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The AT Long Baseline Array

R.P.Norris

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This document is a progress report on the LBA. It reviews the developments so far, tries to identify the current problem areas, and sets out a timetable for future developments. Of all the unknowns surrounding the LBA, the most prominent are the cost and delivery date of the Data Acquisition Systems from the US VLBA.

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D. ... DC
T. ...
G. ... MAN
I. ...
J. W. BROOKS
J. E. WHITEOAK
P. J. HOWSON
C. K. SPENCE

1) INTRODUCTION AND OVERVIEW

1.1) Introduction

At the start of the nominal completion year of the Australia Telescope, it is appropriate to review progress on the Long Baseline Array (LBA). In this document, I first summarise the existing plans, and progress made so far. I then try to identify a number of tasks which lie ahead of us, and draw up a provisional timetable and budget. Paragraphs which contain new (or undocumented) proposals or identify outstanding questions are marked with a bar in the margin.

1.2) Overview of the LBA

The current specification of the LBA is as follows. The LBA will consist of one or more antennas of the Compact Array (CA), together with the 64-m antenna at Parkes, and the 22-m antenna at Mopra (Siding Spring). In addition, we will collaborate with NASA and the University of Tasmania to incorporate the Tidbinbilla and Hobart antennas into the array.

Coherence between the local oscillators at each station will be maintained using radio links via the AUSSAT spacecraft. Data at each station will be recorded on a Data Acquisition System (DAS) similar to that used by the Very Long Baseline Array (VLBA) being constructed in the U.S.A. Data will be played back and correlated at Culgoora, using a correlator similar to that used for the CA, and subsequent data reduction will be done using the AIPS package.

The data will be compatible with VLBA and MkIII data, allowing international collaboration, except that, for internal experiments, phase rotation will be performed at the antennas rather than at the correlator. For international experiments, the antenna phase rotators will be disabled and either (a) the data will have to be correlated overseas, or (b) the Culgoora correlator will have a Hilbert transform phase rotator added to it.

In the event of substantial delays in the delivery of the VLBA DAS systems, an interim system will be set up using MkII recorders. In any case, it is unlikely that we will be able to afford DAS for all the stations participating in LBA experiments, and so the Culgoora correlator must include a facility for playing back MkII tapes, and for correlating these with MkIII tapes.

1.3) Existing VLBI programmes

There already exists in Australia a working VLBI network which was set up to respond to a possible radio flare in the supernova SN1987A, and which has since been making regular astronomical observations using Parkes, Tidbinbilla, Hobart, and Alice Springs. Data from these observations are processed at JPL. It is hoped that this network will continue until the LBA starts operations, that Culgoora and Siding Spring will be added to the array as they become available, and that when the LBA correlator is completed at Culgoora this network will become the LBA. In this way, we may progress steadily towards LBA operations tackling technical problems individually as they arise.

The problem of finding calibration sources for the AT adds impetus to the VLBI operations, and it is hoped to set up a regular program of astrometry in the near future. Long baselines are particularly important to this work, and the addition within the next year of Perth to the VLBI network would be an important step for the AT.

There have also been several major programmes of observations continuing on the Parkes-Tidbinbilla Interferometer, a real-time radio-linked interferometer using the Parkes and Tidbinbilla antennas. As well as being invaluable for the development and testing of AT software, these experiments have served to broaden our experience of problems that we are likely to encounter during LBA operations, particularly those associated with using non-AT antennas. The advantages of real-time operation of the PTI will probably ensure its continued use for some projects even after LBA operations have started.

2) ANTENNAS AND RF SYSTEMS

2.1) Introduction

AT antennas and RF systems have been reviewed extensively elsewhere (e.g. AT/20.1.1/022) and will not be discussed here. Here I will concentrate on the particular problems associated with individual antennas. Antennas which may be used by, or in collaboration with, the LBA are listed in Table 1.

Note the inclusion of Molonglo in Table 1. If, as seems likely, we are confined to MkII operation in the immediate future, then Molonglo, with its effective diameter of 180 m, represents an enormous addition to the LBA. However, Molonglo operates only at 843 MHz. In view of this, I suggest that the frequency of 843 MHz be re-examined as a possible UHF frequency for the AT. This needs to be done now, so that protection can be arranged where possible.

