e-VLBI with LOFAR

Olaf Wucknitz

wucknitz@astro.uni-bonn.de

Argelander-Institut für Astronomie

EUROPEAN vlbi NETWORK

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

- **LO**w **F**requency **AR**ray
- low frequencies
  - ⋆ LBA: ∼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

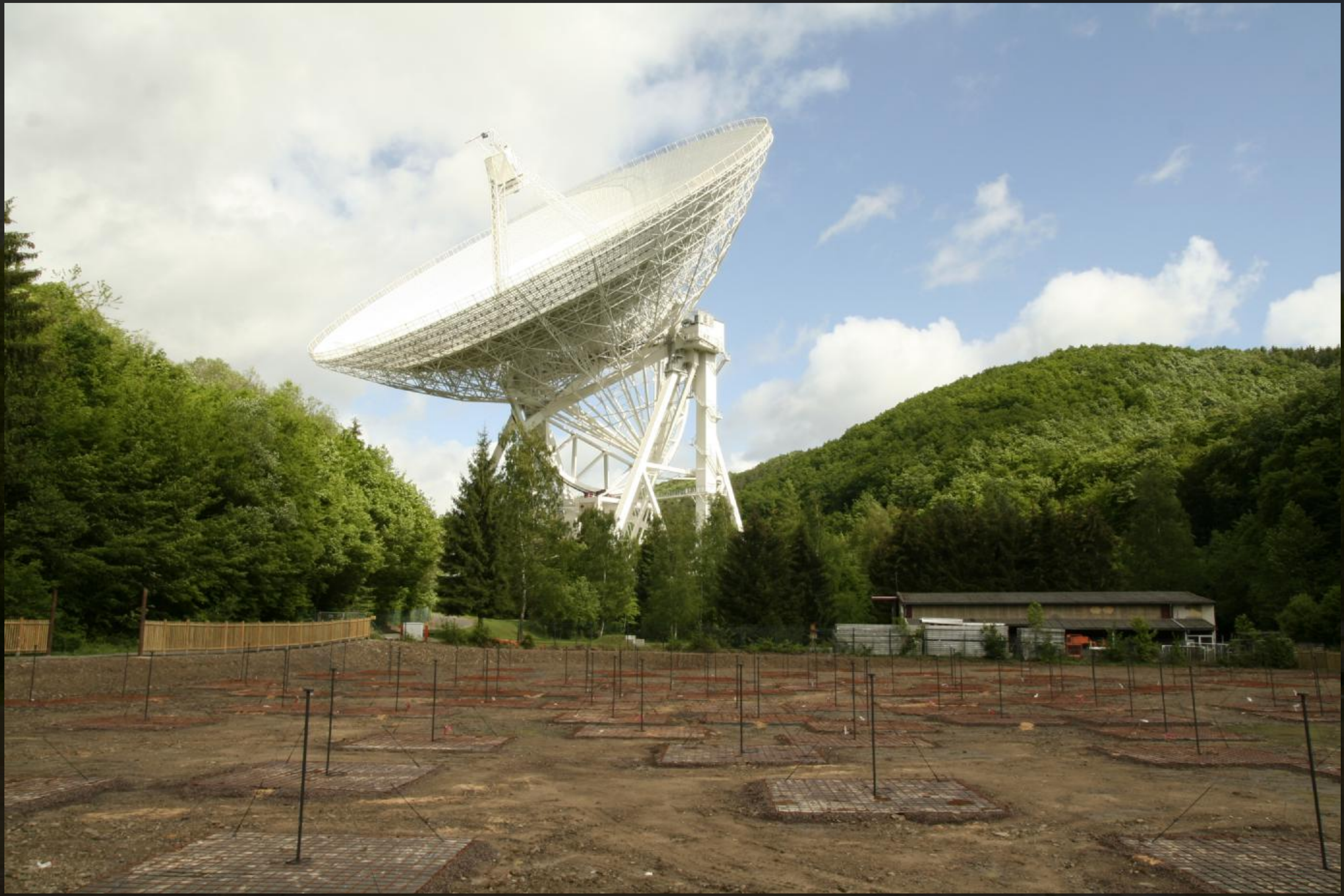
LOFAR resolution

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

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

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

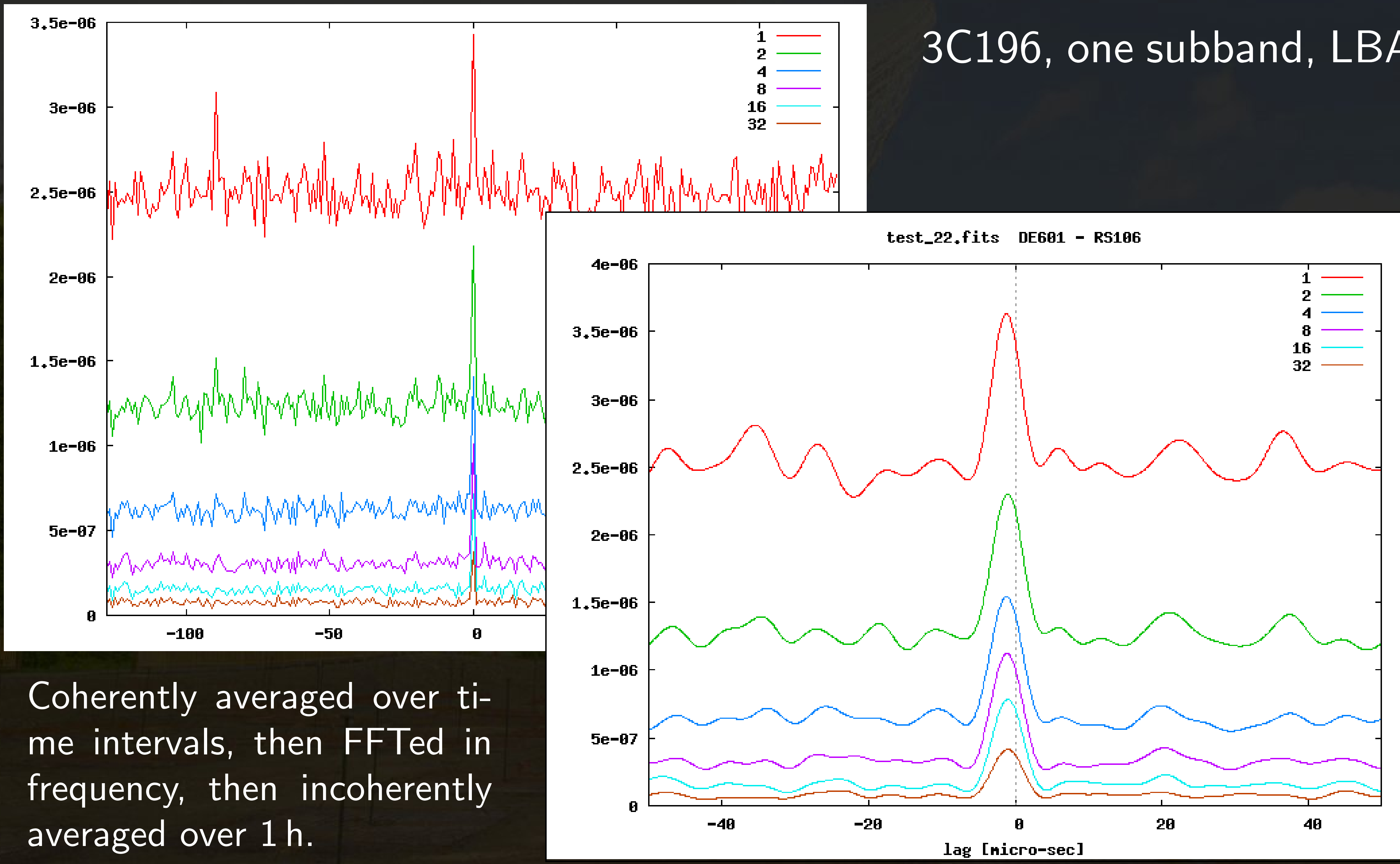
Fringe-fitting for LOFAR

- either for single subbands (BW∼200 kHz, $\Delta\tau \propto 5\,\mu$sec)
- or coherent multi-band (BW∼48 MHz, $\Delta\tau \propto 0.02\,\mu$sec)

- beware of multiple peaks in delay/rate
- produce 2-d delay/rate spectra

- simultaneously ‘fit’ for four parameters
- dispersive/nondispersive delays/rates

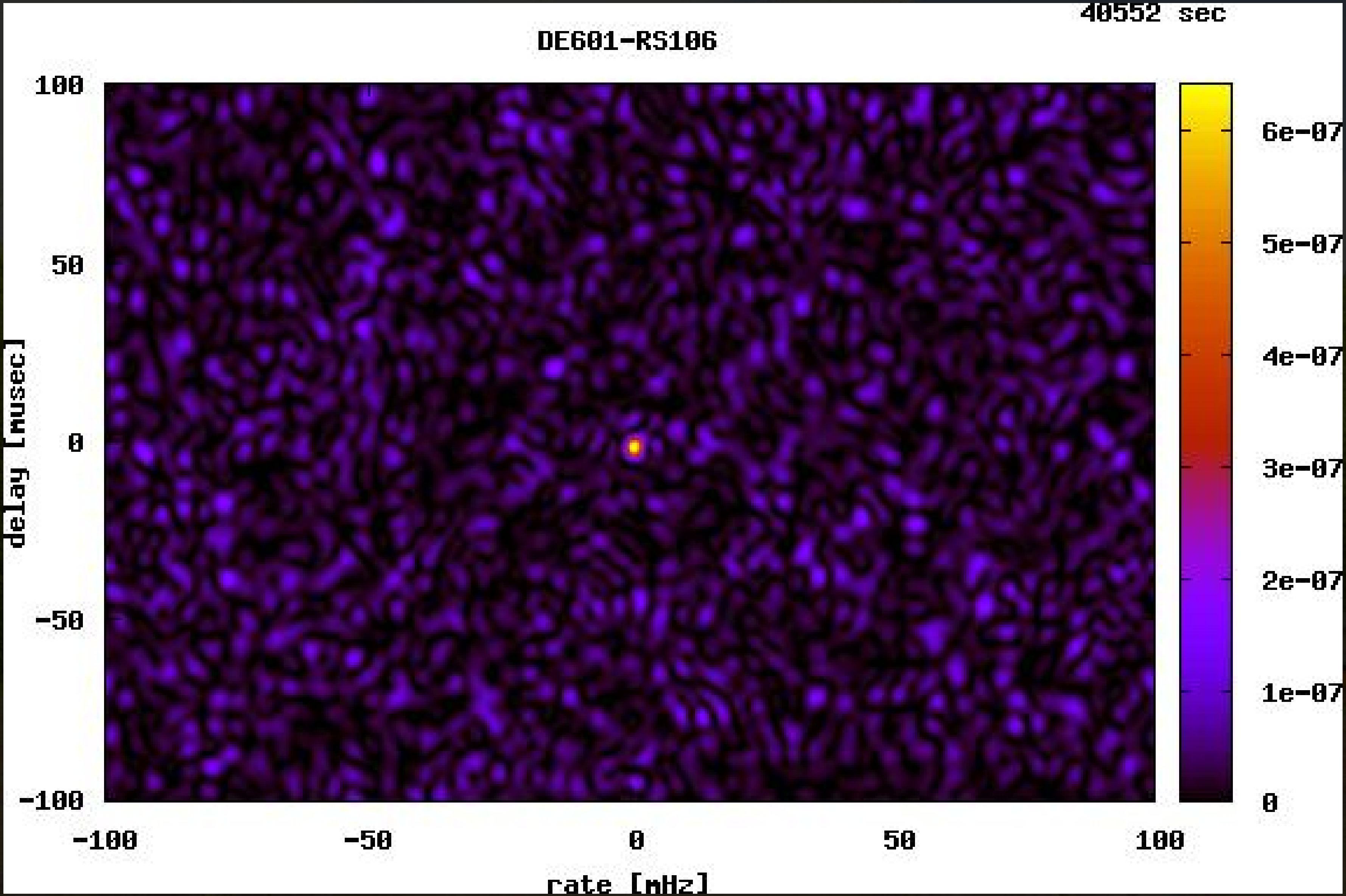
Very first long baseline fringes (NL-Ef, Aug 2009)



