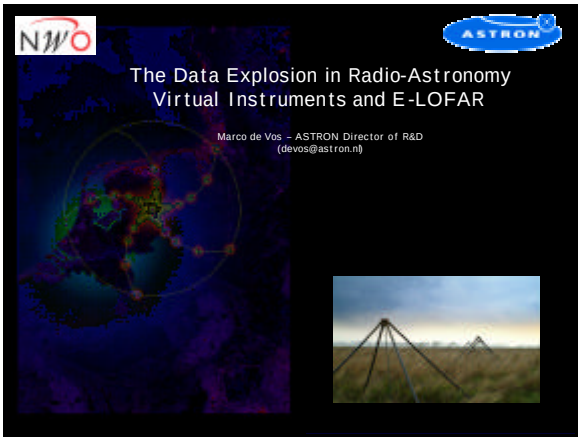
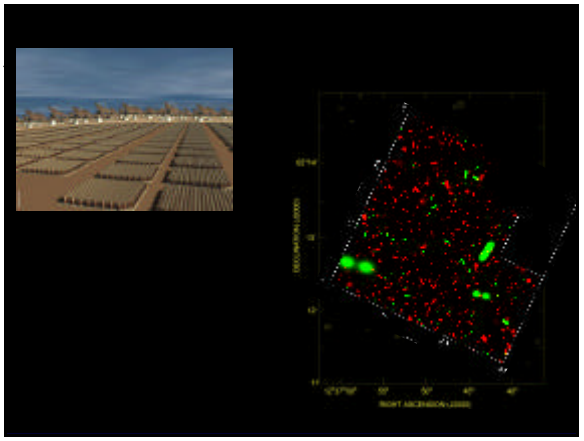
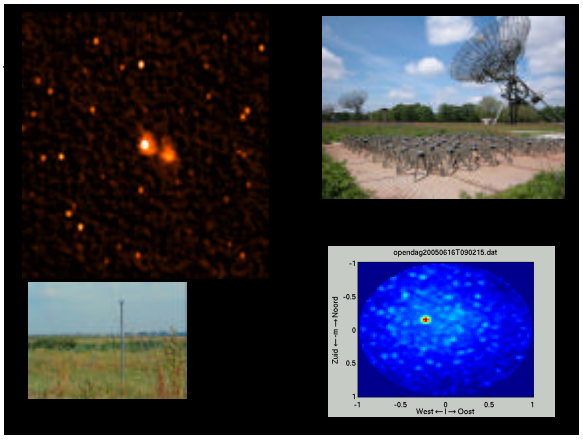




Early history and near future

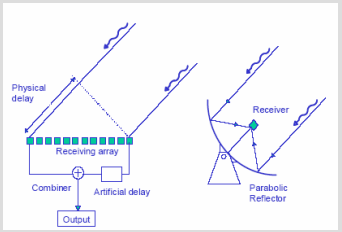
- Start of radio-astronomy:
  - Grote Reber, Karl Jansky @ 20MHz (~1930)
- Next large new facility:
  - LOFAR @ (20-)30-80 MHz and 120-240 MHz
- Why the gap?
  - Relatively easy to get some signal out
  - Quite difficult to get further than ~300 sources



