REPORT OF THE AT LBA WORKSHOP

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CONTENTS:

FIGURES:

TABLES:

1.0 INTRODUCTION

A 3-day workshop was held at Culgoora during 17-19 March 1986 with the primary intention of examining the plans for the the design and operation of the LBA, and of studying various potential problems and areas of uncertainty. The aims of the workshop were to reach a concensus on the design and operation of the LBA and formulate detailed plans for its implementation. During the workshop participants formed small working groups with responsibility for particular areas.

This report contains the conclusions of the working groups and also of the workshop as a whole. It is not intended to be a final definition of the LBA, but rather a statement of the current thinking of the group. For simplicity, statements and sections of this report are not attributed to their individual originators. Similarly, the (overlapping) conclusions of the working groups have been re-distributed to the appropriate sections of this report.

The following philosophy was adopted. Our immediate aim should be to produce a working LBA in 1988-89, which will be of immediate scientific value in tackling a number of outstanding astronomical problems. However, the full scientific value of the instrument will not be realised until it is extended beyond the immediately planned configuration. We should therefore see the LBA not only as a specialised instrument for tackling particular problems, but also as laying the groundwork for a much more extensive array with better u-v coverage within the next decade. Space-borne antennae such as QUASAT and RADIOASTRON will also serve to enhance the usefulness and impact of the future LBA.

Two key questions appeared many times in different contexts during the discussions, and the decisions on these set the key to the whole design. These questions are:

1. To what extent should the LBA be compatible with other VLBI systems, and in particular with the US VLBA?

2. How much of the LBA can be built within the available resources of the AT?

The consensus answers to these are:

1. The LBA should be as compatible with the US VLBA as is possible, in so far as this is consistent with getting the LBA going as soon as possible. In particular, it should be possible to process data from either of these arrays on the correlator of the other. This is best achieved by initially operating the LBA in a mode in which fringe rotation and variable-phase sampling are performed at the antennas, but later providing a 'compatibility mode' in which fringe rotation may be performed at the correlator, possibly with some small degradation in performance.

2. The available budget should cover installation of LBA data acquisition systems at Culgoora, Siding Spring, and Parkes, together with

    1. a spare unit which could be used to record data from Hobart, and

    2. a system to record data from Tidbinbilla using either (a) a NASA-supplied MkIII VLBI recorder at Tidbinbilla, or (b) transferring data from Tidbinbilla to Parkes using the microwave link, and recording the data on the Parkes recorder.

This report is organised so as to present an overview and strategic decisions first, with detailed discussions and justifications subsequently. The system presented here reflects the views of the workshop participants, and is not to be interpreted as official policy.

2.0 RECOMMENDATIONS

1. We should aim to operate a 5-station LBA by 1989/90. Of these, three (Culgoora, Siding Spring, and Parkes) will have their own Data Acquisition Systems, one (Hobart) will use a Data Acquisition System kept as a spare unit by the AT, and one (Tidbinbilla) will either use a MkIII recorder or else transfer the signal to Parkes via Radio Link.

2. The LBA should be constructed initially for fringe tracking at the antenna. At a later date, a compatibility mode will be implemented, in which fringe tracking will be done at the correlator using either a Hilbert transform phase rotator, or a hybrid FFT correlator. Any subsequent observation can use either mode, depending on the merits of each scheme for that particular observation.

3. We note that the inclusion of the 26m antenna at Hobart in the LBA nearly doubles the amount of information in any one map, and so the University of Tasmania (U. Tas.) should be given strong encouragement to acquire the capability to participate in LBA experiments.

4. In order to include the Hobart antenna in the LBA we must choose between two paths: (1) provision for fringe rotation at the correlator (by 1/90): or (2) provision of AT-compatible down-converters, including fringe rotation, for the Hobart antenna (by 1/89).

5. Since an AT backend (i.e. LO and down-converter) would allow U. Tas. to make single-dish observations as well as participate in AT experiments, we suggest that U. Tas. be encouraged to adopt a backend based on the AT design, to our common advantage.

6. The feasibility of supplying a phase rotator for Tidbinbilla should be investigated. This will involve not only provision of a phase-rotated LO and sampler, but also the use of a computer to calculate the rates and drive the rotator.

7. Negotiations should start immediately with NRAO for the purchase of Data Acquisition and Playback Systems. (Note added 29/5/86: these negotiations have now been started.) The AT should acquire four complete VLBA systems (record and playback) by 1/89, with the option of purchasing additional systems at a later date.

8. As a minimum, the LBA should be capable of recording 2 channels of 8MHz bandwidth, recorded with 2-bit sampling, per station. This gives a data rate (64 Mbit/s) which allows a 24-hour interval between tape changes, thus enabling unattended operation of Siding Spring. A double rate (requiring tape changes every 12 hours) should also be possible at twice the above bandwidth.

9. A minimum of two IF channels per station is to be provided initially, although if costs (yet to be determined) permit we should aim for four channels per station.

10. Real-time communication links should be provided to each remote antenna. These communication links should be able to provide coordinates to the antenna control computers, and transfer monitor information back to Culgoora. The communication links should include a data buffer at the remote end, so that commands may be sent ahead of time to minimise the effect of transmission delays or line failures.

11. The available LBA LO distribution systems should be reviewed in September 1986. If the viability of cavity oscillators is then demonstrated, three (for Culgoora, Siding Spring, and Parkes) systems should be purchased for delivery between 1/88 and 1/89. If funds permit, a spare unit which may be used at Hobart should also be purchased.

    If viability cannot be shown by 9/86, development of a satellite distribution system should begin early in 1987 and a system should be in operation no later than 1/90. To facilitate this, we should obtain the services of an appropriate expert to develop satellite LO systems. In the meantime, Rubidium standards (suitable for use up to S-band only) should be provided for each station.

If, however, more money becomes available for the LBA LO systems, acquisition of Hydrogen Maser oscillators should be considered. This is the only system which has proven performance in VLBI networks and it has been chosen for the US VLBA.

12. The LBA correlator should initially consist of 6 blocks, with flexible configuration to optimise the use of variable numbers of antennas. No separate continuum correlator need be provided.

13. In order to assure flexibility and reliability the LBA correlator should not share hardware resources with the CA correlator; it should have its own array processor and control computer.

14. Processing software must be provided for effective use of small numbers (i.e. 1-3) of baselines, as well as mapping software for larger numbers of baselines.

15. Development priorities beyond 1989 should aim to increase u-v coverage rather than increase baseline length.

3.0 ACTION ITEMS

1. KJW to investigate cost of equipping Tidbinbilla-Parkes link with wideband digital encoders/decoders.

2. DLJ to obtain details of VLBI recorder to be installed at Tidbinbilla by NASA

3. DLJ to set out the case for the implementation of simultaneous S/X observing on the LBA.

4. JWB/RHF to contact NRAO to discuss availability of the VLBA record and playback systems.

5. JDO/MSE to run simulations of the effect of Hilbert Transform fringe rotation techniques.

6. JDO/MSE to investigate techniques to handle validity bits, and in particular the feasibility of injecting random noise during flagged data.

7. U. Tas to be encouraged to install an AT-compatible LO and converter system, for their use in both stand-alone and LBA use.

8. KJW/DLJ/RNM to obtain details of access to Tidbinbilla hardware. E.g.: Can we get at the front-ends, and will our equipment need to be moved from antenna to antenna?

9. JWB/RNM to open discussions with JPL/NASA to find out how much time we are likely to get on the Tidbinbilla telescopes after 1988.

10. The feasibility of encoding data streams from two different telescopes on to one VLBA recorder, and subsequently decoding and correlating them, should be investigated.

Progress on these action items should be reviewed at the end of July 1986.

4.0 OVERVIEW

The Long Baseline Array (LBA) of the Australia Telescope (AT) consists of 1-6 22m antennas (in tied mode) of the Compact Array (CA) at Culgoora, a 22m antenna at Siding Spring, and the 64m antenna at Parkes. In addition, the LBA will frequently use the 34m/70m NASA antennas at Tidbinbilla, and the University of Tasmania 26m antenna at Hobart. For the purposes of this report, all five stations are included in the LBA.

As far as possible, each station will be controlled from Culgoora in nearly-real-time, probably using Telecom landlines and data modems. Similarly, monitor data from each antenna will be sent along these lines to Culgoora. A real-time fringe detection capability will be available, in which four Mbits of data can be recorded in RAM at each station and then replayed slowly over the monitor lines to Culgoora, where they can be correlated in software.

The LBA will probably operate with all five stations for only one or two months per year. On the other hand, the LBA will probably operate with a subset of these antennas for over 50% of the year. With all five stations included, the u-v coverage will allow high dynamic range maps to be made of compact galactic and extragalactic radio sources, but the large missing spacings in the u-v plane impose a spatial filter on the data, which will preclude complete maps of complex sources. However, other arrays such as the US and European VLBI networks and MERLIN have shown that a great deal of new and important science can be achieved even with such sparsely filled arrays. With fewer than five stations, the quality of the maps is reduced accordingly, although it should be noted that even three stations will produce usable maps of simple structures. For example, the discovery of circumstellar shells around OH/IR stars was made with only three baselines, during the construction of MERLIN. Even two stations, although not capable of producing a map, can produce valuable data in areas such as astrometry, pulsar proper motions, and mapping of unresolved maser spots.

At each station, the signals will be downconverted using equipment which may vary from station to station. They will then recorded on Data Acquisition Systems (DAS) similar to those used for the US VLBA. In a minimum mode, two 8MHz-bandwidth channels per station will be 2-bit sampled, so that each station will fill a tape in 24 hours. However, wider bandwidths are also possible and will require more frequent tape changes, to a maximum rate of one tape every six hours. The tapes will then be posted to Culgoora where they will be replayed and correlated typically two weeks after the observations.

We cannot yet make the choice of frequency standards to be used at the stations. However, these are likely to be either (a) a cryogenic cavity oscillator being developed by the University of Western Australia, or (b) real time radio links to each station via AUSSAT. If neither of these is available by the start of LBA operations, then Rubidium standards will be purchased for each station, allowing LBA operation at the lower frequency bands. Time standards will also be provided, probably in the form of an off-the-shelf GPS system. Depending on the cost of the time standard, only one portable standard may be purchased, since after the initial observations the astronomical data themselves will yield a clock error for each station.

The workshop discussed extensively the relative merits of fringe tracking at the antennas compared to fringe tracking at the correlator. The former is the system used by the Compact Array (CA) whilst the latter will probably be used by the US VLBA. It was decided that the best compromise would be to take advantage of existing CA design work by running the LBA initially with fringe tracking at the antennas, but at a later date implement a compatibilty mode in which fringe tracking may be done at the correlator.

The correlator at Culgoora will consist initially of only six blocks. These will be capable of being configured in a variety of ways which are shown in Table 9.1. Observing modes beyond these configurations can be handled by processing in more than one pass.

This reduction in correlator size was seen by the majority (but not unanimously) as being justified in view of the probable difficulty in achieving the other goals of the LBA within the allowed budget, assuming that the saving on the correlator can be passed on to other areas of the LBA (e.g. data transfer, clocks and LO's, etc.). However, this decision must await more detailed estimates of the costs of other components of the LBA.

Table 4.1 summarises the components to be provided for the initial operation of the LBA.

5.0 ANTENNAS AND RECEIVERS

5.1 Future Extensions to the LBA

As well as the five antennas listed in the Introduction to this report, we should consider at an early stage what the future extensions of the LBA might be. Table 5.1 lists a number of antennas which have been considered for possible use with the LBA. The first five are the antennas which are expected to be available at the start of LBA operations. The u-v diagram for those five, shown in Fig. 5.1, has two major deficiencies: it lacks East-West spacings and also shorter spacings to fill in the gaps. The most pronounced of these gaps is that between the 6km longest baseline of the compact array and the 115km shortest baseline of the LBA. The effect of these deficiencies is to impose a spatial filter on the source structures which might be mapped. Thus the LBA in its initial mode, whilst capable of mapping many sources of pressing astrophysical interest, will only be sampling a range of the structures which may be present in the source. On the other hand, it should be remembered that other arrays (e.g. MERLIN, VLBI networks) with comparable u-v filling factors have produced a substantial body of exciting astrophysical results, and that there are many Southern objects which cannot be reached by these instruments.

Both the deficiencies referred to above would be overcome by the addition of stations at Adelaide (for longer E-W spacings), Epping (for mid-range E-W spacings), and Cubbo and Gerwa (for short spacings). Note that smaller dishes (such as 14m ex-Fleurs dishes, for wavelengths of 13cm or more) could be used for the shorter spacings. This is because, in any synthesis array, the most sensitive antennas should be on the longest baselines for the following reasons:

1. Source structure is more likely to be resolved out on these spacings, and so spatial features which are prominent on short spacings are likely to be weak on long spacings.

2. In any time interval, a given u-v increment is sampled more frequently by the short spacings than by the long spacings, and so the signal-to-noise ratio in any gridded sample is lower for long

spacings than for short spacings.

The last three sites extend the maximum baselines, and thus enhance the resolution of the LBA. Whilst this is certainly a worthwhile long-term aim, the consensus of the workshop was that highest priority for future extensions of the LBA should be given to the closer sites, in order that the LBA should be able to produce high dynamic range maps of complex sources as soon as possible. U-v plots resulting from the addition of some of these stations are shown in Figs. 5.2 - 5.4.

An interim mode of operation for the LBA would be for some additional antennas (e.g. Perth, Alice Springs) to be equipped with low-cost Mk.II VLBI terminals, using video cassette recorders. Data from experiments using these antennas could then be cross-correlated with the LBA data. Apart from the low costing terminals themselves, this mode would require development of hardware and software to interface the Mk.II playback units to the LBA correlator. Manpower is unlikely to be available for this until 1989, but then this option would yield valuable results on selected sources.

5.2 Frequencies of Operation

The astronomical requirements for frequency coverage are broadly the same as those for the compact array, with the possible exception of the 21cm band, since most HI sources are expected to be over-resolved with the LBA, and the 18cm band is sufficiently close to the 21cm band for most continuum measurements.

An additional requirement stems from the desire to use the LBA for astrometry and geodesy. The effectiveness of the LBA is enhanced for such work if all antennas are equipped for simultaneous S/X (3cm/13cm) operation, since then the ionospheric phase variations can be removed. However, it is not clear (a) to what extent the LBA will be made available for geodetic work, and (b) how effective simultaneous S/X operation is. We note in this latter context that the US VLBA have decided not to provide simultaneous S/X operation initially. DLJ is requested to set out the case for simultaneous S/X operation.

If S/X operation is given sufficient priority, then the installation of dichroic-reflector systems and offset 3 cm feeds for simultaneous S/X operation with the new 22m AT dishes should go first on the "6-km" dish of the compact array and then on the Siding Spring antenna. Installation of S/X systems on Parkes (and Tidbinbilla) is not expected to require substantial development or cost. The AT project should expand its contacts with the geodesic and astrometric community and explore the possibilities of sharing or combining resources to equip other LBA antennas.

