Connecting Radio Telescopes for Global VLBI

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JIVE
Outline

- Introduce concepts
  - What is VLBI, how is it organized in Europe
  - Data intensive radio astronomy
- Achievements of e-VLBI
  - Progress in EXPReS
- NEXPReS
  - Why? What we are addressing
  - Structure and Achievements
- What next
  - Development programme
  - Call for Global baselines
Acronyms/Organisations involved

• **VLBI:** Very Long Baseline Interferometry
  - Radio telescopes thousands kilometres apart

• **EVN:** European VLBI Network
  - Consortium of (European) Telescopes

• **JIVE:** Joint Institute for VLBI in Europe
  - Funded by radio-astronomy institutes and research councils
    - NWO (NL), ASTRON (NL), STFC (UK), INAF (IT), ICN-IG (ES), OSO (SE), MPG (DE)
    - CAS (CN), CNRS (FR), NRF (ZA)
  - Promote the use and advance of VLBI (for astronomy)

• **EXPReS:** FP6 project on establishing e-VLBI
  - Express Production Real-time e-VLBI Services

• **NEXPReS:** FP7 project building on e-VLBI
  - Novel Explorations Pushing Robust e-VLBI Services
Hartebeesthoek a very valued member of the EVN
• Now with 2 antennas on site
• North-south sensitivity on long baselines

South-Africa’s NRF joined JIVE foundation on May 10

Recognizing a joint interest:
• VLBI with KAT7 and MeerKAT
• The potential of the AVN
• Human capacity building
Joint Institute for VLBI in Europe

- Promote the use and advance of VLBI for astronomy
  - Central correlation; User services; Network support; Innovation; EC liaison/representation

- Founded in 1993
  - Base budget from partners in 9 countries:
    - Large number of external projects
    - Hosted by ASTRON, Dwingeloo NL
    - 34 employees

- Just been reviewed
  - Next 5-year funding cycle
  - In a newly build wing

- Aiming to be an ERIC
  - European Research Infrastructure Consortium
The European VLBI Network

- Big telescopes in number of European countries
- 20+ possible antennas
  - Ef, Mc, On, Jb, Nt, Tr, Wb, Sh, Ur, Hh, Ar, Mh, Ys, Sv, Ro, Ku, My, Wz, Sm, Ny, Ka
  - Ran by up to 14 different organizations
  - And 12 more antennas for “Globals” with NRAO

- Covering range of frequencies
  - Workhorse frequencies 18cm, 6cm,
  - Also available: SX, 5cm, 1.2cm
  - And at limited stations 90cm, 21cm, UHF, 50cm, 2cm, 0.7mm

- Reaching mas resolutions
  - From 15mas for 1.4 GHz EVN (can add MERLIN for brightness sensitivity)
  - To 1 mas at 5GHz with Asian, African or American baselines

- Sensitivity of 5μJy in 8hr at 1.4 GHz
  - Combination of Big Antennas and 1 Gbps bandwidth
  - Big antennas also vital for spectroscopy (mJy sensitivity)

- Operational approximately 60 days/year
  - 3 sessions augmented with e-VLBI once a month
First fringes to Irbene, near Ventspils, Latvia
3 data deluges, really...

- **Bandwidth is sensitivity**
  - Bring as much frequency space to the correlator (but not archived)
    - But can live with 2 bit sampled data
  - Currently 128 Mbps - 1 Gbps from 6 - 20 telescopes
  - Future goal: 16 Gbps from 32 telescopes
    - Then SKA plans to have 1000 telescopes...
  - Typically run for 12h, using the earth rotation for imaging

- **Correlation is relatively simple operation**
  - But requires a very high precision geometric model
  - Few operations per incoming bit
  - But huge distribution problem
  - Quadratic: every telescope correlated against every other
  - Results are archived for future use