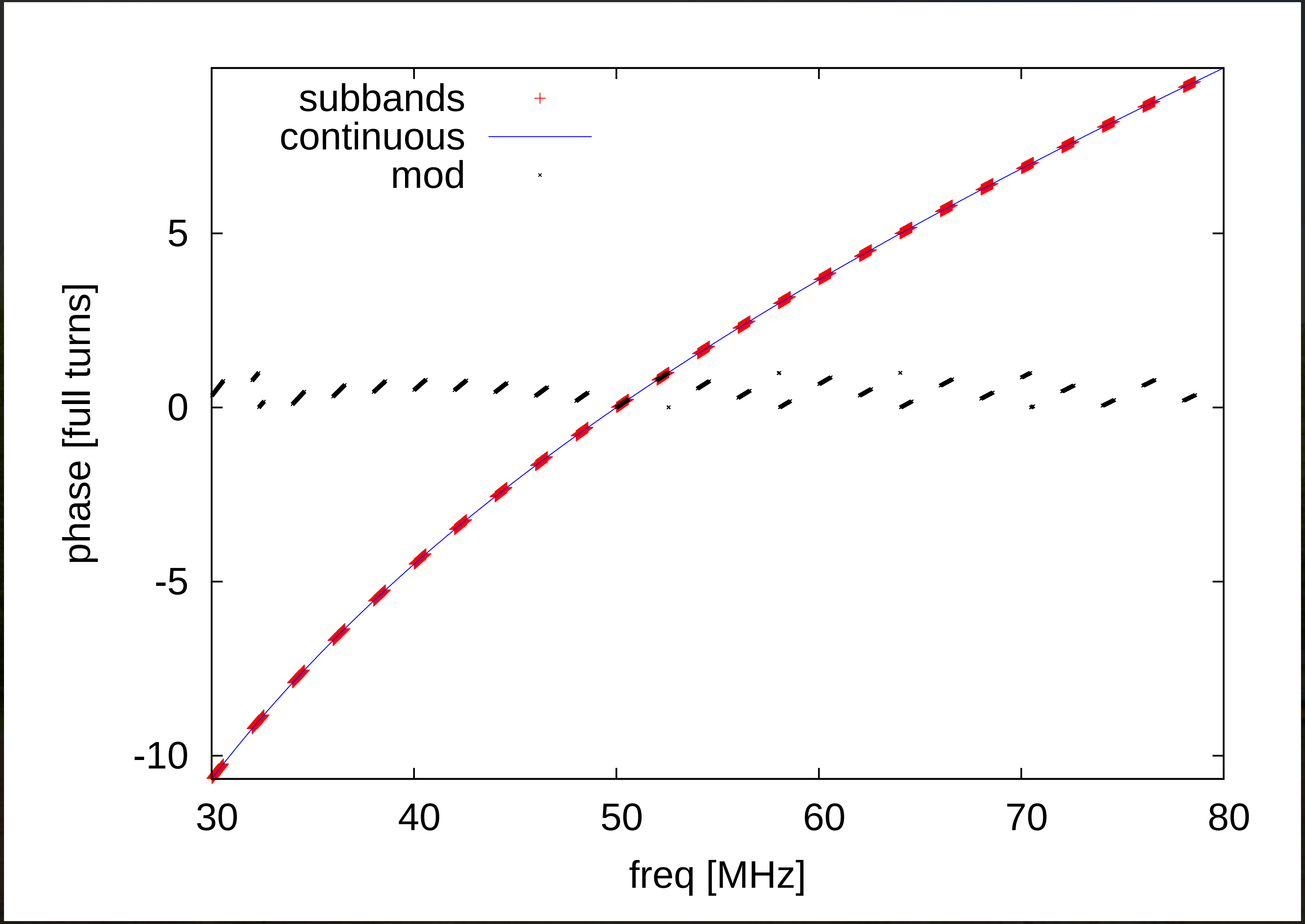
3C196, one subband, LBA

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

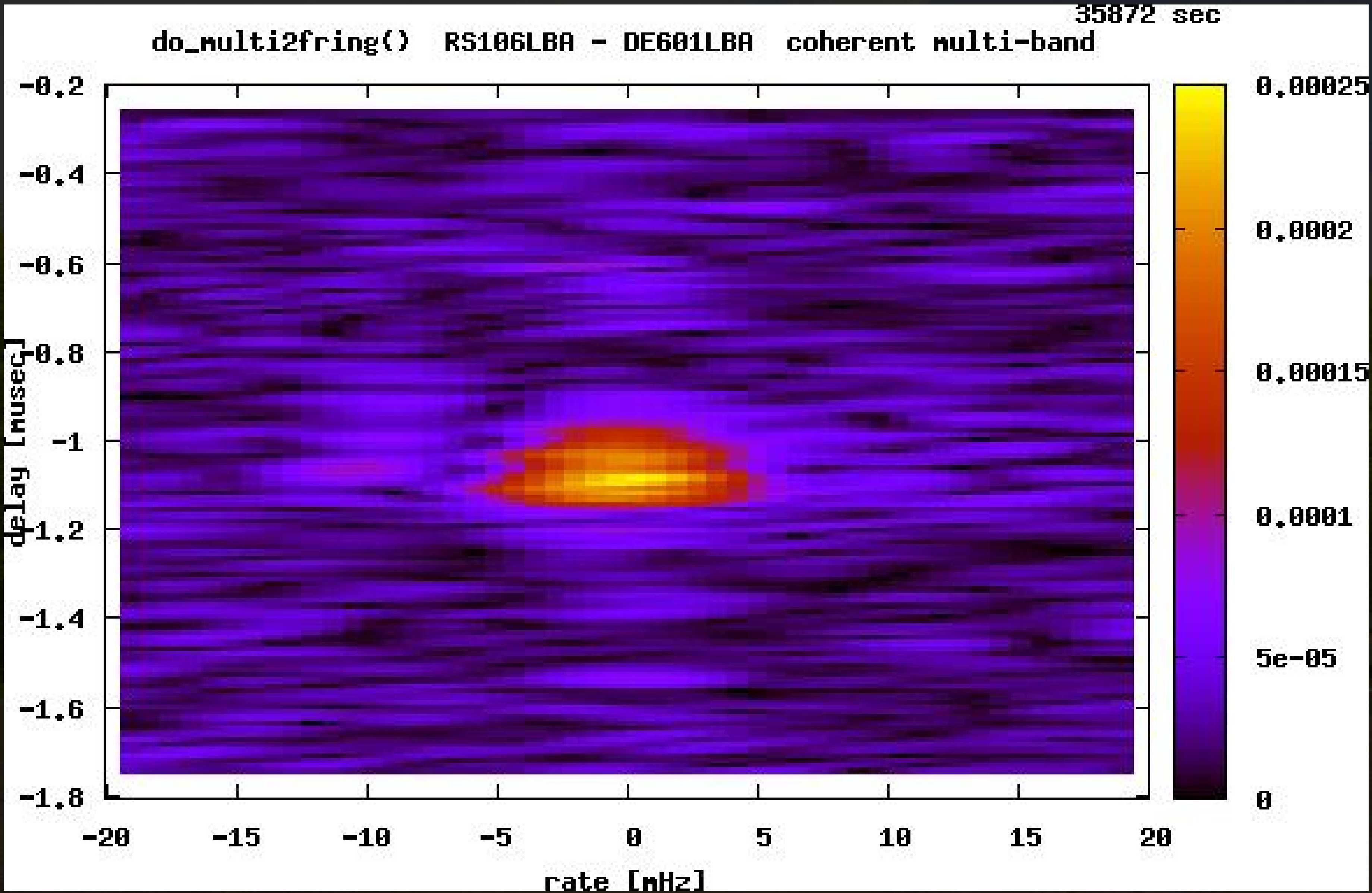
Fringes in delay/rate space (single subband)



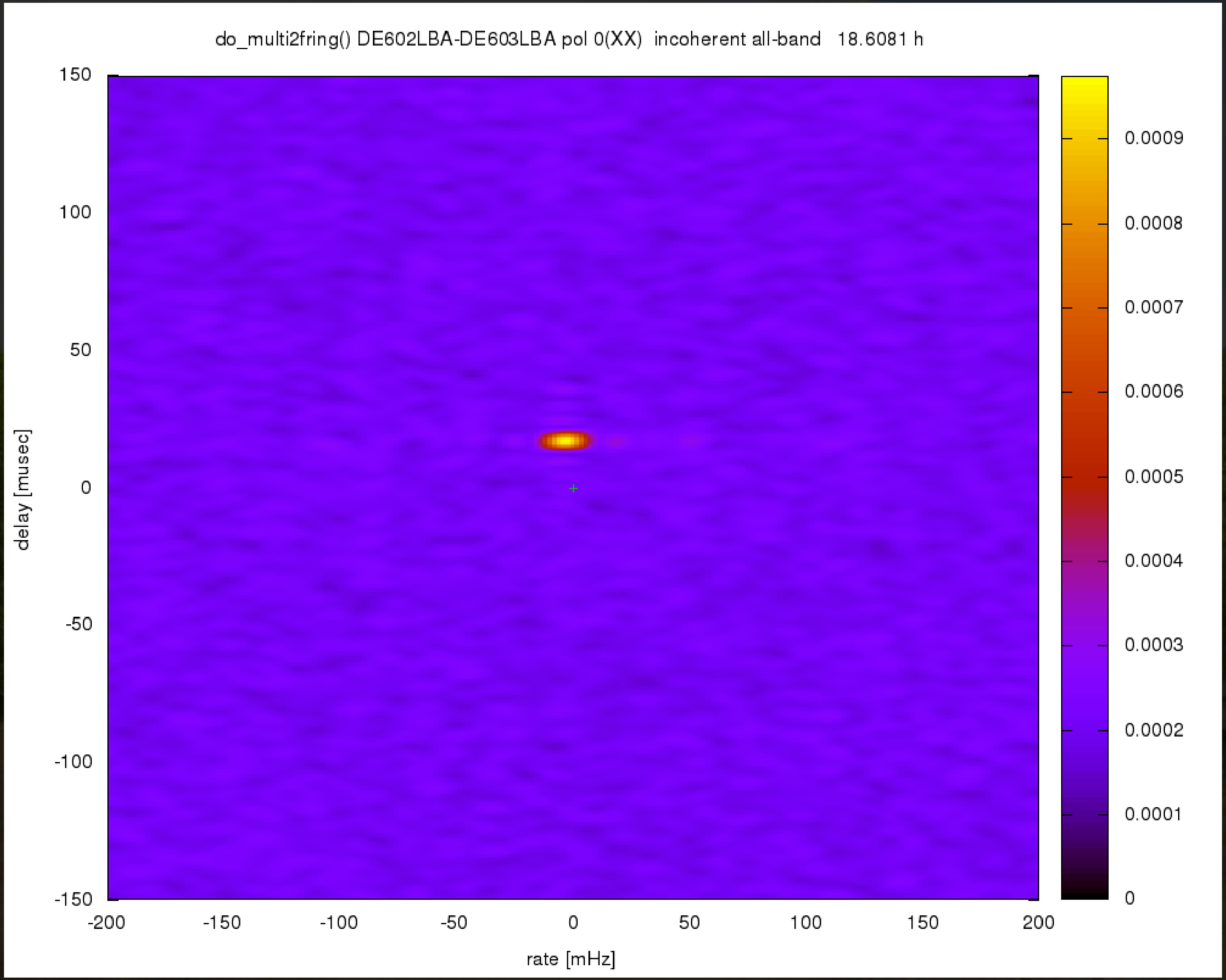
Delays and phases



Multi-band: more sensitivity and higher resolution delay



Fringes to Tautenburg and Unterweilenbach (Jan 2010)



