VLB ARRAY MEMO No. 189

National Radio Astronomy Observatory
Charlottesville, Virginia

March 3, 1983

MEMORANDUM

TO: VLBA and CLBA Design Groups

FROM: Alan Bridle

SUBJECT: VLBA/CLBA Construction Cost Estimate Comparison

To assist comparisons between the estimated costs of the US and Canadian long baseline array plans, I have tabulated the major items in the construction cost estimates for the VLBA and CLBA. I have broken down the estimates into similar line items to the extent that this can be done from the available documents of each project, and have converted the Canadian estimates to US dollars using a rough approximation to the exchange rate over the six months. The VLBA costs and specifications are as in the May 1982 report. The CLBA costs and specifications are as in the CAS document released in January 1983. I have also extracted some details from the Canadian Astronautics Limited (CAL) Implementation Study for the CLBA.

In the Table, items showing costs PER ANTENNA SITE are denoted by (p.s.). To make the items being compared as similar as possible, I have used per-site estimates for the CLBA "radio astronomy" (southern, 32-metre, 5-frequency) sites (excluding the geophysical equipment), and the full 9-element CLBA costs for the other items. Some items which I am unable to identify in one report but which appear explicitly in the other are indicated by question marks. A dashed line signifies an item which has been conglomerated differently with other items in the other report.

Comments on the comparisons follow the Table.

VLBA-CLBA COST COMPARISON in 1982 U.S. dollars
(Canadian dollars converted at 0.80 US)

ITEM	VLBA	CLBA
Antennas (Manuf/Dev.) (p.s.)	1,749,000	2,455,000
Feed Manufacturing (p.s.)	82,400	289,500
Feed Development	260,000	nil
Feed Assembly/Test (p.s.)	10,000	19,000
Feed Mounts (p.s.)	12,000	???????
Subreflector Hardware (p.s.)	45,000	143,000
Subrefl. Design/Instal (p.s.)	4,000	nil
Cryogenics (p.s.)	130,000	62,300
Cryo Design/Devel.	-------	70,000
Front End Hardware (p.s.)	93,000	61,000
Front End Design	150,000	-------
Total Electronic Design	-------	120,000

Converters/Back Ends (p.s.)	97,000	255,000
Receiver Assembly Costs (p.s.)	136,000	80,400
Hydrogen Masers (p.s.)	250,000	267,000
Rb Clocks/Loran (p.s.)	40,000	32,800
Recorders (p.s.)	16,000	5,100
Tape Handlers/Controllers (p.s.)	43,000	7,400
Record Rack Development	130,000	28,000
Record Rack Assembly (p.s.)	7,000	1,640
Data Tape (p.s.)	45,000	25,300
On-Site Control/Monitor (p.s.)	70,000	53,200
Site Select/Develop (p.s.)	285,000	290,000
Site Test Equipment (p.s.)	35,000	18,400
Site Integration	??????	380,000
Water Vapor Radiometer (p.s.)	35,000	(44,000)
Central Control Hardware	254,000	44,800
Control Software	512,000	404,000
Control System Assembly	??????	113,000
Control Center Integration	??????	96,000
Playback System (p.s.)	66,800	65,100
Correlator Modules	730,000	1,453,000
Correlator Assembly	72,000	160,000
Correlator Control Computer	344,000	611,000
Correlator Software Devel.	96,000	558,000
Processor Integration	64,000	30,200
Post-Processing Computer	2,650,000	1,905,000
Post-Proc. Software Devel.	320,000	(415,000)
Commercial Software	nil	62,400
HQ Building/Land/Fittings	1,650,000	3,273,000
HQ Machine Shop	nil	312,000
HQ Test Equipment	200,000	594,000
Antenna Spares	330,000	nil
Spare H Maser	200,000	267,000
Other Spares	1,135,000	274,000
Project Management	2,000,000	640,000
General and Accounting	---------	1,110,000
Contract Profits	nil	1,460,000
Contingency Rate	12%	10%
Design Contracts	nil	400,000

GENERAL COMMENTS ON THE ESTIMATES

While the two proposals arrived at very similar overall costs, there are differences in the cost distribution which represent differences in emphasis, priority, and (sometimes) in technical specifications. The total costs are very similar if one subtracts the elements of the CLBA design which relate to external contractors' profits. Including hidden overhead in the VLBA proposal arising from the use of NRAO and University resources might also balance the totals more closely ?