- **Imaging considerations span orders of magnitude**
  - High spectral resolution from spectrometric applications
  - High spectral and time resolution for wide field imaging
  - Iterative calibration procedures
  - Runs typically in the user domain (GB - TB data sets)
    - Limited by different aspects (user skills, software issues, data quality)
    - Sometimes computer resources
• Hardware correlator from 90s
• Went to disk in 21st century
  • Enormous boost in robustness
  • Correlator efficiency
• The EVN software correlator at JIVE (SFXC)
• 9 stations 1Gbps real-time
  • Pulsar gating
  • Space craft applications
  • Spectral polarimetry
  • Many field of views
JIVE: Heart of the EVN

- VLBI requires central processor
  - Dedicated supercomputer
  - And data playback facilities
  - High precision digital equipment

- Plus all user interfaces
  - Proposal tool
  - EVN observation scheduling
  - Data product
  - Archive

- User support
  - Offer help in all stages
  - Preliminary processing
  - Visitor facilities
    - Currently being upgraded!
  - Point of contact various RadioNet funds

- Telescope support
Now turn to e-VLBI!

- PC based recording
  - Also allows Internet transmission
  - Upgrade EVN to e-EVN
    - Started with a pilot in 2004

- And was boosted with EXPReS
  - Retrofit correlator to work real-time
  - Help solve last mile problem at telescopes
  - Work closely with NRENs on robust connectivity
  - Push to 1024 Mb/s limit
  - Bring in the big telescopes
  - And start the revolution in radio-astronomy culture

- EC FP7 project
  - Radio-astronomy observatories
  - Some NRENs
Friends all over the world ready to collaborate

- All come together on the Dutch SURFnet infrastructure
- Large bundle from Amsterdam to Dwingeloo

Establish connectivity through Europe on GÉANT
- or using cross-border NREN connects
- Often together with LOFAR
- Operational facility
- often dedicated light paths
- Use optimized protocols
- Closed feedback loop makes e-VLBI more robust
Sections 1 and 3). We detected a source with a peak brightness of using the e-VLBI technique (see also Supplementary Information).

We conclude that in SN 2007gr a small fraction of the ejecta produced a low-energy mildly relativistic bipolar radio jet, while the bulk of the ejecta were slower and, as shown by optical spectroscopy, reveal a mildly relativistic expansion in a nearby type Ic supernova. SN 2007gr was one of the closest of its kind. Radio observations during supernova searches.

The class of type Ic supernovae have drawn increasing attention. The off-source noise in the map is 75 mJy per beam, show the map of SN 2007gr observed on 2007 September 6–7 at 5 GHz with the EVN using the e-VLBI technique.

Independent of the supernova explosion, SN 2007gr was less than five days old, based on its non-thermal radio emission. This was followed by a turnover to a bipolar ultra-relativistic jet at a position angle of 53.3°, with the early emission beamed into a narrow jet. The off-source noise is 13 mJy per beam, and the peak is 422 mJy.

The contours are drawn at 2, 5, 10, 20, and 40 mJy per beam. The image is centred at the GBT image of SN 2007gr.

The VLBI location of RA 02 h 43 min 27.975 s, dec. 37° 20′ 44.74″ was obtained at a lower resolution. The apparent position shift in the peak brightness from the centre indicates that at lower resolution there is a positional uncertainty of ±3.5 milliarcseconds (mas). The position measured by the EVN at the first epoch. The apparent position shift with respect to the position measured by the EVN at the first epoch is ±15.26 mas at a position angle of 44.64°.

The VLBI image is centred at the GBT image of SN 2007gr on 2007 November 5–6. At this epoch the off-source noise is 26, 26, 39 and 52 mJy per beam, show the map of SN 2007gr observed on 2007 September 6–7 at 5 GHz with the EVN using the e-VLBI technique. The contours are drawn at 2, 5, 10, 20, and 40 mJy per beam. The image is centred at the GBT image of SN 2007gr.

