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Memo 90

Dish Cost Frequency Scaling

J. Bunton

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John Bunton, CSIRO ICT Centre

Email john.bunton@csiro.au

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Introduction

It is accepted that at the highest frequencies specified in the SKA science case the receptor technology will be parabolic dishes. However the cost of dishes at this frequency currently results in a collecting area much less than one square kilometre. To get sufficient area it might be necessary to reduce the maximum operating frequency.

In this memo historical data is examined in an attempt to determine the relationship between frequency and cost. It appears that the cost of a dish is approximately proportional to the square root of frequency so that reducing the upper frequency by a factor of ten reduces costs by a factor of three.

Comparison

To make a valid comparison it is necessary to eliminate as many variables as possible. Thus dishes that make use of exotic material such as those used in the Pico Veleta telescope or the GBT with an active surface will be excluded. In the latter case the data can still be used but the maximum frequency is that of the telescope without the active surface in operation or about 15 GHz for the GBT. Even with these factors removed there are still the factors of diameter and inflation that can be corrected for, and finally there is the difficulty in actually getting data. It is hope that this memo will bring to light data on more antennas so that the tentative conclusions derived here can be either confirmed or denied.

Cost of existing telescopes

The cost and time of construction for telescopes for which data has been found so far is given in Table 2. This data is firstly corrupted by the fact that the antennas have been built at different times. To overcome this problem the costs are all converted to US dollars at the time of construction and then US inflation data [10] is used to bring the cost to a current dollar cost. The US inflation data is shown in Table 1. Inflation is used rather than CPI (consumer price index) as much of the cost of a telescope is labour and inflation tracks labour cost better than CPI

Table 1 Inflation for the United States [10]

Years	Inflation % per year	Change over period	Cumulative change to 2006
1957-59 (est)	1.92	1.06	11.3
1960-69	1.92	1.21	10.7
1970-79	3.36	1.39	8.84
1980-89	11.68	3.02	6.35
1990-99	5.50	1.71	2.03
2000-06	3.00	1.19	1.19

Converting all data to US dollars and applying the inflation correction given in Table 1 gives the estimated 2006 cost for the telescopes in Table 2

Table 2 Costs of a number of radiotelescopes in current dollars.

	Year Complete	Cost at completion	conversion to US\$	Inflation to 2006	cost US\$M 2006
ATA [1]	2006	\$US41k	1	1	41
Lovell [2]	1957	£st630k	2.8	11.2	19,757
Parkes [3]	1961	\$US1.1M	1	10.416	11,458
Effelsberg [4]	1972	DM34M	0.31	8.176	86,175
GBT [5] ^{note 1}	2000	\$US 75.4M	1	1.19	89,726
VLBA [6] ^{note2}	1993	\$US2.3M	1	1.73	3,979
Radioheliograph [7]	1967	\$US630k	1	9.296	5,856
Component cost [8]	1967	£1k	2.3	9.296	21
GMRT (Dish) [9]	1996	\$US400k	1	1.512	605
Molonglo [10]	1967	\$US746k	1	9.296	6,935
ALMA [17]	2006	\$US6M	1	1	6,000
Pico Veleta [17]	1980	DM25M	0.55	6.35	87,313
HHT [17]	1992	DM7M	0.62	1.89	8,203

note 1 Funding approved in 1989, completed 2000

note 2 Last antenna completed 1993

The costs shown in Table 2 are for telescopes of different sizes and number of antennas. To allow a fair comparison the cost has to be normalised to a common diameter. When Parkes was being designed, it was estimated that cost was proportional to diameter raised to the power 2.5 [12]. Swarup & Shankar [6] quote a figure of 2.5 to 2.7 and many recent authors [13] [14] have used diameter to power 2.7 and even diameter cubed [15] has been used. For the work here a cost proportional to diameter^{2.7} will be used. Using this scaling factor the cost of a single 100m² reflector (diameter = 11.3m) can be calculated. The results of the calculations using these assumptions are shown in Table 3, along with the maximum operating frequency.

The maximum frequency quoted in Table 3 is in most cases the maximum operating frequency at the time of construction. Exceptions are Effelsberg where the central 67m has a higher maximum frequency than the full surface. The full surface, where the outer section is mesh, operates at up to 8 GHz. The GBT requires an active surface to reach its maximum operating frequency. For a fair comparison its operating frequency with the active surface disabled is given.