2.2) Culgoora

For LBA operations, one or more of the Culgoora antennas may be used as a single element. Two modes will probably be prevalent: use of a single antenna (e.g. that at the 6 km station) while the other CA antennas are being used for a CA synthesis observation, and use of the entire CA tied together. In either case, the data from the antenna will be transferred to the central site and phase-rotated to the nominal array centre position before being recorded onto tape. The observing system, other than the 'phase tying', is similar to that for the CA. The phase tying system is described by Graham Nelson in AT/20.1.1/022.

2.3) Siding Spring

The Siding Spring system is similar to that for a Culgoora antenna, in that the data will be sampled in the vertex room and transferred via optical fibre to the control room, where it will be reconstituted into an analogue signal and filtered before being delivered to the DAS.

The system by which the timing of the sampling pulses is tied to that in the DAS, or recorded with the data, has not yet been designed. This is a similar problem to that of aligning the sampling pulses for the CA.

2.4) Parkes

In order to eliminate problems of cable length measurement, etc., it would be preferable to digitise data in the focus cabin. The easiest solution, in terms of manpower, would be to install a system identical to that used for the Siding Spring antenna. Data would then be digitised in the focus cabin and transferred to the control room via optical fibre. The problems of recording the data and timing information are then identical to those at Siding Spring. However, the weight of such a system may be approaching the limit for the focus cabin.

2.5) Tidbinbilla

Two alternative ways of recording data from Tidbinbilla have been considered. The simplest way is to use the existing MkII or MkIII VLBI recorders at Tidbinbilla, and correlate these with the (compatible) LBA tapes at Culgoora. This may have the disadvantage of the Tidbinbilla recorder being compatible with only a subset of the LBA recorder modes. Whether this is a genuine disadvantage depends on which upgrades are made to the Tidbinbilla recorder, and cannot be determined at present.

An alternative way is to transfer the data from Tidbinbilla over the microwave link to Parkes, and record it on the DAS being used for the Parkes observations. To eliminate delay measurement problems, it would be preferable to sample the data at Tidbinbilla. This has the following possible disadvantages:

a) Either the bandwidth is restricted to the 2 * 8 MHz video channels currently available on the link, or additional manpower must be spent developing a system for transferring wider bandwidths (possibly using the 2 * 40 MHz microwave channels).

b) The Parkes DAS would have to be equipped with additional down-converters and formatters.

c) Manpower would have to be spent investigating possible problems associated with recording data from two separate antennas on one tape. (At first sight, this appears not to be a major problem.)

In view of the possibility that the Tidbinbilla VLBI recorder will be adequate for our needs, it is proposed that no effort be expended at this stage on investigating these possible problems.

An additional problem associated with the Tidbinbilla antenna is that we do not have ready access to all components of the RF and back end systems. Thus phase rotation and variable sampling will have to be installed as 'plug-compatible' replacements for existing units at Tidbinbilla, so that they can be inserted into, or removed from, the system with no disruption to other programmes or inconvenience to Tidbinbilla staff. In particular, this means that additional manpower will need to be expended to modify the AT units.

An alternative approach would be to abandon phase rotation at the Tidbinbilla antenna, and treat any experiment involving Tidbinbilla as an 'international' experiment. Whether this has any clear disadvantage depends on the success (or otherwise) of the Hilbert Transform phase rotator. This will be discussed further in Section 6. In cases where Tidbinbilla is the only non-AT antenna, an alternative solution (suggested by JRF and ACY) would be to define Tidbinbilla as the phase reference point for phase rotation at the other antennas.

A further minor problem with Tidbinbilla is the phase shifts associated with the cables from the control room to the receiver cones. These would conventionally be removed by a cable-length measuring device, or by providing a stabilised local oscillator to the receiver cones. In AT antennas, the problem is overcome by sampling in the vertex room. It is not clear how much of a problem this will be at Tidbinbilla, and it is likely that the effects will be noticeable only at the shortest wavelengths. Nevertheless, it is a potential problem which should be quantified.