6.0 CLOCKS AND LO'S

6.1 Introduction

This section discusses both LO standards and timing reference clocks. The distinction is one of function: LO standards control the observing frequency whereas timing clocks control the time at which phase tracking is applied. An error in the timing may cause unacceptable difficulties in searching for fringes during processing, but an error in the LO standards may, in the FTA option, preclude any fringes at all being found. In practice, however, the functions share some components.

The original budget to cover the cost of microwave links has to pay for all clocks, frequency standards, and tape systems except for a timing clock at Culgoora. An amount of $300K has been set aside for clocks but it should be kept in mind that savings here may increase the budget for tapes. The converse is also true.

6.2 LO Reference standards

A minimum of four LO standards allows for one at Culgoora, Parkes and Siding Spring with a spare which would normally be used at Hobart (Tidbinbilla has a maser already).

Present specifications, shown in Fig. 6.1 together with the performance of typical standards, call for 2 ps RMS time jitter (equivalent to 0.7° / GHz) out to 300 seconds integration time and an Allan variance of 5.10^{-15} from 300 to 3000 seconds. This was considered to be less than ideal by a factor of 3 at 10 seconds and a factor of 5 at 3000 seconds. However even H-masers barely meet this ideal. Fig. 6.2 shows coherence times.

We have the following options for the LO standards:

1. The sapphire loaded cavities being developed at UWA will probably exceed our specifications with sufficient development. However there have been delays in reducing the Allan variance much below 10^{-13}. Although this is understandable in a new development there must be doubt whether they can

meet our timescale requirements and whether commercial funding can be sustained if delays continue. This option must therefore be regarded as the best if it succeeds. Cost is uncertain but is likely to be of the order of $80K * 4.

2. LO links via Aussat. This option has been extensively investigated (B. Anderson, AT23.4.1/004). Signal to noise limitations on a satellite link limit the attainable time jitter to 2 ps for short integration times. There is concern that this will limit the LBA in the 40 to 120 GHz bands. There is also concern at the long development time required and the lack of manpower at present. Cost was estimated at $70K * 5 units, including a master station.

3. Rubidium standards. These are usable for mapping over the initial AT bands below 10 GHz but are not very useful for astrometry or for frequencies above 10 GHz. Availability is excellent and cost is approximately $20K each. Since Parkes, Culgoora, and Tidbinbilla will have these (or better), then only Siding Spring needs one.

4. H Masers. These are ideal but costs are very high. This is presently estimated at $250K * 4 units (based on cost to the VLBA).

Our conclusion is that, unless extra funding becomes available, masers cannot be considered. Sapphire cavities are the best hope with satellite links the fallback option. It was decided to review LO standards in six months to allow time for the sapphire cavity position to become more certain. If this option fails, we should obtain the services of an appropriate expert to develop satellite LO systems. A rubidium standard at Siding Spring will allow initial operation to commence without delay.

6.3 TIMING CLOCKS

Timing clocks are required for three stations (Parkes, Culgoora, Siding Spring), together with a spare which could be used at Hobart. It appears that 1 μs stability would be ideal but that 10 μs per month with some means of occasionally determining absolute time to 10 μs is adequate.

The main options, listed in Table 6.1, are:

1. GPS receiver. Better than 1 μs absolute is achievable but present cost of $50K each is very high, although this price appears to be falling.

2. Rubidiums. Cost is $15K to $25K but will probably be available at all sites for LO. They drift by around 10 μs per month and do not give absolute time and must be set accurately.

3. Aussat link. NML intend developing this to replace existing TV signal time distribution and should achieve 10 μs absolute accuracy. Cost could be quite low but is unknown.

The minimum requirement would be satisfied by a rubidium at each site (as suggested for LO) and a travelling GPS receiver (or maybe even a travelling rubidium?).

It was decided that since delivery/development time was not excessive, a final decision should be delayed for at least 6 to 12 months in view of possible changes to GPS receiver pricing, NML Aussat development and the implications of LO standard decisions.

7.0 FRINGE ROTATION AND DOWN-CONVERTERS

7.1 Fringe Rotation: Antenna or Correlator?

There was considerable debate during the workshop over whether fringe rotation should be done at the antenna (Fringe Tracking at Antenna: FTA) or at the correlator (FTC). The US VLBA have been debating the same point, but at present it appears likely that they will opt for FTC. Thus the pros and cons for the LBA are as follows:

PRO FTA:

1. It is compatible with the CA
2. It is compatible with the present correlator design
3. Depending on the implementation of FTC, FTA may have a slightly better signal/noise ratio (see below)
4. No extra design work is needed

PRO FTC:

1. It is (probably) compatible with the US VLBA
2. Fringe tracking calculations need be done only once, thus easing the problem of algorithm accountability.
3. It does not require access to the LO's of non-AT telescopes.
4. It has greater flexibility for multiple phase centres, since the FTA method requires a high correlator dump rate for multiple phase centres.
5. It eliminates the possibility of antenna-based sytematic errors (see A.Rogers & J.Webber: VLBA326)
6. It eliminates the possibility of receiver images (see A.Rogers: VLBA327)

7. It eases the problem of phase glitches caused by the inadequate range of the AT phase rotators.

There are persuasive arguments on both sides. The weightiest argument for the AT is probably that of resources: our present correlator design does not easily allow the use of a 'conventional' FTC scheme. Thus to adopt an FTC scheme we must either re-design the correlator, or else design a Bolt-On-Goodie (BOG), using either (1) a Hilbert Transform technique (see Section 7.2 below, and M. Ewing: AT/17.3.2/002, L. D'Addario: VLBA321), or (2) a pre-correlation FFT device, to turn the correlator into a hybrid correlator. (see M.Ewing: AT/24.1/010) This approach has several (although possibly minor) disadvantages:

1. In the case of a Hilbert Transform technique, there is some (probably ~ 10%) loss of signal-to-noise.

2. In the case of a Hilbert Transform technique, unavoidable ripples in the passband may make spectral-line calibration difficult (see A.Rogers: VLBA328). On the other hand, these effects are predictable from a well-determined algorithm, and so in principle are removable in software.

3. Very strong spectral-line sources (e.g. the strongest H_2O masers) may cause saturation of the passband. This can be cured by reducing the dynamic range of the input signal by, for example, injecting noise in the front-ends.

The final consensus was that:

1. We do not have the resources to develop an LBA correlator which is totally different from the CA correlator.

2. We do not <u>at present</u> have the resources to develop a BOG, but will probably do so in the future.

3. Implementation of an FTA scheme will involve little effort beyond that already required for the CA.

4. Compatibility with the US VLBA, QUASAT, etc. will not be needed for 'Day 1' LBA operation.

It was therefore decided that the following compromise should be adopted: the LBA should be constructed initially for FTA operation. At a later date, a compatibility mode will be implemented, in which fringe tracking will be done at the correlator using a BOG. Any subsequent observation can use either mode, depending on the merits of each scheme for that particular observation.

7.2 Fringe Rotation at the correlator

The inputs to the correlator are single real bit streams. Three basic possibilities exist to fringe rotate the correlated values;

1. Post-correlation fringe rotation. The complex frequency channels after transformation from lag to frequency space can be phase rotated. This implies a sufficiently rapid correlator dump time and Fourier transformation rate. Better still, a longer integration time can be divided into a small number of bins (perhaps 4 or 8) much as for pulsar observations, such that the expected fringe is synchronous with the whole sequence. The first bin is used to accumulate the first portion of each fringe, the second bin the next portion and so forth. Fringe rates of perhaps 125 Hz would be possible but all products in each module would be constrained to have the same fringe rate.

2. VLBI Method The VLBI fraternity habitually use a method whereby the one input is multiplied by cosine and sine "fringes". The result is two components of fringe direction, one desired and one in the reverse direction. The desired direction is selected by performing the correlation separately on both cosine and sine multiplied inputs, phase rotating one correlation by 90° (swapping real and imaginary and inverting one) and combining the two to complete the single sideband mixer. The requirement is a doubling of correlator size and also suppression of correlator counts at some points of the cycle. Both requirements have led Marty Ewing to reexamine the possibility of Fourier transform methods to win back channels.

3. A Hilbert Transform (BOG) Phase Rotator A single sideband mixer can be constructed from a 0 deg and a 90 deg filter by multiplication by the cosine and

sine of the desired fringe rotation. It is possible then to construct a Bolt-On-Goodie (BOG) to sit in front of the correlator in each telescope input which rotates the telescope phase by a desired amount.

7.3 Hilbert Transform (BOG) Fringe Rotator

The basic phase rotator is shown in Figure 7.1. The phase rotated result is obtained by:

F{x(t),phi} = F{x(t),0}.cos(phi) - F{x(t),90}.sin(phi)

where F{x(t),phi} represents a phase rotation of phi. The zero phase rotator is simply a delay (since 90 deg rotation cannot be achieved without a delay), and the 90 deg rotator is a transversal filter with weights given approximately by (1-cos(pi.i)/pi.i for i = ± 0,1,2,...N.

Having progressed this far, it is possible to see the solution to the fractional bit shift problem by a simple extension. The fractional bit shift problem arises from the fact that if delay and fringe rotation are to be performed after sampling, then only integral delay steps are easily performed. Furthermore, since delay correction is performed to within ±0.5 sample interval in each telescope input, the error for a given baseline may be ±1.0 sample intervals which leads to considerable continuum decorrelation, and phase errors for the highest frequency spectral line channels. It would be desirable then to ensure that the fringe rotator simultaneously resamples the output to correct the fractional shift exactly.

The resampling is performed by adjusting the weights of both filters. The weights of the 0 deg filter become sin(pi(i-tau))/pi(i-tau) and those of the 90 deg filter become (1-cos(pi(i-tau))/pi(i-tau). Note that the 90 deg filter is no longer a delay since all weights are in general non zero. The shift parameter tau is in the range -0.5 to 0.5.

A simple filter structure is shown in Figures 7.2 and 7.3. The filter is based upon the idea that for two bit inputs, all possible products with the coefficients for phi, tau can be precomputed and summed and stored in ROM. The delay from filter tap to filter tap is performed by pipelining the accumulation of the partial sum. The desired tap length is purely a question of cost versus performance.

A possible scheme would allow perhaps 32 taps with 16 phase steps and 2 bit shift steps and use 256x8 ROMs.

A problem ignored thus far is the fact that the filter output is multi-bit. The outputs must be requantised to 2 bits for the correlator. A single ROM can perform the quantisation but fundamental problems remain.

Basically we will have performed a 2 bit quantisation on a noise signal with hopefully approximately Gaussian statistics. For low correlated fractions we then expect a further 12% degradation in S/N. In some states of phase, delay correction, the filter passes the signal with no change so a figure less than 12% might be expected. In any case, it would appear necessary to simulate the action of such a filter to gauge the inflence on overall system S/N degradation and and non-correctable nonlinearities. It is likely that little problem will result at 1% dynamic range level.

One problem for which some effects can already be estimated arise from the impossibility of producing an accurate 90 deg phase shift with a finite length filter. The weights quoted above give rise to a square bandpass with ringing on the edges. The amplitude is zero at zero frequency and the Nyquist frequency. A different response is obtained for the 0 deg state so the bandpass is modulated as the phase is rotated.

The modulation is sinusoidal however and probably corresponds to a component of the signal which is rotated in phase in the opposite direction to that desired. Given that offset rates are applied to all fringe rotations, the overall effect would be a small component in the image flipped through 180 degrees and shifted by the fringe offset (a ghost response). This component would lie well outside the envelope defined by the integration period and would not be seen. The only residual effect would be a small additional loss in sensitivity.

Obviously the above potential sources of error and sensitivity loss must be examined carefully before embarking on this path.

7.4 Down Converters

The VLBA Data Acquisition System (DAS) includes a set of down converters which take an IF in the region 492-1008

MHz, convert it to baseband, and filter it to a selected bandwidth before passing it to the formatter where it is digitised. Thus one option for the AT LBA is to supply front-end LO's to convert all bands to 492-1008 MHz, and then use the DAS electronics for all subsequent processing.

An alternative option is to use the AT down-converters, which have already been designed for the Compact Array, and supply a filtered baseband signal suitable for input to the DAS formatter.

Ideally, we would like the down-converters on all LBA telescopes to be identical, in order to ease both calibration and maintenance. Furthermore, the ideal of compatibility with the VLBA suggests that these should be the VLBA down-converters. However, the IF from the tied Compact Array cannot easily be converted to a suitable form for the VLBA down-converters, and so Culgoora at least must use the AT down-converters. The question then becomes: should the remaining down-converters be (a) all AT converters (thus preserving at least uniformity within the LBA), or (b) a mixture of AT and VLBA converters. It should further be noted that use of an AT down-converter enables (but does not demand) the easy use of the rest of the AT LO system, including fringe rotation.

Other relative merits of the two down-converters are:

PRO VLBA CONVERTERS

1. Easily fitted to non-AT antennas

2. Compatible with US VLBA

3. Compatible input with Bonn-type polarimeter, for single-dish work.

PRO AT CONVERTERS

1. Incorporate facilities for measuring polarisation accurately

2. Necessary for Culgoora tied array

3. For stand-alone operation, Parkes and Siding Spring need bandwidths of 32, 64, 128, and 256 MHz, which are not available on the VLBA converters.

4. Ideal for Siding Spring stand-alone operation, since additional LO chain would be needed ahead of VLBA down-converters.

5. Preferable for single-dish short-baseline-flux measurements, in order to maintain compatibility with the tied array.

6. Fringe Tracking at antennas already incorporated.

Thus a compromise seems necessary. The recommended compromise uses AT down-converters for Culgoora, Siding Spring, and Parkes. The choice of converter for Tidbinbilla and Hobart depends on the precise details of our access to their instrumentation. Given a system to which we have total access, it is undoubtedly simpler to install a complete AT LO and converter system than to install a VLBA converter and design an LO system. On the other hand, if we have access only to an IF output then it is probably simpler to interface a VLBA converter to this than an AT converter. Since Hobart does not yet have a backend system designed, and since an AT backend (i.e. LO and converter) would cater for their single-dish as well as AT observations, we suggest that U. Tas be encouraged to adopt an AT LO and converter system, to our common advantage. In this case, it would then be sensible to provide an AT LO system for use at Tidbinbilla. Note that Fringe Tracking at the Antenna can be applied in either case, provided that we have access to the LO's and appropriate computing and timing facilities.

8.0 DATA TRANSFER

8.1 Introduction

The data will be transferred from the remote stations to Culgoora by using tape recording Data Acquisition Systems (DAS), and the corresponding Data Playback Systems (DPS), that we hope to obtain from the US VLBA. The AT DAS will differ from the VLBA DAS in that it will use a smaller bandwidth than the VLBA, which in turn implies that:

1. The electronics become cheaper, since the DAS is highly modularised, and so we can buy a smaller number of modules.

2. Only one tape transport is needed for 24-hour unattended operation, as opposed to the two transports used by the VLBA.