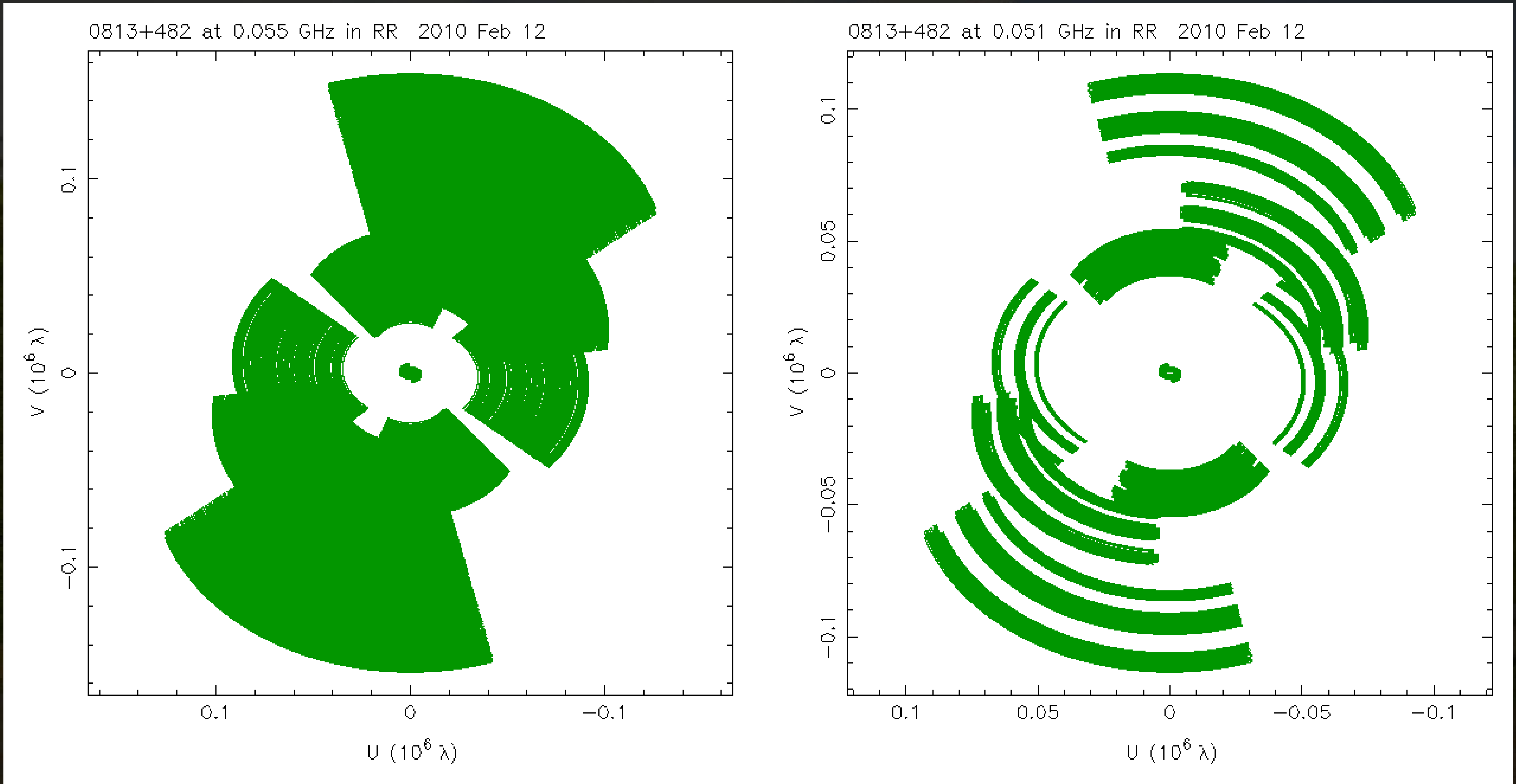
‘Results’ of fringe analysis

- 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!

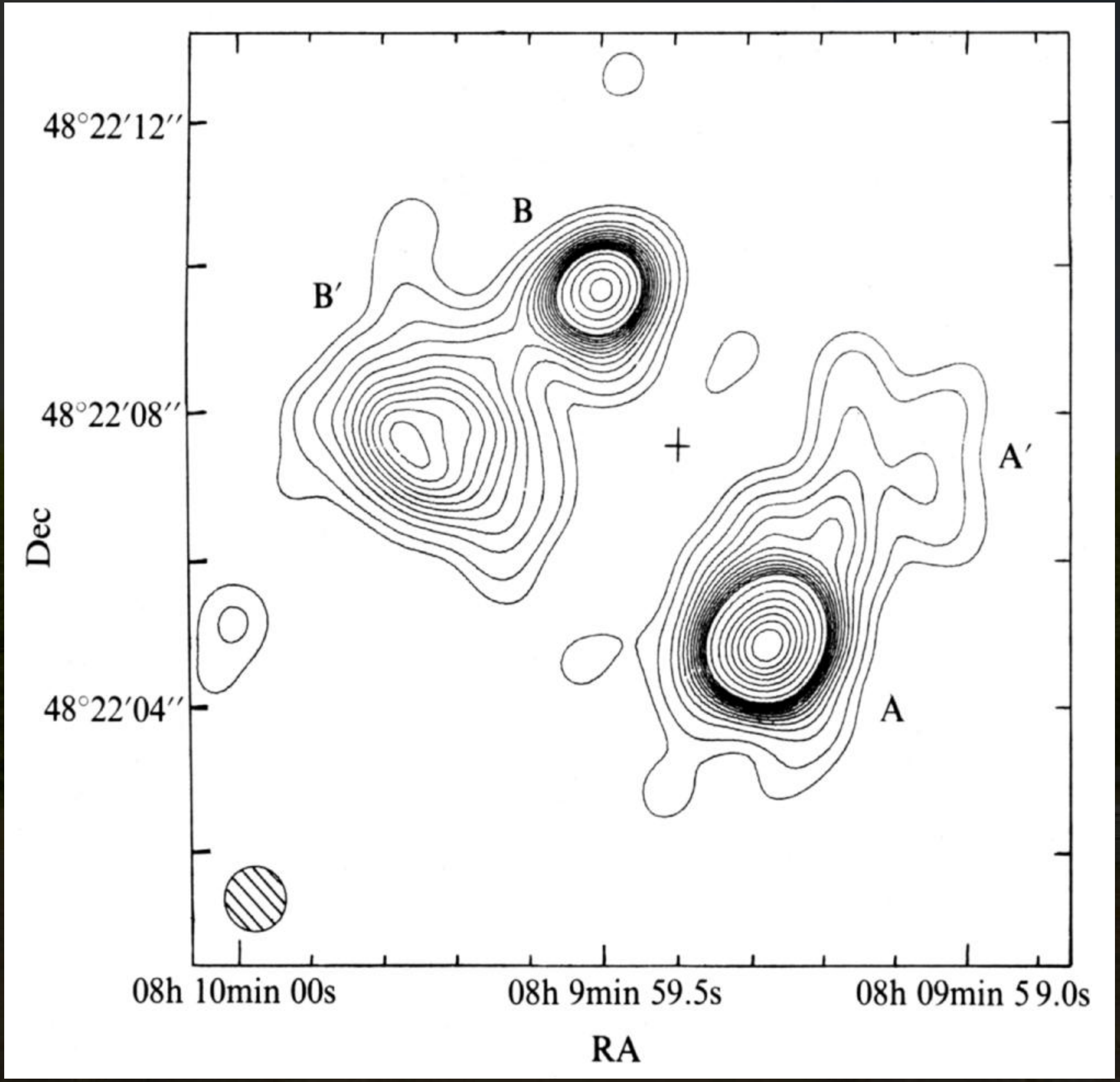
LBA long-baseline map: some details

- 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 μsec and 17 μsec 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

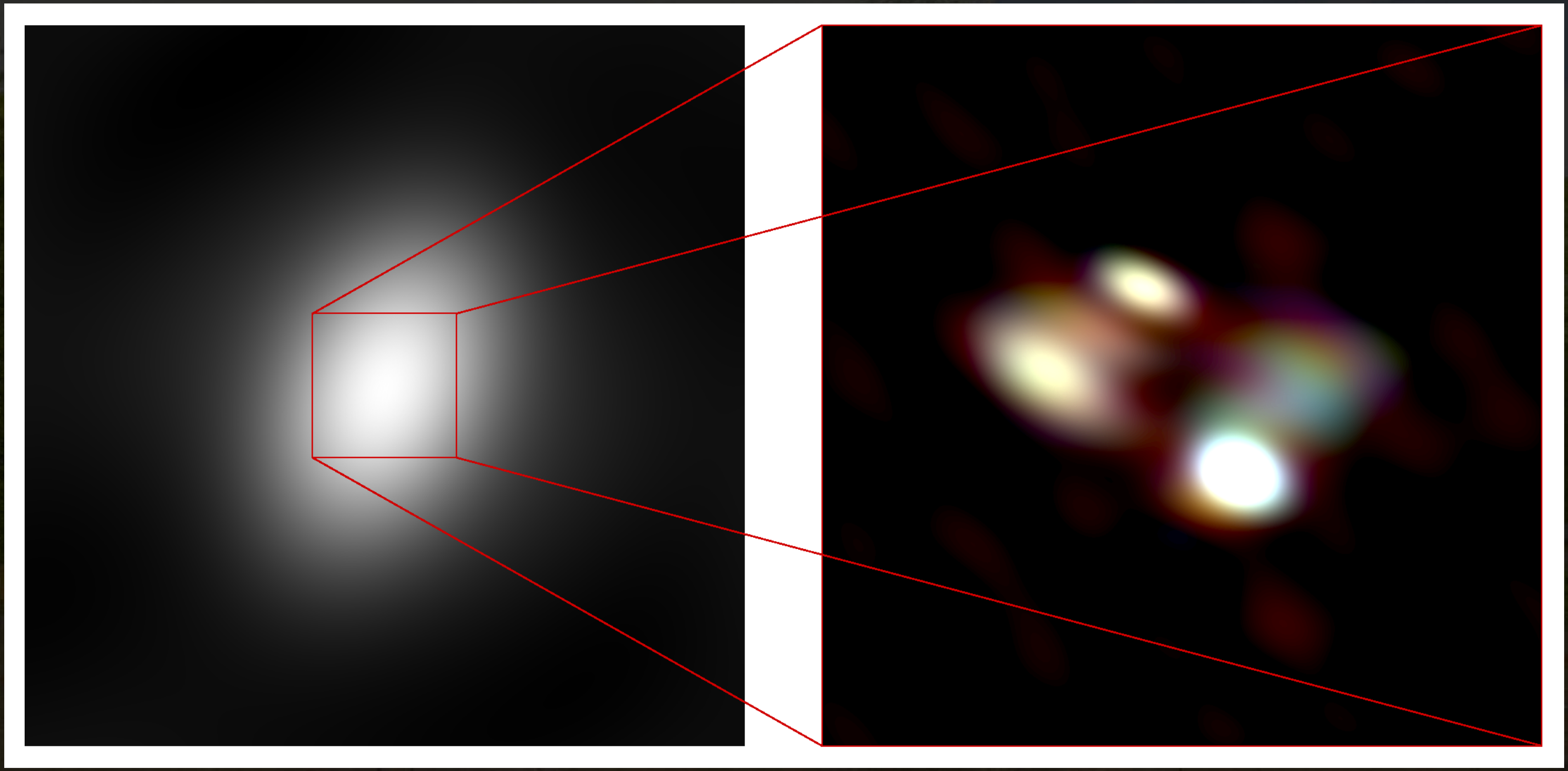


[*Lonsdale & Morison (1980)*]