The greatest discrepancies lie in:
(a) the antenna specifications,
(b) much higher estimates for feed fabrication in the CLBA,
(c) more generous allocation of resources to record systems (and the sparing of record systems) in the VLBA,
(d) specification of a much more powerful Array Control Computer in the VLBA,
(e) significantly higher estimated costs of fabrication of the correlator hardware modules for the CLBA,
(f) much less disk storage visualised in the CLBA post-processor,
(g) much less room per person in the VLBA headquarters, and
(f) more parsimonious sparing policy in the CLBA.

I will not attempt here to assess whether one plan is preferable to the other in these areas of discrepancy. Many of them anyway lie outside my competency to make such judgements. The technical committees of each project may however want to examine the reasons for the discrepancies, and come to their own conclusions. Some more detailed comments follow.

FURTHER COMMENTS

(1) Antennas.

The CLBA costs are based on quotes from TIW for a 32-m antenna good to 22 GHz. The VLBA costs are an estimate for a modified VLA 25-m antenna good to 43 GHz. Antenna development costs for the VLBA are included in the total cost per antenna, for comparison with the total per antenna quoted by TIW for the CLBA. TIW has recently (early 1983) quoted $3.6M (US) to the Canadian NRC for each antenna in a lot of 14 25-m antennas good to 43 GHz (0.004" panels, 0.015" overall). It is not clear whether TIW's estimates here are inflated, or the VLBA estimates optimistic. TIW has been a low bidder for several recent contracts for research antennas. The detailed performance specifications underlying the recent TIW quote should be compared closely with those underlying the VLBA estimate.

The CLBA's choice of 32-m antennas was driven by criteria of cost-effectiveness, given quotes from TIW of $2.46 M for their 32-m as opposed to $2.0 M for their 25-m antennas (both upgraded for use at 22 GHz). According to these quotes, the 64% greater area of the TIW 32-m antenna increases its cost by only 23%, and choosing the larger antenna increased the overall CLBA construction cost by only 7%. Note that these quotes imply a cost-diameter relation for TIW antennas that differs radically from the norms decribed by Jim Moran in VLBA Array Memo No. 178. Also note the large differential between TIW's quotes for 25-m antennas good to 22 GHz and to 43 GHz. The reasons for these unusual cost relationships among different TIW quotes need to be explored more fully.

The CLBA Planning Committee was concerned about whether a suitable network of unresolved calibration sources could be developed adequately with smaller antennas. There has been little quantitative discussion of this point however, due in part to uncertainty about the VLBI source count at the higher frequencies. If the integral source count had a -1.5 exponent, the number of calibrators detected in a given area of sky with a given signal-to-noise would be doubled by using 32-m antennas rather than 25-m. (The average separation between a program source and the nearest suitable external calibrator would be decreased by 1.4). The ABSOLUTE number of calibrators available, or the mean source-calibrator separation, at a given frequency was not estimated in either the VLBA or the CLBA reports.

Many, possibly most, observations with the array will use self-calibration rather than external calibration. Tim Cornwell's VLBA Memo No. 187 discussed the impact of antenna size on self-calibration, and showed that for pointlike sources the r.m.s. gain error decreases inversely as the antenna diameter, for an array of fixed total collecting area. The 32-m antennas would be cost-effective based on the TIW quotes, but not if based on the cost scaling relationships of VLBA Memo No. 178.

