Practical Radio Interferometry

VLBI

Olaf Wucknitz

wucknitz@astro.uni-bonn.de

Argelander-
Institut
für
Astronomie

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VLBI

- Need for long baselines
- What defines VLBI?
- Techniques
- VLBI science
- Practical issues
  - VLBI arrays
  - how to observe
  - calibration
- New developments
  - space VLBI
  - e-VLBI
  - LOFAR

Need for long baselines

- baseline D
- wavelength λ
- resolution $\theta \sim \lambda/D \quad [\ 1'' = 5 \times 10^{-6}$ rad]

	$D = 100$ m	1 km	10 km	100 km	1000 km	10 000 km
$\lambda = 1$ m	30′	3′	20″	2″	200 mas	20 mas
20 cm	6′	40″	4″	400 mas	40 mas	4 mas
6 cm	2′	12″	1″	120 mas	12 mas	1 mas
2 cm	40″	4″	400 mas	40 mas	4 mas	400 μas
7 mm	15″	1.″5	150 mas	15 mas	1.5 mas	150 μas
3 mm	5″	500 mas	50 mas	5 mas	500 μas	50 μas

The situation in the 50s/60s

- Australia: radio-linked interferometers up to $D = 10$ km at $\lambda = 3$ m $\rightsquigarrow \theta = 1'$
- Cambridge One-Mile and 5-km telescopes
- Jodrell Bank: portable antennas radio-linked with 250-ft up to $D = 130$ km at $\lambda = 2$ m down to 6 cm $\rightsquigarrow \theta < 1''$
- later MTRLI (Multi-Telescope-Radio-Linked-Interferometer), later renamed to MERLIN (Multi-Element-Radio-Linked-Interferometer-Network) (1980)
- direct connections or radio-link difficult for longer baselines

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The need for longer baselines

- some sources still unresolved at these scales ($<$ 50 mas)
- interplanetary scintillation: $\sim$ few mas
- synchrotron self-absorption: $\sim$ 1 mas
- flat-spectrum sources: flux variations on time-scales of months or less: $\lesssim$ mas
- resolving these source not possible with connected (or radio-linked interferometers)

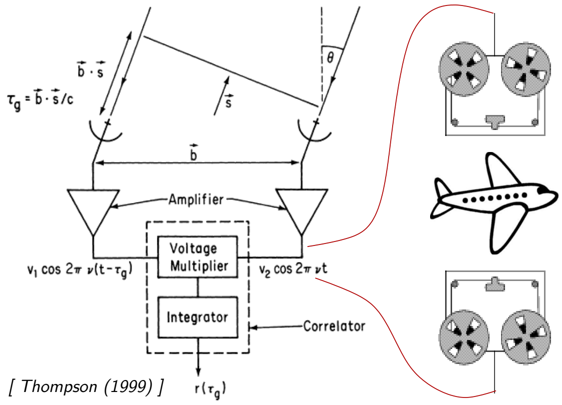
$\rightsquigarrow$ Very Long Baseline Interferometry

Very Long Baseline Interferometry

- very long baselines
- no direct connection between stations
- record signals on tapes, disks, etc.
- play back simultaneously and correlate later

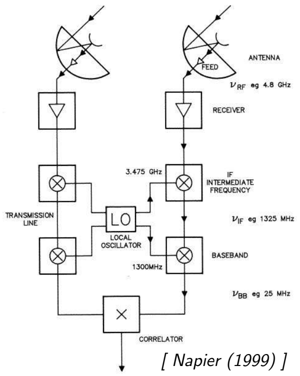
- synchronisation: also record time-stamps
- observe at exactly the same frequency

Connected interferometer → VLBI



[Thompson (1999)]

Connected → VLBI : more details



[Napier (1999)]

- connected interferometer
  - mix down to IF
  - amplify and transmit at IF
  - mix down to baseband
  - correlate
- VLBI
  - mix down to IF
  - amplify at IF
  - mix down to baseband
  - record, fly, play back
  - correlate

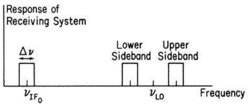
$\rightsquigarrow$ need accurate LOs !

