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Telescope arrays for wide-field sky surveys. A technical assessment and a cost model

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ABSTRACT

In this study we tackled a proxy approach to wide-field large monolithic telescopes in terms of composite assembly of smaller instruments. As a conveniently 'fast' f-number is the ultimate parameter to efficiently carry out inspection of large portions of sky, we show that a telescope array can provide a cost-effective solution, as a factor of $\sqrt{N}$ reduced f-number can be achieved when combining N (similar) telescopes, each of diameter $d_{\rm array}$, to synthesize an equivalent monolithic diameter $D_{\rm mono} = \sqrt{N} d_{\rm array}$. A cost model is developed, in this regard, by comparing the COTS figures for telescopes up to a metric size as supplied by primary international manufacturers. If a standard cost versus diameter relationship is assumed, in the form $C \propto D^{\rm n}$, then data indicate that $n = 2.5 \pm 0.4$. In addition, a more realistic multiparametric dependence is assumed, including the f-number, in the form $C \propto (D^3/f)^m$, with $m = 0.70 \pm 0.08$. This eventually leads us to estimate that cost of the optical tube assembly (OTA) for commercial telescopes scales as $C \propto D^{2.10 \pm 0.24} f^{-0.70 \pm 0.08}$. Even considering the supplementary addition of CCD/CMOS detectors for a telescope array, a general saving scheme confirms that any array solution with $N \geq 4$ telescopes, each with a diameter in excess to 30–40 cm, could be a competitive alternative to a bigger monolithic instrument of metric class (or larger), mainly aimed at wide-field surveys.

Key words: Instrumentation – Wide-field telescopes – Focal ratio – Sky surveys.

1. INTRODUCTION

Wide-field surveys of celestial objects and transient events across the sky span a wide range of cases, not only of strict astronomical interest but also including all those tasks more generally comprised in the different contexts of space situational awareness (SSA).

A thoughtful exploration of distant galaxies at cosmic distances or the comprehensive census of stars within our own Galaxy may therefore accompany a close scrutiny of the Solar System in search for incoming interstellar intruders, or new asteroids and comets. The study of gravitational-wave (GW), gamma-ray burst (GRB), and fast radio burst (FRB) events may also take advantage of wide-field telescope capabilities to timely catch the occasional optical burst. Whenever possible, in the different frameworks, investigation is carried on by multiwavelength observations (we now call it 'Multimessenger Astronomy'), to add further physical value to the straight spatial inventory of celestial objects. In a fully different context, a fresh and somewhat unusual application of this approach is now urged in the framework of 'space surveillance and tracking' (SST), to probe the impact of the surging population of anthropic objects (satellite mega-constellations and space debris) on the space environment surrounding Earth.

Though so different, both the deep-space and circum-terrestrial explorations rely in fact on the same strategy; large *étendue* values (Steel 1974), obtained by enhanced collecting area and wide field of view (FOV), are the ultimate requirement for our telescopes to push target detection and positional accuracy at the faintest magnitude levels.

In this study, we want to further follow up this concept, through a critical assessment of the instrumental strategy such as to enable best value-for-money technical solutions complementary to more classical cases of fast 'monolithic' telescopes, whose image comes from one single (or segmented) primary mirror, in order to preserve the optical coherence of the incoming wave front. Along our discussion we will show, in particular, that a 'proxy' strategy, based on a composite assembly of small instruments to synthesize a bigger telescope, can lead to interesting and cost-effective applications.

Telescope arrays may lead to a substantial financial edge once (i) a wide FOV is of primary interest for our investigation, and (ii) a decoupling may be accepted between resolving power and magnitude limit in target detection, favouring the latter option.

Since the 2000's, this approach has been pursued in a number of cutting-edge instrumental projects. A widely recognized case, in this sense, is certainly the Pan-STARRS project (Kaiser 2004), aimed at hunting potentially hazardous asteroids (PHAs) approaching Earth. It consists (in its final configuration) of a battery of four (now two) 1.8 m f/4.4 Wynne-Cassegrain telescopes combined to reach a FOV of 7 deg^2. On a similar line, project GOTO (Dyer et al. 2020, 2024) aims at searching for GW-optical transients by using a set of eight 40 cm f/2.5 Wynne–Newtonian telescopes, flanked in a common mount to mosaic the sky up to a 44 deg^2 FOV. Celestial transients are also investigated by the LAST project (Ben-Ami et al. 2023), using a battery of 48 f/2.2 telescopes of 27.9 cm covering up to 355 deg^2 on sky.