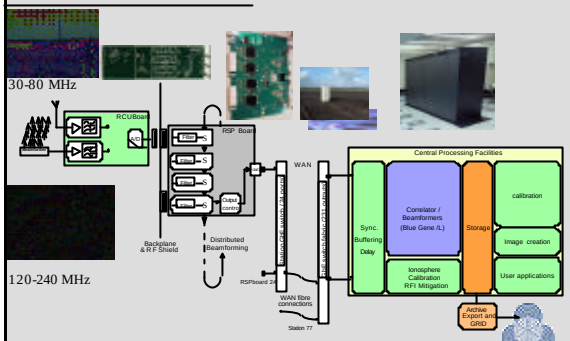
LOFAR in summary

- Large distributed radio telescope
  - 32 central (24 Gbps) + 45 remote (2 Gbps) phased array antenna stations, each ~4 soccerfields in size
  - Full scale aperture synthesis array, extends 100 km
  - ~ 10 long-distance stations being discussed (E-LOFAR)
- Two main bands
  - High Band ~ 7,500 tiles 120 – 240 MHz
    - ~ 120,000 m^2 / 250 K @ 150 MHz
  - Low Band ~ 7,500 dipoles 10 – 80 MHz
    - ~ 375,000 m^2 / 45,000K @ 20 MHz
- Digital Radio 40 MHz processing bandwidth
  - Extreme agility in time/space/frequency
  - Large instantaneous sky coverage
- Fibre network, Software Correlator
- New calibration & RFI mitigation schemes

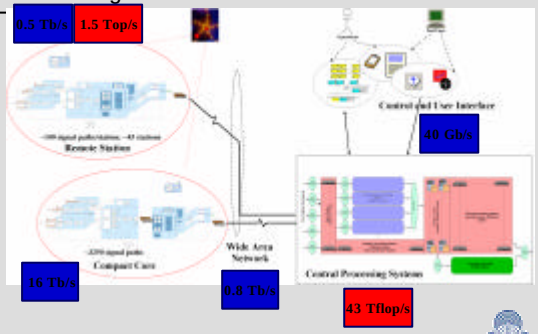
Phased array stations – aperture synthesis array

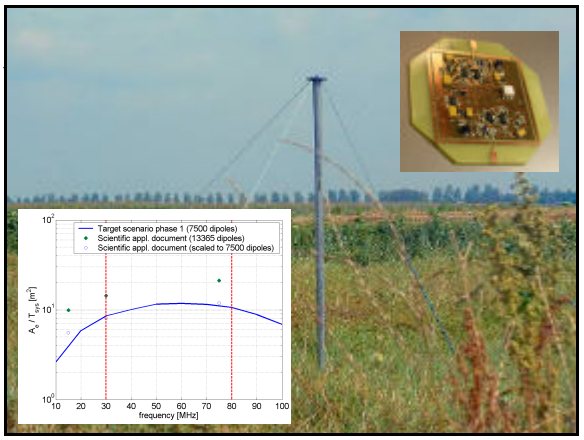


LOFAR top-level architecture

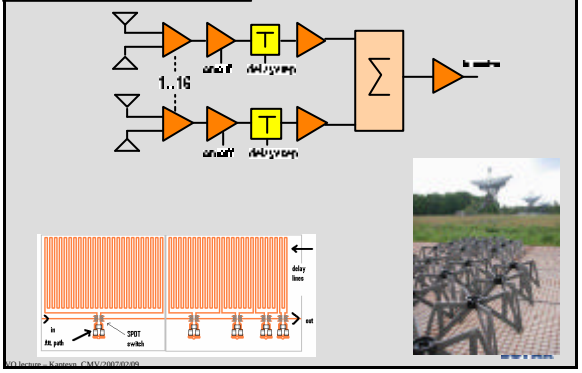


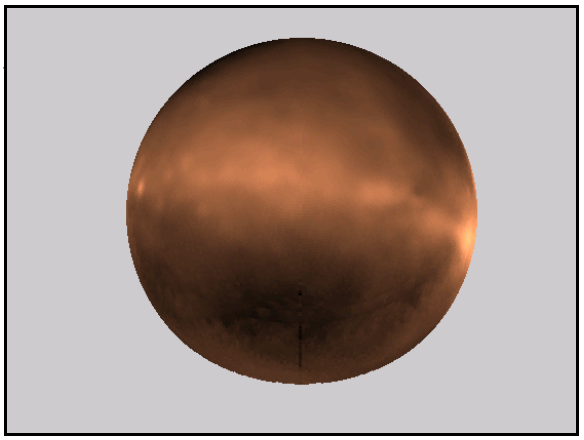
Streaming towards science





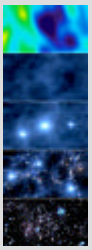
High Band Antenna (120-240 MHz)