An overview of the proposed system is shown in Fig. 8.1. Only four DAS's are to be bought initially. It is difficult to justify the purchase of a DAS for Tidbinbilla until we have a clearer idea of the fraction of time for which this telescope will be available. However, there are two alternative ways of getting data from Tidbinbilla:

1. Send the data to Parkes using the existing microwave link, or

2. Use the MkIII VLBI recorder which is soon to be installed at Tidbinbilla.

Each tape has a maximum capacity of 64 Mbit/s x 24hours, so that for 24 hour unattended operation, the maximum bandwidth is limited to 32MHz x 1-bit, or 2 x 8MHz x 2-bit. We regard this latter mode as being the minimum capability to be provided for the LBA. However, the transports have a maximum data rate of 256 Mbit/s, so that tapes can also be used at up to four times the minimum capability rate for particular experiments, to obtain up to 2 x 32MHz x 2-bit. However, such operation may require modules additional to those proposed here.

If the Tidbinbilla data is recorded onto the Parkes tape, as suggested below, then:

1. The Parkes tape will need to be changed every 12 hours when observing in minimum capability mode

2. The absolute maximum bandwidth for each telescope will be 2 x 16MHz x 2-bit.

8.2 Control and monitor data

Computer communication links are required between the central control building and all remote LBA stations for coordination of antenna control, archival of monitor and calibration data, and for initial data validity checking. Control and monitor information should be transmitted with due regard for the maximum possible time delays on the link if a system such as AUSPACK is used. For unmanned stations a maximum delay of 1 minute is suggested; for manned stations delays up to 15 minutes may be tolerable.

Data validity checking in particular becomes most important if fringe rotation is done at the antennas. LO frequency offsets among the LBA stations produce residual fringe rates which can decorrelate the signals. Transfer of short IF data streams over the computer link provides a method for calibrating LO offsets and also for overall data validity checking. Buffers for storage and transmission of digital IF data for this purpose are provided in the DAS. A system for (pseudo) real-time fringe detection should be implemented for the LBA with delays in data transfer not to exceed 1 hour.

8.3 Overview of the DAS

A block diagram of the DAS, as used for the AT, is shown in Fig, 8.2. Each DAS consists of a set of Down-Converters (unless replaced by the AT down-converters) followed by a formatter, and a tape transport.

The down-converters take a signal in the range 492-1008MHz, convert it to video and filter it. They also include a level control. The available bandwidths range in binary steps from 62.5kHz to 16MHz. Each down-converter contains a double-sideband mixer, and so can produce two filtered channels per converter. The US VLBA (see VLBA515) will probably use initially 8 down-converters per station, thus giving up to 16 x 16MHz channels (upper and lower sidebands: only half of these have independant LO's). For our 'Day-one' LBA, we could make do with only 2 down-converters, although four would be preferable. It is expected that the DAS will have sufficient modularity to permit this. The specifications of the down-converters are given in Table 8.1.

The formatters take the signals from the down-converters and digitise them using either 1-bit or 2-bit digitisation. Each input channel therefore produces a digital data stream of up to 64 Mbit/s. However, each tape track can record a maximum of 8 Mbit/s, and so the data from each channel is spread over several tape tracks. The way in which this is done is software-selectable. The formatter then divides the data up into words and frames, using an error detection method which is not yet finalised. At the head of each frame is encoded the time and other data. The specifications for the formatter are given in Table 8.2. The US VLBA will use formatters with 16 video inputs, whereas we need only two or four. It is not known at present to what extent the modularity of the VLBA formatter will enable us to use a smaller formatter than that of VLBA.

The tape transport is a modified Honeywell Model 96 transport. The principal modification is that the heads have been replaced by video heads milled down to provide 20 μm tracks, so that instead of each tape containing 28 tracks, it now contains 20 x 32 tracks. These are accessed using a 32-head stack which may be moved accurately using an inchworm actuator and position transducer to successive positions across the tape. Thus the tape is recorded in 20 successive passes, with the heads being moved to a different position each time. In addition, not all heads need be addressed each time, so that for narrow bandwidth operation a number of passes may be made using different heads, with the headstack in the same position.

The data quality analyser/data buffer is primarily to provide the capability to detect real-time fringes. It has a memory of 4 Mbits, and can store formatted data and then send that at a reduced data rate over a modem link to Culgoora.

8.4 Overview of the DPS

The Data Playback System is shown in Figure 8.3. The tape transport is identical to that in the DAS, except for the provision of playback electronics rather than record electronics around the head-stack.

The decoder performs the inverse function of the formatter. It reads the formatted data, checks for errors, and outputs a continuous data stream together with a data validity stream for each channel.

The deskew electronics takes these data, buffers them, and aligns them to a fixed reference time, to remove the effect of tape stretch and other timing errors. The precise implementation of this is still under discussion, but it is likely that the correlator will be able to demand data from a particular recording time, to be supplied at a particular wall-clock time. Thus the input to the correlator will be a continuous data stream (+ validity bits) resembling real-time data, but corresponding to some known time in the past.

8.5 The Tidbinbilla MkIII recorder

One option for getting the data from Tidbinbilla is to request use of the MkIII VLBI recorder which, it is understood, will be installed shortly. However, it should be noted that this may be a conventional MkIII (not even MkIIIa !) recorder, with a time between tape changes of 13 minutes at normal (112 Mbit/s) data rates. For LBA use, with 64Mbit/s data rate (e.g. 2 x 8MHz BW x 2 bit sampling), we would need tape changes every 20 minutes (3 passes x 8 tracks x 8Mbit/s/track) These data would be readable on our VLBA playback system, but might require special recording arrangements on the other LBA recorders to ensure compatibility. DLJ is to investigate the precise configuration that Tidbinbilla will be acquiring.

8.6 The Tidbinbilla radio link

The Parkes-Tidbinbilla link consists of two microwave carriers in each direction. Each of these is modulated by a 70 ± 20 MHz signal, which in turn is frequency modulated to provide a high quality link with a bandwidth of 8 MHz. The only inputs and outputs at present available are to the 8 MHz bandwidth modulators and demodulators, but in principle the wider bandwidth 70 MHz channel could be made available. There are three ways in which data might be transferred from Tidbinbilla to Parkes, to be recorded on the Parkes DAS.

1. The video signal from Tidbinbilla could be put onto the FM channels, to provide two 8MHz IF's. The advantage of this scheme is that it's simple, but it has the disadvantage that the link delay must be measured and compensation somehow applied.

2. The video signal could be digitised at Tidbinbilla, and put on to the FM links. Using the available 16MHz link bandwidth, one 8MHz x 1bit, or 4MHz x 2bit, IF could be used. This has the advantage that the digitisation removes the need to measure the link delay, but seriously restricts the available bandwidth.

3. The wider bands could be used. Using sophisticated encoding techniques, bandwidths up to 2 x 32MHz x 2 bit might be available. If feasible, this is the preferred option. However, the necessary equipment for this may be prohibitively expensive. KJW is to investigate this.

It is not possible at present to decide how best to transfer data from Tidbinbilla, or whether such a technique is desirable. The cost of implementing such a transfer must be compared with (a) the cost of a further DAS, (b) the cost (perhaps in man-hours and the extra quantity of tapes required) of using the NASA MkIII terminal, and (c) the cost-effectiveness of an antenna which may be available for only a small fraction of the LBA observing time.

A further potential problem is that it is not clear how easy it will be to encode data from two telescopes on to one tape. In principle, since each data stream is encoded with its own time, there should be no problem, and the only additional hardware required would be an additional variable delay to synchronise the two data streams (either at record or playback time). However, a practical implementation of this may require significant modifications to the VLBA electronics or software. The feasibility of this should therefore be investigated at the earliest opportunity.

9.0 CORRELATOR AND COMPUTER HARDWARE

9.1 Introduction

The BLOCK is shown in Fig. 9.1. It has a set of four X inputs and a set of four Y inputs. Normally each input is one digitised IF signal. In the CA the X inputs come from one antenna, the Y's from another, so that the block looks after one baseline. There are 8 MODULES in a block. Each module correlates one X input with one Y input. The X input of a module can be switched to any of the four X inputs to the block, similarly the Y's. Hence the block can form from 1 to 8 products. For fewer than 8 products, modules can be concatenated to give more delays on a particular product.

In 2-bit mode, a single module provides 128 frequency channels over a 16MHz bandwidth. If all 8 modules are concatenated on one product, 1024 channels are available. At 8MHz bandwidth, this increases to 2048 and at 4MHz to 4096 channels.

9.2 Goals

The following were seen as the goals for the LBA Correlator.

1. The correlator should be capable of processing tapes which have been written at a standard VLBA station.

2. The correlator should be flexible in the sense of distributing the available channels over varying numbers of baselines corresponding to arrays of from 3 to 8 stations.

3. To the maximum possible extent, the LBA correlator should be compatible with the Compact Array correlator, in both hardware and software.

4. In its minimum baseline configuration, the correlator should provide at least 1024 frequency channels in a single product at 16MHz bandwidth. For more products per baseline, up to a maximum of 8, it is acceptable that there be proportionally fewer channels.

Point 1 above was considered an ultimate goal which may not be achieved in time for the start of LBA operations. The initial configuration could operate with fringe tracking at the antennas and a subset of the final LBA correlator which excluded the (add-on) correlator fringe tracking. Ultimately post playback fringe tracking should be available for all stations.

9.3 LBA Computer Configuration.

The proposed computer configuration is shown in Fig. 9.2. It was considered that the following principles should be adhered to.

1. The LBA correlator computer should not be involved with any of the observing tasks, including array control and real (or quasi-real) time data acquisition. Monitor data taken during observing and sent to Culgoora by either telephone lines or transportable media should be handled by the Synchronous or Asynchronous computers.

2. All tasks involved in the data playback process should take place in the LBA correlator computer. This process should operate independently of the other computers with the exception of its need to access the common data base to obtain monitor data etc. It was suggested that the LBA correlator computer could also be available for some forms of post correlation processing.

It was generally agreed that the software effort required for the LBA correlator computer will be considerable. This is despite the fact that many modules will be common to the CA correlator. It is not clear whether the required manpower will be available from the present resources.

9.4 LBA Correlator Configuration.

It was decided by a majority of participants that a separate continuum correlator could not be justified for the LBA. Although there certainly are some experiments for which such a correlator would be an advantage, the fraction of observing time spent on such experiments is unlikely to be large, and so the available resources would be better diverted to other areas of the LBA.

The design of the line correlator posed the following qusetion. How can we use the standard module/block structure of the CA correlator to build a flexible unit capable of processing from 3 to 8 stations ?

Configurations were considered which had as their starting point a structure similar to the CA correlator, with one block per baseline. For example, six blocks could accomodate up to 4 stations with full performance. i.e. 1024 channels distributed over from 1 to 8 products at 16MHz. With only three stations, autocorrelations could also be provided.

A maximum of 48 products is available from this configuration. Naturally as the number of stations increases, the maximum number of products per baseline decreases. With 5 stations, the number of baselines almost doubles, and so it seemed sensible to divide the blocks into two halves. Each baseline is then allotted 4 modules giving 512 channels distributed over from 1 to 4 products.

This process can be taken one step further, the block being divided amongst 4 baselines. A maximum of 24 baselines can be accomodated with 256 channels over one or two products.

A switching scheme to achieve the above configuration has been described since the workshop by A.J.Hunt, and is summarised in Table 9.1.

9.5 Playback Data Validity

Data from the Data Playback System can be flagged invalid for periods of a frame or more (of order 20000 bits).

One way of handling this invalid data is by use of the 'blank' signal which, when active, causes all correlators on a module to cease correlation. However, the data invalid period would need to be prolonged to take account of the data delays (of order 1/[frequency resolution]) in the XCELL chips. Also, counters would be needed to count the number of blanked samples to allow normalisation of the correlator outputs. This might become quite messy, but warrants further investigation. A further problem with this technique is that the expected rate of tape errors coupled with the long delay within an XCELL means that, at lower bandwidths, an unacceptable fraction of the data might be lost.

Another method which was discussed involves replacing invalid data by data from a pseudo random source. Once again the counters would be required. This method will also be investigated.

10.0 SOFTWARE

10.1 Introduction

Many of the software needs of the LBA are common to those of the CA, and so in that sense much of the software already exists, or will exist by 1988. However, there are in addition software needs peculiar to the LBA, and these are listed here for reference, although manpower for providing this software is not expected to become available until next year.

The LBA software needs can be divided up into:

1. On-line control and monitor software

2. On-line playback software

3. Real-time fringe detection software

4. Off-line mapping and calibration software

5. Off-line single baseline reduction software

Each of these will now be considered separately.

10.2 On-line control and monitor software

The telescope control and monitor software is assumed to be that already provided for each antenna. That at Siding Spring will be similar to the Culgoora telescope control and monitor software. However, it will be necessary for each telescope to be controlled and monitored from the central site. Thus each telescope will need software to interface the local control and monitor system to the modems to the central site. In addition, this software should also interface to the Data Acquisition System (DAS) software. Commands will be sent from the central site a few minutes in advance, and each will be labelled at the 'clock-time' at which it is to take effect, so that the system will be independant of occasional data transmission delays or short breaks. Thus the local software at each site must be able to buffer commands, and feed them to the telescope or DAS control system at the appropriate time.

At Culgoora there must be a corresponding system to talk to each of the remote antennas, receive monitor data from them, and place it in the monitor database.

10.3 On-line playback software

Software will be needed at Culgoora to control and monitor the operation of the correlator and Data Playback Systems (DPS). Part of this software (that part controlling the correlator) will be similar to the compact array software, but much of it will be concerned with the control and monitor of the DPS, and will have to be specially written. In addition, software will be required to maintain a database of the location and movement of the tapes from site to site.

10.4 Real-time fringe detection

The DAS has a facility for recording 4 Mbit of data and replaying this at a slow rate over the modem lines to the central site. Minimal software will be needed at the remote site to control this. At Culgoora, however, software will be needed to record (in a normal disc file) the data from each station, correlate it, and display the fringes. In addition, the software should write the data as a file similar to that produced from a normal observation, so that it can be analysed using the normal off-line reduction software. Note that this process does not require the use of the correlator: the quantity of data is small enough for all the correlation to be done in software.

10.5 Off-line mapping and calibration software

Most of the off-line processing software is already available in AIPS, or will be written for the Compact Array processing. However, a number of special-purpose programs are needed to be written in the AIPS environment to perform the following functions.

1. Data correction for simultaneous S/X observations.

2. Data correction for instrumental effects peculiar to the LBA. (We don't yet know what these are, but they are bound to be present!)

3. Spectral-line data correction for Hilbert transform fringe rotation (if adopted).

10.6 Off-line single baseline reduction software

There are many useful observations that can be done with a single baseline (or a small number of baselines), and, since this is the mode in which the LBA will be most readily available, it is important that we make adequate provision for this mode of operation. It is recommended that single-baseline data should be processed within the AIPS environment, since many data correction algorithms will already be implemented within AIPS.

The following programs will be needed. Some of these will already have been written for the Parkes-Tidbinbilla Interferometer, and some (e.g. pulsar programs) are so specialised that we may reasonably expect manpower assistance from the users.

1. Fringe rate mapping

2. Fit sinusoids to phases of data which are switched in either frequency, polarisation, or source, and thus determine the relative positions.

3. Fit sinusoids to phases of spectral line observations, for relative position mapping of masers, etc.

4. Solve phases simultaneously for baseline offsets and position errors.

11.0 SCIENCE AND OPERATIONS

11.1 The Science of the LBA

There have been various estimates of the amount of time the LBA is expected to be in use. These range from 1 to 12 months per year, with the current favourite being around 3 months. A problem with these estimates is that the various telescopes involved in the LBA are available for very different amounts of time. A configuration involving only dedicated LBA antennas (Culgoora, Siding Spring and Parkes in the first instance) could be in use for a much larger proportion of the year than one including Tidbinbilla, Hobart and other telescopes.

