COST SCALING LAWS AND THEIR ORIGIN: DESIGN STRATEGY FOR AN OPTICAL ARRAY TELESCOPE

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ABSTRACT: Power law relationships between cost and aperture of optical telescopes are shown to be approximations to polynomial expressions. These polynomials, which are derived for telescopes of traditional and cost-reduced design, have implications for the cost-effective design of an optical array telescope.

1. Introduction

In recent years it has become common practice to seek a simple scaling law between the construction cost (C) of a telescope and its aperture (D) so that, for some range of D, the construction cost is represented by

$$C = L D^{\alpha} \quad (1)$$

This power law representation is, we suggest, only an approximation to a polynomial expression which is discussed below, and if one wishes to determine analytically how such a scaling law arises or if, for example, one wishes to examine how C for a given aperture can be minimised, it is necessary to consider the aperture dependence and relative importance of the individual contributions which go to make up the total cost.

C is taken here to be the total construction cost of a telescope, and its enclosure so that it includes contributions from the mechanical structure, the drive and control system, bearings, optics, cabling, and dome and site preparation etc., but excludes focal plane instrumentation which is considered later. Some of these cost contributions (such as the tube trusses in an equatorial telescope, and other components which experience

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high bending stresses) are expected to increase as D^4 (see footnote *); others (such as the mirror blank; concrete foundations; and possibly the mirror cell and the dome) where the principal dimensions each scale as D, arise also from the cost of materials but with a D^3 dependence; other labour intensive costs (such as machining of mechanical parts, mirror grinding and polishing, painting, etc.) are dependent on surface area and are expected to increase as D^2; others (such as cabling) lead to a linear dependence on D; and others (such as assembly costs if there are a fixed number of components; computers; commissioning costs; and certain overheads) have little or no dependence on D. This leads to the cost-aperture relationship being expressed as a power series in D

$$C = L_o + L_1 D + L_2 D^2 + L_3 D^3 + L_4 D^4 + \ldots \qquad (2)$$

where the coefficients L_i determine the magnitude of each contribution to the total cost and hence the value of the exponent α in the power law approximation (1). It is assumed of course that (2) is applied only to the inter-comparison of telescopes which use similar designs and methods of construction, and that C is a continuous function of D over the range of D to which it is applied.

2. Influence of telescope/enclosure design

For traditionally designed telescopes (those built prior to the late 1970's) the power law exponent α was driven strongly by (a) the dome cost which could be taken to increase as $D^{2.5}$ or D^3 (and which in many projects contributed as much as 30-50 percent of total project cost); and (b) the cost of the mechanical structure to support a heavy primary mirror in an equatorial mount - a design which necessarily caused several major components (the fork or yoke, the tube, etc.) to experience high bending stresses and hence a high power dependence on D. By plotting the inflation-adjusted cost against D for telescopes in a range of sizes built

* A simple example is a cantilevered beam, anchored at one end and uniformly loaded, of length x and square-section of dimension d. The deflection at the free end produces a slope proportional to x^3/d^2, so that if the length is doubled the beam depth has to be increased by a factor $\sqrt{8}$ for the same slope; for the tube structure of an equatorially mounted telescope the beam width would also have to be increased by $\sqrt{8}$, so the new volume (and hence weight) of the beam has increased by $2.\sqrt{8}.\sqrt{8} = 2^4$. This applies to beams with hollow cross-sections as well as to solid beams. For the same beam in an altazimuth telescope where extra stiffness may be required in only one dimension, the weight need increase only as the power 2.5 of the increase in length (since $2.\sqrt{8} = (2)^{5/2}$).

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prior to the late 1970's it was found empirically (see Meinel 1978, Meinel and Meinel 1980) that the power law exponent in (1) took the value of $\alpha \simeq 2.6$. For a much smaller number of telescopes built in the 1960's with apertures in the range 0.4 - 4.0m, Abt (1980) reported $\alpha = 2.37$.

The project cost data published by Meinel (1978) for traditionally designed optical telescopes (including dome and site development costs but excluding focal plane instrumentation) are fitted, according to Meinel, by a power law with index 2.63, so that project cost $S = 0.42\ D^{2.63}$ where the aperture D is expressed in metres and S (inflation adjusted) is in $ million U.S. (1980). The points actually plotted in Meinel's Figure 3 appear to have a power law index no higher than 2.58, however, and the power law approximation is taken here to be**

$$S = 0.37\ D^{2.58} \qquad (3)$$

This is shown in Figure 1. It is our purpose to suggest how that particular relationship arises for traditionally designed telescopes and to predict how it may change in cost-reduced designs.

