

e-VLBI with LOFAR

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Manchester, 23rd September 2010

Long baseline experiments with LOFAR

- LOFAR
- long baseline issues, fringe-fitting
- first long-baseline fringes
- first long-baseline images
- The Sun!

LOFAR

- **LOw Frequency ARray**
- low frequencies
 - ★ LBA: $\sim 30(10)$ –80 MHz
 - ★ HBA: ~ 110 –250 MHz
- ~ 40 stations in Netherlands
- additional stations in Germany, France, England, Sweden, Italy?, Poland?, . . .
- wide field of view, several beams
- good survey speed
- full synthesis imaging at low frequencies with high resolution
- long baselines: subarcsec resolution, **useful for lens surveys**

LOFAR resolution

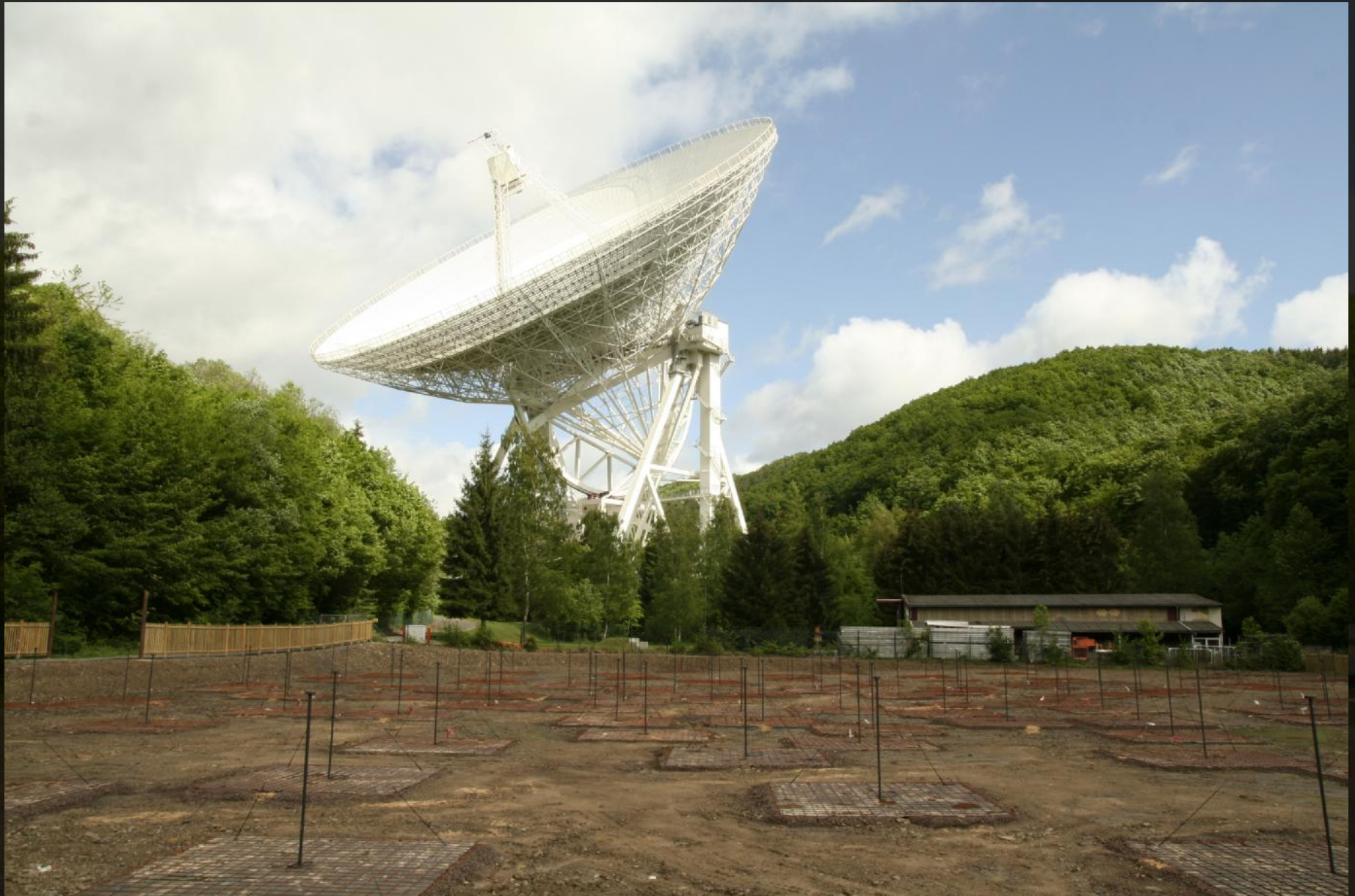
fringe-spacing $\theta = \lambda/L \approx$ resolution

λ / m	freq / MHz	1 km	30 km	300 km	1000 km
30	10	1°7	3'4	21''	6''2
10	30	34'	1'1	6''9	2''1
3.8	80	13'	26''	2''6	0''77
2.5	120	8'6	17''	1''7	0''52
1.9	160	6'4	13''	1''3	0''39
1.4	220	4'7	9''4	0''94	0''28

German LOFAR stations



LBA at Effelsberg



LBA details at Unterweilenbach



HBA + LBA in Tautenburg



VLBI methods for LOFAR

- Long baselines require VLBI techniques
- meaning of *long* depends on circumstances (λ)
- unstable phases, short coherence times
- weak signal: have to average in time and frequency

- solve for delays

$$\tau = \frac{1}{2\pi} \frac{\partial \phi}{\partial \nu}$$

- solve for rates

$$r = \frac{1}{2\pi} \frac{\partial \phi}{\partial t} = \nu \frac{\partial \tau}{\partial t}$$

- non-dispersive

$$\tau = \tau_0$$

- dispersive

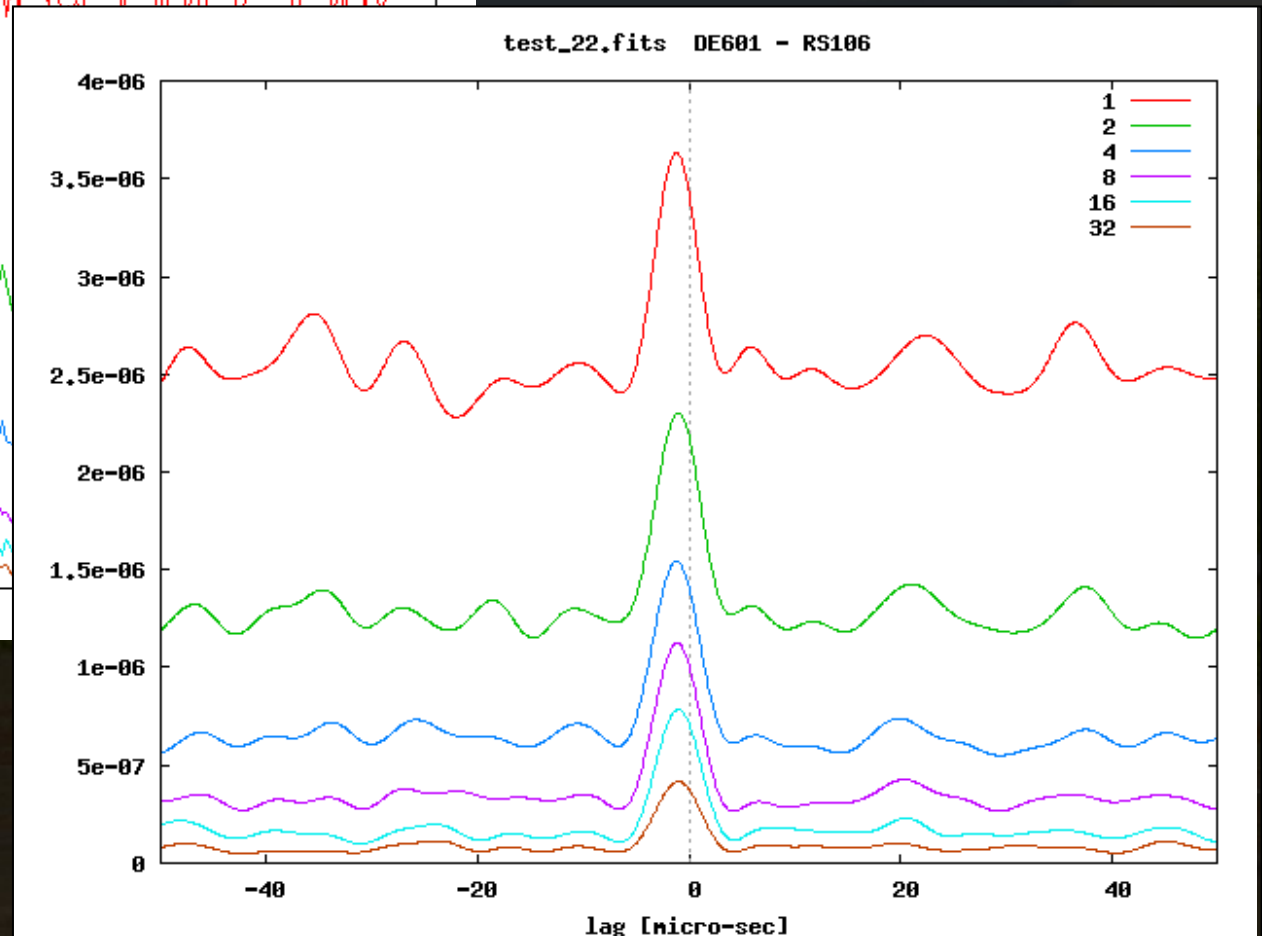
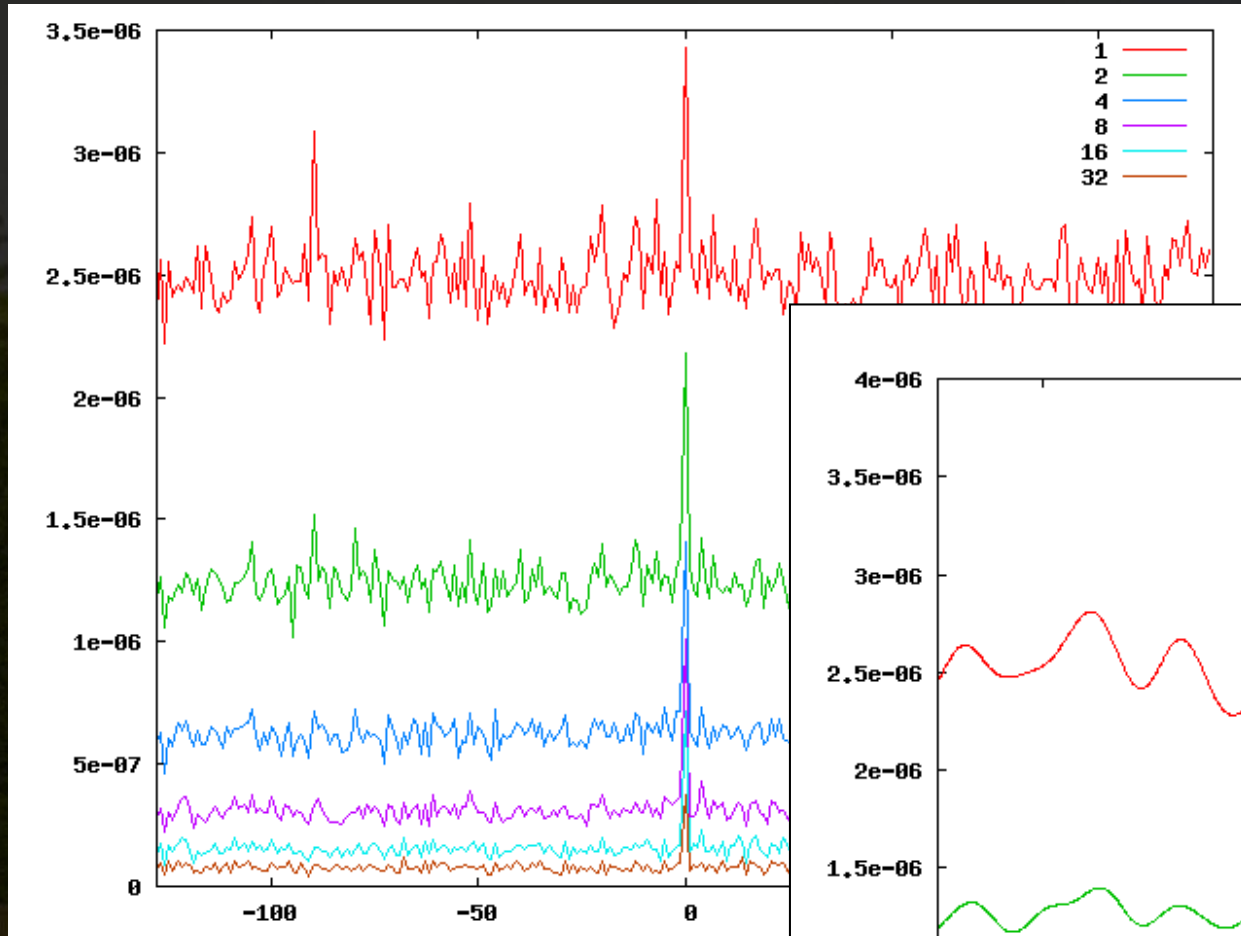
$$\tau = \tau_0 \left(\frac{\nu_0}{\nu} \right)^2$$