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Observations

• Now an operational facility
  • Guaranteed 10 x 24h per year
    • And quite bit more in practice (>30%)

• Flexible ways to get into e-VLBI
  • Request e-VLBI for fast response
    • Can be approved by PC for existing sessions
  • Or for triggered proposals
    • To be submitted at regular proposal dates
    • Requires specific trigger criteria
  • Short requests <2hr
    • e.g. calibrator checks
  • Target of Opportunities
    • EVN agreed to have substantially more of these
  • Or just because you prefer to e-VLBI
  • Or just because the EVN prefers to do e-VLBI
    • Because of logistics or (disk) resources
Observations

- Because of logistics or (disk) resources
What we learned from EXPReS

• Besides building expertise and making new friends:
  • Bandwidths of 1Gbps and above not a problem
  • e-VLBI is probably even more reliable
    • By closing the loop in real-time
  • It can be applicable to Global VLBI
    • Local connectivity often the more serious problem
  • It did produce new science
    • Moreover, users think it is exciting and convenient

• But some questions remain:
  • Will it be cost effective?
  • Cannot accommodate all projects
    • Spectral line, mixed bandwidth
    • Multiple correlator centres
    • Some antennas in some experiments (Noto, Russian, Chinese)
New project: NEXPReS

NEXPReS

Novel EXplorations Pushing Robust e-VLBI Services

- Owns the e-VLBI operations and outreach
- Also some LOFAR transport and storage issues
- And link to SKA development
New project: NEXPReS

- Aims for
  - Allow multiple correlator passes
  - Buffer for more reliable operations
  - Addressed by simultaneous recording
- Be more sensible about resource allocation
  - Bandwidth on demand, limit physical shipping
  - Reach for higher bandwidths (10 - 40 Gbps)
- But also:
  - Continue to connect more telescopes
  - NEXPReS maintains expertise
  - Collaborations with NRENs
  - 'Owns' the e-VLBI operations and outreach
  - Also some LOFAR transport and storage issues
  - And link to SKA development
New project: NEXPReS

• Aims for
  • Correlate in real time what you can,
  • Correlate later what you need

• Allow multiple correlator passes
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NEXPReS project info

• 15 partners
  • Of which 3 choose not receive funds from EC
  • Good mix from astronomy-networking-HPC communities
  • High level of partner-contributed effort

• Year 2 review this week
  • Think we are nice on schedule
  • But delivering user capabilities is a delicate process
2 Joint Research Activities aiming at innovating future operations
Distributed correlation in astronomy domain
Transparent buffering

2 Service Activities
focus on new operational astronomical features:
Higher bandwidth, dynamically cached transport, increasing flexibility of observations

2 user community networks continue from EXPReS
Astronomy use and policy
Network providers/telescope operators

2 special Networking Activities
Management & Outreach
Essential for success
Cloud correlation

- **Infrastructure**
  - Overhaul of local network
  - Flexibly connecting playback
  - Fibres & correlators

- **Control code**
  - Allowing mixed rate operations
  - Making various playback units flexibly usable
  - Unitig correlator interfaces
  - Remote operations

- **Transparent buffering**
  - Working on JIVE Mk5 control code
  - For use in the field
  - And at the correlator
Lots of progress

• Mostly rewriting code
  • for new hardware
  • and new use modes

• Testing in 4Gbps setup
  • Mostly successful
  • Except for the correlation
Bandwidth on demand

- Need to reserve dedicated connections
  - Across many domains
- Work on using flexible assignments NSI
  - Enabling 4 Gbps
  - Also for LOFAR archive
Distributed correlation

- Enhance the software correlator
  - New functionality
    - Space craft modes
    - Multiple field centers
    - Pulsar timing beam
  - Latest interface definition
  - Make ready for e-VLBI
- Push for distributed correlation
  - But moving away from Grid
  - Looking at resources in own domain
  - Can be effective way to construct correlator
  - Interest for round-the-clock VLBI
    - Ready for triggers
- Load balancing over multiple clusters

First e-VLBI fringes at 512 Mbit/s
Web deployable correlator

- Graphic workflow managers
- Dynamic scheduling
  - Automated response to external triggers?
FlexBuff