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Optical designs, which rely on refractive telephoto arrays instead of more standard mirror telescopes, have also been explored in the recent years. A lens-driven optical system overcomes any obstruction or optical disturbance (spider arms etc.) typical of mirror telescopes and it is therefore better suited to detect thin celestial structures with very faint surface brightness. The Dragonfly project (Abraham & van Dokkum 2014) is probably the most popular one, originally conceived for eight commercial cameras Canon 400 mm f/2.8 L IS II USM, each with 14.3 cm aperture, combined to reach a 40 cm equivalent monolithic aperture across a $2.6^\circ \times 1.9^\circ$ FOV, and now in its way to increase up to 120 cameras (or a 1.5 m equivalent monolithic aperture) and beyond (Chen et al. 2024).

On even larger FOV figures, the SuperWASP project (Pollacco et al. 2006) scans the sky for exoplanet transits on stars down to mag 15, by mosaicing a 482 $\deg^2$ FOV, through a set of eight Canon 200 mm f/1.8 telephoto lenses in a common mount, each spanning $8^\circ \times 8^\circ$ across the sky, with minimum overlap. A similar strategy is implemented by the Evryscope project (Law et al. 2015), a collection of 27 individual Rokinon 85 mm f/1.4 telephoto lenses, each covering adjacent $24^\circ \times 16^\circ$ fields. When combined in a common mount, the full array can observe a total of 10 200 $\deg^2$ FOV, covering virtually the entire visible celestial sphere.

Previous arguments on optimized observing performance also found practical realization in the new TANDEM project (Buzzoni et al. 2025), a combo of four 35 cm f/3 Wynne–Newtonian telescopes working in hybrid mode either by covering a 4 $\deg^2$ FOV through a 70 cm synthetic aperture or a 16 $\deg^2$ FOV with the four telescopes to mosaic adjacent (or even sparse) regions of the sky.

Here, we will first assess the technical requirements for an efficient sampling of a target population across the sky. FOV properties versus image resolution and versus magnitude limit are discussed, respectively in Sections 2.1 and 2.2, setting important constraints to the telescope focal length and implied f-number. Section 2 is then completed by a thorough analysis of the reference time-scales which characterize a sky survey, that is the total completion time, the ‘duty cycle’ of our inventory and the ‘search rate’, in case we want to probe the sky in search for recurring or transient events.

Section 3 is entirely devoted to a comparative discussion of the telescope-array concept versus standard monolithic case. In particular, we will develop there an accurate cost model, which takes into account both telescope aperture and f-number properties. This will lead to a reference saving scheme, that will be discussed, together with the other relevant results of our study, in Section 4.

2. WIDE-FIELD CAPABILITIES AND TECHNOLOGICAL ASSESSMENT

A subtly different perception may be noticed between instrumentists and observers in the way they aim at the ‘optimum’ telescope for survey applications. The observer basically wants to detect objects as faint as possible over a FOV as wide as possible. He/she therefore calls for a telescope with a ‘big’ collecting area (to reach fainter apparent magnitudes) and focal length as short as possible (to inspect at a time a larger fraction of the sky). Most of time, target morphological properties (that is shape, angular extension, surface features etc.) are not an issue in this context, rather addressing detection efficiency and integrated aperture photometry to characterize the sampled objects, especially if reasons exist to expect targets of point-source nature.

On their side, telescope builders primarily strive to optimize the optical quality of the instrument in terms of best resolving power across the FOV, and any effort is devoted to recover aberrations such as to make the point spread function (PSF) on the image detector as close as possible to the theoretical diffraction pattern. This may actually prove to be a more than challenging task once dealing with exceedingly large FOV, especially if we aim at optimizing optical design for a standard monolithic telescope. A smart trade-off of the optical parameters has therefore to be envisaged to optimize telescope’s performance for these special applications.

2.1. Resolution and detection performance

According to classical diffraction theory (e.g. Schroeder 1987), angular resolution improves with the telescope aperture (D) compared to the light wavelength at which we choose to observe. At the same time, a larger aperture also implies a wider collecting area (D^2), so that fainter objects can be appreciated across the sky, as well.

