



Using Global Networks to Transform High Angular Resolution Astrophysics

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Australia Telescope National Facility

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The Australia Telescope National Facility

- A division of CSIRO.
- Australia's largest facility dedicated to astronomy.
- Operates as a National Facility for all astronomers.
- ~140 staff; ~\$20m budget.
- 3 observatories in NSW with headquarters in Sydney.
- Heavily involved in the next generation of facilities.



Mopra

Image: Shaun Amy



Australia Telescope Compact Array

Image: Shaun Amy



Parkes Radio Telescope

Image: Shaun Amy

Other Major Australian Radio Astronomy Facilities

- **University of Sydney:**

- The Molonglo Observatory Synthesis Telescope.

- **The University of Tasmania:**

- Mt Pleasant Observatory,
- Ceduna.

- **Tidbinbilla:**

- One of three NASA DSN tracking stations,
- Some time available as part of the host country agreement.

The Molonglo Observatory Synthesis Telescope



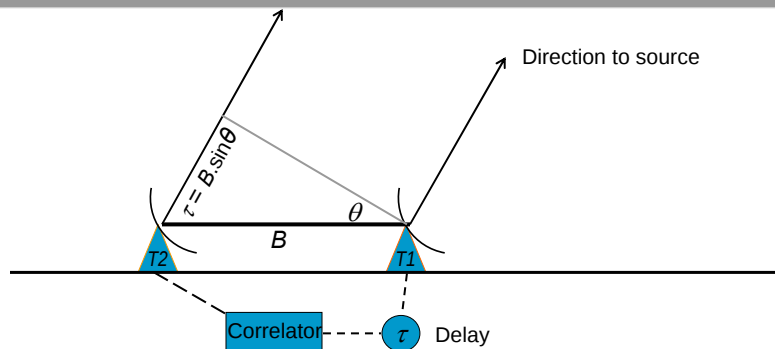
Image: Shaun Amy

Canberra Deep Space Communications Complex



Image: NASA

Principles of Interferometry



- This is known as a connected-element array,
- **Baseline B :**
 - Distance between antennas.
- “Virtual” telescope of diameter:
 - $B \cdot \cos \theta$ (projected baseline)
- Fringe pattern provides information on structure and position of the radio source.



Resolution

Resolution = Observing wavelength / Telescope diameter

Angular Resolution	Optical (5000Å)		Radio (4cm)	
	Diameter	Instrument	Diameter	Instrument
1'	2mm	Eye	140m	GBT+
1"	10cm	Amateur Telescope	8km	VLA-B
0."05	2m	HST	160km	MERLIN
0."001	100m	Interferometer	8200km	VLBI

Atmosphere gives 1" limit without corrections which are easiest in radio

Jupiter and Io as seen from Earth

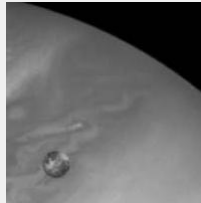
1 arcmin



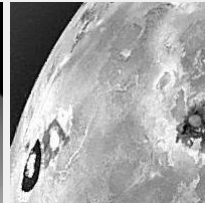
1 arcsec



0.05 arcsec



0.001 arcsec



Simulated with Galileo photo

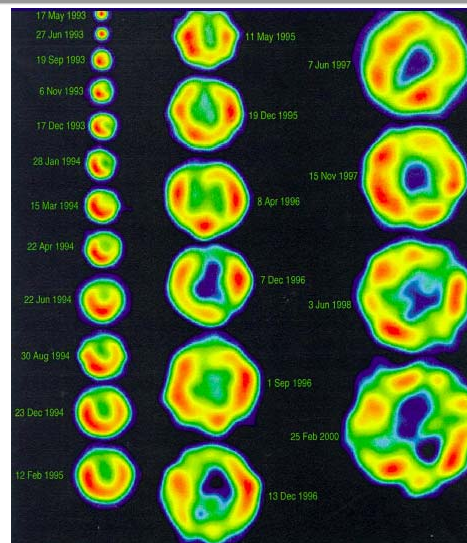
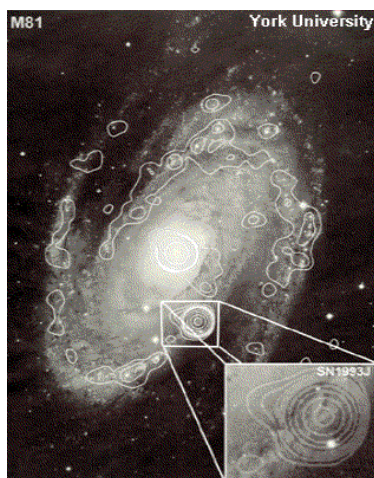
Very Long Baseline Interferometry