It has sometimes been argued that the sensitivity of an array of 25-m antennas could better that of a similar array of 32-m antennas if the former used global fringe-fitting algorithms and the latter did not (or if the former used a superior correlator design). It is fairer however to assume that the best available signal processing algorithms and hardware would ultimately be used with either size of antenna. For frequencies below 30 GHz, the CLBA's planned 32-m antennas would offer long-term advantages over the VLBA's 25-m antennas. The number of usable calibrators which could be acquired at each frequency, and the number of sources which could be self-calibrated, should be estimated using the expected sensitivities of the hardware and fringe-fitting software before it can be decided whether or not the 32-m antenna size represents overkill or the 25-m size is skimping.

Within fixed boundary conditions for the VLBA of 10 antennas and $51 M cost, use of TIW 32-m antennas appears to be too expensive overall, despite their ostensible cost-effectiveness. If we were to explore a joint US/Canada project with different financial constraints, it could however be worthwhile to re-examine the tradeoffs between number of antennas built, size of each antenna, and highest frequency of operation. These tradeoffs would involve the biggest single factor in determining the cost of a joint project.

(2) Feeds.

The CLBA estimates are much higher, particularly as the CLBA estimate is for 5 frequencies, the VLBA for 10. The quoted CLBA figure is NOT the outrageous quote from Spar Aerospace for "guaranteed performance" feeds, but is a reduced estimate derived by the CLBA Feeds and Receivers Committee; it visualises obtaining shop drawings for the feeds from an antenna design company (such as Spar), contracting fabrication out to industrial shops, then testing and commissioning the delivered feeds using project staff and facilities. The proposed feed designs are similar. Estimates obtained by Tom Landecker (DRAO) for fabrication in Canada of the VLA 6 cm feeds (based on drawings supplied by Peter Napier) were all substantially higher than Peter's estimates. This kind of work may be more expensive in Canada due to the smaller demand for it in the Canadian marketplace.

Development costs listed separately in the VLBA plan are embedded in the feed costs and contractor's profits in the CLBA accounting.

(3) Cryogenics.

The estimates are roughly compatible, given that the CLBA has 2 (radio astronomy) cryostats per site while the VLBA has 7 per site. The CLBA planners were aware of VLA cryogenic costs when making their estimates. The CLBA has an explicit estimate for cryogenics design and development, while the VLBA plan lumps all front end development costs (low noise amplifiers and cryogenics) together.

(4) Front Ends (Low Noise Amplifiers)
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Both designs call for uncooled GaAs FET amplifiers below 1 GHz, and cooled GaAs FETs at 1 to 15 GHz. At 22 GHz, the CLBA proposes a cooled GaAs FET, the VLBA a maser cooled to 4 K. The CLBA has no 43 GHz system. The CLBA costs are therefore much higher per frequency; this may reflect the costs of commercial fabrication of the receivers, as opposed to those of Weinreb, Inc.

(5) Converters/Back Ends
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I have not explored the design differences in any detail. The CLBA estimates are a factor of 2.25 higher than those of the VLBA, for a system which handles only half the number of input frequencies.

(6) Local Oscillators/Clocks.
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The specifications and costs have converged here.

(7) Receiver Assembly Costs.
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These are hard to compare using the generally available figures, as the CLBA estimates contain a major item under General and Accounting costs and profits for contractors. The actual (man-hour, person-year) time estimates for receiver construction are needed for more detailed comparisons.

(8) Recorders.
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The CLBA costs are based on 2 data streams at 48 Mbps each using the Yen (enhanced MkII) system on currently available cassette VCRs. Enhanced MkIII was not considered explicitly in the CLBA plan. Eight VCRs are budgeted per CLBA site (spares are accounted separately). The VLBA plan was based on 4 data streams at 25 Mbps each, with a "spare" Record Rack at every site, allowing for failure of the cassette changer mechanism or for bandwidth doubling in special projects; 20 VCRs are budgeted per site. The actual VLBA plans are, of course, somewhat "fluid" at present.

