Toward a cost equation for a multielement station

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For purposes of deciding whether a multielement station for the eVLA is an economical way to construct them, we need a cost equation, relating the cost of the station to the number of elements and their size.

I propose to list here some very rough estimates of the quantities going into the cost equation, for the purpose of comparing the cost of a 25m VLBA type paraboloid with a multielement station, and, if the cost is favorable, to tell us the optimum size and number of elements.

A multielement station will not have the same sensitivity as the paraboloid entirely across the frequency bands. The multielement economics will probably dictate that receivers be less costly, and therefore less sensitive. As we go to lower frequencies, the receiver noise becomes a smaller component of the system temperature, so the multielement station will become relatively more sensitive at lower frequencies, relative to the 25 m paraboloid. It seems to me that the goal should be to make the multielement station have the same sensitivity as a 25 m paraboloid at 50 GHz. One would hope the performance at 90 GHz would not be too degraded, and, of course, the cost of receivers to 90 GHz is part of the cost equation.

Below, N is the number of elements, and D is the diameter of the elements.

So the above design parameter says

$$N * D^2 = 625 * (MultielementSystemTemperature)/(SingleElementSystemTemp)$$

Weinreb suggests that at 50 GHz, a receiver temperature of 22 K at cryogenic (15 K) temperatures, 45 K at cooled (pulse tube cooler) temperature. Allowing about 30 K for losses, spillover, and atmosphere would have the pulse tube cooled system less sensitive than the cryogenic system by a factor of about 1.4. I shall, for present purposes, neglect the difference in efficiency of the various types of feeds, and any difference in system temperature arising from a wide bandwidth. I shall consider only the difference in system temperature caused by the different refrigerator types.

I shall consider three cases. a). Pulse tube cooled MMIC in 1-7 GHz, 15 K cryogenic MMIC in 7-50 GHz, conventional cryogenic receiver at 80 GHz. b). Pulse tube cooled MMIC in 1-7 and 7-50 GHz, conventional cryogenic receiver at 80 GHz, and c). Pulse tube cooled MMIC in all three ranges, with probably a significant hit in sensitivity at 90 GHz. In the case of plan c, one would install the 90 GHz receiver as late as possible in the project, so that improvements in technology would make the 90 GHz band as sensitive as possible.

I now list the cost equation components.

1. One of a kind costs

Probably the largest one-of-a-kind costs are those below, though there are others.

A. Tooling setup costs for antenna production. (A real and substantial cost, though it may well be hidden within an antenna purchase contract.)

B. Construction of the bunker which will house the interface to the fiber optic data transmission, the master local oscillator system, and, for a multielement station, the beam forming equipment.

C. Land acquisition and development (power, water, roads....).

D. Master local oscillator for the station.

E. Monitor and control computer.

Although in practice, these costs will have some slight dependence on the number of elements or their size, for the current purpose, we can consider them constant. They therefore have no influence in choosing the number and size of the elements.

The order of magnitude of the above costs is perhaps $850,000, (VLBA site developement costs scaled for inflation) but is unimportant for current considerations because it is independent of whether the element is a single paraboloid or an array.

2. Antenna structural costs

Antenna construction cost rises with diameter in a fashion usually parameterized as D^x, where x lies somewhere between 2.4 and 3.2. The cost is really the sum of many components, some of which have a flatter dependence on diameter (eg encoders and drive system), some of which have a steeper dependence (pedestal cost probably goes about as D^3).

Within the range from 2.4 to 3.2, there is a good deal of disagreement on the appropriate exponent. It can be argued that, within a given technology, the cost rises with number and diameter as $D^{2.7} * N$. On the other hand, for smaller antennas inherently less expensive technologies can be used, for example hydroforming. For current purposes, we can say we are interpolating between the ATA 6.1 meter antenna, and the VLBA 25 meter antenna. I have increased the ATA price by a factor of 1.3 because we will be ordering much smaller quantities, by another factor of 1.3 to include the pedestal and drives, which are not in the estimate I have seen, and by a further factor of 2 to improve the surface accuracy to 0.3 mm RMS. The comparable prices for the 6.1m antenna and the 25m antenna are thus $35,000 and $2,900,000 respectively, leading to a cost of

$$\$130 * D^{3.1} * N$$

3. Costs that go as number of elements

These costs include:

A. Feeds and focusers. These may possibly have a very small dependence on D. The log periodic zigzag feed is part of the low frequency (1-7 GHz receiver). The feed cost for the two remaining bands, plus the cost of a turret rotator to move one of three receivers to the focus might be of the order of $7,000.