Somewhat erroneously, the previous argument may lead one to conclude that telescope performances are meant to improve all the way with increasing size, as resolution and sensitivity appear to be intimately and synergically related to each other.

In fact, for a ground-based telescope, the nominal resolution of the primary mirror may be severely hampered by external (sky seeing) and technical (detector pixel size) limiting factors. Under somewhat standard atmospheric conditions, a PSF full-width at half-maximum (FWHM) in the range 1.0–2.0 arcsec is in the order at optical wavelength, a figure that, by itself, makes small telescopes of even decimetric size already seeing-limited in their imaging performance.

In designing our ‘optimum’ telescope we therefore would better like to match the CMOS/CCD pixel scale with the seeing figure (Buzzoni 2024), so that

$$\frac{px_\mu}{F} \approx \frac{\mathrm{FWHM}''}{0.206}, \tag{1}$$

with px_μ the pixel size in μm, F the focal length in metres, and the FWHM expressed in arcsec. If we are not concerned with target morphology, this condition allows us to maximize the S/N of our detection as the signal will be entirely comprised in just one pixel.[1] As typical values of 5–10 μm can be envisaged for the pixels size of commercial cff-the-shelf (COTS) medium-format detectors, then equation (1) indirectly poses a condition for the telescope focal length as

$$F \approx 1.37 \left(\frac{px_\mu}{10}\right)\left(\frac{1.5}{\mathrm{FWHM}''}\right) \text{ metres.} \tag{2}$$

Then a focal length on a metric scale may be suitable for a ground telescope, *disregarding the aperture of the primary mirror.* In terms of the so-called f-number of the optical design, defined as $f = F/D$, equation (2) also leads us to conclude that *quite demanding configurations, with $f \sim 1$ or so, should be required when dealing with monolithic telescopes of metric class.*

2.2 Sensitivity and field of view

The threshold in apparent flux ($\ell_{\rm min}$) that can be detected at a given confidence level, that is in terms of fixed $(S/N)_{\rm min}$, becomes fainter when increasing the telescope size (e.g. Schroeder 1987) and scales[2]

[1] In general, the S/N of a detected object sampled by p pixels scales as $(S/N)_p = (S/N)_1/\sqrt{p}$ (e.g. McLean 1997).

[2] Somewhat counterintuitively, note that threshold detection scales with the telescope aperture, not the collecting area. This is because a wider area actually probes a fainter target but also correspondingly enhance the sky noise. Overall, this leads to a shallower contrast of the target against the

as

$$\ell_{\min} \propto \frac{1}{D}. \quad (3)$$

Accordingly, a magnitude limit $m_{\lim}$ can be reached by our telescope along an exposure time $t_{\exp}$ and for a total responsive quantum efficiency factor (RQE), such as

$$m_{\lim} = 2.5\log(D) - 2.5\log(S/N)_{\min} + 1.25\log(t_{\exp}) + 1.25\log(\mathrm{RQE}) + \mathrm{const}, \quad (4)$$

where the constant sets the reference photometric system of our observations and the external environment constraints (i.e. surrounding sky brightness, Moon illumination, clouds etc.).

Following Buzzoni (2024), in case of a perfect aplanatic optical system, the FOV that can be projected on the image detector, simply scales in size with the focal length of the instrument, being

$$\mathrm{FOV}_S \propto \frac{1}{F} = \frac{1}{f\,D}, \quad (5)$$

where the second term sets the dependence on the telescope f-number.[3]

By combining all the previous relations we simply lead to a direct relationship between telescope sensitivity and covered field on sky, as

$$\mathrm{FOV}_S \propto \frac{\ell_{\min}}{f}, \quad (6)$$

or, in magnitude scale,

$$m_{\lim} = -2.5\log(\mathrm{FOV}_S) - 2.5\log(f) + k. \quad (7)$$

Quite interestingly, we have that a larger FOV can only be obtained at cost of a ‘shallower’ magnitude limit unless a correspondingly smaller f-number intervenes to balance the conflicting situation.