2.6) Hobart

At present Hobart are primarily dependent on their own RF and backend equipment, and do not have the resources to buy a DAS. If they are to be serious participants in the LBA, then it is clear that the AT may have to provide much of the hardware. In practice, this might be best achieved by lending the spare CA back-end, including local oscillators, samplers, etc., to Hobart together with a spare DAS, when these spares are avaliable. The expense of this might be mitigated by the fact that Hobart cannot work at wavelengths shorter than 3 cm, so that time-variable cable delays between the focus and the control room may not be important. In this case, it may be sufficient to omit the fibre-optic transmission. If, in addition, phase rotation is performed at the correlator rather than at the antenna then the system becomes simpler still, and may not justify the construction of an additional AT receiver. This area needs a joint investigation by AT and U. Tas staff.

2.7) Other collaborators

There is a growing interest in VLBI from a number of groups in Australia, including groups at Sydney University (Molonglo and Fleurs), Adelaide, and Perth. These groups are represented by a newly-formed body, provisionally called the Australian VLBI Foundation. It is expected that by about 1990, Molonglo (at 843 MHz) and Fleurs (at 1420 and 2700 MHz) will be equipped for MkII VLBI. Possible, but less certain, are the construction of antennas at Adelaide and Perth, or use by the Perth group of the 15-m ESA antenna. In addition, we have been able to take advantage of the satellite facility at Alice Springs for the SN1987A network, and we hope that this will continue into LBA operations. To take advantage of these additional collaborations, the AT must be capable of processing MkII data.

3) ANTENNA CONTROL AND COMMUNICATIONS

The Culgoora antennas will be controlled in the same way as for CA observations. All other antennas in the LBA have different control systems, but must be capable of being driven in synchronism. This is best achieved as follows.

At each antenna there will be an LBA control computer which will run a program (provisionally named LBACON) that can drive both the telescope and the DAS. At AT sites this computer might be the antenna control computer, whilst at other sites (e.g. Tidbinbilla) a PDP 11/73 or even an IBM-PC might be appropriate. LBACON will be able to take a prepared schedule containing source positions, bandwidths, frequencies, DAS configurations etc., and drive both the antenna, local oscillators, and the DAS. LBACON will be written by AT staff, and will then be adapted at each site to interface with whatever control software and hardware exists. Maintenance will be made easiest if the site-dependent routines are isolated from generic routines, in a similar way to the AIPS Y-routines.

LBACON will maintain communications with the observing program LBA_OBS running on the Culgoora synchronous VAX 8250. These communications will run initially either through leased lines or AUSTPAC. When the AUSSAT LO system is working, it may be cheaper to send communications over the same AUSSAT channels that are used for the LO's. Such a scheme would require greater transmitted power (for the same LO S/N ratio) and the cost of this has yet to be determined.

In the event of a break in communications, LBACON will continue to drive the antenna and systems according to its pre-loaded schedule. Thus the communications are used only to update or load schedules, and to send monitor data and fringe-check data back to Culgoora. Therefore, it is not necessary for the communications link to be available all the time, although, depending on the expense, this may be preferable for monitoring purposes.

4) TIME AND PHASE TRANSFER

4.1) Introduction

In late 1986 the choice of local oscillators (LO) seemed to be between a cooled sapphire cavity being developed by the U.WA, and a satellite distribution system using narrow-band channels on AUSSAT. The cooled cavity failed to meet the AT specification, however, and so development on a satellite system was undertaken by N.V.G. Sarma, based on the initial studies by B. Anderson. Since then, further development of the cooled cavity has yielded a performance which is approaching the AT specification, although, at the time of writing, it has not yet been demonstrated in an observatory environment. Thus at present the LBA LO design is still based on a satellite LO system.

The two systems considered by N.V.G. Sarma are briefly described here. In each case, frequency is transferred from one station to another via AUSSAT by sending it as the difference between a pair of tones 192 MHz apart, thus cancelling arbitrary phases introduced by the satellite oscillators. The derived 192 MHz signal is used to compare the phase of the reference station (i.e. Culgoora) with the phase of a remote station.

