The Use of Optical Fibres in Radio Astronomy

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Abstract

The low loss and ease of use of optical fibres for data transmission offers a number of advantages over traditional methods of bringing signals from radio telescopes together. Aperture synthesis techniques involve the correlation of signals from each pair of telescopes in the array. The requirements of radio astronomy systems, where the broad band noise like signals from each telescope have to be brought together coherently over distances as large as hundreds of km or greater in some cases, are discussed in this paper. A number of arrays around the world currently use fibres for data transmission and also for the coherent transfer of local oscillator signals. Further developments in the use of optical fibres in radio astronomy are described as well as new instruments planned for the next millennium, where fibre interconnections will be an essential part of their design.

1 Introduction

Radio astronomy uses large radio antennas equipped with low noise receivers to investigate celestial radio sources at wavelengths ranging from millimetres to metres. An essential feature of the technique is that, in addition to receiver noise and antenna collecting area, the sensitivity is determined by the output fluctuations of the receiver and so the signal to noise ratio is proportional to $(B\tau)^{1/2}$ where B is the bandwidth and τ is the total integration time used [1]. The bandwidth (for continuum signals) is set by that available for the band being observed: for observations at L band (1350-1700 MHz) this is around 30 MHz, but for higher frequencies and less crowded regions of the radio spectrum the bandwidth can be 1 GHz or greater.

Angular resolution comparable to, or better than that regularly obtained in optical astronomy (i.e. around 1 arc sec or less) can be achieved by the use of aperture synthesis techniques, where the noise like signals are brought together over a data transmission system to a central correlator. Traditionally this has been done using coaxial cable. More recently microwave radio link techniques have been used over distances of 200 km, such as in the University of Manchester's MERLIN array [2]. Here the bandwidth is limited to 30 MHz by licensing agreements and technology. Very Long Baseline Interferometry (VLBI) uses telescopes spread throughout the globe and coherent tape recording techniques are used, with correlation performed at a central location subsequent to the observations [3]. Here bandwidths are again restricted to a few 10's of MHz, though recent developments have enabled 1 Gbit/sec data rates to be recorded. A system where signals are correlated in real time would greatly improve the reliability and ease of access for astronomers, however high data rate links over 1000's of km are required.

Though beautiful images of many celestial objects can be obtained with existing instruments, new research is limited by sensitivity. Recent MERLIN images of the Hubble deep field required an integration time of 18 days [4]. This could be reduced to less than one day by using the Gbit/sec data capacity of optical fibres together with planned improvements in receivers.

2 Optical Fibre Systems

The inherent low loss and wide bandwidth capacity of monomode fibre systems make them the obvious choice for modern radio astronomy systems. The choice of analogue or digital signal transmission however is not so clear. Analogue systems have the advantage of simplicity of the electronics at the antenna where only radio frequency signal processing techniques would be required. On the other hand digital systems may have lower component costs and do not suffer from the same signal-to-noise limitations as analogue links. Digital systems may also require more complicated electronics at the antenna, where high-speed digital circuits could give rise to a severe interference problem for the sensitive receivers employed. This uncertainty of choice is reflected in the variety of systems currently in use around the world (table 1).

Table 1 Radio astronomy systems currently using fibre optics

Instrument	Location and year	Link Length	Analogue or Digital and data rate.
Australia Telescope Compact Array (ATCA) [5]	Australia 1988	6 km	D 1 Gbit/sec
Keystone Project [6]	Japan 1998	100 km	D 256 Mbit/sec
VLA-Pie Town [7]	USA 1999	120 km	A 200 MHz
Giant Metre Wave Telescope (GMRT) [8]	India 1999	20 km	A 32 MHz

A number of development projects have been set up for the new instruments of the future. These are outlined in table 2. These all rely on very high data rates (or high bandwidth for analogue signals) over long distances, and therefore effects such as fibre dispersion (for example when using standard single mode fibre at a wavelength of 1550 nm) are important for analogue and digital signals. Descriptions of the projects are given in the following sections.

Table 2 Development projects

Instrument	Location	Link Length	Analogue or Digital and data rate.
MERLIN	UK	200 km	A 1 GHz
European VLBI (EVN)	W. Europe	200-3000 km	D 1 Gbit/sec
ALMA	Atacama Chile	30 km	D >64 Gbit/sec

3 Wide band links for MERLIN

Here the requirement is for links which vary from 15 to 250 km (the distances of the telescopes in the MERLIN array from the correlator at Jodrell Bank). The required bandwidth for a proposed improvement in sensitivity is 1 GHz or higher. A major instrument development is planned, which with new receivers and high data rate links will result in a factor of 25 increase in sensitivity. A collaborative project between the University of Manchester and BT laboratories has been set up (funded by BT and PPARC under the PIPSS programme) to investigate the use of analogue transmission techniques over 200 km of standard fibre at modulation frequencies of 0.1 to 20 GHz.