B. Receivers. Including cooling. We need to explore options on whether the receivers are cooled to 15 K or to 50 K or uncooled. The ATA receiver and feed combination could be adaped to the 1-5 GHz band The cost is $6,800, which, scaled to our smaller quantities comes out about $8,800. This design does not include a switching noise source, which we find necessary for calibration. When this is included, the low frequency receiver comes in at about $10,000.

The design cannot be simply scaled to the 7-50 GHz band because this design has the dewar located inside the feed. At the higher frequency, the 3mm clearance inside the feed is not enough space for a dewar. A serious rethink is needed. I cannot picture coming up with a design that is not significantly more expensive. In the most extreme case, one may need to put some or most of the feed inside the dewar. A wild guess would be twice the low frequency price, $17,000, for a pulse tube system, $45,000 for a full cryogenic system (the latter is approximately the cost of the 7mm systems we are putting on the VLA now). A pulse tube system at 90 GHz might be a bit less expensive than the 7-50 band, because of the lower fractional bandwidth, and because the parts are small enough to conveniently fit inside a small dewar (a good, inexpensive, window might be a problem, though). The ratio of a 50 K cooled system to a 15 K cooled system would probably be just a bit larger than the 1.78 quoted above.

So receiver costs versus plan (see above) are

Plan	a	b	c
1-7 GHz	10,000	10,000	10,000
7-50 GHz	45,000	17,000	17,000
80 GHz	45,000	45,000	15,000
total	100,000	72,000	42,000

C. Local oscillator slave. Slave must be on the element; there are no viable modulators that can bring home the whole RF bandwidth of 1-90 GHz. Does not necessarily imply an actual oscillator on the element - a photonic LO a la ALMA has its attractions (eg essentially free of interference generation). This is, in any event, a fairly simple system, transmitting a LO signal from the bunker to the element, at a suitable power level. An allowance of $5,000 per element seems sufficient.

D. IF signal processing system. I am assuming that the elements will be combinded digitally. It would be possible to design a pure analog beam former, with switched cable delays and lobe rotators in the LOs. It would have to be demonstrated that such a system could be constructed without adverse effects on closure properties, which would require very tight tolerances on the switched delay lengths. The total complexity of the IF processing system is significantly simpler than that of an element in eVLA phase 1, because of the smaller number of receivers that it has to deal with. The eVLA phase I budget includes $72,000 per element in IF processing. It seems reasonable that the IF processing could be done for about $40,000 per element.

However, putting these systems on the element probably requires some form of temperature stabilization, if not a full HVAC system. An allowance of $8,000 per element for temperature control seems necessary.

Total cost: $48,000 per element.

E. Fiberoptic transmission system, element to bunker. Not clear whether the signal should be digitized at the element or in the bunker. I'd be inclined to think the latter. One suspects the cleanest system is then to run four fibers, one for each IF. At the moment, the most economical system would be a high power laser, beam splitters, and four modulators. Total cost per element, about \$3,000 for the laser, \$2,000 each for the modulators, \$1,000 each for the photodiodes in the receivers: \$15,000 per element. But the technology is changing fast.

F. Digitizers. These have the same properties as those needed for the eVLA phase 1, for which we have budgeted \$15,000 per element.

G. Beam formers. The station board boards WIDAR correlator have the right properties. The output of the station boards can be inexpensively combined to form the station's digital output stream. A complete complement of WIDAR station boards would cost \$45,000 per element.