In order to plan effectively for the LBA in terms of design, development priorities and operations, one should consider two things: (1) how much science is there which is appropriate for observations in the various LBA configurations? (2) How much time is available in these configurations? It is also important to keep in mind what we can realistically expect to have operational in the next decade or so, as well as what we hope to achieve when the AT is fully developed.

A rough estimate of the astronomy appropriate for LBA observations is the following:

ASTROMETRY	compact array calibration sources optical identifications geodesy	
PROPER MOTION	stars with planets pulsars masers supernova remnants superluminals	
MAPPING	baselines < 300 km	baselines > 600 km
	jets masers compact gal. sources YGIAGAMs	QSOs AGNs stars YGIAGAMs

It is fairly easy to list broad categories of astronomy which are appropriate for LBA observations, but much harder to estimate how much time astronomers might want to devote to such observations. It is harder still to forsee how much time the various stations will be available for inclusion in the LBA, even for the dedicated AT antennas. Regarding the quantity of science appropriate for LBA observations the conclusion reached at a meeting of the LBA working group which considered the questionn in April 1984 was: "There is sufficient astronomy to keep a three-station, 20 MHz bandwidth, LBA busy for at least 6 months a year."

A rough estimate of the amount of time available on the various antennas for inclusion in the LBA is:

Station:	Culgoora	S.S.	Parkes	Hobart	Tid.	Others?
Diam(m):	55-22	22	64-17	26	70/34	?
Time (mo/yr:)	3-6	10	<6	<3	<2	?

From these considerations four main conclusions can be drawn:

1. The three-station configuration (one or more of the Culgoora antennas, the Siding Spring antenna and Parkes) has the highest availability, and maximal use of this system should be exploited. The Culgoora-Siding Spring baseline in particular should be exploited for its frequency coverage and full AT compatibility.

2. There is enough science to keep the LBA busy, in any of its configurations, for all of its available time. LBA operations and processing should be made as simple and painless as possible to ensure its use by astronomers.

3. Experiments involving five or more antennas are not likely (initially) to occupy more than a few months a year.

4. The LBA correlator should have the flexibility to share its resources (channels) over varying numbers of baselines. It should also be made expandable to cope with future increases in LBA stations and

availability.

11.2 Compatibility

It is important that the LBA is not seen as an array of 3-5 antennas standing in splendid isolation. Such an array might provide some interesting science in the short term, but the long term use of such an instrument is limited. In the future. we might hope to extend our array, collaborate with other antennas (e.g. VLBA, USSR, Japan, China), or use VLBI spacecraft (e.g. QUASAT, RADIOASTRON). The VLBA Data Acquisition System is rapidly emerging as an 'Industry Standard', and we would be foolish to depart very far from that standard. However, other considerations prevent us from adhering rigidly to every detail of that standard, and so we must examine the amount of permissible deviation. To do this, we must first examine what we hope to get out of 'compatibility'.

1. We should be able to participate in International VLBI experiments, in which the data is processed at a foreign (e.g. VLBA) processor.

2. We should be able to use foreign stations in our own experiments, and process their data on our own processor.

3. We should be able to process the same data both on our own processor and on a foreign processor, as a debugging aid.

The system proposed in this report satisfies these requirements with one proviso: assuming that foreign stations use FTC (Fringe Tracking at Correlator), and we use FTA (Fringe Tracking at Antenna), then the data can be processed only by using the BOG phase rotator, which will degrade the sensitivity by a few percent, and perhaps introduce some (hopefully correctable) spectral-line artefacts.

A further aspect of compatibility is that, to experiment collaboratively with the VLBA implies that we must use the same frequencies. All the VLBA bands are included within the AT bands with the exception of the bands at 327MHz, 610MHz, 10.7GHz, 14.9GHz. This should be borne in mind during future receiver developments.

11.3 Parkes-Tidbinbilla interferometer

Software development on the PTI has a high degree of relevance for the LBA. Experience acquired by the use of the PTI is also of value. However, before development of the Parkes- Tidbinbilla radio link for LBA data transfer the possibility of using a NASA-owned recording system at Tidbinbilla should be explored.

11.4 Provision of spectra

Provision of sensitive wide-field spectra is required in order to select a subset of spectral-line channels for archival. On the other hand it should be recognised that sufficiently sensitive autocorrelation spectra are difficult to obtain. For example, a 12-hour synthesis on the 5-station LBA could in principle require a 36-hour integration on Parkes to match the sensitivity in the resulting map. Because archival on to optical disks will be done in real-time directly from the correlator, selection of channels cannot be made after the data have been correlated (except in the case of multi-pass correlation). Thus it must be made prior to correlation of the bulk of the data. One possibility is to run an autocorrelation pass on the data from the largest antenna prior to the cross-correlation run.

11.5 Multiple Phase Centres

When fringe rotation is done at the antenna, high correlator dump rates are required in order to maintain a large field-of-view. However, the poor u-v filling of the LBA means that we are unable to map extended structures, so that we will rarely want to synthesize a large field. Instead, we are more likely to want to map several phase centres simultaneously within the primary beam. Real-time processing of multiple phase centres in the correlator array processor would reduce the dump rate requirement and therefore the amount of data to be archived, provided the number and position of the desired phase centres is known a priori.

There are two alternatives ways of processing multiple phase centres:

1. The integration time may be made short enough (<1s) so that rotation may be done in the off-line processing. This has the advantage of being able to map any point within the primary beam, but suffers from the large data rates involved.

2. The correlator may dump out data into its AP at a high rate, but then the AP might rotate that data to several phase centres, and integrate the data at each of those centres. Thus the data rate from the correlator is relatively low, but the phase centres must be chosen prior to the correlation.

11.6 The location of the LBA Correlator

There was some discussion (again!) of where the LBA correlator should be located, since it is no longer physically connected to the CA correlator. The points raised were:

Pro locating it at Culgoora

1. Astronomers have to go to Culgoora to process their data. This maintains links between Culgoora and Epping (and the outside world which, it is alleged, does exist out there). It is also cheaper than Sydney accomodation for non-Sydney astronomers (e.g. U. Tas).

2. Maintenance is eased: both the resident expert (there will, inevitably, be only one) and the spares can be kept in one place.

Pro locating it at Epping

1. Astronomers don't have to go to to Culgoora to process their data. This makes it more convenient for RP staff and cheaper for other Sydney-based astronomers.

2. An LBA correlator operator would not be needed, since astronomers or other technical staff could handle the correlation (probably not an onerous task).

3. The LBA correlator would be located close to the main post-processing facility.

11.7 Costs

This report does not, on the whole, consider costs in any detail, largely because the costs of most of the items considered are not well known (and no better than in previous AT notes such as AT/17.3.1/004). It should be noted that the following items do not at present appear in the budget:

1. Modems, command buffers, and data communications between remote sites

2. Modulators and demodulators for the Parkes-Tidbinbilla link (if used).

However. it should be noted that $800k has been allocated for recorders and playback, whereas the estimates of AT/17.3.1/004 (amended slightly to reflect the slightly modified system) indicate that FY85 US$610k (see Note 1) should cover all systems <u>including the spare to be used by Hobart</u>. This, coupled with the savings (perhaps $60k) on the correlator indicates that funding for the system proposed here will not exceed the AT budget by more than a small margin. A more definitive statement cannot be made until component prices are more firmly established.

Note 1: Information from NRAO received since the workshop indicate that the costs may be somewhat greater than this.

Table 4.1: LBA components to be provided within the initial budget.

HARDWARE

1. Four data acquisition systems (DAS) (for Culgoora, Siding Spring, Parkes, and a spare to be used at Hobart)

2. One data transmission system to transfer data from Tidbinbilla to Parkes.

3. Four data playback systems, plus playback electronics for Tidbinbilla.

4. LBA Correlator

5. Telescope and system control, monitor, and communications equipment (via AUSPACK modems?)

6. Four Frequency Standards or AUSSAT links.

7. One or more travelling (GPS?) time standards

8. Supply of tapes and transport containers

SOFTWARE

1. Culgoora Online Software (LBAOBS?) for controlling observations

2. Remote antenna online software for controlling telescope and DAS (five systems, each of which will be different in some respects)

3. Offline software for controlling correlator and DPS

4. Offline processing software

5. Real-time fringe detection software

TABLE 5.1: POSSIBLE TELESCOPES TO BE USED WITH THE LBA

LOCATION	DIAM.	WAVELENGTHS	STATUS
Culgoora	22m-54m	90cm-2.6mm	AT antennas
Siding Spring	22m	90cm-2.6mm	AT antenna
Parkes	64m	90cm-3.5mm	AT antenna
Tidbinbilla	34m/70m	20cm-1.3cm	NASA antenna
Hobart	26m	90cm-2cm	U.Tas. antenna
Adelaide	?	?	Possible future site Collab. with U.Ad.?
Epping	?	?	Possible future site
Cubbo	?	?	Possible future site Ex-Fleurs antenna?
Gerwa	?	?	Possible future site Ex-Fleurs antenna?
Himatangi, NZ	?	13cm & 3cm	Remote sensing
Hamilton, NZ.	10m	20 (&13?) cm	Waikato Uni./ Hamilton Astr. Soc.
Perth	15m	13cm & 3cm	ESA antenna
Alice Springs	10m	13cm & 3cm	Remote sensing

TABLE 6.1 LBA TIMING CLOCKS

GPS SATELLITE RECEIVER + RUBIDIUM

$1 \mu s$ EASILY 20 nSec possible

Cost \$50K to 60K

CESIUM ~ $2 \mu Sec$ per month

COST \$60K (+ \$20K PER 3 YEARS ie tube)

AUSSAT LINK UNDER DEV AT NML (HARVEY)

< $10 \mu S$ SHOULD BE EASY

POSSIBLY < \$10K ?

+ RUBIDIUM \$15K ?

OMEGA RHODE & SCHWARZ

< $10 \mu S$ EXPECTED

COST \$25K (INC RUBIDIUM)

NEEDS CALIB - NOT ABSOLUTE.

OTHER TELECOM VIA PHONE LINES

CHEAP

$10 \mu S$ POSSIBLE

RELIABLE ?

RUBIDIUM

$10 \mu S$ PER MONTH

\$15K TO \$30K

RECOMMEND HOLD & REVIEW IN 12 MONTHS

BASEBAND CONVERTER

Input range:	492-1008 MHz
Gain through conv(2 MHz BW):	64 +- 1 dB maximum gain
Level control max atten:	30 dB
Level control phase shift:	< 0.5 deg over full range of atten
Gain for other bandwidths:	-3 dB/ octave increase in bandwidth
Image rejection:	>26 dB over video range 10 kHz to 8 MHz
Output power:	0 +-0.5 dBm
L.O. range:	500-1000 MHz in 10 KHz steps
Energy in 10 KHz sidebands:	< -40 dBc
L.O. phase noise:	< 2 deg. rms
L.O. leakage into video	< -50 dB
Gain compression:	< 0.05 dB (1%)
SNR(noise from converter):	> 25 dB
Dynamic range:	> 30 dB
Temperature coeff of phase:	< 10 deg/ deg C/ GHz
L.O. settling time:	< 1 sec
L.O. leakage into input:	< -60 dBm
Temperature coeff. of gain:	< 0.1 dB/ deg C
4-way input switch isolation:	> 60 dB
Bandpass response:	1) >10 dB down at bandedge x 1.08 2) <0.5 dB ripple across lower 80% 3) <1 dB between units across upper 20% 4) <5 deg phase ripple between units across lower 80% of band 5) <20 deg between units across upper 20% 6) <0.2 deg/deg C temperature coefficient of phase over 80% of band 7) <0.1 dB/deg C temperature coefficient of amplitude over 80% of band (The above should ensure that closure errors are < 0.5 degrees)
Bandwidths:	16, 8,4,2,1,0.5,0.25,0.125,0.0625 MHz and external filter
Data processing:	1) Total power integration and synchronous detection with periods of an integral number of 20 Hz half-cycles or 25 msec 2) Auto-leveling of output power

TABLE 8.1: VLBA DOWN-CONVERTER SPECIFICATIONS

4.3 Formatter

Number of video inputs: 8 (4 USB plus 4 LSB) in each of 2 identical formatters (one per rack)

Number of formatter outputs: 16 (32 for both units)

Sample rates: 32, 16,8,4,2 MHz

Output format: Serial data format with time code, auxillary data, CRC error detection, (if needed to meet playback error rate specs), sync word, parity and programmable data block and frame length.

Video input level: 0+-0.5 dBm
-4+-0.5 dBm for 4-level processing

Input impedance: 50 ohms unbalanced

Threshold equivalent DC offset and hysteresis: < 5 mv

Threshold level: 600 mv (for magnitude) 0 mv (for sign)

Sampling epoch precision and jitter: < 2 nsec

Sampling modes: 2-level (1 bit) and 4-level (2 bits)
(4-level coding -w=00,-1=01,+1=10,+w=11 with MSB (sign) bit and LSB bit on separate tracks)

Formatter modes:
1X (output rate/track = sample rate)
2X (output rate/track = sample rate/2)
4X (output rate/track = sample rate/4)
Notes: In 1X mode adjacent time samples are on the same track
In 2X mode odd and even samples are on separate tracks
In 4X mode there is a 4-way split i.e. 1st. sample to trk w, 2nd. to trk x, 3rd. to trk y, 4th. to trk z

tracks/video signal:

	FORMATTER MODE		
SAMPLING	1X	2X	4X
2-LEVEL	1	2	4
4-LEVEL	2	4	8

Track switch: 32x32 switch to allow an arbitrary reassignment of data samples to recorder tracks - This assignment can be changed dynamically every frame

Output

Signals: 2 independently buffered sets of
32 balanced ECL signals from formatter in each rack
(32 balanced ECL from each of 2 formatters to each of 2 recorders)

TABLE 8.2: VLBA FORMATTER SPECIFICATIONS

TABLE 9.1: PROPOSED 6-BLOCK CORRELATOR

A maximum of 48 products can be handled. All figures below are for 2-bit sampling.