Commercial opto-electronic modulators and detectors are now available which can give a flat amplitude response (to within < 3 dB) over this frequency range. The main problems seem to that of dispersion control and non-linearities in the opto-electronic components. Chirped Bragg gratings were found to give a satisfactory solution, provided that their insertion loss could be compensated by the use of Erbium Doped Fibre Amplifiers (EDFA) [9]. Tests were made both in the laboratory and using BT's installed test fibre in East Anglia (figure 1). An evaluation of the coherence of this link was also made by measuring the difference between the transmitted and received phase of a 2 GHz modulation signal. This was found to be consistent with expected thermal drifts in the fibre, in agreement with results found for a shorter link using modulation at 416 MHz for local oscillator phase transfer [10]. Further work on fully characterising the phase performance of 200 km links is required, particularly in comparison with jitter caused by polarization mode dispersion.

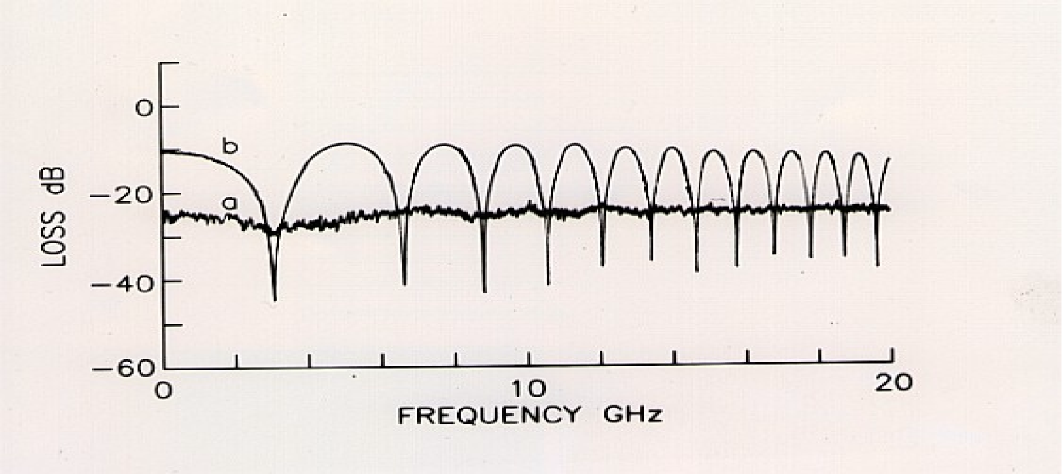

Figure 1 *Plot showing the frequency response of a 200 km link consisting of 186 km of installed fibre link (Martlesham – Ipswich – Norwich and return) (a) with and (b) without Bragg grating dispersion compensation.*

The requirement for an analogue optical link to achieve acceptable radio astronomy results is a minimum SNR of 20dB and a minimum signal-to-spurious of 40dB. The resolution at the correlator is 2 bits which implies a minimum RF signal dynamic range of 14dB. A certain amount of margin on this figure would be desirable to allow for degradation of components over time. We undertook modelling of a 200 km link by assuming parameters for commercially available components. The link was then optimised to achieve the stated dynamic range. One high power EDFA with a gain of 30dB was assumed to compensate for link losses arising from the use of a Mach-Zehnder amplitude modulator and the fibre span (200km). Assuming a laser with an output optical power of 20dBm and losses in the modulator and connectors of 8dB the optical power received at the photodiode was found to be 1dBm, and so the photodiode was not driven into its non-linear region. Stimulated Brilliouin scattering was ignored in the model, so that in practice a lower laser power would have to used to avoid non-linear effects in the fibre. Figure 2 shows the modelled performance with an input TOI (third order intercept) of 31dBm. In line with the specification for minimum SNR and signal-to-spurious level, the maximum RF input power is 11dBm, whilst the minimum power to achieve 20dB SNR is -4dBm. This suggests a maximum system dynamic range of 15dB (2 bits).

