Mészárosová at al. 2006, A&A 460, 865

**Two artificial identical time series, but the 2nd one is shifted by 90º compared to the 1st one.**

**The phase difference between both the time series is 90º.**




**Two observed time series at 1.02 and 4.0 GHz (April 15, 2001 event).**




**Phase differences**

***Bottom panels:***

**Absolute white corresponds to 180º and absolute black to −180º.**

***Left panel*: The phase difference is about 90º (in gray) for dominant period 185 s, which is in agreement with the shift originaly introduced.**

***Right panel*: The phase difference is about −15º, −80º, and −50º for the dominant periods 86, 185, and 300 s, respectively.**

## Methods to study complex radio fine structures: Coherence, phase differences

Mészárosová at al. 2006, A&A 460, 865

| Compared fluxes at frequencies [GHz] | Coherence value | Phase diffrerence [degree] |
|---|---|---|
| 4.0 & 0.90 | 0.9 | -110 |
| 4.0 & 1.00 | 1.0 | -80 |
| 4.0 & 1.02 | 1.0 | -80 |
| 4.0 & 1.10 | 1.0 | -80 |
| 4.0 & 1.20 | 1.0 | -80 |
| 4.0 & 1.30 | 0.7 – 0.9 | -50 |
| 4.0 & 1.40 | 0.6 – 0.8 | -50 |
| 4.0 & 1.50 | 0.6 – 0.8 | -15 – -50 |
| 4.0 & 1.60 | 0.6 – 0.8 | -15 – -50 |
| 4.0 & 1.70 | 0.6 – 0.9 | -15 – -50 |
| 4.0 & 1.80 | 0.8 – 1.0 | -15 – -50 |
| 4.0 & 2.25 | 1.0 | -15 |
| 4.0 & 2.50 | 1.0 | -15 |
| 4.0 & 2.75 | 1.0 | -15 |
| 4.0 & 3.00 | 1.0 | -15 |
| 4.0 & 3.25 | 1.0 | -15 |
| 4.0 & 3.50 | 1.0 | -15 |
| 4.0 & 3.75 | 1.0 | 0 |

Example of the mean wavelet coherence, & phase difference for the period range 160−190 s in the Ondřejov radio fluxes at selected frequencies of the April 15, 2001 drifting burst at 13:31:00−13:59:50 UT.

Mean wavelet coherence values = 1.0 indicate the highest coherences, values = 0.0 indicate the lowest coherences.

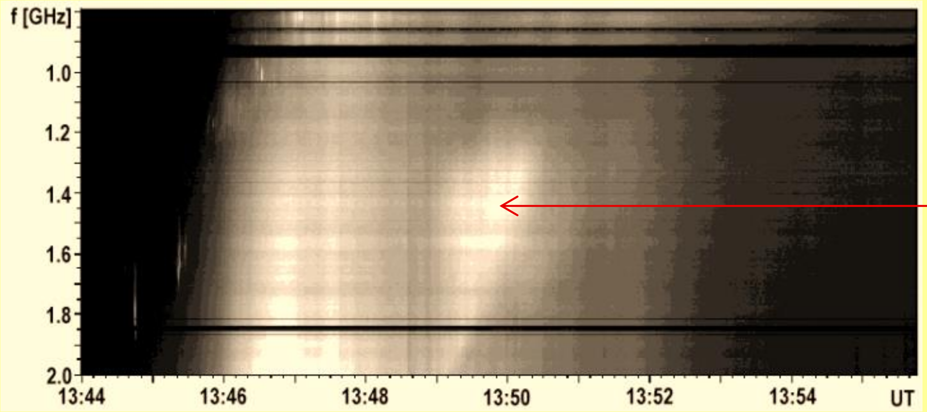
The range of the phase difference values is $-180^{o} \leq \Phi \leq 180^{o}$.

# Methods to study complex radio fine structures: Coherence, phase differences

Mészárosová at al. 2006, A&A 460, 865

## According to the Table (previous slide):

**The decreasing mean wavelet coherence (0.6−0.8) and the start of the increasing phase difference (> -15) are detected at frequencies about 1.3−1.8 GHz of the radio dynamic spectrum. At these frequencies is detected drifting burst that is generated by the plasma emission mechanism. The second burst observed at 0.8−4.5 GHz frequencies can be probably generated by the gyrosynchrotron mechanism.**




**burst at 1.3−1.8 GHz frequencies that is generated by the plasma emission mechanism.**

**Detail of the 0.8−2.0 GHz radio spectrum of the broadband drifting burst observed at the beginning of the April 15, 2001 flare.**

# Methods to study complex radio fine structures: Conclusions

## • Separation methods:

- Based on the wavelet analysis technique for complex radio spectra with many bursts and fine structures.

- We compute a 1-D averaged global wavelet spectrum (AGWS) by averaging the individual GWSs from:
  - individual time series to know characteristic temporal periods, or
  - individual frequency cuts at individual time moments to know characteristic bandwidth of bursts.

- Then we compute new separated radio dynamic spectra for the selected characteristic temporal periods or bandwidths via the inverse wavelet analysis.

- more detailed information in Mészárosová at al. 2011, A&A 525, A88

# Methods to study complex radio fine structures: Conclusions

- **Separation methods:**
- **It allows us to separate individual bursts according to different: time periods/frequency bandwidths/frequency drifts/their combinations (arbitrary option).**
- **The method allows us to detect hidden structures in a radio dynamic spectrum (hidden because of more intense flare structures).**
- **We can use this method for removal of instrumental interferences in a radio dynamic spectrum.**
- **We can use the method for a data detrending, i.e. for a removal of onsets in a radio time series (due to underlying continua).**
- **We can use the method for easier detection of a time and place with waves and oscillations via the fine structures separation, via the data detrend and removal of instrumental interferences.**
- **This method can be used also for spatial data, e.g. SDO maps.**

# Methods to study complex radio fine structures: Conclusions

- **Separation methods:**
- **proofs of identity of the separated radio (sub)structures:**
  - **we can compare the original flux with the separated one to prove that the selected flux peaks really exist in the original dynamic spectrum. flux = time series or frequency cuts**
  - **we can compare our results of the separation of the same radio event observed simultaneously by more than one independent instrument (if it is possible).**
- **Method limitations:**
  - **Due to the a finite length of the time and frequency data cuts:**
    - **Separation in temporal periods: deviations on the left and right edges of the separated dynamic spectrum,**
    - **Separation in bandwidths: deviations at the top and bottom edges of the separated dynamic spectrum.**
  - **Too close values of characteristic temporal periods or frequency bandwidths cannot be distinguished, i.e. cannot be separated from each other.**

# Methods to study complex radio fine structures: Conclusions

- **Coherence & Phase Differences method**
- **The usual cross-correlation function of radio time series at different frequencies provides us with a basic information about similarity and time delay between these compared time series.**
- **The method of Coherence and Phase Differences provides us with an information about similarity and phase delay between compared wavelet spectra of time series thus, about similarity and phase delay between compared oscillations in the original time series.**
- **The mean wavelet coherence spectrum informs us about dominant periods that are common for both compared wavelet spectra of the both time series.**
- **The phase difference spectrum informs us about phase differences between compared oscillations for the dominant period determined by the coherence spectrum.**
- **These method help us to find out and specify differences between oscillation phenomena that can be present in compared radio time series.**

**Thank you**
**for your attention!**