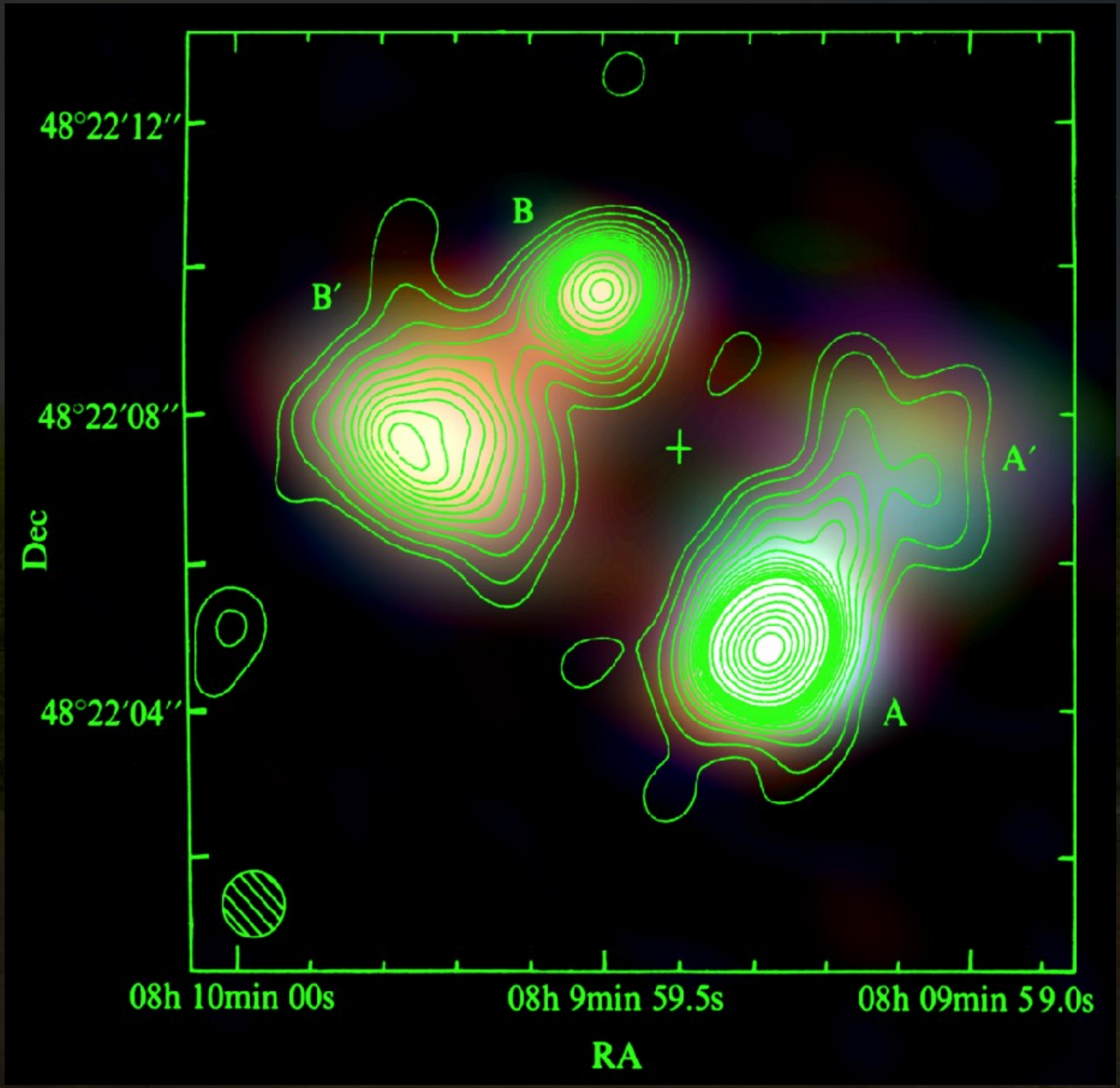
LOFAR maps of 3C196 (LBA: 30-80 MHz)

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

NL+DE, $1\farcs5 \times 0\farcs9$ beam



LOFAR LBA vs. MERLIN 408 MHz

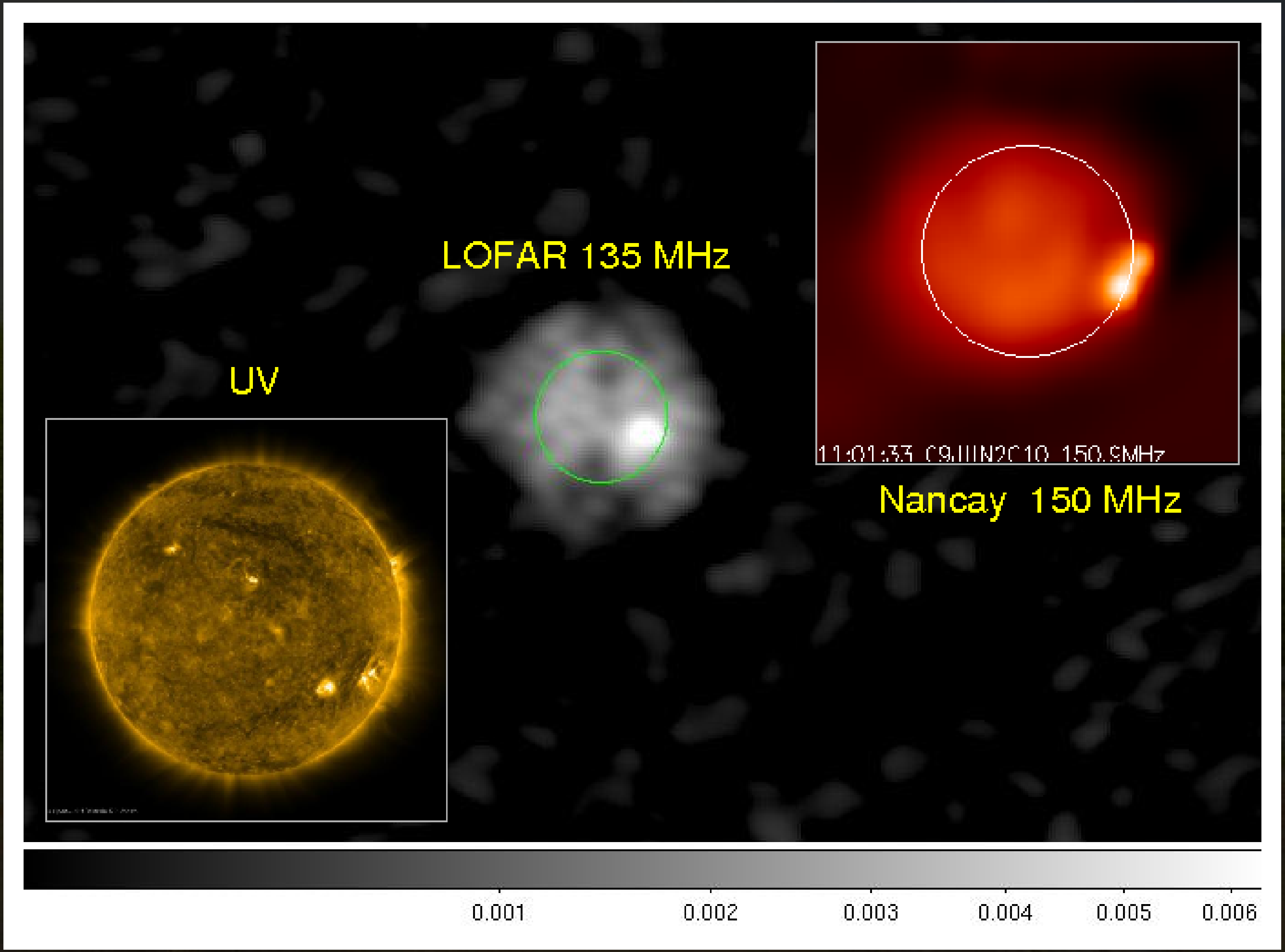


[Wucknitz + Lonsdale & Morison (1980)]

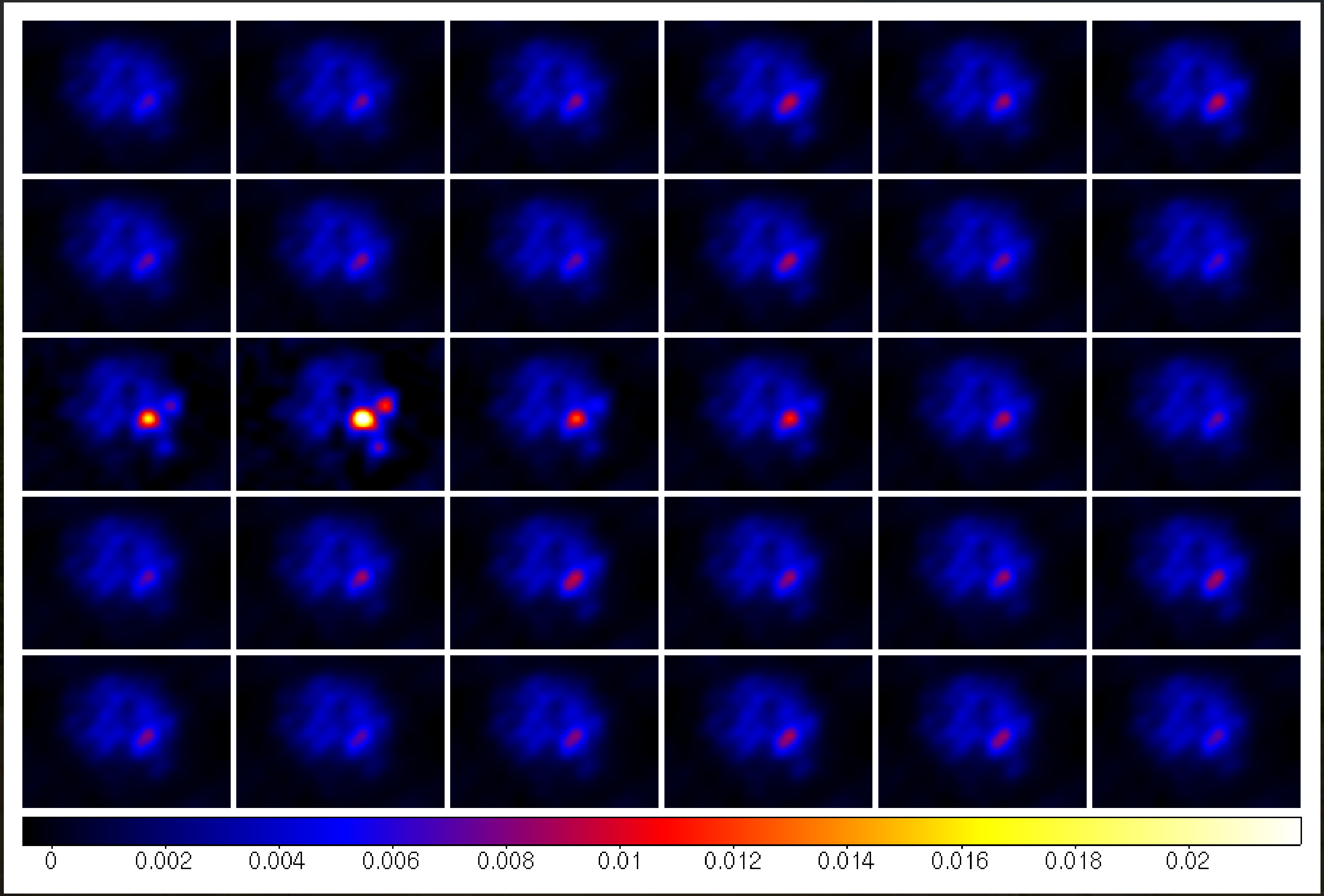
First interferometric Solar observations