Fringe-fitting for LOFAR

- either for single subbands ($BW \sim 200$ kHz, $\Delta\tau \propto 5 \mu\text{sec}$)
- or coherent multi-band ($BW \sim 48$ MHz, $\Delta\tau \propto 0.02 \mu\text{sec}$)
- beware of multiple peaks in delay/rate
- produce 2-d delay/rate spectra
- simultaneously 'fit' for four parameters
- dispersive/nondispersive delays/rates

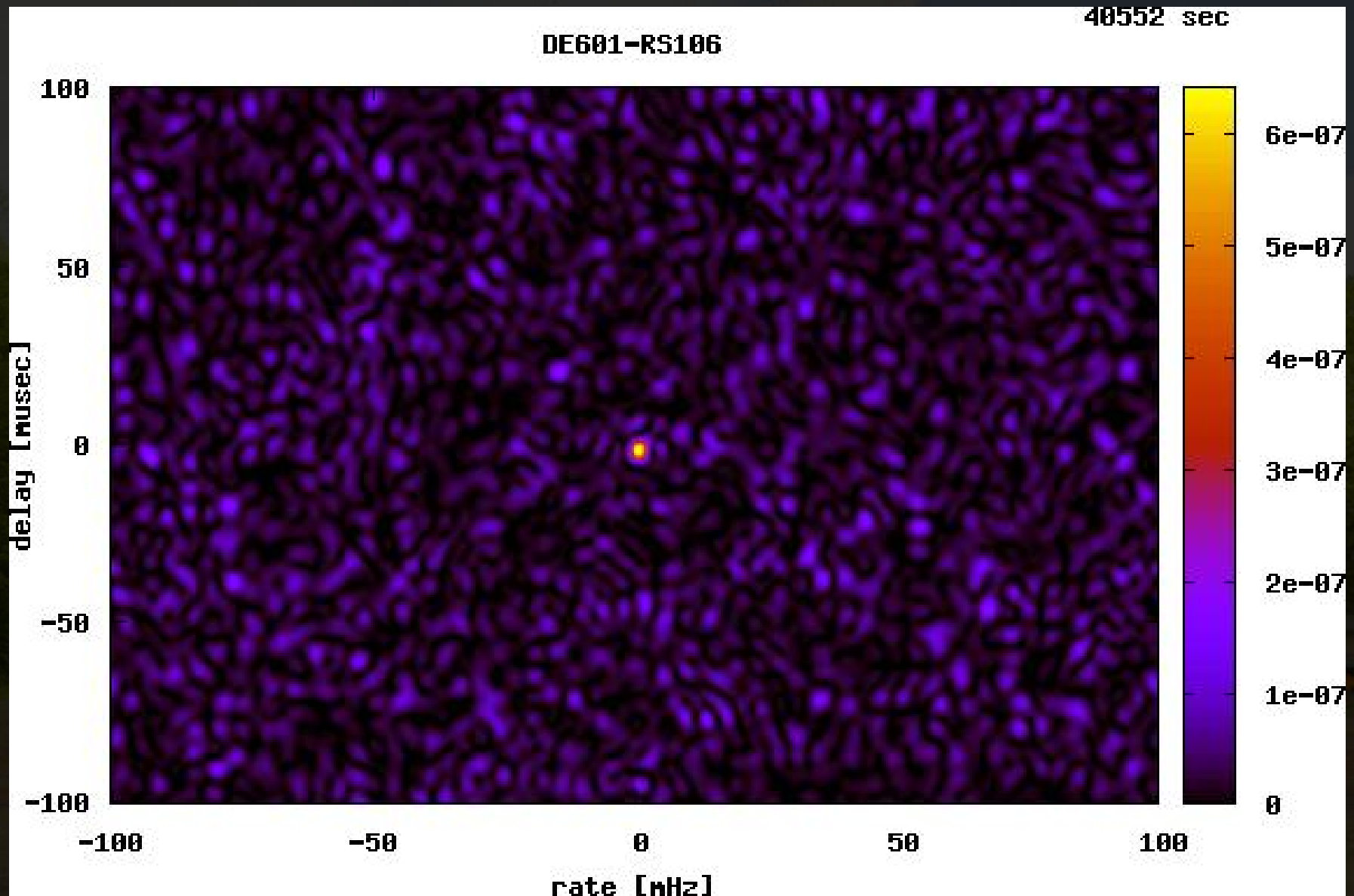
Very first long baseline fringes (NL-Ef, Aug 2009)

3C196, one subband, LBA

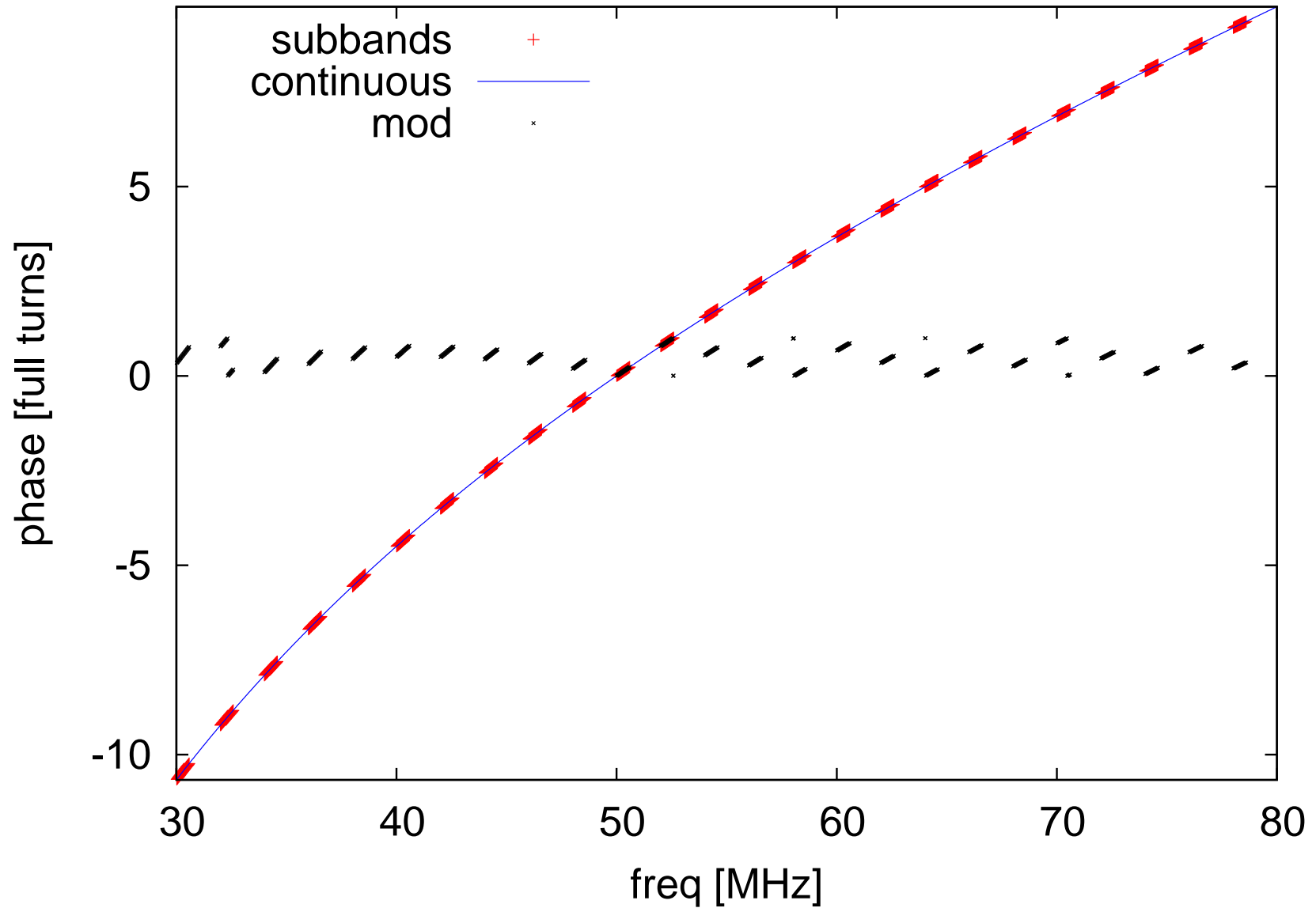


Coherently averaged over time intervals, then FFTed in frequency, then incoherently averaged over 1 h.

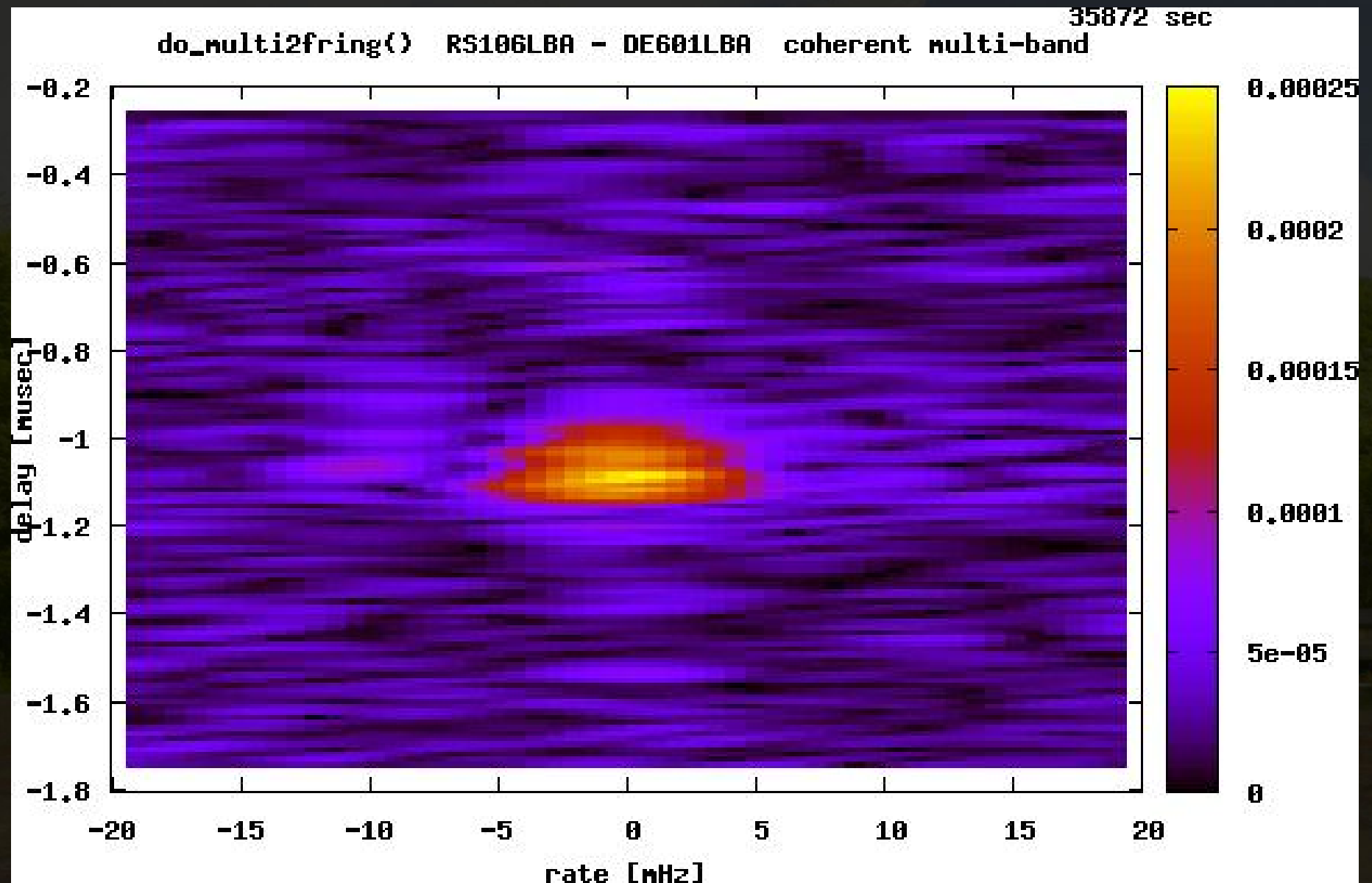
Fringes in delay/rate space (single subband)