Table 3 Cost of a 100m² antenna based on cost for existing telescopes

	cost 2006 \$USk	Diameter metres	number elements	Cost scaled by D ^{2.7} to 100m ²	Maximum Frequency
ATA	41	6	1	227,000	11
Lovell ^{note1}	19757	76	1	115,000	3
Parkes ^{note1}	11458	64	1	106,000	3
Effelsberg	86175	100	1	239,000	8
GBT ^{note2}	112000	105	1	218,000	15
VLBA	3461	25	1	466,000	44
Radioheliograph	5856	13.7	96	36,000	0.16
Component cost	21	13.7	1	13,000	0.16
GMRT (Dish)	605	45	1	14,000	1.4
Molonglo	5578	12	354	17,000	1.4
ALMA	6,000	12	1	5101	950
Pico Veleta	87,313	30	1	6254	300
HHT	8,203	11	1	9748	950

^{note1} Maximum designed frequency at time of construction, numerous upgrades have increased performance

^{note2} Maximum frequency for GBT without active surface, with active surface its hope to work to 100 GHz.

For the first five reflectors (ATA to VLBA), the quoted cost is almost exclusively for the construction of the dish. For Lovell, Parkes, Effelsberg and GBT each cost more than ten million dollars making the cost of other components such as receivers and control buildings a small part of the total. For the ATA and VLBA actual costs of the antennas are known. The cost versus frequency results for these reflectors is shown in Figure 1. It is seen that most of the data points are all close to the fitted function except for Effelsberg (8 GHz) and the GBT. The higher cost of Effelsberg probably represents the added cost of including the inner 67m high frequency surface. For the GBT it is known that the contractor had cost overruns, but the true nature of these is not known.

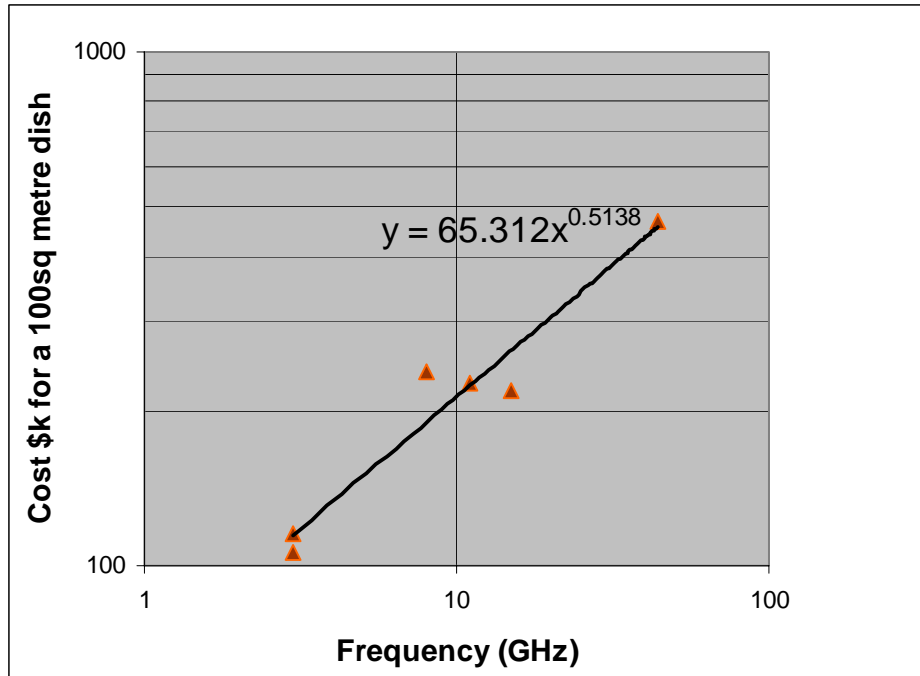


Figure 1 Normalised cost as function of maximum operating frequency at time of completion

The data shown in Figure 1 is highly suggestive that the cost of dish reflectors is approximately proportional to the square root of frequency. To confirm the result more data points are needed especially at higher and lower frequencies.

Unfortunately at higher frequencies dishes become thermally limited rather than gravitationally limited [Christansen and Hogbom]. This is exemplified by the use of exotic materials and thermally controlled backing structures. This makes such dishes unsuitable for a direct comparison with the dishes in Figure 1.