Bearing in mind the comments which were made in the introductory Section, we seek a quartic polynomial which, when approximated by a power law, is least squares fitted by equation (3) over the range of D for which data are available and which has acceptable coefficients as defined below. It is found by trial and error that a polynomial which satisfies these requirements is that which has the coefficients shown in the first row of Table 1. This is labelled P1 and is shown also in Figure 1. By altering the coefficients of P1 it is possible to obtain slightly closer fits but in doing so the set of power term coefficients may then become unacceptable.

The coefficients in P1 are considered acceptable in the sense that (a) they all have positive sign, (b) the correlation coefficient of (3) and P1 is close to unity, and (c) the individual power terms give fractional contributions to the total cost, at chosen values of D, which are sensible as judged by practical experience. That the coefficients are presented

** This is obtained as a least squares fit by excluding the five points to the left of Meinel's 'optical' line (which otherwise would reduce the index even further) and by excluding the MMT (which is of non-traditional design). See Figure 1.

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Table 1 Coefficients of terms in the suggested polynomial cost/aperture expressions for traditional and cost-reduced telescopes

Polynomial	Design	L_4	L_3	$L_{2.5}$	L_2	L_1	L_o
P1	traditional	0.015	0.109	–	0.145	0.032	0.119
P2	cost-reduced	0.0033	0.0145	0.005	0.178	0.032	0.119

Table 2 Fractional contributions to total construction cost by individual terms in the polynomial expressions P1 and P2

Polynomial	Aperture (m)	L_4D^4	$L_3D^3+L_{2.5}D^{2.5}$	L_2D^2	L_1D	L_oD^0
P1 (traditional)	D = 1	0.04	0.26	0.34	0.08	0.28
	D = 4	0.29	0.52	0.17	0.01	0.01
P2 (cost-reduced)	D = 1	0.01	0.05	0.51	0.09	0.34
	D = 4	0.17	0.21	0.57	0.03	0.02

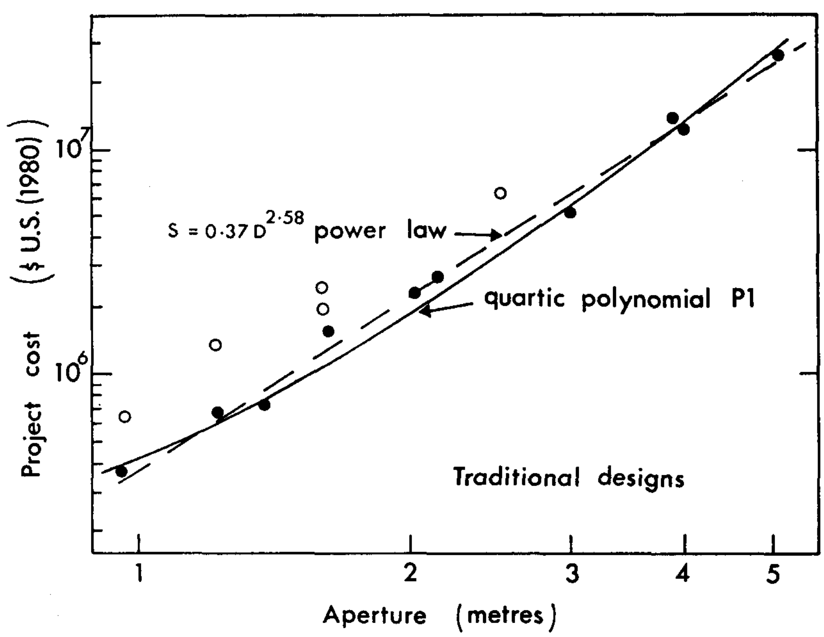

FIGURE 1. Comparison of polynomial cost-aperture relationship with power law for traditional designs. Circled data are those of Meinel (1978). Only the filled circles have been used here. Projects which may be described arguably as excessively expensive (open circles) have been ignored in order to improve homogeneity in the original sample which covered projects of different design and performance, and which were costed by different institutes.

in Table 1 with the number of decimal places shown merely reflects the need to obtain a self-consistent set such that P1 is least-squares fitted by (3); it is not an indication of the accuracy with which it is considered that the various cost contributions can be estimated.

