Attachment B –Reduced Costs and Increased Benefits of Fast Network Links to Radio Astronomy Observatories

A. Tzioumis 20/4/2004

This note provides estimates of current costs and attempts to quantify the gains that will result from fast network links. The most significant aspect is the greatly enhanced performance of the network and the consequent enabling of new science.

Position CSIRO as a World Leader in e-VLBI

Other research groups working on real-time correlation for VLBI are aiming at data rates of 1-2 Gb/sec. CSIRO aims to operate with data rates of at least 2 x 8 Gb/sec within 3 years and this would provide the world's best VLBI sensitivities. This will open new avenues of astronomical research and has the potential to revolutionise the VLBI field and lead to significant new discoveries.

An interim 1 Gb/s network would be useful scientifically and a technologically necessary step towards the higher data rates. The ATNF would be able to utilise shared Gb/s links but dedicated multiple 1 Gb/s links would provide much better opportunities for significant scientific improvements.

Current Costs and Outputs

Costs for the VLBI project at ATNF and partners in Australia. Values are approximate and rounded off.

- The components are
  - ~5% of time on ATNF telescopes, total value of about $200M (ATCA $100M, Parkes $80M, Mopra $20M)
  - + 5% of time on UTas antennas, valued at $40M (Hobart $20M, Ceduna $20M)
  - + 2% of Tidbinbilla time, total value of ~$100M

- Special correlation equipment (correlator, PTs, tapes) valued at $1M

- ~5% of cost of operating & maintaining the telescopes and general ATNF facilities. ATNF operations budget is ~$10M (out of total of $20M). Hence, pro-rata operating cost of VLBI is about $0.5M per year. This includes VLBI specific components i.e.
  - Staff for operations support and correlation at ATNF ~ 1 FTE
  - Support for VLBI observations at ATNF of at least 20-25 person weeks/year (2-3 people/antenna x 3 ATNF antennas x 3x1-week periods/year)
- + Operating costs at UTas & Tidbinbilla.

Annual output about 8 papers/year (= 5% of ATNF papers (156 in 2003))

With Shared Gigabit Links

When all the telescopes and correlator facilities have gigabit connections via a shared backbone, there are a number of options to use the network to:

- streamline current operations, with real productivity gains
- achieve a modest increase in network sensitivity and performance.

To achieve any of these gains a substantial proportion of the network links will need to be devoted to e-VLBI during observing sessions.

However, it should be noted that shared 1 Gb/s links will only approach the performance already achieved with disk-based VLBI systems. To improve on that the ATNF could use multiple dedicated 1 Gb/s links if these became available. The advantages will be:

A. The ability to transfer the current data rates (128 Mb/s) in real time to the correlator facility in Sydney would greatly benefit operations, i.e.
   - save most of the 20-25 person weeks/year needed to support observations. 2-3 people could run most of the network remotely, and some of this support could also come from current correlator operations support. Up to 20 person weeks/year may be saved.
   - provide near real-time results, which will greatly enhance the reliability of the VLBI network and provide the ability to react to transient events
   - attract new astronomers to VLBI by greatly simplifying the effort currently needed.

B. Increase the data rates (2, 4 or 8 times) to increase VLBI sensitivity (Attach. C).
   - 256Mb/s are available now at the telescopes and could be handled with a little effort at the Sydney correlator. Sensitivity increase ~40%.
   - 512 Mb/s are available but need a modest effort to interface to the network. Will have to be processed by the Swinburne super-computer by storing on disks and correlating more slowly. Sensitivity increased x 2.
   - 1 Gb/s may be achievable for special projects by duplicating some equipment at the telescopes. Again only the Swinburne supercomputer could handle these rates. Sensitivity increased ~ x3.

The increases in data rates and sensitivity substantially enhance the achievable science. The largest impact is increasing the numbers of fainter astronomical objects that could be studied. These are relatively moderate for the 2-3 times increase in sensitivity offered by this network and comparable to what is achievable with disk systems.

The value of these increases could be quantified by comparisons with equivalent increases in observing time or antenna size. Details are given in Attachment C. In summary, the faster network rates are effectively equivalent to:

- utilising 10-40% of the network while only using 5% of time
- increased productivity by "saving" equivalent costs of $1-4M/year
- increasing the effective value of the ATNF facilities from $200M to $260-500M. Thus the 5% VLBI time effectively increases in value from $10M to $12-25M.

