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REPORT OF A.T. SYSTEM CONCEPT WORKSHOP

HELD AT PARKES, 7-9 DECEMBER 1982

Present: R.H. Frater, J.G. Ables, C.E. Jacka, A.G. Little, P.J. Napier, J.D. O'Sullivan

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Preamble

This document is a report of a Workshop. It contains the views of the workshop participants on what is achievable and what is needed for the AT. The statements on design criteria are in no way meant to pre-empt further discussions and final decisions. Rather they are intended to alert the reader to what is considered feasible with current technology and to encourage comments and ideas so as to allow for the design of the best possible system with the available funds.

It is envisaged that further elaboration on the design concepts will form the subject of future documents in the AT Memoranda Series in due course.

Readers are urged to respond to this document in writing. Contributions may be lodged as either AT Memoranda Series documents (for substantive comments) or as AT File Notes (for less detailed comments).

R.H. Frater

1. INTRODUCTION AND OVERVIEW

This meeting was conducted with the general aims of:

(1) Establishing a strawman total system concept

(2) Identifying areas of the project requiring urgent and detailed attention

(3) Highlighting key personnel requirements for the project.

Those present at the workshop were:

Bob Frater (Chairman) [RP]
Jon Ables [RP]
Colin Jacka [RP]
Peter Napier [NRAO]
Alec Little [University of Sydney]
John O'Sullivan [SRZM]

There was considerable discussion of the aims of the AT project, and the priorities that should be considered in the workshop. This discussion led to a number of conclusions:

(1) One of the key features of the instrument would be its ability to make maps with wide field and high spectral resolution.

(2) The prime effort should go into ensuring the best possible performance in the 6km array (Ref.section 6 and Attachments 2 and 3).

(3) Considerable concern was expressed on the viability of the mobile antenna as an element of either the 6km or LBI arrays.

The basic specification for the AT was taken from the draft description of the project (AT/15.1/005B; RNM:25 November 1982). A number of concerns were expressed in relation to that description:

(1) It is not clear that operation will be possible at 115 GHz with baselines of hundreds of metres. The following comparison of the site altitude with sites specialising in mm work highlights one aspect:

Site	Elevation
Plateau de Bure	2550 m
Nobeyama	1350 m
Owens Valley	1222 m
Hat Creek	1043 m
Culgoora	210 m

In addition, actual water vapour data for Northern NSW suggests that Culgoora is 2 to 3 times worse than the VLA site (2100 m elevation).

(2) Recent information on communication links and TV transmitters in the Siding Spring region raises serious questions about the possible affect of interference on the operation of the proposed Siding Spring antenna.

(3) The use of a mobile antenna as an adjunct to both arrays is of questionable viability and needs more consideration.

The workshop concluded that:

(1) No additional cost should be incurred to provide 115 GHz performance. As far as the system is concerned this means the acceptance of a phase specification over the 6 km array of approximately 1°/GHz (RMS).

(2) The interference environment at Siding Spring (and Culgoora) must be investigated immediately. The viability of all the possible sites on the mountain should be assessed.

(3) While the viability of the mobile antenna is questioned, it is clear at least two small fixed antennas between Siding Spring and Culgoora would be needed for a viable long baseline array. This possibility should be investigated as a possible lower cost alternative to the mobile antenna.

2. REVIEW OF OVERALL PROJECT TIME SCHEDULE

The current Australia Telescope Planning Schedule (Attachment 1, AT/14/001; Revision 1, D.N. Cooper, 10 November 1982), was reviewed. The only significant change recommended is to delay the acquisition of the data reduction computer by one year to maximise the size of the computer that can be obtained for the available funds. So that software development is not delayed, a new activity line should be added entitled "Data Reduction Software" which will involve the selection of STARLINK and/or AIPS and/or GYPSY and/or DWARF and/or another suitable software package and its/their adaptation to the Radiophysics VAX. This will ensure that data reduction facilities are available when the first astronomy is started on the AT at the end of 1985, and will provide the basis for new software development in the AT data reduction computer when it is available.

It is recommended that the name of the correlator activity be changed to "Digitizer/Correlator".

The breakdown of the AT project as defined in the Planning Schedule was considered acceptable. A brief description of each activity is given below, together with the name of the individual providing currently assigned responsibility of providing the leadership for the activity.

It is clear that immediate action is needed in assigning responsibilities for detailed design for the various sections of the project.

At this stage (9 December 1982) only interim arrangements are possible and indeed, most of the people nominated for the tasks in the schedule are heavily committed elsewhere.

The relationship of the electronics subsystems are shown in the top-level block diagram of Figure 2.1.

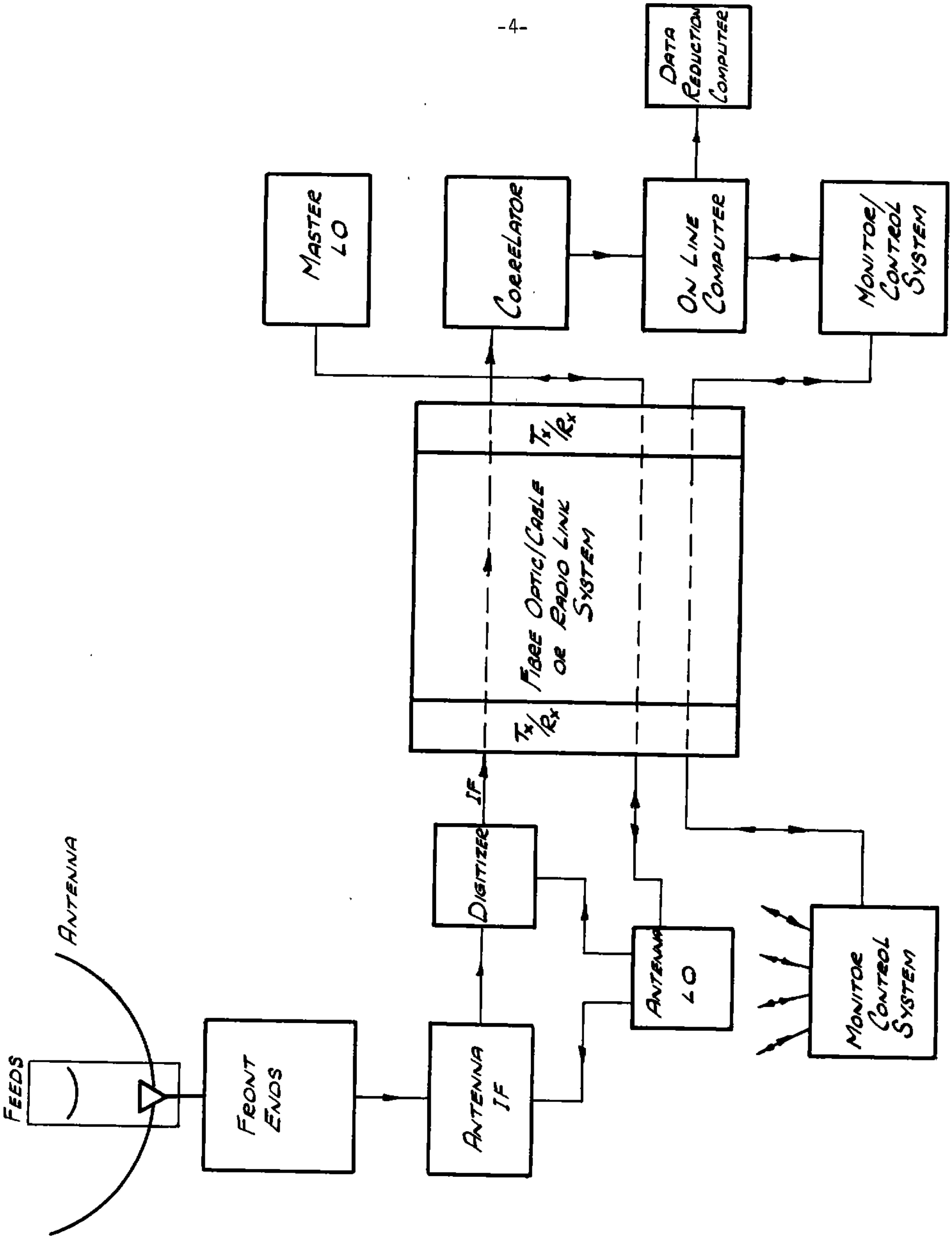

ANTENNA
FEEDS
FRONT ENDS
ANTENNA IF
DIGITIZER
IF
ANTENNA LO
MONITOR CONTROL SYSTEM
Tx/Rx
FIBRE OPTIC/CABLE OR RADIO LINK SYSTEM
Tx/Rx
MASTER LO
CORRELATOR
ON LINE COMPUTER
MONITOR/CONTROL SYSTEM
DATA REDUCTION COMPUTER

Figure 2.1

Configuration Design:	R.N. Manchester. Determination of top level scientific specifications for the AT, such as angular resolution, sensitivity, image quality, spectral resolution, temporal resolution etc. for the various proposed operating modes as well as the determination of these modes.
Antennas:	D.N. Cooper. Specification, design, procurement and testing of the antenna elements.
Antenna Surface Panels:	B.F. Parsons. Specification, design, procurement and alignment of the reflector panels for the antenna elements.
Antenna Servo System:	D.N. Cooper. Specification, design, procurement and testing of the antenna servo system.
Antennas 1 - 7:	Project Manager. Outfitting and system testing of each fully equipped antenna element.
Parkes:	J.G. Ables and D.N. Cooper. Preparation of the Parkes 64 m antenna for its normal observing duties, ESA and NASA support and preparation for radio link array observations during the AT project.
First Interferometer:	Project Manager. Provision of all necessary hardware and software to allow interferometry to start, the testing of the interferometer and decisions on need for design changes.
Feeds:	G.L. James. Specification, design, fabrication, testing and installation of the feeds for the antenna elements, including responsibility for all polarization splitting devices.
Front Ends:	J.W. Brooks and/or M.W. Sinclair. Specification, design, fabrication, testing and installation of the low noise receivers and their cryogenic systems. Responsibility includes all hardware between the rectangular waveguide or coax input to the dewar and the input to the first I.F. mixer. Includes input of injected noise amplitude calibration system.
Fibre Optics/Cables:	A.G. Little. Specification, design, procurement, installation of all fibre optic, coaxial cable and telephone line communication links in the Culgoora east-west array. These links will carry all LO, IF, Monitor and Control, and Voice Communication data, between the antennas and the Central Electronics Building. Responsibility includes the physical cables and all transmit/receive electronics at each end of the cable.

Radio Links:	M.W. Sinclair. Specification, design, procurement, installation and testing of all radio links between Parkes, Siding Spring and Culgoora. These radio links will carry LO signals from Parkes out to Siding Spring and Culgoora; digital commands from Parkes to Siding Spring and Culgoora; digital monitor data from Parkes and Siding Spring to Culgoora. Responsibility includes all antennas, radio towers, and transmit/receive and repeater electronics.
Antenna IF:	J.W. Brooks and/or M.W. Sinclair. Specification, design, fabrication, testing and installation of electronics in the antenna between the input to the first IF mixer and the input to the high speed digitizer. Responsibility includes all frequency converters, bandpass filters, ALC circuits, and total power and calibration signal detectors.
Antenna LO:	J.G. Ables. Specification, design, fabrication, testing and installation of the electronics which provide all phase stabilized LO's and clock signals needed at the antenna. Responsibility includes provision of phase switching, fringe rotation and variable rate sampling clocks.
Monitor/Control:	C.E. Jacka. Specification, design, fabrication, testing and installation of the system which disseminates command information from the on-line control computer to all hardware in the AT, and collects monitor information from that hardware and returns it to the on-line computer. Responsibility includes the interface between the on-line computer and the communication link in the central Electronics Building, and all monitor/control electronics and microprocessors at the antenna.
Master Local Oscillator:	J.G. Ables. Specification, design, fabrication, testing and installation of the primary frequency standards in the central Electronics Building, the electronics to disseminate these references to all antennas and the system to measure the phase and stability of the reference signal returned from each antenna. Also, the provision of a means of locking the primary reference to a Hydrogen Maser located at Tidbinbilla.
Digitizers/Correlators:	J.G. Ables. Specification, design, fabrication, testing and installation of the high speed digitizers at the antennas and the recirculating spectral line correlation system. Responsibility includes provision of "special features: such as a tied array mode, one to two bit conversions with reduced bandwidth and external gating capability required for pulsar observations.

Parkes Electronics:	Project Manager. Specification and design of "one-of-a-kind" electronics systems needed specially for the Parkes 64 m antenna because it is different from the other AT antennas.
Heliograph Modifications:	K.V. Sheridan. Specification and installation of all changes needed to the Culgoora Radio-heliograph to allow it to coexist with the AT.
On-line Computers:	C.E. Jacka. Procurement and programming of the on-line computer which controls and monitors the array, carries out the real time lag-to-frequency FFT's and performs preliminary data correction and calibration.
Data Reduction Computer:	R.H. Frater. Provision and programming of the computer system which performs final data calibration, forms images from UV-plane data and provides image processing facilities.
Data Reduction Software:	R.H. Frater. Selection of one or more existing synthesis data reduction packages for use on the Radiophysics VAX. Modification and testing of this package so that it is available on the RP VAX in time for the First Astronomy.
Site Electrical Works:	W.J. Payten. Provision of all electrical services to all fixed and movable antenna sites at and near Culgoora and Siding Spring. Includes provision of emergency generators, where necessary, to keep cryogenics cold and stow antenna during power outages.
Buildings:	Project Manager. Provision of all necessary temporary buildings.

3. THE I.F. SYSTEM

The I.F. system takes 0 - 128 MHz signals from the front-end converters, limits the bandwidth, amplifies the signal to a level suitable for digitising and produces either a 1-bit or 2-bit TTL level signal for delivery to the transmission system. At this stage it is not possible to specify all the levels in the system.

The decision to digitize at the antennas has the following implications:

(1) Fringe Rotation has to be done through the LO at the antenna.

(2) All narrow band filters have to be at the antennas.

(3) The I.F. cable phase stability requirements are relaxed.

(4) It will not be possible to go to any analogue transmission from antennas to the central electronics in the future without stabilising the I.F. cables.

(5) The maximum digitizing rate is limited by the digital transmission system.

(6) As will be mentioned in the correlator section, the correlator chip can only handle the full bandwidth for 1-bit operation and half bandwidth for 2-bit operation so the digitizer has to be able to do both 1-bit and 2-bit digitization.

(7) To achieve full sensitivity in tied array mode, e.g. for long baselines or fan beam operation, 3-or 4-bit digitization may be desirable.

The block diagram of the system is shown below (Figure 3.1). There are two of these complete systems, one for each polarization. The second output is an option for spectral line observations but will not be provided at this stage - only the transmission link will be installed.

Both the LO and sampling clocks can be derived from a master oscillator which is Doppler shifted to allow for the fringe rotation (the "unified clock" method). A block diagram of a possible system is shown below (Fig. 3.2). This allows a basic system which is the same for all bands, with different frequency bands being selected by the appropriate locking system at the antennas. For this system to work, it must be capable of producing internally a phase stability of about 1°/GHz with a maximum of about 40° above 40 GHz. This figure is a maximum and it would be desirable to be even less. The main LO pilot signal can be sent out at say a few hundred MHz using a phase stabilized link.

For tied array operation such as for VLBI using 1-bit operation there could be a loss of sensitivity of about 25% if the full bandwidth is used. However it may be sufficient to reduce the bandwidth before sampling whilst still maintaining the fast sampling in which case the signal is oversampled and the loss will be negligible.

Note:

Because the sampler is operating at such a high speed, considerable attention will have to be paid to shielding of the sampler to avoid interference to the telescope, particularly since the sampling will be coherent at each antenna.

Manpower:

High-level engineering is required immediately for systems design of the sampler and LO systems; the other components are relatively straightforward. From experience with TEST, this could be approximately one man-year.

For production, allowing for 6 elements at Culgoora, 1 element at Siding Spring, Parkes and Tidbinbilla, and one spare (10 units total), an estimate of two/three technicians for one year full-time.

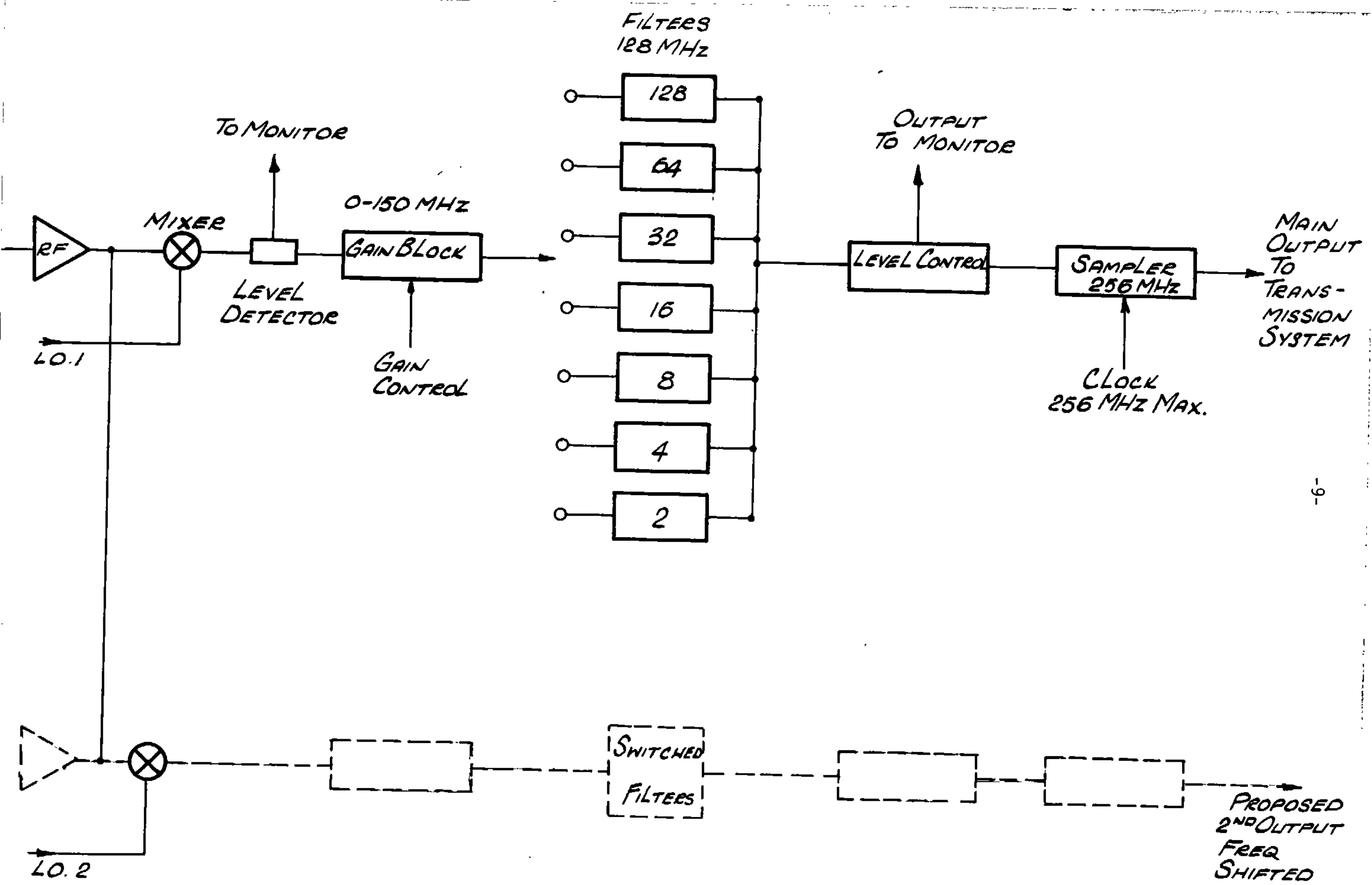


Figure 3.1 : IF Block Diagram

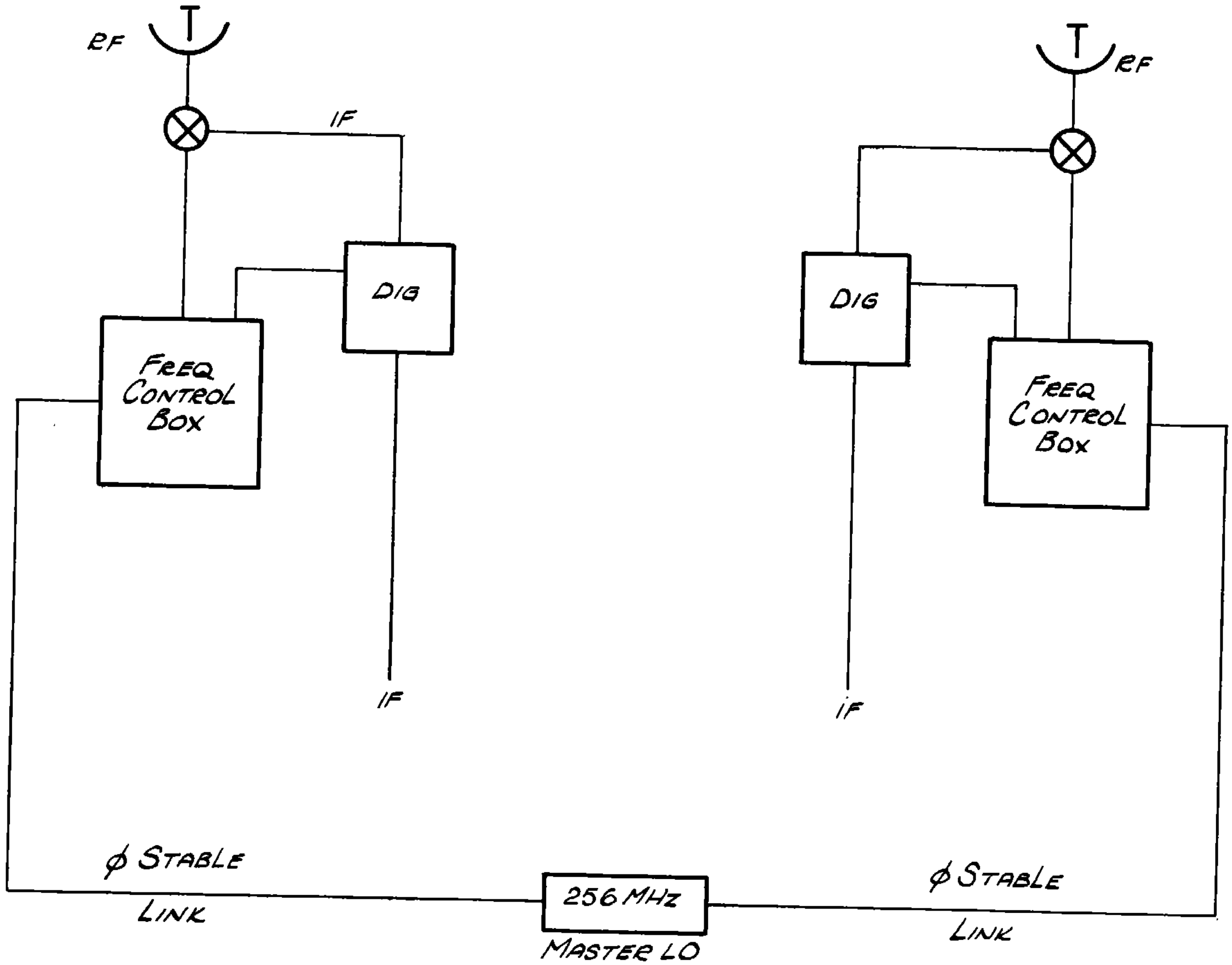


Figure 3.2 : PROPOSED CLOCK-LO SYSTEM

4. THE CORRELATION SYSTEM

4.1 Factors influencing the correlator specifications

4.1.1 Basic astronomical requirements

The document "Proposed Spectral Line Correlation System" (AT/10.4/001) primarily determines the overall size of the correlator. The relevant extreme parameters are summarized in the following:

Bandwidth	Spectral Channels/Pol	Recirculation Factor
128 MHz	128	2^0 (= 1)
2 MHz	8192	2^6 (=64)

Given 1-bit correlation with the existing design for the VLSI correlator chip, this indicates the use of 15 x 2 x 256 channels capable of a sampling rate of 256 MHz. Each correlator chip provides (conservatively) 8 channels at 80 MHz sampling rate thereby requiring $\frac{7680 \times 4}{8} = 3840$ chips.

A new chip might provide 2-bit operation at half bandwidth. We conclude on the basis of costing that full bandwidth operation must be restricted to 1-bit.

4.1.2 Implications of full field mapping

The requirement that the entire field of view be mapped out to the 10 dB point for the primary beam sets limits on the maximum frequency channel width and correlator readout rate.

(i) Radial bandwidth smearing

Given a synthesised beam of approximately λ/B radians, and a field radius of approximately λ/D radians, then a maximum radial smearing of

$$\frac{\Delta\nu}{\nu}\cdot\frac{\lambda}{D}\cdot\frac{B}{\lambda} = \frac{\Delta\nu}{\nu}\cdot\frac{B}{D}$$

results from a fractional bandwidth $\Delta\nu/\nu$. Setting a limit of 50% linear smearing, which implies a point source decorrelation of approximately 5% gives

$$\frac{\Delta\nu}{\nu} \leqslant 0.5 \text{ D/B}$$

For ν = 3 GHz (the lowest frequency at which full bandwidth is likely to be available), $\Delta\nu$ = 5.4 MHz results.

(ii) Circumferential integration time smearing

An integration time of Δt seconds determines a movement of the synthesized beam during Earth rotation at a radius of λ/D radians in the field given by

$$\Delta t.\frac{\pi}{43200}.\frac{\lambda}{D}$$

from which a circumferential smearing of

$$\Delta t.\frac{\pi}{43200}.\frac{\lambda}{D}.\frac{B}{\lambda}$$

results.

A requirement of less than 50% smearing yields

$$\Delta t \leqslant \frac{21600}{\pi}.\frac{D}{B} \approx 25 \text{ seconds}$$

4.1.3 Maximum readout rate

The maximum readout rate is influenced by:

(i) Astronomical wishes which suggest maintaining the possibility to read out a limited subset of the correlator data (i.e. only continuum points) at intervals as short as 1ms.

(ii) Loss of observing time due to correlator blanking during readout. The VLSI chip readout time is of the order 0.1 ms.

(iii) Prescale quantisation noise in the VLSI chip. For 6 bits prescaling we have

$$\sigma^2(\text{quant}) = \left(\frac{2^6}{\sqrt{12}}\right)^2$$

and for an integration time Δt

$$\sigma^2(\text{thermal}) = \Delta t \nu_0$$

The requirement σquant $\ll$ σthermal yields

$$\Delta t \gg 2^{12}/3\nu_0$$

where ν_0 is the basic correlator sampling rate (10 MHz). We obtain $\Delta t \gg 0.03$ ms.

(iv) Readout data rate - to be considered in a later section.

(v) Recirculation requirements - to be considered in a later section.

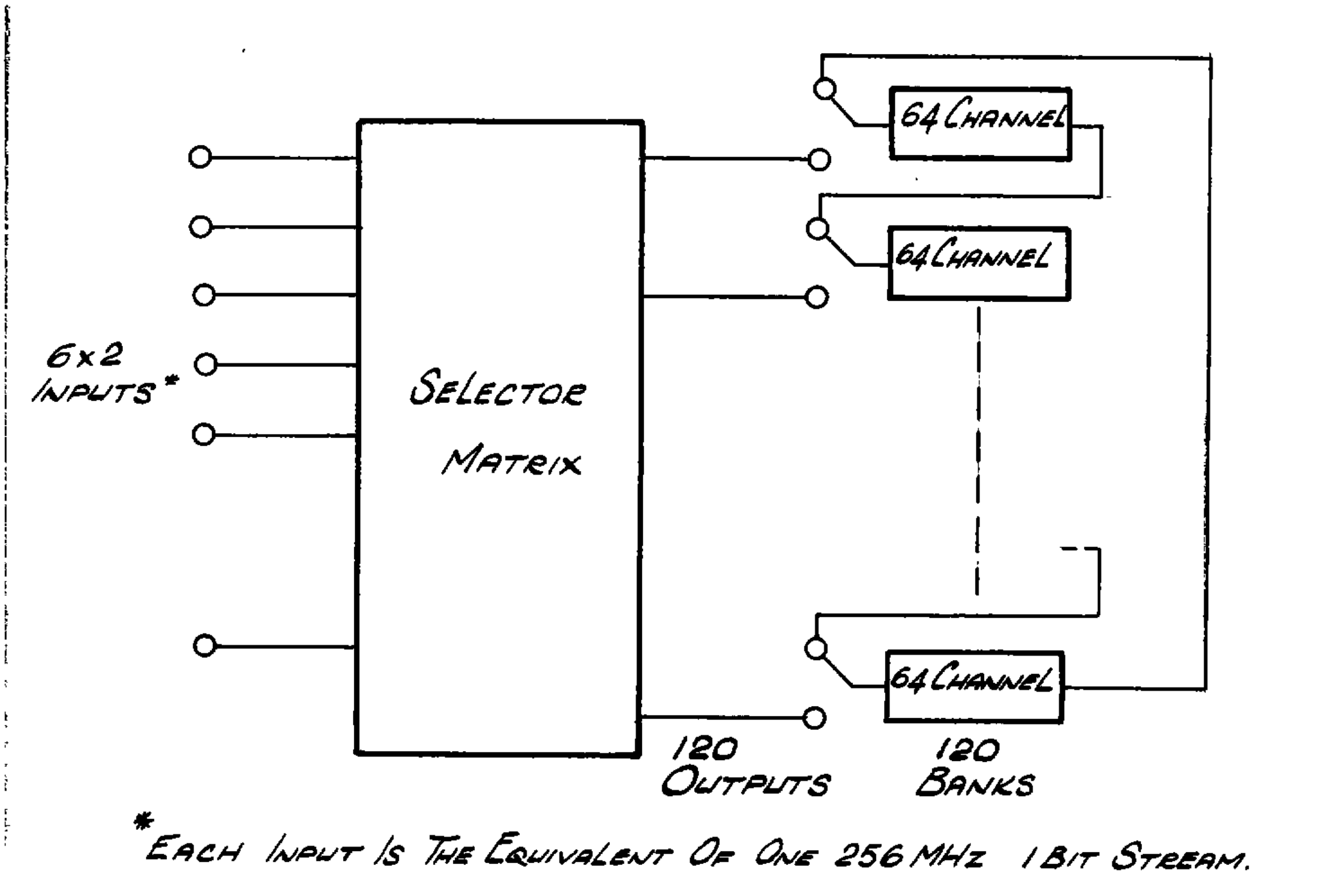
4.1.4 Correlator configuration flexibility

All 7680 physical channels will commonly be configured as 15 baselines x 2 polarisations x 256 channels. Some possible other modes might include

Baselines	Polarisations or Separate I.F.'s	Channels
15	2	256
15	4	128
0 or 1	2	3840*

*For example: Tied array autocorrelation spectra or grating tied array cross correlation spectrum for pencil beam high spectral resolution work.

