e-VLBI with LOFAR

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Long baseline experiments with LOFAR

LOFAR

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

titlepage introduction summary contents

bonus

back forward

previous next

fullscreen

1

LOFAR

LOw Frequency ARray

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 $heta=\lambda/L~pprox$ 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

titlepage introduction summary contents

tents

bonus

German LOFAR stations



titlepage introduction summary contents

bonus

back forward

previous next

LBA at Effelsberg



titlepage introduction summary contents

bonus

back forward

previous next

fullscreen

5

LBA details at Unterweilenbach



titlepage introduction summary contents

nts

bonus

back forward

previous next

fullscreen

HBA + LBA in Tautenburg



titlepage introduction summary contents

bonus

back forward

fullscreen

7

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

solve for rates

non-dispersive

dispersive

titlepage introduction summary contents

bonus

previous next

 $au = au_0 \left(rac{ extsf{V}_0}{ extsf{v}}
ight)^2$

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

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

 $au = au_0$

Fringe-fitting for LOFAR

• either for single subbands (BW \sim 200 kHz, $\Delta \tau \propto 5 \,\mu$ sec)

• or coherent multi-band (BW \sim 48 MHz, $\Delta \tau \propto 0.02 \,\mu {
m sec}$)

beware of multiple peaks in delay/rate

produce 2-d delay/rate spectra

simultaneously 'fit' for four parameters

dispersive/nondispersive delays/rates

bonus

titlepage introduction summary contents

ts

back forward

previous next

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



titlepage introduction summary contents

bonus

back forward

previous next

Fringes in delay/rate space (single subband)



titlepage introduction summary contents

bonus

Delays and phases



titlepage introduction summary contents

Multi-band: more sensitivity and higher resolution delay



titlepage introduction summary contents

Fringes to Tautenburg and Unterweilenbach (Jan 2010)



titlepage introduction summary contents

bonus back

back forward

14

'Results' of fringe analysis

long baseline fringes found

- 🕨 clock offsets in some stations 🗸
- \bullet confusion in LBA polarisation labels \checkmark
- 🔸 strong 8 MHz ripple 🗸
- 63 MHz LBA resonance
- \bullet strong differential Faraday rotation \checkmark

time for imaging!

titlepage introduction summary contents

bonus

back forward

previous next

fullscreen

15

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



titlepage introduction summary contents

s bonus

back forward

previous next

fullscreen

MTRLI (MERLIN) observations of 3C196 at 408 MHz



titlepage introduction summary contents

bonus

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

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

NL+DE, 1.5×0.9 beam



titlepage introduction summary contents

bonus

back forward

previous next

fullscreen

LOFAR LBA vs. MERLIN 408 MHz



titlepage introduction summary contents

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)



titlepage introduction summary contents

bonus

back forward

previous next

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

titlepage introduction summary contents

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)

CS00/[Hide]				Göteborg Boras Jonköp	Karte Satellit	Gelände
	(0)		<u></u>	O Kungsbacka	111 Th 12 10 1 1	Gotian
CS024 [Hide]	Okherdeen		Aalborg	Varberg		1.1.1
CS032 [Hide]	+		2 C 2	OFalkenberg	Vaxio	J.
CS101 [Hide]	A CARACTER STATE			• • • •	Kalmar	
CS201 [Hide]	Dundee	North Sea		Hard	and	
CS401 [Hide]	19		A A A	Helsingborg O	OKarlskrona	
CS501 [Hide]	Glasg w		Here and the second sec	København	tad	
"In provinces" stations (significant			Danmark	Maimö		
construction, but not validated):	A Decomposition		No Al		5	
[Show all] / [Hide all]	Upon Tyne		Flemburg			
DE602 [Hide]	- Middlesbrough		- Kurl	- 6	Ship	sk Gdynia
EP606 [Hide]	e of Man		Neumünster	Rostock	Koszalin	Gdańs
UK608 [Hide]	Rep. Of and that		C Lubeck	LAND REAL	C. Andrew	
RS406 [Hide]	Preston C Sheffield Grimsby		Bremerhaven Hamburg Sch	Neubrandenburg	Contractor Contractor	Grudzie
RS508 [Hide]		Leeuwarden	Gron Bremen	Sz	zecin	Bydgoszcz
CS011 [Hide]	Nottingham		Emme Oldenburg		Gorzów-	OTor
CS013 [Hide]	Peterborough Nor	Alkmaar O	Almalo Hannover	Brandenburg an der Havel	Pozna	an
CS017 [Hide]	Q Northampton Ipsw	AmsterdamO OAlmer	e Osnabrück O OBraur	nschweig Potsdam	5	Pole
CS028 [Hide]	Luton O Chelmsford	Den Haago	Bielefeld ODetmold	Dessau Cott	Zielona Góra Dus	Kalisz ,
CS031 [Hide]	Swansea Swindon London QSout	thend on Sea	Gen Recklinghausen OPaderborn	Leipzig	Low X	Fill of
Future stations (not manned):	Cardiff Gillingham	Dunkergue Brussel Düs	seldorf O Wuppertal	Dresden	Legnica	Window
DE605	Southampton Brighton	Calais Lille O Q	Cht Koln Siegen OMarburg Germany Je	Gera Chemnitz	Liberec Walbrzych	Opole
SE607	Phymouth Bournemouth Portsmouth Eastbourne	België Aa	o Gießen o Fulda	OPlauen Labern	Hradec?	0
RS104		Belgum	WiesbadenO O Frankfurt	Pr	aha o	Rybnik O
RS210 RS310		Amiens Saint-Quentin Luxe	mibourg Darmstadt	OBayreuth Pizen	eská Republika	01-
RS404	Guernsey RouenO	Beauvais	embourg Saarbrücken OMannheim Of	Nümberg	Czech Republic	mouc
RS407	Jersey Carely Evre	Paris Met	ZO Karistube	Regensburg Bude	ské ejovice Brno	Zlin
RS409 RS410	QSaint-Malo	A CANASA	Nancy Baden Baden O Aalen	Ingoistadt	m	SI SI
	Brest O Rennes (A los	Strasbourg Reutingen OUIm OAu	ugsburg	Bratis	lava B
See latest LOFAR status meeting for	ampero Lorient O O O	Orléans	Preiburg im Breisgau	OMünchen	Wien	S.S.C.
stations.	POULTATO BY I LODINGHAM	© Blois	Mulhouse O Zurich OKonstanz	Österre	ich S	Bud
	GOOS Sa Hittoring I o Angers	Dijon	Basel Q QSt Gallen) Inne Besançon Kartendaten	2010 Europa Technologies,	PPWK Genz Atlas	hasheddan oren