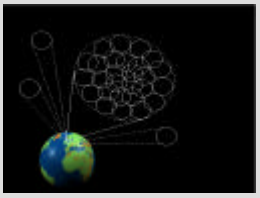




Relevance to the SKA

- Science PathFinder
  - In particular for EoR, Pulsars and Transients

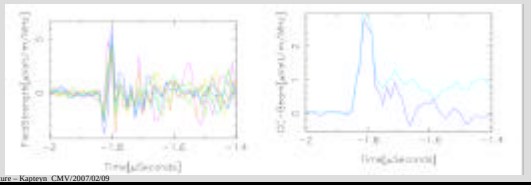




LOFAR Prototype Station (LOPES):

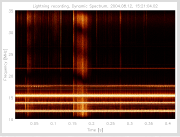
detection of nanosecond radio flashes from ultra-high energy elementary particles

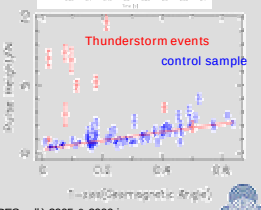
Falcke et al. (2005), *Nature*, Vol. 435, p. 313



Thunderstorm Events

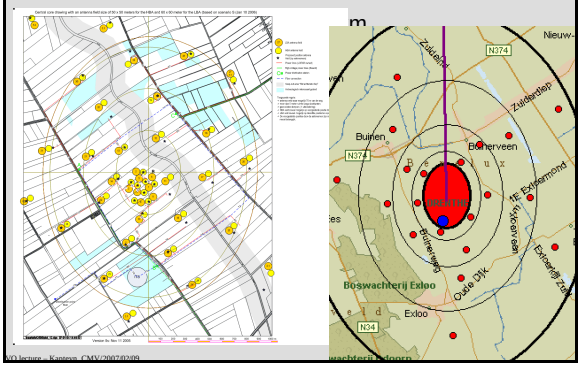
- Does the Electric field of the atmosphere influence CR radio signal?
- For E>100 V/cm E-field force dominates B-field:
  - Fair weather: E=1 V/cm
  - Thunderstorms: E=1 kV/cm
- Select thunderstorm periods from meteorological data:
  - ⇒ Clear radio excess during thunder storms
  - ⇒ B-field effect dominates under normal conditions
  - ⇒ >90% duty cycle possible





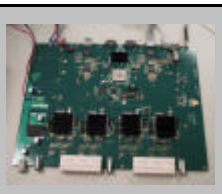
Buitink et al. (LOPES coll.) 2005 & 2006 in prep.

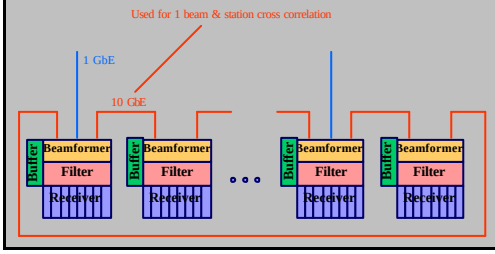
Configuration



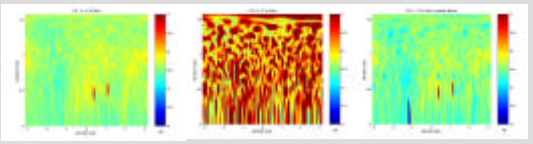
Station based processing

- Input data rate: ~ 460 Gbps
- Output data rate: ~ 2 Gbps
- Processing capacity: ~ 1.5 Tmul/s
- Storage capacity: 96 Gbyte