(9) Tape Handling/VCR controllers
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The CLBA documents mention automatic cassette changing but do not plan development of a custom-made changer and book-keeping engine on the scale of the VLBA plan. The VLBA plan assigns significant costs to the Record Rack development, both mechanical and electronic. The additional costs in the VLBA plan lead to redundancy (and hence to reliability) at each site in normal operation. It is not clear whether the lack of such redundancy would significantly impact the operational reliability of the CLBA.

(10) Record System Development
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Either the CLBA labor is coming cheap in this case, or very little new development is visualised for this item ?

(11) Data Tape
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The CLBA plans for a 30-day supply of tape; the VLBA for a 60-day supply.

(12) On-site Control/Monitoring
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The proposals are very similar here. The VLBA calls for an LSI11/23 class computer with 128k byte memory and 2 10 M byte disks, with CRT, printer and keyboard. The CLBA calls for a PDP11/24 with 128k byte memory, one 10 M byte disk and a dual floppy disk drive, VT100 and LA120 printer. In both cases communication with the Array Control Center is costed on the basis of full-time dedicated lines offering data rates up to 9600 bps.

(13) Site Development/Outfitting
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There is good agreement in this area, though some details differ.

(14) Water Vapor Radiometers
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These are considered an integral part of the VLBA project, but are discarded as a "luxury" from the CLBA.

(15) Central Control System
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The VLBA plan calls for an Array Control Computer with 512K byte memory, two 1600/6250 bpi tape drives, 244 Mbytes of disk, 2 graphics and 8 text CRTs and other usual peripherals. An extra Telescope Control Computer is budgeted at the VLBA Control Center for software development. The CLBA calls only for a very slightly expanded version of its Telescope Control Computer (256K byte memory instead of 128K bytes), essentially the equivalent of the VLBA's "extra" software development computer.

(16) Playback System (Station Modules)
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There is good agreement here.

(17) Correlator Hardware.
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The CLBA estimate for the actual correlator hardware for two 48 Mbps data streams from 10 antennas greatly exceeds the VLBA estimate for four 25 Mbps data streams from 14 antennas (normal continuum operation). The CLBA estimate is that of Canadian Astronautics Ltd. (CAL) based on a subcontractor manufacturing a design using custom gate arrays (presently available ECL type arrays). (CAL reported that manufacturers of very large HCMOS gate arrays using 2 micron technology projected the availability of devices which would reduce their estimate by $240,000 US. CAL also estimated $1.84 M US for commercial fabrication of an alternative design based on the VLA-2 chip). The May 1982 VLBA estimate is based on the VLA recirculating correlator design and experience. (The VLBA report estimates $72,000 for the assembly cost, which in the CLBA estimate is embedded in the hardware cost because of the subcontracting). In VLBA Memo No. 176, Marty Ewing has estimated the cost of VLBA correlators using VLSI correlator chips developed at JPL as $720,000 US. A major difference between the Canadian and US cost estimates (a factor of 4 on a per-baseline basis) may again be due to subcontracting to industry in the Canadian plan.

(18) Correlator (Playback) Control Computer
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In the CLBA Processing Center design a Master VAX11/780 acts as a host to set of three PDP11/24's which in turn "direct traffic" in Aptec Dimensional

Processing Systems with 16 Mbyte mass memories and pairs of FPS AP-120/B Array Processors (64K fast main data memory). One of these (PDP11/24 + DPS + 2AP) subsystems controls the correlator. It is this subsystem, excluding its host VAX, whose cost is compared with the VLBA Playback Processor Computer. The subsystem capacity and cost specified by the CLBA are significantly larger than for the VLBA Playback Processor. I have not attempted to determine whether the CLBA is over-specified or the VLBA under-specified here.

(19) Correlator Software.

