VLBA CORRELATOR MEMO
VC 045
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EUROPEAN VLBI DATA PROCESSING FACILITY FOR THE 1990'S

A PLAN FOR COLLABORATIVE ACTION BY THE EUROPEAN VLBI CONSORTIUM

NFRA, 15 January 1985

Table of Contents

Abstract

It is proposed that the European VLBI Consortium members collaborate in the construction of a Data Processing Facility (DPF) for the 1990's to be located in Dwingeloo. The main features of the DPF are (i) a state-of-the-art 12 station, 2-bit, wide-bandwidth correlator based on custom-designed chips, (ii) a data playback system constructed along similar lines to the United States VLBA concept, and (iii) provision of a "standard product" to users consisting of edited, calibrated data.

A suggested division of labour amongst Consortium members is that the Netherlands Foundation for Radio Astronomy provide the overall management of the project during the construction phase, as well as the design and construction of the correlator, while the Max-Planck-Institut für Radioastronomie manage the procurement and final testing of the data playback system, and possibly of VLBA-type data acquisition terminals. Other members of the Consortium could provide staff or technician level support for the hardware or offline software aspects of the project.

The estimated costs of implementing the DPF are about 22.0 Mfl, including 8 Mfl for manpower. The cost of 11 data acquisition terminals for use in the field (7 for Consortium members, 4 for affiliates) is about 7.0 Mfl, bringing the total to 29 Mfl. Construction of the DPF should begin in 1987 in order to be completed by 1991.

Operating the DPF will require 8 to 9 manyears/year within the infrastructure of the Dwingeloo Radio Observatory. The total costs of operation are estimated to be about 2.9 Mfl per year.

1. Introduction

It is now generally accepted that European radio astronomy requires a large VLBI processor to cater for the expected demands in the 1990's for global arrays at centimetre and millimetre wavelengths and for observations with an orbiting element (QUASAT). The Netherlands Foundation for Radio Astronomy has carried out a preliminary investigation of the specifications of the correlator segment, reporting to the Committee of Directors (now European VLBI Consortium Board of Directors) on two previous occasions. The correlator is designed to support the simultaneous correlation of 2-bit data from 12 stations at bandwidths per station of up to 1.024 GHz. The following pages outline a plan for the complete processor which calls for a collaborative effort amongst the members of the European VLBI Consortium in order to bring the project to realisation.

2. Key Elements of the Project

The three key elements of the project are the correlator, the data playback system, and the provision of a standard product to users.

The correlator is based on a custom integrated circuit designed in the NFRA to serve the needs of four possible correlator projects: a replacement for the present WSRT digital spectral line backend, a 1024 channel 1.024 GHz spectrometer for the UK/NL millimetre telescope, a 2-dimensional autocorrelator for Speckle interferometry with the 4.2 m Herschel telescope on La Palma, and the VLBI processor. Two other observatories in Europe have indicated interest in this chip for autocorrelators.

The size of the VLBI correlator has been set by the requirement that correlation of 2-bit, one-polarisation data from 12 stations should proceed simultaneously at the maximum bit rate per station permitted by the recording/playback technology. This is expected to be 256 Mbits/sec in 1991; however the correlator can accommodate 2.048 Gbits/sec per station. The 12-station correlator capacity is sufficient for high sensitivity mm-wavelength global VLBI (see Table 1). After reconfiguration to a lower sensitivity (1-bit) mode, continuum observations with up to 17 stations can be processed simultaneously for high dynamic range measurements at cm wavelengths with both ground-based arrays and QUASAT. VLBI arrays of up to 18 telescopes have already been used. Spectral line observations with 512 complex frequency points per baseline will be possible with 12 stations. The various modes of operation are outlined in section 3.

Table 1: Telescopes which could form a global array at λ 3.6 mm.