ITS Spatial Filter Experiment



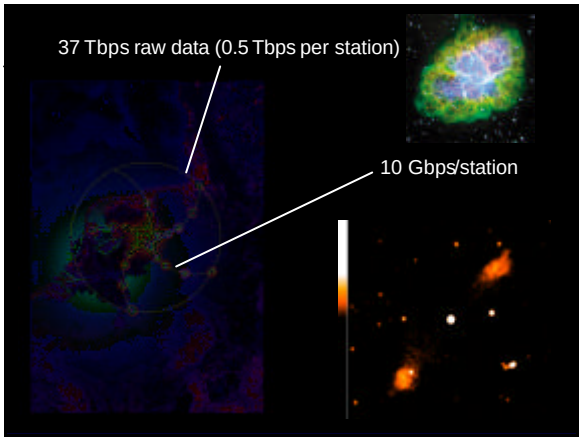
ITS sky map at 27.85 MHz, no RFI. Two strong sources (Cas A, Cyg A) visible

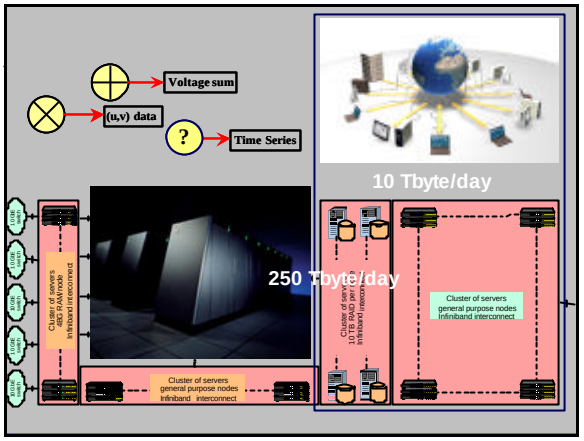
ITS sky map at 27.81 MHz, strong RFI at (Az,el) = (-1.3,0) rad

ITS sky map at 27.81 MHz, fixed null at (Az,el) = (-1.3,0) rad

ITS observation , 26 Feb. 2004, 60 antennas, df=10 kHz, 6.75 s integration

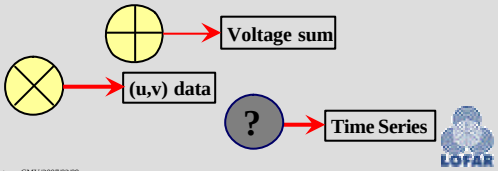
A.J. Boonstra, March 15, 2004

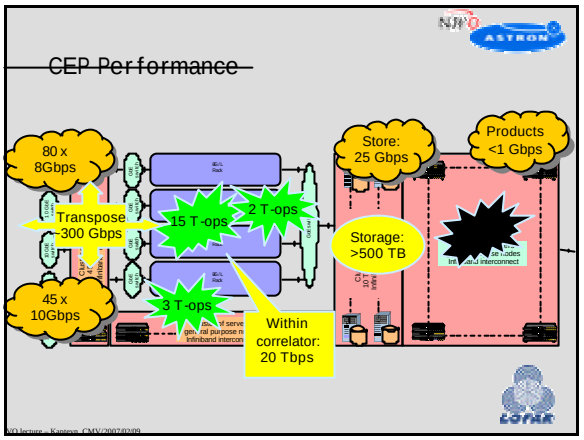




Central Processor Main Modes

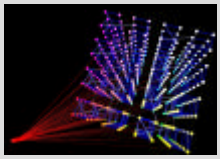
- Correlator for all station inputs (32 MHz) - imaging
- Correlator for Core Stations only and more FOV's - EOR
- Tied Array Beamforming using all stations - pulsars
- Tied Array Beamforming for Core Stations only - transients, pulsars