The role of the local oscillators

- keep the time
  - need to play back signals synchronised
  - required accuracy: coherence time
  - coherence time $\sim 1/$ bandwidth
  - keep synchronisation over observation

- define the observing frequency
  - observing frequency ν shifted to baseband
  - recorded frequency ν': $\quad \nu' = \nu - \nu_0$
  - error in ν_0 translates to error in ν', ν

[Thompson (1999)]



The correlation

- direct correlation of signals V_1 and V_2
  - signals $\quad V_1(t) = A_1\,\mathrm{e}^{2\pi\mathrm{i}\nu t} \qquad V_2(t) = A_2\,\mathrm{e}^{2\pi\mathrm{i}\nu t}$
  - correlation: $C_{12} := \langle V_1(t) V_2^\star(t)\rangle$
    $$= \left\langle A_1 A_2^\star\,\mathrm{e}^{2\pi\mathrm{i}(\nu-\nu)t}\right\rangle = A_1 A_2^\star$$

- correlation of down-mixed signals V_1' and V_2'
  - frequencies of local oscillators: ν_1 and ν_2
  - signals $\quad V_1'(t) = A_1\,\mathrm{e}^{2\pi\mathrm{i}(\nu-\nu_1)t} \qquad V_2'(t) = A_2\,\mathrm{e}^{2\pi\mathrm{i}(\nu-\nu_2)t}$
  - correlation: $\quad C_{12}' := \left\langle V_1'(t) V_2'^\star(t)\right\rangle$
    $$= \left\langle A_1 A_2^\star\,\mathrm{e}^{2\pi\mathrm{i}(\nu_1-\nu_2)t}\right\rangle$$

VLBA station system

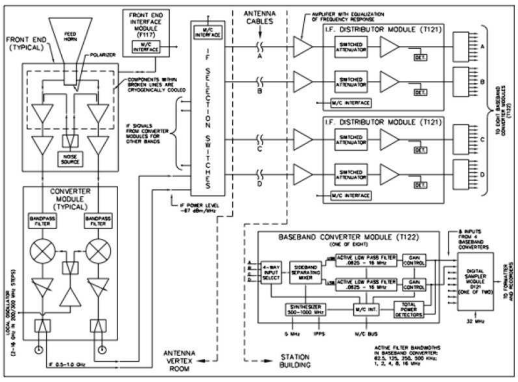


Figure 5.3: Simplified block diagram of the analog signal path at RF, IF, and baseband frequencies.

Sampling and digitisation

- mix down to baseband (for several bands)
- frequency range 0 – bandwidth
- Nyquist sampling $2\times$ bandwidth
- typical sampling width 1 or 2 bits
  - recording bandwidth limited
  - optimal 1–2 bit
  - typical 2 bit

bits per sample	sampling sensitivity	relative bandwidth	bandwidth sensitivity	total sensitivity
1	1	1	1	1
2	1.38	1/2	$1/\sqrt{2}$	0.98
4	1.5	1/4	1/2	0.75

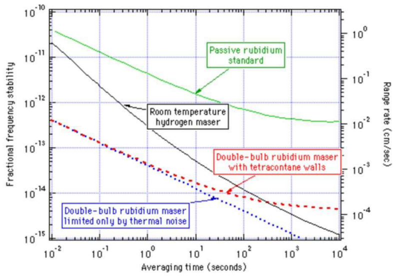
Recording systems

- Canadian analog system studio TV recorders, 4 MHz, 3 h
- MkI digital 7-track computer tape, 330 kHz, 1-bit, 150 sec
- MkII video recorders (later VCR), 1-bit, 2 MHz
- MkIII 28-track tape recorders, 1-bit, 4 MHz per track
- Canadian S2 VCR (8 in parallel), 128 Mb/s
- Japanese K-2, K-3, K-4
- VLBA 1 or 2-bit, 8 bands, 32-track tape, 256 Mb/s per recorder
- MkIV similar to VLBA but up to 512 Mb/s
- $\boxed{\text{Mark 5}}$ → Mark 5C disk recording, 1024 Mb/s (→ 4096)
- PC-EVN, Japanese K5, . . .