VLBI: Very Long Baseline Interferometry

- Angular resolution: $\text{Wavelength} / \text{Baseline}$
- VLBI uses various telescopes in an autonomous manner.
- Traditional mode of operation:
 - data recorded on tape or more recently disk,
 - transported to a correlator facility and “played back”,
 - data processed by correlator often weeks or months after the observation.
- Some issues:
 - very labour intensive,
 - setup /equipment configuration errors often not discovered until correlation,
 - difficult to respond to target of opportunity observations or conduct regular monitoring of certain classes of sources.



SN1993J: VLBI data



Credit: Bartel et al.



e-VLBI: Very Long Baseline Interferometry

- **Science requirements:**

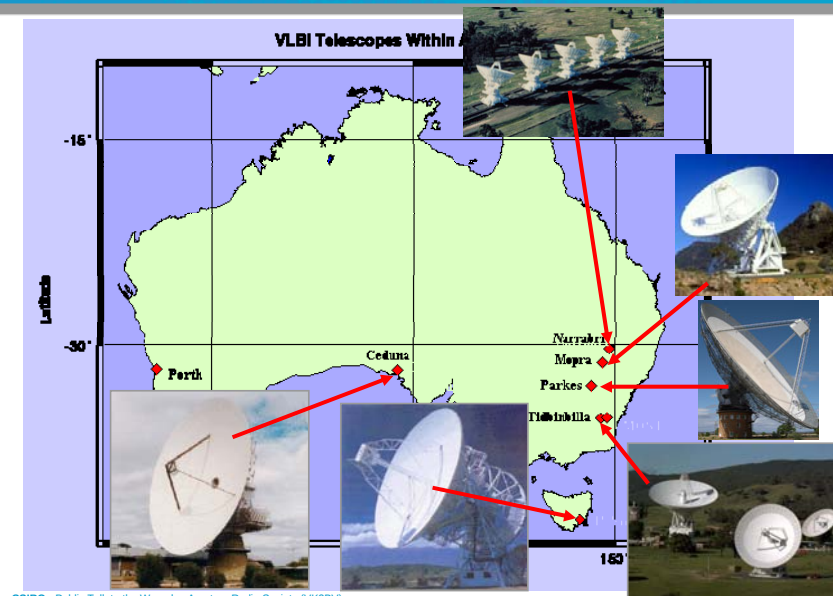
- higher sensitivity from higher bandwidth means higher data rates,
- facilitate wide-field imaging,
- fast response to “targets of opportunity”,
- routine/regular monitoring of evolving events,
- immediate assessment of results.

- **Transition to e-VLBI:**

- requires network infrastructure:
 - telescopes are typically built in remote locations,
 - may take many years before these observatories have connectivity capable of supporting e-VLBI operations (need hybrid approach),
- correlation on supercomputer clusters now possible:
 - Swinburne University DiFX software,
- obtain near to real-time operation,
- what happens if the network fails?