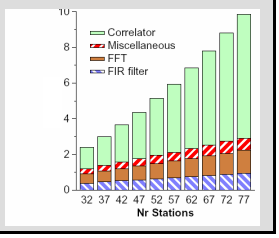




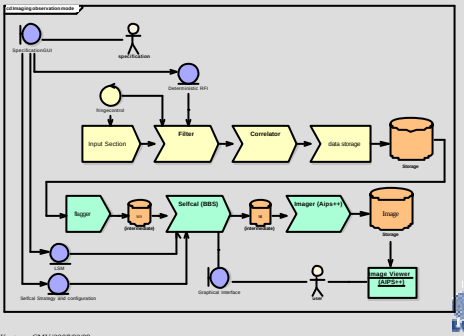
TFlopCorrelator demo

- Real-time correlation of predefined analog signals
- Performance: 97.5% of theoretical maximum





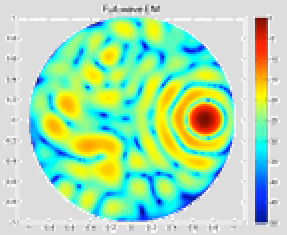
CS1 Imaging Pipeline



The LOFAR calibration challenge

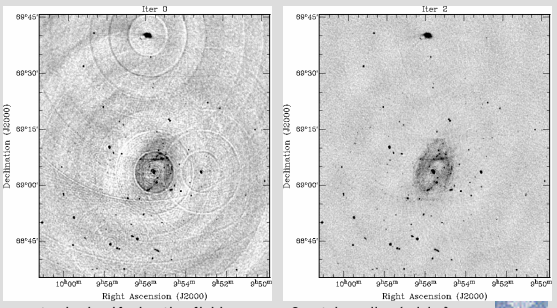
- Pathological Ionosphere (1 rad / 10 sec)
  - Affects source subtraction and imaging
- (Very) crowded fields
  - Source confusion
  - PSF sidelobe confusion: increases noise
- Unstable station beam shapes
  - Affects source subtraction and imaging
- High station side-lobes
  - Bright sources (incl galactic plane and Sun)

LOFAR Calibration = All Sky Calibration!



