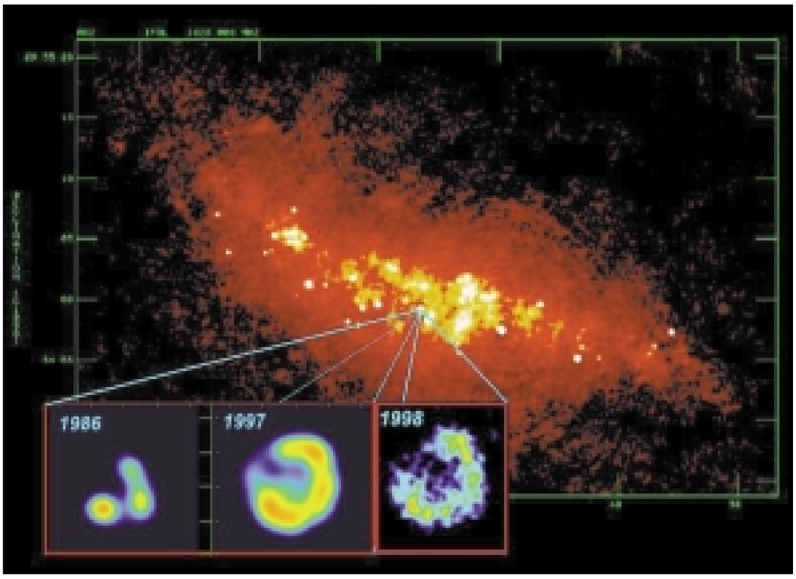
Data highway to the stars

Connecting individual radio telescopes by microwave links has allowed radio astronomers to create instruments with resolving powers equivalent to a single telescope hundreds of kilometres in diameter. **Brian Smith** describes how optical fibre links could yield a further dramatic increase in our ability to explore the furthermost reaches of the universe

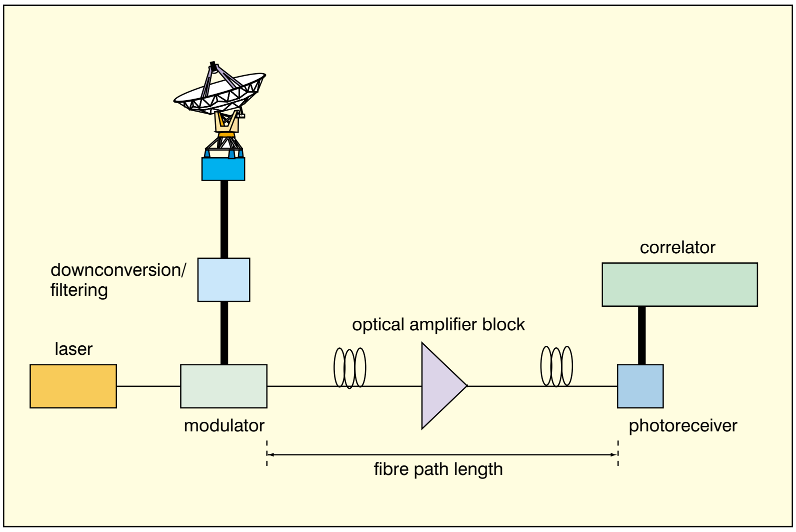
Small may be beautiful, but for radio telescopes used individually big is indisputably best. At a wavelength of 6 cm, the resolving power of a single telescope such as the 76 m Lovell telescope at Jodrell Bank is significantly less than that of the human eye. Since they work at much longer wavelengths than their optical counterparts, a single radio telescope would require a dish diameter of around 200 km to match the resolution of the Hubble Space Telescope.

To overcome this limitation, telescopes are linked in interferometer arrays, where the combination of two smaller antennas is equivalent to a single dish with a diameter equal to the distance between them. In this way the astronomy community can achieve greater measurement resolution. Within the UK, six telescopes form an array extending across the English countryside with a maximum telescope separation (baseline) of 217 km. The MERLIN (multi-element radio-linked interferometer network) array transmits data from each telescope over dedicated microwave links to Jodrell Bank, where the signals are correlated in real time using a specially constructed computer.