- 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)



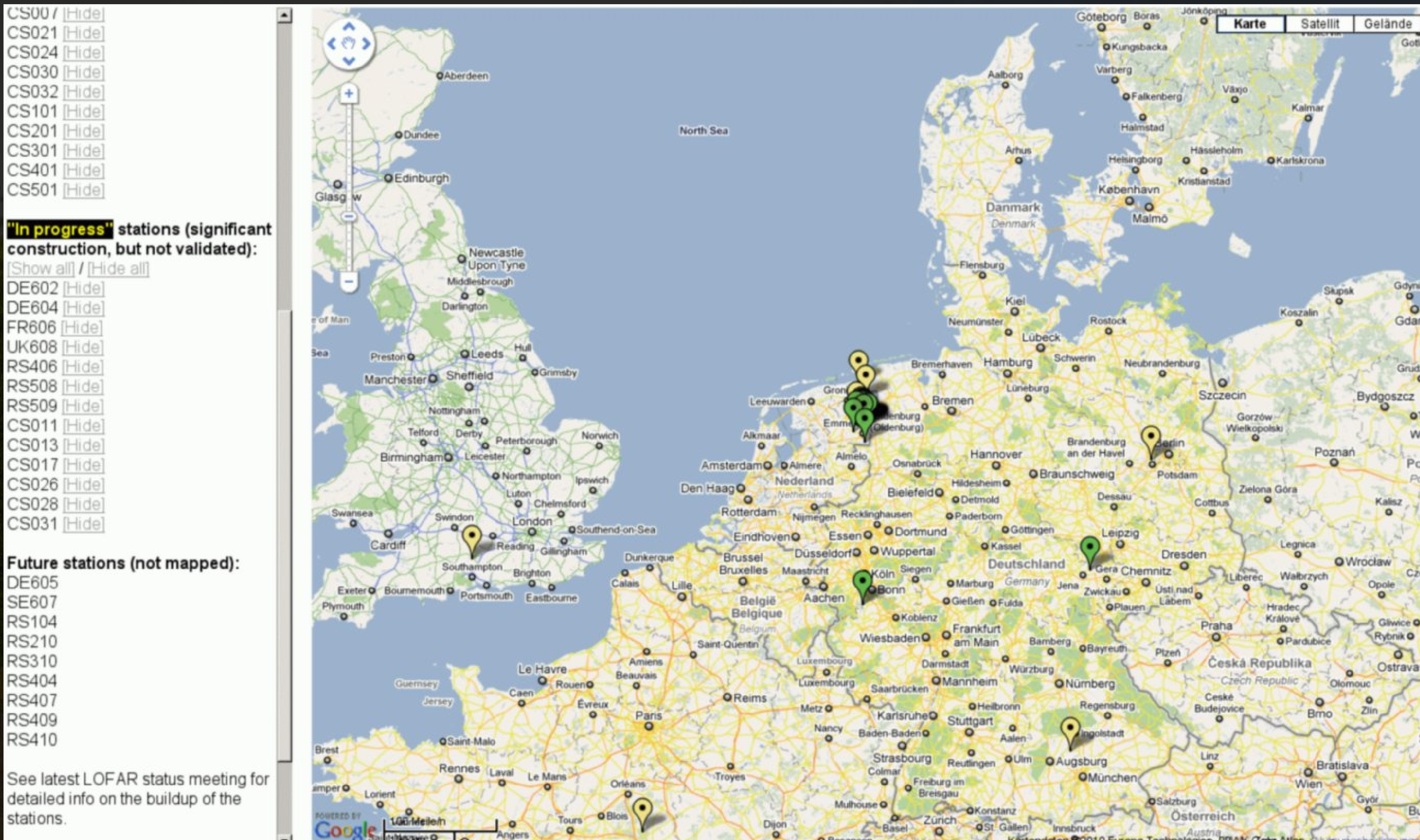
Summary

- 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)



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 $\quad V(\nu) = \mathrm{e}^{2\pi \mathrm{i} \nu \tau(\nu)} V_0(\nu)$
- hope that $V_0(\nu) = \text{const}$ and correct for delay
- find maximum of

$$\left| \int \mathrm{d}\nu \, \mathrm{e}^{-2\pi \mathrm{i} \nu \tau(\nu)} V(\nu) \right|^2$$

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

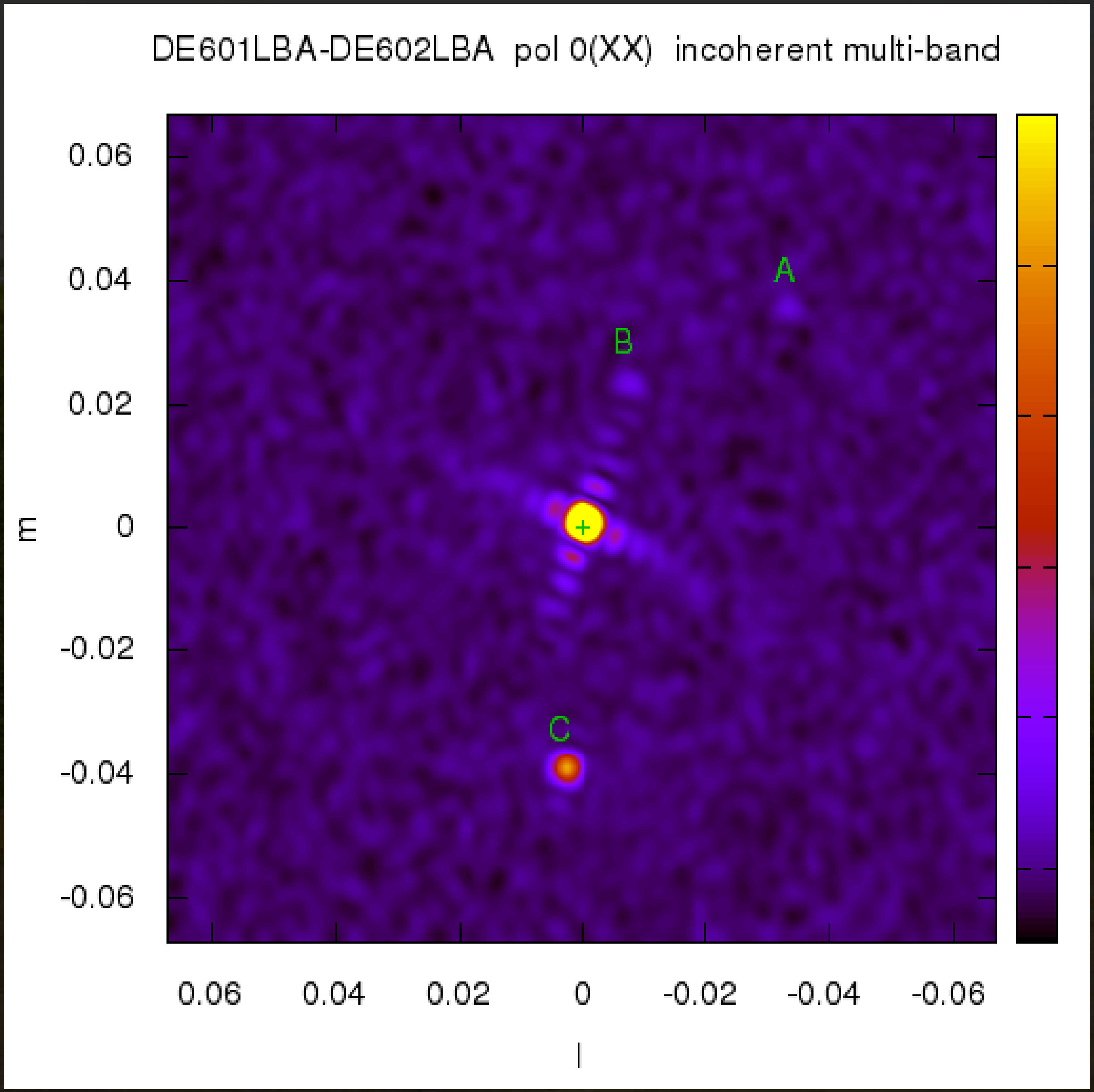
Multi-band delay fitting

- delay almost constant within subbands
- apply FFT for all subbands
- combine the results incoherently
- combine the results coherently
- $f_i(\tau_i) = \int_i \mathrm{d}\nu \, \mathrm{e}^{-2\pi \mathrm{i}(\nu - \nu_i)\tau_i} V(\nu)$ with coarse FFT
- $F[\tau] = \sum_i \mathrm{e}^{-2\pi \mathrm{i} \nu_i \tau(\nu_i)} f_i(\tau(\nu_i))$ 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
- $r = \dfrac{\partial \tau}{\partial t}$ dispersive/non-dispersive
- $f_i(\tau_i, r_i) = \int\limits_i \mathrm{d}\nu\, \mathrm{e}^{-2\pi \mathrm{i}(\nu - \nu_i)\tau_i} \int \mathrm{d}t\, \mathrm{e}^{-2\pi \mathrm{i}(t - t_0)\, r_i}\, V(\nu, t)$
- $F[\tau, r] = \sum_i \mathrm{e}^{-2\pi \mathrm{i}\nu_i \tau(\nu_i)}\, f_i\big(\tau(\nu_i), r(\nu_i)\big)$
- all phase rates are frequency-dependent