Country	Telescope	Diameter (m)	Country	Telescope	Diameter (m)
Japan	Nobeyama	45	USA	Amherst	15
USSR	Samarkand	70 (1)		Kitt Peak	12
Iraq	Mt. Korek	30		OVRO	3x15
Finland	Metsahovi	14		Hat Creek	3x8
Sweden	Onsala	20		Mauna Kea (UK/NL)	15
Germany	Effelsberg	14 (2)	Chile	La Silla (Sweden/ESO)	15
France	Plateau de Bure	3x15	Australia	AT	6x22
Spain	Pico Veleta	30			
	Madrid (IGN)	14			

(1) It is not known what effective area will be achieved at λ3.6 mm.
(2) Effective area expected at λ3.6 mm, if pointing and weather permit.
(3) At wavelengths ≲ 3 mm, a number of the antennas would no longer be able to observe effectively.

Specification of the data playback system (DPS) for the European processor will have to follow that of the United States Very Long Baseline Array (VLBA) since there is no immediate prospect of an alternative system originating in Europe for data acquisition and playback. There are obvious advantages to standardising recording systems around the world both for data integrity and ease of operations. In the future, options for data acquisition and playback systems to succeed the VLBA standard should be investigated by a joint team from Europe, USA and Japan. The European Consortium should be prepared to allocate resources to this project.

In the current circumstances there are two options open to us for DPS units:

i) the European Consortium buys DPS units in the USA, or
ii) it contracts the construction of these units out to European industry. The latter course relies on the goodwill of our American colleagues to make the DPS specifications available. It may be the only course open if European sources of finance requires capital expenditures to be made in Europe.

There are also two options open to us for data acquisition terminals (DAT):

i) procure VLBA-standard data acquisition terminals for the European Consortium and affiliate stations. These could be purchased in the USA or contracted out to European industry. An item has been included in the budget in section 6 for data acquisition terminals.

ii) use the density upgraded MK3 terminals in the field as data acquisition terminals, and play the data back through the DPS units at the processor before entering the correlator. Note that DPS units are planned to handle VLBA and MK3 data. However we will then dependent on the older MK3 technology and be limited to a maximum bandwidth per station of 56 MHz.

3. The Processor

3.1. General considerations

A simple block diagram of the processing centre is given in Figure 1. A more detailed view of the processor hardware is given in Figure 2. There are four major components:

(i) data playback system including delay tracking

(ii) a data input and fringe stopping unit

(iii) a digital correlator

(iv) phase tracking integrators.

The size, complexity and cost of the system are mainly determined by three parameters:

(i) the maximum number of stations to be correlated simultaneously

(ii) the maximum bitrate per station

(iii) the number of lags per interferometer.

The number of cross- and auto-correlations to be made is given by:

$$N_c=(N_s(N_s-1)/2+N_s)N_b N_\tau$$

where N_s= the number of stations

N_b= the number of input bands per station

N_τ= the number of lags.

The required correlator capacity is then

$$C=N_c.2B.a \quad \text{WOPS}$$

where B = the bandwidth per input band

a = {1 for a real correlator
 {2 for a complex correlator

WOPS stands for word operations per second

In the VLBA data acquisition system, data is written on tape in 32 tracks, each corresponding to a band of frequencies (so N_b=32), time multiplexed to allow a graceful degradation in performance if failure occurs in one track. Each track has a maximum bandwidth, B, of 4 MHz in the present concept. The number of lags N_τ is normally equal to 32 to allow accurate phase corrections to be applied after transformation to frequency space. For a 12 station correlator the number of correlations, N_c, is equal to 79872. The total capacity required for a complex correlator is then 10^4 giga WOPS (GWOPS).

For a given correlator capacity, it is possible to

a) increase the number of stations at the expense of bandwidth by combining modules (see Table 2).

b) increase spectral resolution at the expense of the number of stations and/or bandwidth (see Table 3).

c) increase the polarisation information at the expense of stations and/or bandwidth (see table 4).

The minimum bandwidth per correlator module will be equal to 16 MHz. The correlator hardware will be designed such that the potential bandwidth per station of 1.024 GHz available for mm VLBI can be achieved with no more than minor modifications.

Table 2: Number of stations versus number of input bands per station for data in one hand of circular polarisation with 2 bits/sample. The number of input bands (i.e. total bandwidth recorded) per station doubles for 17 and 24 stations for data with 1 bit/sample.