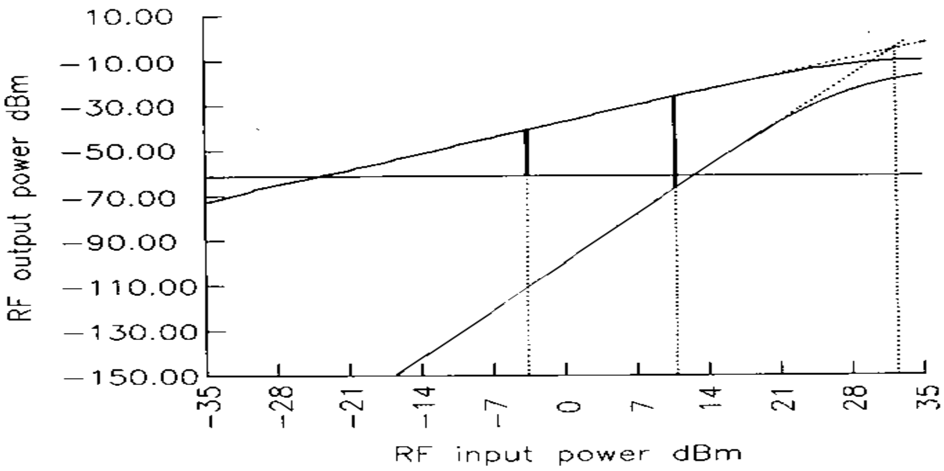

Figure 2 *Plot of RF power in against RF power out showing signal, noise and third order inter-modulation products. The model uses an instantaneous bandwidth of 1GHz with a fibre length of 200km. The third order intercept point occurs at 31 dBm input power and the noise is shown as a horizontal line at –62 dBm output power. The two solid vertical lines show the input power (11 dBm) to give the maximum allowed harmonic level, and the minimum input power (-4 dBm) to give 20 dB signal-to-noise ratio.*

As mentioned above, chromatic dispersion in long haul optical fibre links is a potentially limiting factor for wide band systems. The carrier-to-noise penalty resulting from this is a factor of the maximum RF frequency, the dispersion parameter and the length of fibre used [11][12]. For a maximum RF frequency between 10 and 20GHz, the penalty is such that dispersion compensation is required (see figure 1). If the instantaneous bandwidth is limited to 1GHz (equivalent to a data rate of 6.6 Gbits/sec for a signal: noise of 20 dB) as is suggested with the modelled link, then the chromatic dispersion penalty is within acceptable limits (<0.1dB) and can be ignored. The modelling therefore gave results consistent with the laboratory tests. However it would appear that dynamic range (and therefore the ability to cope with interfering signals) would have to be compromised if bandwidths much in excess of 1 GHz are used in analogue transmission.

4 European VLBI

The European VLBI network consists of radio telescopes situated in Germany, Holland, Italy, Poland, Sweden and the UK. Regular observing sessions occur where all the telescopes are coordinated using the GPS satellite navigation and timing system, and data recorded on magnetic tape. Coherence for interferometry is maintained by using atomic hydrogen frequency standards. The array produces images at around the 1/1000 of a second of arc level. A project to investigate the feasibility of 1 Gbit/sec data transmission on installed fibre to a correlator in Holland has been set up funded under an EU RTD programme. Here the natural choice is digital transmission (since the bulk of the electronic equipment is already in use). The main problem here is access to sufficient bandwidth within installed fibre at a reasonable cost.

5 The Atacama Large Millimetre Array (ALMA)

This exciting new project has recently been agreed between the USA, the EU and Japan. A large (64 antennas, each 12m diameter) array with a maximum baseline of around 20 km is to be built in the Atacama desert in Chile at an altitude of 5000m. The array will operate in the range 40–800 GHz, and requires a site with low atmospheric water vapour above the antennas. Photonic phase transfer will be used for the local oscillator systems [13]. The signal bandwidths will be 8 GHz in each of two channels. This will require a link from each antenna to the correlator with a data rate of 64 Gbits/sec if 2 bit digitisation is used as for MERLIN above, or 128 Gbits/sec if 4 bits are used. These data rates are within the currently available capability of commercial digital systems, though wavelength division multiplexing will have to be used. An investigation into alternative analogue links is planned (because of the interference problem) in a development project at Jodrell Bank, together with tests on digital systems. In the meantime the construction of a prototype system of just 2 antennas and the associated receivers and electronics by the National Radio Astronomy Observatory (NRAO) is under way in the USA.

6 Conclusion

Several trials of radio astronomy systems using optical fibres for the transfer of both signals and local oscillator phase are in progress. Laboratory experiments and link modelling have shown that high bandwidth transmission is possible over links of around 200 km. It is unclear whether digital or analogue formats offer the best solution for radio astronomy in general. The choice of one or the other depends on further constraints such as the cost, performance and location of the equipment for any given link under consideration. Limits to the capability of links to transfer phase information have yet to be investigated, with the most demanding application to date being for millimetre wavelength instruments. Finally, the continued development of opto-electronics technology presents exciting opportunities for the radio telescopes of the future.

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