Such considerations dictate flexibility in assigning inputs to correlator banks and chaining of consecutive correlator banks. Detailed consideration must be given to these points. Preliminary indications suggest that correlators arranged in banks of 64 lag channels with full input selector flexibility for each bank should be viewed as a design goal. Schematically we have (Figure 4.1)



*each input is the equivalent of a 256 MHz 1-bit stream.

Additional features to be provided include phase switch demodulation in each input line, correlator blanking (pulsar observations), one bit - two bit selection. These plus certain extra selector functions such as selection of 6km array or radio linked array as input to the correlator should be identified as separate functions where possible to prevent hidden restrictions in as yet unforeseen operating modes.

4.2 Requirements for Correlator Recirculation

A recirculation factor of $F_R = 2^6$ is suggested to fully utilize correlator capacity down to 2 MHz bandwidth.

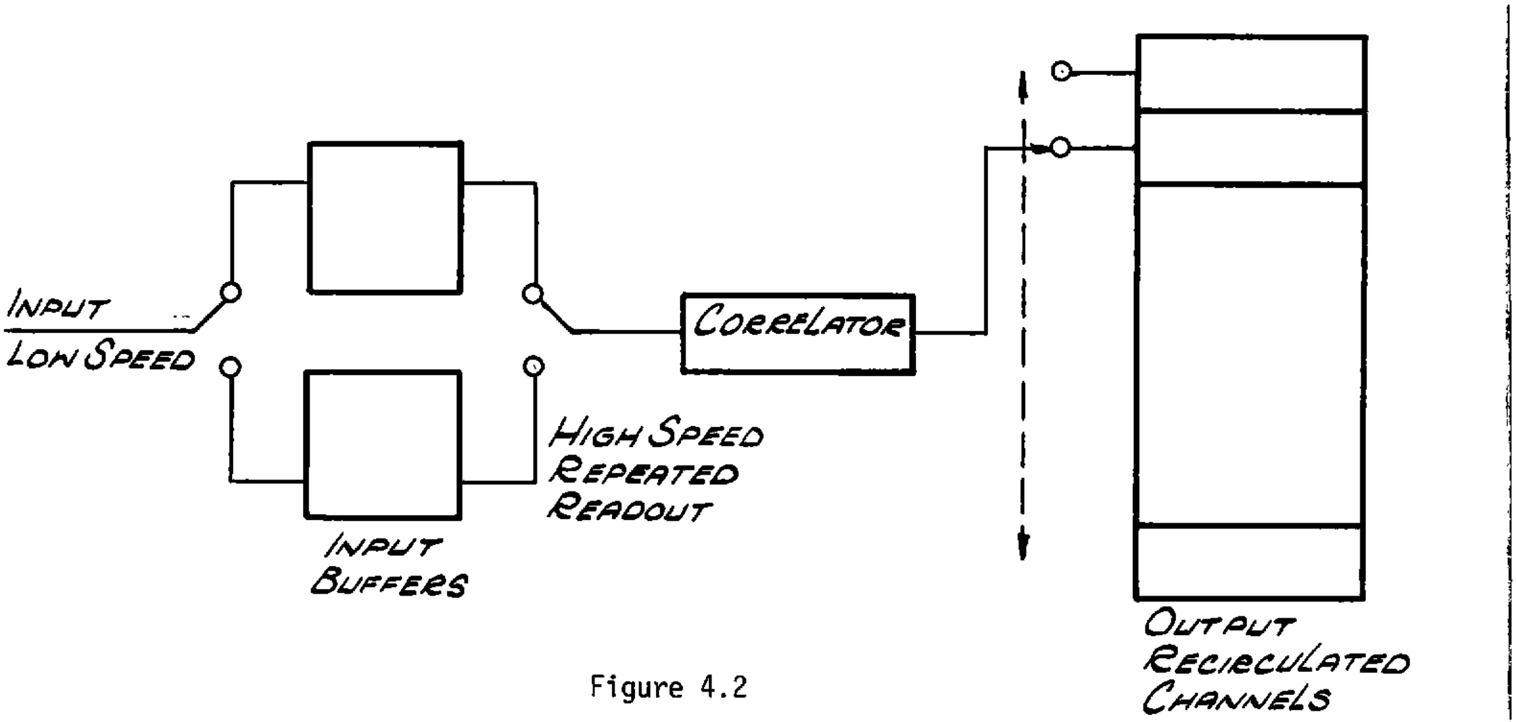


Figure 4.2

The recirculation method allows multiplication of the number of correlator channels by a factor F_R. In principle this need not be restricted to an increase in spectral channels but could allow multiplication of baselines, I.F.'s, etc. as the correlator may be reconfigured between recirculation cycles. The recirculation method reads data into one of two input buffers at the reduced input rate $\left(\frac{256}{F_R}\right)$Mbits/sec for a bandwidth of $\left(\frac{128}{F_R}\right)$MHz. The other input buffer is readout F_R times at 256Mbits/sec rate with, for example, successively altered lags to allow F_R separate utilisations of the correlator.

Given a readout rate or basic recirculation interval t_c, two input buffers of size 256 t_c Mbits are required. For the proposed system, F_R x 7680 separate accumulators are required. Depending on the exact method of handling the VLSI correlator chip output, this could rise to F_R x 3840 x 64 = 245760 F_R separate 24 bit accumulators (47 MB). It is therefore advisable to combine all 32 subproducts immediately in F_R x 7680 separate 32 bit accumulators (2 MB).

The time required to complete a recirculation cycle is $F_R t_c$.

<u>Recirculation with $t_c = 5ms$</u>
$F_R = 2^6$

Input buffer size	320 KB/input 38 Mbyte total
Output buffer size	2 MB
Readout rate	320 ms

The input recirculation memory is a high speed serial in-serial out buffer but should be implemented with normal RAM technology thereby allowing considerable economy. Considerable flexibility in readin and readout address sequencing should be considered to allow full potential of the recirculation principal to be realised.

4.3 Correlator System Outline

The diagram (Figure 4.3) outlines the entire correlator system for both 6km and radio linked systems. Some comments are appropriate concerning the separate subsystems.

(a) Serial-parallel conversion

The high speed data streams from the antennas are reduced at the earliest possible stage to parallel, low speed bit streams.

(b) 6km delay path tracking

Although potentially combinable with other functions in the system (recirculating buffers), it is felt that system simplicity and flexibility is improved with the use of a separate subsystem for the path delay tracking. Because of the use of the "unified clock method", the delay tracking memory is also first-in, first-out (FIFO) but should be designed around standard RAM chips.

(c) Modulator matrix

In particular, any phase switch modulation could be demodulated here.

(d) Summation units

At least two separate adders are envisaged to allow

(i) operation of the 6km array as a tied array with or without the radio linked array

(ii) high resolution grating array spectrometry.

Inputs to the summation units should be individually selectable.

(e) Radio link/6km array selector

To avoid unnecessarily complicating the full selector matrix, a simple 2-way switch is envisaged here.

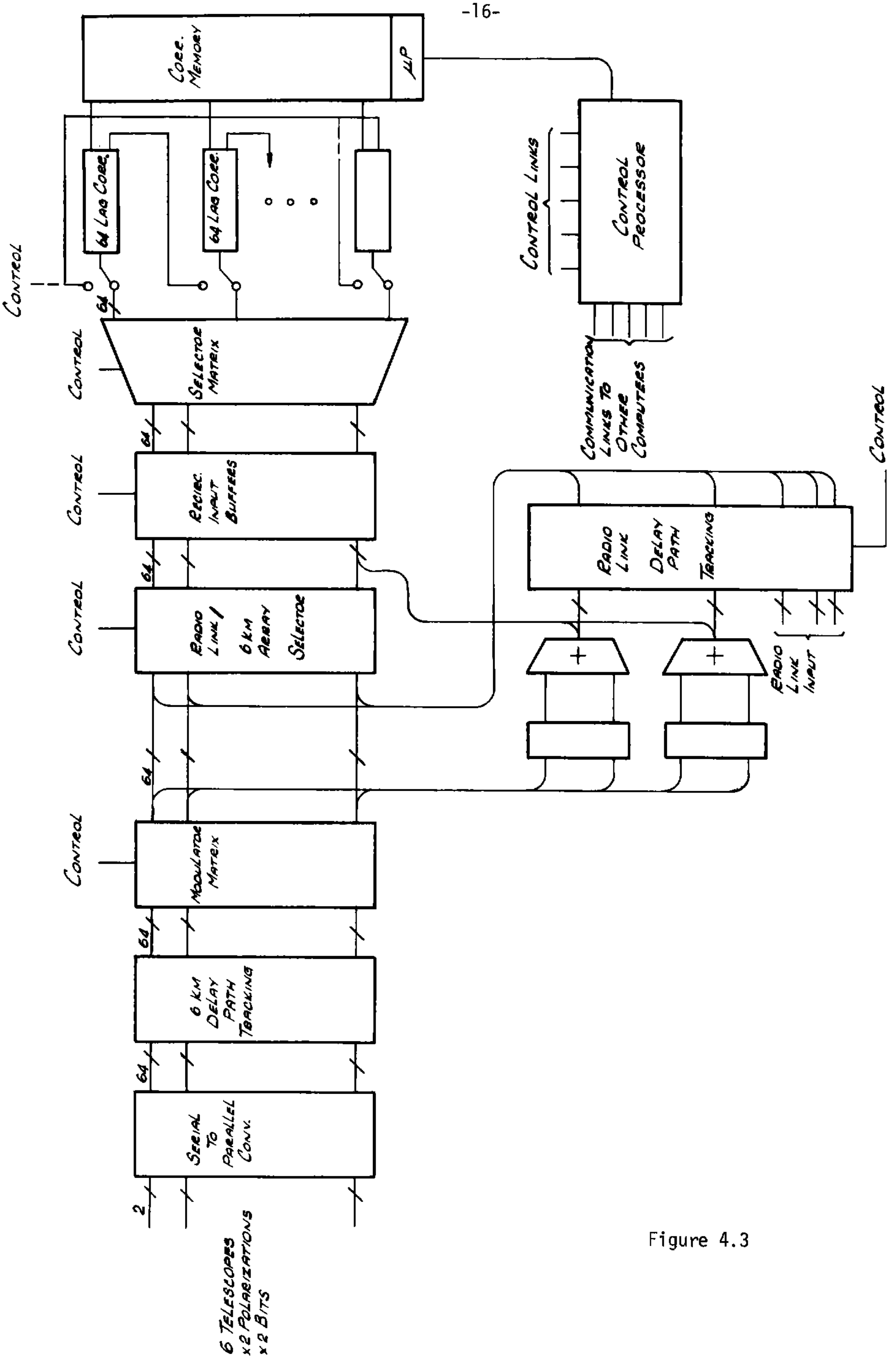

CORR. MEMORY
µP
64 LAG CORR.
64 LAG CORR.
CONTROL
64
CONTROL
SELECTOR MATRIX
64
CONTROL
RECIRC. INPUT BUFFERS
64
CONTROL
RADIO LINK / 6 KM ARRAY SELECTOR
64
64
CONTROL
MODULATOR MATRIX
64
6 KM DELAY PATH TRACKING
64
SERIAL TO PARALLEL CONV.
2
6 TELESCOPES
x 2 POLARIZATIONS
x 2 BITS
CONTROL LINKS
CONTROL PROCESSOR
COMMUNICATION LINKS TO OTHER COMPUTERS
CONTROL
RADIO LINK DELAY PATH TRACKING
+
+
RADIO LINK INPUT

Figure 4.3

(f) Radio link delay path tracking

A separate delay correction should be provided for the low bit rate (20 Mbit/sec) but large path length radio linked array.

(g) Recirculating input buffers

See discussion in section 4.2.

(h) Selector matrix

See section 4.1.4.

(i) Correlator banks

See section 5.

(j) Recirculating output buffers

See section 4.2.

(h) Control section

The control section is responsible for storage of all configuration information. Some thought must be given to altering configurations at the basic recirculation cycle time (approx. 5ms).

5. THE A.T. DIGITAL CORRELATOR SUBSYSTEM

5.1 Introduction

The AT correlator is based on a very wideband digital correlator with a parallel, pipe-lined architecture using a large number of identical computational elements implemented with VLSI NMOS circuitry. The lag range for smaller bandwidths is increased by operating the basic correlator with a recirculation memory system. The VLSI chips are combined to form correlator modules which become the building blocks for the correlation system.

5.2 System Architecture

Input and output signal data paths are 32 bits wide and operate at a maximum rate of $\sim 32 \times 10^6$ bits/sec. The source of input data depends on the operating mode and may be either the delay tracking memory system or the recirculation memory system. The data source and signal data linkage between modules is determined by a data selector matrix.

Output correlation data paths are also 32 bits wide and connect to the data logging computer system. Data rates on the output paths is determined by the logging system as well as the correlator system needs.

The communication bus provides the path by which the on-line computing systems are able to configure and command the correlators and to receive status information from the correlators. The timing bus provides the path by which the correlators are synchronised with external systems.

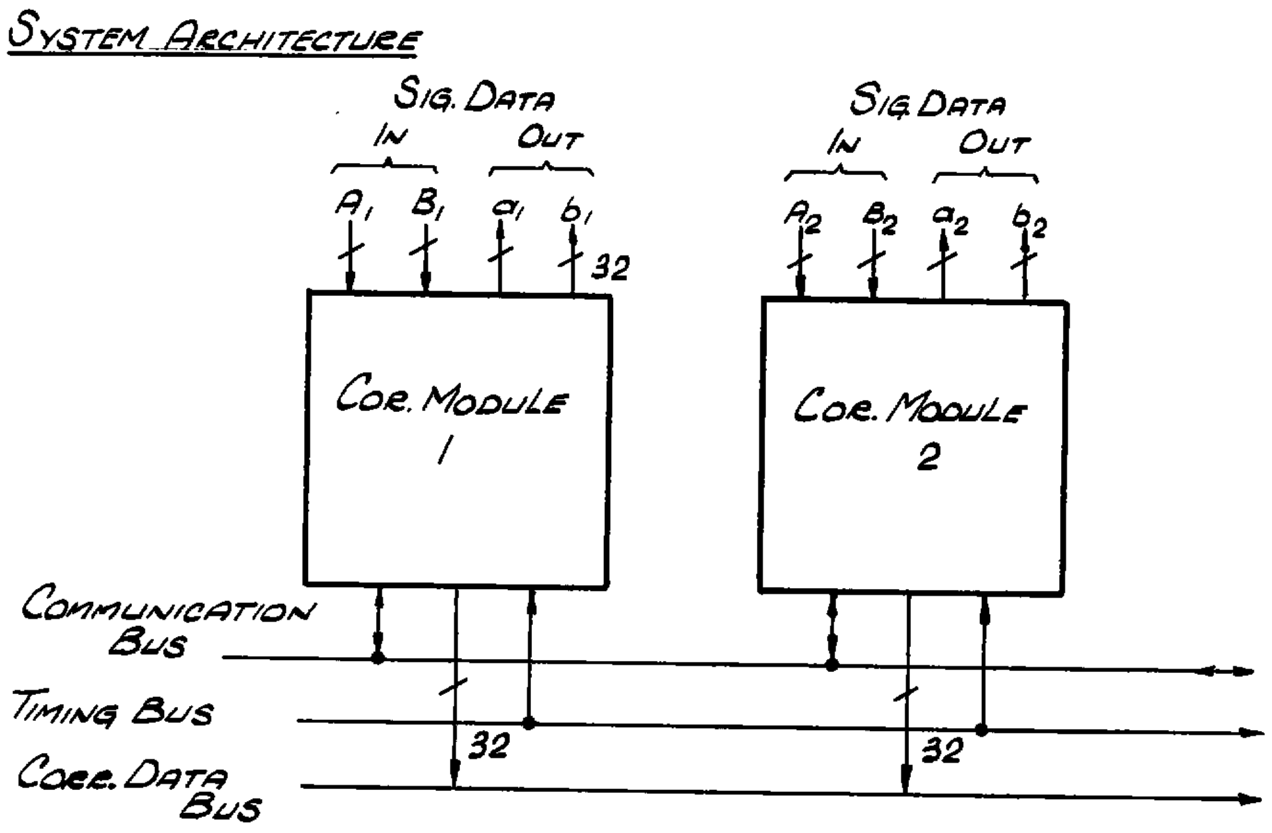


Figure 5.2

5.3 Correlator Module Specifications (Preliminary)

Bandwidth:	256×10^6 samples/sec (1-bit)
	128×10^6 samples/sec (2-bit)
Lag range:	64 (unidirectional)
Signal data paths:	32 bit parallel synchronous
Corr. data path:	32 bit parallel asynchronous
Integration time (T):	1ms to 25sec
No. of VLSI chips/module:	32
Construction:	single board (pc, wirewrap or multiwire)
On-board corr. data management:	microprocessor + memory
Power:	5V at approx. 20W

5.4 VLSI Correlator Chip Architecture

The well-known Weinreb digital correlator (and multi-bit extensions of the basic one-bit version) may be considered as a pipeline processor for computing sums of lagged products of a pair of digitised sample data streams. The "pipeline" is the shift register (SR) down which the delayed stream flows. The upper limit on processing speed is determined by the minimum time required for the multiplier-accumulator (MAC) attached to each SR stage to perform one operation. (The SR is usually faster than the MAC). Only one sample at a time is input to the processor.

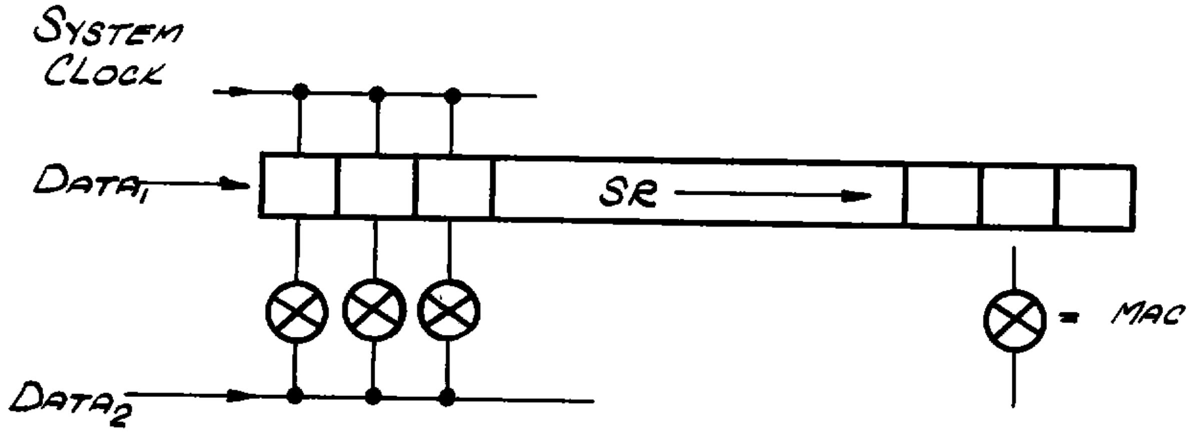


Figure 5.2 : WEINREB DIGITAL CORRELATOR

Now consider the computational element (CE) diagramed below.

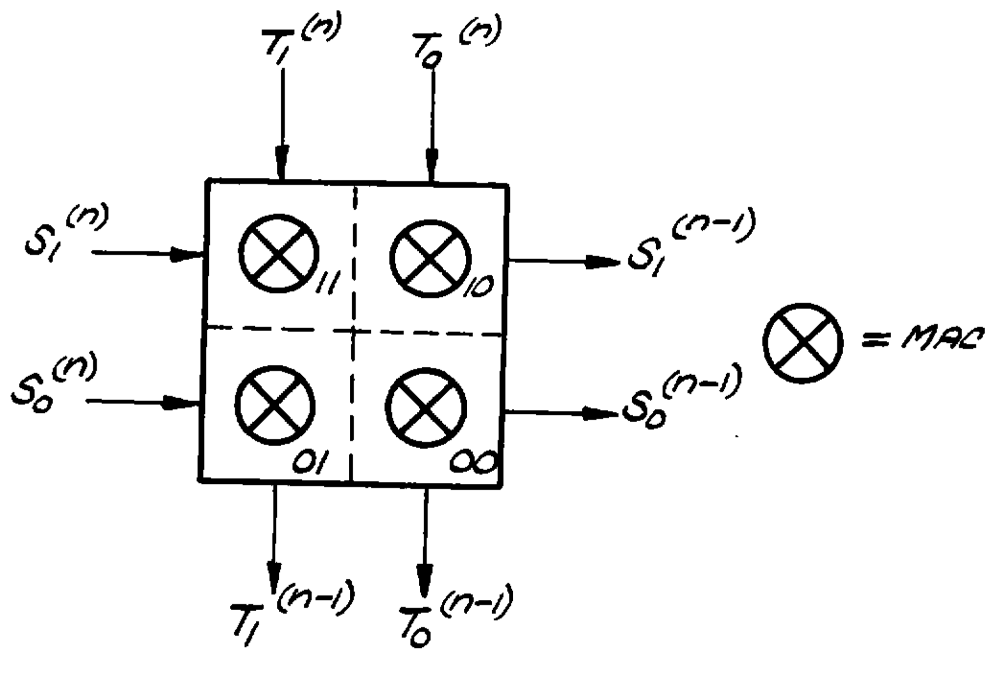


Figure 5.3

S and T are data samples from the two streams so that $(S_0(n),S_1(n))$ is the n-th sample block from stream S. Here N = 2; i.e. the data is blocked into groups of two samples. The MAC's operate on the "intersections" of the data streams within the CE. Date input at the top and left side appear, delayed by one block time, at the bottom and right side respectively.

The new architecture described here differs from the Weinreb correlator in that it operates on successive blocks of N samples (which may be multi-bit) with all operations on the N samples taking place at the same time at each pipeline stage. For a given logic speed this achieves an N-fold speed increase over the Weinreb architecture but at a cost of using N times as many SR elements and MAC's. The advantage of the parallel processing method is that speed is achieved through the use of more circuitry rather than higher speed circuits. This means that the cheapest circuitry now known, VLSI poly-silicon gate NMOS circuitry, can be used to reach speeds not possible using the Weinreb architecture, even with the fastest (and extremely expensive) logic now available.

The CE in the first figure is designated (for obvious reasons) a 2X2 CE. A CE that accepts blocks of N samples from both data streams is called NXN. Rectangular CE's (NXM) are also possible, but they do not seem to have any particular advantage over the symmetrical NXN CE and are more complex to interconnect. An NXN CE computes all the partial sums of lagged products from blocks of N samples necessary to determine the correlation over N lags. To extend the lag range, CE's can be cascaded to lengthen the pipeline. The CE's can also be ganged in parallel, with appropriate interconnections, to increase the input sample block length in multiples of N. The structure of a correlator with an input block length of six and a lag range of 12, built from 2X2 CE's, is shown in Figure 5.4.

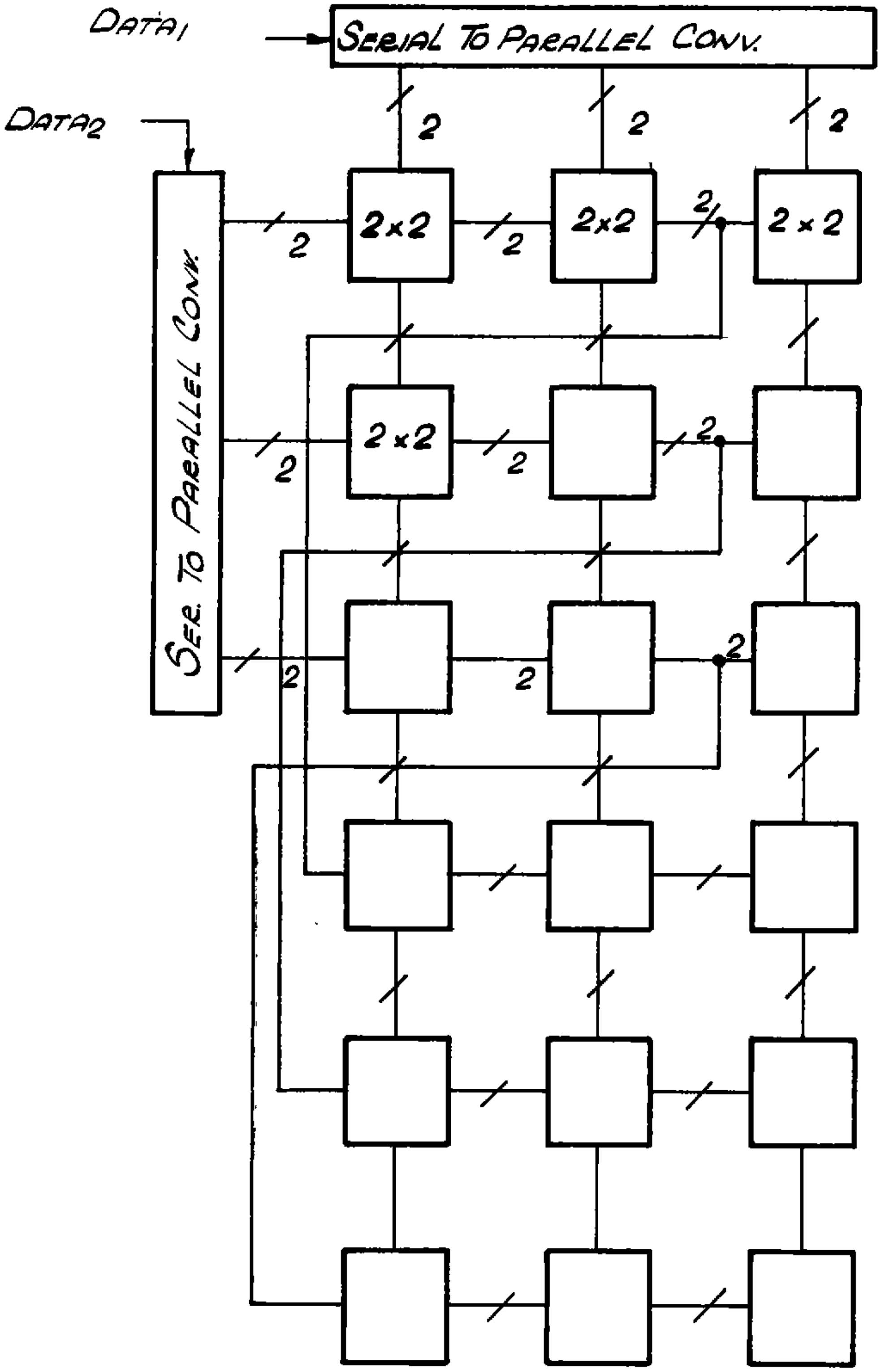

DATA1
SERIAL TO PARALLEL CONV.
DATA2
SER. TO PARALLEL CONV.
2
2×2
2 × 2

Figure 5.4

5.5 Broad Specifications for AT Correlator IC Chip (XCELL)

* Type:	8X8
* Bits per sample:	1 or 2 selectable
* Process rate:	10 MHz (5 MHz for 2-bit mode)
* Prescale factor:	64
* Read out:	serial (approximately 150 microsec)
* Accumulator length:	24 bits
* Package:	Standard 40-pin ceramic
* Technology:	Polysilicon-gate NMOS 3 to 5 micron minimum line width

5.6 Correlation Subsystem Requirements

(Correlator only, i.e. not including recirculation memory or selector matrix)

Correlation modules:	Culgoora correlator	120
	Parkes correlator	16
		136
	+ spares (20%)	24
		160
XCELL 8X8 chips:		approx. 5000
Power:	Culgoora	3KW
	Parkes	400W
Space:	Culgoora	4 racks
	Parkes	1 rack

Time and Money* (rough estimates)	Man Years
VLSI design & procurement	2
testing	1
Module design	0.5
construction	0.5
testing	0.5
System integration and testing	1

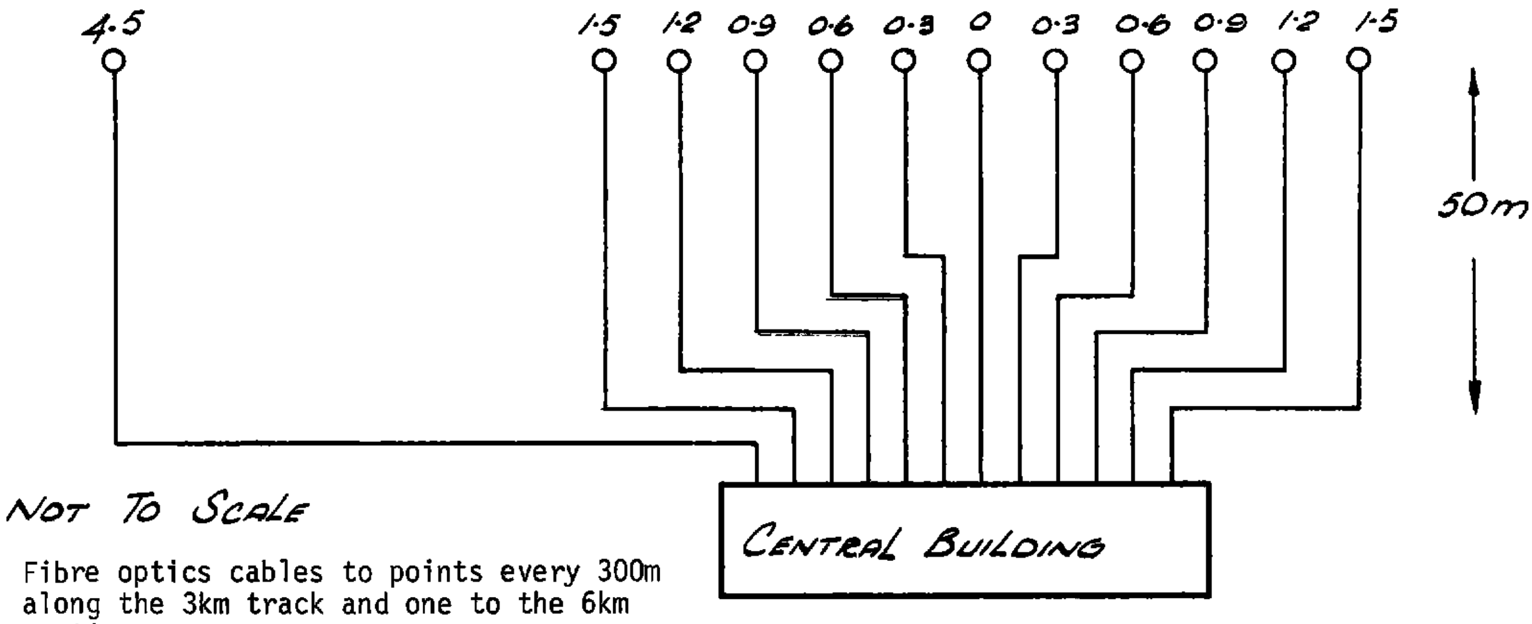
	$A (1982.9)
XCELL chips (packaged)	$32
Correlator module (tested)	$2000
Culgoora correlator system	$300K
Parkes correlator system	$40K

* costs do not include salaries or overheads.