2.3 Search rate and survey completion time

A remarkable conclusion of previous discussion is that the two leading parameters set to inherently characterize a survey, that is FOV and magnitude limit, are not *directly* driven by the telescope aperture but rather by its f-number. On this line, it is also interesting to note that the f-number is in fact a direct ‘proxy’ of the *étendue* parameter (ε)[4] as, by definition,

$$\varepsilon \propto D^2\mathrm{FOV}_S^2 \propto \frac{1}{f^2}. \quad (8)$$

Clearly, as far as timing for a survey completion is concerned, a bigger telescope may help speed up the operation, as a shorter exposure time is needed per single frame, under the condition

$$\frac{\mathrm{d}D}{D} = \frac{1}{2}\frac{\mathrm{d}t_{\exp}}{t_{\exp}}, \quad (9)$$

which follows from equation (4), by differentiating with fixed magnitude limit. On the same line, by recalling equation (5), the total time required to complete a full mosaic of the celestial region of interest, down to a fixed detection limit, scales with the inverse of the *étendue* parameter, namely

$$t_{\mathrm{TOT}} \propto \frac{t_{\exp}}{\mathrm{FOV}_S^2} \propto \frac{f^2 D^2}{D^2} \propto f^2 \propto \frac{1}{\varepsilon}. \quad (10)$$

Furthermore, t_{TOT} also sets the ‘duty cycle’ of our observations, while $(1/t_{\mathrm{TOT}})\propto\varepsilon$ constrains the ‘search rate’, in case we want to probe the sky in search for recurring or serendipitous events.[5]

3. TELESCOPE ARRAY VERSUS MONOLITHIC DESIGN: A COST ANALYSIS

Thought still a challenging endeavour, the assembly of big telescopes with short focal length and correspondingly ‘fast’ f-numbers, is a common practice, nowadays, by taking advantage of the cutting edge technologies and new materials (the LSST project; Tyson 2002; Ivezić et al. 2019, is certainly a reference milestone in this regard; see also Terebizh 2011, for a timely review). None the less, in case of ground-based telescopes, one has to seriously assess the cost of increasing the aperture diameter, in a standard monolithic context, as this will hardly add to imaging resolution given the limiting effect of atmospheric seeing.

As well known, adaptive optics may overcome the problem (e.g. Roddier 1981, 2004 for a classical assessment), allowing the telescope to match the inherent diffraction limit of the primary mirror, but at magnified costs and drastically reduced FOV capabilities (see e.g. Dekany et al. 2004 for an informative review). For this reason, if exquisite angular resolution is not a point against increased FOV, then an array assembly of small telescopes may provide a substantially cost-effective solution compared to the monolithic scenario.

A brief analysis of some reference figures of the current COTS market may be worth of consideration, in this respect, by relying for instance on the large inventory of instruments, as offered by the Astroshop portal.[6] We have especially focused our analysis on four leading telescope providers, namely Celestron, Meade, Officina Stellare, and Orion, each of them offering a wide range of optical solutions for mirror telescopes, with diameters between 150 and 800 mm and f-numbers between 2 and 11. Only the cost of the optical tube assembly (OTA) has been considered, including correcting optics (Wynne multiplets, Schmidt corrector plates etc.), whenever applicable, but excluding the CCD/CMOS image detector and the telescope mount.

As extensively recognized in literature (Meinel 1978, 1982; Stepp et al. 2003; van Belle et al. 2004; Stahl et al. 2011; Stahl & Allison 2019, 2020), the aperture diameter is certainly the leading parameter which constrains the telescope cost. A scaling law of cost (C) versus diameter (D) may be envisaged in the form $C\propto D^n$, where the index n summarizes the different contributions to the total budget. For the latter, optical polishing procedures are likely meant to add according to mirror surface D^2, while mechanical assembly of the telescope (and architectural premises) perhaps better scales with the volume, or D^3. Overall, a value of n in the range 2–3 may likely be expected.

surrounding field and a poorer S/N. See Schroeder (1987) for an exhaustive discussion.

[3]Throughout the paper, with FOV_S we intend the angular extension (diameter) of the full corrected field offered by the telescope. With this notation, please consider that the solid angle subtended on sky is therefore proportional to FOV_S^2.

[4]See, in this respect, the comprehensive fig. 1 in Förster et al. (2021).