For D = 4m and D = 1m the fractional contributions of the individual terms in P1 are given in Table 2. As explained above, the D^4 contribution in a fork or yoke mounted equatorial telescope will arise from those parts of the tube structure and mount which experience high bending stresses; the D^3 contribution is taken to arise partly from the dome and partly from the telescope; the D^2 contribution arises from several sources but principally the optics.

Such fractions are broadly in line with those which have been encountered in building traditional 4m and 1m telescopes. Individual telescope designs may show wide variations from the situation described, of course, and the examples given here should be taken to be illustrative only. And, since the source data do not comprise a homogeneous set of designs covering the aperture range of interest with similar bases for their costings, it is not possible to verify that the observational points are fitted better by P1 than by (3). Of possible significance is that Meinel's data show quite a wide scatter at low D and this may conceal evidence for the levelling off predicted by P1. However, the polynomial interpretation given here is entirely consistent with Abt (1980) finding a lower value for α (α = 2.37) when applied to telescopes in a range which includes smaller aperture sizes.

Consider now a weight-reduced telescope in which cost savings have been made principally by: (a) the use of an altazimuth mount in which the stresses are mainly compressive rather than bending; (b) the use of optimised stiffness to weight ratios for all components including the primary mirror, i.e. finding a minimum weight design solution which just allows the performance requirements to be met; (c) replacement of the traditional dome and support building by an enclosure consisting of a simple steel framework with low cost cladding. As a result of (a), the mounting structure is now more compact and the D^4 contribution is largely removed. The bending stresses in the tube now give rise to a $D^{2.5}$ term; (b) leads to weight reduction all round and a decrease in the coefficients of the telescope D^3 terms; and (c) reduces that part of the D^3 term

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contributed by the dome and replaces it by a term which is more nearly D^2.

Suppose then that polynomial P1 is modified to incorporate these changes for a cost-reduced telescope as shown in Table 3. No attempt is made here to give a strict justification of the magnitude and nature of these changes. They are merely rough estimates based upon an approximate weight apportionment between (telescope tube)/(fork or york)/(base support) for traditional telescopes plus the knowledge that for D ~ 4m the total weight of a telescope of traditional design can be reduced by at least a factor of 3 (the 3.6m CFHT and 3.8m UKIRT indicate that this is so, though it raises also whether similar levels of performance are attained). Thus, replacing the D^4 and D^3 terms of P1 by those in column 3 of Table 3, and adding the new $D^{2.5}$ and D^2 terms, gives the polynomial labelled P2 with coefficients shown in Table 1. The least-squares fitted power law approximation to P2 is now

$$S = 0.31\ D^{2.0} \tag{4}$$

and the fractional contributions to the total construction cost given by P2 for D = 4m and D = 1m are then as shown in the second row of Table 2. For the D = 4m example, instead of some 80 per cent of total project cost being locked up in the D^4 and D^3 terms for traditional telescopes, polynomial P2 predicts that for cost-reduced telescopes the terms higher than D^2 contribute only about 40 per cent of total project cost and the main contributor is now the D^2 term.

What is interesting is that cost savings on the scale indicated above appear already to have been made, or to have been considered feasible, in the cost-reduced telescope construction projects completed or proposed within the last five years. These include the Australian Universities' Telescope, 2.3m; UKIRT, 3.8m; and MMT, 4.4m. Although there are insufficient data for any firm conclusion to be reached, the indication is that new, low-cost telescopes already have a scaling law index close to 2.0. And, we take this as providing some evidence at least that the polynomial form of the aperture dependence of telescope construction costs as described in this paper, although possibly deficient in precise detail, may indeed be close to the true situation. For all these reasons we choose to use (4) as our best estimate of the approximate cost-aperture relationship for the present generation of low-cost optical telescopes.

Table 3 Transformation of polynomial expression P1 to give P2

Term in P1	Presumed origin and apportionment for traditional designs	Terms for cost-reduced telescopes	Reason for change
$0.015D^4$	Tube, trusses, top end ($0.005D^4$)	$0.005D^{2.5}$	Altazimuth design (see footnote in Section 1).
	Telescope mount ($0.010D^4$)	$0.0033D^4$	Small D^4 term for residual bending stresses.
$0.109D^3$	Dome ($0.0654D^3$)	$0.0327D^2$	D^2 dependence due to design + reduction of 2X using low cost cladding.
	Telescope ($0.0436D^3$)	$0.0145D^3$	Weight reduction by factor 3.