With a baseline of 217 km, MERLIN is capable of resolving a 10p coin at a distance of 75 km. Some of the telescopes within the MERLIN array are used in a world-wide network to achieve even higher resolution in a technique known as VLBI (very large baseline interferometry). Here the data is recorded onto tape at each telescope, which is then sent to be time sequenced and correlated at a designated site. With a maximum VLBI baseline of around 9000 km, this technique would be capable of resolving the 10p coin at a distance of 3000 km! Improvements in resolution with increased baseline lengths can be observed in images of the unstable starburst galaxy M82 shown in Figure 1. The Very Large Array in New Mexico, with 27 antennas and a 35 km baseline, is capable of picking out the diffuse radio emission (red cloud) and the unresolved sources (white spots). MERLIN, with a 217km baseline, can resolve individual supernova remnants (white spots in the figure) into identifiable shells, whilst the European VLBI Network is able to produce high-resolution images of each of the supernovae (inset), showing their expansion over time.



1 Unstable starburst galaxy M82. Main image produced using MERLIN and the Very Large Array. High-resolution insert, showing expansion of supernova remnants over time, produced using the European VLBI Network



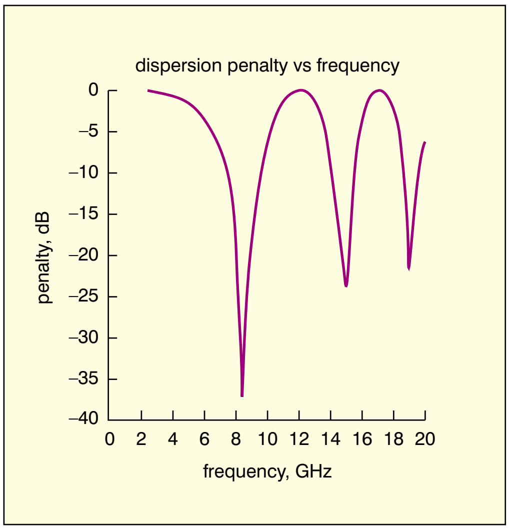
2 Typical system configuration for analogue optical signal distribution. The digital equivalent would include a digisation stage after downconversion and filtering at the telescope

Bandwidth—a sensitive subject

Improving the sensitivity of radio astronomy measurements is of prime importance for continued scientific discovery both within and outside our own galaxy. Improved sensitivity will allow astronomers to observe objects that have previously been too faint to study. There is also the possibility that newer, more distant galaxies could be discovered, providing fresh evidence to enhance our understanding of the origins of the universe. There are several ways that the sensitivity of existing telescopes can be improved:

- increasing the collecting area of the telescope
- increasing the measurement integration time
- reducing the receiver noise
- increasing the measurement bandwidth.

The first of these options is not economically viable since only minor sensitivity improvements could be achieved at the expense of the significant investment that would be required in telescope redesign and construction.



3 Effects of chromatic dispersion on the system frequency response. The troughs in the response indicate conditions where the phase difference between the sidebands is approaching 180°

Similarly, increasing the integration time is problematic since the rotation of the Earth limits the time for which a source is observable in any 24-hour period. Reductions in receiver noise are also constrained by fundamental physical limits. The devices currently being produced at Jodrell Bank are cooled using compressed helium, and are nearing their noise floor limit. In practice, therefore, increasing the measurement bandwidth is the only way of improving telescope sensitivity.

For MERLIN, the bandwidth allocated to the microwave links between the telescopes and the correlator at Jodrell Bank is currently restricted to 28 MHz. Recent work, funded by PPARC and BT under the PIPSS (PPARC Industrial Programme Support Scheme) programme has investigated the feasibility of using wideband analogue optical fibre links (over a 20 GHz bandwidth) in place of the narrowband microwave interconnect. Theoretical modelling has also been performed comparing the performance of analogue and digital optical links with a view to preparing a plan for future implementation. The study is also being extended with funding from a European RTD grant, to look at similar techniques for replacing tape-recorded VLBI with real-time optical fibre connections within the European network. (The best magnetic tape technology currently has recording speeds limited to less than 2 Gbit/s, uses expensive specialised equipment and demands significant manpower resources at each site for maintenance and scheduling).

Analogue versus digital

Optical fibre is needed to achieve very large bandwidth transmission over long distances with low loss. However, there is currently a debate as to how signals should be transmitted to achieve the best performance, at the lowest cost, with the minimum of instrumental complexity at remote telescope locations.