[5]Alternative to the *étendue* approach, optimized timing strategy for ‘slice’ surveys, intended to probe the Universe ‘in depth’, on volumes at increasing distance, may better rely on the so-called ‘grasp’ parameter (G), extensively investigated by Ofek & Ben-Ami (2020).

[6]According to published official information, Astroshop is the largest commercial network on Europe market, based in Germany, Belgium, France, Poland, Italy, Spain, and Portugal. The Web portal can be accessed at https://www.astroshop.eu/.

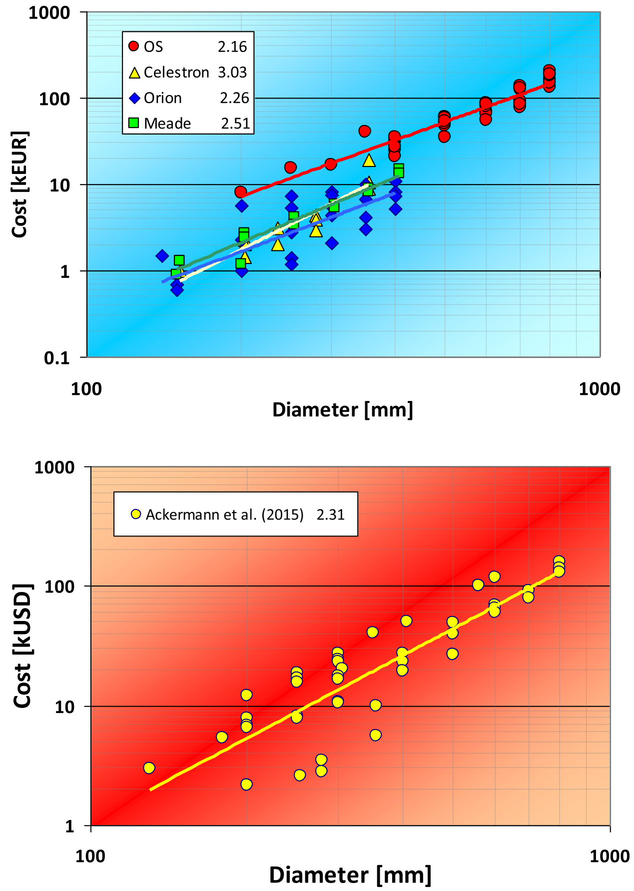

Figure 1. (Upper panel): cost versus telescope aperture scaling relationship for a few primary manufacturers in the European market, as labelled in the plot. The value of index 'n' of the fitting power law ($C \propto D^n$) is reported in the legend. (Lower panel): same, as derived from the Ackermann et al. (2015) compilation, mainly aimed at the US market.

Cost estimating models for space and 'giant' (3-m class or greater) ground-based telescopes have been evolving along the years as a consequence of the technology innovations. According to Meinel (1978), the cost of big telescopes since 1980 was meant to scale with an index $n \sim 2.8$. The scaling law then showed a flattening with $n \sim 2.5$ for later instruments in the 90's (van Belle et al. 2004) with substantial arguments for both ground- and space-based projects in the recent years (Stahl 2010) to fit with an index value consistent with a straight mirror surface dependence, that is $n \sim 2.0$. As far as OTA estimates alone are concerned, this trend may currently even flatten further (e.g. $n \sim 1.8$; Stahl et al. 2005) making 'extremely big' telescopes (8-m class or greater) to become increasingly cheaper with increasing diameter.

In spite of this optimistic trend for large monolithic mirrors, things are comparatively more conservative as far as smaller COTS telescopes (of metric class or smaller) are concerned. This is shown in the two panels of Fig. 1, where we compare the n-index estimate from our compilation (upper panel) and a similar fit of the telescope sample recently studied by Ackermann et al. (2015) (lower panel).

In both cases, a consistently steeper dependence of the OTA cost with the diameter is found, with $n \sim 2.5 \pm 0.4$ for the average estimate of the four providers considered in our survey, with a lower boundary of $n \sim 2.16$ for Officina Stellare and an upper limit of $n \sim 3.03$ for Celestron. Our results are in excellent agreement with the Ackermann et al. (2015) compilation, for which we obtain $n \sim 2.3$.

Table 1. Savings scheme for the cost of an array configuration with respect to the equivalent monolithic case, assuming the telescope diameter as the main driving parameter.