The only dish at lower frequencies where the author has data is the Culgoora Radioheliograph. One datum is the US\$630,000 granted for the construction of the telescope. If all this was used for the construction of the 13.7m dishes then each dish has a current cost of \$36,000 when scaled to 11.3m diameter. But included in the construction cost is infrastructure, a complex analogue beamformer and signal transmission from the antennas to the beamformer. This indicates that the actual dish cost is less than \$36,000. The second datum is a comment made to Mike Kesteven [private communication] at the opening of the AT by the Radioheliograph dish designer Keith McAlister who indicated that he had one thousand Australian Pounds to build each dish. This is apparently the cost of the hardware for each dish because the labour to build the dishes was supplied by Radiophysics. Using this data indicates that the scaled cost of a Radioheliograph dish is greater than \$13,000. Thus for this dish only the limits to the cost are known. These data are plotted in Figure 2

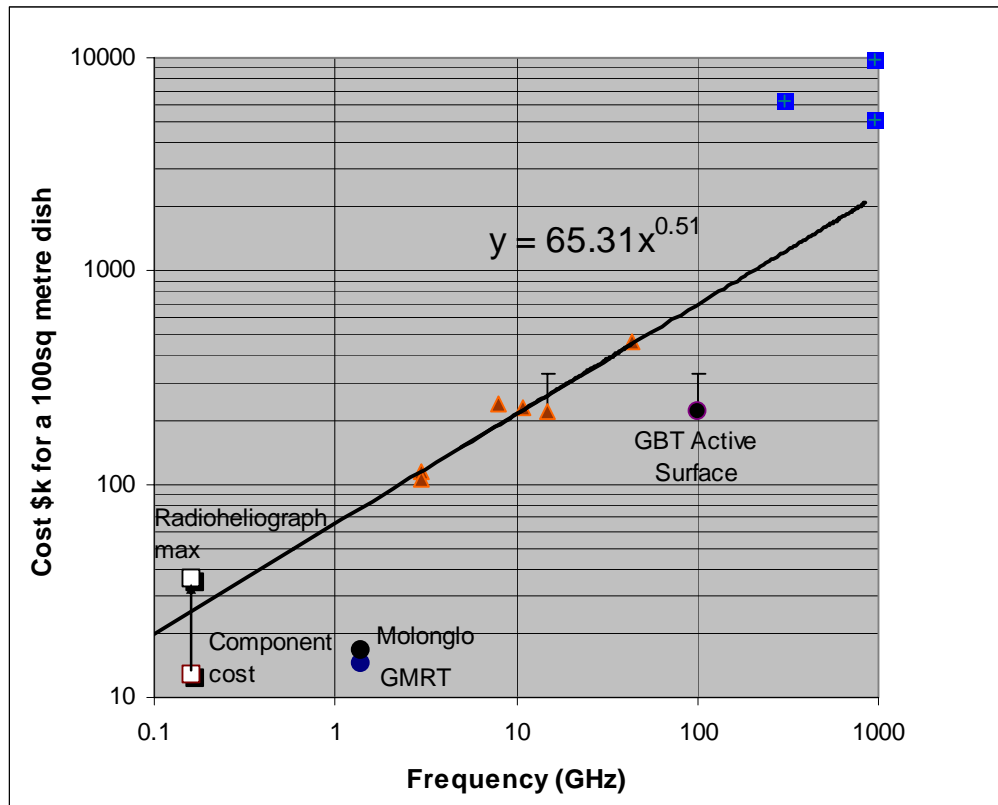


Figure 2 Plot of all available data

Extrapolation of the fitted line for the 3 to 40 GHz data to 0.16 GHz shows that the extrapolation is compatible with the known cost limits for the Radioheliograph dishes. Thus the Radioheliograph data does not refute the conclusion that dish cost scales as approximately the square root of frequency but neither does it significantly add to our confidence as to the actual exponent. For example adding the component cost value to the estimate gives a dish cost that varies as frequency to the power 0.64 and using the maximum Radioheliograph cost gives frequency to the power 0.45.