With Dedicated multiple 10 Gb/s Links

When the new correlator and the dedicated 2 x 8 Gb/s data paths are in use (in about 3 years), the correlation will be done in real time, and the sensitivity will be enhanced about 10 times. This will:

- open up new avenues of research by greatly increasing the number of astronomical objects for study. This has the potential for many significant discoveries in high resolution radio astronomy.
- provide savings in operating costs by effectively eliminating the specific VLBI costs of the current network and integrating operations with the ATCA at Narrabri.
- enhance and facilitate access to VLBI observations for the whole astronomical community and it is expected to bring many new users to VLBI. Thus VLBI in Australia will cease to be a niche technique and will join the mainstream of radio astronomy observing.
- increase the proportion of VLBI time by increasing the scientific capabilities and attracting new users.
- generate equivalent savings by greatly increasing the productivity of the telescopes (see Attachment C for details). In summary these are effectively equivalent to:

- the 5% of time is increased 128-fold! 1-week then will be equivalent to 2.5 years of continuous observing on the current systems. Or 1 day on the new system would be equivalent to the combined rates of the previous 6 years on the current VLBI system!
- equivalent operational budget of $64M at current data rates
- equivalent to having telescopes worth ~$2.7B The 5% VLBI time then effectively increases from ~$10M to ~$135M.

The development of the networks, new correlators and the e-VLBI operation are all key technologies for the SKA. Thus these developments will facilitate demonstration of SKA capabilities in Australia and enhance Australia's prospects to host the ~US$1B SKA.

Attachment C - Quantifying the gains from increased VLBI data rates & sensitivity

A. Tzioumis 20/4/2004

Introduction

It is difficult to accurately quantify the gains that may be achieved by increasing the data recording rates The approaches here often oversimplify the situation and are meant only as a guide. They give an idea of the cost of achieving similar increases by other available means. Alternatively, they provide an indicative dollar value of the proposed improvements in data rates.

Some concepts

Radio telescopes record extremely faint signals, many millions of times below the radio noise level. Hence, high sensitivity and special correlation techniques are used to detect the signal from the general radio noise.

The sensitivity of a radio telescope or array, is determined primarily by:

- The size of the antenna. Sensitivity is proportional to the dish Area (A), which is determined by the dish Diameter (D). Area $A = \pi \left(D/2 \right)^2$
- The sensitivity of the receivers, as measured by the system Temperature (Tsys). State-of-the-art receivers achieve Tsys = 20K. Sensitivity is proportional to $1/Tsys$.
- The Bandwidth (B) of the receiving system in MHz or GHz. This determines the output data rate in Mb/s or Gb/s. Usually, output data rates are 4 x B.
- The integration time T i.e. the time that raw data is appropriately averaged together to increase the signal-to-noise-ratio (SNR) of the data.
- Sensitivity is proportional to $\sqrt{B \times T}$

The sensitivity of the telescope provides a measure of the weakest radio signals that can be detected. The vast majority of astronomical objects emit very weak radio signals. Hence, sensitivity increases open to study a much greater population and wider range of astronomical objects. This enhanced "parameter space" of study most often provides the most exciting discoveries in astronomy.

Sensitivity enhancement

The sensitivity of a radio telescope or array can be increased by:

- increasing the size of antenna. This can be very expensive as the cost of an antenna scales as $D^{2.7}$ (See Thompson, Moran, and Swenson, p. 163).
- decreasing the system temperature Tsys. Improvements are made in this area all the time but changing receiver hardware can also be expensive.
- increasing the Bandwidth B, and hence the data rates. This is the area that fast network speeds have an impact.
- increasing the integration time T. This is also very expensive as telescopes are expensive to operate. In some cases like VLBI, the utility of longer integration is often limited by other technical factors like phase stability and coherence.

The improved sensitivity resulting from increases in Bandwidth (made possible by higher network rates) can be quantified at a simple level by comparing with the equivalent costs of changing other parameters in the system like Time (T) and antenna Area (A).