Number of stations	Number of input bands per station	Number of correlations (cross + auto) per input band per lag
12	32	78
17	16	153
24	8	300

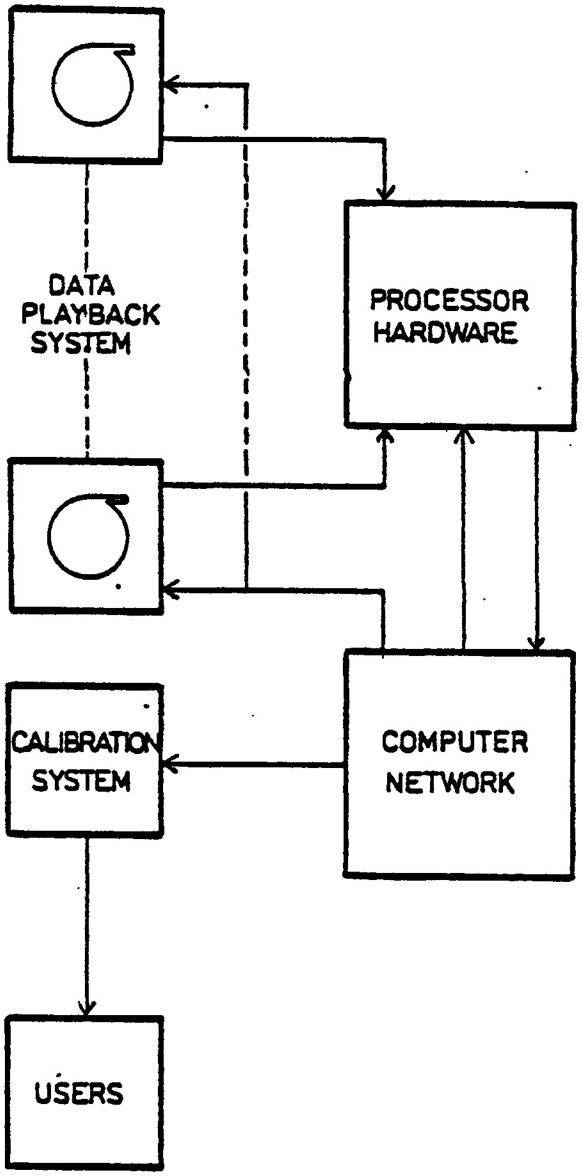

Figure 1 : Overview of the VLBI Processing Centre

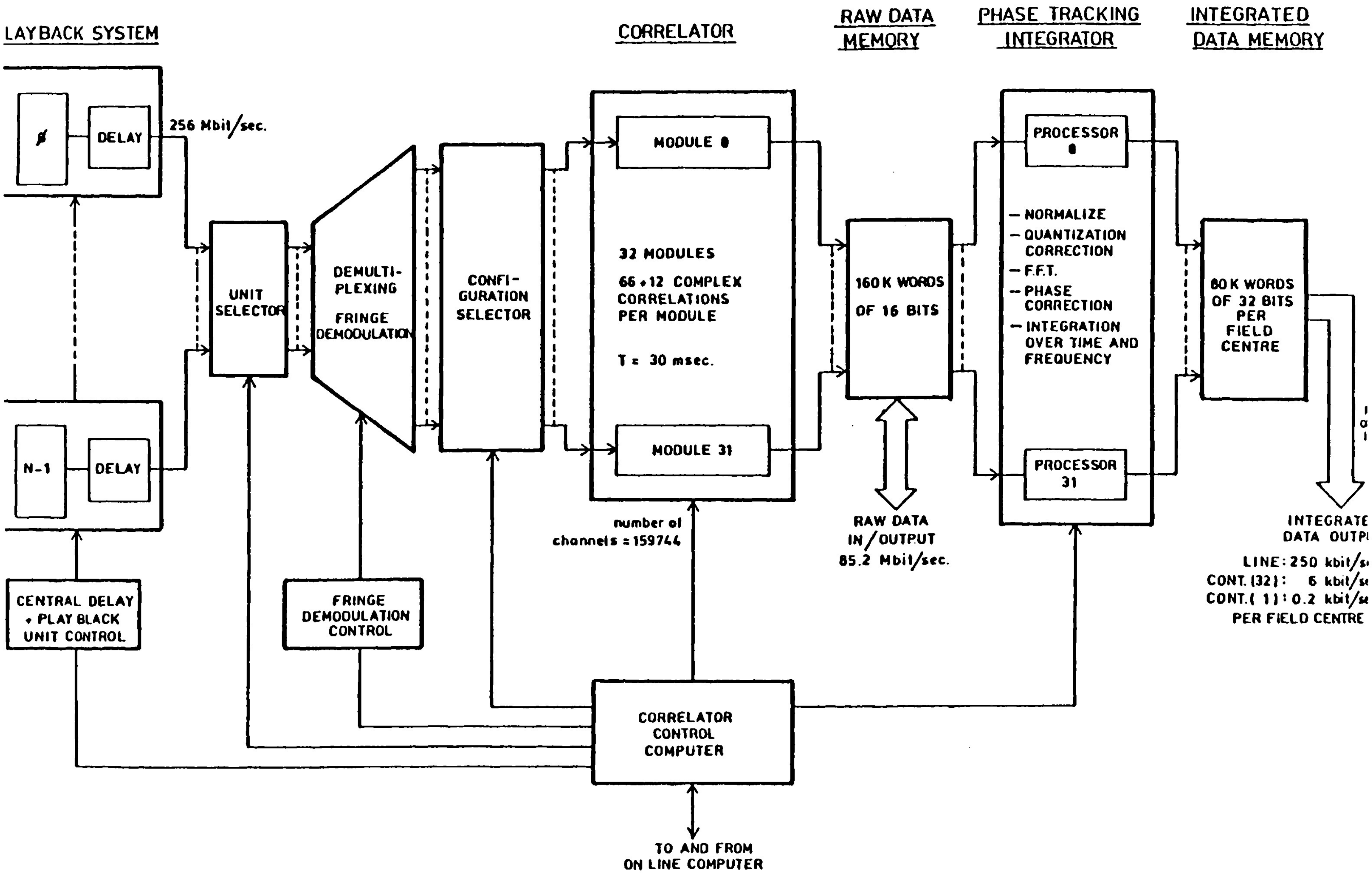

Figure 2 : Detailed blockdiagram of VLBI Processor

Table 3: Frequency points per baseline versus number of input bands per station for data in one hand of circular polarisation with 2 bits/sample. The number of frequency points doubles for data with 1 bit/sample.

Number of input bands per station	Number of complex frequency channels for $N_s = 12$	$N_s = 17$	$N_s = 24$
32	16	-	-
16	32	16	-
8	64	32	16
4	128	64	32
2	256	128	64
1	512	256	128

Table 4: Number of input bands per station versus number of stations, for full polarisation processing for data with 2 bits/sample. The number of input bands per station doubles for data with 1 bit/sample.

Number of stations	Number of input bands per station
12	8
17	4
24	2

3.2. Brief functional description of the processor (see Figure 2)

A bitstream of up to 256 Mbits/sec per data playback unit is sent to the correlator. The playback units are controlled by the control computer via a playback unit control which provides the motion control and the station delay tracking. The correlator organization is determined by a combination of a unit selector and a configuration selector. The configuration selector determines the organization of the correlator hardware. The unit selector determines which of the data streams are correlated.

The bitstreams from the playback units are demultiplexed after the unit selector to minimise the number of interconnections. Each of the demultiplexed bitstreams is phase rotated in a fringe demodulator and sent to the input of one or more correlator modules. Phase rotation is done per antenna rather than per interferometer in order to reduce hardware. The phase rotators are controlled by the correlator computer via a dedicated controller.

The correlator itself is divided into 32 modules. Each module has the capacity to calculate the correlations between 12 inputs (66 cross correlations and 12 autocorrelations). As pointed out earlier, combination of 2 or 4 modules allows correlations between 17 or 24 inputs.