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

titlepage introduction summary contents

bonus

b

Delay fitting

do not fit phases directly

- \star 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 $V_0(v) = \text{const}$ and correct for delay

find maximum of

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

• this is Fourier transform $\int \tau = \text{const}$

titlepage introduction summary contents

s bonus

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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

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

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

titlepage introduction summary contents

bonus

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 • $f_i(\tau_i, r_i) = \int \mathrm{d}\boldsymbol{v} \,\mathrm{e}^{-2\pi\mathrm{i}(\boldsymbol{v}-\boldsymbol{v}_i)\tau_i} \int \mathrm{d}t \,\mathrm{e}^{-2\pi\mathrm{i}(t-t_0)r_i} V(\boldsymbol{v}, t)$ • $F[\tau, r] = \sum_{i} e^{-2\pi i v_i \tau(v_i)} f_i(\tau(v_i), r(v_i))$

• all phase rates are frequency-dependent

titlepage introduction summary contents

bonus

back forward

previous next

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

titlepage introduction summary contents

bonus

back forward

previous next

fullscreen

VLSS vs. LOFAR map of field around 3C196



titlepage introduction summary contents

bonus

back forward

previous next

fullscreen

31

3C196 on long baselines: expectations



titlepage introduction summary contents

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 $8\,\mu$ 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 $1.0^{\prime\prime} \times 0.5^{\prime\prime}$



Dirty YY beam. Array: LOFAR 0813+482 at 0.144 GHz 2010 May 22



titlepage introduction summary contents

bonus

back forward

previous next

fullscreen

LBA + HBA images of 3C196



LBA + HBA images of 3C196 with contours



titlepage introduction summary contents

nts bonus

back forward

previous next

fullscreen

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Dynamic spectra of the Sun



Significant variability as function of time and frequency!

titlepage introduction summary contents

bonus

back forward

previous next

fullscreen

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



bonus

previous next

fullscreen

39

Contents

- 1 Long baseline experiments with LOFAR
- 2 LOFAR
- 3 LOFAR resolution
- 4 German LOFAR stations
- 5 LBA at Effelsberg
- 6 LBA details at Unterweilenbach
- 7 HBA + LBA in Tautenburg
- 8 VLBI methods for LOFAR
- 9 Fringe-fitting for LOFAR
- 10 Very first long baseline fringes (NL-Ef, Aug 2009)
- 11 Fringes in delay/rate space (single subband)
- 12 Delays and phases
- 13 Multi-band: more sensitivity and higher resolution delay
- 14 Fringes to Tautenburg and Unterweilenbach (Jan 2010)
- 15 Results of fringe analysis
- 16 LBA long-baseline map: some details
- 17 UV coverage with long and short baselines

- 18 MTRLI (MERLIN) observations of 3C196 at 408 MHz
- 19 LOFAR maps of 3C196 (LBA: 30-80 MHz)
- 20 LOFAR LBA vs. MERLIN 408 MHz
- 21 First interferometric Solar observations
- 22 The very first map
- 23 Variability: 30 sec in 1 sec steps (8 subbands)
- 24 Summary
- 25 Additional material
- 26 The International LOFAR Telescope (ILT)
- 27 Delay fitting
- 28 Multi-band delay fitting
- 29 Include fringe rates
- 30 Delay/rate map of field around 3C196
- 31 VLSS vs. LOFAR map of field around 3C196
- 32 3C196 on long baselines: expectations
- 33 First long baseline maps of 3C196
- 34 HBA observations of 3C196: some details
- 35 HBA observations: uv coverage, dirty beam
- 36 LBA + HBA images of 3C196
- 37 LBA + HBA images of 3C196 with contours
- 38 Dynamic spectra of the Sun

Variability: 10 min in 10 sec steps (1 subband) 39

40 Contents

titlepage introduction summary contents

bonus

back forward

previous next

fullscreen

42