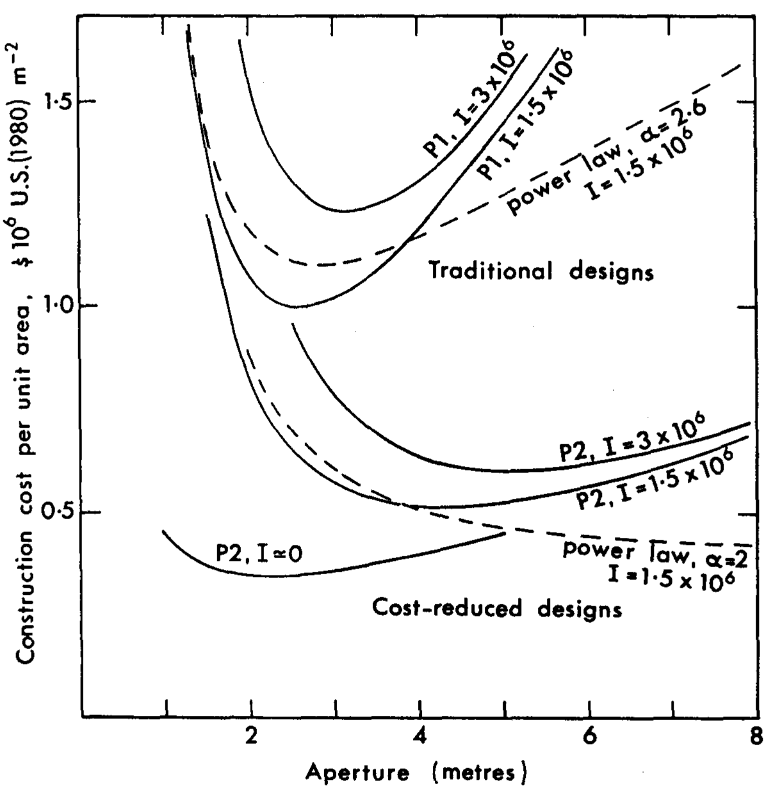

FIGURE 2. Predicted aperture dependence of project cost (including instrumentation) per unit collection area using polynomials (solid curves) and scaling law approximation (dashed curves). I is the instrumentation cost per telescope.

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3. Telescope arrays: preliminary comments

Consider what happens if instead of increasing the aperture D of a single optical telescope by a multiplying factor n to obtain a collection area n^2D^2 (ignoring multiples of $\pi/4$), one obtains the desired collection area by keeping the aperture constant and building an array of n^2 telescopes.

The cost of the contributions which rise in (2) as D^4 will now increase only as n^2D^4 (instead of n^4D^4 for a single telescope). Those which rise as D^3 will increase only as n^2D^3 (instead of n^3D^3). There will be no change in the D^2 terms (both rise as n^2D^2) but the costs which depend linearly on D will now rise as n^2D (instead of nD) and many of the costs which are independent of D will also be greater than those of the single telescope; for example, there will be n^2 as many components to assemble, n^2 as many telescopes to commission, and at least n^2 as much cabling. It follows from this that an array can compete with a single telescope on grounds of cost if, in terms of the polynomial coefficients in (2),

$$\frac{(n+1)}{n} L_o + L_1 D \leqq n L_3 D^3 + n(n+1) L_4 D^4$$

or, in terms of the power law approximation, if

$$n^2 L D^\alpha < L (nD)^\alpha$$

i.e. if $\alpha > 2$. In general these conditions are satisfied only if those terms which scale as D or D^o form a small part of the total cost. If, as we suspect already, cost-reduced telescopes have a cost scaling law with $\alpha \simeq 2$ then construction costs are approximately independent of $N = n^2$ for an N-element array where N can take any value including N = 1. However, the latter statement assumes that the scaling law is valid for large D and, so far, we have not considered the effect of instrumenting the array. Both of these shortcomings are rectified in the next Section.

4. Cost optimised optical arrays, including instrumentation

Disney (1972) compared the overall photon detection effectiveness of an array with that of a single telescope built for the same total expenditure including instrumentation. The optimum number and size of the array units were shown to depend on the observational mode (e.g. direct imaging or photometry; slitless spectroscopy; grating-limited spectroscopy etc.)