The Australian Long-Baseline Array

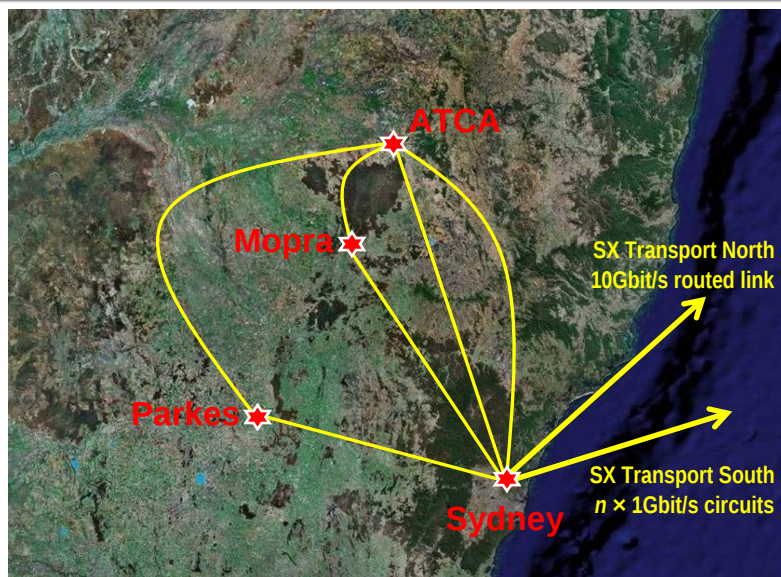


e-VLBI using the Australian LBA

- First e-VLBI science in March 2007.
- 512Mbit/s from Parkes, Mopra and the ATCA works reliably:
 - uses CSIRO shared network infrastructure,
 - layer 2 used for e-VLBI.
- Limited to 64Mbit/s from Hobart:
 - AARNet currently lease commercial capacity across Bass Strait,
 - 2 × 155Mbit/s links for all AARNet traffic in Tasmania.
- 1Gbit/s on a single baseline (Parkes - ATCA) commissioned in November 2007:
 - current data acquisition system provides two 512Mbit/s data streams,
 - requires "manual" traffic engineering,
 - used for a science experiment during the June 2008 session.
- Uses dedicated front-end I/O hosts for receiving the data.
- Data correlated using an existing cluster at Parkes.



Some (Network) Geography



EXPreS: Express Production Real-time e-VLBI Service

- **European Commissions FP6 project:**
 - the aim is to “create a distributed astronomical instrument of continental and intercontinental dimensions using e-VLBI.”
 - lead institution is JIVE
- **Australia’s involvement and contribution:**
 - ATNF and AARNet are partners in the project,
 - demonstrate real-time e-VLBI;
 - use telescopes in Australia,
 - process the data using the EVN correlator located at JIVE in the Netherlands.
- **3 x 1Gbit/s “lightpaths” from each observatory to JIVE:**
 - ATNF - AARNet - CENIC - CANARIE - SurfNet – JIVE.
- **Long round trip time:**
 - ~340ms.

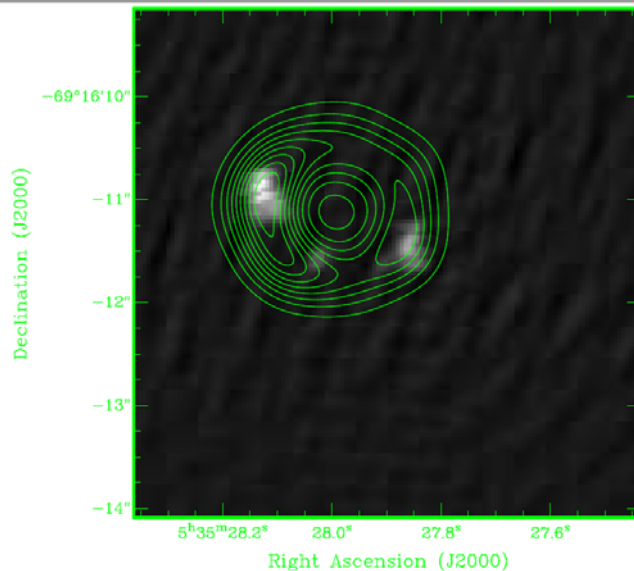


EXPreS: Science Observations

- **Three ATNF observatories used:**
 - ATCA, Mopra and Parkes,
 - observing conducted remotely from Sydney.
- **Data streamed at 512Mbit/s across three lightpaths:**
 - used existing LBA data recorders with on-the-fly format conversion,
 - sustained for 11 hours continuously,
 - used UDP.
- **Observed SN1987a at 1.6GHz:**
 - One of the aims was to determine if there was any emission from a compact central source.