4 STATIONS / 6 BASELINES
Upto 8 products/baseline
products/baseline * no channels = 16384 / bandwidth (MHz)
up to a maximum of 8192
E.g.:

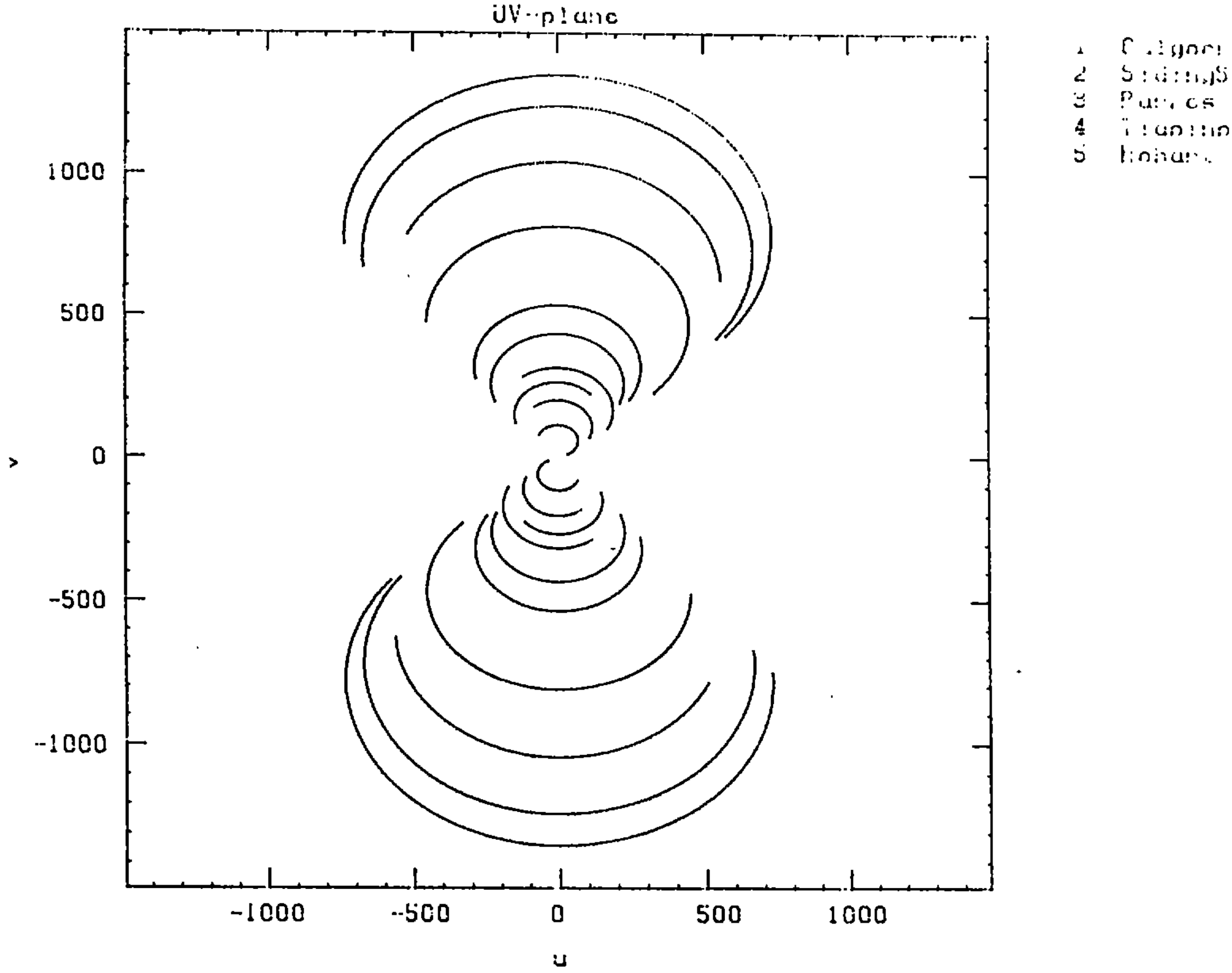
Bandwidth	Products/basline	Channels/product
16MHz	8	128
16MHz	1	1024
0.5MHz	8	1024
0.5MHz	1	8192

5 STATIONS / 10 BASELINES
Up to 4 products / baseline
products/baseline * no channels = 8192 / bandwidth (MHz)
up to a maximum of 4096
E.g:

Bandwidth	Products/baseline	Channels/product
16MHz	4	128
16MHz	1	512
0.5MHz	4	1024
0.5MHz	1	4096

6 STATIONS / 15 BASELINES
7 STATIONS / 21 BASELINES
Up to 2 products / baseline
products/baseline * no channels = 4096 / bandwidth (MHz)
up to a maximum of 2048
E.g.:

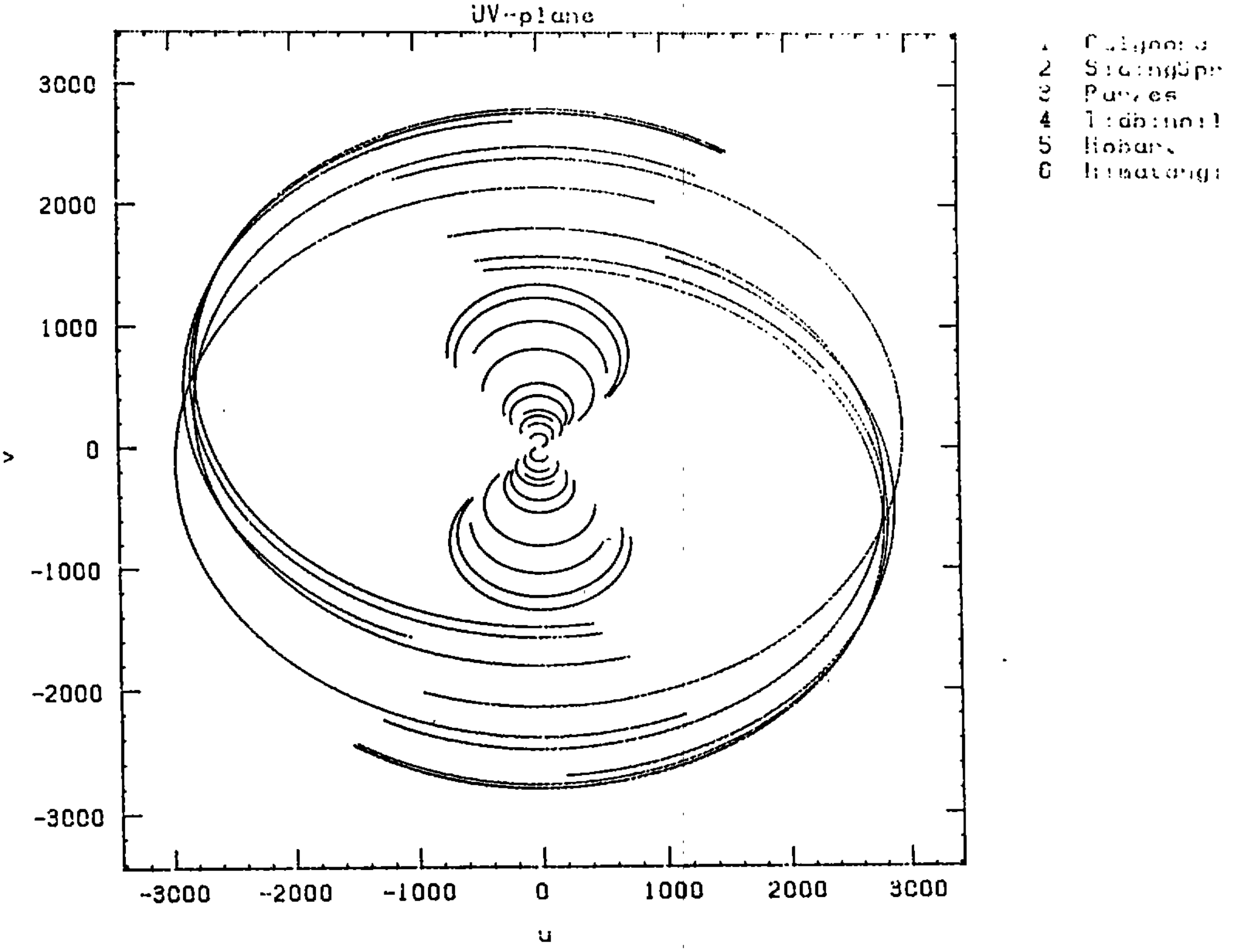
Bandwidth	Products/baseline	Channels/product
16MHz	2	128
16MHz	1	256
0.5MHz	2	1024
0.5MHz	1	2048




```
Array generated 14-MAR-86 17:36:37
Ha=   -7.47 to     7.47 (hours).
Dec=  -50.00 (degs),  lat=  -30.00 (degs)
Elevation>   10.00 (deg).
Plotted: 14-MAR-86 17:37:11   for AT
```

1. Culgoora
2. Siding Spring
3. Parkes
4. Tidbinbilla
5. Hobart.

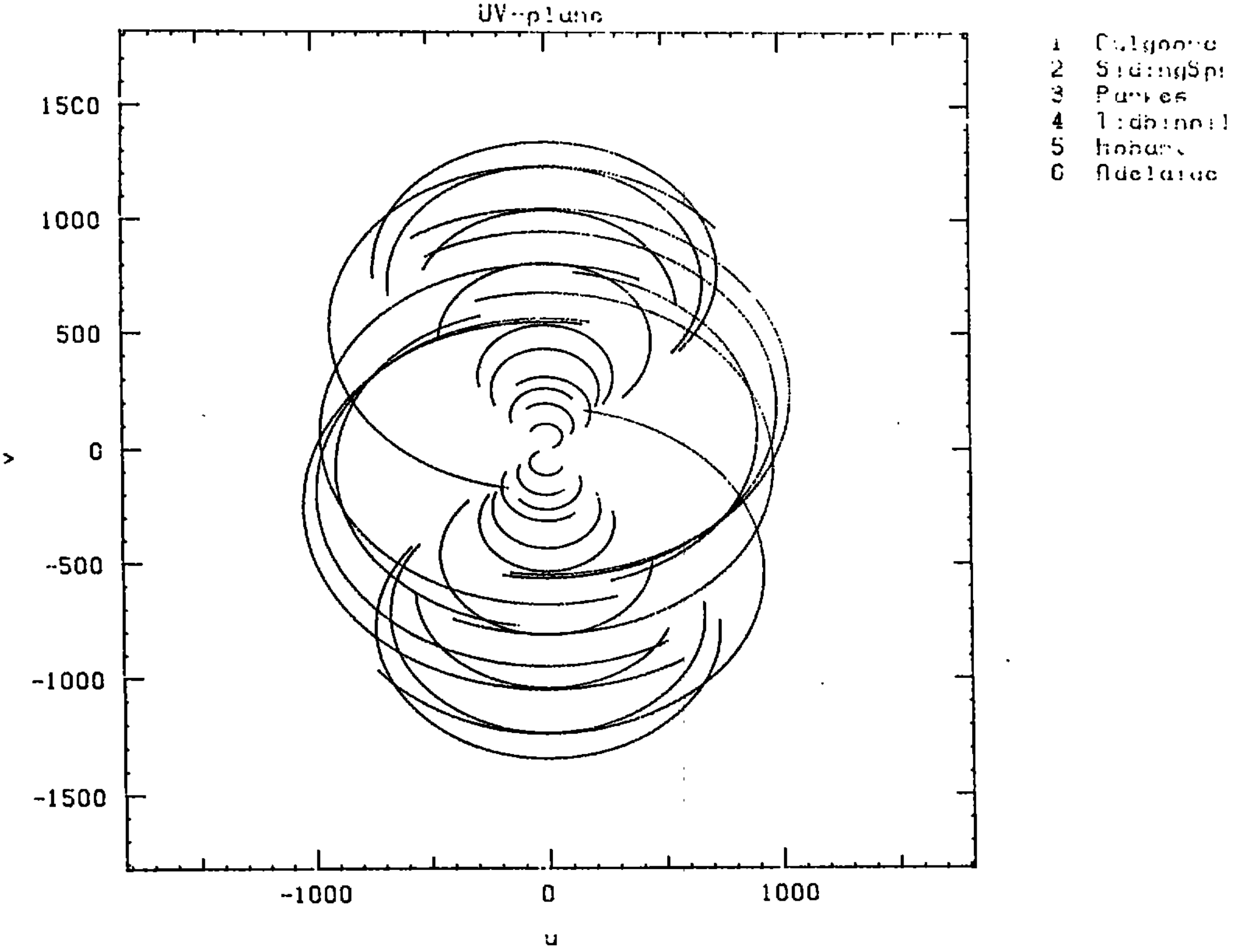
Figure 5.1



Array generated 14-MAR-86 17:37:50
Ha= -7.47 to 7.47 (hours).
Dec= -50.00 (degs), lat= -30.00 (degs)
Elevation> 10.00 (deg).
Plotted: 14-MAR-86 17:38:30 for AT

1. Culgoora
2. Siding Spring
3. Parkes
4. Tidbinbilla
5. Hobart
6. Himatangi (NZ)

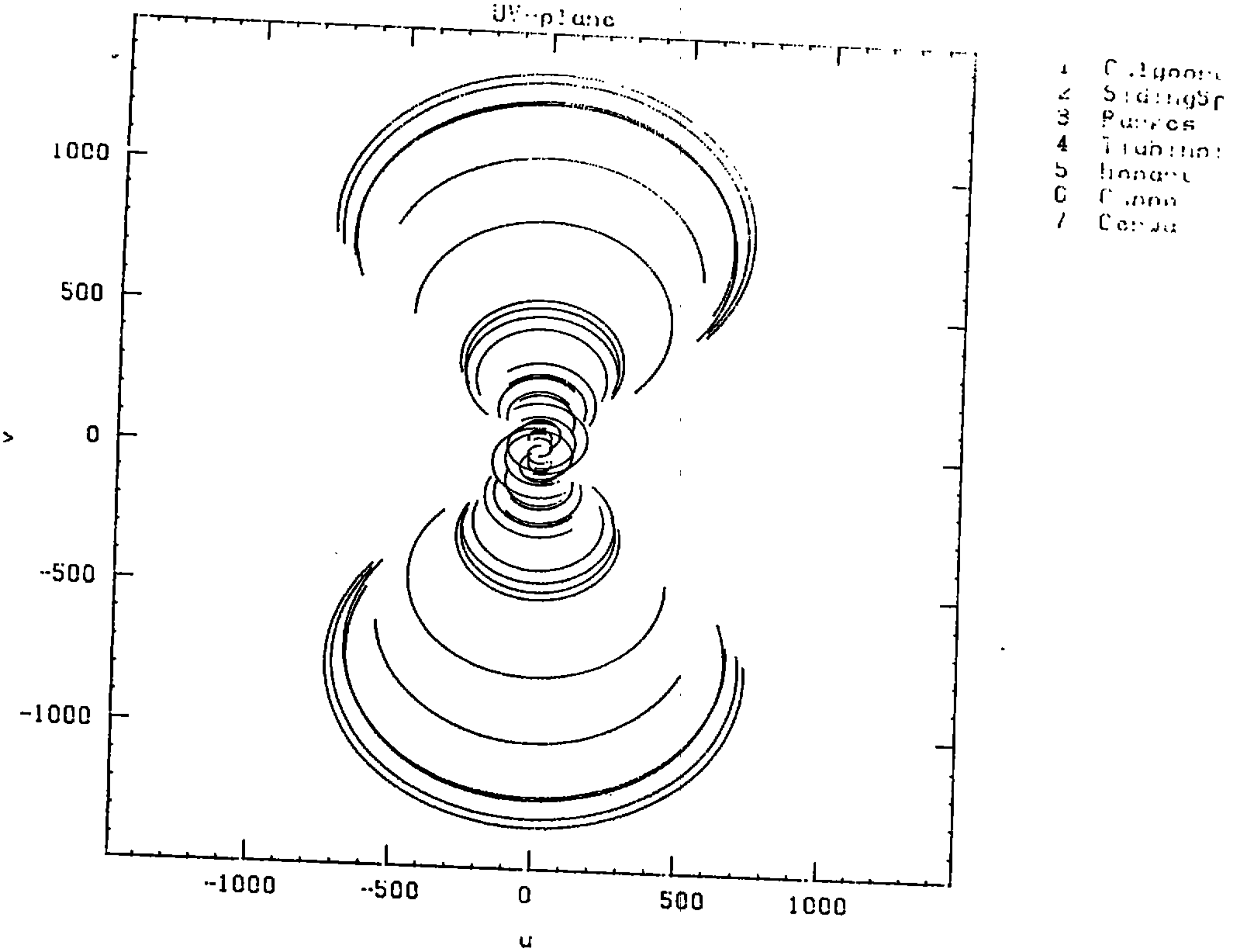
Figure 5.2



Array generated 14-MAR-86 17:35:21
Ha= -7.47 to 7.47 (hours).
Dec= -50.00 (degs), lat= -30.00 (degs)
Elevation> 10.00 (deg).
Plotted: 14-MAR-86 17:36:06 for AT