6. LOCAL OSCILLATOR DISTRIBUTION SYSTEM

An important starting point in the design of the local oscillator distribution system for the AT is the selection of a phase stability specification for the instrument. On time scales of 10's of minutes the instrumental phase errors should be small compared to the atmospheric phase errors. At the VLA, a phase stability specification of 1° rms phase/GHz has proven adequate to ensure this. Since precipitable water vapour at Culgoora is 2 to 3 times higher than the VLA, it can be expected that tropospheric phase errors will be worse at the AT by this amount. Therefore on time scales of a few 10's of minutes a phase stability spec. of 1° rms/GHz should be adequate. On shorter time scales, on the order of a minute, we require that there be no loss of correlation in an integration period used for self-calibration. A suitable specification for this purpose would be 1° rms for frequencies less than 10GHz, 10° rms for frequencies higher than 10GHz in a one minute integration time. Both the short and long term specifications need to be met.

Of the possible communication links which can be considered for the LO link on the 6km array, radio links can be rejected due to interference and spectrum availability problems. Waveguides are too expensive and coaxial cables have too much attenuation. A fibre optics LO link is attractive from the point of view of the low cost of optical fibres and the low attenuation that is available in modern mono-mode fibres. The current state-of-the-art in phase stabilized fibre optics links is reviewed in the Attachments 2 and 3 by T. Cole (Wideband Single-Mode Fibrelinks with Phase Stability) and G. Lutes (Development of Optical Fibre Frequency and Time Distribution Systems).



Fibre optics cables to points every 300m along the 3km track and one to the 6km station.

Figure 6.1 (see text on next page)

For costing purposes one could consider the prototype fibre optics system shown in Figure 6.1. In this system cables are run to points separated every 300m along the railway track. An umbilical cable would connect each antenna to its nearest fibre link. The total cable length in this system would be approximately 14km. Allowing a generous 12 fibres for each run, the total cost of fibre at $1.3/metre per fibre is 14000 x 12 x 1.3 approx. $220000 (without installation costs). This is within range of the current budget but clearly an extension of the fibre link from the 6km station out to 18km will only be possible if there are cost savings elsewhere.

There are 3 basic methods of phase stabilizations for long cable runs. These are shown in Figure 6.2. Either the Two Oscillator or the Round Trip Phase method would be suitable for stabilizing a fibre optics link. The bandwidths of commercially available fibre optic cables would suggest that the highest frequency LO distributed to the antennas should be in the range 100 to 400 MHz.

The phase stabilized fibre optics link is one of the areas of the AT that needs most development work. Experiments should start immediately and will require at least 1 full-time engineer/scientist and one high level technician for the duration of the project.

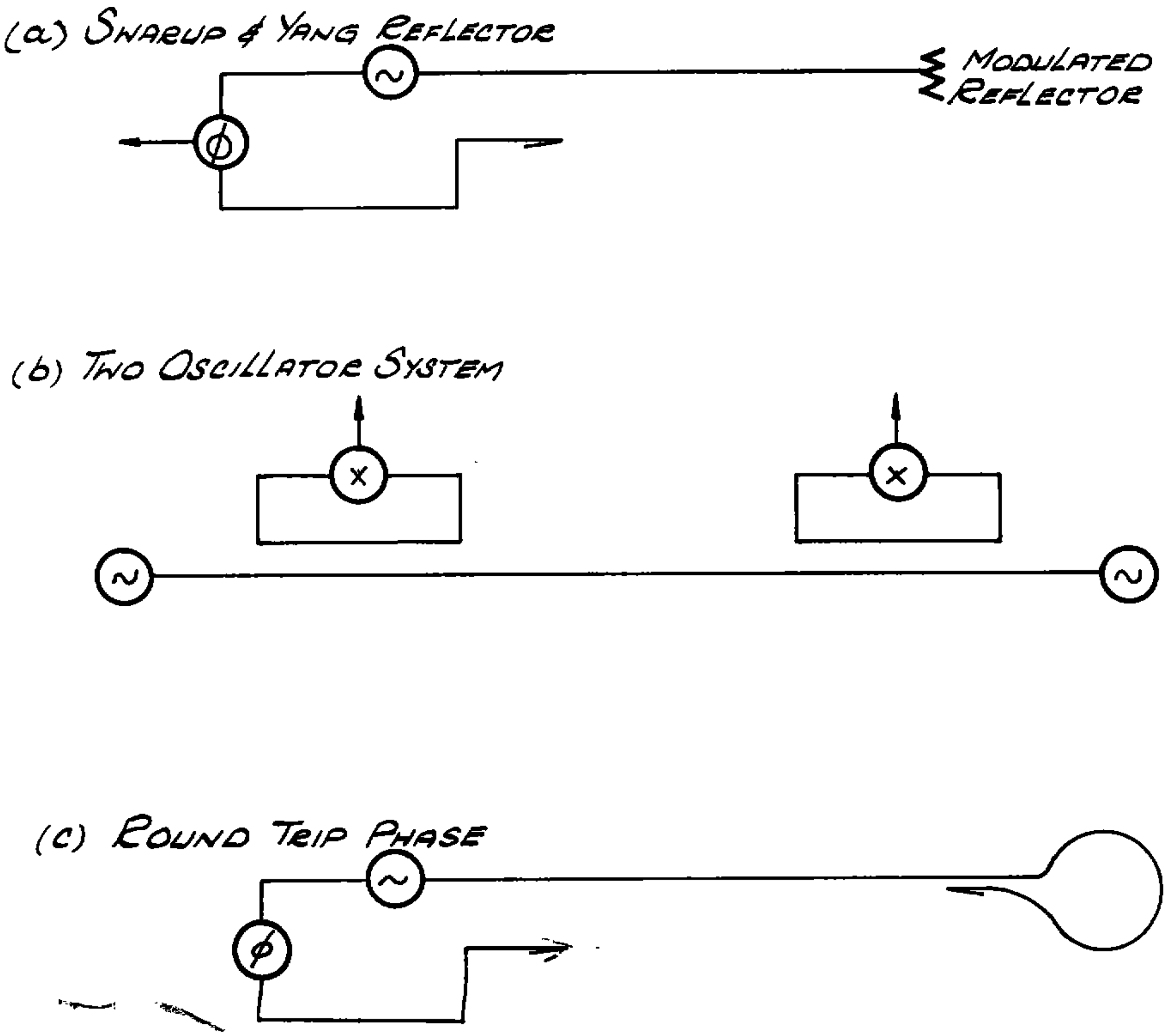


Figure 6.2 : Three Methods of Phase Stabilization

7. RADIO LINKS FOR THE LBI ARRAY

Any consideration of a radio linked array between Culgoora and Tidbinbilla presupposes the installation for NASA of a radio link between Parkes and Tidbinbilla for the Voyager/Uranus project. It is probable that this link will provide full-duplex frequency diversity operation with a mixture of S- and X-band hops. The proposed system provides TV baseband modulated onto a 24 MHz bandwidth channel. The bandwidth available for TV approaches 9 MHz with a pilot tone in this region also.

This system would be available for radioastronomy use. In its simplest application, analog data could be transmitted between Tidbinbilla and Parkes. In the most probable mode of operation a 20 Mbit/sec data stream would be encoded onto the TV band and transmitted to Parkes.

8. THE PARKES-SIDING SPRING-CULGOORA LINK

The most economical approach to this link would require the use of a duplex S-band system based on a 24 MHz channel. This system would be used for both LO and data. The LO distribution could be similar to the two-frequency system described by van Ardenne *et al.* ("A High Precision Phase Comparison Experiment using a Geostationary Satellite"; submitted for publication to IEEE Transactions on Instrumentation and Measurements - July 1981. Copy of preprint available in RP Epping Library) for satellite use. The 24 MHz band would be split into three bands of about 7 MHz. This would allow a 20 Mbits/sec data stream from each of Tidbinbilla, Parkes and Siding Spring to Culgoora. The future provision of extra channels in the Parkes to Culgoora direction would allow for operation up to 80 Mbits/sec but would impose considerable strain on the correlator design. (See elsewhere in this report.)

Detailed investigation is needed of the following questions:

(i) The possible use of existing towers and the siting of new towers.

(ii) The capital cost of the proposed system.

(iii) The projected operating costs.

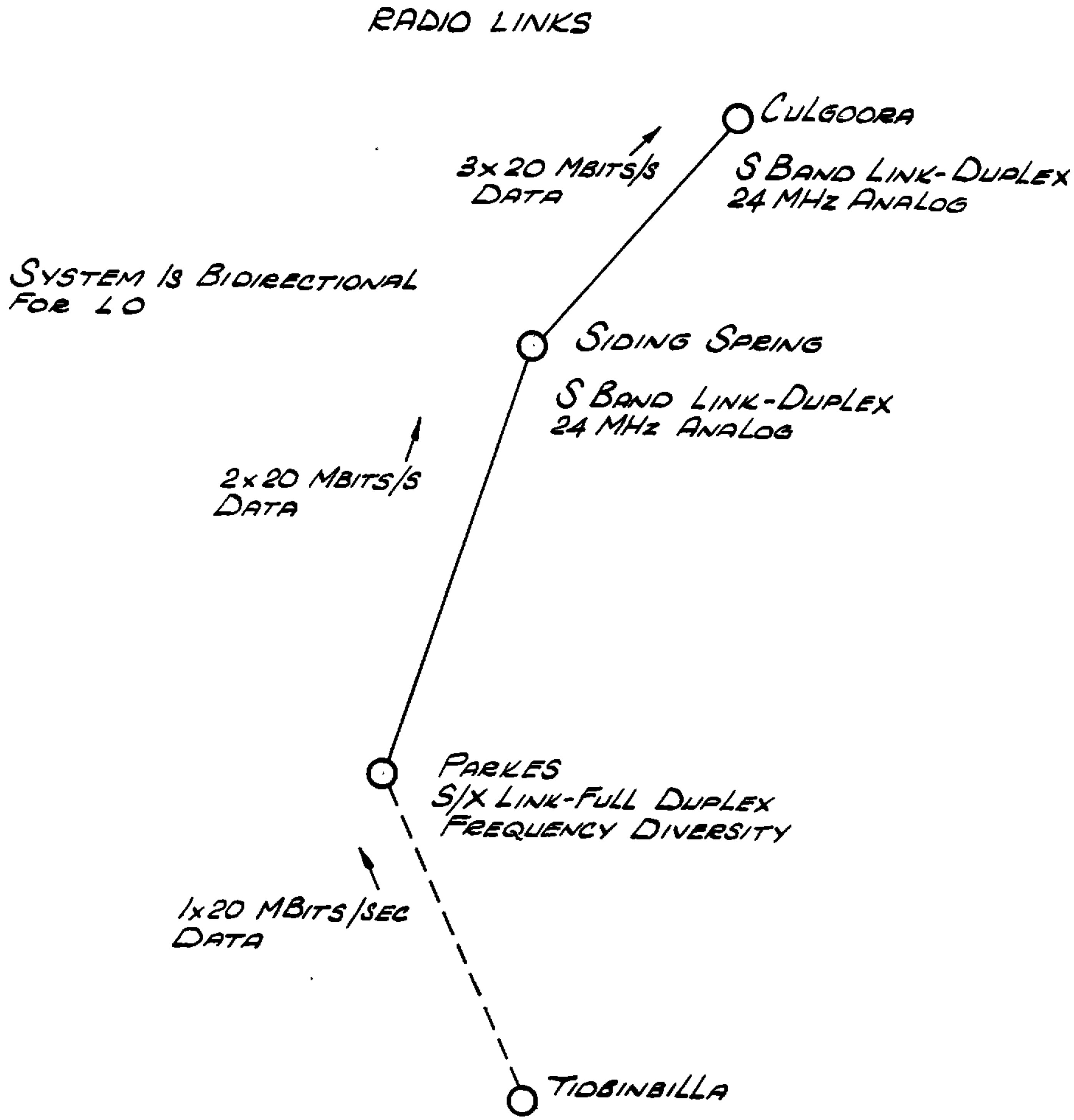

RADIO LINKS
CULGOORA
3x20 MBITS/S
DATA
S BAND LINK-DUPLEX
24 MHz ANALOG
SYSTEM IS BIDIRECTIONAL
FOR LO
SIDING SPRING
S BAND LINK-DUPLEX
24 MHz ANALOG
2x20 MBITS/S
DATA
PARKES
S/X LINK-FULL DUPLEX
FREQUENCY DIVERSITY
1x20 MBITS/SEC
DATA
TIDBINBILLA

Figure 8.1

9. MONITOR CONTROL

Although this subject was not discussed at the meeting, this note is included to give an idea of the requirements. See also Figure 9.1.

9.1 Telescope Drive

The telescope drive could be controlled either from a central computer or by a local microprocessor under slave control from the centre. The latter might have some advantages since it allows each telescope to be a stand-alone unit. However each time the telescope is moved the master clock would be interrupted which could be a nuisance.

9.2 Monitor

The monitor system keeps track of the behaviour of the telescope and the electronics, and either flags faults or maybe, if possible, switches over from a faulty component to a spare. Use of the latter would depend on the cost of the component and whether it could be easily switched in or out. Flagging will probably be the system used.

9.3 Control and Monitor Wiring List to each Telescope

(i) 3 Phase Power: for aerial drives
electronics
helium refrig.
air conditioning
lights
KVA = ?

(ii) Monitor leads for: aerial pointing
temp - several places
radiometer gain - several places
LO status - i.e. lock
power
freq. select
bandwidth select
digitizer freq. select
cable - OK
helium refrig. - OK

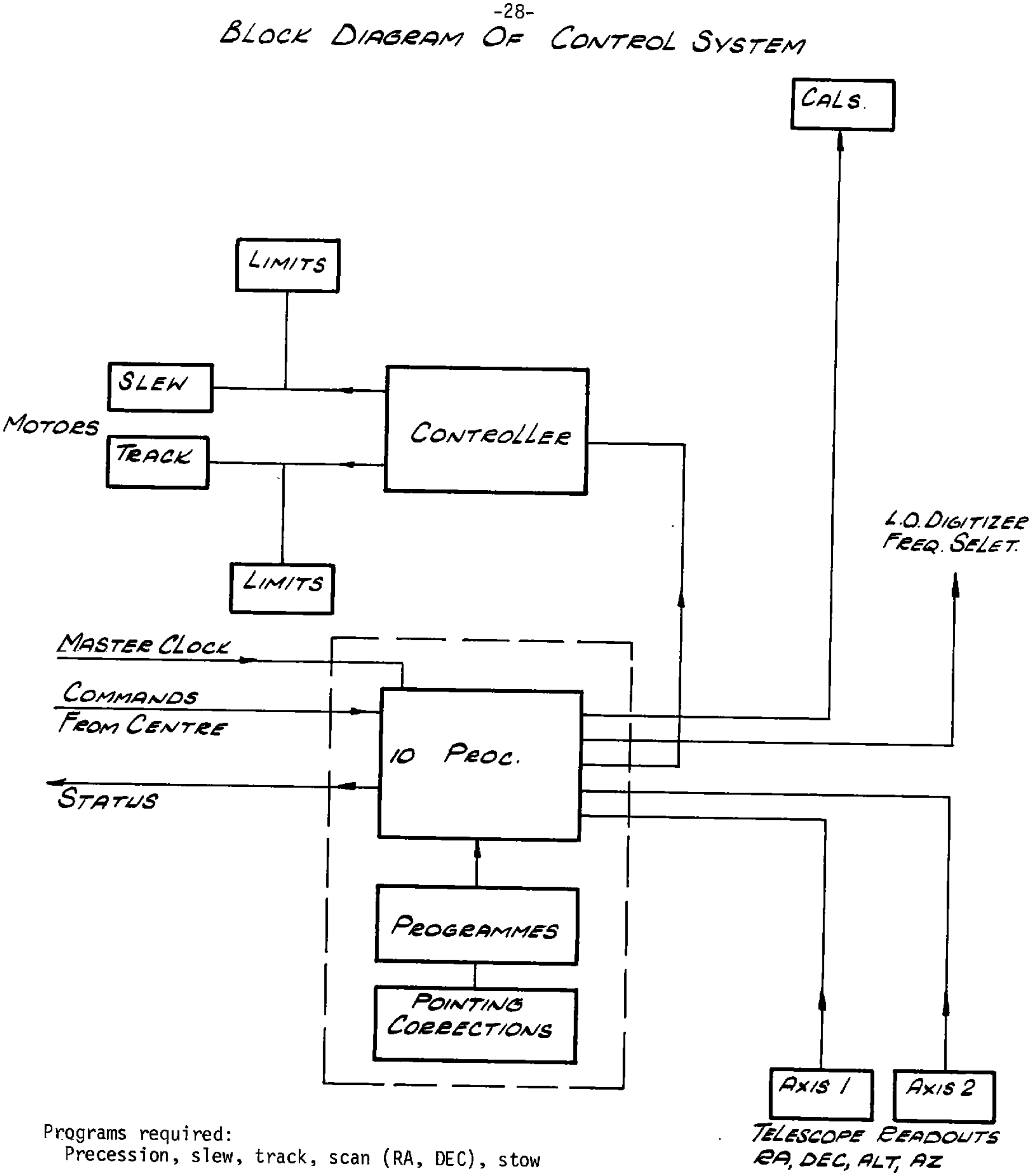
Note: These could be multiplexed and could go onto one of the optical fibres.

(iii) Hard wired crash control

(iv) TV monitor for remote sites?

(v) IF) optical
Local oscillator) fibres

(vi) Intercom

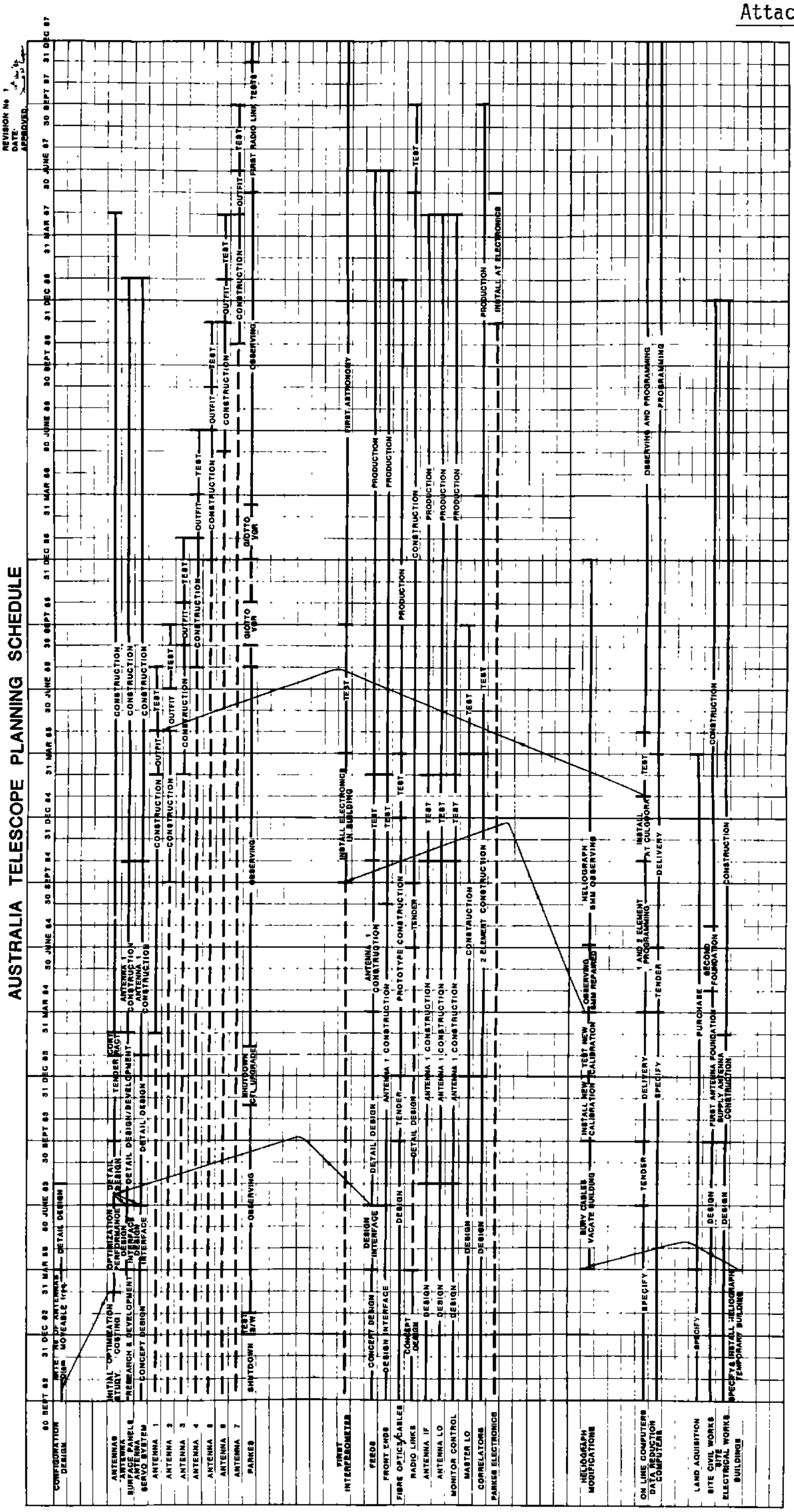


Programs required:
Precession, slew, track, scan (RA, DEC), stow

All units inside dashed box could be at centre.

Figure 9.1

Attachment 1



An uncompensated accuracy of $2x10^{-9}$ could only be achieved then with a temperature stability of about 0.01°c. Clearly active compensation is needed for the example chosen. (However if the requirements are less severe in terms of baseline and operating frequency, a simple system could suffice).

Practical experience in the compensation of optical fibre links has been obtained [3] at Jet Propulsion Laboratories. A 3 km multimode fibre of bandwidth 1.5 GHz.km and loss 3db per km has been in use at 850 nm. One interesting observation was of (excessively large) non-reciprocal delay changes on bending this multimode fibre. Such effects are absent from single mode fibre which also has a wider bandwidth and losses below 1db per km.

An 8 km single mode link at 1300 nm is undergoing installation with goals of 30 km links and 400 MHz bandwidth. The lower loss of single mode fibre produces better signal to noise ratio and hence more accurate compensation.

The cables are simply ploughed into the ground to a depth of 1.5 m at which depth a 1°C diurnal temperature variation is expected with short sections subject to step changes in temperature of perhaps 10°C.

In confirmation of the results above, the temperature coefficient of phase (α) for a loosely jacketed fibre was found to be 7 ppm or approximately 10^{-5}/°C.

Regular diurnal variations of temperature can be modelled to improve the stability but active phase correction systems will usually be needed. One such optical system is illustrated [3] in Figure 1. The signal is sent out and then, by directional couplers, is returned. One transmits sin $(wt+\zeta)$ such that the returned signal is $\sin(wt-\zeta)$. The signal at the far end must then simply be $\sin(wt)$. The accuracy of correction depends on temperature changes in fibre source and detector as well as signal-to-noise of the receiver and integration time.

It is necessary to convert the JPL frequency stability results to the radio interferometry application. JPL reports stabilities as the rms deviation σ between successive assessments of frequency from the fibre taken over some sampling interval τ.

Their results show that present state of the multimode fibre link with stabilisation gives $\sigma = 5x10^{-13}$ divided by the interval time in seconds. This is valid over intervals up to several hours. Changing to an improved single mode system at JPL is projected to give a $\Delta f/f$ of about 50 times better than the multimode system over intervals up to an hour. Beyond this the σ stabilizes at an expected limit of about 10^{-17} independent of sample time.

In terms of phase stability, one takes the mean phase departure in an interval to be half the difference between the

phases at beginning and end of the interval.

So $\sigma = 5x10^{-13}$ over one second implies

$$\Delta\phi = 5x10^{-13} \times 1 \times 4x10^{10} \times 360 \times \tfrac{1}{2}$$

$$= 3.6 \text{ degrees at } 40 \text{ GHz}$$

That is, the multimode system could compensate to a length accuracy of 75 microns. If one wished to achieve the full compensation to within 20 microns it may well be necessary to use a single mode fibre link.

Remembering the basic temperature variation of about 10^{-5}/°C the phase calibration system would need to be capable of an improvement factor of 10^{3}. In such a system the result is achieved by very careful attention to phase stabilities of laser sources and photodetectors. The fibre is only one of the components of the system. Nevertheless fibre systems can satisfy the requirements for radio interferometer timing disseminations.

Experimental work at the University of Sydney centres around a kilometre of single mode fibre for operation at 1.3μm. Although sources and detectors at 1.3μm are still to be bought some stabilization work on systems at 0.83 μm has proceeded. The two aims of the experimentation are phase stability and very wideband operation. The work is sponsored by the Sydney County Council.

References

1. N. Lagakos, J.A. Bucaro and J. Jarzynski, "Temperature-induced Optical Phase Shifts in Fibers" (sic), Applied Optics, vol.20, No.13, pp.2305-2308, 1981

2. N. Lagakos and J.A. Bucaro, "Minimizing Temperature Sensitivity of Optical Fibers" (sic), Applied Optics, vol.20, No.19, pp.3276-3278, 1981

3. G. Lutes, "Development of Optical Fiber (sic) Frequency and Time Distribution Systems", Proceedings of the 13th Annual Precise Time and Time Interval (PTTI) Application and Planning Meeting, pp.243-262, December, 1981

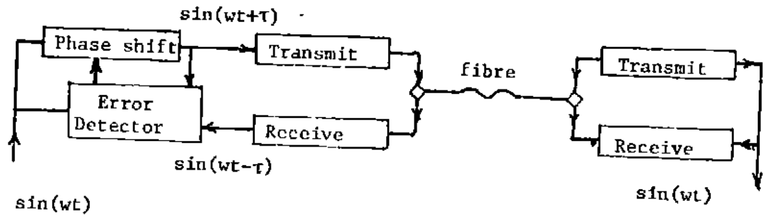


Figure 1. Phase compensation by two-way transmission in the fibre [3]

Attachment 3

PROCEEDINGS OF THE 13th ANNUAL PRECISE TIME AND TIME INTERNAL (PTTI) APPLICATIONS AND PLANNING MEETING, DECEMBER 1981

DEVELOPMENT OF OPTICAL FIBER FREQUENCY AND TIME DISTRIBUTION SYSTEMS*

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ABSTRACT

The Jet Propulsion Laboratory is engaged in the development of ultra stable optical fiber distribution systems for the dissemination of frequency and timing references. The ultimate design goals for these systems are a frequency stability of 10^{-17} for $\tau \geq 100$ sec and time stability of ±0.1 ns for 1 year and operation over distances ≥30 km. This paper will review last years report, describe a prototype system being implemented and discuss progress made in the past year.