- Problem: high bandwidth storage
  - Feeding into the caching demands of VLBI
    - Multiple 4Gbps streams
    - Read & write simultaneous
  - But also at massive (distributed) archives
  - Must be Linux based and off-the-shelf

- Prototype hardware delivered
- And software suite
  - Writing larges blocks
Network activities

- **Management**
  - Doing all the nasty stuff
  - Including dealings with EC
    - On finances for example

- **EVN-NREN**
  - Interactions with Networking experts
  - Had first meeting in Aveiro, PI

- **EVSAG**
  - e-VLBI Science Advisory Group
  - On policies and operational issues
    - Overlaps with EVN-PC
  - Meeting in Madrid last week

- **Outreach & Dissemination**
  - Maintains internal information
  - And external outreach material
    - Display booth
    - e-VLBI/JIVE film
Noto, Sicily, antenna repaired and now on-line

Successful tests done with Korea
NEXPReS impact on EVN

- Continuity in development programme
  - Essential in keeping local expertise
  - Vital for keeping in touch with NRENs
  - Continued effort in outreach/dissemination

- NEXPReS upgrades e-VLBI
  - Upgrades of equipment
  - Notably Mk5Cs at JIVE

- Step towards all EVN in e-VLBI
- Raise level of availability
  - Culture change on-going
  - New requests for (new) observing types
    - RadioAstron telescope in orbit
    - Observations of spacecraft (planetary/fundamental)
    - Monitor programmes/astrometry/joint observations
    - Triggers set by other observatories (link with LOFAR)

- Must offer new services
  - Offer tailored arrays? More e-VLBI days
VLBI for Space applications...

- BepiColombo
- ExoMars
- RadioAstron
- Huygens
- MarcoPolo-R?
- Europa Jupiter System Mission
- JUICE-Laplace
VLBI for Space applications...

J2211-13, 0.17 Jy reference source at a distance of 2.5 deg (South) from the target.

VEX track around Venus, 28.03.2011

RadioAstron

Huygens
Next? More VLBI!

• Increasing data rate will not stop any time soon:
  • New stations: Africa, Goonhilly, Madeira, Brasil....
  • Joint observations with e-MERLIN
  • Joint observations with ALMA

• Need for better sensitivity, more digital bandwidth
  • with more bit sampling against interference
  • Science synergy with new survey instruments
Next correlator

• Current EVN MarkIV
  • 16 telescopes, 8 sub-bands (128 MHz), 4 pols
  • 1 Gb/s, or 512 Msamples/s for 2-bit sampling, per telescope
  • ~40 Tops

• Current SFXC: 256 cores, 2 racks, 9.5 kW
  • Can keep up with 9 stations

• Next generation correlator: 100 fold more capacity
  • 32 stations, 16 Gbps, high resolution
  • On software: 131072 cores, 1024 racks, 4.9 MW
  • UniBoard as 4GHz next generation correlator: 64 boards, 25.6 kW
Needed: next generation correlator

• Aiming for 32 station 10+ Gbps FPGA correlator
  • Flexibility of software correlator
  • Power consumption should be much better
  • Started in RadioNet::UniBoard, next step in RadioNet3

• Feeding into the SKA programme
  • As well as being used for EVN, LOFAR, WSRT, Effelsberg
Ambition: clock distribution

- VLBI depends on availability of extremely accurate clock and frequency standard ($10^{-15}$)
  - All telescopes must have 100k€ maser clock
    - In principle can be distributed over dedicated fibre

- Investigate clock distribution on public network
  - Requires dedicated wavelength and stable amplification
  - To measure return loop

- Will improve stability, operations
- And many more VLBI sites!
VLBI Future

• Unique science: long baselines and high frequencies
  • Keep up with EVLA/MERLIN sensitivity
    • Going for 4Gbps in 2011
    • Follow up LOFAR, MeerKAT, ASKAP

• Like to link up with
  • US and VLBA antennas
  • African VLBI Network
    • Under ‘construction’

• Even in the SKA era
  • At least for phase I
  • Most certainly phase II
  • Spacecraft applications (and geodesy) need Northern Hemisphere
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