[Alef (2004)]

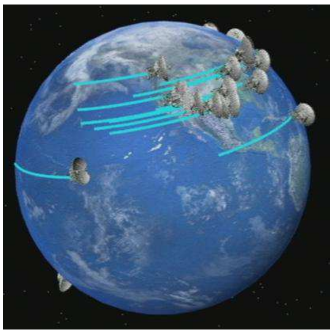
Stability of local oscillators

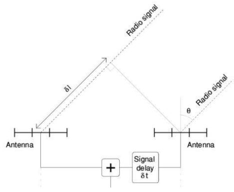
- atomic clocks (rubidium or hydrogen masers)



- long-term synchronisation with GPS receiver

Geometric delays





$$\boxed{\begin{aligned} \tau &\sim \frac{10\,000\,\mathrm{km}}{300\,000\,\mathrm{km/s}} \\ &\sim 30\,\mathrm{ms} \\ \frac{1}{\nu} &\sim 1\,\mathrm{ns} \\ \tau\,\nu &\sim 3\cdot 10^{7} \end{aligned}}$$

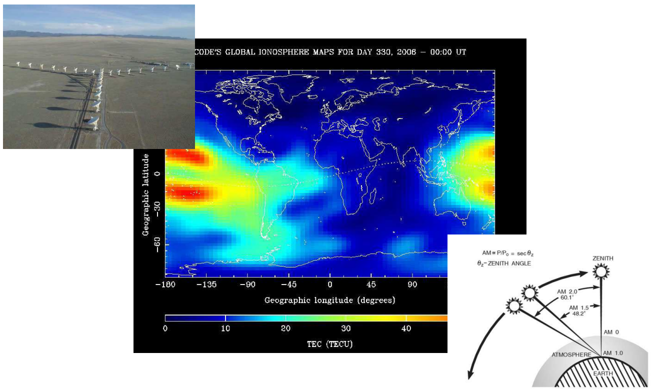
Delays, phases, rates

- effect of a delay τ
  - telescope signal $\quad V_j(t) = A_j \mathrm{e}^{2\pi\mathrm{i}\nu(t-\tau_j)}$
  - correlation $\quad \langle V_1\,V_2^\star\rangle = A_1 A_2^\star \mathrm{e}^{2\pi\mathrm{i}\nu(\tau_2-\tau_1)}$
  - phase $\quad \boxed{\phi = 2\pi\nu(\tau_2-\tau_1)}$

- frequency dependence
  - $\boxed{\dfrac{\partial\phi}{\partial\nu} = 2\pi\tau}$ ‘delay’ is frequency-derivative of phase

- phase rate and delay rate
  - $\boxed{\dfrac{\partial\phi}{\partial t} = 2\pi\nu\dfrac{\partial\tau}{\partial t}}$ equiv. Doppler effect, frequency error

Delays: connected vs. VLBI



Delay model

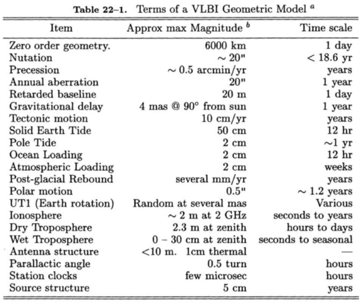


Table 22–1. Terms of a VLBI Geometric Model [a]