INTRODUCTION

Preliminary work on an optical fiber reference frequency distribution system was reported at last year's PTTI conference. This paper is a progress report on this effort and will begin with a brief review, followed by a description of the prototype system and progress made in the last year.

REVIEW

It was reported at last year's PTTI conference that a 3-km experimental multimode optical fiber link operating at 850 nm wavelength was installed at JPL. It was to be used in the development of ultra-stable frequency and timing distribution systems.

The link was stabilized using the conjugation method, reference 1, and achieved a stability of 4×10^{-15} for $\tau = 100$ seconds.

Several problems with this link were reported. The stability was limited by the optical transmitters and receivers. Delay changes as a result of bending multimode fibers are nonreciprocal under some circumstances, and excessively large. This precludes their use for frequency

*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

and the reference distribution in non-stationary environments. The minimum loss in optical fibers operating at 850 nm wavelength is about 3 dB/km, which is too large to achieve a 30 km operating distance. The bandwidth of currently available multimode fibers, about 1.5 GHz-km, is not adequate for this use over these distances.

It was concluded in last year's report that, although the results obtained were encouraging, there was still a lot of work to be done.

PROTOTYPE SYSTEM

A prototype system, 8 km in length, will be installed between two stations in the Deep Space Communications Complex (DSCC) at Goldstone, California. It will be a single-mode fiber system and will operate at 1300 nm wavelength. The conjugation type of stabilization that will be used in this system will be an improved version of the one used in the experimental system reported last year.

The goal for frequency stability for distances up to 30 km is shown in Figure 1. With this stability the distribution system will not excessively degrade the stability of future frequency references having a stability of up to 10^{-17} for $\tau = 100$ seconds.

The time distribution stability goal is ±0.1ns for 1 year. This goal has not yet been addressed in detail because it can probably be met with minor additions to the frequency distribution system. In any case, most of the problems will have been resolved in the implementation of the more difficult frequency distribution system.

Another goal, not directly related to frequency and timing distribution, is the capability to distribute 400 MHz bandwidth IF signals over 20 km. This goal will be met as a consequence of the frequency and timing distribution work.

These goals can be approached using single-mode optical fibers operating at 1300 nm wavelength. The delay through such fibers is affected very little by bending and the modulation bandwidth is much wider than that of multimode fibers. Also, 1300 nm is near the wavelength which gives minimum dispersion (equivalent to the widest bandwidth) and lowest loss (≤1 dB/km).

A block diagram of the system is shown in Figure 2. In this system, a signal is sent to the far end of the cable where it is turned around and returned to the near end. The transmitted signal, $\sin(\omega t + \tau)$, is forced by the control circuit to be the conjugate of the return signal, $\sin(\omega t - \tau)$. Since the forward and return paths have equal delays - being the same path - the phase at the far end of the cable is halfway between the transmitted phase and the return phase or ωt. The phase of

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University of NSW, Sch. Electrical Engineering and
Computer Sci. 8-9 December 1982.

WIDEBAND SINGLE-MODE FIBRELINKS WITH PHASE STABILITY

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Laboratory for Imaging Science and Engineering
School of Electrical Engineering
University of Sydney

Accurate time dissemination is important in a number of applications. One of the most challenging is radio interferometry in which the time of arrival of a wavefront at each of two antennas needs to be measured to high accuracy. One technique is to use separate clocks at each station (Very Long Baseline Interferometry) compared by clock transport and radio observational techniques. This paper concentrates on the alternative process of using one clock whose timing information is transmitted by cable to the two antennas.

The magnitude of the problem can be summarized as perhaps requiring 1^o of phase accuracy at an observing frequency of 40 GHz (wavelength = 7.5 mm) over an antenna separation of 10 kilometres. This accuracy would be required for each several second integration over a total observing session of 12 hours. Such a performance is necessary for a map to have an accuracy range of intensity of several thousand to one.

In terms of phase ϕ, one sees that the requirement translates to a relative accuracy of

$$\frac{\Delta\phi}{\phi} = \left(\frac{10\text{x}10^6}{7.5} \text{ x } 360\right)^{-1} = 2\text{x}10^{-9}$$

or alternatively, to within $\lambda/360$ or 20 microns. Current practice uses coaxial cable and a frequency of several hundred megahertz. At the antenna, frequency multiplication and phase locking are used to reach the desired local oscillator frequency.

In several systems (at Cambridge for example) simple burial of the cable gives sufficient stability when appropriate "zero-coefficient" cables are used. Further stability in a Japanese antenna system is obtained by controlling the gas pressure inside the cable as the temperature changes in an already controlled environment. However in most cases it is accepted that the temperature cannot be controlled to a sufficient degree and active phase calibration and compensation schemes have been employed. These take various forms but all rely on a two way transmission along the cable.

Several factors make optical fibres a more attractive technique for accurate time dissemination. These include large

ATTACHMENT 2.

bandwidth, low loss, low cost, simplicity of installation and immunity to interference. The relative unknown is the phase stability which, on first look, could be good due to the low thermal expansion coefficient of silica. The full story is more complicated.

The phase shift produced in fibres by a temperature change has been studied by a number of authors, [1,2,3].

Using the nomenclature of Lagakos, if $k = 2\pi/\lambda$ (for λ the vacuum wavelength), the phase length of a length ℓ of fibre of refractive index n is

$$\frac{\Delta\phi}{\phi} = \frac{\Delta\ell}{\ell} + \frac{\Delta n}{n} = \varepsilon_z + \frac{1}{n}\left(\frac{\partial n}{\partial T}\right)_\rho \Delta T + \left(\frac{\delta n}{n}\right)_T$$

where ε_z is the axial strain in the core due to length changes, ρ is core density and we see the refractive index effects split into components at constant density and at constant temperature.

Further expansion gives the fractional phase change per degree as

$$\frac{\Delta\phi}{\phi\Delta T} = \frac{1}{n}\frac{\partial n}{\partial T}_\rho + \frac{1}{\Delta T}\left(\varepsilon_z - \frac{n^2}{2}[(P_{11}+P_{12})\varepsilon_r + P_{12}\,\varepsilon_z]\right)$$

where P_{11} and P_{12} are Pockels coefficients in the core and ε_r is the radial strain in the fibre.

Analysis to determine the strains depends on the dimensions and composition of core, cladding, substrate, buffer material and the fibre jacket. Lagakos et al report [1] on two ITT single mode fibres (one bare and one coated) with silica core, silca + 5% B_2O_3 cladding and silica substrate. The jacketed fibre had silicone buffer and a polyester jacket. The results were

$\frac{\Delta\phi}{\phi\Delta_T}$ for	experiment	calculation
bare fibre	$0.68\text{x}10^{-5}/^oc$	$0.70\text{x}10^{-5}/^oc$
jacketed fibre	$1.80\text{x}10^{-5}/^oc$	$1.64\text{x}10^{-5}/^oc$

The low expansion coefficient of silica makes the $(\frac{\partial n}{\partial T})_\rho$ term dominant for the bare fibre. In the jacketed fibre the major effect is the length change followed by temperature changes of refractive index. The photoelastic effects are not insignificant. In general, a tight jacket worsens the performance due to its larger expansion coefficient.

Although study [2] indicates that better fibre compositions could be chosen and that a hypothetical fibre could be built with zero phase changes, the best suggestion was the use of Nd-laser glass core and a calculated phase sensitivity of $0.13\text{x}10^{-5}/^oc$.

the input reference is also ωt, therefore the phase at the output is the same as the phase at the input.

In Figure 3 the calculated signal-to-noise ratio (S/N) (reference 2) for such a system is shown as a function of the loss in the cable. An operating frequency of 100 MHz and a bandwidth of 10 Hz are assumed. The calculations are supported by measurements made on the 3-km experimental link. The difference between single-mode and multimode fibers is due to greater signal loss in multimode fibers caused by dispersion.

The cable connecting the two stations will contain two single-mode and two multimode optical fibers designed to operate at 1300 nm wavelength. These fibers will be used to develop frequency and timing distribution systems and wideband communications systems. The cable will also contain two multimode optical fibers designed to operate at 850 nm wavelength which will be used for utility communications services between the two stations. The cable will be received in 1- or 2 km lengths and will be plowed into the ground to a depth of 1.5 meters.

The degradation of the stability of a frequency reference signal passing through this cable, without stabilization, has been estimated as follows.

The stability of frequency references is specified at JPL in terms of the square root of the Allan variance (reference 3). The algorithm for computing it is:

$$\sigma = \frac{1}{\sqrt{2}\,\omega_0 \tau} \sqrt{\frac{1}{N}\sum_{n=1}^{N} \left(f_n - f_{n+1}\right)^2}\,, \qquad (1)$$

where:

f_n = average frequency in the interval between t_n and t_{n+1}

f_{n+1} = average frequency in the interval between t_{n+1} and t_{n+2}

t_n = the n^{th} sampling time

τ = the interval between samples,

ω_0 = the nominal angular frequency and,

N = the number of samples of $\left(f_n - f_{n+1}\right)$.

Only the degradation caused by ambient temperature variations will be considered since this is the predominate source of instability. We consider first sinusoidal variations in temperature and then a step change in temperature.

Assume that a perfectly stable reference frequency is disseminated over a long single-mode optical fiber cable which is buried in the ground. Also assume that the cable is buried deeply enough that the diurnal change in temperature is essentially sinusoidal.

At time (t) the varying component of temperature (T) of the cable is,

$$T = T_p \sin \omega t \qquad (2)$$

where

T_p = the peak temperature variation,

P = the period of one cycle of the temperature variation and

$\omega = \frac{2\pi}{P}$ = the frequency of the temperature variation.

The delay (β) in radians through the transmission line as a function of temperature is,

$$\beta = \frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T}{v} \qquad (3)$$

where

$\frac{\omega_0 \ell}{v}$ = the delay at the mean temperature in radians,

ω_0 = the nominal angular frequency of the disseminated signal,

ℓ = the length of the line in meters,

v = the velocity of propagation in the line ($\approx 2.1 \times 10^8$ m/s for optical fiber) and,

α = the cable's temperature coefficient of delay ($\approx 10^{-5}/°C$).

The phase (β) as a function of time (t) is from (2) and (3),

$$\beta = \frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_P}{v} \sin \omega t. \qquad (4)$$

The average frequency (f) over a time interval (τ) is the total phase accumulated (β_A) during the time interval divided by the time interval (τ),

$$f = \frac{\beta_A}{\tau} \qquad (5)$$

Therefore from (4) and (5), the average frequency (f_n) in the interval (t_n, $t_n+\tau$) is

$$f_n = \left[\frac{\beta(t)}{\tau}\right]_{t_n}^{t_n+\tau} = \frac{1}{\tau}\left[\frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_P}{v} \sin \omega t\right]_{t_n}^{t_n+\tau} \qquad (6)$$

and the average frequency (f_{n+1}) in the next interval ($t_n+\tau$, $t_n+2\tau$) is,

$$f_{n+1} = \left[\frac{\beta(t)}{\tau}\right]_{t_n+\tau}^{t_n+2\tau} = \frac{1}{\tau}\left[\frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_P}{v} \sin \omega t\right]_{t_n+\tau}^{t_n+2\tau}. \qquad (7)$$

The absolute value of the difference between these average frequencies is from (6) and (7),

$$\left| f_n - f_{n+1} \right| = \left| \frac{\omega_0 \ell \alpha T_P}{v\tau} \left[2 \sin \omega \left(t_n+\tau\right) - \sin \omega t_n - \sin \omega \left(t_n+2\tau\right) \right] \right|$$

$$= \left| \frac{4\omega_0 \ell \alpha T_P}{v\tau} \left[\sin^2 \omega \frac{\tau}{2} \sin \omega \left(t_n+\tau\right) \right] \right|. \qquad (8)$$

Then, from (1) and (8), the square root of the Allan variance of a signal passing through a transmission line having a sinusoidal variation in delay becomes,

$$\sigma = \frac{4 \ell \alpha T_P}{\sqrt{2}\tau v} \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left[\sin^2 \omega \frac{\tau}{2} \sin \omega \left(t_n+\tau\right) \right]^2}. \qquad (9)$$

This equation is evaluated in Figure 4, for values of τ from 1 second to 10^6 seconds and variables $\ell = 10^4$ meters, $\alpha = 10^{-5}/°C$, $T_P = 1°C$, $v = 2.1 \times 10^8$ meters per second and $\omega = 2\pi/86400$ radians per second (diurnal variation). These are realistic values based on measurements made at JPL and at the Goldstone Deep Space Complex.

Now consider a cable that is subjected to a step change in ambient temperature. The change is assumed to be much faster than the time constant of the cable. The relative temperature (T) of the cable at time (t) is,

$$T = T_S\left(1 - e^{-t/\tau_c}\right) \qquad (10)$$

where

T_S = the step change in ambient temperature,

t = the time elapsed since a step change in ambient temperature and,

τ_c = the time constant of the cable.

The phase (β) as a function of time (t) is from (3) and (10),

$$\beta = \frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_S}{v}\left(1 - e^{-t/\tau_c}\right). \tag{11}$$

Therefore, from (11) and (5), the average frequency (f_n) in the first interval $(t_n, t_n+\tau)$ is,

$$f_n = \left[\frac{\beta(t)}{\tau}\right]_{t_n}^{t_n+\tau} = \frac{1}{\tau}\left[\frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_S}{v}\left(1 - e^{-t/\tau_c}\right)\right]_{t_n}^{t_n+\tau}, \tag{12}$$

and the average frequency (f_{n+1}) in the second interval $(t_n+\tau, t_n+2\tau)$ is,

$$f_{n+1} = \left[\frac{\beta(t)}{\tau}\right]_{t_n+\tau}^{t_n+2\tau} = \frac{1}{\tau}\left[\frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_S}{v}\left(1 - e^{-t/\tau_c}\right)\right]_{t_n+\tau}^{t_n+2\tau}. \tag{13}$$

The absolute value of the difference between the average frequencies (f_n) and (f_{n+1}) is from (12) and (13),

$$\left|f_n - f_{n+1}\right| = \left|\frac{\omega_0 \ell \alpha T_S}{\tau v}\left[2e^{-\frac{t_n+\tau}{\tau_c}} - e^{-\frac{t_n}{\tau_c}} - e^{-\frac{t_n+2\tau}{\tau_c}}\right]\right|$$

$$= \left|\frac{\omega_0 \ell \alpha T_S}{\tau v} e^{-\frac{t_n+\tau}{\tau_c}}\left[2 - e^{-\frac{\tau}{\tau_c}} - e^{\frac{\tau}{\tau_c}}\right]\right| \tag{14}$$

Thus, the algorithm for the square root of the Allan variance of a signal passing through a transmission line having an exponential change in delay becomes from (1) and (14),

$$\sigma = \frac{\ell \alpha T_S}{\sqrt{2}\tau v}\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left[e^{-\frac{t_n+\tau}{\tau_c}}\left\{2 - e^{-\frac{\tau}{\tau_c}} - e^{\frac{\tau}{\tau_c}}\right\}\right]^2} \tag{15}$$

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REFERENCES

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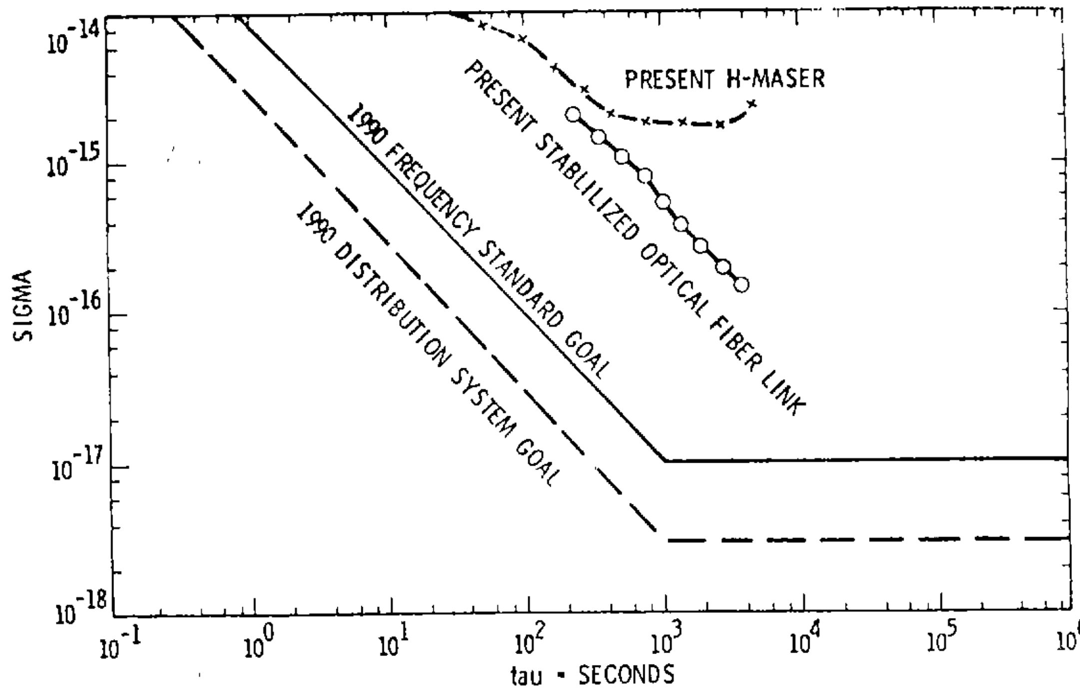

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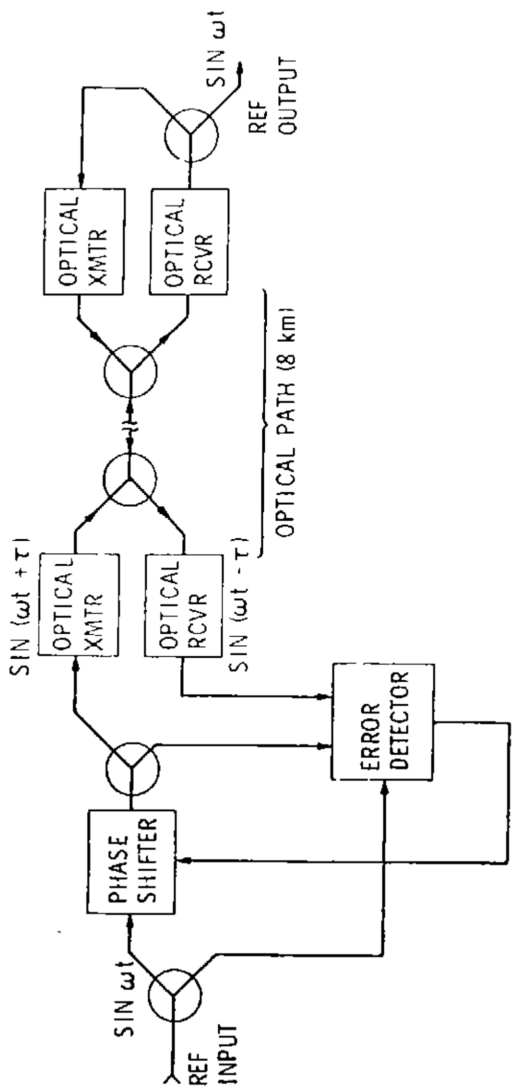

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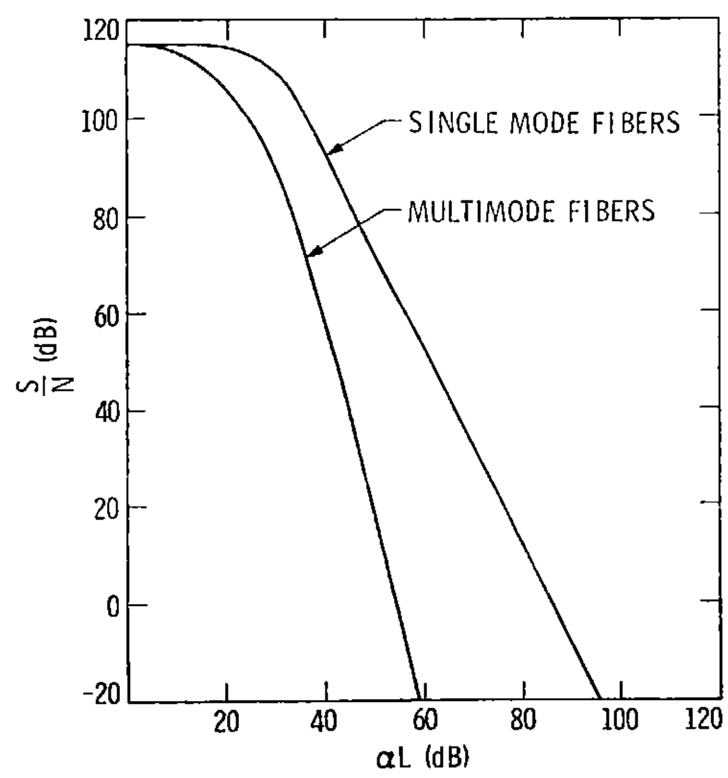

Figure 3. Signal-to-Noise Ratio vs Total Fiber Attenuation (10 Hz Bandwidth) at F_o = 100 MHz

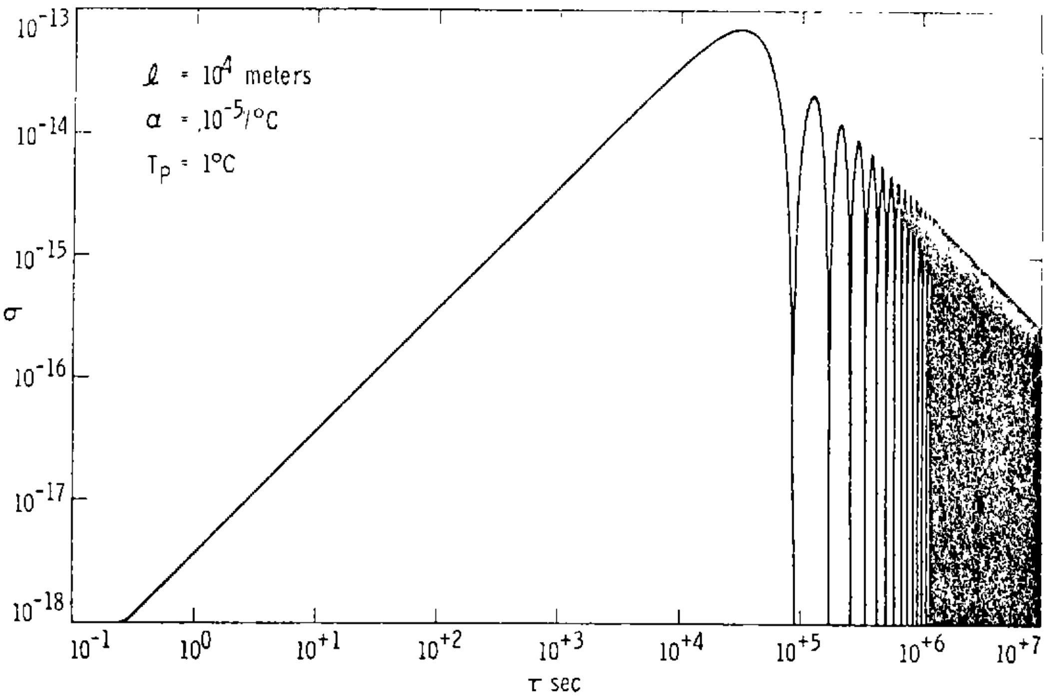

Figure 4. Estimated Frequency Stability vs Sampling Period for an Unstabilized Single Mode Optical Fiber Link

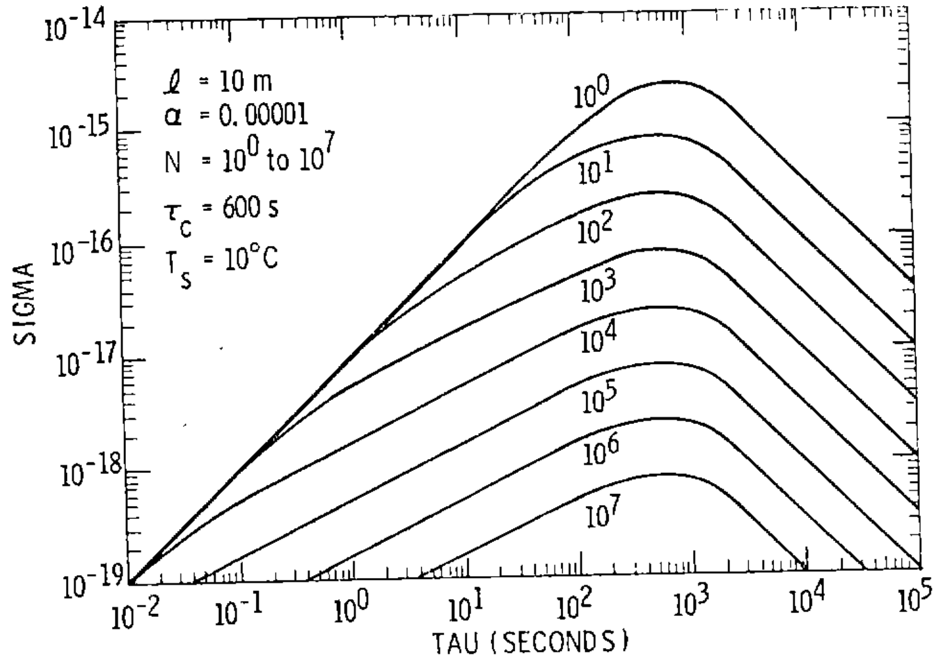

Figure 5. Stability as Affected by a Step Change in Temperature on a Cable

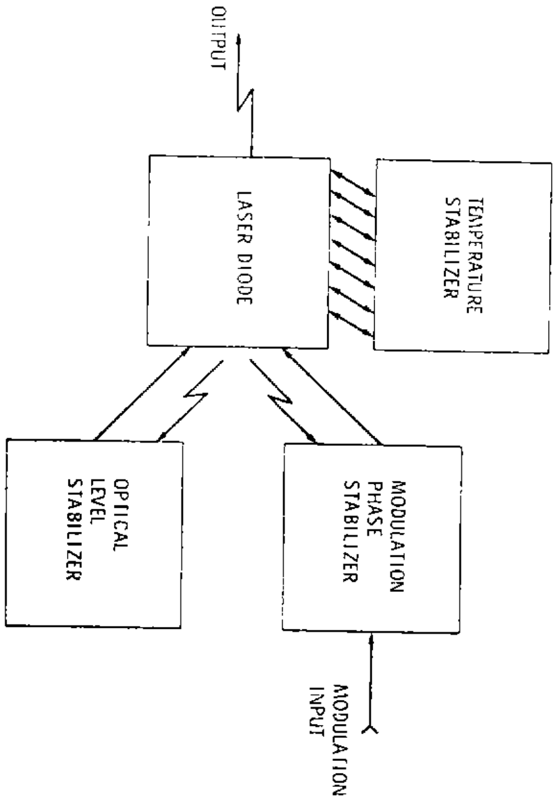

Figure 6. Block Diagram of the Laser Transmitter

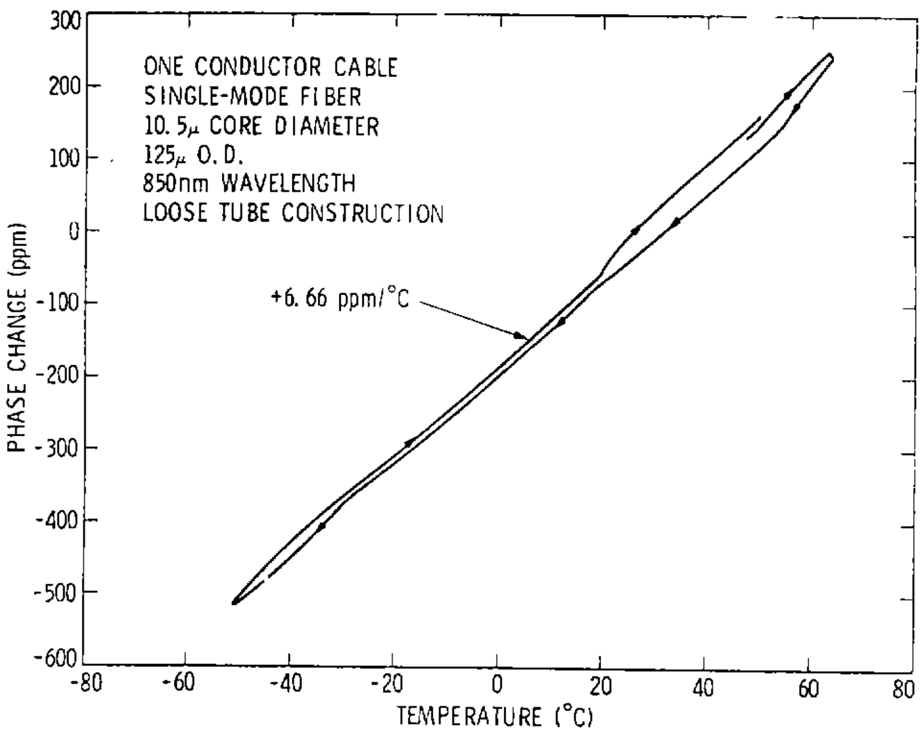

Figure 7. Phase Delay vs Temperature of a Single Mode Optical Fiber Cable

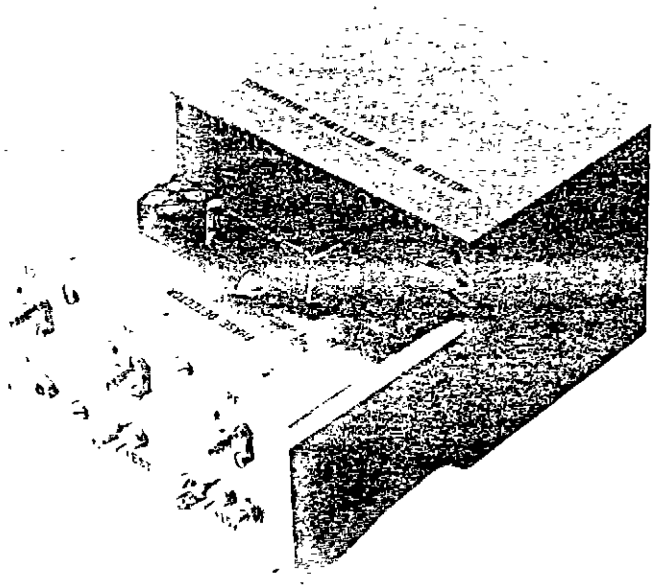

Figure 8. The Temperature Stabilized Phase Detector with the Insulation Removed

QUESTIONS AND ANSWERS

MR. JIM KEMPARO, Aerospace Corporation

How concerned are you with spectral aging of the laser diode?