Number of array telescopes (N)	Array relative cost (OTA)	Savings as from equation (11)
1	100	0 per cent
2	87	13 per cent
4	76	24 per cent
8	66	34 per cent
16	57	43 per cent

In general, for any index in excess of 2, a saving factor (s) can be estimated for the cost by replacing a monolithic telescope with diameter $D_{\rm mono}$ with an array of N identical telescopes, each with diameter $d_{\rm array} = D_{\rm mono}/\sqrt{N}$, such as to supply the same total collecting area:

$$s = 1 - \left(\frac{C_{\rm array}}{C_{\rm mono}}\right) = 1 - \frac{N d_{\rm array}^n}{\left(\sqrt{N} d_{\rm array}\right)^n} = 1 - N^{(1-n/2)}. \qquad (11)$$

If we adopt a value of $n \sim 2.4$ as an average representative figure for current US and European COTS markets, then a savings scheme for the cost of the array configuration with respect to the equivalent monolithic case derives, as in Table 1.

To a deeper scrutiny, in addition to the previous budgeting considerations, one should consider in fact a substantial supplementary plus of the array configuration compared to the standard monolithic case. As the optical performance of the single-mirror telescope is broken down through the combined contribution of N smaller telescopes, all with given f-number $f_{\rm array} = F_{\rm array}/d_{\rm array}$, it is immediate to see that the resulting f-number $f_{\rm mono}$ of the synthetic telescope is always 'faster' than the array contributors as

$$f_{\rm mono} = \left(F_{\rm array}/D_{\rm mono}\right) = f_{\rm array}\Big/\sqrt{N}. \qquad (12)$$

For example, by combining four f/3 telescopes, a synthetic f/1.5 monolithic telescope could be obtained with twice the aperture diameter.

This arrangement may have direct impact on the manufacturing budget of the system as, compared with the reference monolithic case, a 'faster' optical design can be achieved with a shallower sagittal depth in the mirror processing. Fig. 2 gives a sketch of the problem. According to the figure, the sagittal depth S to be attained to shape the mirror such as to reach a planned f-number can be evaluated remembering that

$$\begin{cases} R \sin\theta &= D/2 \\ R \cos\theta &= 2F - S \\ F &= R/2 \end{cases} \qquad (13)$$

On the other hand, as $(\cos^2\theta + \sin^2\theta) = 1$, by squaring the three equations, and recalling the f-number definition, with little arithmetic, it leads to a simple definition for the sagitta as

$$S = 2F\left(1 - \sqrt{1 - \frac{1}{16 f^2}}\right). \qquad (14)$$

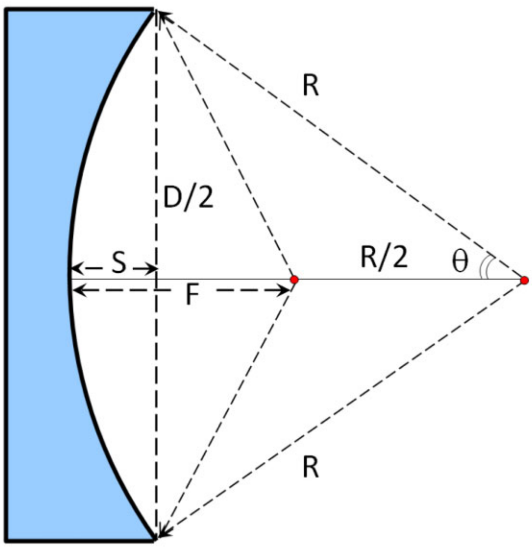

Figure 2. An illustrative sketch of the sagittal depth (S) and other reference parameters of equation (13) to assess the geometry of the telescope primary mirror.