4.2) Scheme 1: Two-way Phase Comparison Method

In this scheme, a pair of tones derived from the reference oscillator is broadcast from Culgoora to each of the N remote sites, and then each remote site sends a pair of tones derived form its local oscillator back to Culgoora. N+1 pairs of tones are therefore needed. Each of the N remote sites then measures the phase difference ϕ_A between the received reference signal and the local signal, and at Culgoora the N phase differences ϕ_i between each of the received signals and the reference signal is measured. $(\phi_i + \phi_A)/2$ then gives the difference in phase between the reference oscillator and the remote oscillator.

This information can be treated in one of two ways: either the ϕ_i and ϕ_A are simply recorded and used to correct the observed data during correlation, or else $(\phi_i + \phi_A)/2$ is calculated on-line and used to correct the remote oscillators by using a phase rotator. The former has the disadvantage that the LBA data are then non-standard, and cannot easily be processed at other correlators. The latter has the advantage that the remote oscillators are effectively phase-stable, so that the data obtained is similar to that obtained using H masers, and is compatible with international VLBI data, but has the disadvantage that the corrections must be transmitted digitally to remote sites in real-time. A suitable way of achieving this would be to encode it on the AUSSAT signal, but the feasibility and cost of this have yet to be investigated.

4.3) Scheme 2: Round-trip Phase correction

An alternative technique is to send a pair of tones derived from the remote station to Culgoora, subtract their 192 MHz difference from the 384 MHz reference standard, send the resulting 192 MHz pair of tones back to the remote site, and add it to the remote standard. The resulting signal can then be shown to be effectively locked to the reference standard. For N remote sites, this scheme again uses 2N pairs of tones.

A variation on this is to reverse the process to transfer each of the remote phases to the central site, and measure their difference from the reference standard. As in Scheme 1, this difference can then either be recorded or else transmitted digitally to the remote sites for real-time correction. This variation uses only N+1 pairs of tones, and so is more easily expandable to include additional stations.

4.4) Summary

There are a variety of alternative schemes for satellite stabilisation of local oscillators, and Sarma is at present setting up tests to investigate their relative merits. However, from the point of view of compatibility with the outside world, a scheme that gives real-time stabilisation is much to be preferred over schemes that require data to be corrected at correlation time.

5) DATA ACQUISITION AND PLAYBACK

5.1) Introduction

Present plans are to record the data using the Data Acquisition Systems (DAS) designed for the US VLBA. These DAS, which are developed from, and compatible with, the MkIII VLBI terminals can typically record for 24 hours on one tape with a 56 MHz bandwidth. They also have advantages over the MkIII terminals of increased flexibility and reduced cost.

However, in view of the increasing delays associated with the DAS, it may be necessary to use MkII VLBI recorders initially, and upgrade to the DAS as they become available. The MkII recorders are extremely cheap, being based on domestic VHS video recorders, and use standard 3 or 4 hour video tapes. However, they can record at a maximum bandwidth of only 2 MHz, giving greatly reduced sensitivity compared to the VLBA DAS.

Even after the introduction of DAS, it is likely for the foreseeable future that we will use DAS only at Culgoora, Parkes, Siding Spring, and perhaps Hobart. It is assumed that Tidbinbilla will be using its own MkIII recorder. Perth, Fleurs, Molonglo, and Alice Springs are likely to be equipped with MkII recorders only. Thus we will need to ensure that our playback and correlation facilities will be able to correlate MkII tapes with one 2 MHz track of MkIII tapes. This is not expected to be a problem, but will clearly require additional manpower.

5.2) VLBA Progress

Initial development of the DAS and the corresponding Data Playback System was done at Haystack Observatory, under contract to the VLBA. At present, prototypes have been built of all the parts of the DAS, and a complete prototype DAS has been shipped to the Pie Town VLBA site. Haystack are now working under a 'pre-production' contract, at the end of which (late this year?) they will be able to quote firmer prices. Production of the electronics will probably take place at NRAO, and production of the recorders will probably continue at Haystack.