MR. LUTES:

Well, we're very concerned. We hope eventually to be able to put the diode in an inert environment and cool it below room temperature to protect it, and we believe that will greatly extend the life. Hopefully, it will extend it enough that we don't have a problem with that if we have a regular maintenance program.

MR. LAUREN RUEGER, JHU/APL

Are you doing anything to compensate for frequency dispersion over the large bandwidths you are trying to transmit on this fiber optic?

MR. LUTES:

The dispersion of the cable that we're buying, single mode fiber in the cable is such that we're hoping to get one gigahertz bandwidth to go over the eight kilometer distance. Of course, bandwidths as great as 30 to 35 gigahertz kilometer have been reported.

Nobody really knows how to measure that yet without having a long cable; so, we have a problem in that area, but I don't think it is going to be a problem at the levels that we're looking at.

DR. FRED WALLS, NBS

What's the level of sensitivity of your precision phase detector?

MR. LUTES:

I don't know off hand. It's a high-level Schottky Diode mixer.

DR. WALLS:

Sure. But if the amplitude of the signal changes by a couple of dB, how many picoseconds does that cost you?

MR. LUTES:

I don't know. I don't have those numbers.

DR. WALLS:

Thank you.

JET PROPULSION LAB
TO USE SIECOR CABLE

Hickory, North Carolina—The California Institute of Technology's Jet Propulsion Laboratory recently awarded Siecor Optical Cable a contract for eight kilometers of 6-fiber optical cable. Each cable will contain two single mode fibers, two 1000 MHz fibers and two commercial grade fibers. The cables will be installed at NASA's Deep Space Communication Complex as part of a program to evaluate fiber optics in standard frequency distribution systems. Siecor's loose tube construction will be used to manufacture ultra-stable performance cables for a wide range of conditions.

IFOC, April 1982

PROCEEDINGS OF THE 13th ANNUAL PRECISE TIME AND TIME INTERNAL (PTTI) APPLICATIONS AND PLANNING MEETING, DECEMBER 1981

DEVELOPMENT OF OPTICAL FIBER FREQUENCY AND TIME DISTRIBUTION SYSTEMS*

George Lutes
Jet Propulsion Laboratory, Pasadena, California

ABSTRACT

The Jet Propulsion Laboratory is engaged in the development of ultra stable optical fiber distribution systems for the dissemination of frequency and timing references. The ultimate design goals for these systems are a frequency stability of 10^{-17} for $\tau \geq 100$ sec and time stability of ±0.1 ns for 1 year and operation over distances ≥30 km. This paper will review last years report, describe a prototype system being implemented and discuss progress made in the past year.

INTRODUCTION

Preliminary work on an optical fiber reference frequency distribution system was reported at last year's PTTI conference. This paper is a progress report on this effort and will begin with a brief review, followed by a description of the prototype system and progress made in the last year.

REVIEW

It was reported at last year's PTTI conference that a 3-km experimental multimode optical fiber link operating at 850 nm wavelength was installed at JPL. It was to be used in the development of ultra-stable frequency and timing distribution systems.

The link was stabilized using the conjugation method, reference 1, and achieved a stability of 4×10^{-15} for $\tau = 100$ seconds.

Several problems with this link were reported. The stability was limited by the optical transmitters and receivers. Delay changes as a result of bending multimode fibers are nonreciprocal under some circumstances, and excessively large. This precludes their use for frequency

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*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

and time reference distribution in non-stationary environments. The minimum loss in optical fibers operating at 850 nm wavelength is about 3 dB/km, which is too large to achieve a 30 km operating distance. The bandwidth of currently available multimode fibers, about 1.5 GHz-km, is not adequate for this use over these distances.

It was concluded in last year's report that, although the results obtained were encouraging, there was still a lot of work to be done.

PROTOTYPE SYSTEM

A prototype system, 8 km in length, will be installed between two stations in the Deep Space Communications Complex (DSCC) at Goldstone, California. It will be a single-mode fiber system and will operate at 1300 nm wavelength. The conjugation type of stabilization that will be used in this system will be an improved version of the one used in the experimental system reported last year.

The goal for frequency stability for distances up to 30 km is shown in Figure 1. With this stability the distribution system will not excessively degrade the stability of future frequency references having a stability of up to 10^{-17} for τ = 100 seconds.

The time distribution stability goal is ±0.1ns for 1 year. This goal has not yet been addressed in detail because it can probably be met with minor additions to the frequency distribution system. In any case, most of the problems will have been resolved in the implementation of the more difficult frequency distribution system.

Another goal, not directly related to frequency and timing distribution, is the capability to distribute 400 MHz bandwidth IF signals over 20 km. This goal will be met as a consequence of the frequency and timing distribution work.

These goals can be approached using single-mode optical fibers operating at 1300 nm wavelength. The delay through such fibers is affected very little by bending and the modulation bandwidth is much wider than that of multimode fibers. Also, 1300 nm is near the wavelength which gives minimum dispersion (equivalent to the widest bandwidth) and lowest loss (≤1 dB/km).

A block diagram of the system is shown in Figure 2. In this system, a signal is sent to the far end of the cable where it is turned around and returned to the near end. The transmitted signal, sin ($\omega t + \tau$), is forced by the control circuit to be the conjugate of the return signal, sin ($\omega t - \tau$). Since the forward and return paths have equal delays - being the same path - the phase at the far end of the cable is halfway between the transmitted phase and the return phase or ωt. The phase of the input reference is also ωt, therefore the phase at the output is the same as the phase at the input.

In Figure 3 the calculated signal-to-noise ratio (S/N) (reference 2) for such a system is shown as a function of the loss in the cable. An operating frequency of 100 MHz and a bandwidth of 10 Hz are assumed. The calculations are supported by measurements made on the 3-km experimental link. The difference between single-mode and multimode fibers is due to greater signal loss in multimode fibers caused by dispersion.

The cable connecting the two stations will contain two single-mode and two multimode optical fibers designed to operate at 1300 nm wavelength. These fibers will be used to develop frequency and timing distribution systems and wideband communications systems. The cable will also contain two multimode optical fibers designed to operate at 850 nm wavelength which will be used for utility communications services between the two stations. The cable will be received in 1- or 2 km lengths and will be plowed into the ground to a depth of 1.5 meters.

The degradation of the stability of a frequency reference signal passing through this cable, without stabilization, has been estimated as follows.

The stability of frequency references is specified at JPL in terms of the square root of the Allan variance (reference 3). The algorithm for computing it is:

$$\sigma = \frac{1}{\sqrt{2}\,\omega_0 \tau} \sqrt{\frac{1}{N}\sum_{n=1}^{N} \left(f_n - f_{n+1}\right)^2}\,, \qquad (1)$$

where:

f_n = average frequency in the interval between t_n and t_{n+1}

f_{n+1} = average frequency in the interval between t_{n+1} and t_{n+2}

t_n = the n^{th} sampling time

τ = the interval between samples,

ω_0 = the nominal angular frequency and,

N = the number of samples of $\left(f_n - f_{n+1}\right)$.

Only the degradation caused by ambient temperature variations will be considered since this is the predominate source of instability. We consider first sinusoidal variations in temperature and then a step change in temperature.

Assume that a perfectly stable reference frequency is disseminated over a long single-mode optical fiber cable which is buried in the ground. Also assume that the cable is buried deeply enough that the diurnal change in temperature is essentially sinusoidal.

At time (t) the varying component of temperature (T) of the cable is,

$$T = T_p \sin \omega t \tag{2}$$

where

T_p = the peak temperature variation,

P = the period of one cycle of the temperature variation and

$\omega = \frac{2\pi}{P}$ = the frequency of the temperature variation.

The delay (β) in radians through the transmission line as a function of temperature is,

$$\beta = \frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T}{v} \tag{3}$$

where

$\frac{\omega_0 \ell}{v}$ = the delay at the mean temperature in radians,

ω_0 = the nominal angular frequency of the disseminated signal,

ℓ = the length of the line in meters,

v = the velocity of propagation in the line ($\approx 2.1 \times 10^8$ m/s for optical fiber) and,

α = the cable's temperature coefficient of delay ($\approx 10^{-5}/°C$).

The phase (β) as a function of time (t) is from (2) and (3),

$$\beta = \frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_P}{v} \sin \omega t. \tag{4}$$

The average frequency (f) over a time interval (τ) is the total phase accumulated (β_A) during the time interval divided by the time interval (τ),

$$f = \frac{\beta_A}{\tau} \tag{5}$$

Therefore from (4) and (5), the average frequency (f_n) in the interval (t_n, $t_n+\tau$) is

$$f_n = \left[\frac{\beta(t)}{\tau}\right]_{t_n}^{t_n+\tau} = \frac{1}{\tau}\left[\frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_P}{v} \sin \omega t\right]_{t_n}^{t_n+\tau} \tag{6}$$

and the average frequency (f_{n+1}) in the next interval ($t_n+\tau$, $t_n+2\tau$) is,

$$f_{n+1} = \left[\frac{\beta(t)}{\tau}\right]_{t_n+\tau}^{t_n+2\tau} = \frac{1}{\tau}\left[\frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_P}{v} \sin \omega t\right]_{t_n+\tau}^{t_n+2\tau}. \tag{7}$$

The absolute value of the difference between these average frequencies is from (6) and (7),

$$\left| \quad - f_{n+1} \right| = \left| \frac{\omega_0 \ell \alpha T_P}{v\tau} \left[2 \sin \omega \left(t_n + \tau\right) - \sin \omega t_n - \sin \omega \left(t_n + 2\tau\right) \right] \right|$$

$$= \left| \frac{4\omega_0 \ell \alpha T_P}{v\tau} \left[\sin^2 \omega \frac{\tau}{2} \sin \omega \left(t_n + \tau\right) \right] \right| . \qquad (8)$$

Then, from (1) and (8), the square root of the Allan variance of a signal passing through a transmission line having a sinusoidal variation in delay becomes,

$$\sigma = \frac{4 \ell \alpha T_P}{\sqrt{2} \tau v} \sqrt{ \frac{1}{N} \sum_{n=1}^{N} \left[\sin^2 \omega \frac{\tau}{2} \sin \omega \left(t_n + \tau\right) \right]^2 } . \qquad (9)$$

This equation is evaluated in Figure 4, for values of τ from 1 second to 10^6 seconds and variables $\ell = 10^4$ meters, $\alpha = 10^{-5}/°C$, $T_P = 1°C$, $v = 2.1 \times 10^8$ meters per second and $\omega = 2\pi/86400$ radians per second (diurnal variation). These are realistic values based on measurements made at JPL and at the Goldstone Deep Space Complex.

Now consider a cable that is subjected to a step change in ambient temperature. The change is assumed to be much faster than the time constant of the cable. The relative temperature (T) of the cable at time (t) is,

$$T = T_S \left(1 - e^{-t/\tau_c}\right) \qquad (10)$$

where

T_S = the step change in ambient temperature,

t = the time elapsed since a step change in ambient temperature and,

τ_c = the time constant of the cable.

The phase (β) as a function of time (t) is from (3) and (10),

$$\beta = \frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_S}{v}\left(1 - e^{-t/\tau_c}\right). \tag{11}$$

Therefore, from (11) and (5), the average frequency (f_n) in the first interval (t_n, $t_n+\tau$) is,

$$f_n = \left[\frac{\beta(t)}{\tau}\right]_{t_n}^{t_n+\tau} = \frac{1}{\tau}\left[\frac{\omega_0 \ell}{v} + \frac{\omega_0 \ell \alpha T_S}{v}\left(1 - e^{-t/\tau_c}\right)\right]_{t_n}^{t_n+\tau}, \tag{12}$$

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The absolute value of the difference between the average frequencies (f_n) and (f_{n+1}) is from (12) and (13),

$$\left|f_n - f_{n+1}\right| = \left|\frac{\omega_0 \ell \alpha T_S}{\tau v}\left[2e^{-\frac{t_n+\tau}{\tau_c}} - e^{-\frac{t_n}{\tau_c}} - e^{-\frac{t_n+2\tau}{\tau_c}}\right]\right|$$

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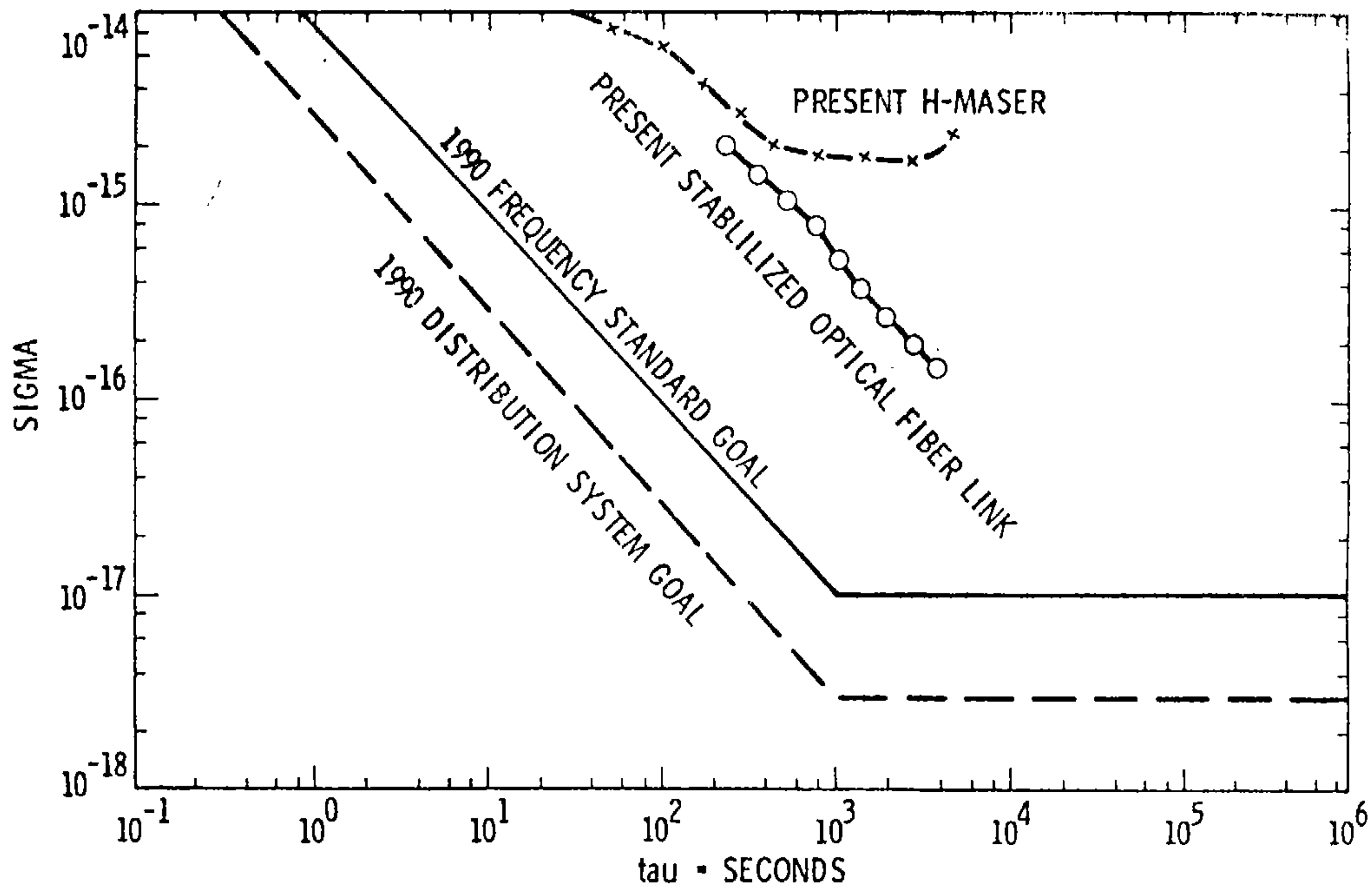

Figure 1. Present State-of-the-Art and Goals

1.5×10^{-16} in 4000 sec at 40 GHz = [illegible] $\times 10^{?}$ × 4000 × 1.5×10^{-16} [illegible] 4.[illegible]°

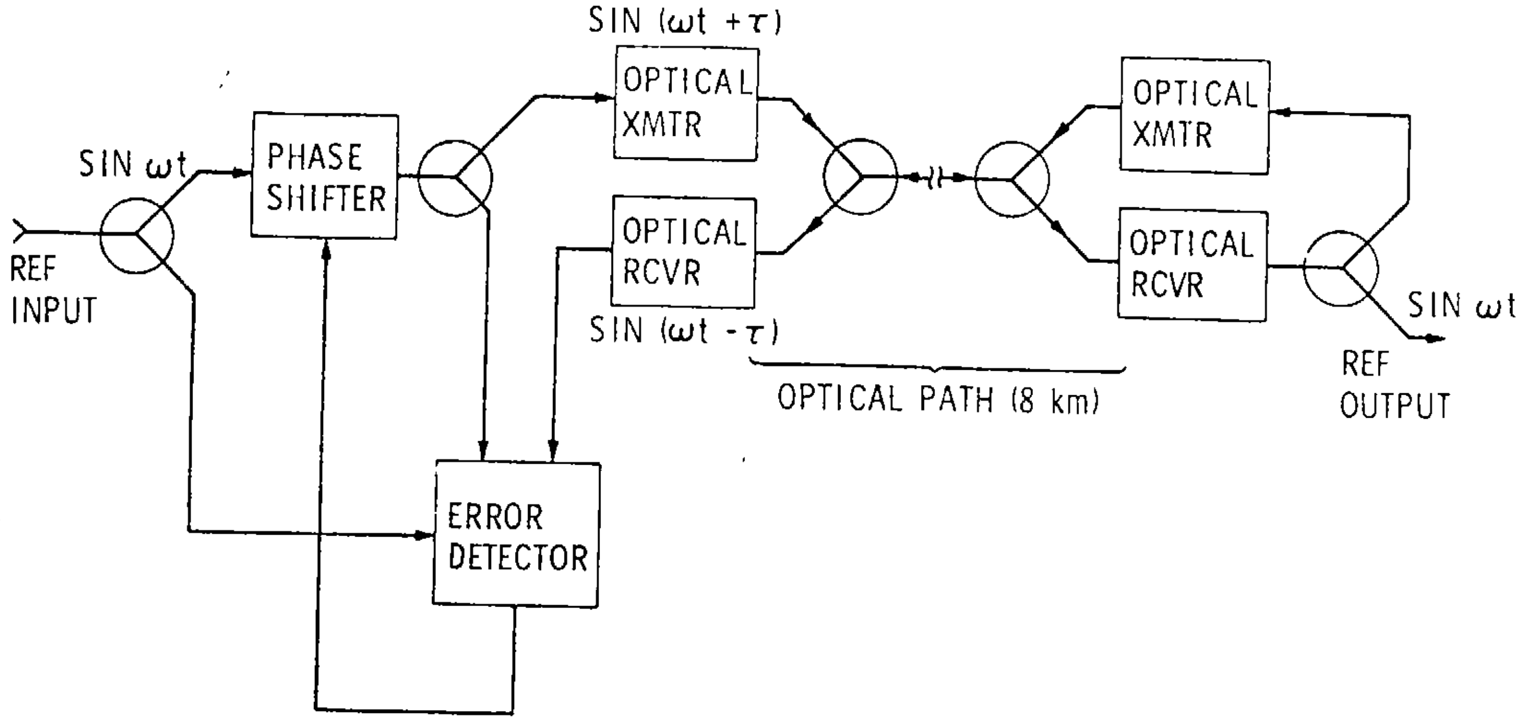

Figure 2. Conjugation Method of Phase Stabilization

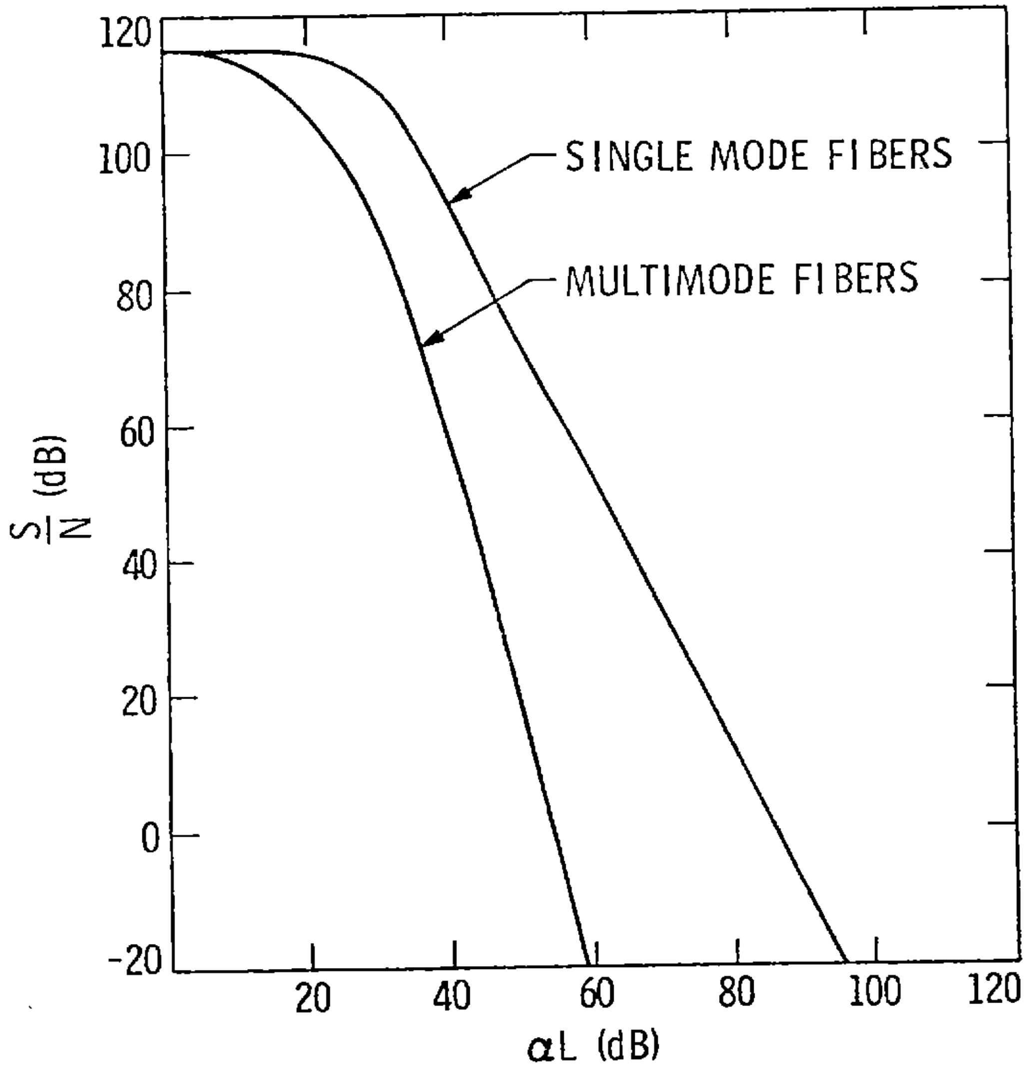

Figure 3. Signal-to-Noise Ratio vs Total Fiber Attenuation (10 Hz Bandwidth) at F_o = 100 MHz

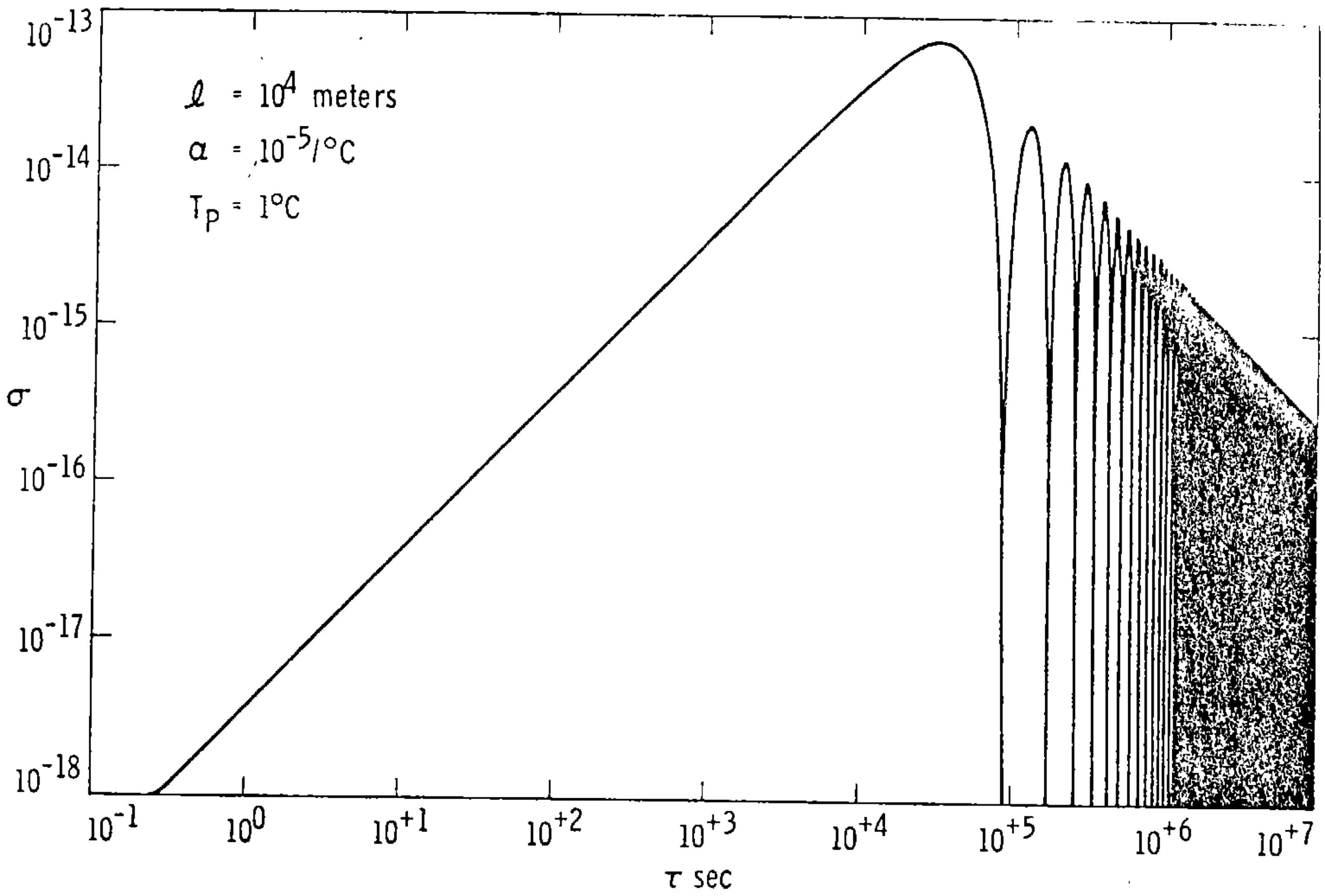

Figure 4. Estimated Frequency Stability vs Sampling Period for an Unstabilized Single Mode Optical Fiber Link