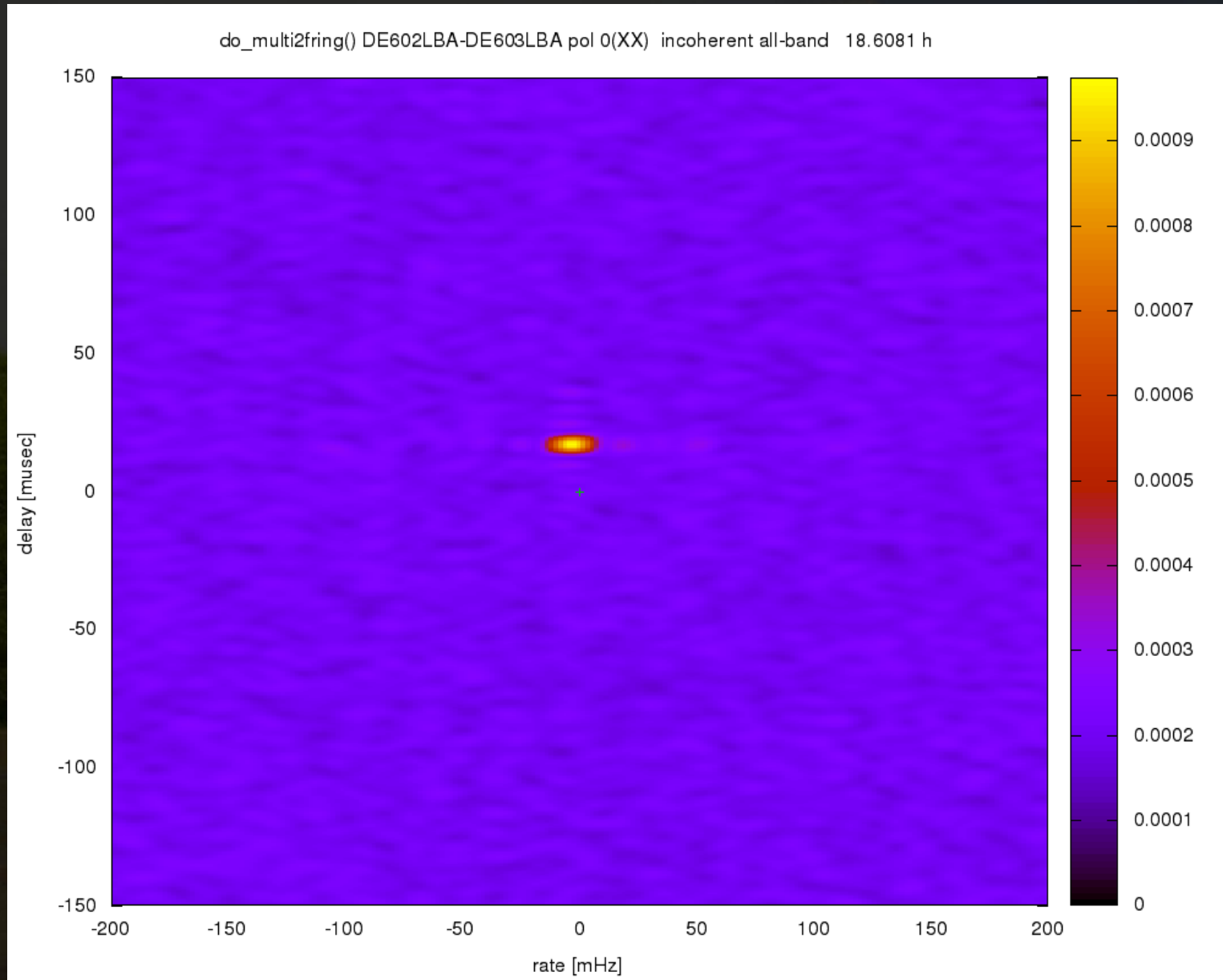
Delays and phases



Multi-band: more sensitivity and higher resolution delay



Fringes to Tautenburg and Unterweilenbach (Jan 2010)



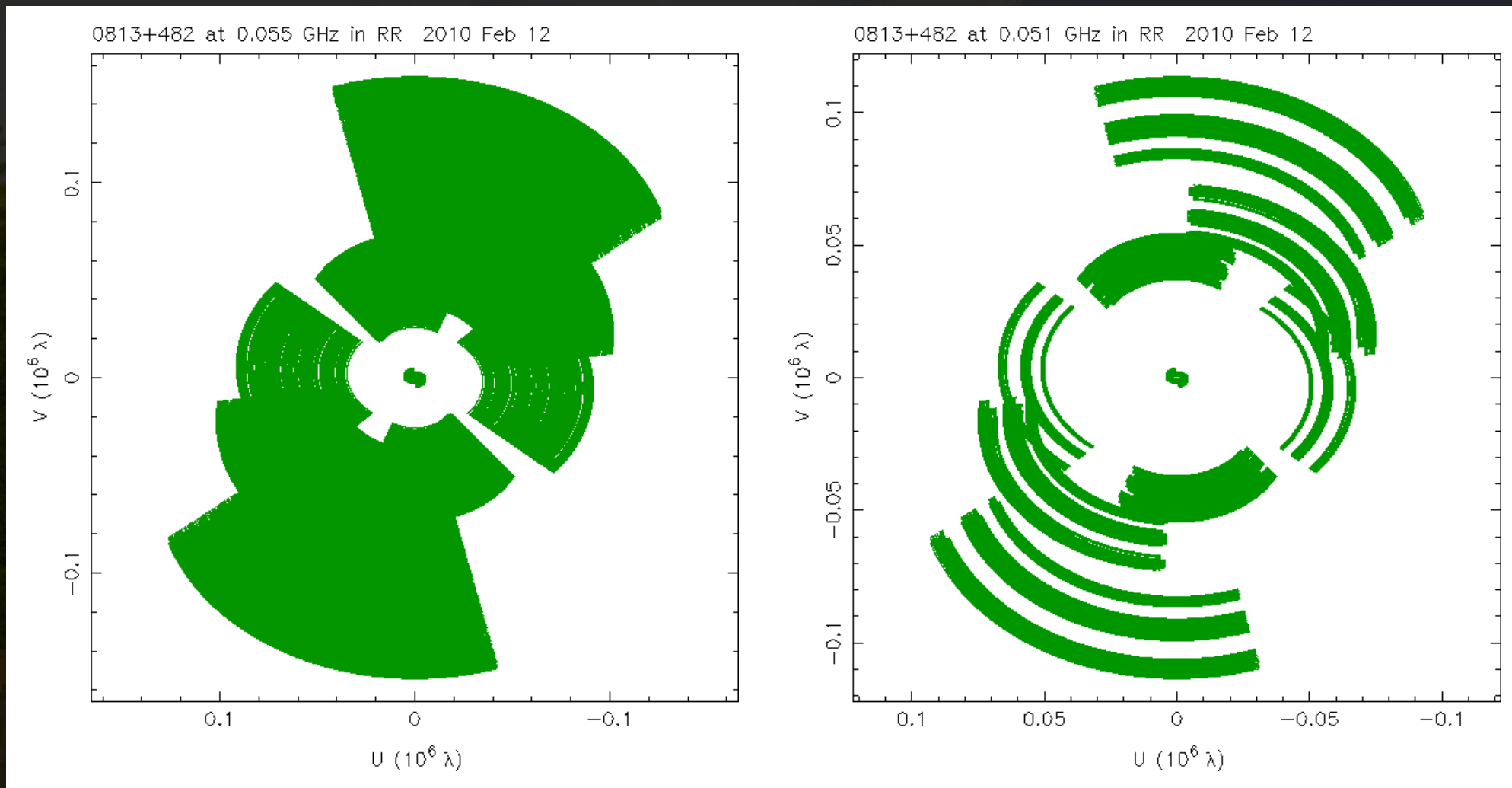
'Results' of fringe analysis

- long baseline fringes found
- clock offsets in some stations ✓
- confusion in LBA polarisation labels ✓
- strong 8 MHz ripple ✓
- 63 MHz LBA resonance
- strong differential Faraday rotation ✓
- time for imaging!

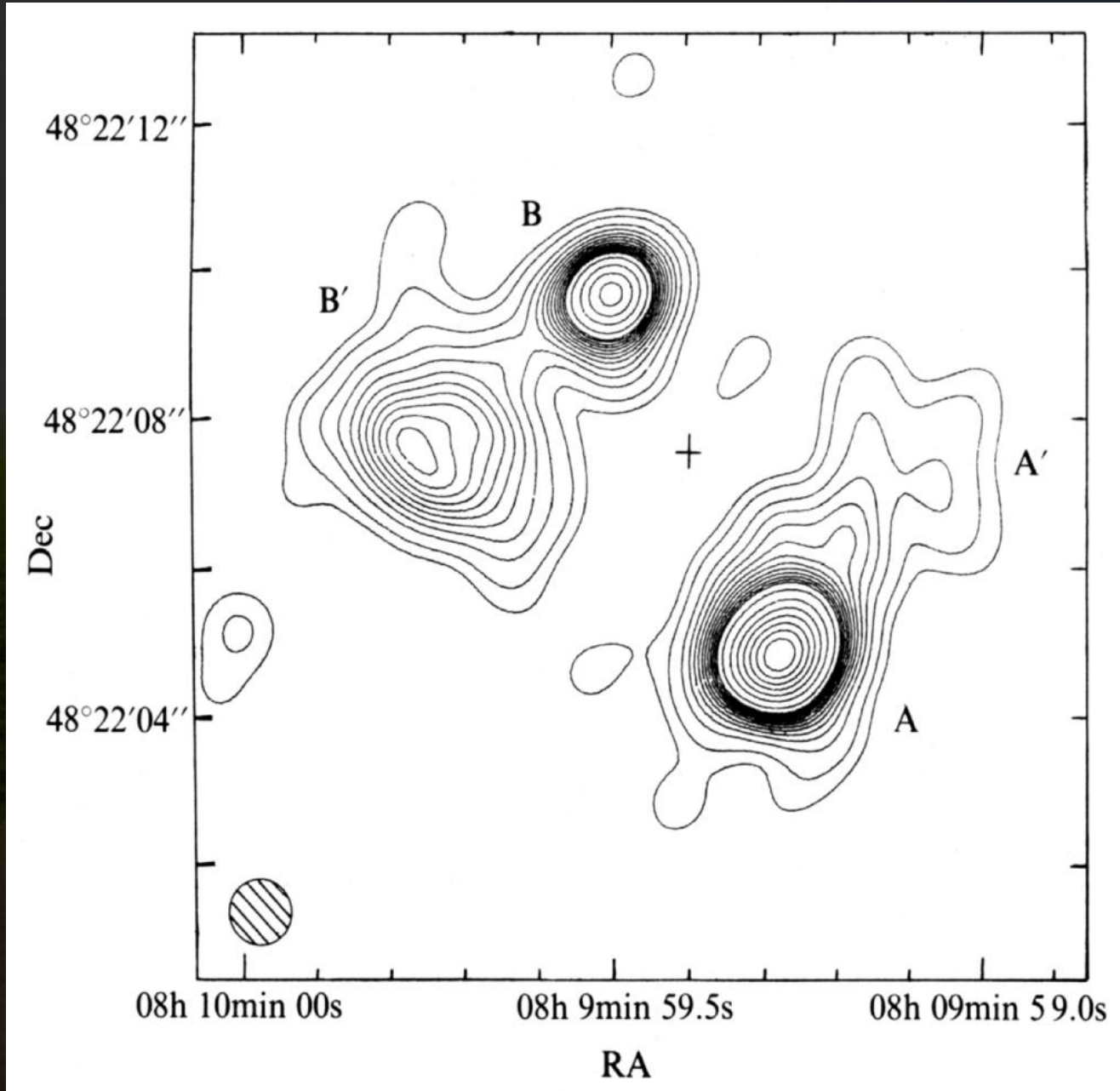
LBA long-baseline map: some details

- 3C196, LBA, 31 / 160 subbands, 44–59 / 30–80 MHz (ripple!)
- bandwidth 6 MHz / 48 MHz
- D2010_16704 6 h on 12/13 Feb 2010
- 5 NL + 3 DE stations (Effelsberg, Unterweilenbach, Tautenburg)
- corrected for 1 μ sec and 17 μ sec constant delays
- RR and LL from XX/XY/YX/YY using geometric model
- (self-)calibrated and imaged LL/RR in difmap
- MFS with/without spectral index correction