LBA Station beam @ 30 MHz

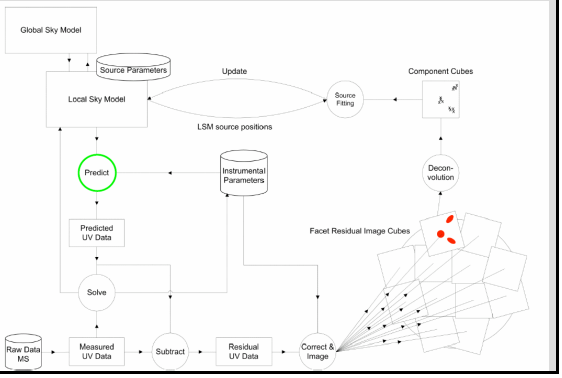
Peeling WSRT data

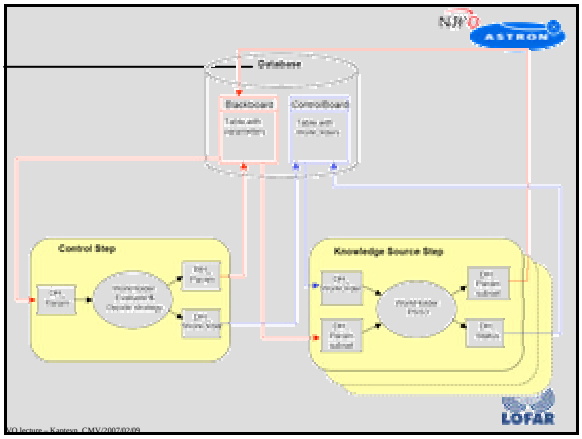


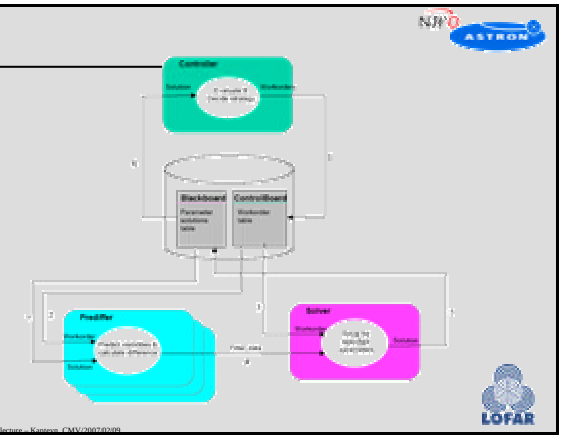
standard selfcal entire field

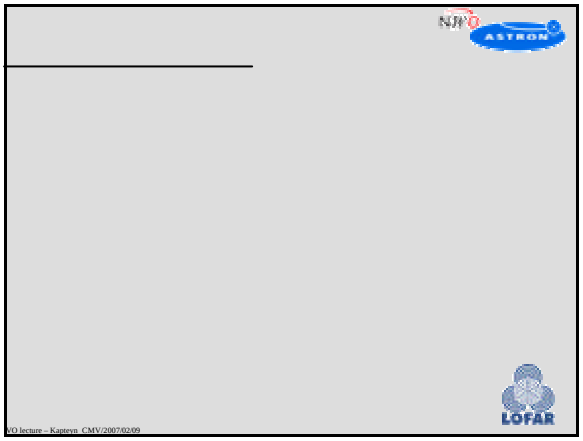
2-patch peeling (miriad)

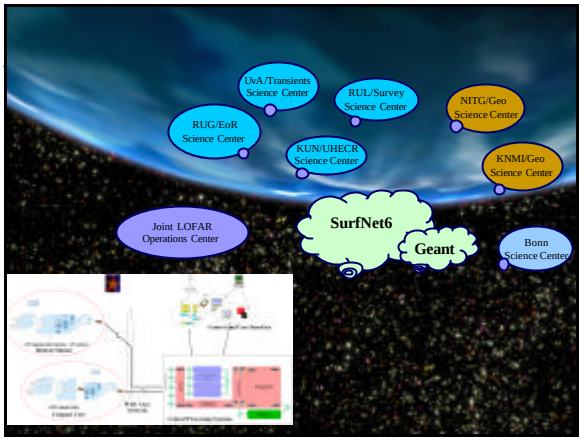
Major Cycle











Mapping on GigaPortNG/Surfnet6

Location	Institute	Datarate	Role/Comments
Groningen	RUG/RC: CEP	40 Gbps	LOFAR Central processor ***total outgoing***
Dwingeloo	ASTRON	4...10 Gbps	LOFAR Operations Center
Groningen	RUG/Astronomy	n/a (local)	Epoch of Reionization; Science Support
Amsterdam	SARA	20 Gbps	Long term storage (tbc)
Amsterdam	UvA/Astronomy	20 Gbps	Transients, pulsars bps sustained)
Leiden	RUL/Astronomy	10 Gbps	Surveys
Nijmegen	KUN/Astronomy	20 Gbps	Cosmic rays (average 1 Gpbs sustained tbc)
Utrecht	TNO-NITG	10 Gbps	Geophysical data centre
Utrecht	KNMI	1 Gbps	Geophysical processing; weather data
Bonn	MPIfR	1 Gbps ?	German Science Centre (via Géant)

Multi-tier models for LHC & LOFAR

Large Hadron Collider

- Tier-0 (CERN):
  - copy of all raw data
- Tier-1 (~8-10 centers)
  - archive 1/n fraction of raw data & reconstructed data
  - regular re-processing of the raw data
  - archiving data from Tier-2 centers
  - provide central grid services: grid accessible computing and data resources
  - support coordination
- Tier-2 (~100 centers):
  - data analyses
  - no data archiving