1. Culgoora
2. Siding Spring
3. Parkes
4. Tidbinbilla
5. Hobart
6. Adelaide

Figure 5.3



Array generated 14-MAR-86 17:46:56
Ha= -7.47 to 7.47 (hours).
Dec= -50.00 (degs), lat= -30.00 (degs)
Elevation> 10.00 (deg).
Plotted: 14-MAR-86 17:47:36 for AT

1. Culgoora
2. Siding Spring
3. Parkes
4. Tidbinbilla
5. Hobart
6. Cubbo (41 km W, 24 km S)
7. Gerwa (162 km W, 78 km S)

Figure 5.4

LBA LO CLOCKS

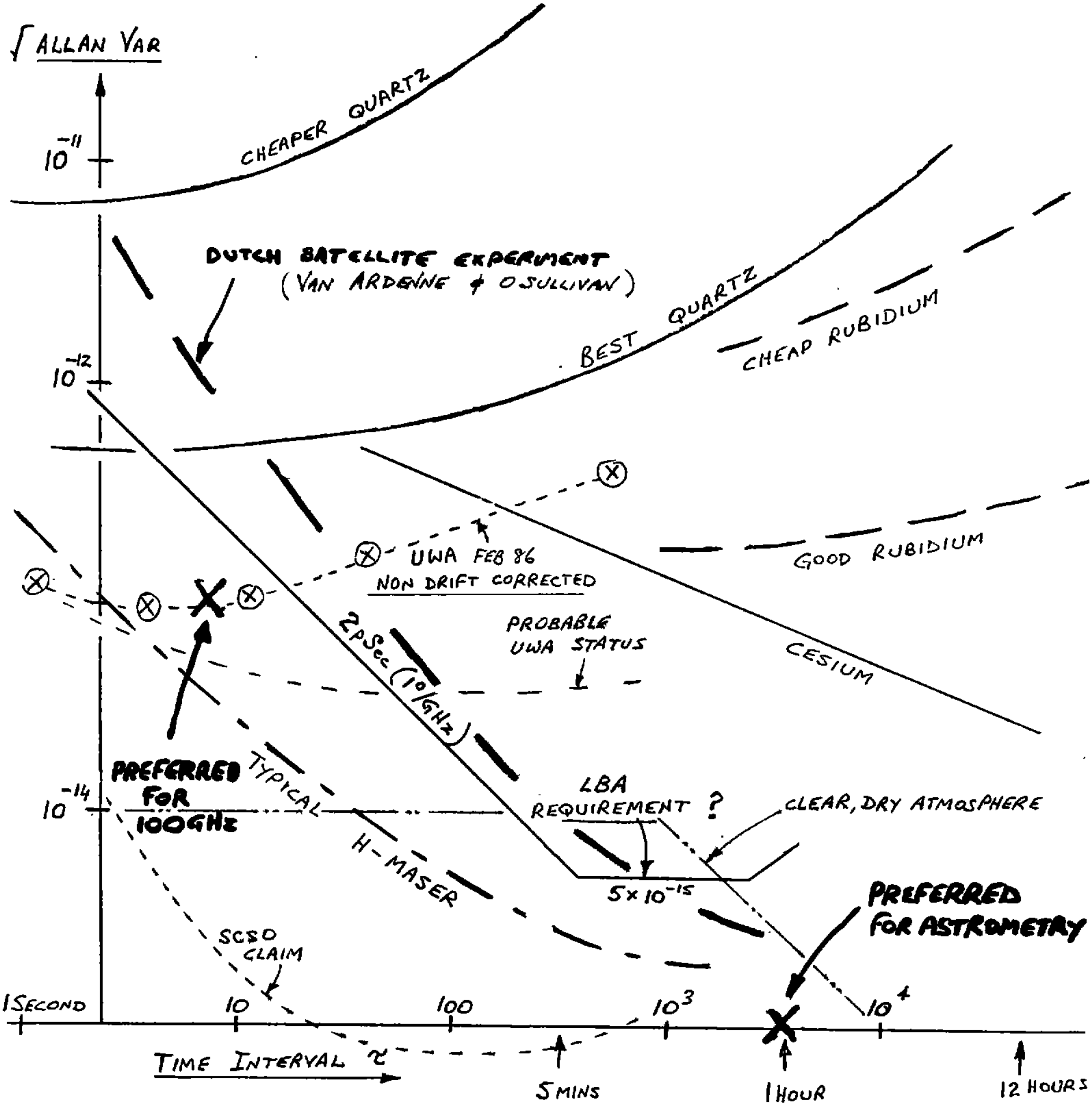


Figure 6·1

A. YOUNG
MARCH 86

Fig 6·1

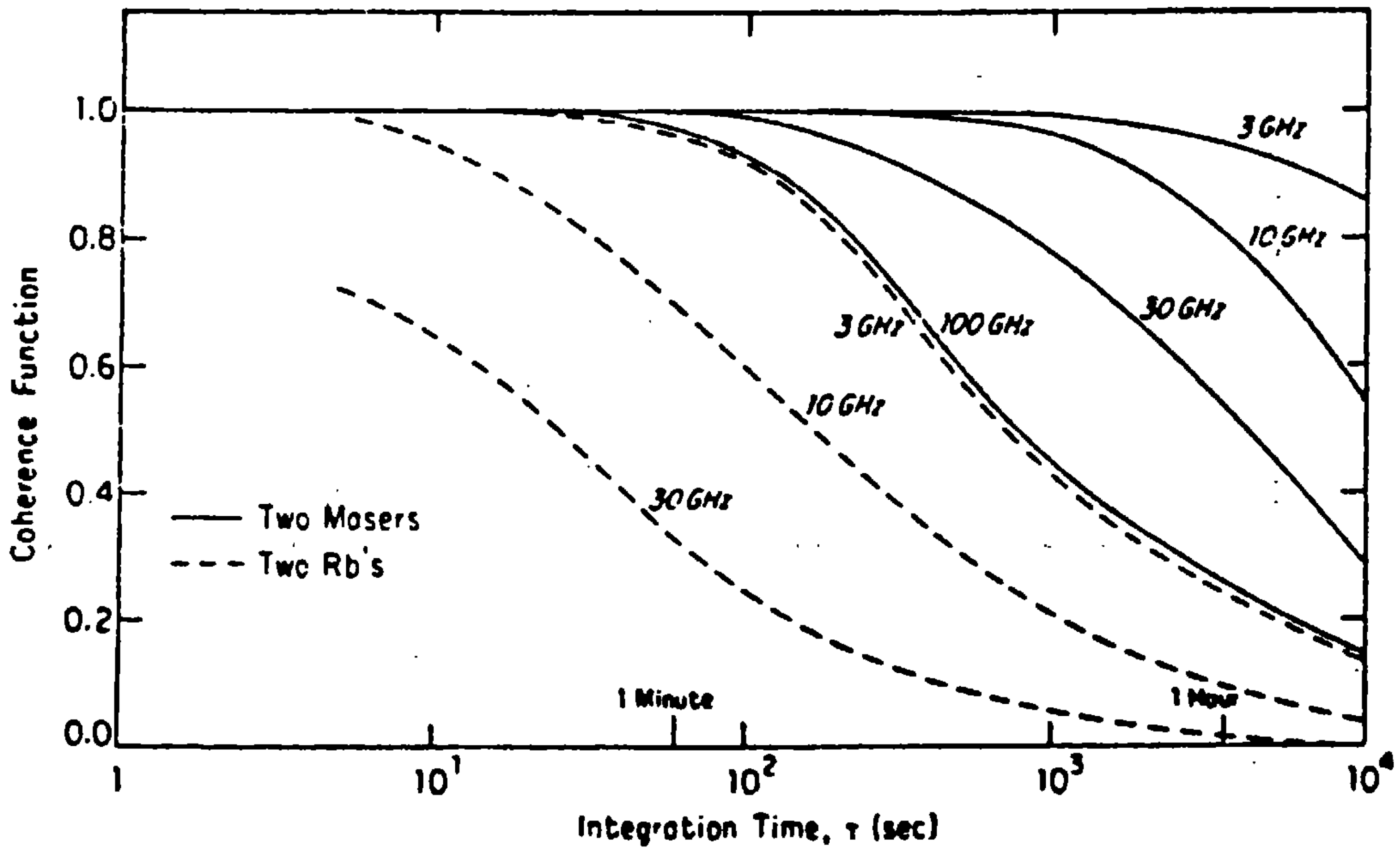


Figure 6.2 Coherence estimates for Rb and Maser frequency standards as a function of frequency and integration time. Taken from data given by Rogers and Moran (1981).