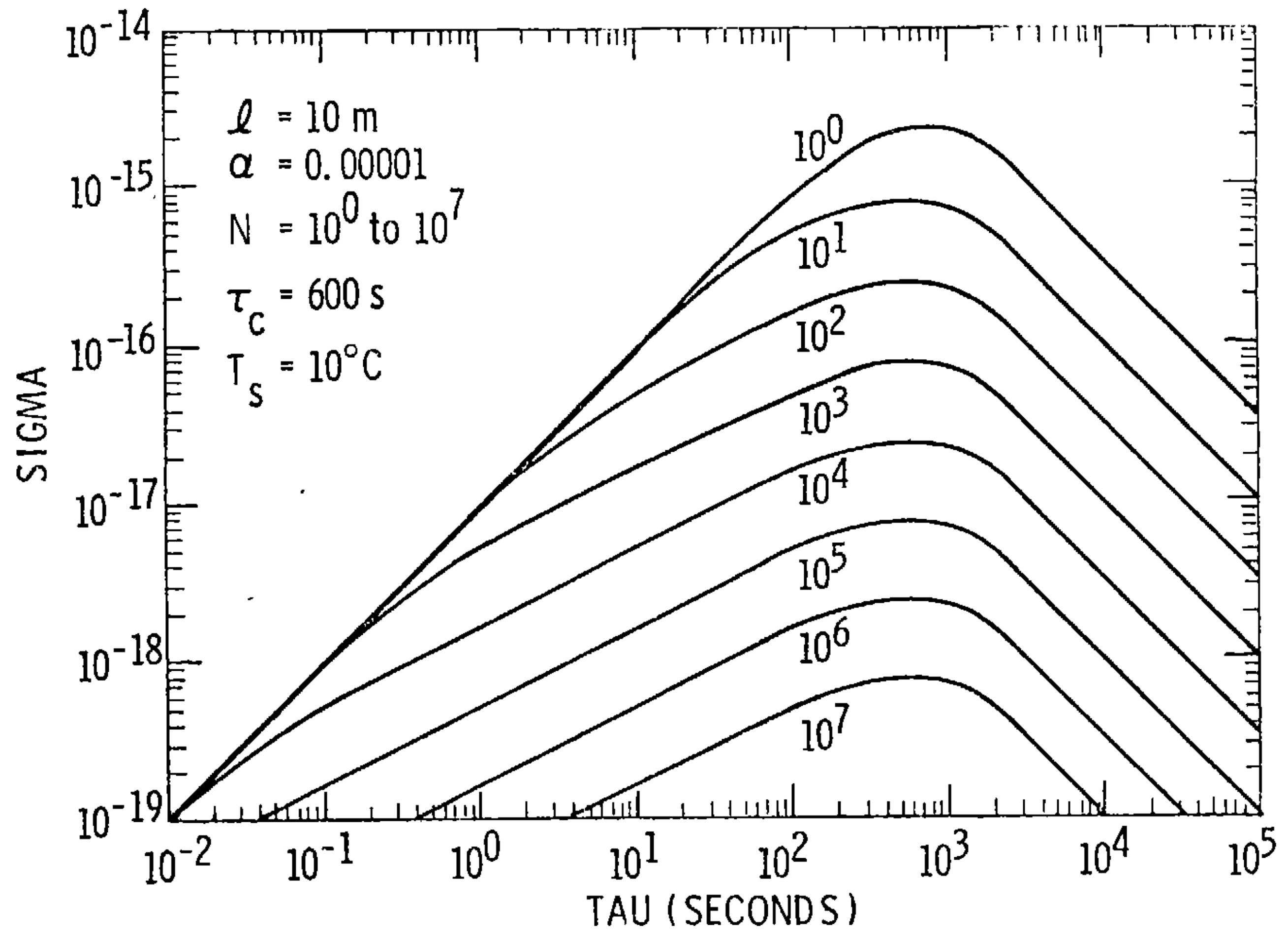

Figure 5. Stability as Affected by a Step Change in Temperature on a Cable

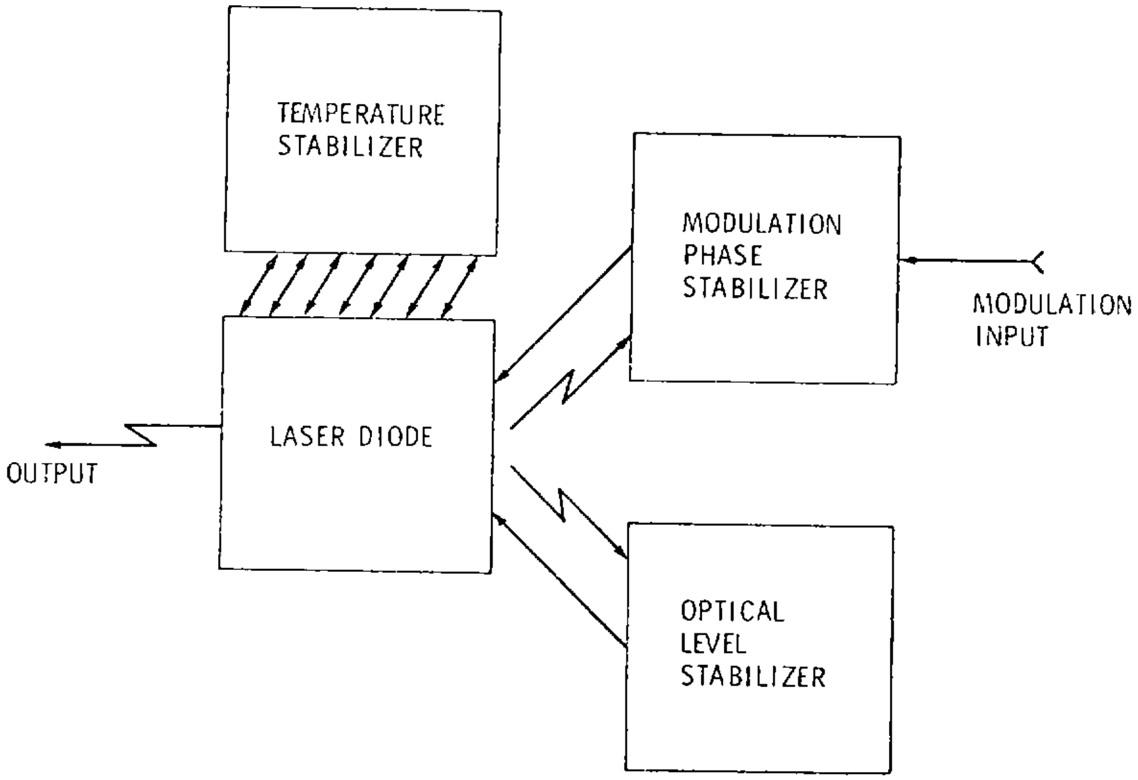

Figure 6. Block Diagram of the Laser Transmitter

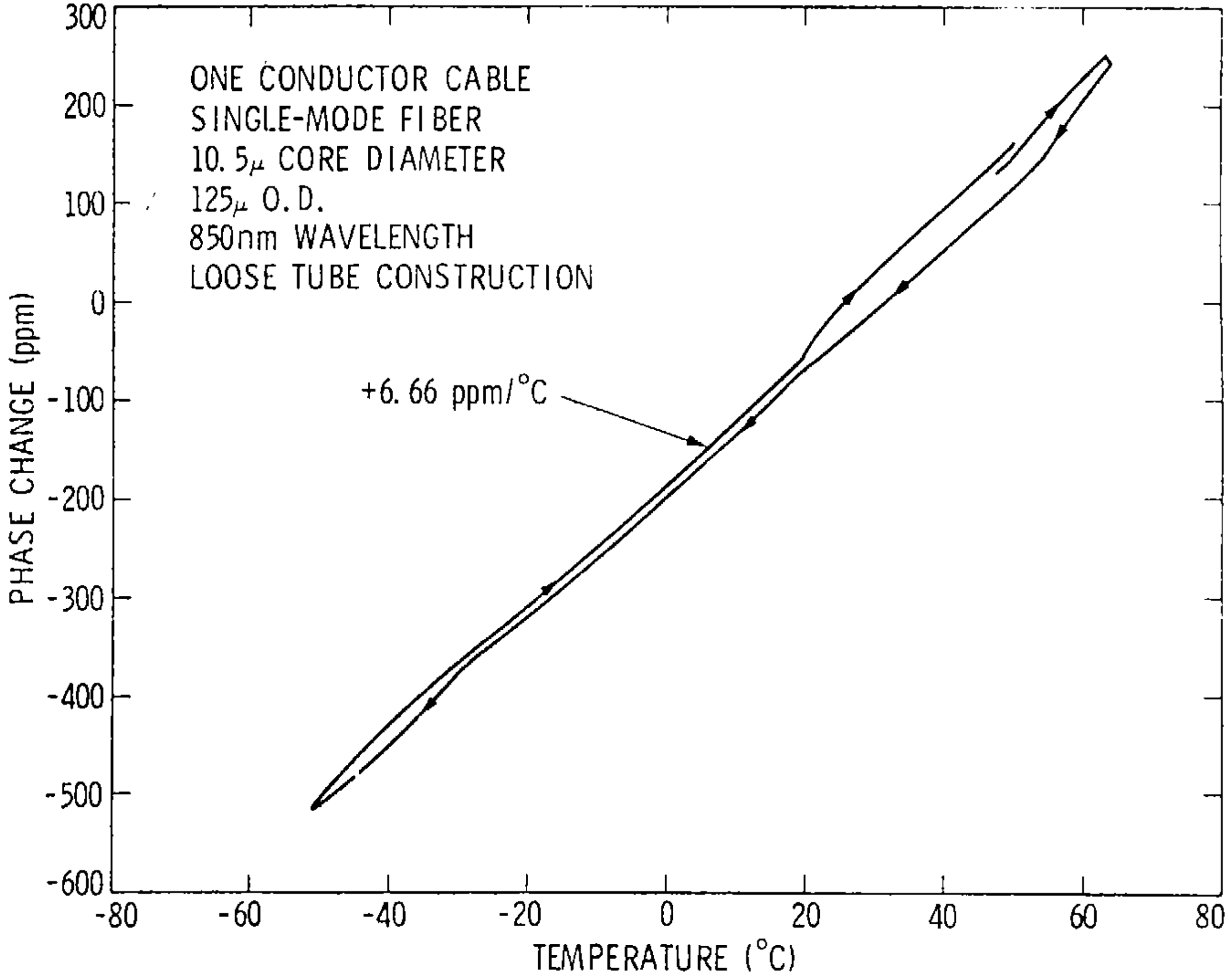

Figure 7. Phase Delay vs Temperature of a Single Mode Optical Fiber Cable

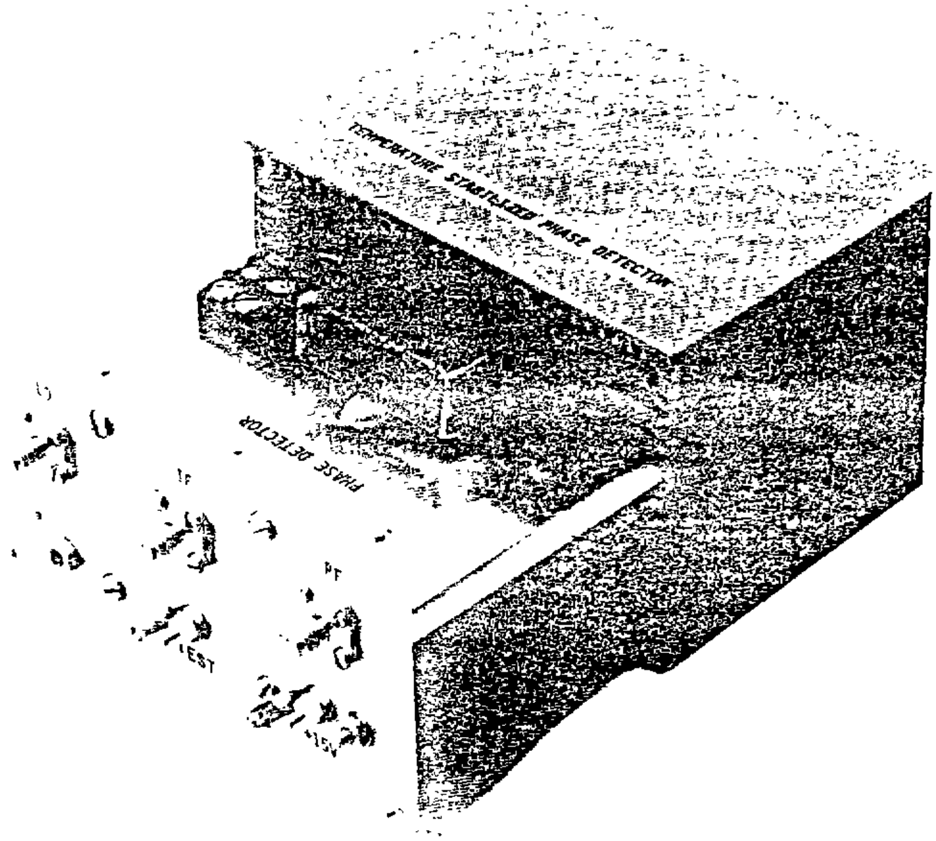

Figure 8. The Temperature Stabilized Phase Detector with the Insulation Removed

QUESTIONS AND ANSWERS

MR. JIM KEMPARO, Aerospace Corporation

How concerned are you with spectral aging of the laser diode?

MR. LUTES:

Well, we're very concerned. We hope eventually to be able to put the diode in an inert environment and cool it below room temperature to protect it, and we believe that will greatly extend the life. Hopefully, it will extend it enough that we don't have a problem with that if we have a regular maintenance program.

MR. LAUREN RUEGER, JHU/APL

Are you doing anything to compensate for frequency dispersion over the large bandwidths you are trying to transmit on this fiber optic?

MR. LUTES:

The dispersion of the cable that we're buying, single mode fiber in the cable is such that we're hoping to get one gigahertz bandwidth to go over the eight kilometer distance. Of course, bandwidths as great as 30 to 35 gigahertz kilometer have been reported.

Nobody really knows how to measure that yet without having a long cable; so, we have a problem in that area, but I don't think it is going to be a problem at the levels that we're looking at.

DR. FRED WALLS, NBS

What's the level of sensitivity of your precision phase detector?

MR. LUTES:

I don't know off hand. It's a high-level Schottky Diode mixer.

DR. WALLS:

Sure. But if the amplitude of the signal changes by a couple of dB, how many picoseconds does that cost you?

MR. LUTES:

I don't know. I don't have those numbers.

DR. WALLS:

Thank you.

Proc. of 7th Aust. W/shop on Optical Communication
University of NSW, Sch. Electrical Engineering and
Computer Sci. 8-9 Dec. 1982.

WIDEBAND SINGLE-MODE FIBRELINKS WITH PHASE STABILITY

TREVOR W. COLE

Laboratory for Imaging Science and Engineering
School of Electrical Engineering
University of Sydney

Accurate time dissemination is important in a number of applications. One of the most challenging is radio interferometry in which the time of arrival of a wavefront at each of two antennas needs to be measured to high accuracy. One technique is to use separate clocks at each station (Very Long Baseline Interferometry) compared by clock transport and radio observational techniques. This paper concentrates on the alternative process of using one clock whose timing information is transmitted by cable to the two antennas.

The magnitude of the problem can be summarized as perhaps requiring 1^{o} of phase accuracy at an observing frequency of 40 GHz (wavelength = 7.5 mm) over an antenna separation of 10 kilometres. This accuracy would be required for each several second integration over a total observing session of 12 hours. Such a performance is necessary for a map to have an accuracy range of intensity of several thousand to one.

In terms of phase ϕ, one sees that the requirement translates to a relative accuracy of

$$\frac{\Delta\phi}{\phi} = \left(\frac{10\text{x}10^6}{7.5} \text{ x } 360\right)^{-1} = 2\text{x}10^{-9}$$

or alternatively, to within $\lambda/360$ or 20 microns.
Current practice uses coaxial cable and a frequency of several hundred megahertz. At the antenna, frequency multiplication and phase locking are used to reach the desired local oscillator frequency.

In several systems (at Cambridge for example) simple burial of the cable gives sufficient stability when appropriate "zero-coefficient" cables are used. Further stability in a Japanese antenna system is obtained by controlling the gas pressure inside the cable as the temperature changes in an already controlled environment. However in most cases it is accepted that the temperature cannot be controlled to a sufficient degree and active phase calibration and compensation schemes have been employed. These take various forms but all rely on a two way transmission along the cable.

Several factors make optical fibres a more attractive technique for accurate time dissemination. These include large bandwidth, low loss, low cost, simplicity of installation and immunity to interference. The relative unknown is the phase stability which, on first look, could be good due to the low thermal expansion coefficient of silica. The full story is more complicated.

The phase shift produced in fibres by a temperature change has been studied by a number of authors, [1,2,3].

Using the nomenclature of Lagakos, if $k = 2\pi/\lambda$ (for λ the vacuum wavelength), the phase length of a length ℓ of fibre of refractive index n is

$$\frac{\Delta\phi}{\phi} = \frac{\Delta\ell}{\ell} + \frac{\Delta n}{n} = \varepsilon_z + \frac{1}{n}\left(\frac{\partial n}{\partial T}\right)_\rho \Delta T + \left(\frac{\delta n}{n}\right)_T$$

where ε_z is the axial strain in the core due to length changes, ρ is core density and we see the refractive index effects split into components at constant density and at constant temperature.

Further expansion gives the fractional phase change per degree as

$$\frac{\Delta\phi}{\phi\Delta T} = \frac{1}{n}\frac{\partial n}{\partial T}_\rho + \frac{1}{\Delta T}\left(\varepsilon_z - \frac{n^2}{2}[(P_{11}+P_{12})\varepsilon_r + P_{12}\,\varepsilon_z]\right)$$

where P_{11} and P_{12} are Pockels coefficients in the core and ε_r is the radial strain in the fibre.

Analysis to determine the strains depends on the dimensions and composition of core, cladding, substrate, buffer material and the fibre jacket. Lagakos et al report [1] on two ITT single mode fibres (one bare and one coated) with silica core, silca + 5% B_2O_3 cladding and silica substrate. The jacketed fibre had silicone buffer and a polyester jacket. The results were

$\frac{\Delta\phi}{\phi\Delta_T}$ for	experiment	calculation
bare fibre	$0.68\times10^{-5}/^{o}c$	$0.70\times10^{-5}/^{o}c$
jacketed fibre	$1.80\times10^{-5}/^{o}c$	$1.64\times10^{-5}/^{o}c$

The low expansion coefficient of silica makes the $(\frac{\partial n}{\partial T})_\rho$ term dominant for the bare fibre. In the jacketed fibre the major effect is the length change followed by temperature changes of refractive index. The photoelastic effects are not insignificant. In general, a tight jacket worsens the performance due to its larger expansion coefficient.

Although study [2] indicates that better fibre compositions could be chosen and that a hypothetical fibre could be built with zero phase changes, the best suggestion was the use of Nd-laser glass core and a calculated phase sensitivity of $0.13\times10^{-5}/^{o}c$.

An uncompensated accuracy of 2×10^{-9} could only be achieved then with a temperature stability of about 0.01°c. Clearly active compensation is needed for the example chosen. (However if the requirements are less severe in terms of baseline and operating frequency, a simple system could suffice).

Practical experience in the compensation of optical fibre links has been obtained [3] at Jet Propulsion Laboratories. A 3 km multimode fibre of bandwidth 1.5 GHz.km and loss 3db per km has been in use at 850 nm. One interesting observation was of (excessively large) non-reciprocal delay changes on bending this multimode fibre. Such effects are absent from single mode fibre which also has a wider bandwidth and losses below 1db per km.

An 8 km single mode link at 1300 nm is undergoing installation with goals of 30 km links and 400 MHz bandwidth. The lower loss of single mode fibre produces better signal to noise ratio and hence more accurate compensation.

The cables are simply ploughed into the ground to a depth of 1.5 m at which depth a 1°C diurnal temperature variation is expected with short sections subject to step changes in temperature of perhaps 10°C.

In confirmation of the results above, the temperature coefficient of phase (α) for a loosely jacketed fibre was found to be 7 ppm or approximately 10^{-5}/°C.

Regular diurnal variations of temperature can be modelled to improve the stability but active phase correction systems will usually be needed. One such optical system is illustrated [3] in Figure 1. The signal is sent out and then, by directional couplers, is returned. One transmits sin ($wt+\zeta$) such that the returned signal is sin($wt-\zeta$). The signal at the far end must then simply be sin(wt). The accuracy of correction depends on temperature changes in fibre source and detector as well as signal-to-noise of the receiver and integration time.

It is necessary to convert the JPL frequency stability results to the radio interferometry application. JPL reports stabilities as the rms deviation σ between successive assessments of frequency from the fibre taken over some sampling interval τ.

Their results show that present state of the multimode fibre link with stabilisation gives $\sigma = 5 \times 10^{-13}$ divided by the interval time in seconds. This is valid over intervals up to several hours. Changing to an improved single mode system at JPL is projected to give a $\Delta f/f$ of about 50 times better than the multimode system over intervals up to an hour. Beyond this the σ stabilizes at an expected limit of about 10^{-17} independent of sample time.

In terms of phase stability, one takes the mean phase departure in an interval to be half the difference between the phases at beginning and end of the interval.

So $\sigma = 5\times10^{-13}$ over one second implies

$$\Delta\phi = 5\times10^{-13} \times 1 \times 4\times10^{10} \times 360 \times \tfrac{1}{2}$$

$$= 3.6 \text{ degrees at } 40 \text{ GHz}$$

That is, the multimode system could compensate to a length accuracy of 75 microns. If one wished to achieve the full compensation to within 20 microns it may well be necessary to use a single mode fibre link.

Remembering the basic temperature variation of about $10^{-5}/^{\circ}C$ the phase calibration system would need to be capable of an improvement factor of 10^9. In such a system the result is achieved by very careful attention to phase stabilities of laser sources and photodetectors. The fibre is only one of the components of the system. Nevertheless fibre systems can satisfy the requirements for radio interferometer timing disseminations.

Experimental work at the University of Sydney centres around a kilometre of single mode fibre for operation at 1.3μm. Although sources and detectors at 1.3μm are still to be bought some stabilization work on systems at 0.83 μm has proceeded. The two aims of the experimentation are phase stability and very wideband operation. The work is sponsored by the Sydney County Council.

References

1. N. Lagakos, J.A. Bucaro and J. Jarzynski, "Temperature-induced Optical Phase Shifts in Fibers" (sic), Applied Optics, vol.20, No.13, pp.2305-2308, 1981

2. N. Lagakos and J.A. Bucaro, "Minimizing Temperature Sensitivity of Optical Fibers" (sic), Applied Optics, vol.20, No.19, pp.3276-3278, 1981

3. G. Lutes, "Development of Optical Fiber (sic) Frequency and Time Distribution Systems", Proceedings of the 13th Annual Precise Time and Time Interval (PTTI) Application and Planning Meeting, pp.243-262, December, 1981

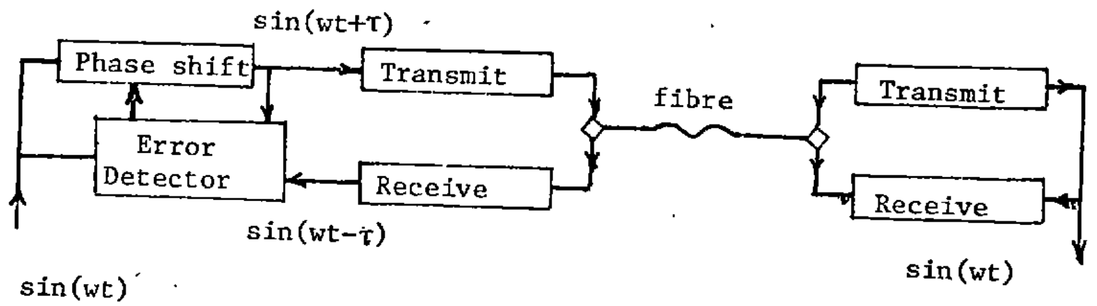

Figure 1. Phase compensation by two-way transmission in the fibre [3]

AT MEMORANDA SERIES.Systems and Performance
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REPORT OF A.T. SYSTEM CONCEPT WORKSHOP

HELD AT PARKES, 7-9 DECEMBER 1982

Present: R.H. Frater, J.G. Ables, C.E. Jacka, A.G. Little, P.J. Napier, J.D. O'Sullivan

Contents — Page

Preamble

This document is a report of a Workshop. It contains the views of the workshop participants on what is achievable and what is needed for the AT. The statements on design criteria are in no way meant to pre-empt further discussions and final decisions. Rather they are intended to alert the reader to what is considered feasible with current technology and to encourage comments and ideas so as to allow for the design of the best possible system with the available funds.

It is envisaged that further elaboration on the design concepts will form the subject of future documents in the AT Memoranda Series in due course.

Readers are urged to respond to this document in writing. Contributions may be lodged as either AT Memoranda Series documents (for substantive comments) or as AT File Notes (for less detailed comments).

R.H. Frater

1. INTRODUCTION AND OVERVIEW

This meeting was conducted with the general aims of:

(1) Establishing a strawman total system concept

(2) Identifying areas of the project requiring urgent and detailed attention

(3) Highlighting key personnel requirements for the project.

Those present at the workshop were:

Bob Frater (Chairman) [RP]
Jon Ables [RP]
Colin Jacka [RP]
Peter Napier [NRAO]
Alec Little [University of Sydney]
John O'Sullivan [SRZM]

There was considerable discussion of the aims of the AT project, and the priorities that should be considered in the workshop. This discussion led to a number of conclusions:

(1) One of the key features of the instrument would be its ability to make maps with wide field and high spectral resolution.

(2) The prime effort should go into ensuring the best possible performance in the 6km array (Ref.section 6 and Attachments 2 and 3).

(3) Considerable concern was expressed on the viability of the mobile antenna as an element of either the 6km or LBI arrays.

The basic specification for the AT was taken from the draft description of the project (AT/15.1/005B; RNM:25 November 1982). A number of concerns were expressed in relation to that description:

(1) It is not clear that operation will be possible at 115 GHz with baselines of hundreds of metres. The following comparison of the site altitude with sites specialising in mm work highlights one aspect:

Site	Elevation
Plateau de Bure	2550 m
Nobeyama	1350 m
Owens Valley	1222 m
Hat Creek	1043 m
Culgoora	210 m

In addition, actual water vapour data for Northern NSW suggests that Culgoora is 2 to 3 times worse than the VLA site (2100 m elevation).

(2) Recent information on communication links and TV transmitters in the Siding Spring region raises serious questions about the possible affect of interference on the operation of the proposed Siding Spring antenna.

(3) The use of a mobile antenna as an adjunct to both arrays is of questionable viability and needs more consideration.

The workshop concluded that:

(1) No additional cost should be incurred to provide 115 GHz performance. As far as the system is concerned this means the acceptance of a phase specification over the 6 km array of approximately 1°/GHz (RMS).

(2) The interference environment at Siding Spring (and Culgoora) must be investigated immediately. The viability of all the possible sites on the mountain should be assessed.

(3) While the viability of the mobile antenna is questioned, it is clear at least two small fixed antennas between Siding Spring and Culgoora would be needed for a viable long baseline array. This possibility should be investigated as a possible lower cost alternative to the mobile antenna.

2. REVIEW OF OVERALL PROJECT TIME SCHEDULE

The current Australia Telescope Planning Schedule (Attachment 1, AT/14/001; Revision 1, D.N. Cooper, 10 November 1982), was reviewed. The only significant change recommended is to delay the acquisition of the data reduction computer by one year to maximise the size of the computer that can be obtained for the available funds. So that software development is not delayed, a new activity line should be added entitled "Data Reduction Software" which will involve the selection of STARLINK and/or AIPS and/or GYPSY and/or DWARF and/or another suitable software package and its/their adaptation to the Radiophysics VAX. This will ensure that data reduction facilities are available when the first astronomy is started on the AT at the end of 1985, and will provide the basis for new software development in the AT data reduction computer when it is available.

It is recommended that the name of the correlator activity be changed to "Digitizer/Correlator".

The breakdown of the AT project as defined in the Planning Schedule was considered acceptable. A brief description of each activity is given below, together with the name of the individual providing currently assigned responsibility of providing the leadership for the activity.

It is clear that immediate action is needed in assigning responsibilities for detailed design for the various sections of the project.

At this stage (9 December 1982) only interim arrangements are possible and indeed, most of the people nominated for the tasks in the schedule are heavily committed elsewhere.

The relationship of the electronics subsystems are shown in the top-level block diagram of Figure 2.1.