Delay/rate map of field around 3C196

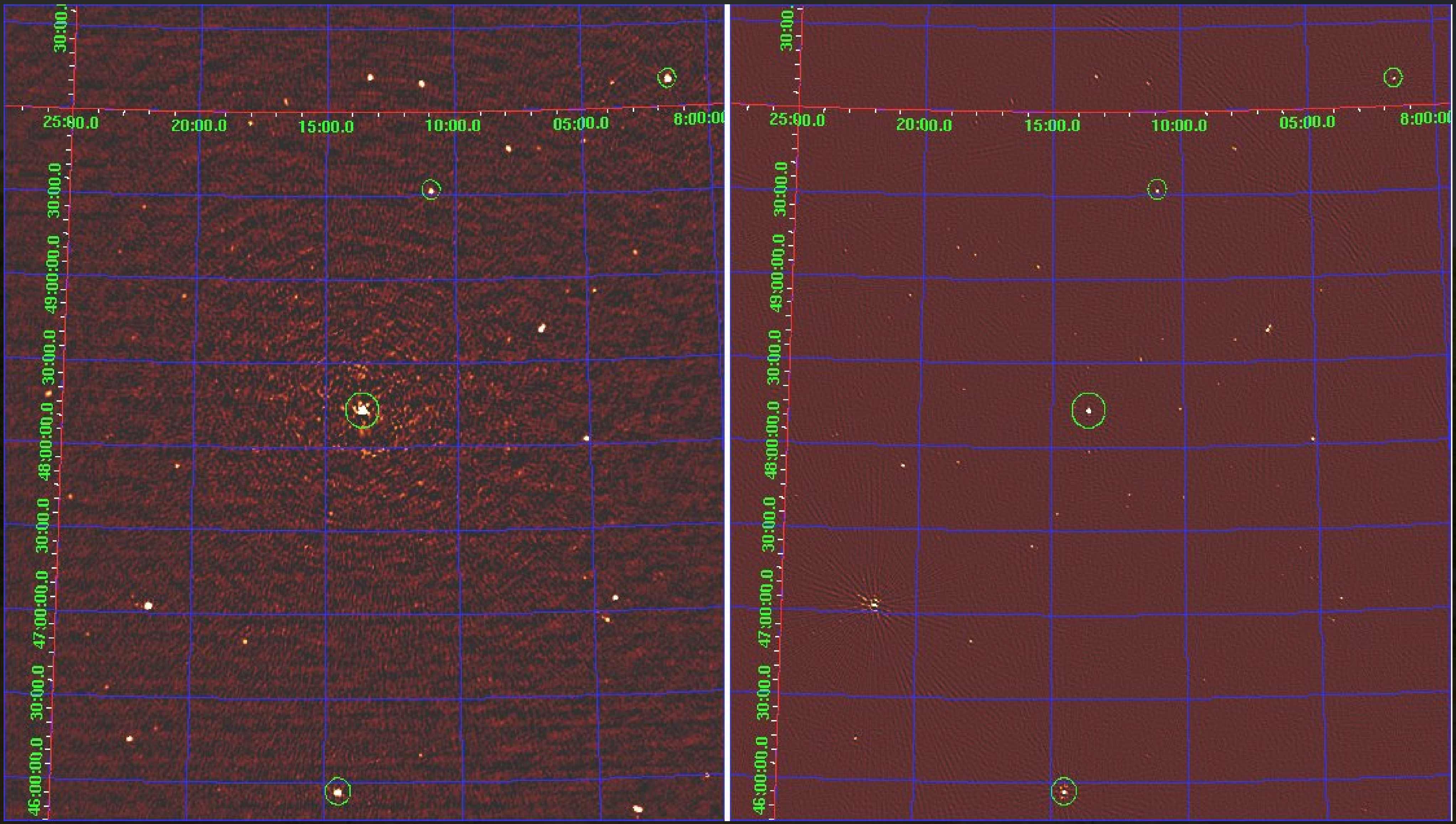


VLSS (74 MHz):

A	19 Jy
B	6 Jy
C	17 Jy

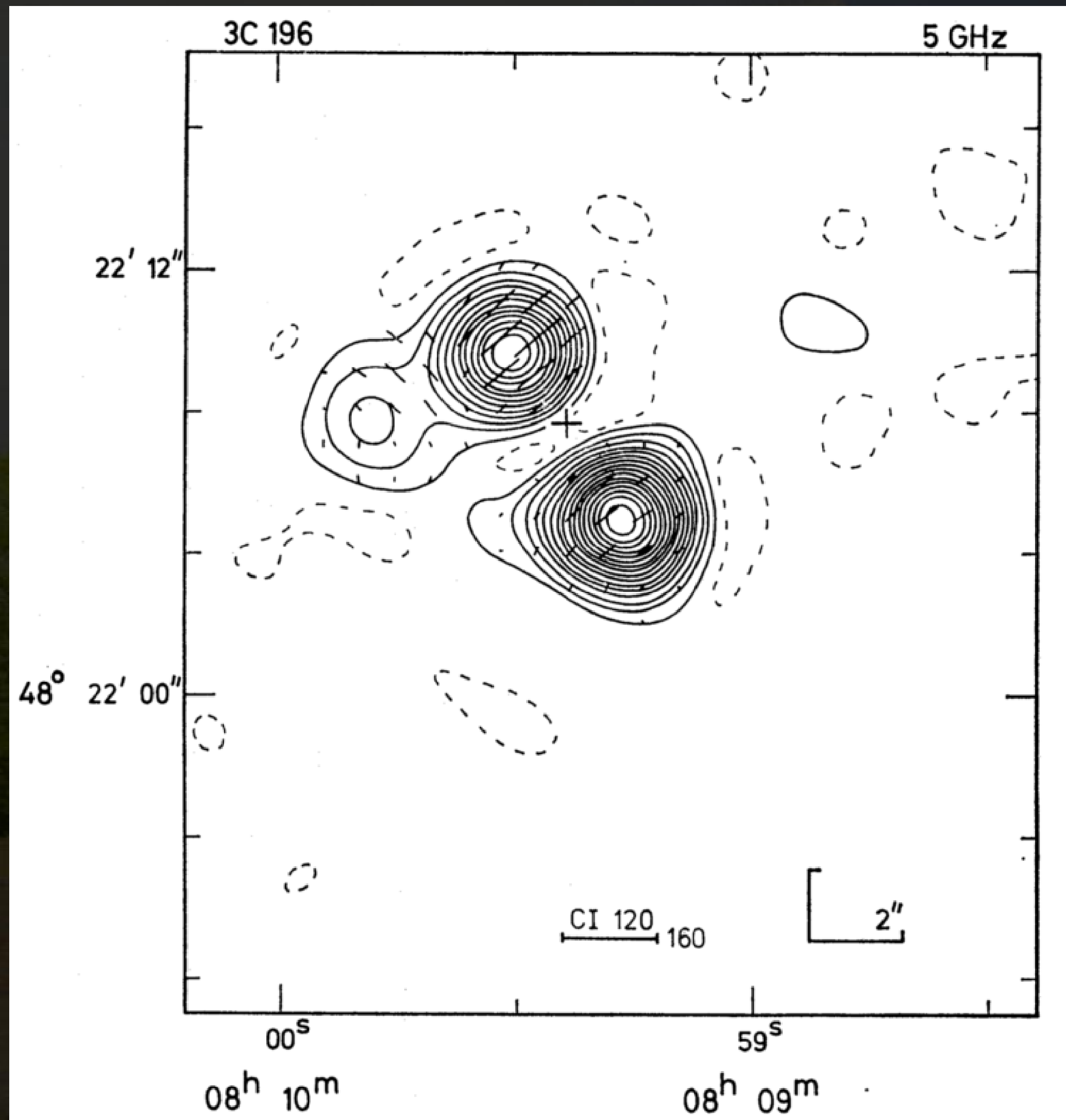
3C196 140 Jy

VLSS vs. LOFAR map of field around 3C196



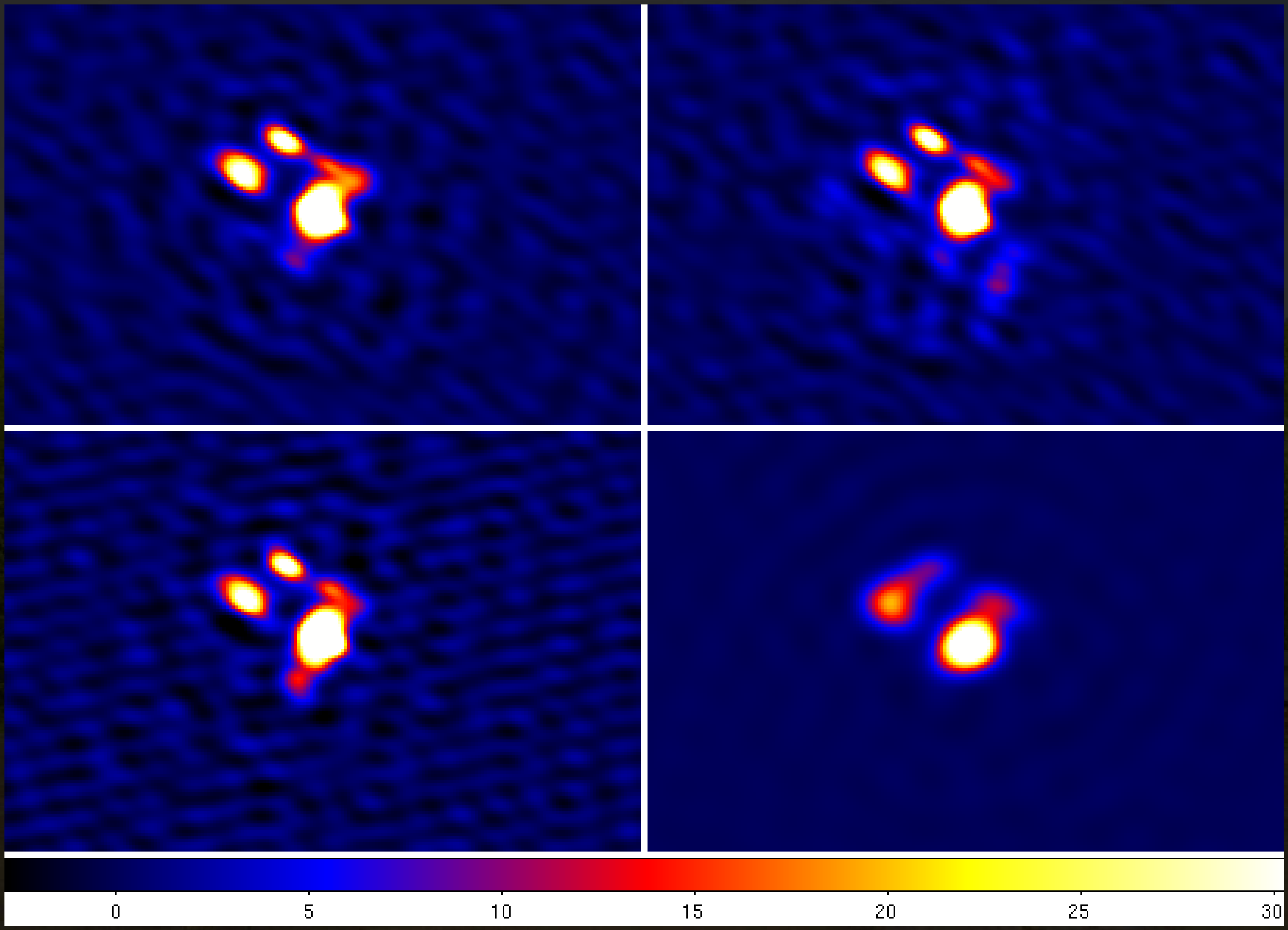
3C196 on long baselines: expectations

Cambridge 5km at 5 GHz



[Pooley & Henbest (1974)]