The total number of physical channels is 159744 which will be read out at intervals of $\geq$ 30 msec into a raw data buffer. This raw data buffer will be provided with an I/O port which allows temporary storage and reprocessing of intermediate results using a data acquisition terminal as storage medium. The raw data are processed in a set of special purpose processors which operate as phase tracking integrators. The phase tracking integrators are used to track the phase for one or more field centers and integrate at these points for of the order of 10 seconds depending on the field of view. For continuum observations, a substantial reduction in output data rate is obtained by averaging the 16 frequency points and the $\leq$ 32 individual input bands. The integrated output data are transferred to the online computer system for further processing. The online computer also provides the correlator computer with the parameters for delay and phase tracking.

3.3. Computers

Three levels of computing power are required for the processing centre:

(i) a correlator control computer (CCC) which interfaces with all sections of the processor in Figure 2, providing control of the DPS units and their delay, fringe demodulation, the correlator modules, and phase tracking integrators. A CPU of the class of an HP A900 and disk drive are required.

(ii) an on-line computer which (a) controls the CCC (providing the parameters of the observations, correlator configuration, interferometer geometry and so on), (b) provides the final integration of the data being output from the integrated data memory, and (c) writes the correlation coefficients and auxiliary data out on tape for archiving and dispatch to Principal Investigators.

It may also be possible to carry out the amplitude calibration directly in this computer.

If multiple field centres are requested for line observations, the data rate may be higher than can be handled by one mini-computer, and parallel processing with multiple CPU's may be required.

(iii) an off-line computer of the VAX 11/785 class to provide image analysis capabilities for quality monitoring purposes and local VLBI astronomical use.

4. Data Processing

4.1. General considerations

Providing calibrated data to the users of the EVN and global arrays will allow astronomers to concentrate on the astrophysical interpretation of their data rather than on the gathering of that data. After the tapes are received at Dwingeloo from all the elements of the network, correlation would be carried out by operators in a routine manner unless special instructions come from the astronomer. Normally the astronomer need not be present during correlation or calibration. Calibration of the amplitudes will usually be a routine matter requiring standard measurements of system temperature and antenna gains at each element. The corresponding calibration of phase will be a more complicated procedure if phase referencing techniques come to play an important role in continuum observations.

Accurate baseline calibration in the manner now carried out in geodetic VLBI work will be required as a precursor to phase referencing observations in order to make transfers of phase from reference to program source to sufficient accuracy. Provision of baseline coordinates on a regular basis (one or two weeks) is a service task requiring continuity of approach and an overview of all calibration material available, and therefore a task for the Processor staff.

Calibrated, edited data is proposed to be the "standard product" delivered directly from Dwingeloo to the users of the VLBI system for use with their own software at their home institutes. Astronomers from elsewhere would of course be welcome at any stage of the correlation/calibration procedures, and to use the Dwingeloo general computing facilities.

4.2. Data processing tasks

The tasks can be divided into 3 groups:

(a) **On-line computing tasks**

- delay and fringe rate steering
- correlation of the raw data
- on-line correction of phases in phase tracking integrators
- temporary storage of 30 msec output data from correlator.

(b) Calibration tasks

- calibration: running global fringe fit solutions to calibration observations, running baseline solutions, preparing calibration information;
- correction of the correlation coefficients using the calibration information, including phase referencing;
- editing the data to produce the "standard product".

(c) Analysis tasks

- monitoring performance of the VLBI system;
- archiving;
- administration.
- map and image analysis for line and continuum;

5. Housing of the Processor in Dwingeloo

Projections of the volume of hardware in the complete processor range up to 42 standard 19-inch racks (see Table 5), which may be difficult to accommodate in the present building complex in Dwingeloo. A figure of 1.5 Mfl has been included in the budget (see section 6) to allow for extensions to the building.

It is estimated that the heat output of the electronics may lie in the region of 40 kW. Provision for temperature control requires further detailed study. The interference potential of the electronics is substantial, which may necessitate screening the rooms. Storage for 2000 video tapes (13 m^3, 16 metric tons) is required in a temperature and humidity controlled room.

Table 5: Rack requirements for the VLBI Processor.