Fig 6.2

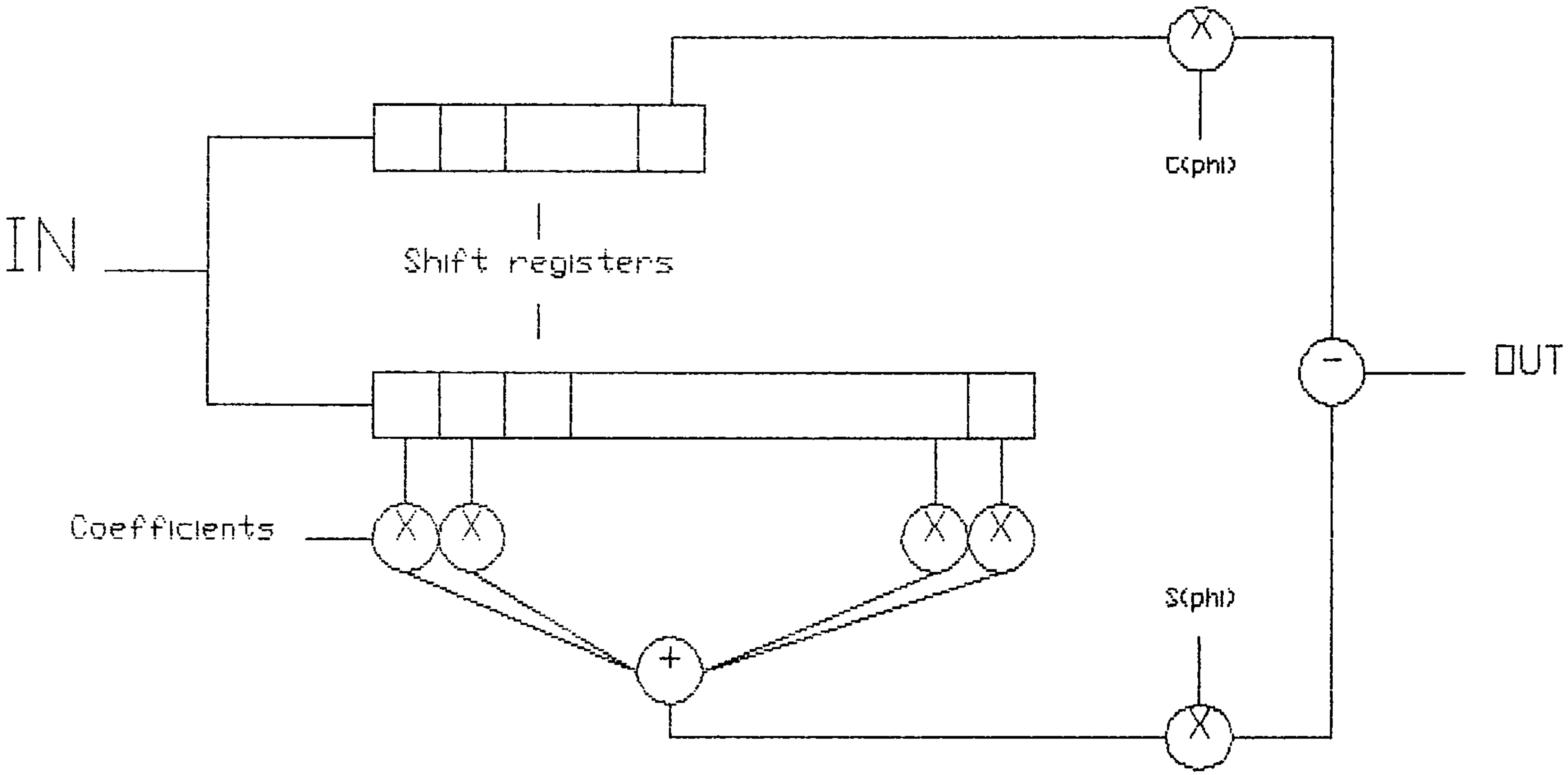


Fig.7.1: Idealised SSB Fringe Rotator

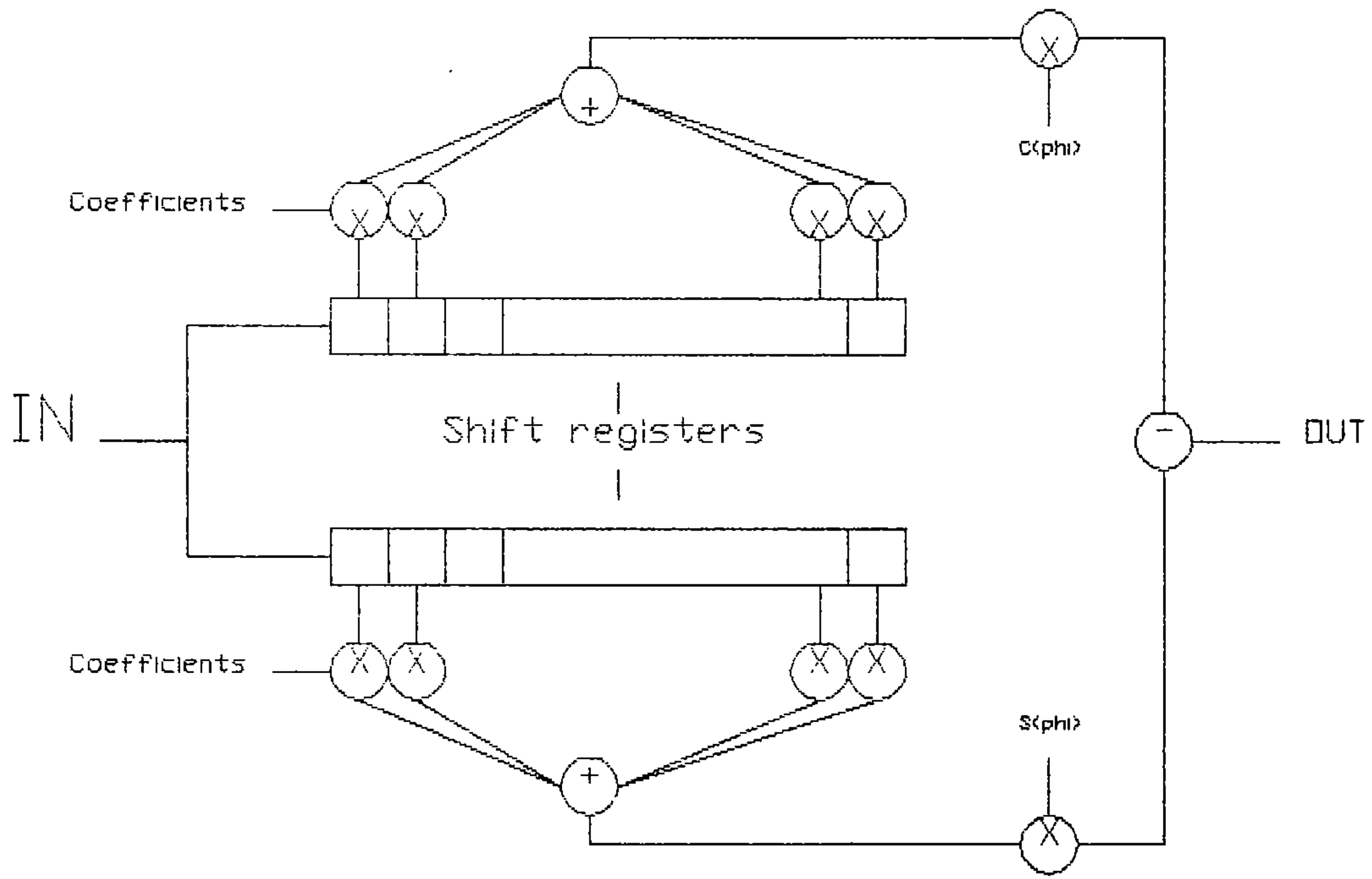


Fig.7.2: SSB Fringe Rotator with Fractional Bit Shift

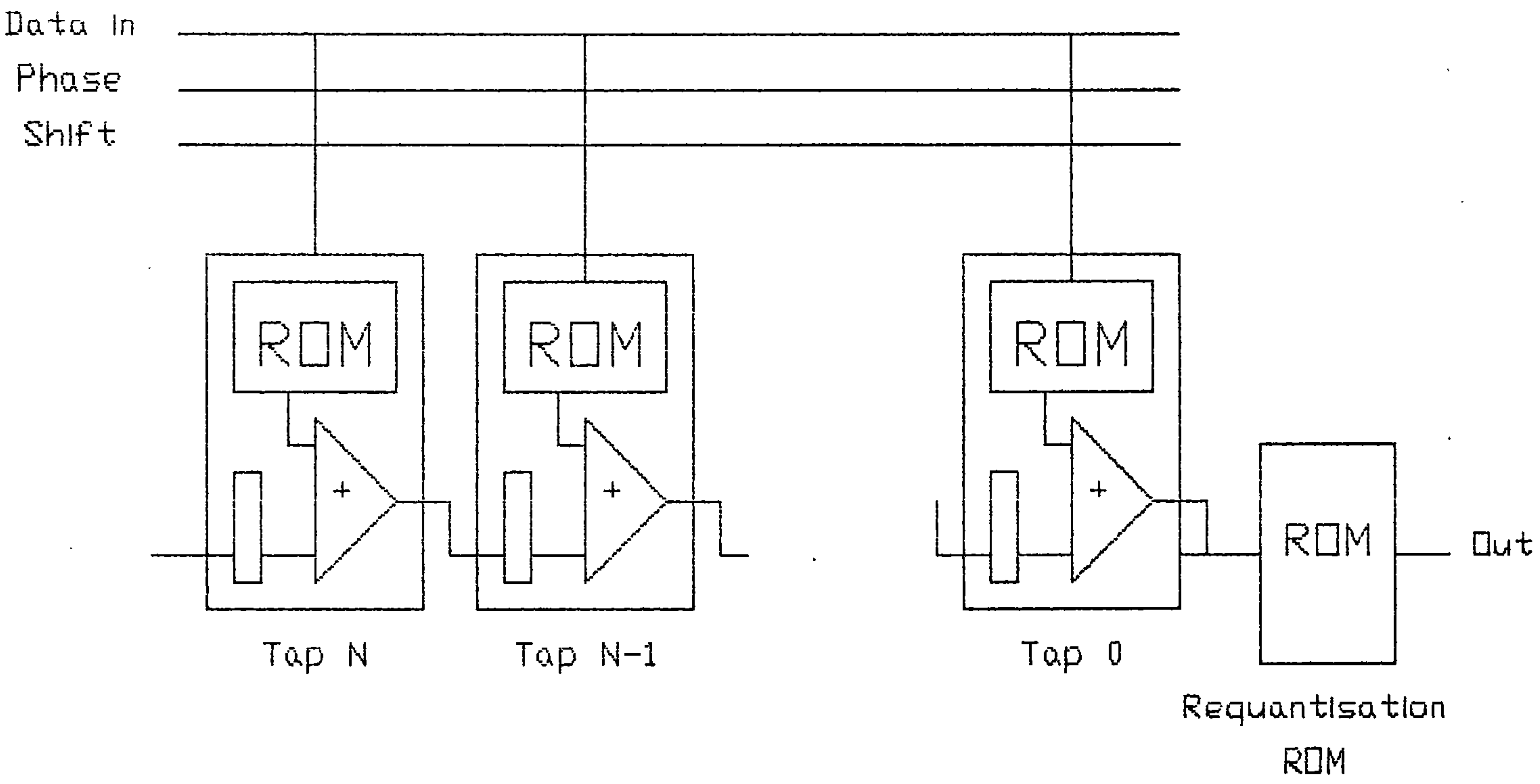


Fig.7.3 Practical implementation SSB Fringe Rotator with bit shift

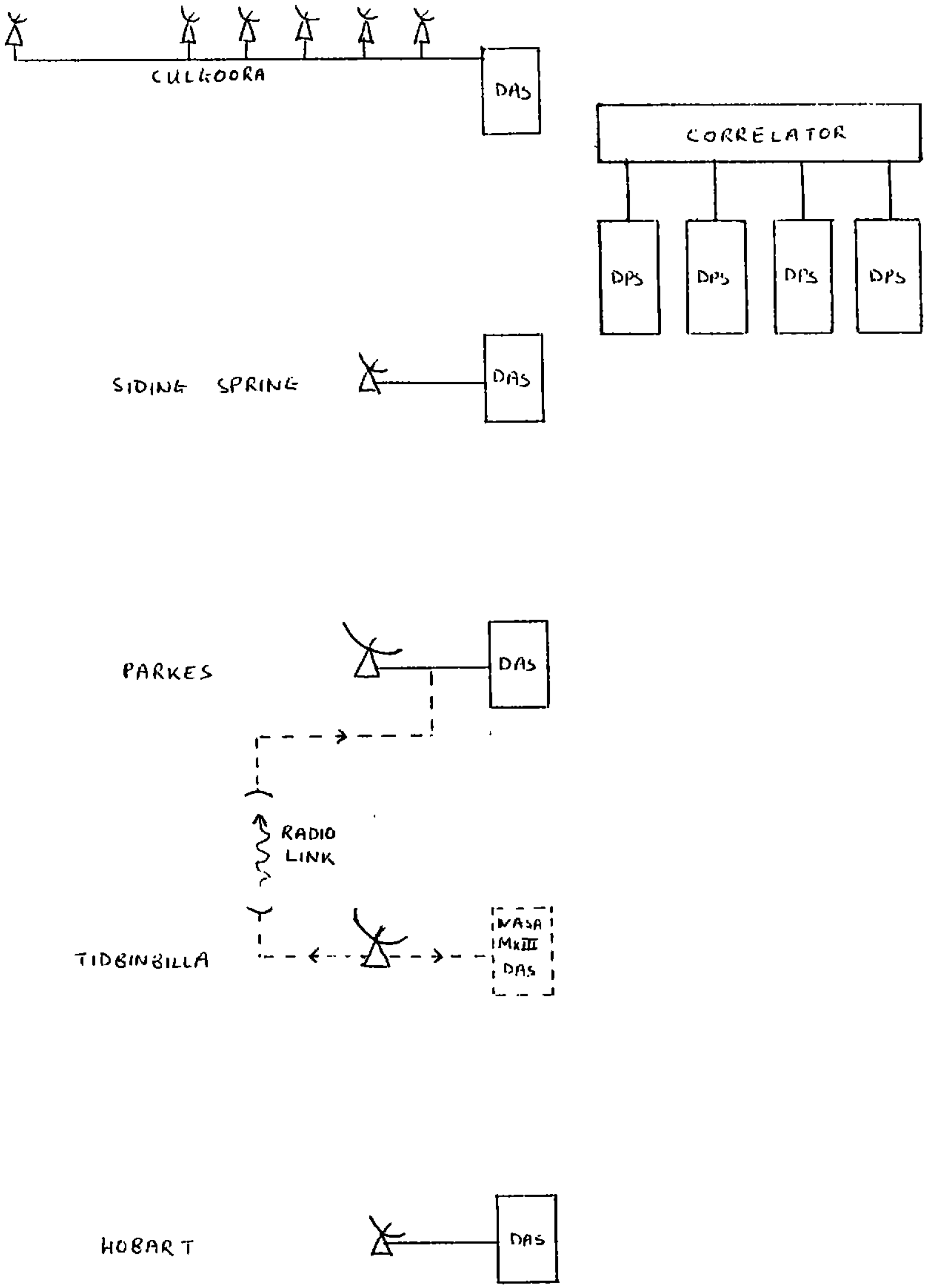


FIGURE 8.1: OVERVIEW OF LBA DATA TRANSFER IN 1989

NB: DAS = DATA ACQUISITION SYSTEM
DPS = DATA PLAYBACK SYSTEM

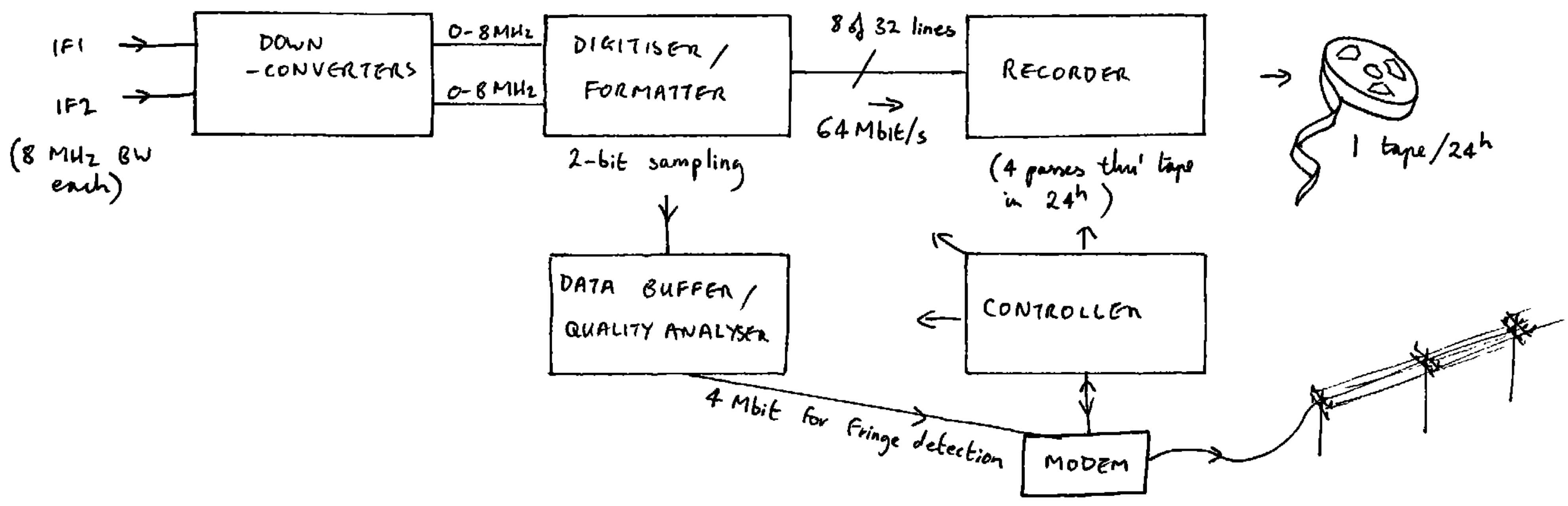


Fig. 8.2: Data Acquisition System. Rates are for 'minimum' mode. Other configurations (e.g. wider/narrower bandwidth, slower tape with 2 passes) are also possible.