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and on the proportion of the total cost spent on instrumentation but, assuming that the telescope cost contribution was at that time governed by a cubic scaling law ($\alpha = 3$), the performance of the optimised array as defined by Disney was found in nearly all cases to surpass that of the single telescope built for the same expenditure. In a later paper (Disney 1978) the consequences of α having a value lower than 3 were considered.

It can be argued alternatively that the effectiveness of a telescope system should be measured only by the total number of photons collected from a given area of sky in a given time and not by technological limitations imposed by the instrumentation (which may change during the lifetime of the telescope) or by the various observational modes in which it can be used. Otherwise, one would need to know before the telescope was designed the frequency of use for each mode of observation during the lifetime of the telescope so that appropriate weights could be assigned. This cannot be done with confidence. Thus the effectiveness of a telescope system is taken here to be determined simply by the collection area $A = \pi ND^2/4$ for an N-element array and we examine how the total cost per unit collection area can be minimised by an appropriate choice of D. Unless stated otherwise it is assumed throughout that the array is to be operated by adding the signals from N sets of instrumentation using low-noise detectors.

For N telescopes each of aperture D the total cost of the instrumented array is, as given by Disney,

$$S_N = N(LD^{\alpha} + I) \qquad (5)$$

where I is the cost of equipping a single telescope with instrumentation, and the scaling law approximation has been used for the individual telescope cost contributions. Thus the cost per unit collection area is

$$\frac{S_N}{A} = \frac{N(LD^{\alpha} + I)}{\pi ND^2/4} = \frac{4}{\pi}\left[LD^{\alpha-2} + \frac{I}{D^2}\right] \qquad (6)$$

This function is plotted against D in Figure 2 (shown with dashed curves for traditional and for cost-reduced telescopes using scaling laws (3) and

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(4), respectively). The cost units throughout this paper are those used by Meinel, viz. $ million U.S. (1980), and an instrumentation expenditure (I) per telescope of $1.5 million U.S. (1980) has been assumed. An expression similar to that obtained by Disney for the optimum aperture size corresponding to the minimum of the function plotted can be obtained for $\alpha > 2$ by differentiating (5) and equating to zero, but when $\alpha = 2$ the cost per unit area continues to decrease as D increases.

Since the emphasis in this paper has been to point out that telescope construction costs have a polynomial origin, it is of more concern here to examine what happens when polynomials P1 and P2 are used to obtain the cost per unit collection area. In this case the cost of the instrumented N-element array is

$$S_N = N(L_4D^4 + L_3D^3 + L_2D^2 + L_1D + L_o + I) \qquad (7)$$

and the cost per unit area is now

$$\frac{S_N}{A} = \frac{4}{\pi}\left[L_4D^2 + L_3D + L_2 + L_1D^{-1} + (L_o + I)\, D^{-2}\right] \qquad (8)$$

When the coefficients of P1 or P2 are inserted in (8) (for P2 an extra term $L_{2.5}D^{0.5}$ is required), the labelled curves shown in Figure 2 are obtained for the variation of total cost per unit collection area with aperture.

The expenditure per telescope on focal plane instrumentation for the array is a matter of policy determined by the range of scientific programmes for which the installation is designed. For a special-purpose array with very simple instrumentation (or for a beam-combined array using a single set of instrumentation), the cost could be almost negligible compared with other costs; for a general-purpose array with post-detection addition of signals capable of being operated over a wide spectral range, the instrumentation cost could be much larger than our initial assumption of $I = \$1.5 \times 10^6$ U.S. (1980) per telescope, particularly when it is considered that the useful lifetime of the telescope will be well in excess of 20 years. To cover these cases, separate curves are shown in Figure 2 for $I \simeq 0$, $I = 1.5 \times 10^6$ and $I = 3 \times 10^6$.