UV coverage with long and short baselines



MTRLI (MERLIN) observations of 3C196 at 408 MHz

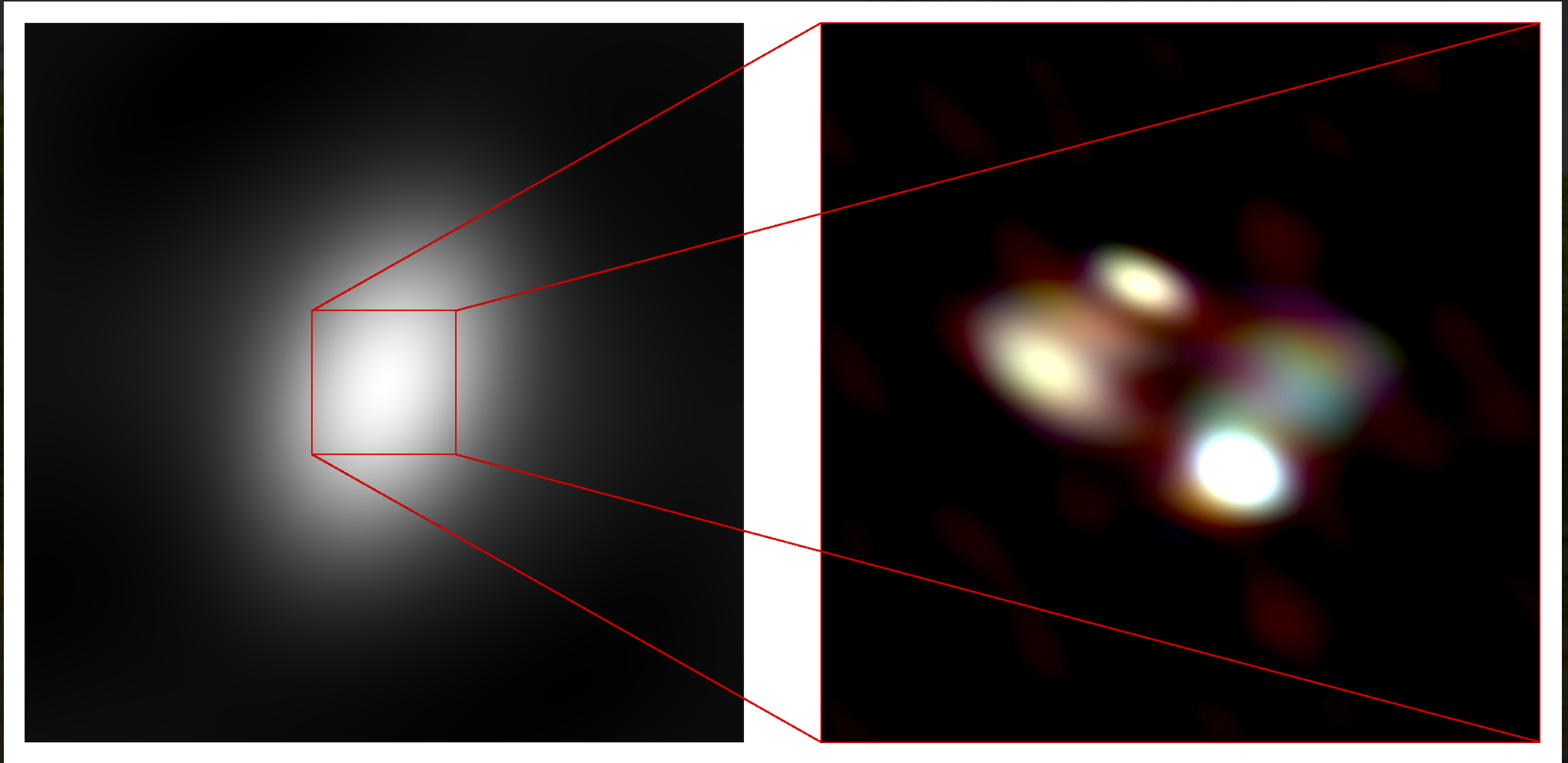


[Lonsdale & Morison (1980)]

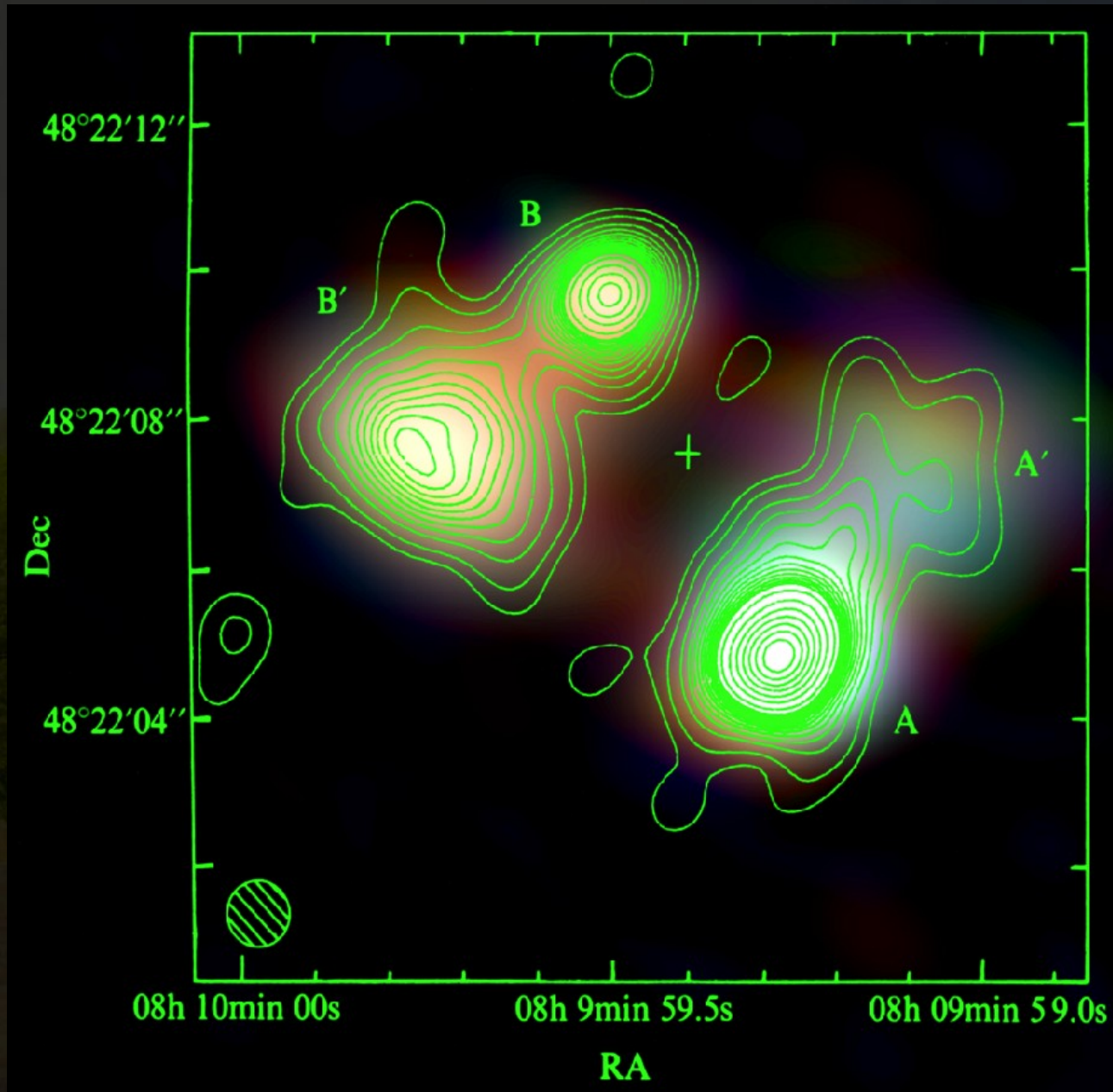
LOFAR maps of 3C196 (LBA: 30-80 MHz)

NL only, $35'' \times 22''$ beam

NL+DE, $1''.5 \times 0''.9$ beam



LOFAR LBA vs. MERLIN 408 MHz

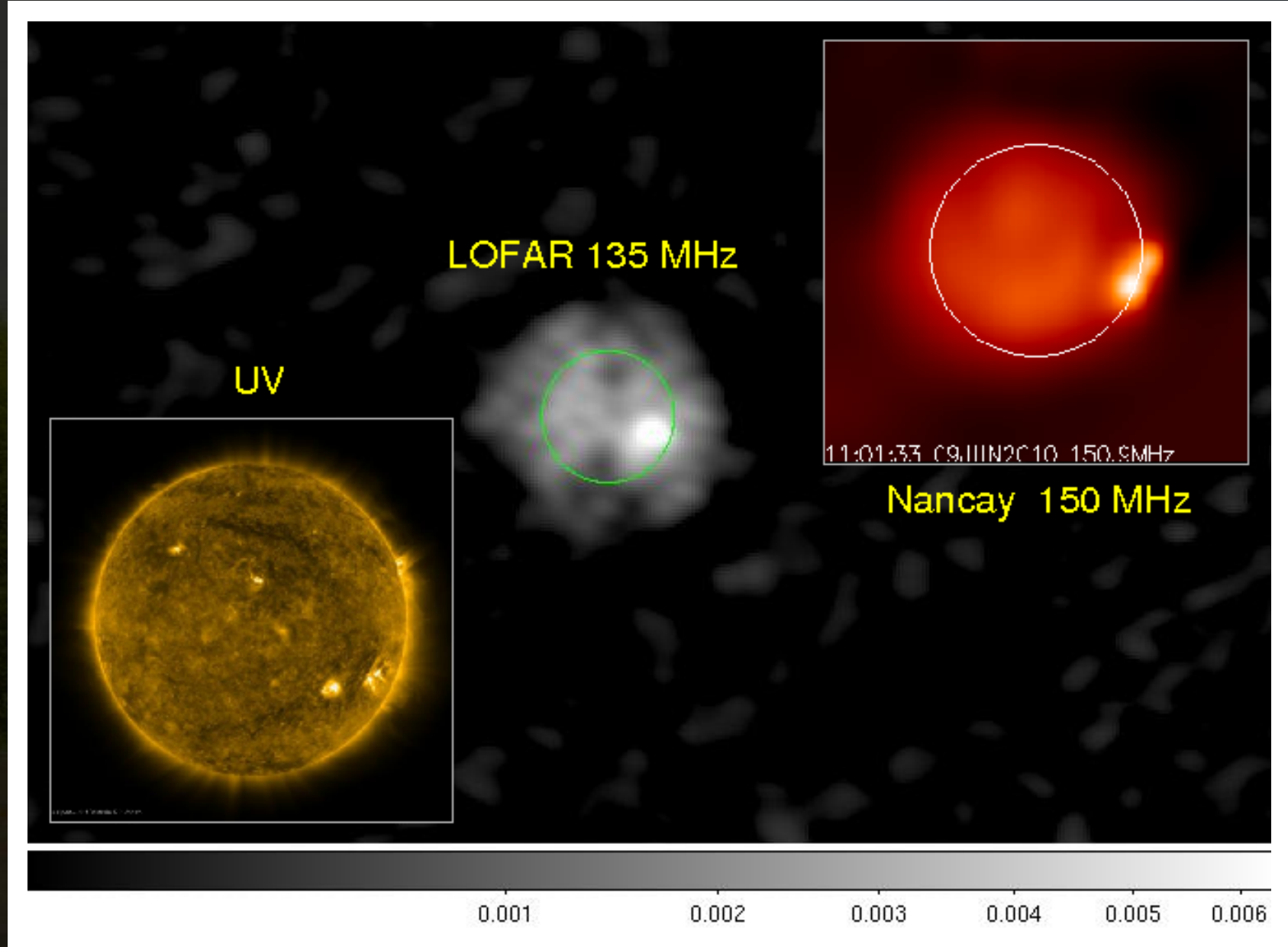


[Wucknitz + Lonsdale & Morison (1980)]