The CLBA estimate is for 10 man-years of software development, the VLBA estimate for 3 man-years. The much greater discrepancy between the COST estimates may be due to overhead being included in the CLBA software costs but not in the VLBA costs.

(20) Post-Processing

In the VLBA design the Processor Controller controls the correlator and handles some preliminary fringe-fitting. Beyond this is a system based on 4 VAX 11/780s, costed at $2,650,000 (VLBA report p. VII-12). I have equated this 4-VAX system with Levels II and III in the CLBA design (labelled "Default ImageProduction" and "Interactive Image Manipulation" in the CLBA report, Fig. 4-11). I have assigned the CLBA's VAX11/780 entirely to Levels II and III, ignoring its role in talking/listening to the correlator control subsystem.

The (PDP11/24 + DPS + AP) subsystems in Levels II and III of the CLBA plan are basically used as super-APs and mass memories (16 Mbytes with each DPS) for AIPS running in the one VAX. The main factor in the cost difference is that the CLBA plan calls for much less disk storage (only 1.8 Gbytes) than the VLBA in its post-processor. There are many detailed differences between the post-processor designs, too numerous to list here. Once the difference in disk storage is accounted for, there is no residual cost advantage in the CLBA design. It would have to offer improved throughput to compensate for its hardware diversity, which could make it more cumbersome to maintain or to modify. The CAL report does not discuss the pros and cons of this design relative to a network of VAXes, as is visualised in the VLBA design (and earlier by the CLBA Image Processing Committee). With the rapid evolution of this field, the final choice of post-processing hardware may anyway differ from all of these plans.

The VLBA estimate for post-processor software development calls for 10 man-years; the CLBA estimate (in brackets in the Table because it appears only in the CAL report, not in the CAS document) calls for 6.75 man-years. The COST estimates appear more similar (due to differences in overhead accounting ?).

(21) Headquarters

The costs per unit floor area of the proposed headquarters buildings are similar. The CLBA calls for 3,500 square metres (37,700 square feet) of floor area, housing a staff of 75 plus visitors, with development labs and a machine shop. The VLBA calls for 20,000 square feet housing a staff of 60 plus visitors. Neither plan specifies space allocations in detail. (The CAL report planned a 2,600 square metre (28,000 square feet) CLBA Headquarters Building, assuming a staff of 43 plus visitors, but this was rejected for various reasons by the CLBA Planning Committee).

(22) Site and HQ Integration

The CLBA plans assign explicit costs to system integration, at the sites, at the HQ, and in the HQ-site interface. For example, 180 man-days for each of one engineer and two technologists (costed at $140,000 US overall) are assigned to integrating the HQ control system with the first completed antenna site, followed by 120 man-days of testing with an interferometer employing the first two sites. Further allocations are made for adding each site, commissioning the entire array, and commissioning the Correlation Center. These activities are not costed explicitly in the VLBA plan. This may partly reflect the fact that some of this work on the VLBA would be done "free" by scientists and engineers from its participating institutes. Such work may have to be costed, and shared, explicitly in any joint project, however.

(23) Antenna Spares

The CLBA does not plan a spares inventory for the antennas. Tom Legg has reminded me that the decision not to spare major parts such as drive motors, etc. was based on a recommendation from the CLBA Reliability Study done by Telesat Canada. This estimated a long mean time between failures with minimal impact on array availability. It is not clear (to AHB or to Tom Legg) whether the lack of provision for spares for minor antenna parts was an oversight. CAL recommended sparing at $138,000 US. The VLBA estimate was presumably based on previous NRAO practice.

(24) Other spares.

The VLBA spares inventory is much more extensive, especially after separating out the allocation for one spare hydrogen maser (made in both plans).

(25) Oversight/Accounting/Profits

The two plans have quite different methods of apportioning various overheads, due to the adoption of very different mixes of in-house and commercial effort, and to different styles of accounting. I leave a detailed comparison for those with administrative expertise.