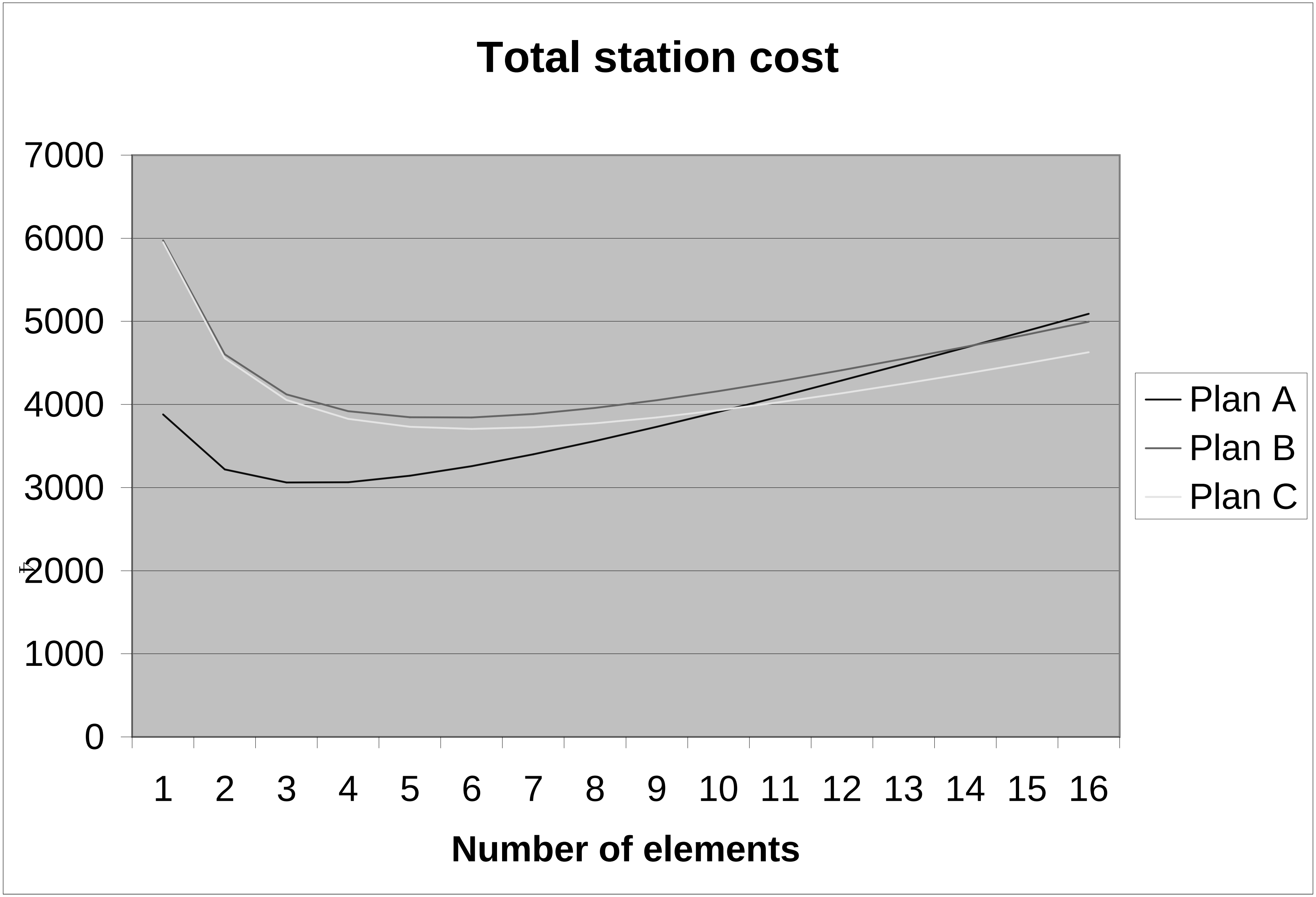
The attached figure shows the cost equation above, plotted versus number of elements.

CONCLUSIONS

An array of about eight 10.5m dishes with inexpensive receivers is of comparable cost with a traditional 25m paraboloid, the same to within the accuracy of this first attempt at a cost equation. This array has the same sensitivity at 50 GHz as a 25m paraboloid, and a slightly higher sensitivity at lower frequencies. However, it is clear that a major cost saving by using the "large N" technologies is not available for eVLA purposes.

It should be noted that at the electronics costs per element have four roughly equal contributors - receivers, digital signal processing, IF processing, and everything else. A significant cost reduction, to make the "large N" approach more attractive, must attack all four areas.

Even in the case of the 25m paraboloid, one element of the ATA technology deserves serious consideration. With a large subreflector, using a zigzag feed to feed a single MMIC for a band from 1 to 7 GHz, or even 1 to 10 GHz, may be feasible, and a significant cost saving. For the small subreflector of the current VLA dishes, the feed is probably prohibitively long.


Total station cost
7000
6000
5000
4000
3000
2000
1000
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Number of elements
Plan A
Plan B
Plan C