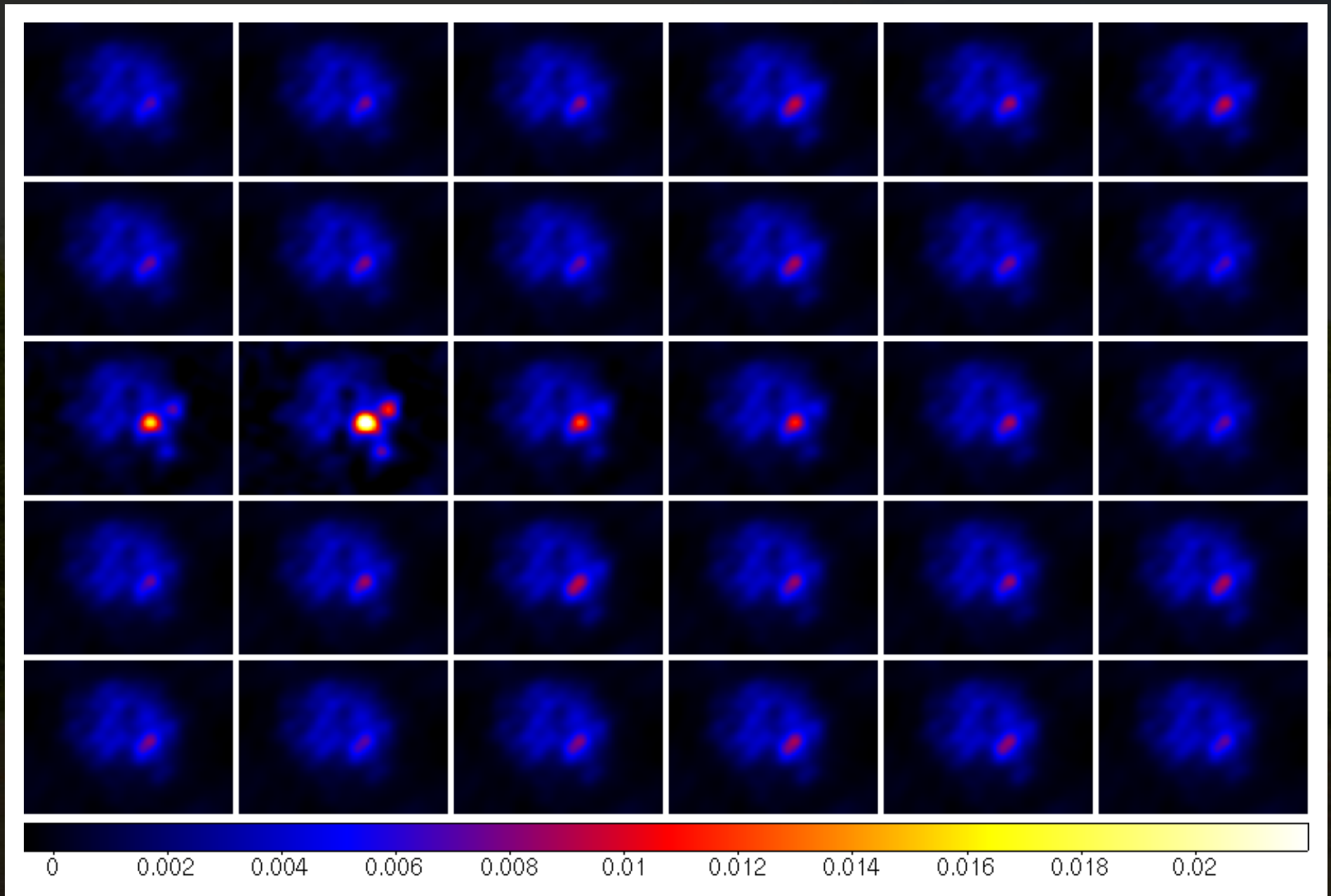
First interferometric Solar observations

- initiated by J. Anderson, F. Breitling, G. Mann, A. Polatidis, C. Vocks, O. Wucknitz (alphabetical order)
- 8 ten-minute scans on 9th June 2010, 9:48 – 15:50 UT
- 4 with LBA and HBA each
- phase/pointing centre near Sun and calibrator sources
- LBA
 - ★ difficult, other sources dominating: 3C123, CygA, CasA, . . .
 - ★ situation unclear
- HBA
 - ★ much clearer signal, Sun dominating on short baselines
 - ★ self-calibration possible because of compact component
- **only short baselines used!**

The very first map



Variability: 30 sec in 1 sec steps (8 subbands)



Summary

- long baseline LOFAR works!
- but no pipeline yet
- fringe analysis revealed a number of technical problems (mostly solved now)
- Sun can be observed and resolved with LOFAR!
- to do
 - ★ full fringe-fitting and calibration
 - ★ not independent of polarisation calibration (differential Faraday rotation)
 - ★ Sun as function of time *and frequency*

Additional material

- International LOFAR stations
- Multi-band delay fitting (details)
- Delay/rate map of 3C196
- Expectations: 3C196 at 5 GHz
- Very first LBA long-baseline imaging attempts
- First HBA long-baseline imaging attempt
- Dynamic spectra of the Sun
- 10 min movie of the Sun


The International LOFAR Telescope (ILT)

CS007 [\[Hide\]](#)
CS021 [\[Hide\]](#)
CS024 [\[Hide\]](#)
CS030 [\[Hide\]](#)
CS032 [\[Hide\]](#)
CS101 [\[Hide\]](#)
CS201 [\[Hide\]](#)
CS301 [\[Hide\]](#)
CS401 [\[Hide\]](#)
CS501 [\[Hide\]](#)

"In progress" stations (significant construction, but not validated):
[\[Show all\]](#) / [\[Hide all\]](#)
DE602 [\[Hide\]](#)
DE604 [\[Hide\]](#)
FR606 [\[Hide\]](#)
UK608 [\[Hide\]](#)
RS406 [\[Hide\]](#)
RS508 [\[Hide\]](#)
RS509 [\[Hide\]](#)
CS011 [\[Hide\]](#)
CS013 [\[Hide\]](#)
CS017 [\[Hide\]](#)
CS026 [\[Hide\]](#)
CS028 [\[Hide\]](#)
CS031 [\[Hide\]](#)

Future stations (not mapped):
DE605
SE607
RS104
RS210
RS310
RS404
RS407
RS409
RS410

See latest LOFAR status meeting for detailed info on the buildup of the stations.



The map displays the International LOFAR Telescope (ILT) station locations across Europe. The stations are marked with green pins. The map includes labels for various cities and countries, and several green pins indicating station locations. A sidebar on the left lists station IDs and their status.

<http://www.astron.nl/~heald/lofarStatusMap.html>

Delay fitting

- do not fit phases directly
 - ★ only know phase modulo 2π
 - ★ data are noisy
- equivalent (but better!): maximise the corrected signal
- measured and original visibility $V(\mathbf{v}) = e^{2\pi i \mathbf{v} \tau(\mathbf{v})} V_0(\mathbf{v})$
- hope that $V_0(\mathbf{v}) = \text{const}$ and correct for delay

- find maximum of

$$\left| \int d\mathbf{v} e^{-2\pi i \mathbf{v} \tau(\mathbf{v})} V(\mathbf{v}) \right|^2$$

- this is Fourier transform if $\tau = \text{const}$

Multi-band delay fitting

- delay almost constant within subbands
- apply FFT for all subbands
- combine the results incoherently

- combine the results coherently

- $f_i(\tau_i) = \int d\nu e^{-2\pi i(\nu - \nu_i)\tau_i} V(\nu)$ with coarse FFT

- $F[\tau] = \sum_i e^{-2\pi i\nu_i\tau(\nu_i)} f_i(\tau(\nu_i))$ on fine grid, interpolation

- τ arbitrary function of frequency (non-/dispersive)

Include fringe rates

- have to integrate in time to increase S/N
- take into account rates (time-derivatives)
- do not use phase rates but delay rates

- $r = \frac{\partial \tau}{\partial t}$ dispersive/non-dispersive

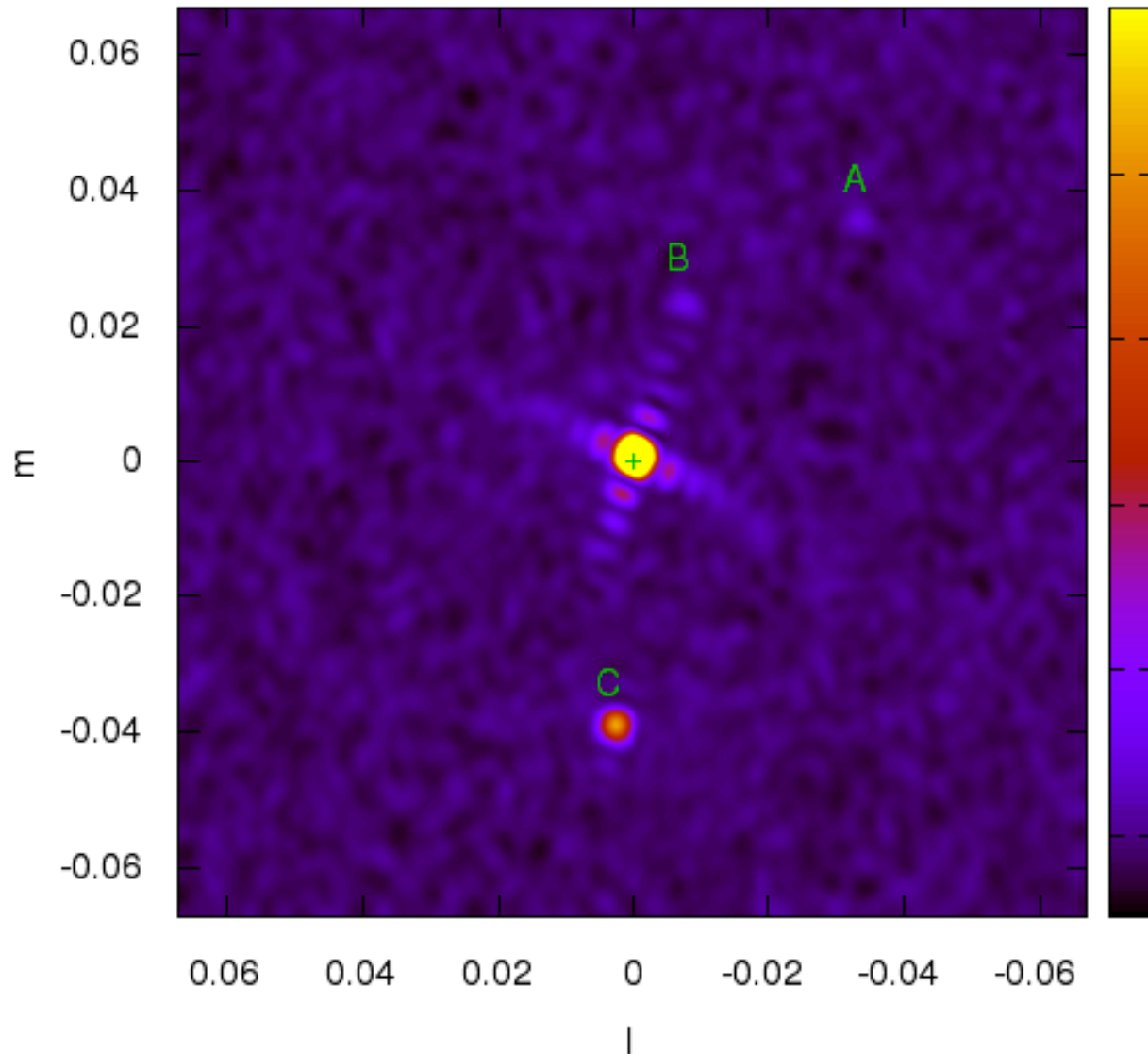
- $f_i(\tau_i, r_i) = \int_i d\mathbf{v} e^{-2\pi i(\mathbf{v}-\mathbf{v}_i)\tau_i} \int dt e^{-2\pi i(t-t_0)r_i} V(\mathbf{v}, t)$