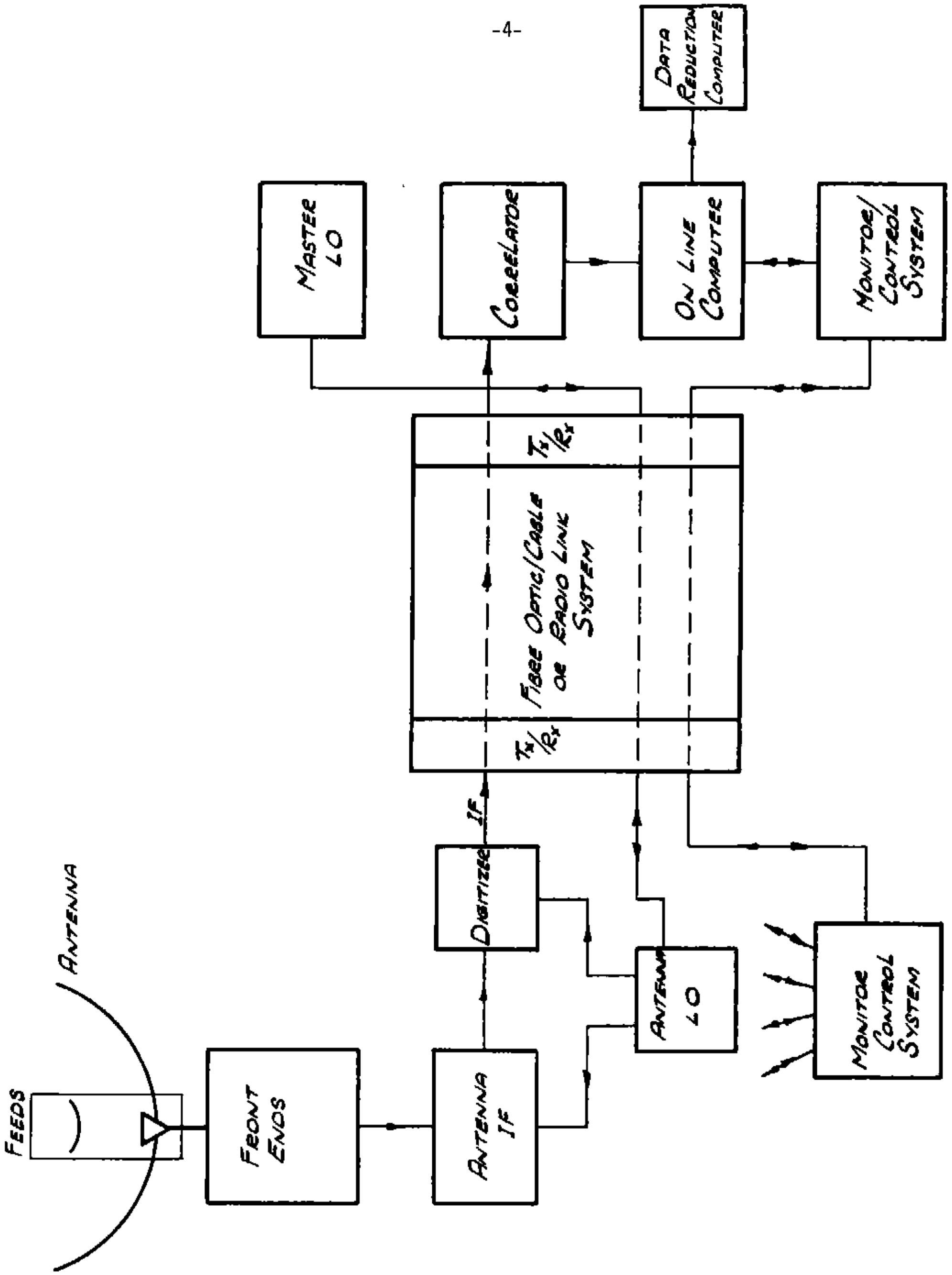


Figure 2.1

Configuration Design:	R.N. Manchester. Determination of top level scientific specifications for the AT, such as angular resolution, sensitivity, image quality, spectral resolution, temporal resolution etc. for the various proposed operating modes as well as the determination of these modes.
Antennas:	D.N. Cooper. Specification, design, procurement and testing of the antenna elements.
Antenna Surface Panels:	B.F. Parsons. Specification, design, procurement and alignment of the reflector panels for the antenna elements.
Antenna Servo System:	D.N. Cooper. Specification, design, procurement and testing of the antenna servo system.
Antennas 1 - 7:	Project Manager. Outfitting and system testing of each fully equipped antenna element.
Parkes:	J.G. Ables and D.N. Cooper. Preparation of the Parkes 64 m antenna for its normal observing duties, ESA and NASA support and preparation for radio link array observations during the AT project.
First Interferometer:	Project Manager. Provision of all necessary hardware and software to allow interferometry to start, the testing of the interferometer and decisions on need for design changes.
Feeds:	G.L. James. Specification, design, fabrication, testing and installation of the feeds for the antenna elements, including responsibility for all polarization splitting devices.
Front Ends:	J.W. Brooks and/or M.W. Sinclair. Specification, design, fabrication, testing and installation of the low noise receivers and their cryogenic systems. Responsibility includes all hardware between the rectangular waveguide or coax input to the dewar and the input to the first I.F. mixer. Includes input of injected noise amplitude calibration system.
Fibre Optics/Cables:	A.G. Little. Specification, design, procurement, installation of all fibre optic, coaxial cable and telephone line communication links in the Culgoora east-west array. These links will carry all LO, IF, Monitor and Control, and Voice Communication data, between the antennas and the Central Electronics Building. Responsibility includes the physical cables and all transmit/receive electronics at each end of the cable.

Radio Links:	M.W. Sinclair. Specification, design, procurement, installation and testing of all radio links between Parkes, Siding Spring and Culgoora. These radio links will carry LO signals from Parkes out to Siding Spring and Culgoora; digital commands from Parkes to Siding Spring and Culgoora; digital monitor data from Parkes and Siding Spring to Culgoora. Responsibility includes all antennas, radio towers, and transmit/receive and repeater electronics.
Antenna IF:	J.W. Brooks and/or M.W. Sinclair. Specification, design, fabrication, testing and installation of electronics in the antenna between the input to the first IF mixer and the input to the high speed digitizer. Responsibility includes all frequency converters, bandpass filters, ALC circuits, and total power and calibration signal detectors.
Antenna LO:	J.G. Ables. Specification, design, fabrication, testing and installation of the electronics which provide all phase stabilized LO's and clock signals needed at the antenna. Responsibility includes provision of phase switching, fringe rotation and variable rate sampling clocks.
Monitor/Control:	C.E. Jacka. Specification, design, fabrication, testing and installation of the system which disseminates command information from the on-line control computer to all hardware in the AT, and collects monitor information from that hardware and returns it to the on-line computer. Responsibility includes the interface between the on-line computer and the communication link in the central Electronics Building, and all monitor/control electronics and microprocessors at the antenna.
Master Local Oscillator:	J.G. Ables. Specification, design, fabrication, testing and installation of the primary frequency standards in the central Electronics Building, the electronics to disseminate these references to all antennas and the system to measure the phase and stability of the reference signal returned from each antenna. Also, the provision of a means of locking the primary reference to a Hydrogen Maser located at Tidbinbilla.
Digitizers/Correlators:	J.G. Ables. Specification, design, fabrication, testing and installation of the high speed digitizers at the antennas and the recirculating spectral line correlation system. Responsibility includes provision of "special features: such as a tied array mode, one to two bit conversions with reduced bandwidth and external gating capability required for pulsar observations.

Parkes Electronics:	Project Manager. Specification and design of "one-of-a-kind" electronics systems needed specially for the Parkes 64 m antenna because it is different from the other AT antennas.
Heliograph Modifications:	K.V. Sheridan. Specification and installation of all changes needed to the Culgoora Radioheliograph to allow it to coexist with the AT.
On-line Computers:	C.E. Jacka. Procurement and programming of the on-line computer which controls and monitors the array, carries out the real time lag-to-frequency FFT's and performs preliminary data correction and calibration.
Data Reduction Computer:	R.H. Frater. Provision and programming of the computer system which performs final data calibration, forms images from UV-plane data and provides image processing facilities.
Data Reduction Software:	R.H. Frater. Selection of one or more existing synthesis data reduction packages for use on the Radiophysics VAX. Modification and testing of this package so that it is available on the RP VAX in time for the First Astronomy.
Site Electrical Works:	W.J. Payten. Provision of all electrical services to all fixed and movable antenna sites at and near Culgoora and Siding Spring. Includes provision of emergency generators, where necessary, to keep cryogenics cold and stow antenna during power outages.
Buildings:	Project Manager. Provision of all necessary temporary buildings.

3. THE I.F. SYSTEM

The I.F. system takes 0 - 128 MHz signals from the front-end converters, limits the bandwidth, amplifies the signal to a level suitable for digitising and produces either a 1-bit or 2-bit TTL level signal for delivery to the transmission system. At this stage it is not possible to specify all the levels in the system.

The decision to digitize at the antennas has the following implications:

(1) Fringe Rotation has to be done through the LO at the antenna.

(2) All narrow band filters have to be at the antennas.

(3) The I.F. cable phase stability requirements are relaxed.

(4) It will not be possible to go to any analogue transmission from antennas to the central electronics in the future without stabilising the I.F. cables.

(5) The maximum digitizing rate is limited by the digital transmission system.

(6) As will be mentioned in the correlator section, the correlator chip can only handle the full bandwidth for 1-bit operation and half bandwidth for 2-bit operation so the digitizer has to be able to do both 1-bit and 2-bit digitization.

(7) To achieve full sensitivity in tied array mode, e.g. for long baselines or fan beam operation, 3-or 4-bit digitization may be desirable.

The block diagram of the system is shown below (Figure 3.1). There are two of these complete systems, one for each polarization. The second output is an option for spectral line observations but will not be provided at this stage - only the transmission link will be installed.

Both the LO and sampling clocks can be derived from a master oscillator which is Doppler shifted to allow for the fringe rotation (the "unified clock" method). A block diagram of a possible system is shown below (Fig. 3.2). This allows a basic system which is the same for all bands, with different frequency bands being selected by the appropriate locking system at the antennas. For this system to work, it must be capable of producing internally a phase stability of about 1°/GHz with a maximum of about 40° above 40 GHz. This figure is a maximum and it would be desirable to be even less. The main LO pilot signal can be sent out at say a few hundred MHz using a phase stabilized link.

For tied array operation such as for VLBI using 1-bit operation there could be a loss of sensitivity of about 25% if the full bandwidth is used. However it may be sufficient to reduce the bandwidth before sampling whilst still maintaining the fast sampling in which case the signal is oversampled and the loss will be negligible.

Note:

Because the sampler is operating at such a high speed, considerable attention will have to be paid to shielding of the sampler to avoid interference to the telescope, particularly since the sampling will be coherent at each antenna.

Manpower:

High-level engineering is required immediately for systems design of the sampler and LO systems; the other components are relatively straightforward. From experience with TEST, this could be approximately one man-year.

For production, allowing for 6 elements at Culgoora, 1 element at Siding Spring, Parkes and Tidbinbilla, and one spare (10 units total), an estimate of two/three technicians for one year full-time.

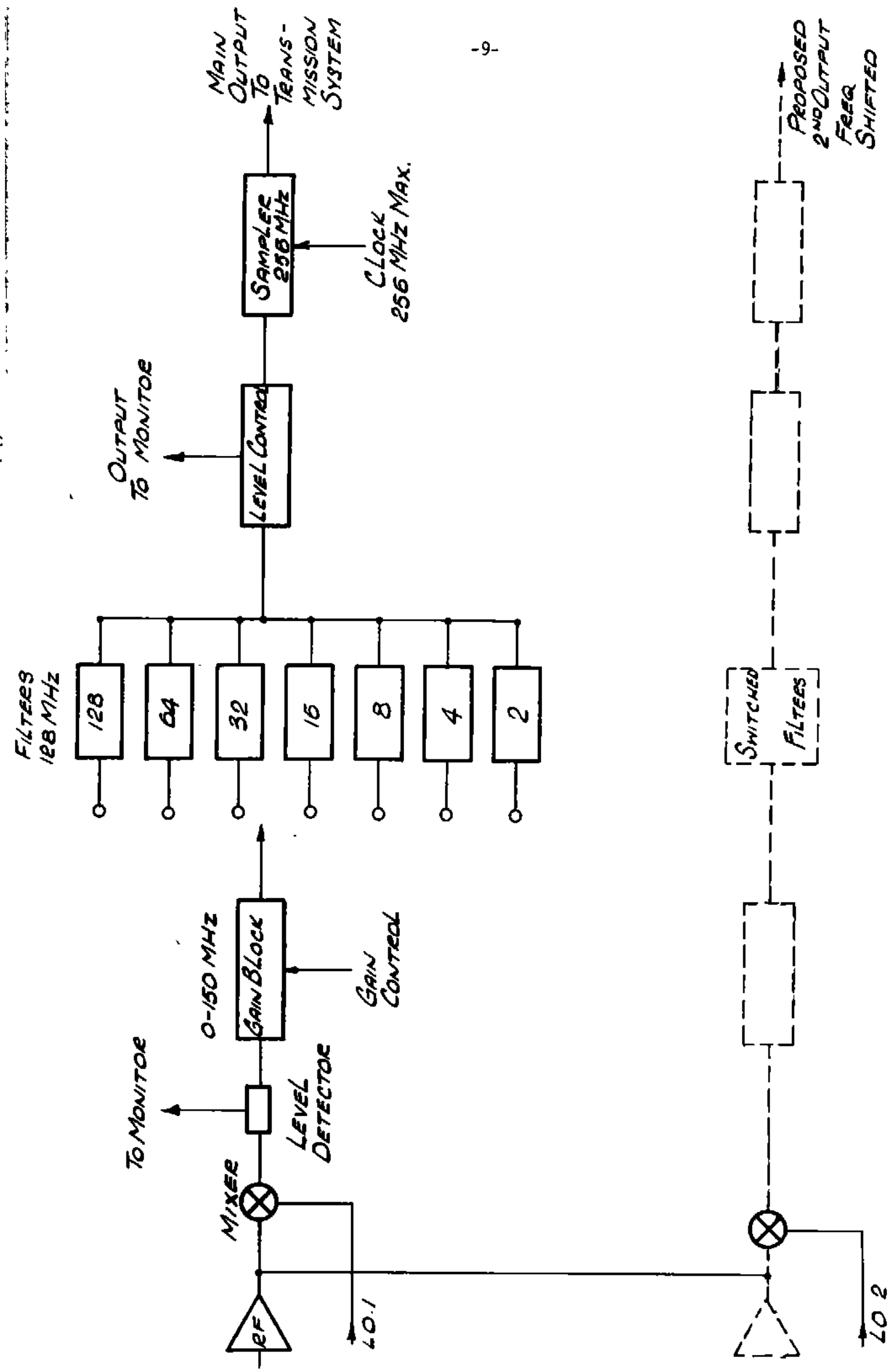


Figure 3.1 : IF Block Diagram

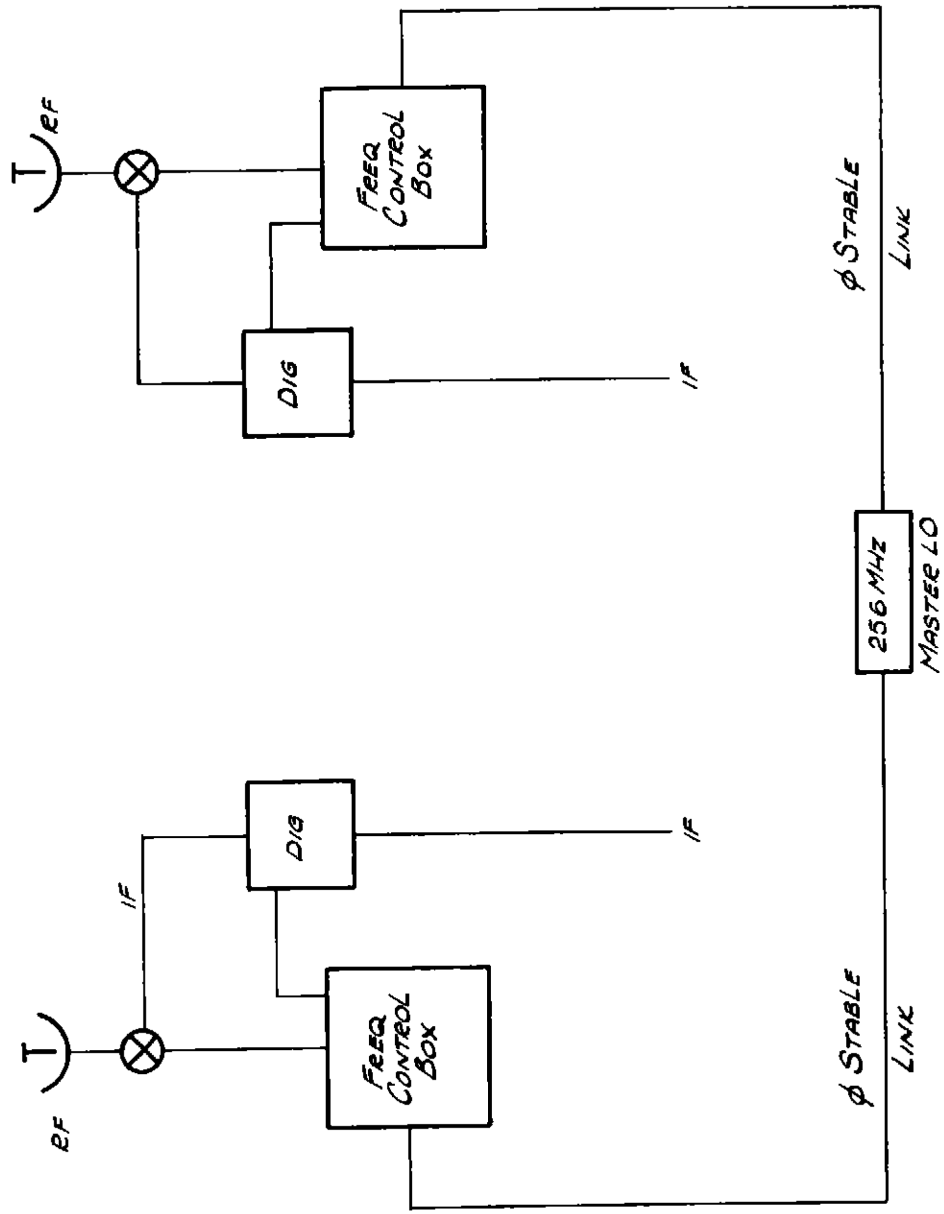


Figure 3.2 : *PROPOSED CLOCK-LO SYSTEM*

4. THE CORRELATION SYSTEM

4.1 Factors influencing the correlator specifications

4.1.1 Basic astronomical requirements

The document "Proposed Spectral Line Correlation System" (AT/10.4/001) primarily determines the overall size of the correlator. The relevant extreme parameters are summarized in the following:

Bandwidth	Spectral Channels/Pol	Recirculation Factor
128 MHz	128	2^0 (= 1)
2 MHz	8192	2^6 (=64)

Given 1-bit correlation with the existing design for the VLSI correlator chip, this indicates the use of 15 x 2 x 256 channels capable of a sampling rate of 256 MHz. Each correlator chip provides (conservatively) 8 channels at 80 MHz sampling rate thereby requiring $\frac{7680 \times 4}{8} = 3840$ chips.

A new chip might provide 2-bit operation at half bandwidth. We conclude on the basis of costing that full bandwidth operation must be restricted to 1-bit.

4.1.2 Implications of full field mapping

The requirement that the entire field of view be mapped out to the 10 dB point for the primary beam sets limits on the maximum frequency channel width and correlator readout rate.

(i) Radial bandwidth smearing

Given a synthesised beam of approximately λ/B radians, and a field radius of approximately λ/D radians, then a maximum radial smearing of

$$\frac{\Delta\nu}{\nu}.\frac{\lambda}{D}.\frac{B}{\lambda} = \frac{\Delta\nu}{\nu}.\frac{B}{D}$$

results from a fractional bandwidth $\Delta\nu/\nu$. Setting a limit of 50% linear smearing, which implies a point source decorrelation of approximately 5% gives

$$\frac{\Delta\nu}{\nu} \leqslant 0.5\ D/B$$

For ν = 3 GHz (the lowest frequency at which full bandwidth is likely to be available), $\Delta\nu$ = 5.4 MHz results.

(ii) Circumferential integration time smearing

An integration time of Δt seconds determines a movement of the synthesized beam during Earth rotation at a radius of λ/D radians in the field given by

$$\Delta t . \frac{\pi}{43200} . \frac{\lambda}{D}$$

from which a circumferential smearing of

$$\Delta t . \frac{\pi}{43200} . \frac{\lambda}{D} . \frac{B}{\lambda}$$

results.

A requirement of less than 50% smearing yields

$$\Delta t \leqslant \frac{21600}{\pi} . \frac{D}{B} \approx 25 \text{ seconds}$$

4.1.3 Maximum readout rate

The maximum readout rate is influenced by:

(i) Astronomical wishes which suggest maintaining the possibility to read out a limited subset of the correlator data (i.e. only continuum points) at intervals as short as 1ms.

(ii) Loss of observing time due to correlator blanking during readout. The VLSI chip readout time is of the order 0.1 ms.

(iii) Prescale quantisation noise in the VLSI chip. For 6 bits prescaling we have

$$\sigma^2(\text{quant}) = \left(\frac{2^6}{\sqrt{12}}\right)^2$$

and for an integration time Δt

$$\sigma^2(\text{thermal}) = \Delta t \nu_0$$

The requirement σquant $\ll \sigma$thermal yields

$$\Delta t \gg 2^{12}/3\nu_0$$

where ν_0 is the basic correlator sampling rate (10 MHz). We obtain $\Delta t \gg 0.03$ ms.

(iv) Readout data rate - to be considered in a later section.

(v) Recirculation requirements - to be considered in a later section.

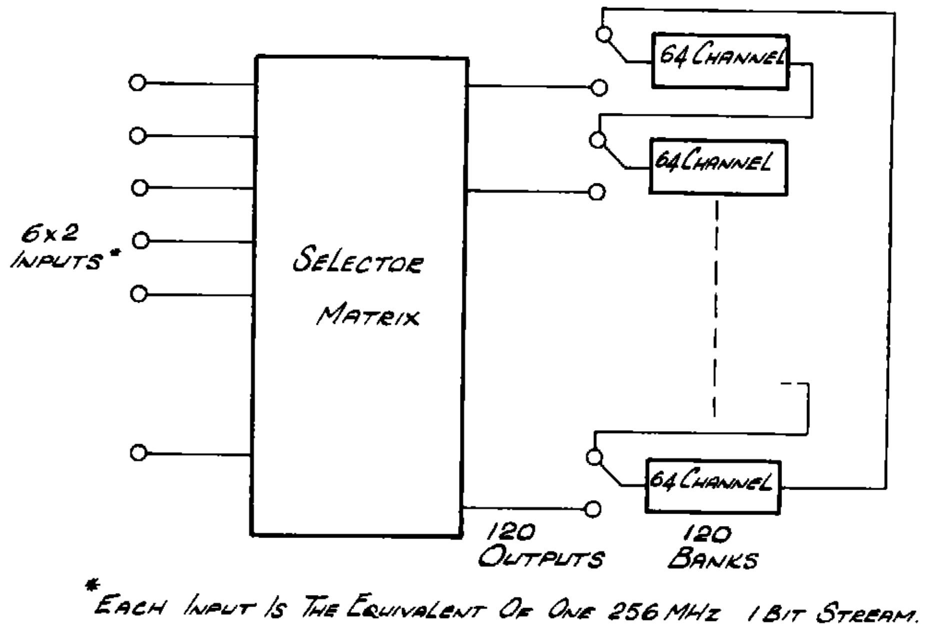
4.1.4 Correlator configuration flexibility

All 7680 physical channels will commonly be configured as 15 baselines x 2 polarisations x 256 channels. Some possible other modes might include

Baselines	Polarisations or Separate I.F.'s	Channels
15	2	256
15	4	128
0 or 1	2	3840*

*For example: Tied array autocorrelation spectra or grating tied array cross correlation spectrum for pencil beam high spectral resolution work.

Such considerations dictate flexibility in assigning inputs to correlator banks and chaining of consecutive correlator banks. Detailed consideration must be given to these points. Preliminary indications suggest that correlators arranged in banks of 64 lag channels with full input selector flexibility for each bank should be viewed as a design goal. Schematically we have (Figure 4.1)



*each input is the equivalent of a 256 MHz 1-bit stream.

Additional features to be provided include phase switch demodulation in each input line, correlator blanking (pulsar observations), one bit - two bit selection. These plus certain extra selector functions such as selection of 6km array or radio linked array as input to the correlator should be identified as separate functions where possible to prevent hidden restrictions in as yet unforeseen operating modes.

4.2 Requirements for Correlator Recirculation

A recirculation factor of $F_R = 2^6$ is suggested to fully utilize correlator capacity down to 2 MHz bandwidth.

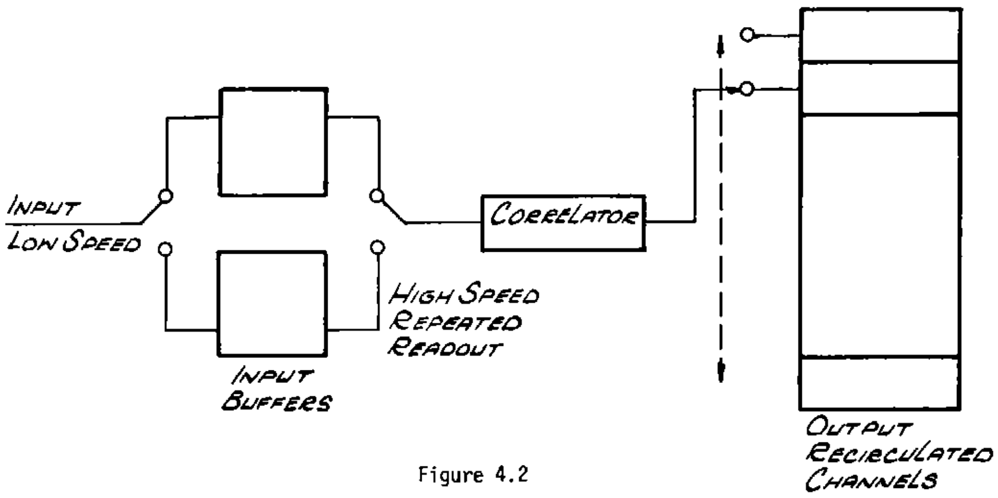


Figure 4.2

The recirculation method allows multiplication of the number of correlator channels by a factor F_R. In principle this need not be restricted to an increase in spectral channels but could allow multiplication of baselines, I.F.'s, etc. as the correlator may be reconfigured between recirculation cycles. The recirculation method reads data into one of two input buffers at the reduced input rate $\left(\frac{256}{F_R}\right)$Mbits/sec for a bandwidth of $\left(\frac{128}{F_R}\right)$MHz. The other input buffer is readout F_R times at 256Mbits/sec rate with, for example, successively altered lags to allow F_R separate utilisations of the correlator.

Given a readout rate or basic recirculation interval t_c, two input buffers of size 256 t_c Mbits are required. For the proposed system, F_R x 7680 separate accumulators are required. Depending on the exact method of handling the VLSI correlator chip output, this could rise to F_R x 3840 x 64 = 245760 F_R separate 24 bit accumulators (47 MB). It is therefore advisable to combine all 32 subproducts immediately in F_R x 7680 separate 32 bit accumulators (2 MB).

The time required to complete a recirculation cycle is $F_R t_c$.

Recirculation with t_c = 5ms
$F_R = 2^6$

Input buffer size	320 KB/input 38 Mbyte total
Output buffer size	2 MB
Readout rate	320 ms

The input recirculation memory is a high speed serial in-serial out buffer but should be implemented with normal RAM technology thereby allowing considerable economy. Considerable flexibility in readin and readout address sequencing should be considered to allow full potential of the recirculation principal to be realised.

4.3 Correlator System Outline

The diagram (Figure 4.3) outlines the entire correlator system for both 6km and radio linked systems. Some comments are appropriate concerning the separate subsystems.

(a) Serial-parallel conversion

The high speed data streams from the antennas are reduced at the earliest possible stage to parallel, low speed bit streams.

(b) 6km delay path tracking

Although potentially combinable with other functions in the system (recirculating buffers), it is felt that system simplicity and flexibility is improved with the use of a separate subsystem for the path delay tracking. Because of the use of the "unified clock method", the delay tracking memory is also first-in, first-out (FIFO) but should be designed around standard RAM chips.

(c) Modulator matrix

In particular, any phase switch modulation could be demodulated here.

(d) Summation units

At least two separate adders are envisaged to allow

(i) operation of the 6km array as a tied array with or without the radio linked array

(ii) high resolution grating array spectrometry.

Inputs to the summation units should be individually selectable.

(e) Radio link/6km array selector

To avoid unnecessarily complicating the full selector matrix, a simple 2-way switch is envisaged here.

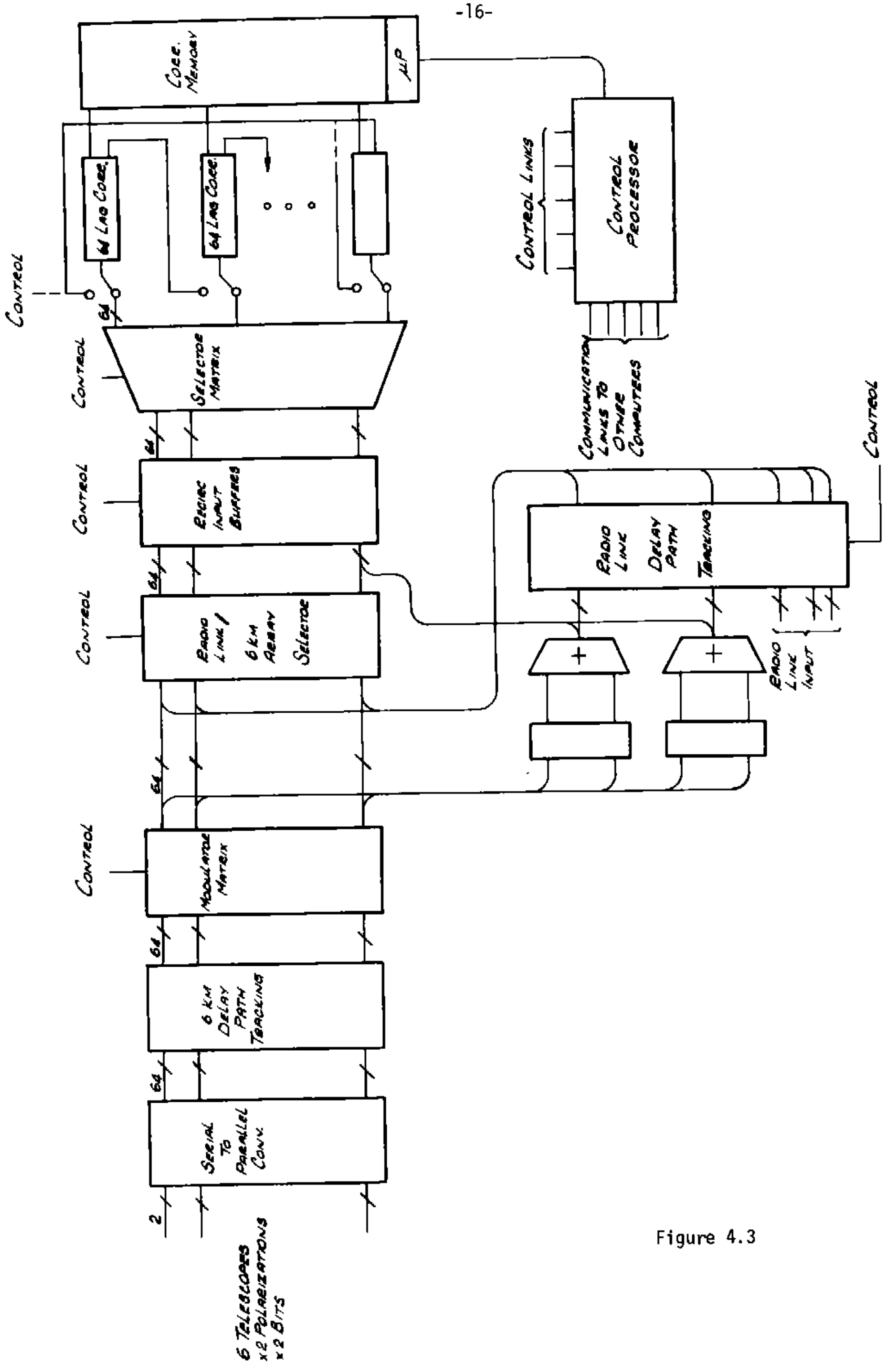


Figure 4.3

(f) Radio link delay path tracking

A separate delay correction should be provided for the low bit rate (20 Mbit/sec) but large path length radio linked array.