Analogue RF transmission over optical fibre is a well known technique for implementing high-bandwidth communications links between geographically remote antennas. Figure 2 shows the basic principle, where a filtered portion of the signal band (RF or IF), is amplitude modulated onto a highly monochromatic laser signal, using a Mach-Zehnder electro-optic modulator. After propagation along the single-mode fibre strand, the signal can be recovered using a photodetector. There are modulator and photodetector components available on the market, which are capable of operating with a relatively flat pass-band up to 40 GHz.

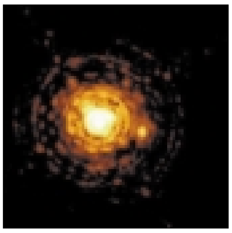
This would seem to offer an ideal solution.

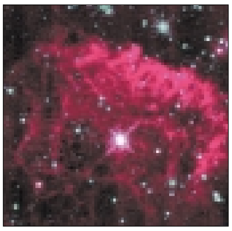
Compared with radio link bandwidths, an optical implementation using 40 GHz components would represent a forty-fold increase in the sensitivity of the current MERLIN array, making it the most powerful instrument on the planet. Practical considerations mean that, regrettably, the true realisable performance gains are significantly short of the ideal. In particular, radio frequency interference, from mobile phones etc, at the antenna limits the maximum useable bandwidth to approximately 4 GHz. Also, chromatic dispersion in single mode fibre causes signals at different wavelengths to travel at different speeds—placing a further limit on the realisable bandwidth.

The modulated signal consists of an optical carrier with two sidebands separated from the carrier by the RF frequency. As the signal propagates in the fibre, each of the sidebands experiences a different phase change. At some points along the link, the phase change will be 180° leading to extinction of the signal at the detector. Figure 3 shows the effect of dispersion on the frequency response of a fibre link. The components may operate over 40GHz, but the filtering effect of chromatic dispersion in the fibre limits the bandwidth of the link to around 5 GHz. Dispersion compensation can be included in a link, but this increases attenuation and reduces the distance over which the specification can be achieved.

One of the unique aspects of linking telescopes for radio astronomy is the requirement for relative phase stability between paths. The signals are noise-like, and are essentially multiplied at the processor. If a relative phase error exists between them, the result will be de-correlation and degradation of the measured data. A de-correlation of less than 1% is acceptable, which means that the two signals must not vary in relative phase by more than 7°. Recent experimental work performed at Jodrell Bank has shown that phase fluctuations in signals transmitted over optical fibre are significantly worse than this. As a result, meeting the stability requirements will be one of the major challenges to be addressed if analogue techniques are to be adopted within the link.

Phase fluctuations observed experimentally have time constants which suggest that some form of feedback control system could be used to improve the performance. Assuming this to be the case, theoretical and experimental work has shown that analogue links can perform within specification over distances of up to 250 km.



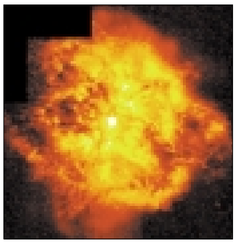


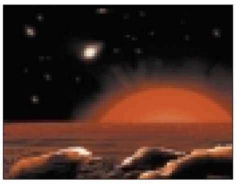
Digital communications systems have many advantages over their analogue counterparts brought about by the need to detect only the presence or absence of a pulse rather than its absolute shape. Digital systems are currently being implemented world-wide that are capable of 10 Gbit/s capacity per wavelength in the fibre. Improvements in optical amplifier and wavelength division multiplexing technologies are leading to more and more optical wavelength channels, approaching Terabit/s capacities. Developments are continually being reported which will eventually lead to capacities in excess of 80 Gbit/s per wavelength. It is likely that future instruments such as ALMA and SKAI will benefit from these increased capacities.

The technology is essentially identical to that used for analogue optical links—a combination of high-stability lasers (effectively fixed wavelength but with lower optical powers), high-speed electro-optic modulators and photodetectors with post-detection clock-recovery circuits. For long-haul applications, wide-band optical amplifiers are used and negative dispersion fibre placed at appropriate points along the link, provides compensation for pulse spreading due to chromatic dispersion. Repeater-free transmission over very long distances is possible, limited only by the bit error rate degradation that occurs as a result of cascading multiple optical amplifiers.

A measurement bandwidth of 2·5 GHz for example, corresponds to a ten-fold increase in sensitivity compared to the current MERLIN array. Converting this analogue signal into a two bit digital word—as is usually the case with radio astronomy measurements—leads to a channel bit rate of 10 Gbit/s (assuming sampling at the Nyquist rate). Chromatic dispersion limits the fibre length to 58 km at this rate, and exceeding this without sufficient dispersion compensation will degrade the performance of the link.