A question that is unanswered by the data is the smoothness of the trend. Undoubtedly the required stiffness of backing structures and mounts increases smoothly with frequency but what about changes in technology. The latter should introduce break points in the costs. For example moving from a mesh surface to a solid surface causes an increase in cost but the reduction in leakage usually leads to a much higher operating frequency. So a change in technology may lead to gaps in the data with mesh below 3GHz and solid surfaces above 10GHz. Could this be true for all technology changes? Unfortunately there is insufficient data to tell. But certainly a radical technical innovation should lead to designs that fall below the trend line as is exemplified by the GMRT.

High Frequency Designs

Data for three antennas (ALMA, Pico Veleta and HHT) whose performance approaches one teraHertz is shown in Figure 2. Unlike the 3-40 GHz antennas, which are gravity limited these high frequency antennas are thermally limited. This

necessitates a change in design philosophy away from steel structures to more exotic materials such as invar and carbon fibre as well as the addition of thermal stabilisation system such as the air conditioned backing structure on Pico Veleta. It would appear that these factors coupled with the difficult sites where these antennas are built leads to antennas that lie well above the line fitted to the lower frequency data.

Low cost designs

Also shown in Figure 2 is the data for the GBT with active surface, GMRT and Molonglo. Each of these operates at points that lie significantly below the fitted power law for standard designs and each provides a possible means of reaching SKA cost targets.

The target operating frequency for the GBT is 100 GHz and currently with open loop compensation good efficiency is achieved at 40 GHz. This shows that an active surface is an effective way of increasing maximum operating frequency. It suggest that greater consideration should be given to a light weight 10-15m dish which is gravity limited to ~5GHz together with active surface compensation to take its maximum operating frequency to 30-50 GHz. The cost prediction for this is about \$1500/m² for an 11.3m dish. Using cooled receivers with a half square kilometre of collecting area allows the SKA target to be met. This must be tempered somewhat by the uncertainties in the cost of the GBT. On completion there was a significant dispute with the contractor, which if it had been decided in the contractors favour would have significantly increased cost. Also the GBT was built at a time of high inflation and if the payment for the telescope occurred earlier than 2000 then the cost in 2006 dollars would be higher. To illustrate the possible effect of these errors the GBT data points in Figure 2 are plotted with a +50% error bar.

A completely different approach to low cost dishes is exemplified by the GMRT. This 45m-diameter dish has an innovative surface that consists almost entirely of wire rope and mesh. However with a cost that may be more than a factor of four less than conventional dishes this design might provide the large collecting area needed for HI science. What needs checking for this design is the labour cost component as the dishes were constructed in India where labour costs are low.

The Molonglo cylindrical reflector is also a low cost design, and like the Radioheliograph the grant money was used to build reflectors as well receivers, beamformers, correlators and onsite building. Unlike the heliograph the University of Sydney did not have internal manpower resources that could be used to help construction thus all mechanical construction costs came from the grant money. There is also the difference between the two arms of the telescope with one moveable arm that could be a prototype for SKA requirements and one fixed arm. The mechanical structure of the fixed arm is cheaper but it also included complex mechanical phase shifters that increased cost. So for a first approximation to the cost, all the grant money is attributed to reflector construction to give the value of \$17,000 for 100 m² in 2006 dollars. A second point of reference is the recollection by Bernie Mills [16] that US\$600,000 was spent on the reflectors. If the fixed reflector was half the cost of the moveable one then again the cost is about \$17,000 for 100 m² in 2006 dollars.

Thus the estimated cost of cylindrical reflectors, from historical data, is one quarter that of conventional dishes. This appears low and more recent estimates [SKA EWG antenna white paper 2006] have the cost closer to half that of a conventional dish. Savings in using a cylindrical reflector come from a reduction in the drive cost as there is only one axis of rotation not two, approximately half the foundation cost as each support needs to handle loads in one direction not two, and greater ease of surface attachment as there is bending in one direction only.

Conclusion

From the small amount of data available it is estimated that the cost of standard steel manufactured parabolic dishes is approximately \$65,000 times the square root of frequency (in GHz) for an 11.3 m reflector (100 m² in area). The author does not have a great deal of confidence in this result and, to confirm it, significantly more data are needed. Please send any usable data to the author as it is hoped that this memo can be updated in the future.

Other designs point the way to lower cost solutions. For example, the Indian GMRT design should be explored more fully; if high frequency performance is needed then an active surface might prove useful; while cylindrical reflectors provide a known low cost solution to building collecting area.

Acknowledgements

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