Item	Approx max Magnitude [b]	Time scale
Zero order geometry.	6000 km	1 day
Nutation	~ 20"	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration	20"	1 year
Retarded baseline	20 m	1 day
Gravitational delay	4 mas @ 90° from sun	1 year
Tectonic motion	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 cm	~1 yr
Ocean Loading	2 cm	12 hr
Atmospheric Loading	2 cm	weeks
Post-glacial Rebound	several mm/yr	years
Polar motion	0.5"	~ 1.2 years
UT1 (Earth rotation)	Random at several mas	Various
Ionosphere	~ 2 m at 2 GHz	seconds to years
Dry Troposphere	2.3 m at zenith	hours to days
Wet Troposphere	0 – 30 cm at zenith	seconds to seasonal
Antenna structure	<10 m. 1cm thermal	—
Parallactic angle	0.5 turn	hours
Station clocks	few microsec	hours
Source structure	5 cm	years

[Walker (1999)]

- predictable delays are corrected by the correlator
  - geometric delay
  - earth rotation
  - aberration
  - dry atmosphere
- unpredictable delays have to be calibrated later
  - wet atmosphere
  - ionosphere
  - station clocks

Calibration of VLBI data

- very similar to connected interferometers
- additional steps due to
  - long baselines → high resolution
    - ∗ need accurate source positions
    - ∗ no amplitude calibrators available
    - ∗ use T_{sys} to calibrate
    - ∗ limited field
  - long baselines → unstable phases
    - ∗ need bright fringe-finder source
    - ∗ phase-referencing
    - ∗ stop phase-winding: fringe-fitting
- other issues
  - sparse uv coverage

Amplitude calibration

- correlation coefficient $C_{jk} = B\frac{V_{jk}}{\sqrt{N_j N_k}}$
- B: digitisation etc., V: visibility amplitude [Jy]
- N: Source Equivalent Flux Density (SEFD) [Jy]
  - $N = \frac{T_{\mathrm{sys}}}{G}$
  - G: antenna gain [K/Jy] elevation dependent increase in system temperature for a 1 Jy source
  - T_{sys}: system temperature [K] highly variable
  - T_{sys} measured (with additional noise source)
    - ∗ VLBA: continuously
    - ∗ EVN: during recording gaps

Practical amplitude calibration in AIPS

- T_{sys} and G already in data (EVN, VLBA)
  - `FITLD` the data with `TY` and `GC` table
- otherwise
  - load ASCII tables with `ANTAB`
- use `APCAL` to produce `SN` table
- `CLCAL` to apply `SN` and produce `CL` table

Phase-cal (a.k.a. pulse calibration)

- calibrate instrumental delays for each observing band
- phase-cal tones (e.g. VLBA)
  - injection of pulses every 1 μs near feed
  - regular coherent spikes every 1 MHz
  - intrumental phases and delays from them
  - `PCLOD` to load ASCII table → `PC` table
  - `PCCOR` to produce `SN` table, `CLCAL` → `CL` table
- manual phase-cal (e.g. EVN)
  - use strong calibrator source
  - fringe-fit (see later) for delay and phase
  - apply solutions to all data

The need for fringe-fitting

- large time-varying delays
  - phases change rapidly
  - phase changes frequency-dependent
- standard calibration techniques
  - determine phases regularly
  - ∼ constant between the measurements
  - had to do this every few seconds!
- fit delays and rates instead of phases
  - allows for rapid changes
  - rate of changes and delays vary more slowly

Linear approach for residual phases

$$\phi(t,\nu) = \phi_0 + \frac{\partial\phi}{\partial\nu}\Delta\nu + \frac{\partial\phi}{\partial t}\Delta t \quad [+\text{dispersive delay}]$$

- have to determine
  - phase ϕ_0
  - delay $\frac{\partial\phi}{\partial\nu}$
  - rate $\frac{\partial\phi}{\partial t}$
- delays and rates are stable over a longer time and wider band than $\phi(t,\nu)$
- the process to find phase, delay, rate is called ‘fringe-fitting’