A. Comparison with Time T

As sensitivity is proportional to $\sqrt{B \times T}$, any increase in Bandwidth B while Time remains constant is directly equivalent to keeping B constant but increasing Time by the same amount. For the proposed e-VLBI systems the Bandwidth increases have the same effest as the data rate increases. Hence:

- The 1 Gb/s shared network proposed will allow increases in data rates from the current 128 Mb/s to 256 or 512 Mb/s or even up to 1 Gb/s. Thus data rates increase by factors of 2-8. This is equivalent to increasing the time of operation 2-8 times. As VLBI uses 5% of time on CSIRO facilities valued at $200M, increases by factors of 2-8 provide that many times increase in productivity of these assets. It may be thought of as equivalent to utilising 10-40% of the facilities while only really using 5% of the time. Equivalently, the 5% of VLBI time can be considered to cost 5% of the ATNF operating budget of $10M/year i.e. $0.5M/year. An effective time increase of 2-8 times can then be thought to provide equivalent productivity increases in saved operating costs of $1-4M/year! It would cost that much if one could buy the extra time on the telescopes.

- The 2x8 Gb/s e-VLBI network that would be made possible with the advanced 10 Gb/s network links, achieves an 128-fold increase in data rates or equivalently in bandwidth. Translating these to Time gives a 128-fold increase in effective time utilisation. Thus the 5% on the $200M facilities becomes 640% i.e. it is equivalent to using full-time 6 such facilities or using the facilities exclusively for VLBI for 6 years! Similarly, the $0.5M/year pro-rata operational budget in ATNF for VLBI becomes an equivalent $64M saving!

CAUTION: These need to be treated carefully, as in many cases the increases in bandwidth cannot actually be substituted by increases in time. The above figures are intended to give a feel for equivalent costs.

B. Comparison with telescope Area A

Sensitivity is also directly proportional to the size of the antennas and the costs of these are relatively well known. So, the increases in sensitivity due to the increase data rates and hence Bandwidth can also be translated to equivalent increases in telescope collecting area.

Increases in Bandwidth increase sensitivity as $\sqrt{B}$ and hence the equivalent increase in Area also scales as $\sqrt{(increase\_in\_B)}$. The telescope Area A scales as the Diameter D^2. Thus an increase in B would correspond to a Diameter D increase of $(increase\_in\_B)^{\frac{1}{4}}$.

However, it has been well established that antenna building costs scale as $D^{2.7}$.

Thus antenna costs would scale as $(increase\_in\_B)^{(2.7 \times \frac{1}{4})}$.

The ATNF antennas comprise 7 x 22m antennas (ATCA and Mopra) and the 64m antenna at Parkes. Mechanical construction costs of these are about $100M ($4m for each 22m antenna, $70M for Parkes).

- The 1 Gb/s shared network proposed will allow increases in data rates from the current 128 Mb/s to 256 or 512 Mb/s or even up to 1 Gb/s. Thus data rates increase by factors of 2-8. This is equivalent to increasing the area of the antenna by 1.4-2.8 times and the antenna cost by 1.6-4 times. Effectively, the equivalent value of the ATNF facilities increases from $200M to $260-500M. The 5% VLBI share increases accordingly (from $10M to $12-25M).

- The 2 x 8 GB/s e-VLBI network that would be made possible with the advanced 10 Gb/s network links, achieves an 128-fold increase in data rates or equivalently in bandwidth. The increase in sensitivity or equivalently in area is 11 times and the effective antenna cost increase is 26 times! Hence, the equivalent value of the ATNF facilities increases to $2.7B!! The 5% VLBI time effectively increases in value from $10M to $135M.

CAUTION: Again, these numbers are meant only to demonstrate that increases in data rates achieve increases in telescope sensitivities that could be achieved by building bigger telescopes costing many $10Ms or even $100Ms.

Comparison with other planned facilities

The only planned high data rates facility is the e-MERLIN in the UK. It is a similar instrument but covers shorter distances from 5-200km and has less overall collecting area. It will use dedicated fibre links for rates up to 24 Gb/s but the effective Bandwidth will be the same as the ATNF proposal. The extra bits are to be used for RFI mitigation which is a lesser problem in Australia. However, we can achieve similar RFI mitigation effects by increasing our rates as our correlator can handle a phenomenal 128 Gb/s from each telescope!

This project has been funded as an upgrade of the existing MERLIN radio-linked instrument and will cost about A$20M. (Details in http://www.merlin.ac.uk/e-merlin/)

Summary

The proposed increases in data rates for VLBI that will be provided by the new network connections will provide very significant increases in observational capacity. These can be roughly quantified by comparison with equivalent increases that could be achieved by increasing observational time or the size of the telescopes. In both cases, the equivalent savings in operational costs or the equivalent increase in the value of the facility are many millions of dollars.

However, the main impact of the increased sensitivity is the opening of new areas of study in radio astronomy and the huge scientific impact that these can have.