- $F[\tau, r] = \sum_i e^{-2\pi i\mathbf{v}_i\tau(\mathbf{v}_i)} f_i(\tau(\mathbf{v}_i), r(\mathbf{v}_i))$

- all phase rates are frequency-dependent

Delay/rate map of field around 3C196

DE601LBA-DE602LBA pol 0(XX) incoherent multi-band



VLSS (74 MHz):

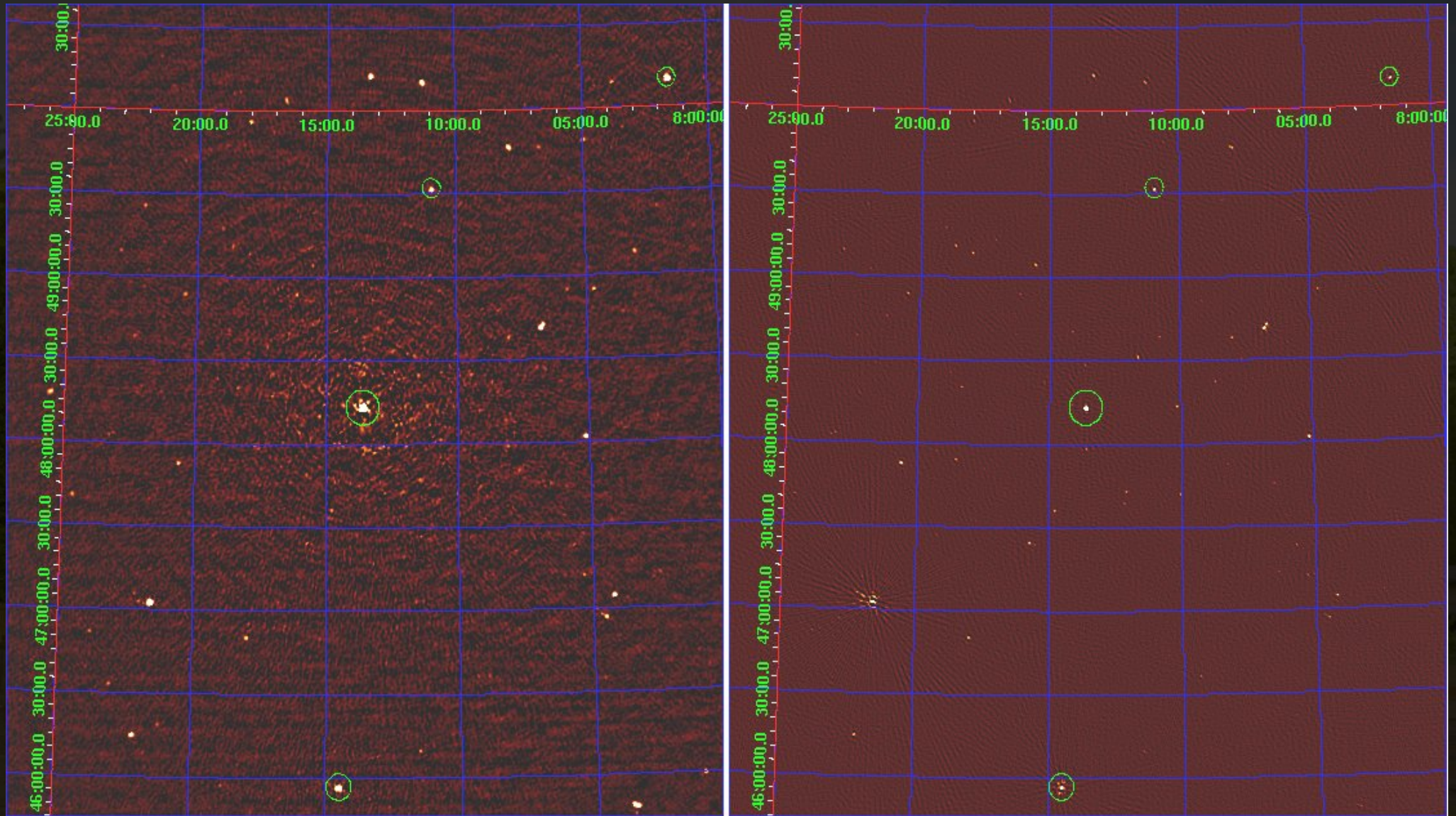
A 19 Jy

B 6 Jy

C 17 Jy

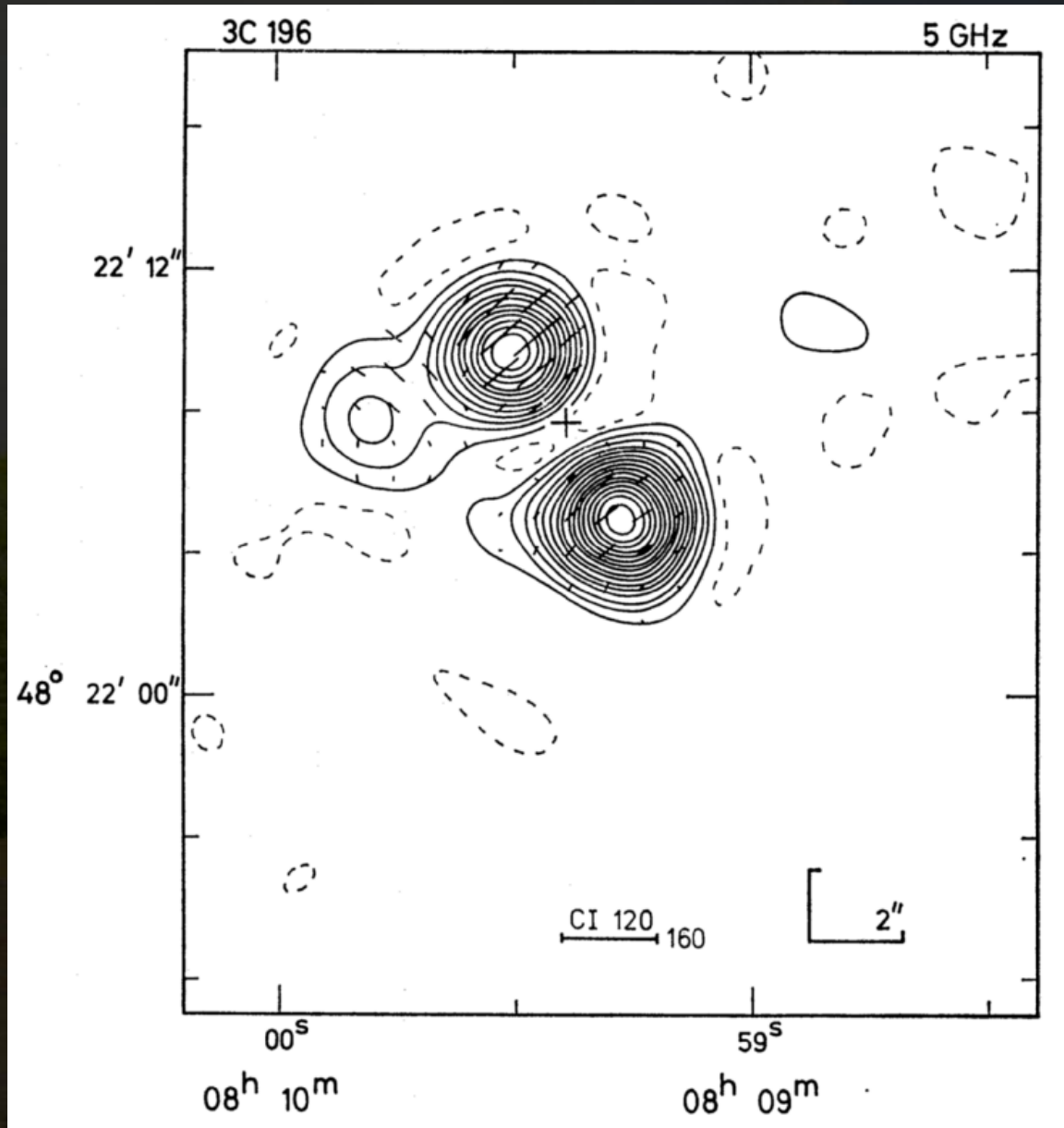
3C196 140 Jy

VLSS vs. LOFAR map of field around 3C196



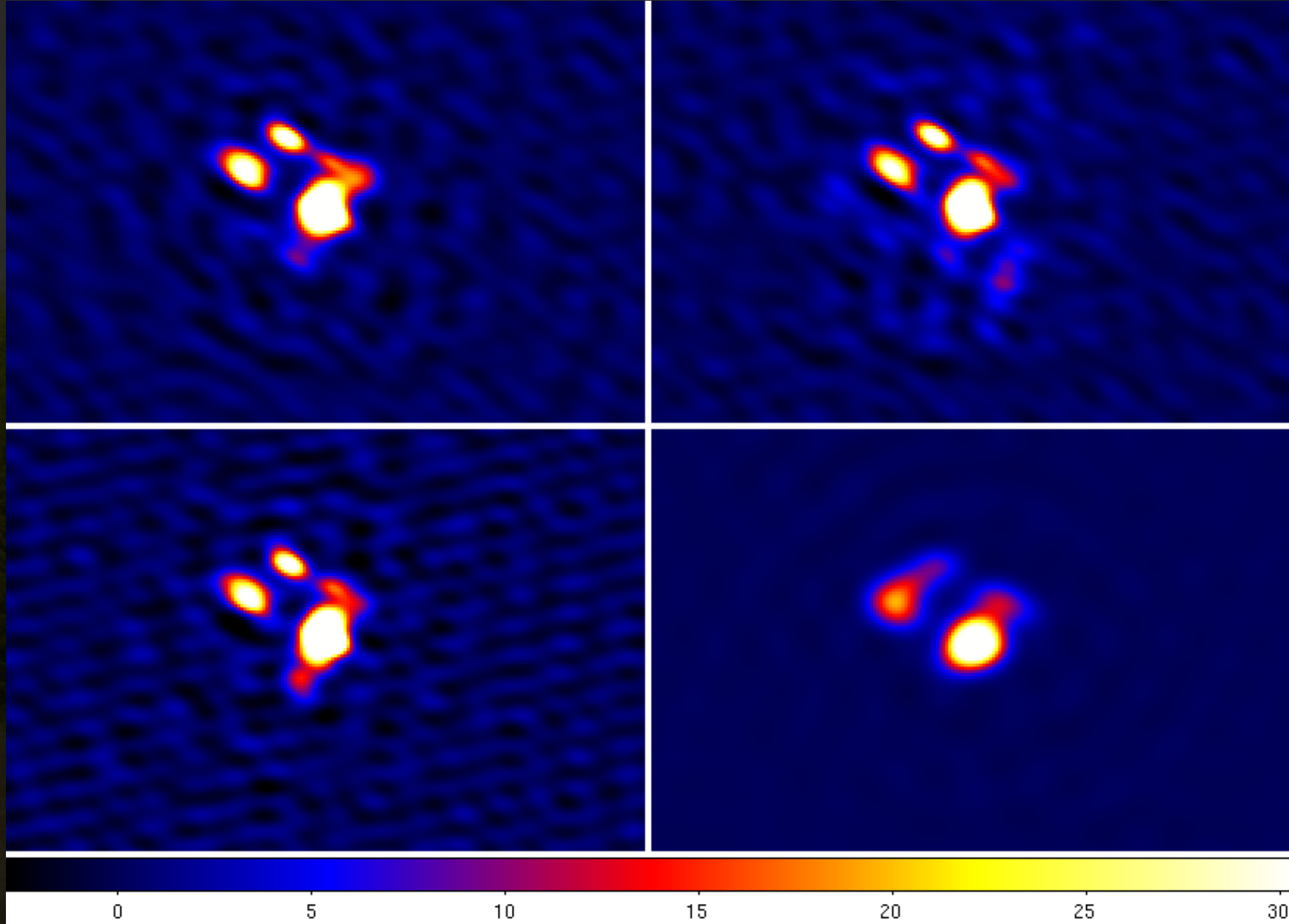
3C196 on long baselines: expectations

Cambridge 5km at 5 GHz



[Pooley & Henbest (1974)]