First long baseline maps of 3C196

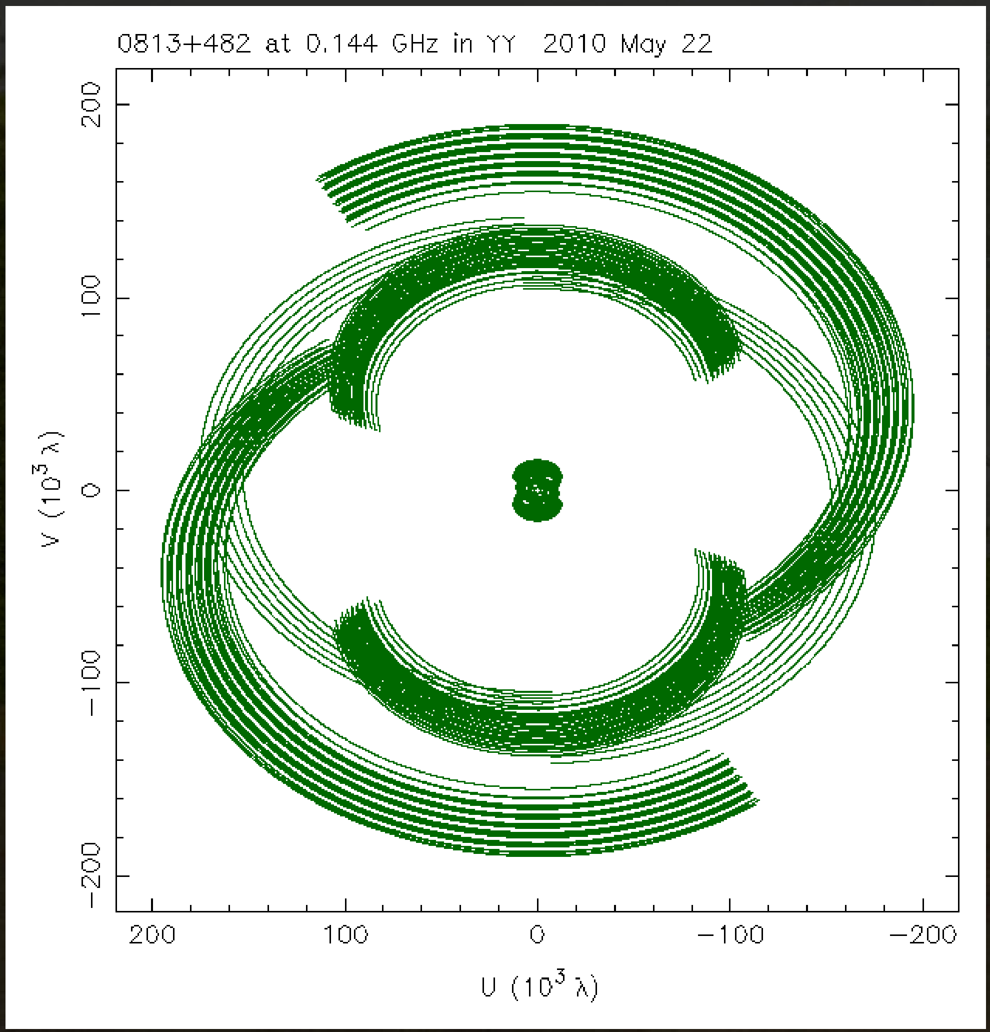


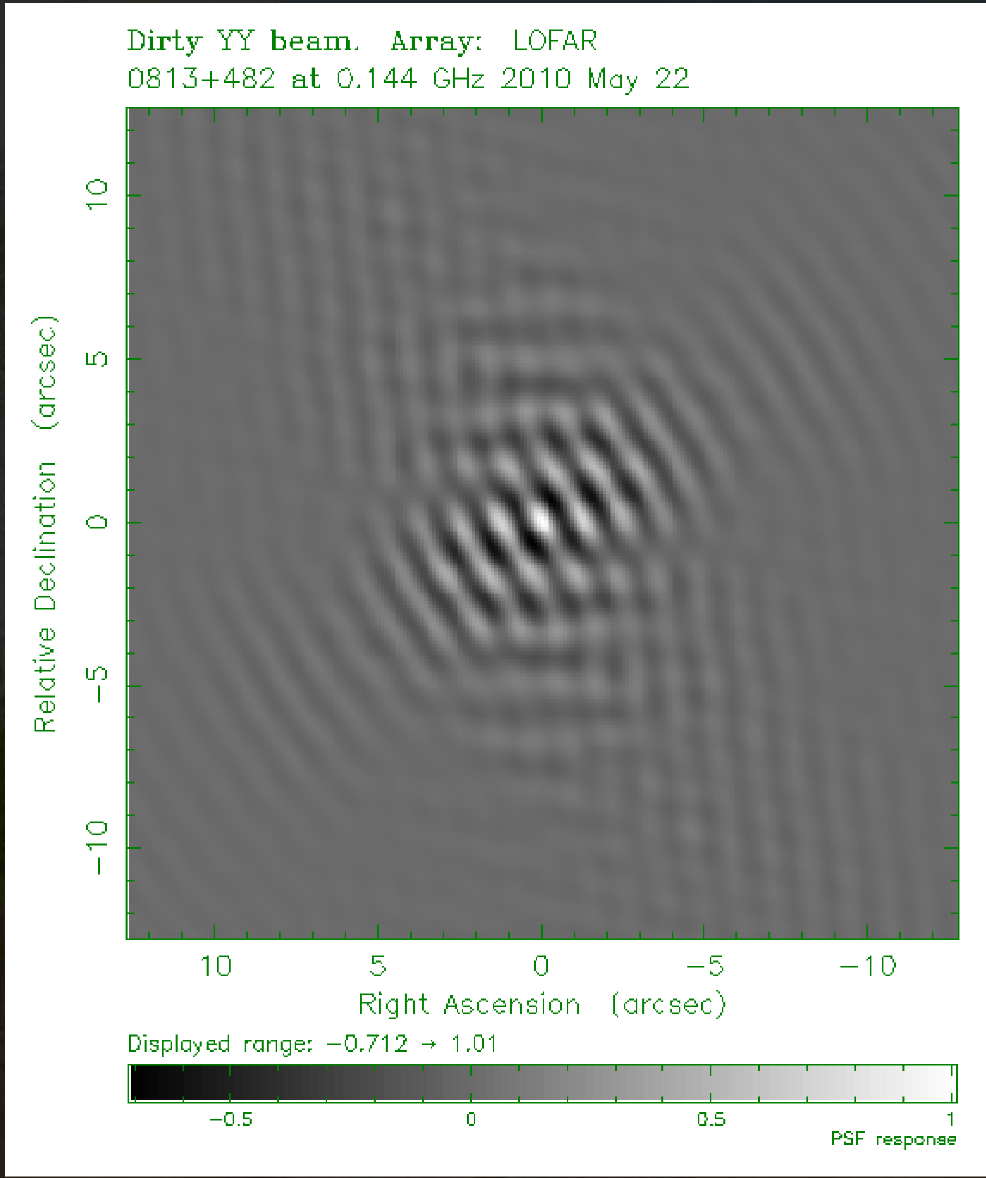
HBA observations of 3C196: some details

- 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 μsec 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

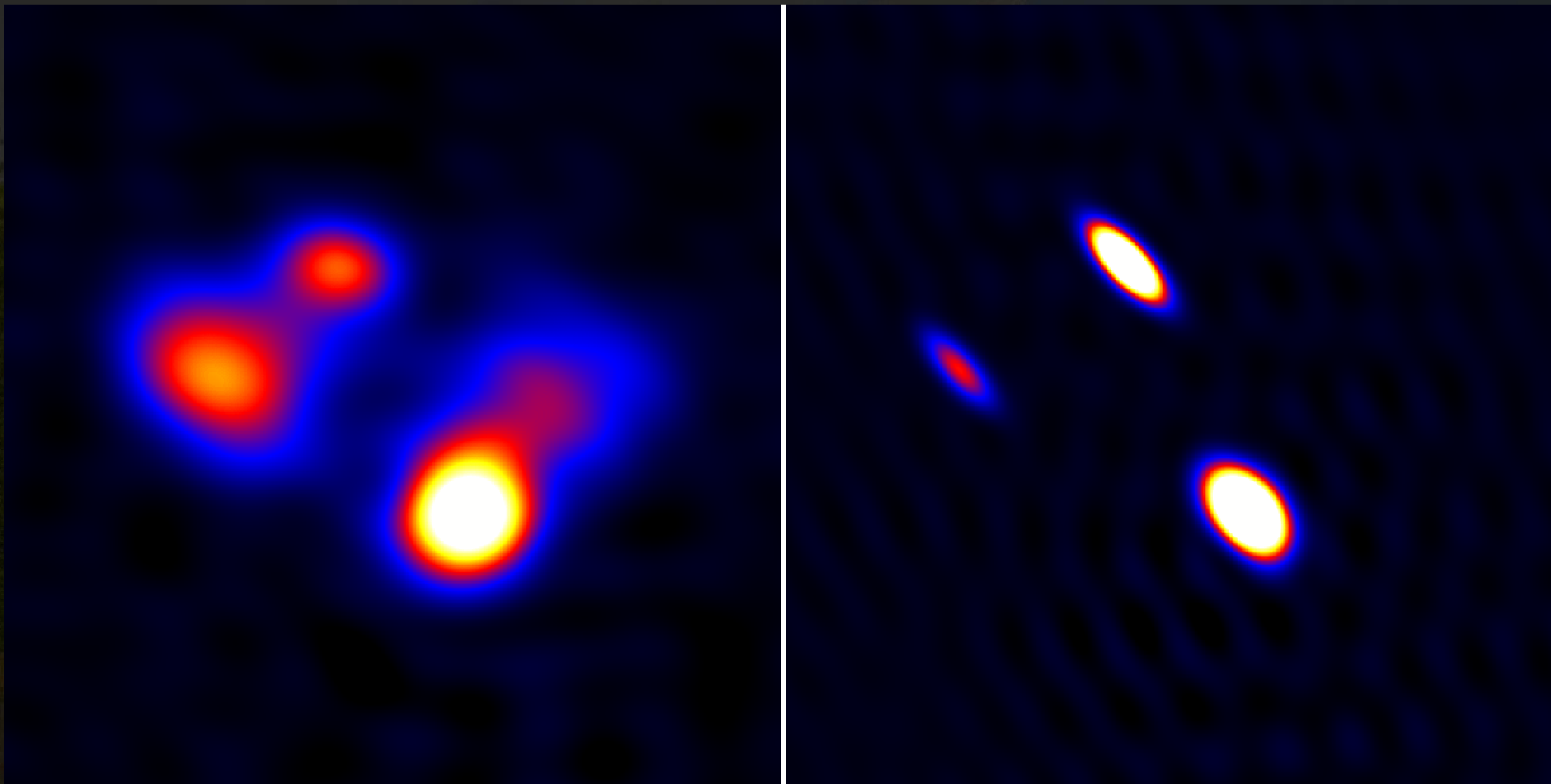
HBA observations: uv coverage, dirty beam