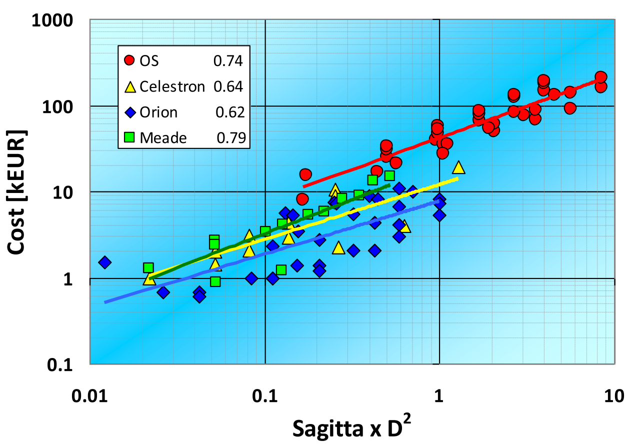

Figure 3. Cost versus SD^2 scaling relationship for the few primary manufacturers taken as a reference, as labelled in the plot. The SD^2 parameter is a measure of the departure from the initial flat surface of the mirror blank, to be accounted along the optical manufacturing process, according to the targeted f-number of the telescope. The value of index 'm', according to equation (16), is reported in the legend.

As the function of equation (14) is very regular and smooth, a nice fit with a power law can be obtained, in the form

$$\left(\frac{S}{F}\right) = 0.064\, f^{-2.0}, \tag{15}$$

within a ∼1 per cent relative uncertainty.

A fair estimate of S could be useful to assess the final cost of a mirror, as the amount of glass to be removed along the manufacturing process scales as SD^2, and this may likely impact on the final cost of the mirror. This case has been verified in Fig. 3, on our considered sample of COTS telescopes.

Actually, a nice correlation is in place among the different providers. Again, a power law can be envisaged for the general relationship with $C \propto (SD^2)^m$. The average value for the full sample is $m = 0.70 \pm 0.08$.

Table 2. Savings scheme for the cost of an array configuration, with respect to the equivalent monolithic case, assuming the telescope diameter and f-number, as the main driving parameters. The maximum allowed cost of the CCD/CMOS detectors is evaluated in the last column, according to equation (18).

Number of array telescopes (N)	Array relative cost (OTA)	Savings as from equation (17)	$c_{\mathrm{CCD}}/c_{\mathrm{array}}$
1	100	0 per cent	–
2	76	24 per cent	0.64
4	57	43 per cent	0.99
8	44	56 per cent	1.48
16	33	67 per cent	2.17

In force of the fitting function of equation (16), we can further explore the budgeting constraints leading to a more informing and valuable relationship for the cost versus telescope diameter and f-number:[7]

$$C \propto \left(SD^2\right)^m \propto \left(\frac{FD^2}{f^2}\right)^m = \left(\frac{D^3}{f}\right)^m. \tag{16}$$

By relying on equation (17), we can further re-assess the saving scheme of the telescope array versus monolithic equivalent case. By retaking

$$s = 1 - \left(\frac{C_{\mathrm{array}}}{C_{\mathrm{mono}}}\right) = 1 - N\left[\frac{d^3_{\mathrm{array}}\big/ f_{\mathrm{array}}}{\left(d_{\mathrm{array}}\sqrt{N}\right)^3 \Big/ \left(f_{\mathrm{array}}\big/\sqrt{N}\right)}\right]^m$$
$$= 1 - N^{(1-2m)}. \tag{17}$$

With $m = 0.7$, $s = 1 - N^{-0.4}$, and the update saving scheme is reported in Table 2.

By comparing with the original scenario of Table 1 (which leads to $s = 1 - N^{-0.2}$), one sees that even more cost-effective figures can be reached for the array solution when considering the additional cost dependence on the telescope f-number, besides the absolute diameter of the primary mirror. For example, by taking again the previous example and combine four f/3 telescopes we eventually synthesize an f/1.5 monolithic telescope at a 43 per cent discount price.

Clearly, our full budget account should consider as well that additional CCD/CMOS detectors are required by the telescope array. Especially in case of small telescopes of decimetric class, this item could drastically impact on the total cost.

Given the saving figures of Table 2, we could set an upper limit to the cost that can be afforded for the electronic imager within the financial margins with respect to the monolithic case. By considering that, in any case, a minimum of one detector is always required, we have that the per-item cost (c_{CCD}) of the additional $N - 1$ detectors should be maintained within a value $[s/(N-1)]C_{\mathrm{mono}}$ of the

[7]To our knowledge, no detailed studies exist to properly assess the impact of the f-number on the telescope costs, especially for ground-based instruments, given the entangled interplay of this parameter with other structural properties. In their analysis, Stahl et al. (2005) report that, 'as far as *the total observatory cost* is concerned, the telescope *f*-number has been indicated to reduce cost, essentially due to a smaller dome and a lighter telescope mount. However, these arguments do not concern the OTA costs and more likely apply to the context of 'giant' (3-m class or greater) telescopes, where infrastructure takes a substantial part of the budget (see e.g. table A.1 in Borra 2003).