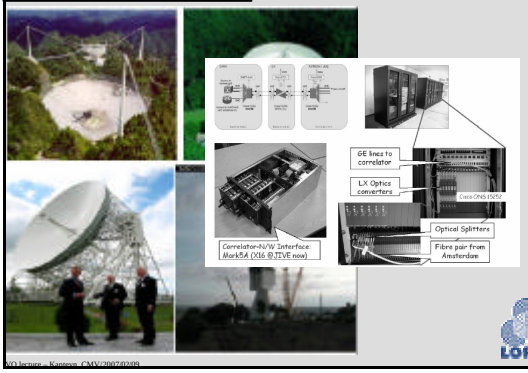
LOFAR

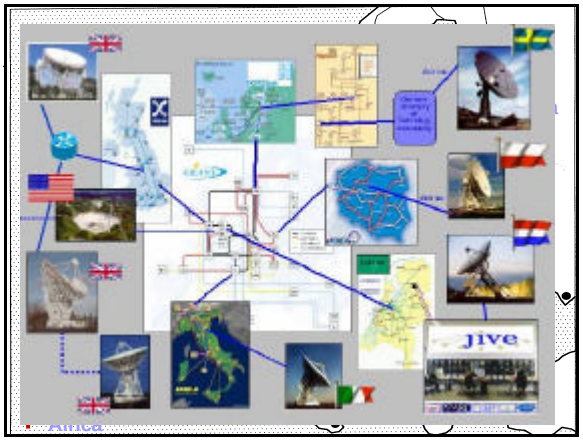
- Tier-0 (RUG): central processor
  - lots of processing, limited archive
- Tier-1 (~6-8 centers)
  - specialized science analysis
  - advanced processing of (large) data sets
  - dedicated archive, also for Tier-2 centers
  - provide central grid services: grid accessible computing and data resources
  - support coordination
- Tier-2 (~100 centers):
  - individual scientists
  - data analyses
  - no data archiving

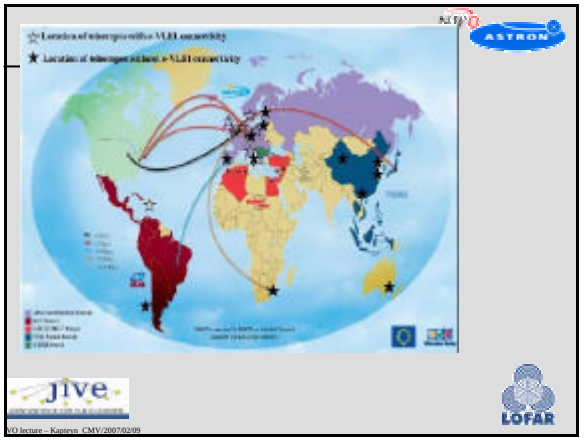
Towards a European Sensor Grid

LOFAR	For each Sensor Field	Phase 1 2008	European 2010
Sensor Fields (including Central Core)		77	93
Sensors			
Astronomical "LF" antennas	100	7700	9300
Astronomical "HF" antenna tiles	100	7700	9300
Geophysical vibration sensors (geophones)	18	1386	1674
Geophysical microbarometers (infrasound)	3	231	279
Agriculture sensors	80	6160	7440
Other sensors	8	616	t.b.d.!!!
Datarates			
Total digitized datarate from sensors	0.5 Tb/s	37 Tb/s	45 Tb/s
Datarate over LOFAR Backbone	10 Gb/s	0.8 Tb/s	1 Tb/s
Outgoing datarate over SURFnet6		40 Gb/s	60 Gb/s
European datarate over Géant		20 Gb/s	0.2 Tb/s
Installed Processing Power			
Total processing power		160 Tops/s	190 Tops/s
Distributed at Sensor Fields	1.5 Tops/s	116 Tops/s	150 Tops/s
Central Processor (including BlueGene)		43 Tflop/s	60 Tflop/s
BlueGene		33 Tflop/s	