Data Playback System: 18 recorders + electronics	27 racks
Correlator + 1 DAT	12
Correlator computer CPU + disk	3
	42 racks

6. Implementation and Operating Costs of the Processing Centre

6.1. Implementation

The hardware costs and manpower requirements for implementation of the hardware and software aspects of the processor at Dwingeloo by 1991 are given as totals in Table 6, together with the costs of procuring data acquisition terminals. A total of 22.0 Mfl is required for the processor, and a grand total of 29 Mfl if DAT's are included.

Table 6.

Hardware	
Data playback system (18 units)	3.0 Mfl
Correlator (including 1 DAT for data storage)	5.0
Computers	
1 correlator control computer (1 disk unit)	0.3
1 on-line computer (1 disk unit, 2 tape drives)	0.7
1 VAX class off-line computer (2x1 Gbyte disk units + 4 tape drives)	1.5
Building	1.5
Manpower 60 manyears hardware	6.0
20 manyears software	2.0
Contingency	2.0
Total for Processor	22.0
Data Acquisition Terminals (11 units) (7 consortium institutes + 4 affiliates)	7.0
GRAND TOTAL	29.0 Mfl

(excluding value added tax)

6.2. Operation

Finance required

Yearly operating costs of ~2.9 Mfl per year are attributable to the processing centre (see Table 7).

Table 7.

Maintenance of hardware (10% of purchase price - includes technical manpower)	1000 kfl
Video tape replacement (4 year life, 2000 tapes)	350
Video tape transport (16 stations x 20 kg x 120 days observing, two way transport	300
Tape drive head replacement (15 kfl per unit, lifetime 8000 hours)	90
Electricity (40 kW)	70
Telephone	20
Manpower (9 manyears/year, see below))	900
General	170
Total	2.9 Mfl

Manpower required

Consideration of the tasks expected of the processor staff during operation leads to the manpower requirement of 8 to 9 manyears/year shown in Table 8. In addition, engineering and technical support will be required and this is budgeted in the first item in Table 7. This manpower would, of course, operate within the environment of the Dwingeloo observatory, and take advantage of the observatory facilities.

Table 8:

1 astronomer	- scheduling
	- supervising correlator processing
	- supervising calibration
	- VLBI astronomy
1 staff member	- calibration
	- interaction with European geodetic groups
1 assistant	- video tape administration
	- visibility tape administation
	- calibration processing
1 chief operator	- scheduling network observing
	- correlator processing
2 to 3 assistant operators	- correlator processing
2 programmers	- processor software
	- calibration software

7. Development Time-Scale

The following action is required in order to have an operational correlator in 1991.

1) Definition, building and testing of a custom designed chip set.
2) Realisation of the custom IC's by a manufacturer plus development of standard building blocks.
3) Development and testing of a small prototype of the basic correlator and final system design.
4) Construction of the correlator system and design of the signal processing.
5) Construction, system integration and testing.
6) Commissioning.

Procurement of the other segments of the processor such as the data playback system, fringe rotation and delay tracking systems, on-line and off-line software, and computing hardware, will need to move ahead on similar time lines if the processor is to be operational in 1991.

Figure 3 is a bar-chart showing the major milestones for the correlator, and a possible timescale for QUASAT.

8. A possible division of labour amongst Consortium members

8.1. Implementation

Task Description	Institute
Overall management of project	Netherlands Foundation for Radio Astronomy
Design and construction of correlator	Netherlands Foundation for Radio Astronomy
Procurement of Data Playback System	Max-Planck-Institut für Radioastronomie
Procurement of Data Acquisition Terminals	Max-Planck-Institut für Radioastronomie.

If it does not prove possible to finance the whole project, including manpower, from external funds, the estimated 60 manyears for hardware and 20 manyears for software is proposed to be provided as follows:

NFRA	20 manyears hardware (correlator)
	10 manyears software (correlator)
MPIfR	10 manyears hardware (DPS and DAT assembly and testing)
Externally funded contract labour	10 manyears software (correlator),
	30 manyears hardware (correlator)

Other Consortium members are encouraged to contribute to the engineering and software by seconding staff or technicians to Dwingeloo and/or Bonn.

It is expected that a project group would be formed from the sub-project leaders in the various Consortium institutes.