(g) Recirculating input buffers

See discussion in section 4.2.

(h) Selector matrix

See section 4.1.4.

(i) Correlator banks

See section 5.

(j) Recirculating output buffers

See section 4.2.

(h) Control section

The control section is responsible for storage of all configuration information. Some thought must be given to altering configurations at the basic recirculation cycle time (approx. 5ms).

5. THE A.T. DIGITAL CORRELATOR SUBSYSTEM

5.1 Introduction

The AT correlator is based on a very wideband digital correlator with a parallel, pipe-lined architecture using a large number of identical computational elements implemented with VLSI NMOS circuitry. The lag range for smaller bandwidths is increased by operating the basic correlator with a recirculation memory system. The VLSI chips are combined to form correlator modules which become the building blocks for the correlation system.

5.2 System Architecture

Input and output signal data paths are 32 bits wide and operate at a maximum rate of ~ 32×10^6 bits/sec. The source of input data depends on the operating mode and may be either the delay tracking memory system or the recirculation memory system. The data source and signal data linkage between modules is determined by a data selector matrix.

Output correlation data paths are also 32 bits wide and connect to the data logging computer system. Data rates on the output paths is determined by the logging system as well as the correlator system needs.

The communication bus provides the path by which the on-line computing systems are able to configure and command the correlators and to receive status information from the correlators. The timing bus provides the path by which the correlators are synchronised with external systems.

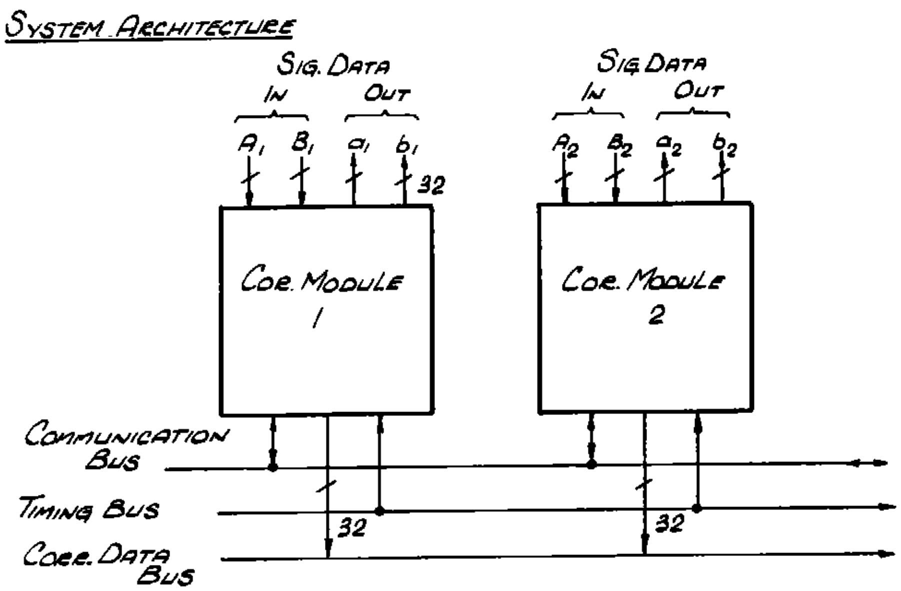


Figure 5.2

5.3 Correlator Module Specifications (Preliminary)

Bandwidth:	256 x 10^6 samples/sec (1-bit)
	128 x 10^6 samples/sec (2-bit)
Lag range:	64 (unidirectional)
Signal data paths:	32 bit parallel synchronous
Corr. data path:	32 bit parallel asynchronous
Integration time (T):	1ms to 25sec
No. of VLSI chips/module:	32
Construction:	single board (pc, wirewrap or multiwire)
On-board corr. data management:	microprocessor + memory
Power:	5V at approx. 20W

5.4 VLSI Correlator Chip Architecture

The well-known Weinreb digital correlator (and multi-bit extensions of the basic one-bit version) may be considered as a pipeline processor for computing sums of lagged products of a pair of digitised sample data streams. The "pipeline" is the shift register (SR) down which the delayed stream flows. The upper limit on processing speed is determined by the minimum time required for the multiplier-accumulator (MAC) attached to each SR stage to perform one operation. (The SR is usually faster than the MAC). Only one sample at a time is input to the processor.

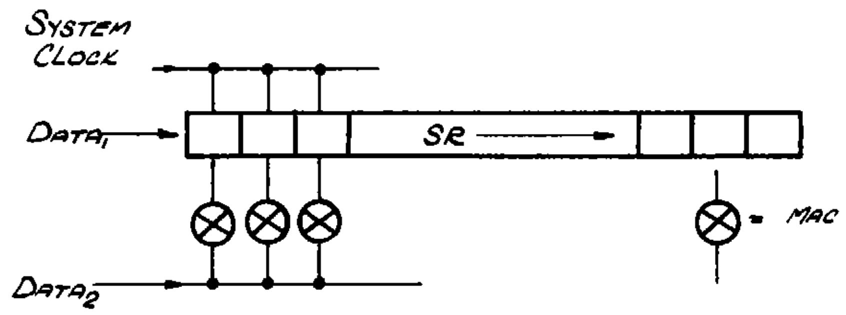


Figure 5.2 : WEINREB DIGITAL CORRELATOR

Now consider the computational element (CE) diagramed below.

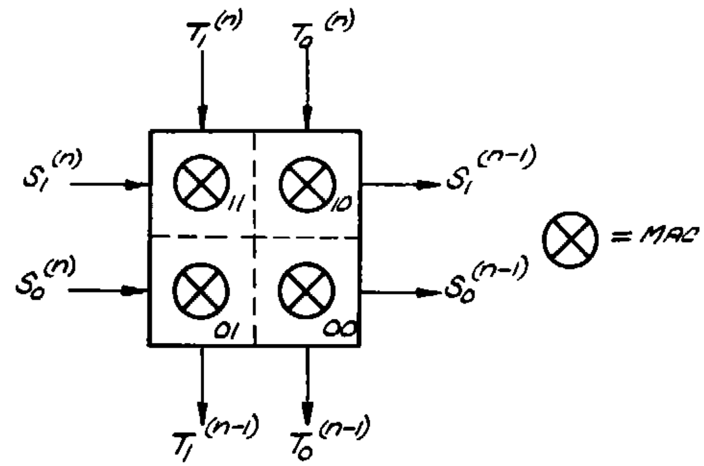


Figure 5.3

S and T are data samples from the two streams so that $(S_0(n),S_1(n))$ is the n-th sample block from stream S. Here N = 2; i.e. the data is blocked into groups of two samples. The MAC's operate on the "intersections" of the data streams within the CE. Date input at the top and left side appear, delayed by one block time, at the bottom and right side respectively.

The new architecture described here differs from the Weinreb correlator in that it operates on successive blocks of N samples (which may be multi-bit) with all operations on the N samples taking place at the same time at each pipeline stage. For a given logic speed this achieves an N-fold speed increase over the Weinreb architecture but at a cost of using N times as many SR elements and MAC's. The advantage of the parallel processing method is that speed is achieved through the use of more circuitry rather than higher speed circuits. This means that the cheapest circuitry now known, VLSI poly-silicon gate NMOS circuitry, can be used to reach speeds not possible using the Weinreb architecture, even with the fastest (and extremely expensive) logic now available.

The CE in the first figure is designated (for obvious reasons) a 2X2 CE. A CE that accepts blocks of N samples from both data streams is called NXN. Rectangular CE's (NXM) are also possible, but they do not seem to have any particular advantage over the symmetrical NXN CE and are more complex to interconnect. An NXN CE computes all the partial sums of lagged products from blocks of N samples necessary to determine the correlation over N lags. To extend the lag range, CE's can be cascaded to lengthen the pipeline. The CE's can also be ganged in parallel, with appropriate interconnections, to increase the input sample block length in multiples of N. The structure of a correlator with an input block length of six and a lag range of 12, built from 2X2 CE's, is shown in Figure 5.4.

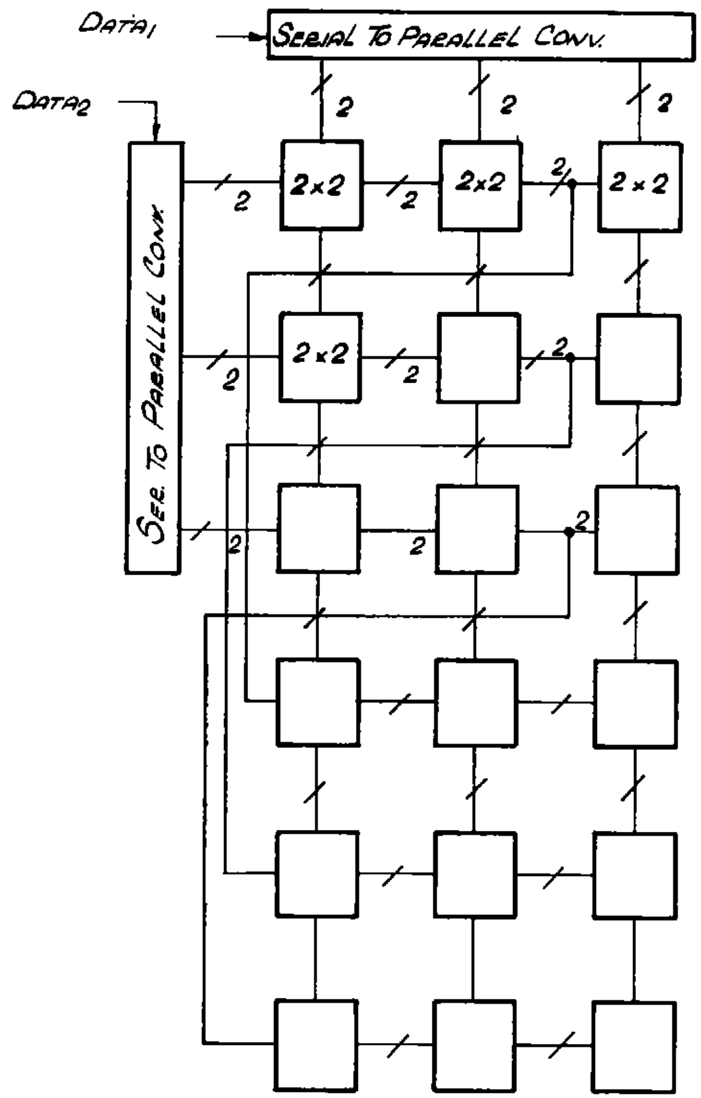


Figure 5.4

5.5 Broad Specifications for AT Correlator IC Chip (XCELL)

* Type:	8X8
* Bits per sample:	1 or 2 selectable
* Process rate:	10 MHz (5 MHz for 2-bit mode)
* Prescale factor:	64
* Read out:	serial (approximately 150 microsec)
* Accumulator length:	24 bits
* Package:	Standard 40-pin ceramic
* Technology:	Polysilicon-gate NMOS 3 to 5 micron minimum line width

5.6 Correlation Subsystem Requirements

(Correlator only, i.e. not including recirculation memory or selector matrix)

Correlation modules:	Culgoora correlator	120
	Parkes correlator	16
		136
	+ spares (20%)	24
		160
XCELL 8X8 chips:		approx. 5000
Power:	Culgoora	3KW
	Parkes	400W
Space:	Culgoora	4 racks
	Parkes	1 rack

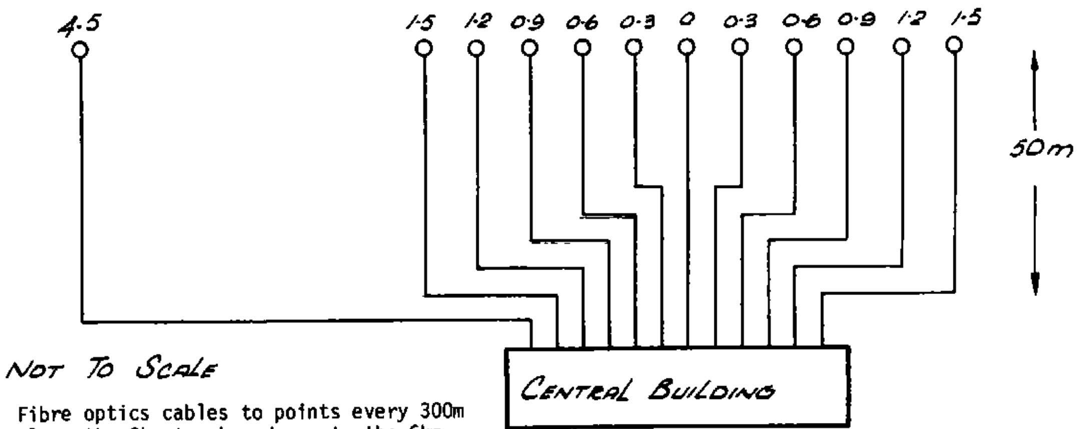
Time and Money* (rough estimates)	Man Years
VLSI design & procurement	2
testing	1
Module design	0.5
construction	0.5
testing	0.5
System integration and testing	1
	$A (1982.9)
XCELL chips (packaged)	$32
Correlator module (tested)	$2000
Culgoora correlator system	$300K
Parkes correlator system	$40K

* costs do not include salaries or overheads.

6. LOCAL OSCILLATOR DISTRIBUTION SYSTEM

An important starting point in the design of the local oscillator distribution system for the AT is the selection of a phase stability specification for the instrument. On time scales of 10's of minutes the instrumental phase errors should be small compared to the atmospheric phase errors. At the VLA, a phase stability specification of 1° rms phase/GHz has proven adequate to ensure this. Since precipitable water vapour at Culgoora is 2 to 3 times higher than the VLA, it can be expected that tropospheric phase errors will be worse at the AT by this amount. Therefore on time scales of a few 10's of minutes a phase stability spec. of 1° rms/GHz should be adequate. On shorter time scales, on the order of a minute, we require that there be no loss of correlation in an integration period used for self-calibration. A suitable specification for this purpose would be 1° rms for frequencies less than 10GHz, 10° rms for frequencies higher than 10GHz in a one minute integration time. Both the short and long term specifications need to be met.

Of the possible communication links which can be considered for the LO link on the 6km array, radio links can be rejected due to interference and spectrum availability problems. Waveguides are too expensive and coaxial cables have too much attenuation. A fibre optics LO link is attractive from the point of view of the low cost of optical fibres and the low attenuation that is available in modern mono-mode fibres. The current state-of-the-art in phase stabilized fibre optics links is reviewed in the Attachments 2 and 3 by T. Cole (Wideband Single-Mode Fibrelinks with Phase Stability) and G. Lutes (Development of Optical Fibre Frequency and Time Distribution Systems).



Fibre optics cables to points every 300m along the 3km track and one to the 6km station.

Figure 6.1 (see text on next page)

For costing purposes one could consider the prototype fibre optics system shown in Figure 6.1. In this system cables are run to points separated every 300m along the railway track. An umbilical cable would connect each antenna to its nearest fibre link. The total cable length in this system would be approximately 14km. Allowing a generous 12 fibres for each run, the total cost of fibre at $1.3/metre per fibre is 14000 x 12 x 1.3 approx. $220000 (without installation costs). This is within range of the current budget but clearly an extension of the fibre link from the 6km station out to 18km will only be possible if there are cost savings elsewhere.

There are 3 basic methods of phase stabilizations for long cable runs. These are shown in Figure 6.2. Either the Two Oscillator or the Round Trip Phase method would be suitable for stabilizing a fibre optics link. The bandwidths of commercially available fibre optic cables would suggest that the highest frequency LO distributed to the antennas should be in the range 100 to 400 MHz.

The phase stabilized fibre optics link is one of the areas of the AT that needs most development work. Experiments should start immediately and will require at least 1 full-time engineer/scientist and one high level technician for the duration of the project.

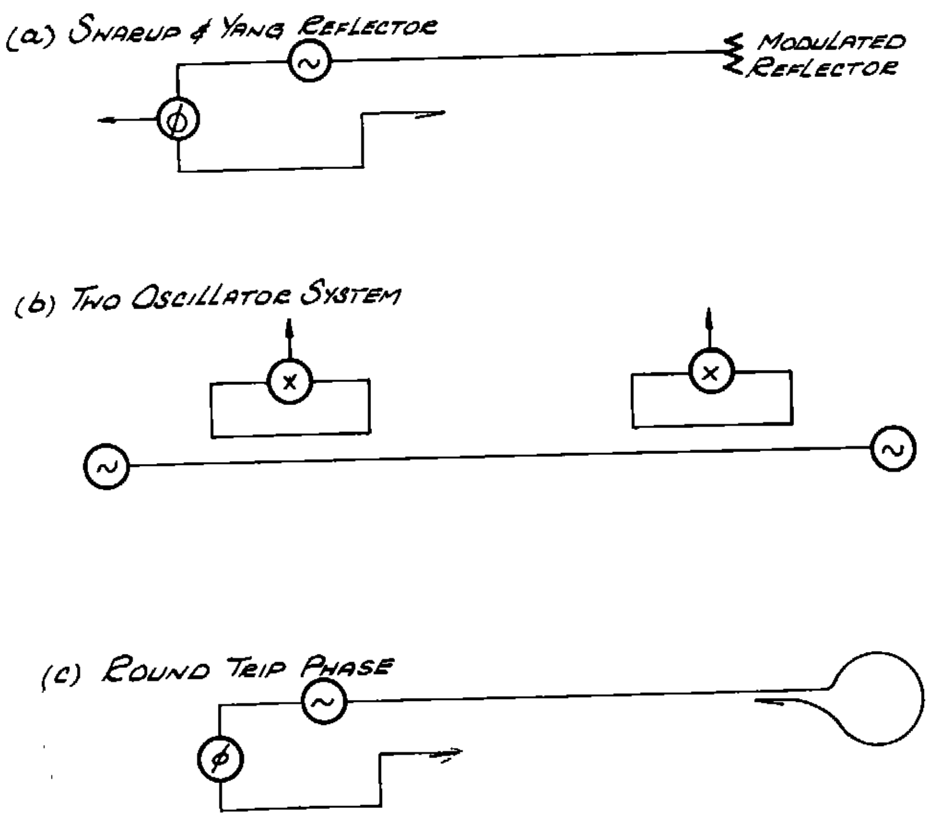


Figure 6.2 : Three Methods of Phase Stabilization

7. RADIO LINKS FOR THE LBI ARRAY

Any consideration of a radio linked array between Culgoora and Tidbinbilla presupposes the installation for NASA of a radio link between Parkes and Tidbinbilla for the Voyager/Uranus project. It is probable that this link will provide full-duplex frequency diversity operation with a mixture of S- and X-band hops. The proposed system provides TV baseband modulated onto a 24 MHz bandwidth channel. The bandwidth available for TV approaches 9 MHz with a pilot tone in this region also.

This system would be available for radioastronomy use. In its simplest application, analog data could be transmitted between Tidbinbilla and Parkes. In the most probable mode of operation a 20 Mbit/sec data stream would be encoded onto the TV band and transmitted to Parkes.

8. THE PARKES-SIDING SPRING-CULGOORA LINK

The most economical approach to this link would require the use of a duplex S-band system based on a 24 MHz channel. This system would be used for both LO and data. The LO distribution could be similar to the two-frequency system described by van Ardenne *et al.* ("A High Precision Phase Comparison Experiment using a Geostationary Satellite"; submitted for publication to IEEE Transactions on Instrumentation and Measurements - July 1981. Copy of preprint available in RP Epping Library) for satellite use. The 24 MHz band would be split into three bands of about 7 MHz. This would allow a 20 Mbits/sec data stream from each of Tidbinbilla, Parkes and Siding Spring to Culgoora. The future provision of extra channels in the Parkes to Culgoora direction would allow for operation up to 80 Mbits/sec but would impose considerable strain on the correlator design. (See elsewhere in this report.)

Detailed investigation is needed of the following questions:

(i) The possible use of existing towers and the siting of new towers.

(ii) The capital cost of the proposed system.

(iii) The projected operating costs.

RADIO LINKS

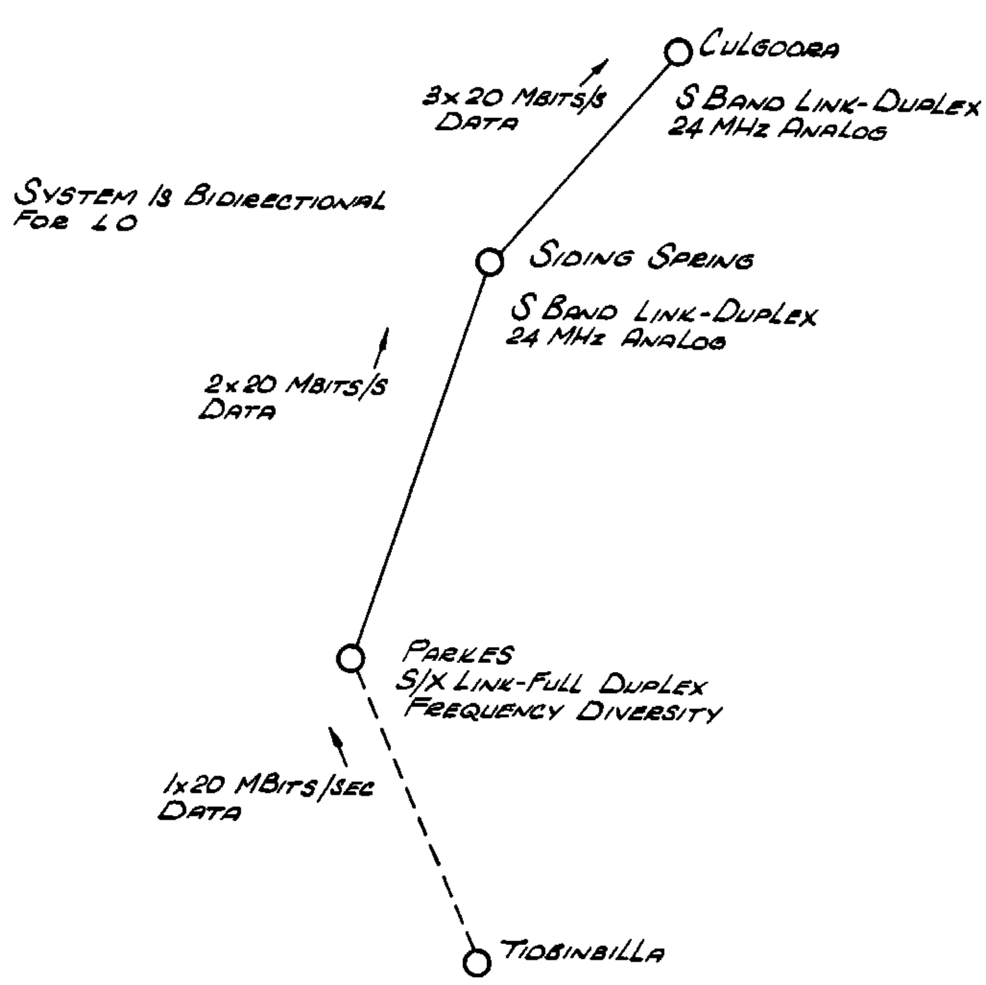


Figure 8.1

9. MONITOR CONTROL

Although this subject was not discussed at the meeting, this note is included to give an idea of the requirements. See also Figure 9.1.

9.1 Telescope Drive

The telescope drive could be controlled either from a central computer or by a local microprocessor under slave control from the centre. The latter might have some advantages since it allows each telescope to be a stand-alone unit. However each time the telescope is moved the master clock would be interrupted which could be a nuisance.

9.2 Monitor

The monitor system keeps track of the behaviour of the telescope and the electronics, and either flags faults or maybe, if possible, switches over from a faulty component to a spare. Use of the latter would depend on the cost of the component and whether it could be easily switched in or out. Flagging will probably be the system used.

9.3 Control and Monitor Wiring List to each Telescope

(i) 3 Phase Power: for aerial drives
electronics
helium refrig.
air conditioning
lights
KVA = ?

(ii) Monitor leads for: aerial pointing
temp - several places
radiometer gain - several places
LO status - i.e. lock
power
freq. select
bandwidth select
digitizer freq. select
cable - OK
helium refrig. - OK

Note: These could be multiplexed and could go onto one of the optical fibres.

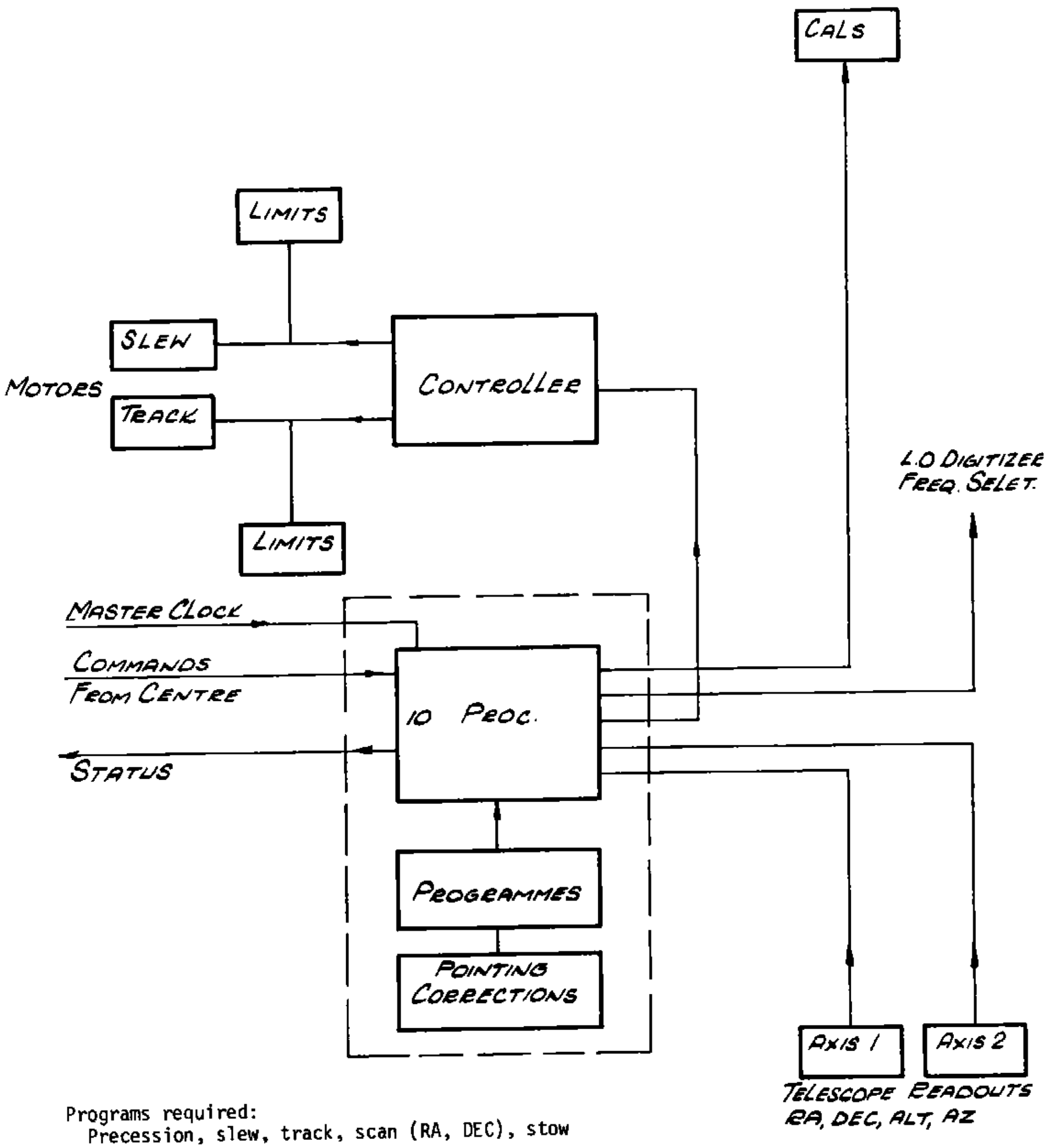
(iii) Hard wired crash control

(iv) TV monitor for remote sites?

(v) IF) optical
Local oscillator) fibres

(vi) Intercom

BLOCK DIAGRAM OF CONTROL SYSTEM



Programs required:
Precession, slew, track, scan (RA, DEC), stow

All units inside dashed box could be at centre.

Figure 9.1

Attachment 1