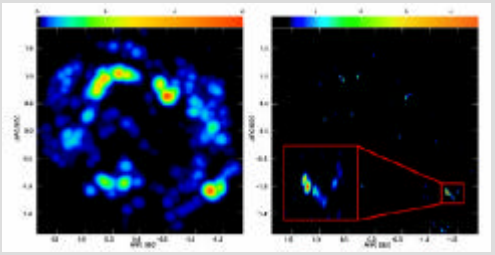
Very Long Baseline Interferometry







First e-VLBI results



jive

LOFAR

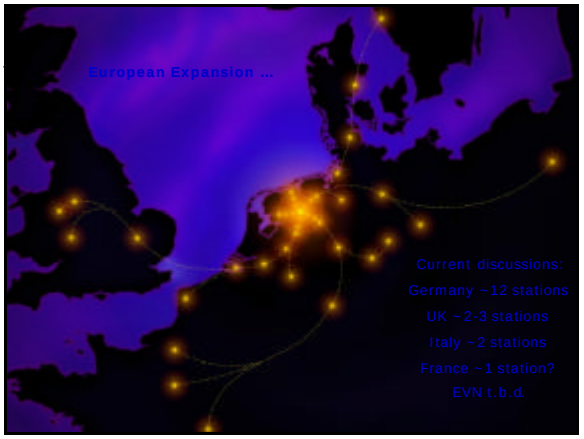
LOFAR Performance

Frequency (MHz)	A_{eff} (m^2)	T_{sys} (in K)	dS in 1s (mJy)	dS in 10h (mJy)	dS in 100h (mJy)
30	3.3×10^5	23k	68	0.35	0.11
75	5.2×10^4	2450	46	0.24	0.07
120	3.3×10^5	820	2.4	0.013	0.004

Approximate sensitivity per beam, with 4 MHz BW and for a single polarization

LOFAR

GLOW – German Long Wavelength Consortium

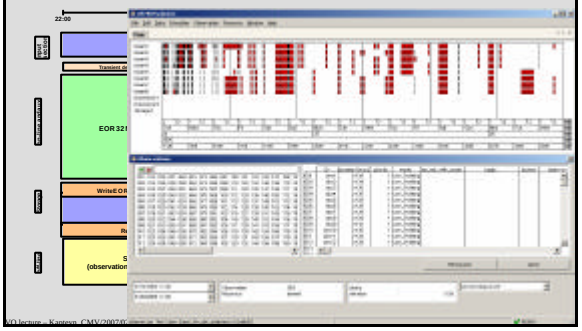


Some actual LOFAR stations

Baselines and Resolution

				240	115	80	30	MHz
Site:	**Latitude**	**Longitude**	**D(km)**	**125**	**261**	**375**	**999**	**cm**
CS-1	52,927	6,877	0					
LOFAR 77			50	5,2	10,8	15,5	41,2	"
Effelsberg	50,533	6,883	267	1,0	2,0	2,9	7,7	"
Potsdam	52,400	13,067	422	0,6	1,3	1,8	4,9	"
Onsala	57,400	11,917	595	0,4	0,9	1,3	3,5	"
Chilbolton	51,144	-1,436	602	0,4	0,9	1,3	3,4	"
Nancay	47,383	2,200	702	0,4	0,8	1,1	2,9	"
Torun	53,017	18,617	786	0,3	0,7	1,0	2,6	"
Medicina	44,521	11,645	997	0,3	0,5	0,8	2,1	"

Pioneering new operational models



The path to the SKA

	Long Haul data network			*Central processor*	*Output data rate*
	Distance	**Net data rate to processor**	**Technology**		
LOFAR	160 km	800 Gb/s	8 GbE CWDM	43 Tflop/s	10 TByte/day
E-LOFAR	2000 km	1 Tb/s	10 GbE	60 Tflop/s	20 TByte/day
SKADS demo.	single tile	30 Gb/s	10 GbE	10 Tflop/s	0.3 Tbyte/day
APERTIF	2 km	1.6 Tb/s	10 GbE	0.5 Pflop/s	200 Tbyte/day
e-VLBI	9000 km	2 Tb/s	t.b.d.	1 Pflop/s	400 Tbyte/day
SKA	>3000 km	10 Tb/s	t.b.d.	~ 10 Pflop/s	~ Pbyte/day