Virtual Observatories and access to radio interferometry data

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RADIO INTERFEROMETRY

Radio interferometry produces visibility data which can be processed flexibly to achieve higher resolution or surface brightness sensitivity. Milli-arcsec angular resolution and velocity resolution <0.1 km/s can be achieved, in full polarization, with high position accuracy - radio sources are used to define the ICRF. These results are now within the reach of any astronomer as radio archives appear on-line and pipelines and other user-friendly data reduction tools become common. Images from the MERLIN archive, the NVSS, SUMSS and other surveys and many radio catalogues are already published electronically directly and via CDS. All raw VLA data are now available by ftp via a web form offering many search parameters. Radio astronomy archives are not data retirement homes, but a primary route to data via an increasing range of services, getting closer to delivering tailor-made analysis ready products.

VIRTUAL OBSERVATORIES

Virtual Observatories provide a single interface to compare radio data with results from across the electromagnetic spectrum. This means being able to select data of matched resolution, transform galactic, equatorial and other coordinates and understand flux and energy units from 10 MHz to 10 MeV. The AVO (European Virtual Observatory) has developed a prototype based on Aladin for displaying and measuring spectra and datacubes, source extraction, cross-matching and a variety of other services. The work of VOs around the world is coordinated through the International Virtual Observatory Alliance (IVOA). A vital part of its work is establishing a common language to describe data - metadata. The work of AstroGrid (UK) includes developing a user-driven tool to build complex workflows and testing IVOA Registry standards in practice at real data centres. Some examples of these developments are given below

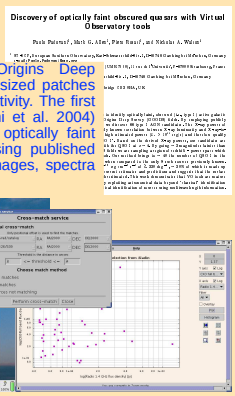
SURVEY OF RADIO DATA PROVIDERS

Nine radio observatories (ALMA, ATNF, BIMA, CARMA, IRAM, JCMT, JIVE, MERLIN, NRAO) responded to an IVOA questionnaire, covering metre to sub-mm waves, real-time correlation and VLBI. Data providers and users want:

- Clean images for analysis/multiwavelength comparison
- High spatial and spectral resolution datacubes
- Images from any part of the field of view
- Images of combined visibilities from different arrays
- Visibility 'light curves' for variable objects
- Standard metadata for VO use
- VO tools which understand radio units, field of view etc.
- Full history and quality characterisation
- Standardised export product format, not observatory software
- Remote friendly-interface access to user-driven pipelines
- Options depending on user experience

AVO INVESTIGATIONS OF THE GOODS FIELDS

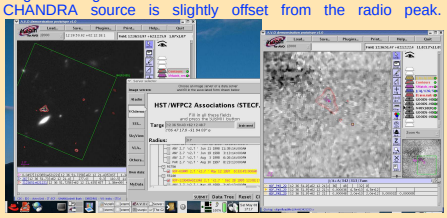
The Great Observatories Origins Deep Surveys are studies of Moon-sized patches of sky at unprecedented sensitivity. The first AVO science paper (Padovani et al. 2004) uses VO tools to search for optically faint quasars - 'type 2' AGN - using published CHANDRA, HST and ESO images, spectra and catalogues.



EMBBEDDED AGN IN STARBURST SYSTEMS?

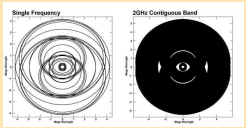
Radio waves also probe such highly obscured systems. The figure above (left) shows the coincidence of many MERLIN+VLA 1.4 GHz sources (red) and CHANDRA sources (blue), overlaid on the 8' CHANDRA image. The VLA image forms the background of this poster. The central insert shows the use of AVO tools to cross-match the Muxlow et al. (2004) and Alexander et al. (2003, AJ, 126, 539) catalogues. The VOPlot (right) shows that there is no obvious relationship between radio and x-ray luminosity. The radio emission from the majority of sources fainter than 100 microJy is extended, suggesting that it is of starburst origin, whilst their hardness ratio suggests that there is a significant AGN contribution to some associated x-ray sources.

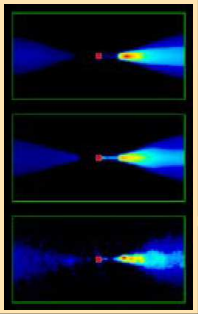
IVOA protocols are used for dynamic discovery of archive data which the AVO tool presents in convenient form such as stacked HST associations. The screenshot below (left) shows contours of the 1" radio source J123651+621221, which is not associated with the optically bright galaxy to the south. The NICMOS image (below right) shows a faint source within the radio contours. Note the change in orientation; overlaid images are automatically translated. There is also an ISO detection (gold) within the 3" ISO position uncertainty, all supporting a starburst origin for long-wavelength emission from J123651+621221. The hard CHANDRA source is slightly offset from the radio peak.



NEXT GENERATION INTERFEROMETERS

Many of the instruments coming on-line in the next decade, from LOFAR to ALMA, are introduced elsewhere in this conference. One of the first will be e-MERLIN. Using optical fibres to achieve up to 2 GHz bandwidth, it will take a single day to reach a similar noise level (1σ ~4 microJy) as the 2-week HDF(N) MERLIN image. The dense coverage of the visibility plane will improve image fidelity as well as sensitivity.