For a 217 km link equivalent to that between Jodrell Bank and the 32 m telescope in Cambridge, the specification requires a signal-to-noise ratio better than 20 dB. This is equivalent to 1 bit error in every million bits or 1 bit error every 100 ms at 1 Gbit/s and is a simple target to meet considering that today's long haul communications links operating at equivalent bit rates are offering quality of service figures better than 1 bit error in every 1013 bits. Again, stability is an important parameter to consider, with the specification requiring better than 30 ps timing jitter at the above bit rate. If the currently installed standard single-mode fibre network is used in the implementation, the jitter specification could be compromised as a result of Polarisation Mode Dispersion (PMD). Newer fibres currently being installed within the UK and Europe would not pose the same problem since their PMD values have been significantly improved.





The big issue

Perhaps the most challenging aspect of providing the astronomy community with real-time optical fibre links is in the implementation. At first glance it might seem like a straightforward exercise to integrate telescopes into the installed optical network using custom optical components and either analogue or digital transmission. There are however several important aspects that need to be addressed.

There is no guarantee that the telescopes will be within easy reach of a network hub, indeed the opposite is likely to be the case since, to avoid RFI problems, radio telescopes tend to be located as far as possible from metropolitan areas. Significant investment will be required to provide both right of way and installed fibre between the sites and the network.

The bandwidth needed would be of the order of 1 GHz (for an analogue system) or 10 Gbit/s for a digital system. Current technology in the UK is installed to meet SDH interface requirements, with 16 channels at 155 Mb/s multiplexed up to a maximum rate of 2·5 Gbit/s per wavelength on the fibre. Further stages of multiplexing are performed offering customers a range of bandwidths for voice and data applications. Dedicated optical components connected to a ‘dark fibre’ or a unique wavelength channel would address the gap between what is required and what is available on the network.

Bandwidth is very expensive and the above requirements far exceed those available to single customers. It may be that the costs will be prohibitively high, especially if dedicated links are required. In addition, there may be regulatory difficulties supplying such a large transmission capacity to a single user.

These are just a few of the important issues that must be addressed within the currently funded programme. To date, theoretical modelling and experimental measurements have indicated that whilst an analogue option may be suitable for interconnecting arrays with span lengths less than 250 km (MERLIN), digital transmission will be required to achieve real time connection within European VLBI. Such a wide-spread fibre network proposal will involve collaboration and agreement with major European telecommunications organisations spanning at least eight countries. The scientific case is very strong but full scale implementation will still be a significant challenge, even when the required funding is made available.

Looking ahead

After more than half a century, Jodrell Bank remains at the forefront of radio astronomy research. Several major developments are required to ensure that this continues in the coming years and the recent approval of £2million JIF funding for resurfacing the Lovell telescope is of significant impact. Improved sensitivity is one of the most fundamental requirements, where the need for greater bandwidth can be met by the spiralling increase in optical fibre network capacity. Analysis suggests that analogue optical modulation techniques are capable of operating within specification over a 1 GHz bandwidth and up to distances of 250 km. The phase stability of the signals is fundamentally important in synthesis arrays and is an issue that needs to be addressed in more detail for the analogue case. A ten-fold increase in instrument sensitivity could be realistically achieved using emerging digital optical technology at 10 Gbit/s. More than adequate system performance can be maintained over distances of thousands of kilometres, assuming that the effects of chromatic dispersion and polarisation mode dispersion are addressed. The dominant issues here and now are how to implement such a super-network and the cost of doing so, but as the market drives the cost of bandwidth down, who knows what may be possible in the next five years?

Acknowledgements

The work described in this article has been funded by BT and PPARC under the PIPSS programme and more recently by a European RTD grant. The author is grateful to Ralph Spencer, Bryan Anderson, Phil Diamond and Alan Pedlar of Jodrell Bank Observatory for useful discussions.

Further reading

Details on this activity and more general information about Jodrell Bank Observatory, MERLIN and European VLBI can be found at www.jb.man.ac.uk. Information on the VLA and ALMA can be found at www.nrao.edu/telescopes/.

Dr Brian Smith is the Optical Fibre Systems Engineer in the Development Laboratory at Jodrell Bank, Macclesfield, Cheshire SK11 9DL (tel +44 (0)1477 571321; bsmith@jb.man.ac.uk).