The corresponding Data Playback System (DPS), which consists of a Playback Drive (PBD) and a Data Playback Crate (DPC), is well behind schedule. The PBD is similar to the recorder used in the DAS, and so no major problems are expected in that area. However, a review of the DPS found that the existing design for the DPC was likely to be prohibitively expensive, as a result of which the DPC was completely redesigned to be integrated into the correlator front-end, and renamed a Playback Interface (PBI). The design of this unit has now been taken over by the correlator group in Charlottesville.

The major implication of this change for the AT is that we will have to design much of our playback interface ourselves, requiring additional high-level manpower. On the other hand, this may even turn out to be an advantage since it was always apparent that some sort of interface between our correlator and the VLBA DPS would be needed, and so an integration of this interface into the DPS may well turn out to be more efficient and probably cheaper (except in manpower!). Certainly our design could borrow much from the VLBA design, and it will almost certainly mean that, given the manpower, we will be able to get the DPS earlier than might otherwise be the case.

In view of this change, I suggest that the correlator group should take formal responsibility for designing the DPI, and that this should be incorporated into the plans for the LBA correlator.

5.3) Tape costs

Tape costs are very uncertain at this stage because of the uncertainty in the types of tapes available and the manufacturers future plans. However, the following types of tape are probably suitable:

Standard MkIII tapes (Fuji H621 and 3M 5198). These are used currently for MkIII VLBI and contain 9 kft on a 14 in metal reel. Current cost is believed to be around US$300 per tape including reel.

D1 (digital video standard) tapes (Sony, Ampex, 3M). These new tapes are half the thickness of standard tapes and give a higher bit density, so that a 27kft tape can be packed on a 16 in. reel . Their disadvantage is that they have to be packed on glass reels. They should be available some time in 1988. Cost is likely to be US$800 for tape plus US$200-$300 for the reel.

In the future (within five years) evaporated metal tapes may also become available, giving a further substantial increase in bit density. For the present, however, we may base our cost estimates on either of the first two options, both of which work out at about US$600 per station for a typical (64 Mbit/s) 24-hour AT run. If we assume that all LBA data can be correlated and returned within one month, then an initial purchase of a one month tape supply for 4 stations working at a 50% duty cycle will cost about US$40k. An estimate for tape replacement gives an annual cost of about US$8k.

5.4) Hardware costs

The cost of the DAS is still not known with any certainty. However an updated guesstimate would put the cost of a 4-converter DAS at about US$80k, including overheads, for the electronics, and a further US$85k for the recorder, giving a total cost of US$165k. The Playback Drives will also cost about US$85k each. Thus we have a total price of US$250k (or ~ A$350k) per station for the equipment to be bought from the VLBA.

In addition to this, there is the cost of the interface electronics to the correlator (which we must design and build ourselves) which, at a guess, might cost around A$30k per station, although this clearly needs to be designed at least in outline before meaningful estimates are made.

5.5) Timetable

A timetable was suggested 9 months ago in AT/23.5/009, and since then development of the DAS and DPS has, as mentioned above, been considerably delayed. It is therefore unlikely that any equipment could be made available to the AT before late 1989.

We have at present no formal agreement with the VLBA, but informal talks have included a proposal that some of our payment should be in the form of manpower - i.e. one of our engineers might spend a year working at Charlottesville and/or Haystack. A suitable time for this might be in 1989.

This timetable and the costs are unlikely to be made firmer until the VLBA finishes its pre-production run of the DAS. In the meantime, a provisional timetable is set out in the Summary.

6) WHERE TO TRACK FRINGES: FTA or FTC?

There was some while ago a debate between Fringe Tracking at the Antenna (FTA) and Fringe Tracking at the Correlator (FTC). It was concluded in the AT LBA workshop (AT/17.3.1/008) that, at least initially, fringe tracking should be done at the antenna rather than at the correlator but that a Hilbert phase rotator should be built for the correlator at some later stage for international VLBI experiments. I now propose to re-open this debate on the following grounds:

(1) We are now considering more seriously the inclusion of non-AT sites in the LBA. Designing fringe rotators for each of these will be expensive and difficult.