8.2. Operation

If the operational costs cannot be completely financed from external funds, the NFRA is prepared to provide 1 Mfl of the 2.9 Mfl required. Any remainder would then have to come from the other Consortium institutes.

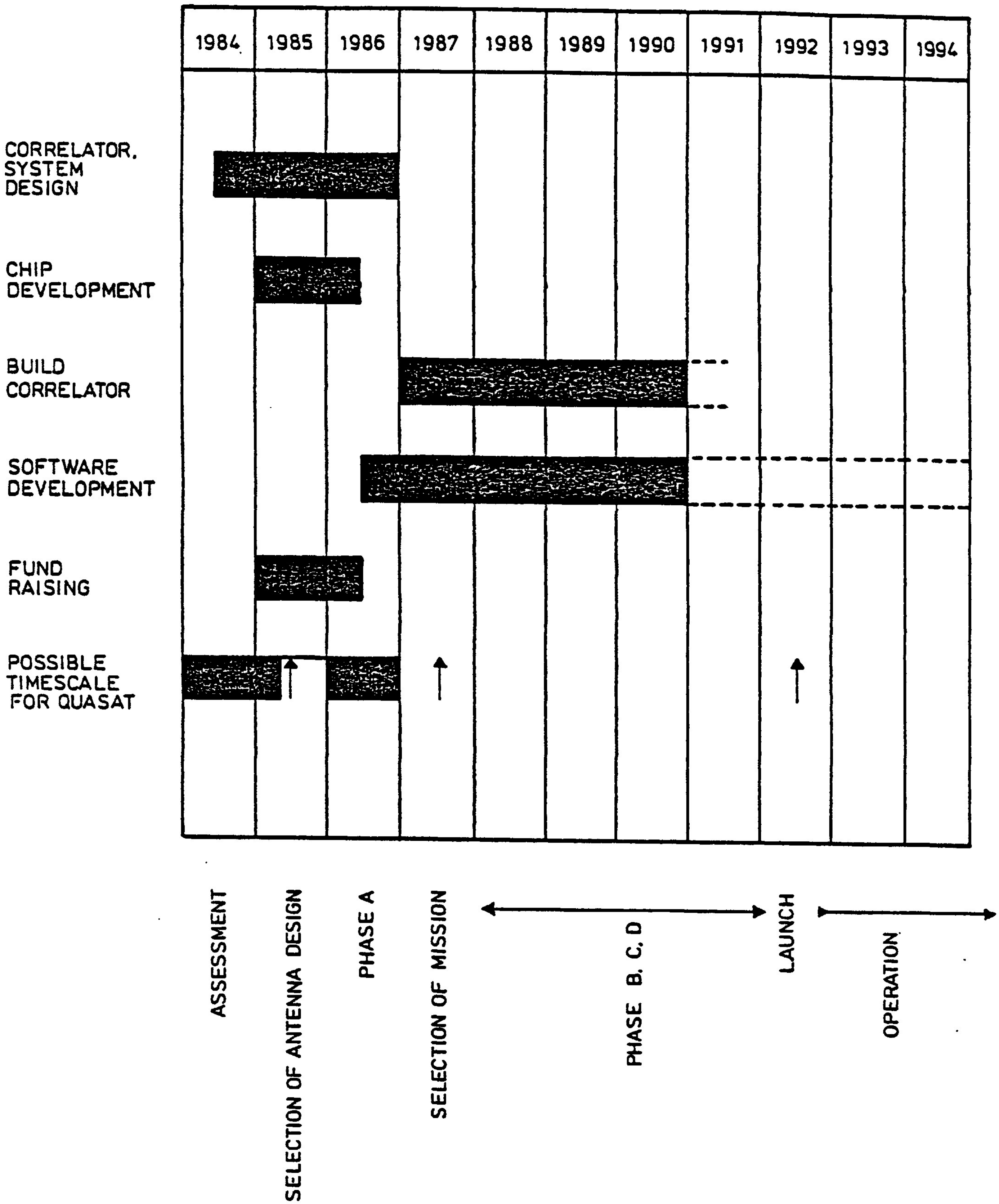

Figure 3: The proposed time-line for the VLBI Correlator and a possible time-line for QUASAT.