Considering only cost-reduced systems, the following conclusions can be drawn from Figure 2: (1) when the polynomial form of the telescope construction cost is used, our optimisation criterion (total cost per unit area including instrumentation) does indeed show a minimum at some optimum aperture size D_{opt}. This contrasts with the result predicted by the scaling law approximation with $\alpha = 2$; (2) the value of D_{opt} depends on the cost per telescope of the focal plane instrumentation but, for the range of I values which we have used, it lies in the range of monolithic primary mirror sizes which already exist or which are currently considered feasible; (3) the total cost per unit collection area for a cost-reduced telescope array varies only slowly with aperture i.e. the minima are very shallow. This is a crucial point since it means that if, for entirely separate and overriding reasons, one wished to use array units with apertures somewhat different from D_{opt}, then the cost penalty incurred by doing so may not be a severe one. For example, if one chose to use D = 7.5m (with $I = 3 \times 10^6$ per telescope) instead of D_{opt} = 5m, the penalty for choosing that non-optimum aperture would be an increase of 15 per cent in total project cost; (4) the approximation involved in using a scaling law to predict costs is such that large errors are introduced at values of D much larger than the range of D for which the scaling law approximation is valid. This is obvious but the point here is that for cost-reduced designs with $\alpha = 2$, entirely erroneous conclusions may be reached at large D if the scaling law is used.

Notwithstanding conclusion (3) above, the difference in the curves in Figure 2 for $I \simeq 0$ and I greater than, say, 1.5×10^6 is appreciable and it is essential to define at the earliest stage of design whether a general-purpose array will be operated with beam combination and a single suite of instrumentation (small effective I per telescope), or whether each unit telescope of the array will be equipped with separate instrumentation for post-detection addition. Our views on this matter are summarised as follows: Prime focus operation of a large aperture telescope should have the highest priority; otherwise, additional reflection losses and, for large apertures, pixel mismatch lead to a reduction in effective aperture which is unacceptable. For a beam combined array with 5 additional reflections (Learner, 1978; NGT Report No. 5, 1978) this loss is equivalent to at least 40 per cent of the total collection area. Additionally there are problems to be overcome in combining the beams if the distances involved are large and it follows also that the resulting field of view will be very small. For these reasons we strongly favour post-detection addition as advocated by Disney in 1972.

If such an array started out as a special-purpose system with simple, low-cost instrumentation, we believe that it would not end up like that; pressure to provide a comprehensive set of instrumentation at each telescope would be so great that we consider it only realistic to admit at the outset that expenditure per telescope on focal plane instrumentation is likely to be somewhere at the upper end of the range of I values which we considered above. Thus, on the basis of the cost-optimisation argument, we are led to believe that a large aperture optical array should be designed around units having an aperture in excess of 5m.

The number of separate units in an N-element array follows from the desired collection area A, where $N = 4A/\pi D^2$ and D is equal to or close to D_{opt} as discussed above. For an 18m equivalent aperture array, this would require 13 units if $D_{opt} \approx 5m$ or 6 units if $D_{opt} \approx 7.5m$. Thus for equivalent apertures of about 15 to 20m, the cost optimisation argument leads to an array comprising a relatively small number of large telescopes rather than a very large number of small telescopes.

The discussion above has been restricted to the comparison of systems in which individual telescopes have monolithic (or honeycomb) primary mirrors of fixed focal aperture ratio. For multiple-mirror and segmented-mirror designs, we expect (for design reasons already stated) the functional form of the cost-aperture relationships to be quartic polynomials also but at present there are insufficient data to indicate whether these have term coefficients similar to those for cost-reduced designs using single monolithic primaries. However, a preliminary comparison of the itemised costs (excluding focal plane instrumentation) for a 6 x 7.5m multiple-mirror telescope and an array of six separate 7.5m telescopes suggests that the total construction costs for these are the same to within the uncertainties involved in the estimates. Regarding the instrumentation for a multiple-mirror design or an array of separate singles (assuming the same multiplicity, the same total collection area, and the same individual focal aperture ratios), identical options exist for each system, viz. beam addition or post-detection addition of signals, so that instrumentation

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costs do not affect the argument here. Both systems also have the capability for coherent operation by combining apertures in pairs for speckle interferometry.

However, there are two particular applications where a singles array has an inherent advantage over a multiple-mirror design. First, for observational programmes where there are many objects to be observed at brightnesses above the limiting magnitude of an individual telescope unit (or multiplets) of the array, it can be shown that a post-detection array can be more efficient in the use of available time (by up to 20 per cent for faint object photometry with a 6-element system) than a multiple-mirror design. This arises from the fact that the acquisition of several sky objects can be performed simultaneously with an array, whereas a multiple-mirror system on a single mount must by necessity perform each acquisition sequentially. Second, an array designed for coherent operation is not constrained by the fixed and redundant baseline features of a multiple-mirror system on a single mounting. Other advantages of incoherent arrays (scheduling flexibility; the capability of being enlarged at a later date; design using existing technology leading to predictable commissioning results and operational reliability; pixel matching considerations) have been given by several authors including Code, 1971; Disney, 1972; Angel 1978; Disney 1978; Richardson and Grundmann, 1978.