First long baseline maps of 3C196

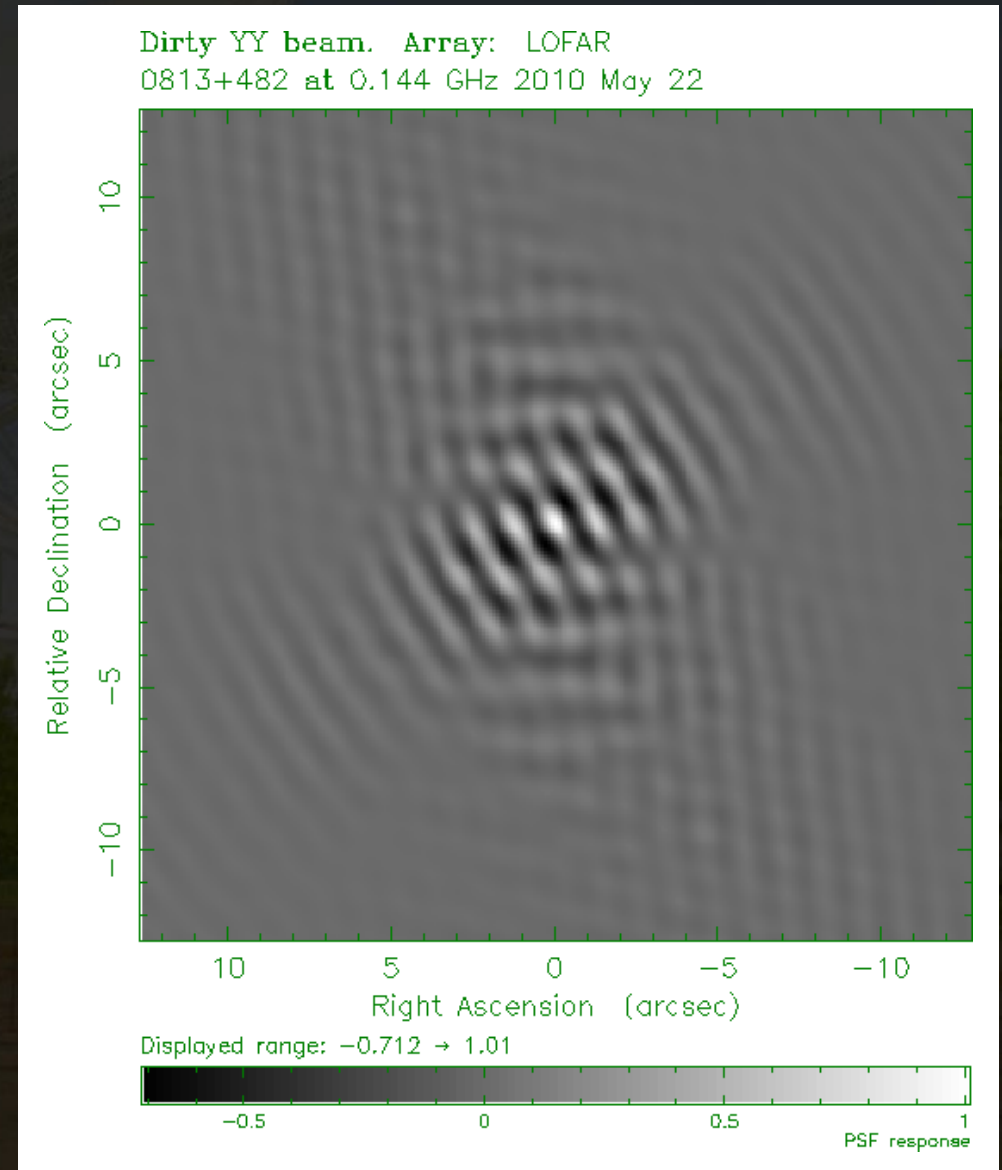
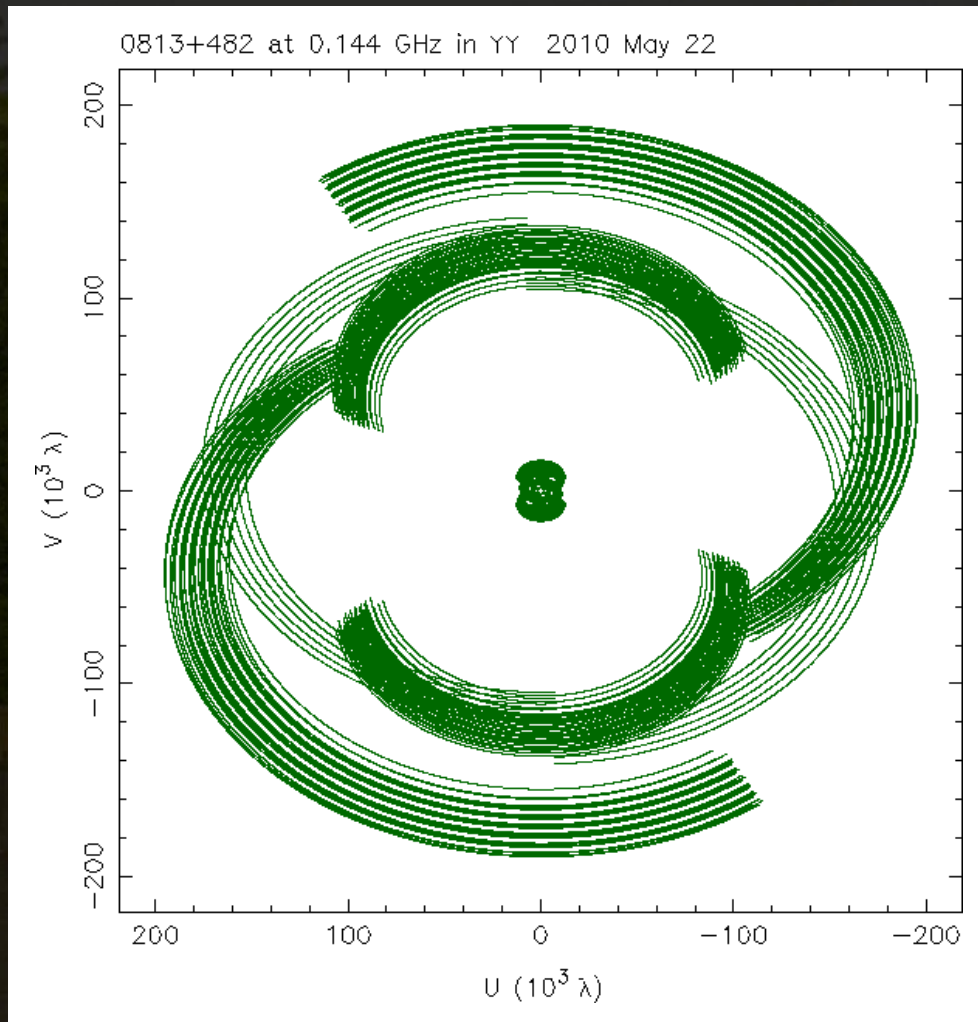


HBA observations of 3C196: some details

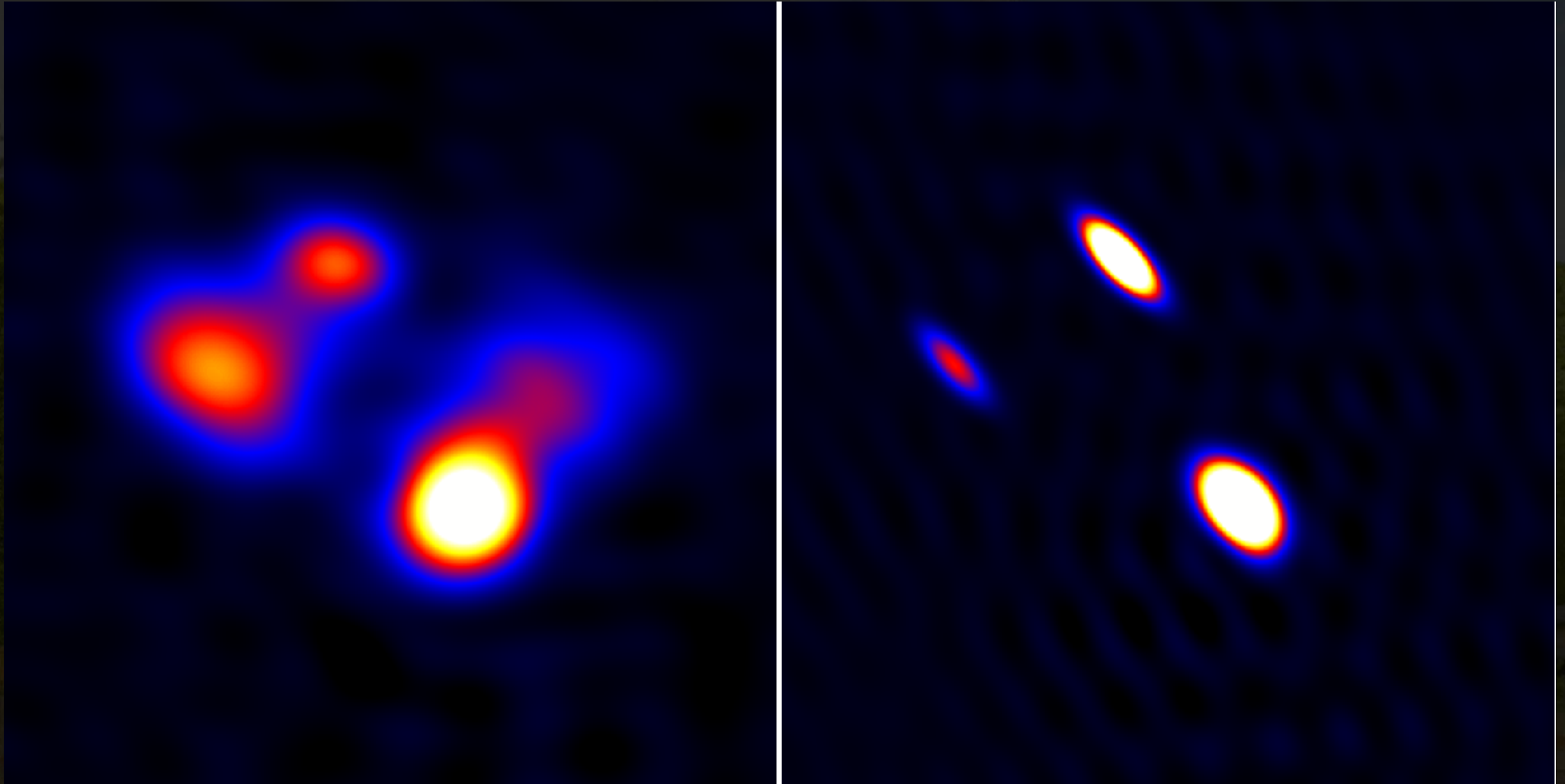
- 3C196, HBA, 120 / 244 subbands, 131–155 MHz
- bandwidth 24 MHz
- L2010_07608 12 h, 22nd May 2010
- 7 NL + 2 DE stations (Effelsberg, Tautenburg)
- corrected for 8 μ sec in superterp, . . .
- (self-)calibrated and imaged YY in difmap
- phase jumps, rates, inconsistent delays (in freq)
- low S/N in German stations most of the time
- imaging very tough, details not reliable yet