An SN1987a e-VLBI Image



Contours: ATCA 9GHz image (0.4" FWHM); Greyscale: e-VLBI image



SN1987a: Results

- Highest resolution radio observation to date:
 - 85×168 milli-arcsec restoring beam:
 - comparable resolution to the HST,
 - $350 \mu\text{Jy}/\text{beam}$ RMS noise,
- 3σ upper limit of 1mJy on time-averaged pulsar emission, or a compact pulsar-powered nebula.
- Full ring resolved out by VLBI:
 - only 3 baselines.
- VLBI consistent with tilted optically thin ring model (see Gaensler *et al.* 2007):
 - brightness enhancements, longest path length regions along line of sight,
 - re-sampling model with equivalent spatial frequencies to that observed with this VLBI observation gives qualitatively similar image.



e-APT Demonstration (Shanghai, June 2008)

- **Connections:**

- Narrabri to Parkes at 512Mbit/s,
- Mopra to Parkes at 512Mbit/s,
- Shanghai to Parkes at 256Mbit/s,
- Kashima to Parkes at 512Mbit/s.

- **Correlation:**

- DiFX software correlator running on the Parkes APSR cluster.

- **AARNet have provisioned 3×622 Mbit/s circuits:**

- mixture of SDH and layer 2/3,
- AARNet, CENIC, JGN2, CSTNet, Pacific Wave, HKOEP,
- presented as gigabit Ethernet.

- **Transport protocols:**

- UDP used for overseas links,
- TCP used between ATNF observatories.

CSIRO, eVLBI-Aus

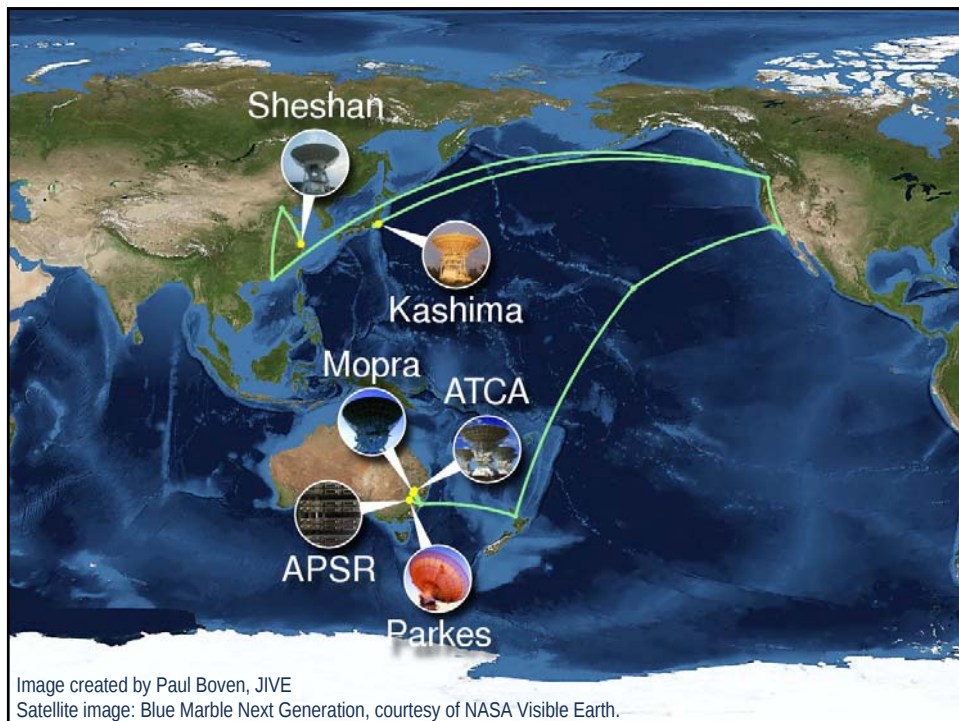
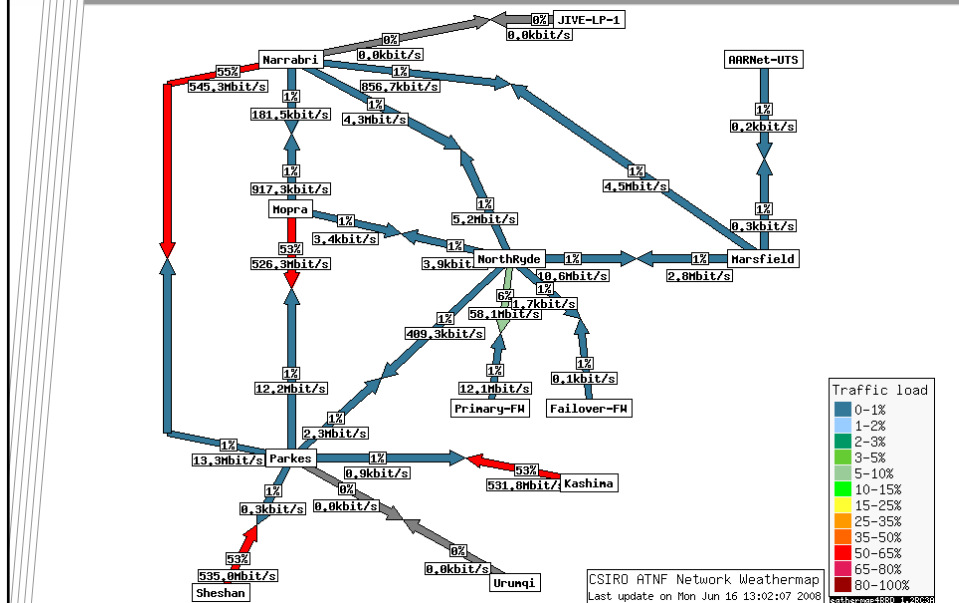