Practical fringe-fitting with AIPS

- tasks `FRING` or `KRING`
- more sophisticated version of `CALIB` (but no amplitudes)
- first step: coarse grid-based search for baselines (maybe with stacking)
  - FFT from frequency-time to delay-rate domain
  - find peak delay and rate
- second step: refine on station-basis
  - least-squares solution → `SN` table
- can use multi-band or dispersive delay
- transfer solutions from calibrators to target sources
  `CLCAL` to apply `SN` table and produce `CL` table

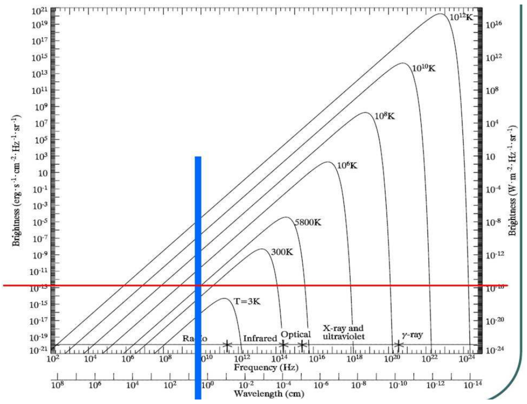
Other issues

- high resolution
  - use small pixels for maps (`CELLSIZE` in `IMAGR`)
  - field very small
  - maybe clean several sub-fields simultaneously
- *uv* coverage
  - mapping and self-calibration not very stable
  - hopefully simple source structure
- field-size limitations
  - primary beams (same as connected interferometers)
  - maximal field width:
    (array size) / (telescope size) ~ $(10^5\text{–}10^6)^2$ pixels
  - bandwidth smearing, time-averaging smearing
  - wide-field VLBI is a challenge!

VLBI science: objects

- sensitivity (μJy/beam) not less than other arrays
- **but:** beam is much, much smaller
- surface-brightness sensitivity is poor
- need bright but small sources
- high brightness temperature
- Planck-law: $\boxed{I_\nu = \dfrac{2h\nu^3}{c^2}\,\dfrac{1}{\mathrm{e}^{h\nu/(kT)}-1}}$
- Rayleigh-Jeans approximation: $\boxed{I_\nu \approx \dfrac{2kT\nu^2}{c^2}}$

Planck and Rayleigh-Jeans



Flux density and brightness temperature

- Rayleigh-Jeans approximation: $I_\nu \approx \dfrac{2kT\nu^2}{c^2}$
- flux density S_ν per beam: multiply with beam area

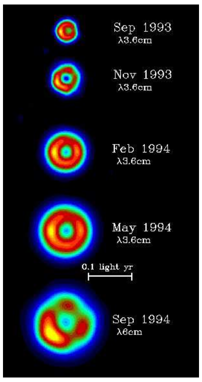
$$\text{beam area} \approx \left(\frac{\lambda}{L}\right)^2 = \frac{c^2}{\nu^2 L^2}$$

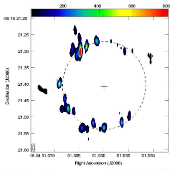
- baseline length L
- $\boxed{S_\nu \approx \dfrac{2kT}{L^2}}$ independent of ν !
- e.g. $L = 10\,000\,\mathrm{km}$, $S_\nu = 1\,\mathrm{mJy} \rightsquigarrow T = 4\cdot 10^7\,\mathrm{K}$
- VLBI sensitive mostly to non-thermal processes

VLBI science

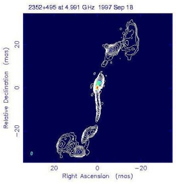
- jets from AGN, microquasars
- superluminal motion
- gravitational lenses
- extragalactic supernovae
- masers
  - circumstellar
  - megamasers in AGN
- astrometry
- geodesy

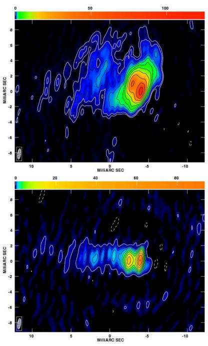
Some pictures . . .