The cost optimisation results summarised in Figure 2 can also be used to compare the expenditure on a giant single-dish telescope with that of an optimised array of the same total collection area, assuming that common design principles are used and that a single cost polynomial applies over the requisite range of aperture sizes. On that basis, using curve [P2, $I = 3 \times 10^6$] of Figure 2, a hypothetical monolithic 10m installation would be expected to cost one half as much again as an optimised 4 x 5m array (the cost for which including enclosures and multiple sets of instrumentation is predicted here to be about \$50 million U.S. (1980)). Comparison of a segmented-mirror telescope with these systems should also be possible using the semi-analytic approach described in this paper though we have not attempted this. One obvious design difference in a segmented-mirror structure is the extremely low mass per unit area for the primary mirror; this will affect several of the term coefficients in the cost-aperture polynomial and reduce the cost differential over an

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optimised array of the type we have been considering. On the other hand, if the full development costs for a segmented-mirror telescope are taken into account, that benefit could easily be dissipated.

We conclude by indicating very briefly how an optical/IR array based on the principles described in this paper may be realised in practice. The equivalent aperture has been taken to be 18m and the system is designed for variable baseline interferometry as well as incoherent operation. The preferred arrangement is a 6-element array of individual 7.5m f/2 altazimuth telescopes. The aperture chosen for the individual units was determined by the cost optimisation arguments of this paper taking into account the likely instrumentation costs during the lifetime of the installation for a wide range of optical and IR observing programmes including interferometry. Each telescope has provision for operation at prime and Nasmyth focii as well as pair-wise beam combination. The telescopes and their roll-off enclosures are on separate rail systems with traction provided by electric motors. The moving masses are 230 tonnes (telescope units) and 175 tonnes (enclosures), and several hard-pad stations are provided at fixed locations along each baseline. Each enclosure is a simple cover using corrugated aluminium sheet cladding on steel section girders and columns (as used in the construction of conventional industrial buildings). The base is a rigid box girder with powered wheels and the hinged doors are operated hydraulically. Speckle interferometry is performed by combining the six pupils in pairs, with baselines of up to 200m and a non-redundant layout configuration which allows efficient sampling of the (u,v) spatial frequency plane. We have also considered an alternative system comprising three twin 7.5m altazimuth telescopes; this gives some cost savings but lacks the flexibility of the Six-Single Array. Further details of these systems and a discussion of interferometric requirements and performance will be given elsewhere (Greenaway et al., 1984).

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DISCUSSION

G. Burbidge: If you build an array of 8m class telescopes, which is the price per unit? Also, have you taken into account the cost of equipping each telescope with a full set of instruments?

C.M. Humphries: The square power law approximation gives the project cost for a single 7.5m unit (excluding instrumentation) as \$ 17×10^6 U.S. (1980). Using the polynomial expression, the figure is somewhat higher. Instrumentation costs have been taken into account and are discussed in the write-up.

R.G. Tull: State-of-the-art auxiliary instruments tend to be built in units of one or two. This fact argues in favour of a large telescope with a single focus, rather than an array of many telescopes.

C.M. Humphries: It means that the instrumentation development costs are high and this applies to all telescope systems regardless of their design. Thereafter, for an array, the unit instrumentation cost drops rapidly and it is then a matter of building in reliability. I think this argues in favour of an array.

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R. Racine: Would taking into account the operating costs significantly affect your conclusions?

C.M. Humphries: We don't find the operating costs for an array to be significantly different from those for other systems. However, it is essential to build in a high level of reliability for the instrumentation so that the effort on repair and maintenance is small.

G.J. Odgers: Were you aware that Grundmann and I estimated (in paper at Imperial College last year) that the boule design for an array is an order of magnitude less expensive?

C.M. Humphries: We did not include boule telescopes for consideration since we had no experience of building or using them. It would certainly be of interest to know more precisely how their costs scale with aperture and hence what the optimum size is.

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