Image created by Paul Boven, JIVE

Satellite image: Blue Marble Next Generation, courtesy of NASA Visible Earth.

e-APT Network Weathermap



Internet2: Wave of the Future

- Winners of inaugural award!
- 10 Gbit/s connection on Internet2 (continental USA) for a one year period
- Possible usage:
 - eVLBI to Haystack,
 - eVLBI to JIVE,
 - eVLBI to other locations using the US as transit (e.g. asia).
- Hope to use this and existing network connections to further investigate some of the performance issues.
- Implementation details are still being worked out!

Network Issues

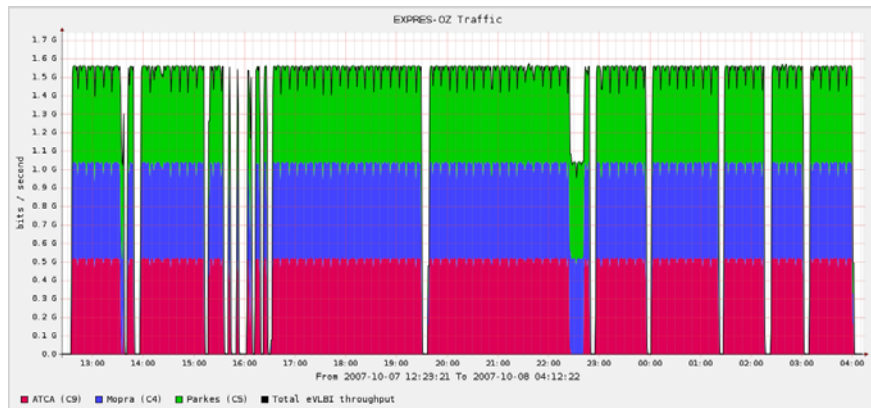


Network Issues

- BDP tuning is the easy part!
- Significant performance issues with the 10Gbit/s routed path:
 - network drops,
 - the long RTT seems to tickle problems in TCP implementations:
 - SACK issues?
 - use a customized version of TCP, CTCP written by JIVE and ATNF:
 - "ignores" network loss,
 - assumes no network congestion,
 - fixes the congestion window based on requested bandwidth and RTT.
- EXPReS: Lightpaths work much better than the routed network, but on all three lightpaths, see drops every 10 minutes:
 - various loopbacks (resulting in even a longer RTT), at points along the path, result in a very stable network,
 - maybe a subtle incompatibility with GFP between the two endpoints...



Australia – Netherlands Data Transfer



Credit: Paul Boven, JIVE



Where to now...