HBA observations: uv coverage, dirty beam

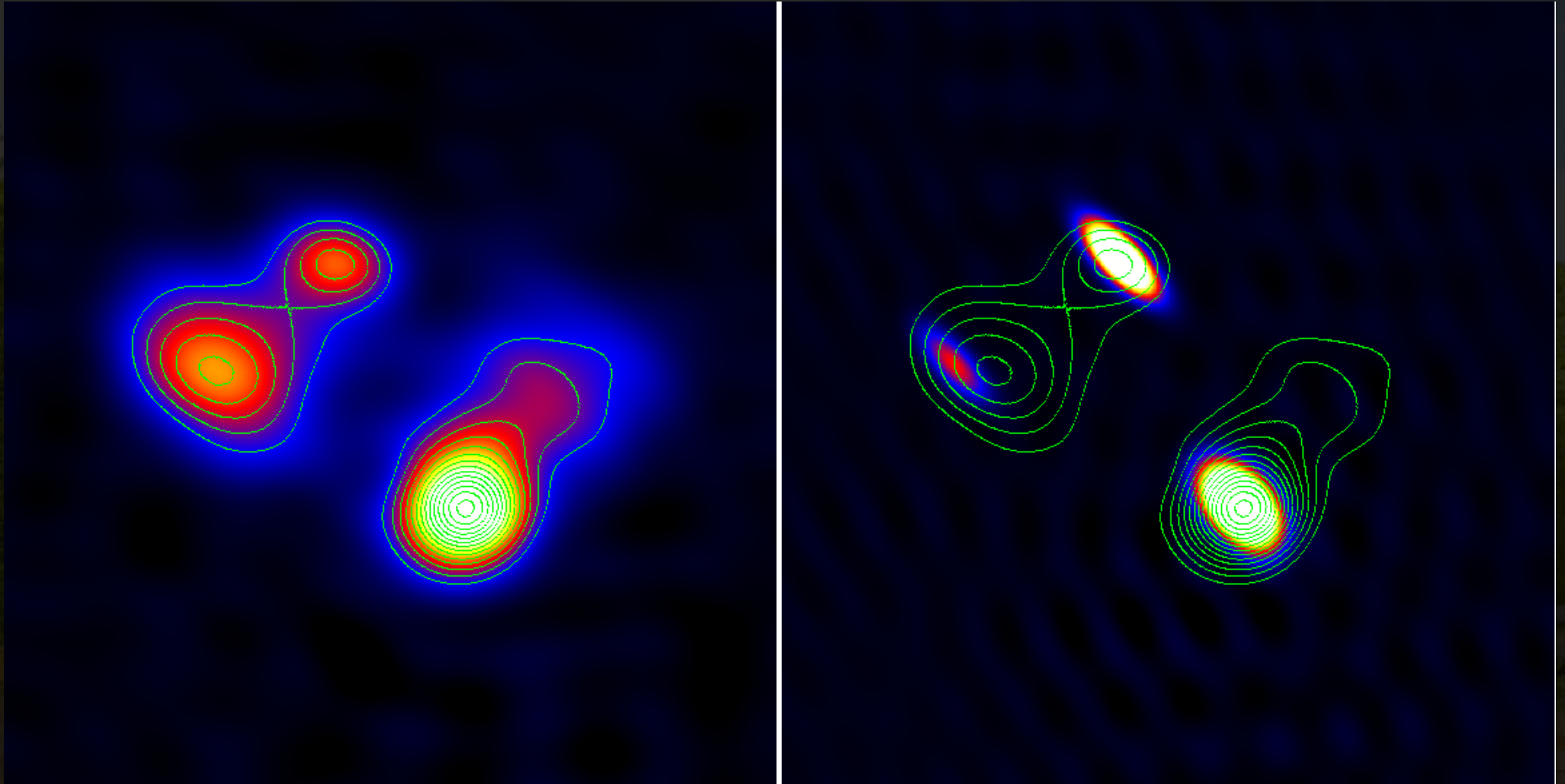
beam size $1''.0 \times 0''.5$



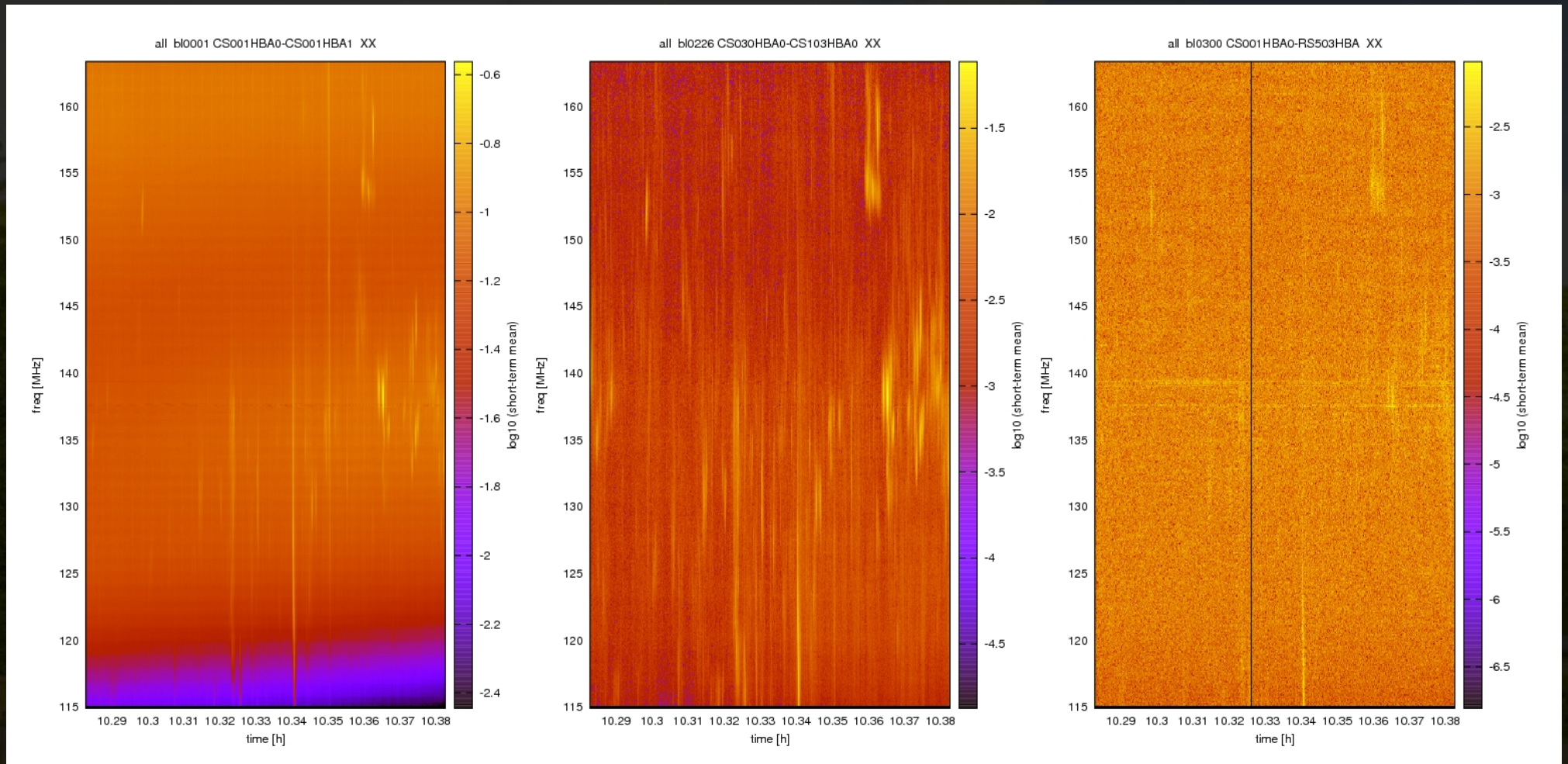
LBA + HBA images of 3C196



LBA + HBA images of 3C196 with contours

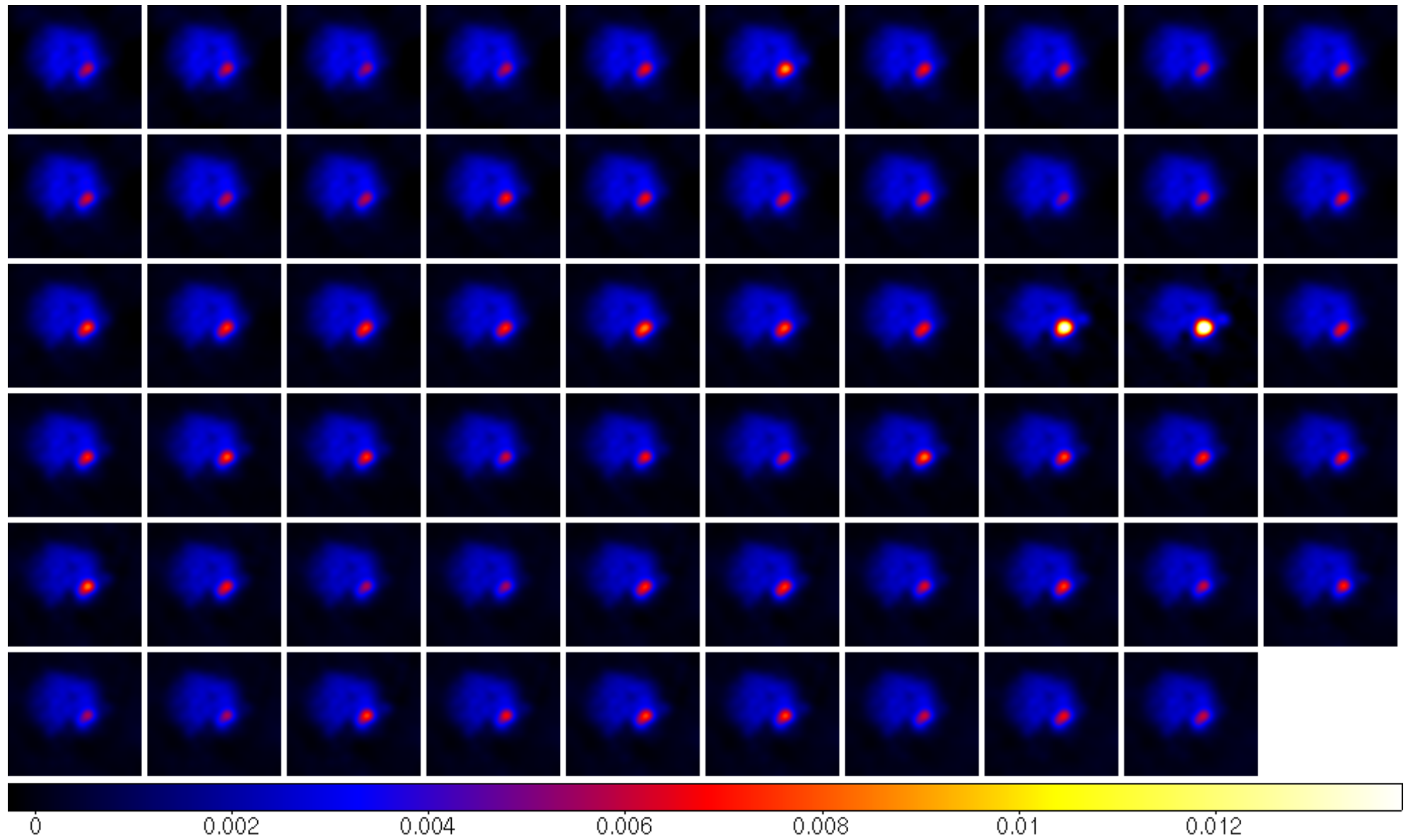


Dynamic spectra of the Sun



Significant variability as function of time and frequency!

Variability: 10 min in 10 sec steps (1 subband)



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