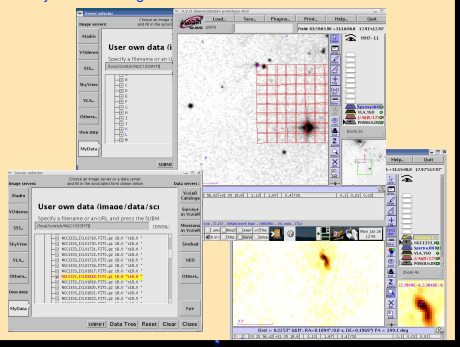




The 12-hr VLA image of 3C31 (bottom right) does not reach the necessary level to discriminate between the two decelerating radio jet models above (Laing & Bridle, 2002, MNRAS 336, 1161).
e-MERLIN at 20 cm will give twice the resolution and four times the signal/noise ratio in the same time.

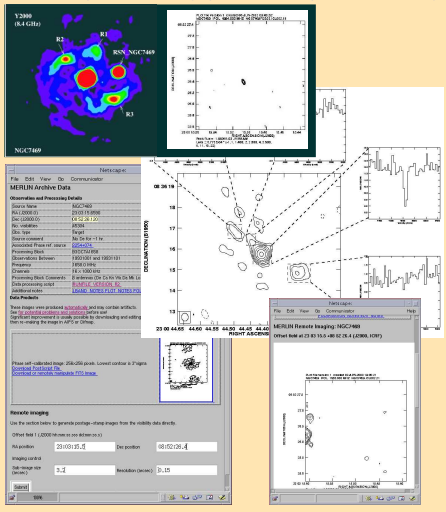
STAR FORMATION IN NGC 1333

The field of view of MERLIN at 6 cm is 8' while the resolution is a few tens of mas - potentially a Gpixel image! As the whole of NGC1333 is of interest, 814 Mpixel sub-images were made. The IDHA hierarchical data model provides organised access to multi-scale images. The MERLIN data collection was dynamically discovered on request, the AVO tool extracting metadata from the FITS headers to construct an informative tree. Clicking on a branch shows where its images lie on the low-resolution (POSSII) image; clicking on a point in that image is used to load the corresponding high-resolution radio map. The viewer provides tools to measure the angular size and flux density in the MERLIN image of MMS3. This gives a brightness temperature ~8000 K consistent with thermal emission from a low-mass YSO microjet ~80 au long.



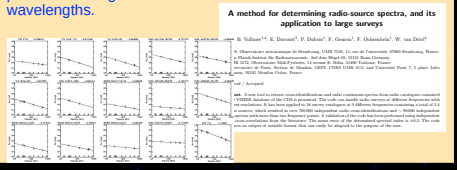
REMOTE USER-DRIVEN PROCESSING PROTOTYPE

The public MERLIN archive gives access to ready made FITS images of the field centres directly, or to calibrated visibility data on request. The ready-made images only cover a few percent of the field of view and the spatial, spectral and time resolution can be modified in re-imaging. In 1993 the core of the Seyfert galaxy NGC 7469 was observed for HI absorption (Beswick et al., 2002, MNRAS 335, 1091, spectra below right). Colina et al.(2001, ApJ 553 L19) discovered radio supernova 2000ft in one of its spiral arms (VLA image below, upper left). It was also detected by MERLIN in 2001 (below, upper centre). An experimental archive form (below, lower left) allows the supernova region to be imaged by averaging all the 1993 data, showing that it was not present in those data (below, lower right) and had errupted more recently.



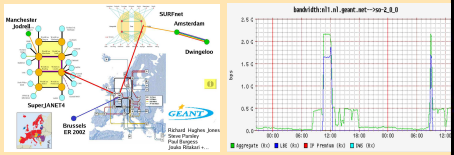
CROSS-IDENTIFYING RADIO SOURCES

The first challenge in analysis is to identify sources from different images and catalogues with a range of resolutions and position accuracy. Significant progress is being made using the method of Vollmer et al. (2004), based on the typical non- thermal spectral index of bright radio sources. This will lead to the inclusion of these sources in the SIMBAD data base as well as providing spectral indices for VO use. The next steps are to develop routines for relating extended sources and for objects which produce the brightest emission from different locations at different wavelengths.

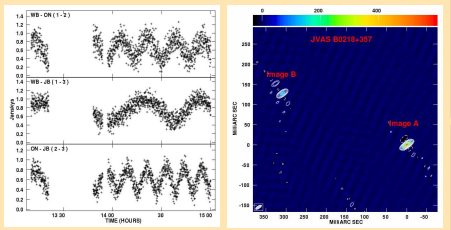


RADIO ASTRONOMY DATA TRANSPORT

The NGC 1333 images described above took 14 days of observation and 2 months 2-GHz processor time to reduce a 10 Gb visibility data set. e-MERLIN will reach 1000x the MERLIN data rate. Such developments add urgency to the VO mantra *"move the results, not the users nor the data"* and the need for specialised interferometry data centres. Parallelised data processing is already in use e.g. for pulsar searching (COBRA, JBO) and its application to interferometry data using `aips++` tools is being explored by NRAO and in the development of the CARMA sub-mm array. The JIVE VLBI correlator now provides pipelined calibration tables and diagnostic plots on-line and uses high-capacity links to achieve contemporaneous correlation of test EVN data. The plot below shows the DANTE academic network able to transport >10x its usual traffic.



On 2004/04/28 the first EVN data correlated in real time, from 3 countries, was used to image a gravitationally lensed galaxy.



RadioNet: Advanced Radio Astronomy in Europe

RadioNet (`www.radionet-eu.org`) promotes collaboration between European radio astronomy facilities:

- Science workshop and training group
- European Radio Astronomy engineering forum
- Software and users forum
  - ALBUS joint research activities
  - Parallelization
  - Wide-band/wide-field imaging
  - Software package evaluation
  - Archives and Virtual Observatories
- ALMA forum
- Astronomy across Europe:
  - Liaison - OPTICON, ILIAS, JENAM
- Radio frequency management

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