- **Routed network:**
 - should be able to get 512-1024Mbit/s across a 10Gbit/s routed path!
 - need to deploy some network performance and monitoring tools at key points in these long-haul networks.
- **Lightpaths:**
 - huge engineering effort:
 - OK for one-off events but not viable longer-term,
 - 1Gbit/s circuits are not ideal for e-VLBI use:
 - circuit rates to suit science requirements would be ideal (e.g. recent circuits have been provisioned as 622Mbit/s links).
 - e-VLBI use is "bursty" (but not in the traditional network sense):
 - needed for only certain periods of time,
 - really would like cross-NREN dynamic circuits that could be booked in advance,
 - fault-finding is difficult and time consuming:
 - we need (better) Layer 2 and SONET/SDH tools.



The Next Generation of Radio Telescopes



The Square Kilometre Array (SKA)

- SKA Key Science Goals:
 - probing the dark ages,
 - galaxy evolution, cosmology and dark energy,
 - origin and evolution of cosmic magnetism,
 - was Einstein right?
 - cradle of life.
- 17 countries.
- \$2B dollars.
- Sited in either Australia or Southern Africa (final site selection in about 2011).
- Pathfinder instruments:
 - ASKAP,
 - MeerKAT,
 - ATA,
 - MWA.



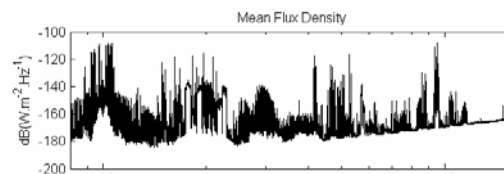
The Australian SKA Pathfinder (ASKAP)

- Technology for the SKA:
 - infrastructure,
 - COTS equipment,
 - remote operation,
 - focal-plane arrays,
 - computing challenges.
- Approximately 1% of SKA.
- Useful astronomical instrument in its own right.
- Funded: A\$100.9m.
- Up to $45 \times 12\text{m}$ antennas located near Boolardy station in Western Australia.

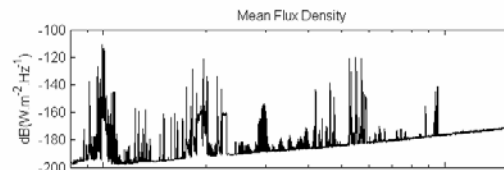


Comparing the RF Environment

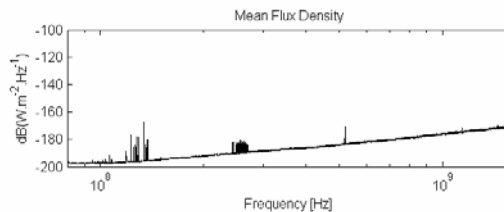
Sydney
Pop. 4 million



Narrabri
Pop. 6,000



Murchison
Pop. 4



ASKAP: Temporary Infrastructure

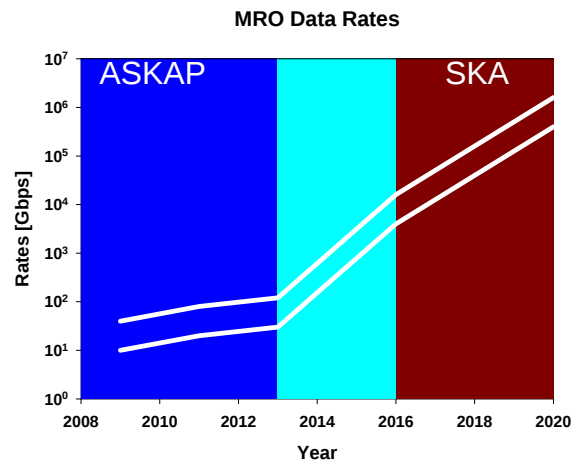


From ASKAP to SKA...

	ASKAP (1% Pathfinder)	SKA Phase 1 (10% Pathfinder)	SKA
Number 12 m dishes	45	500	5000
Frequency Range	0.7 – 1.8 GHz	0.3 – 10 GHz	0.3 – 22 GHz
Number of receivers	9,000	200,000	1,000,000
Bandwidth	0.3 GHz	2 GHz	4 GHz
DSP Processing	30 Teraflop	6,000 Teraflop	200,000 Teraflop
Computer Processing	2 Teraflop	1,200 Teraflop	24,000 Teraflop



ASKAP and SKA: Data Rates



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