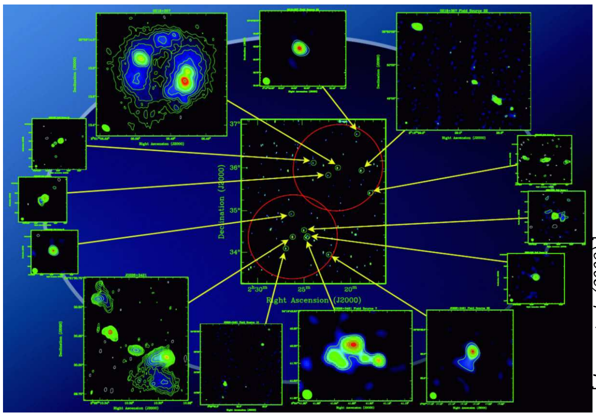


Total intensity (zero moment map) of G23.657–0.127.



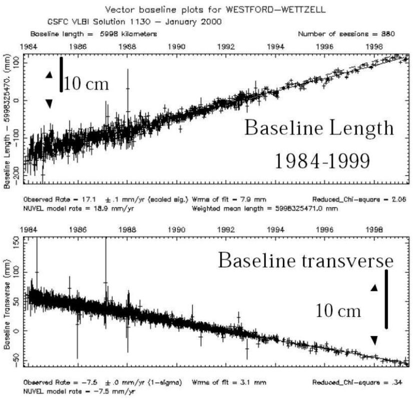


Wide-field VLBI at 90 cm



[*Lenc et al. (2008)*]

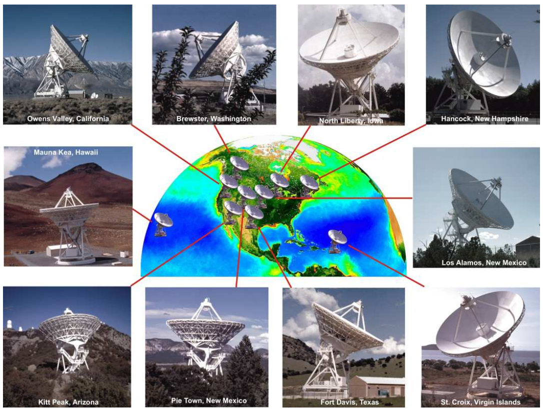
Geodesy



VLBI arrays

- Very Long Baseline Array (VLBA)
  - 10 identical telescopes of 25 m (USA)
  - full-time VLBI array
- European VLBI Network (EVN)
  - ∼ 18 telescopes (Europe, Asia, South Africa, Arecibo)
  - 3 sessions each year (+ e-VLBI)
- VLBI Exploration of Radio Astrometry (VERA)
  - 4 stations (Japan)
- High Sensitivity Array (HSA)
  - VLBA + VLA + Arecibo + Green Bank + Effelsberg
- Long Baseline Array (LBA)
  - 8 telescopes in Australia
- global VLBI
  - VLBA + EVN + anything