beam size 1.″0 × 0.″5

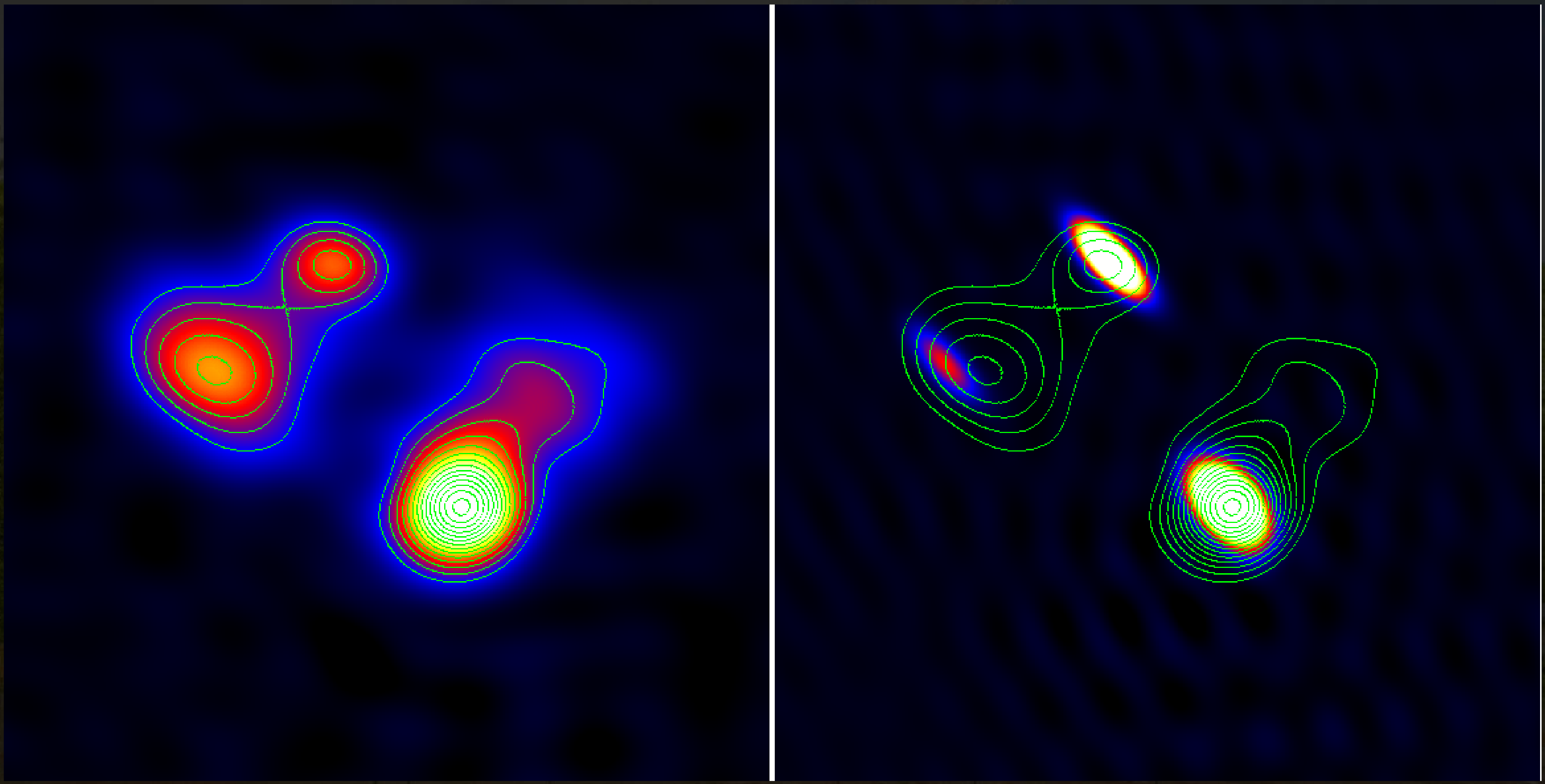




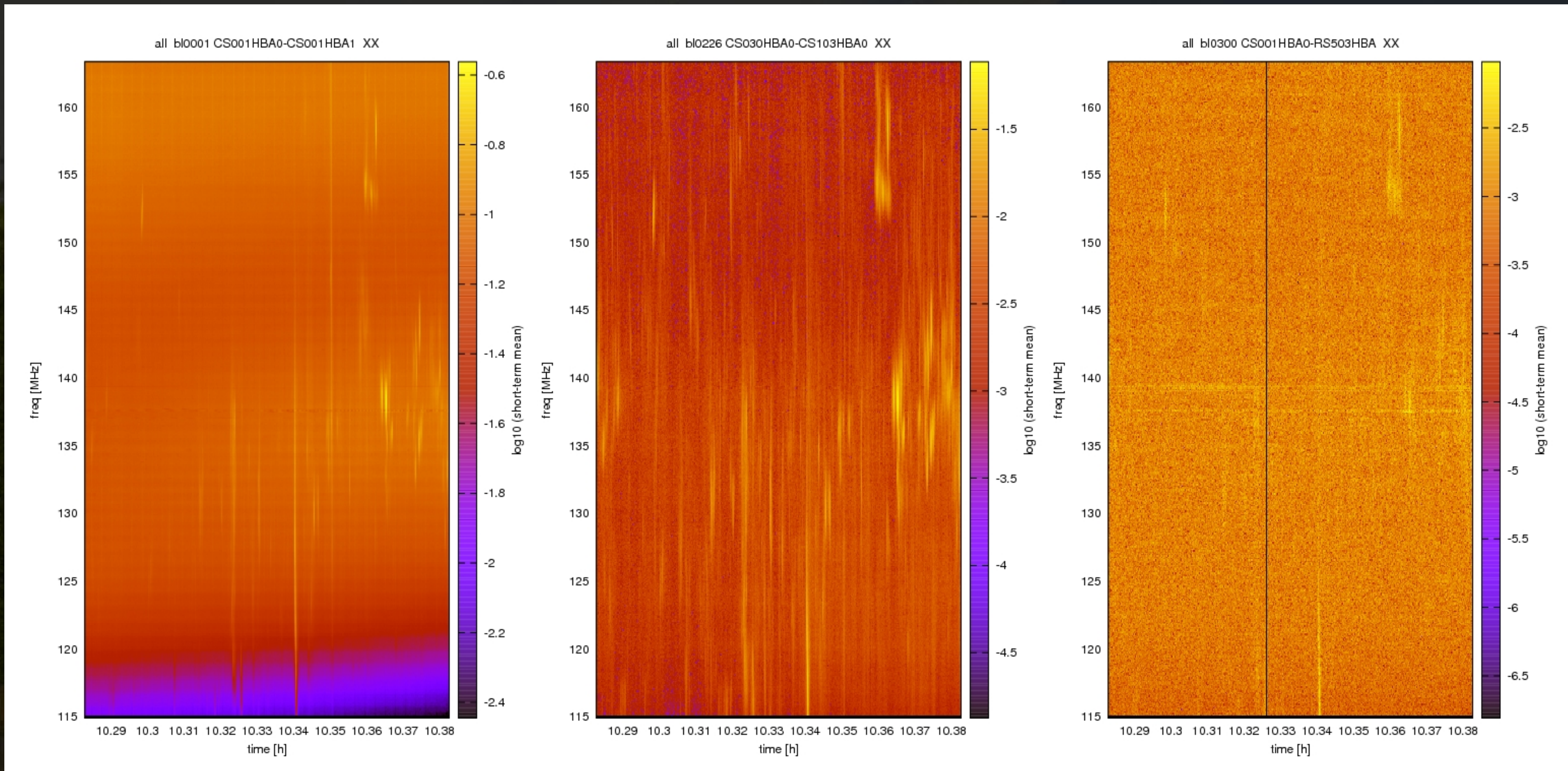
LBA + HBA images of 3C196



LBA + HBA images of 3C196 with contours

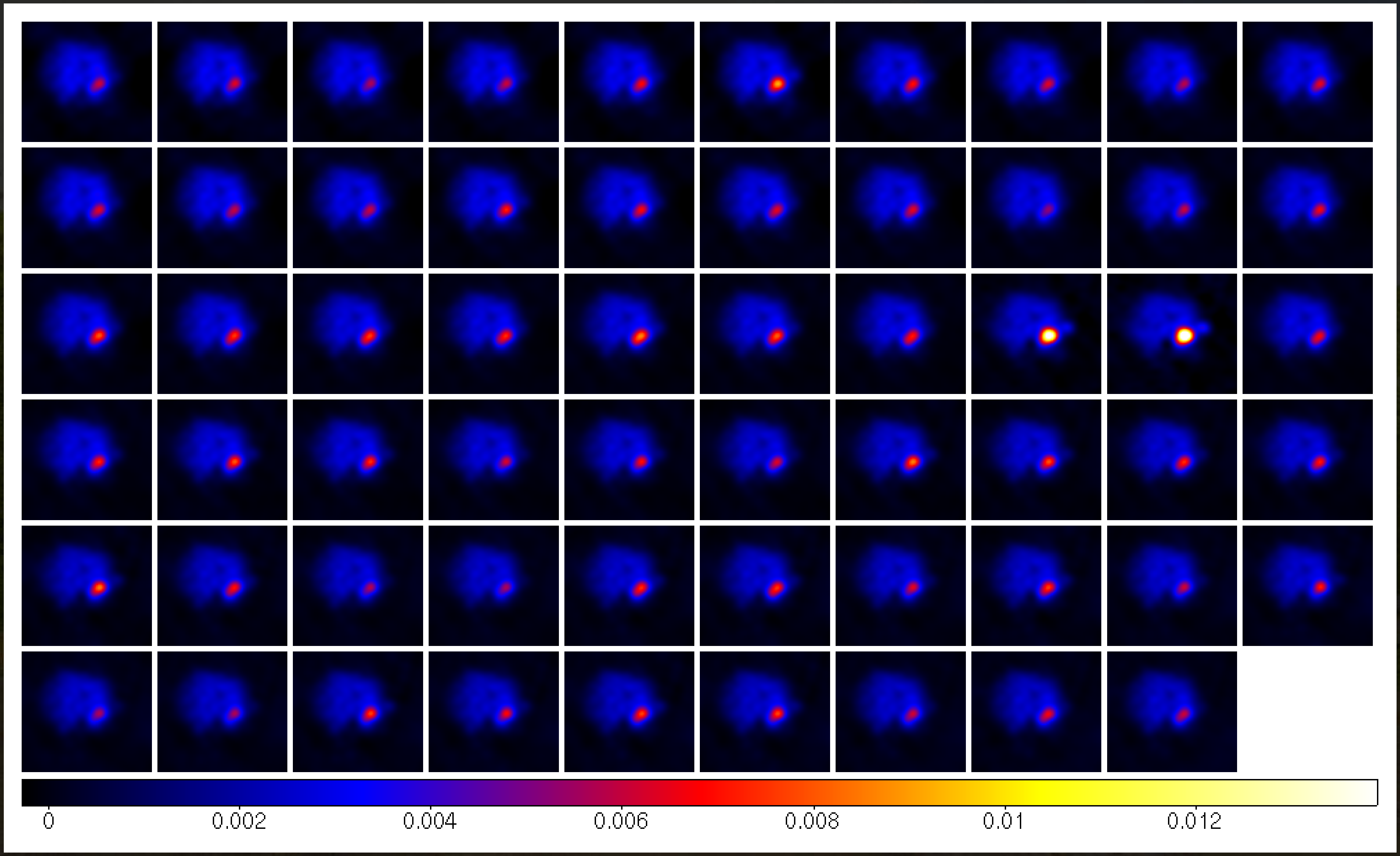


Dynamic spectra of the Sun



Significant variability as function of time and frequency!

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



Contents