(2) We are now having to design our own correlator playback interface. Inclusion of a Hilbert fringe rotator (as described in AT/17.3.1/008) into this design would not be as much of a problem as designing one for an existing unit imported from the VLBA.

(3) We are committed to an involvement in RADIOASTRON and possibly QUASAT, with the additional international VLBI involvement implied by this. FTA is not suitable for international VLBI as it is not an option anywhere else.

These, together with the advantages listed in 17.3.1/008, constitute a formidable case for using FTC rather than FTA for the LBA. I therefore suggest that, as part of the Playback Interface design, the performance and design of a Hilbert phase rotator should be studied in detail, to see whether an effective FTC design can be efficiently incorporated into the interface design.

7) SUMMARY

The schedule and cost of the LBA at present depends heavily on progress made within the VLBA. The best estimate puts delivery of the DAS and DPS in 1990 or later, with a total cost approaching A$1.6M for equipment to handle four stations, including playback facilities and correlator interface electronics. This is a considerable increase on the original projections, and is approaching the stage where the AT may not be able to afford such a system.

Nevertheless, we can in the shorter term build up a working LBA using MkII recorders. In the immediate future, there are a number of tasks before us as follows:

1) Design the Playback Interface between the Playback Drive and the correlator. This should include a serious study of the performance and possible disadvantages of a Hilbert Transform phase rotator, and a study of possible problems in correlating MkIII/VLBA and MkII tapes together.

2) Design the interface between the AT receivers and the Data Acquisition System. This should include a study of the relationship between the two samplers in both the FTC and FTA cases.

3) Design an LBA system for Parkes. This should include a study of the benefits of sampling in the focus cabin and transferring data via optical fibre to the control room vs. other techniques of transferring the signal, bearing in mind the weight limit in the focus cabin.

4) Design an LBA system for Hobart. This clearly needs to be done by a team consisting of both AT and U.Tas staff. This study must await final prices and timetables from the VLBA.

5) Look at the overall requirements for Siding Spring, for both LBA and stand-alone use.

6) Design the software (LBACON) for controlling LBA antennas and DAS.

7) Investigate the possibility of sending digital data at slow speed over the AUSSAT phase stabilisation tones. This might include phase stabilisation information (as discussed in Section 4.2) and control/monitor data.

8) Reconsider the possibility of using 843 MHz as an AT UHF frequency, in view of the enormous benefits to be gained by collaborating with Molonglo.

A provisional timetable might be as follows:

Correlator	
Early 1988	Start design studies for DPI (Data Playback Interface), and investigate Hilbert Transform rotator
Late 1988	Start detailed design of DPI
Late 1989	Start construction of LBA correlator and DPI
Late 1990	MkII correlator working at Culgoora.
Late 1991	LBA correlator complete with DPS
Other LBA systems	
1988 - 1990	Continue with VLBI (processed in US) and PTI observations
Late 1988	Finish design study for LO and phase transfer and begin construction of prototypes
Late 1988	Get detailed costs and prices from VLBA and make final decision on overall system
Late 1989	AT engineer starts work at VLBA
1989-1990	Progressively equip remote sites with front ends and back ends as available. Progressively install LO and phase transfer systems and communications links.
Mid 1990	Delivery of 1st DAS, to be used for testing and development.
Late 1990	LBA working with MkII, including correlating at Culgoora
Late 1991	LBA complete

Table 1: Australian antennas which will/may be used with the LBA

Name	Diam. (m)	F_{max} (GHz)	Status
Culgoora	54 (eff)	115	AT antenna
Mopra	22	115	AT antenna
Parkes	64	43	AT antenna
Tidbinbilla	70	22	NASA antenna
Hobart	25	12?	U. Tas. antenna
Fleurs	25?	2.7?	Syd. Uni. EE - propose to tie several elements and install MkII recorder
Molonglo	180 (eff)	0.843	Syd. Uni. Physics - propose to install MkII recorder
Alice Spr.	10	10?	Landsat Antenna used for SN1987A VLBI
Perth	15	10?	ESA antenna. UWA are interested in operating it for VLBI
Adelaide	?	?	Uni. Adelaide interested in acquiring an antenna for VLBI