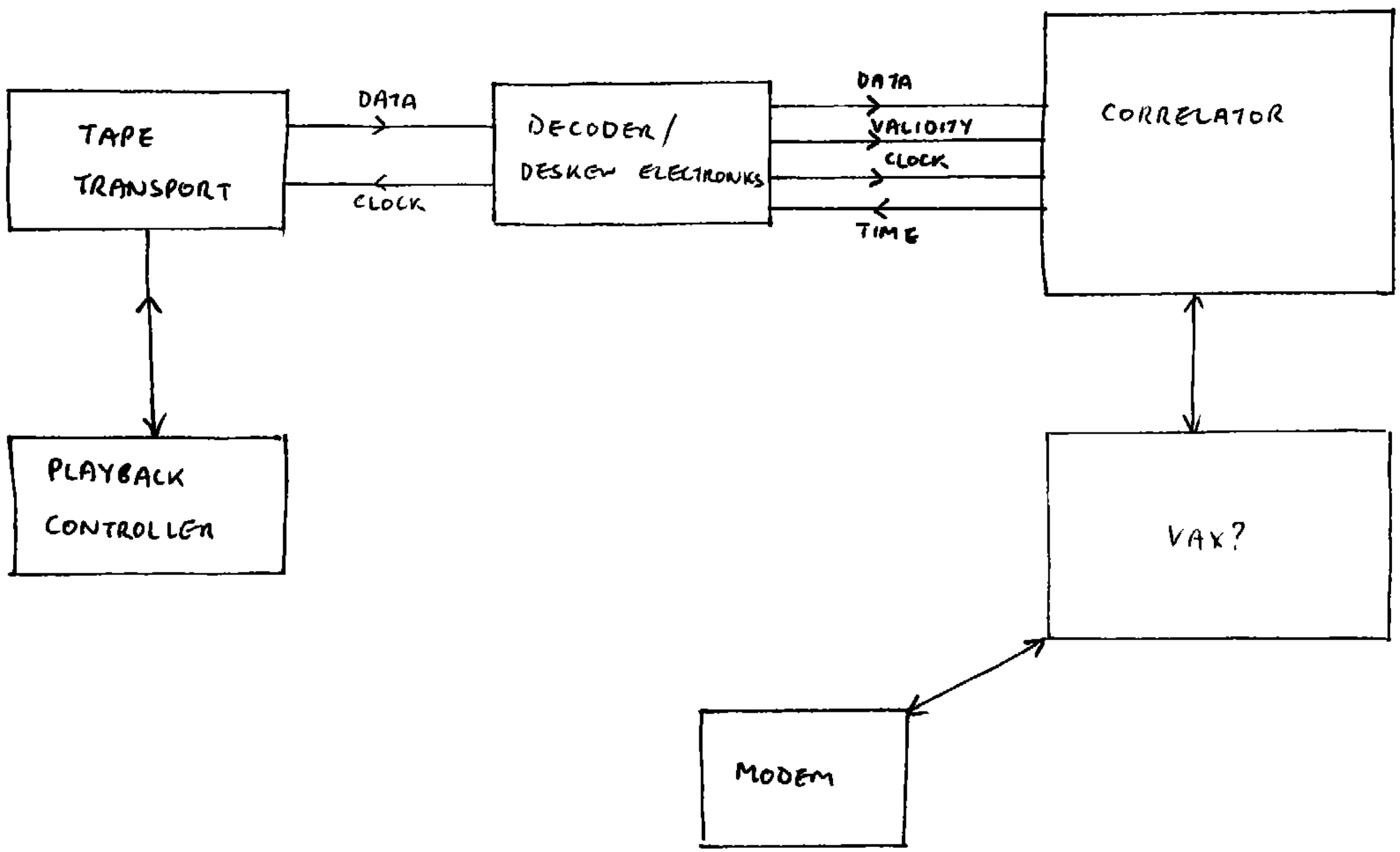


Fig. 8·3: Data Playback System

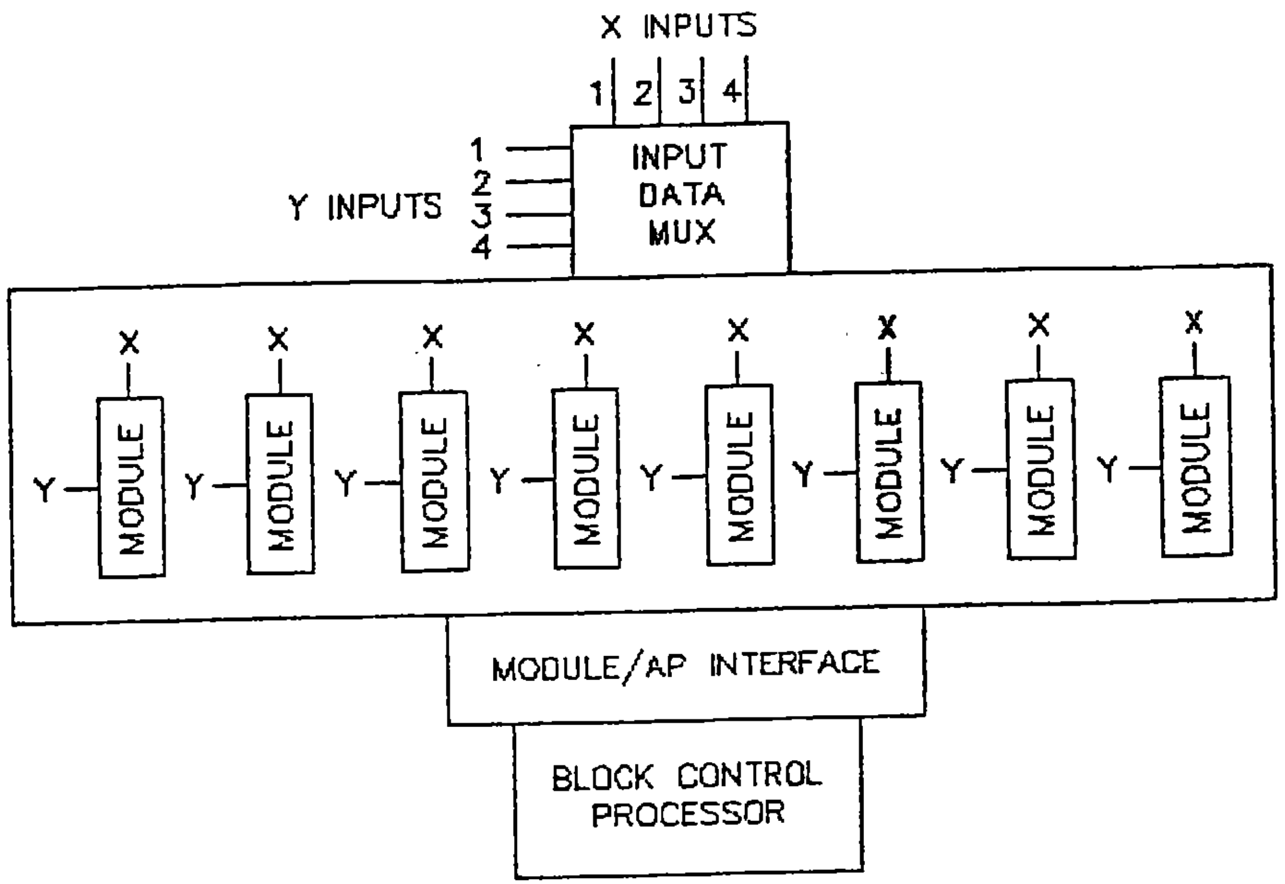


FIG. 9.1: A CORRELATOR BLOCK

(NB: All cross-products are possible)

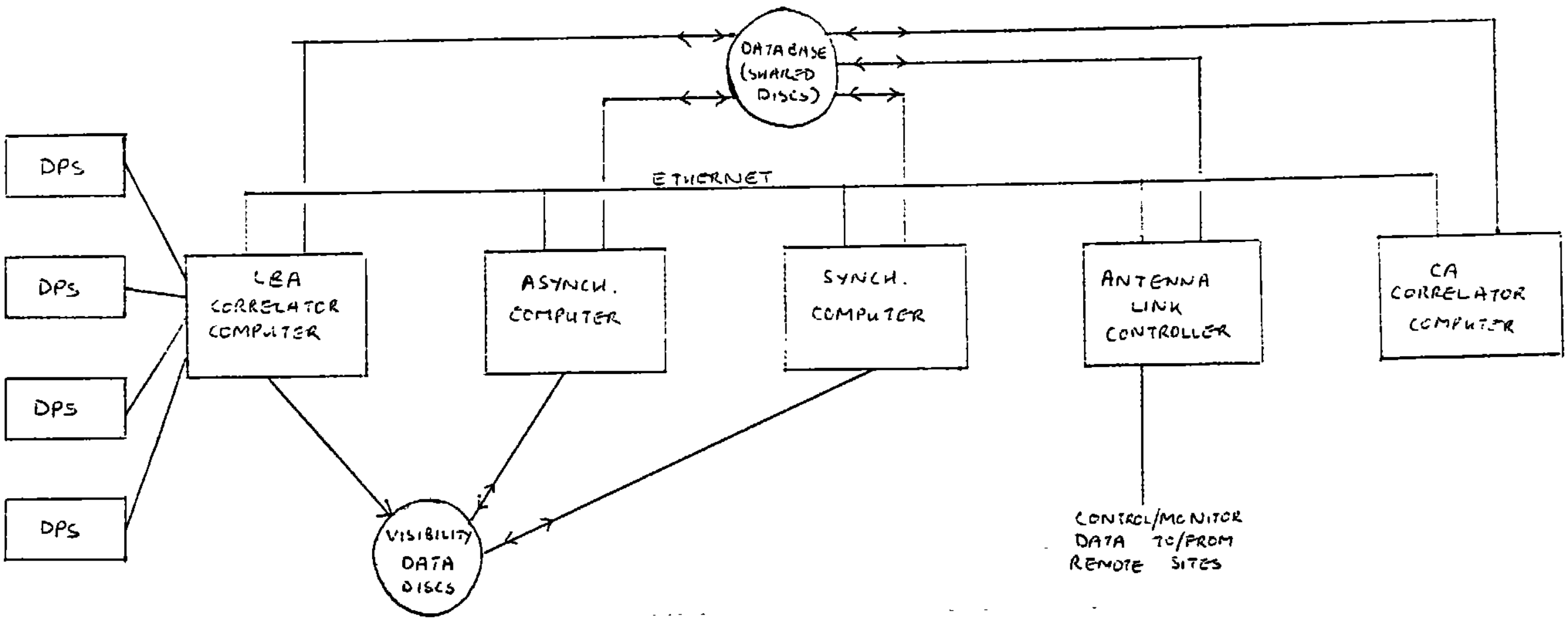


FIGURE 9.2 · THE COMPUTER CONFIGURATION

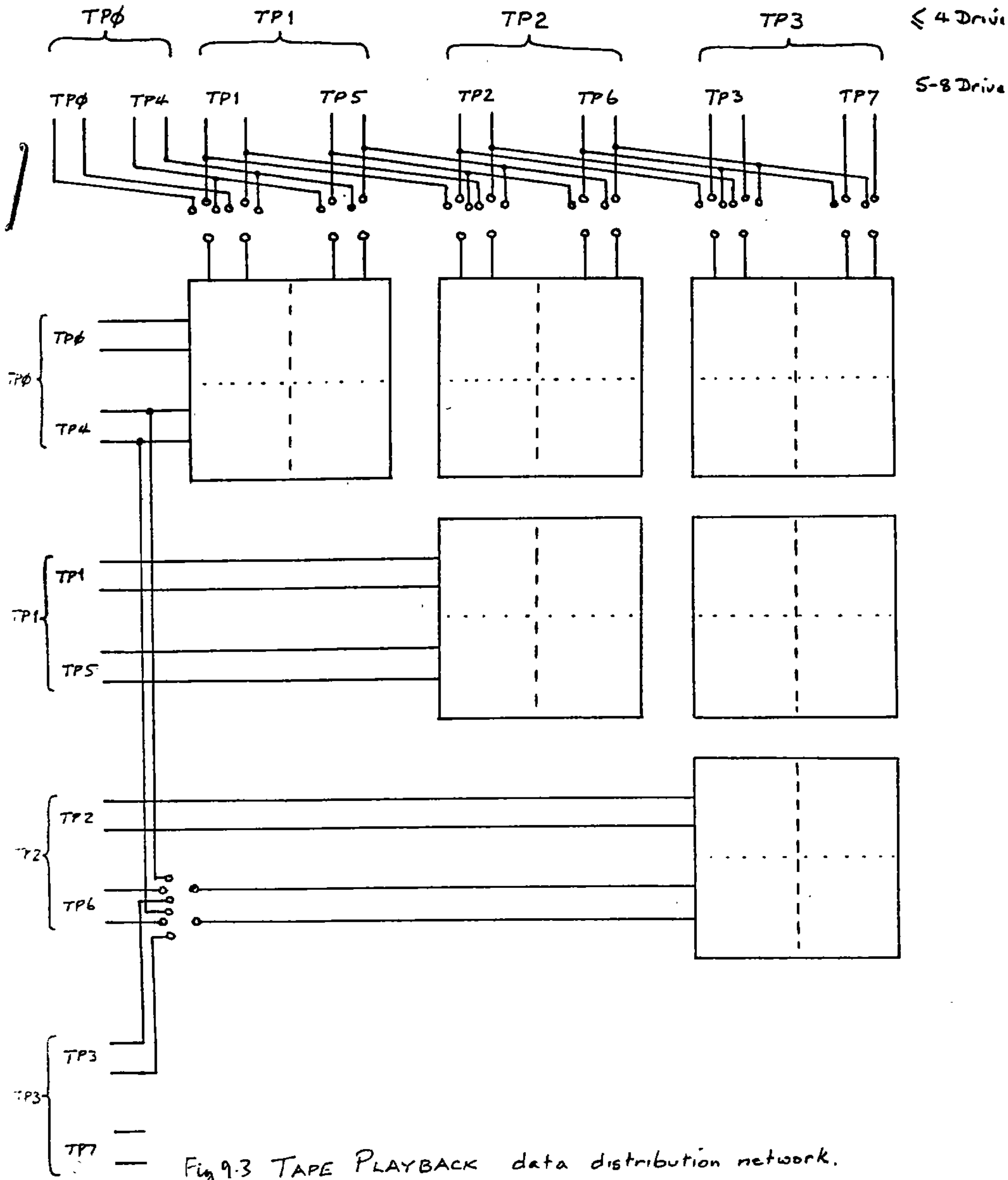


Fig 9.3 TAPE PLAYBACK data distribution network.

With 4 or fewer drives, each provides up to 4 data streams to the network inputs. As each additional tape drive is added the frequency-2 path of the first available drive is switched (or repatched) to the frequency-1 outputs of the new drive. In the case of two stations being recorded on a single tape, the second station is replayed on the frequency-2 channel.

```
|<---------1986-------->|<---------1987-------->|<--------1988--------->|<--------1989--------->|<--------1990-------->|

DAS/DPS-----------------------------3/4 delivered--------------------------->|-further 2 delivered------------->|

                          start AUSSAT                                          AUSSAT
               /-------------developoment & use-------------------------->|---------------system----------->|
              N              Rb stds. meanwhile                                 complete
             /
Freq.-------< <--decide on U.WA cavities
Std.         \
              Y                                  Acquire                        Acquire
               \ --------------------------------- 3/4 -------->|------------ further 2---------->|
                                                 cavities                       cavities?

                                                             Complete        Develop
Correlator---------------- Development & Construction ---------without->|-------- BOG -----------Complete->|
                                                                BOG

                          /----Use NASA MkIII recorder--------------->|------------------------------->|
TID                      /
data--------------------< <-decide on TID data transfer
transfer                 \                                                Develoo
                          \----Use radio link------------------------>|-------radio link--------------->|
                                                                          + encodina/
                                                                          decoding

   ---------------------------------------------
   |     3-station LBA complete                |
   |     + TID (if usina FTA and NASA DAS)     |
   |     + Hobart (if using FTA and 4th DAS acquired) |-------------|
   |                                           |
   |     Usable for:                           |
   |     All bands (if usina UWA cavities) OR  |
   |     Low freq only (if usina Rb. stds)     |
   ---------------------------------------------
                                                        ----------------------------
                                                        |   5/6? - station LBA     |
                                                        |   complete in all        |
                                                        |   modes                  |
                                                        ----------------------------
```

FIGURE 11.1: LBA TIMETABLE (critical paths only)

RPN 30/5/86

APPENDIX: A GLOSSARY OF ACRONYMS

AGN	Active Galactic Nucleus
AT	Australia Telescope
BOG	Bolt-on Goodie: the Correlator Phase Rotator, consisting either of a Hilbert Transform device (see Section 7.2) or a pre-FFT unit to make a hybrid correlator (AT/24.1/010).
CA	Compact Array (the 6km array at Culgoora)
DAS	Data Acquisition System
DPS	Data Playback System
FTA	Fringe Tracking at the Antenna
FTC	Fringe Tracking at the Correlator
IF	Intermediate Frequency
LBA	Long Baseline Array (of the AT)
LO	Local Oscillator
NML	National Measurement Laboratory
PTI	The Parkes-Tidbinbilla Interferometer
SS	Siding Spring
U. Tas.	University of Tasmania
VLBA	The U.S. Very Long Baseline Array
YGIAGAM	Your guess is as good as mine