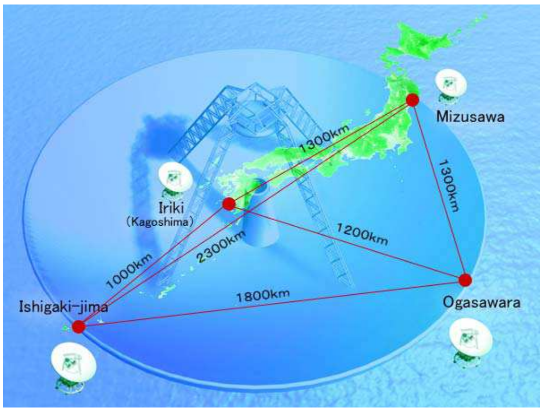
VLBA



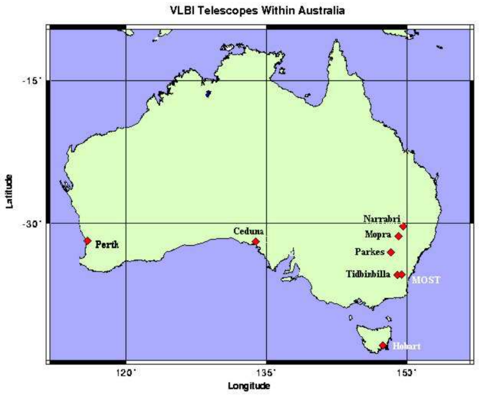
EVN

EVN correlator at JIVE

VERA

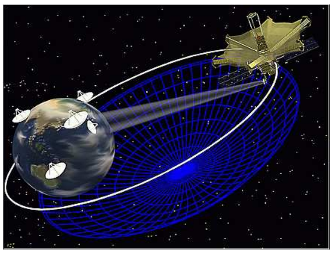


LBA

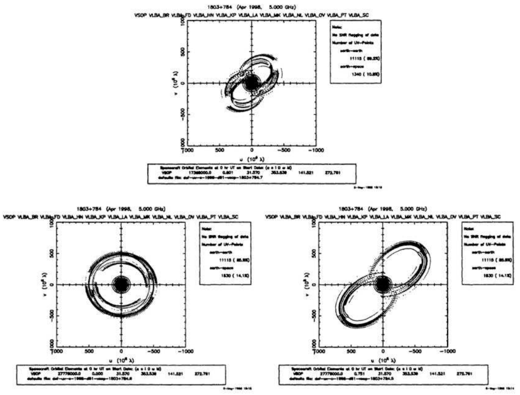


Special developments: Space VLBI

- VLBI Space Observatory Programme (VSOP)
- satellite HALCA (Highly Advanced Laboratory for Communications and Astronomy)
- launched 1997
- last contact 2003
- 8 m antenna
- 1.6 GHz and 5 GHz
- VSOP2 is planned



uv coverage with HALCA



[Ulvestad (1999)]

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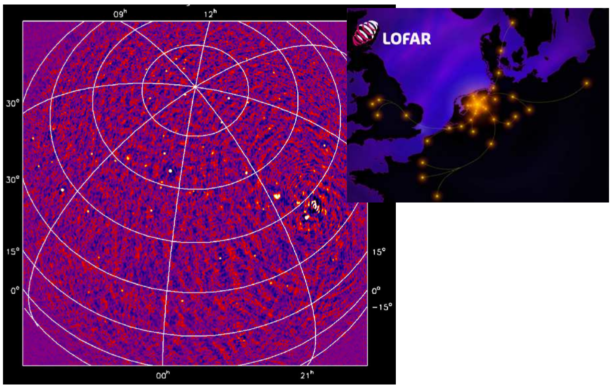
e-VLBI

- classical VLBI
  - record on tape/disk
  - ship tapes/disks to correlator
  - correlate later
- *e*-VLBI
  - send data directly to correlator
  - high-bandwidth data links (‘internet’)
- advantages of *e*-VLBI
  - immediate feedback
  - quick turnaround
- disadvantages of *e*-VLBI
  - cannot repeat correlation
  - no multiple passes

LOFAR



How to observe

- choose array, frequency, correlator mode, etc.
- write proposal
  - deadlines for VLBA, EVN, global: 1 Feb, 1 Jun, 1 Oct
  - special dates for EVN *e*-VLBI (changed ?)
- wait . . .
- write the schedule with `SCHED`
- wait for the correlated data
- calibrate, analyse, . . .
- general recommendation: ask the experts!