equivalent monolithic telescope or, equivalently, via equation (17),

$$c_{\rm CCD} \le \left(\frac{1-N^{(1-2m)}}{N^{(1-2m)}}\right)\left(\frac{N}{N-1}\right) c_{\rm array}, \quad (18)$$

being $c_{\rm array} = (C_{\rm array}/N)$ the cost one single telescope of the array ensemble. With the adopted m index, the ceiling price of the CCD/CMOS detector can be computed as in the last column of Table 2.

For a 4-telescope array, each telescope could still be conveniently equipped with a CCD/CMOS camera of OTA comparable cost. Allover, by referring also to Fig. 1, this makes the array solution a competitive alternative to a bigger monolithic telescope providing to use diameters in excess to 30–40 cm for the telescope assembly.

4. RESULTS AND DISCUSSION

In this study we tackled a classical (yet not fully appraised) proxy approach to wide-field large monolithic telescopes in terms of composite assembly of smaller instruments. A recognized experience exists, of course, to assemble segmented primary mirrors (the Gran TeCan telescope, Alvarez et al. 1998, is an outstanding example in this sense), thus fully preserving the optical coherence of the incoming wave front, that is both intensity and phase angle. Such a challenging approach actually paved the way, in the last decades, to multimirror telescopes (the MMT case; Beckers et al. 1981; Hege et al. 1985, being an outstanding milestone) and active optics technologies, nowadays the standard for big-class (>4 m) telescopes worldwide or for new-generation telescopes in space, such as the *JWST* case (Sabelhause & Decker, 2004).

However, as far as the resolving power of ground-based telescopes at optical wavelength is concerned, such a demanding (and expensive) technological effort cannot overcome the obvious drawback that makes the telescope image quality eventually constrained by the atmospheric seeing, not the inherent diffraction pattern of optics. More elaborated adaptive optics solutions could greatly alleviate the situation, though always at cost of drastically reducing the FOV capabilities of our instrument.

For this reason, if exquisite angular resolution is not a leading issue against wide-field capabilities, then a suitable assembly of small telescopes to synthesize the full collecting area of a bigger instrument may provide a basically equivalent and cost-effective solution. In particular, along our discussion, we have shown that this strategy may have a substantial financial edge once (i) a wide FOV is of interest for our research, and (ii) a decoupling may be accepted between resolving power and magnitude limit in target detection, favouring the latter option.

Deep sky surveys or quick-alert optical recognition of sky transients (e.g. Supernovae, GW, and GRB events), are the elected astronomical contexts which may take advantage of wide-field telescopes with a large collecting area, but a strategic role of these telescopes can be envisaged also for any optical tracking of fast-moving objects across the sky, like for SST activities aimed at sensing the satellites and space debris traffic around Earth.

Equation (6) is the key relationship in our discussion of Section 2. It shows that a conveniently 'fast' f-number is the ultimate parameter to tune-up the telescope performance for our aims, as a larger FOV would in general benefit of a shorter telescope focal length, while a fainter magnitude limit would be reached by a larger diameter of the primary mirror.

In this framework, a plain (yet decisive) technical argument in favour of a telescope–array solution has been pointed out in Section 3, as equation (12) shows that a factor of $\sqrt{N}$ reduced f-number can be achieved when combining N (similar) telescopes, each of diameter $d_{\rm array}$ and focal length $F_{\rm array}$, to synthesize an equivalent monolithic diameter $D_{\rm mono} = \sqrt{N} d_{\rm array}$.

If a straight power law, such as $C \propto D^n$, can be envisaged to scale cost versus diameter, at least for standard market figures, then equation (11) shows that, for the telescope array to overcome the monolithic equivalent case, we need $(1 - n/2) < 0$, or $n \geq 2.0$. This is actually the case once comparing the COTS figures for telescopes up to a metric size as supplied by primary international manufacturers, as in Fig. 1. From the fit we obtain, on average,

$$C \propto D^{2.5\pm0.4} \quad (19)$$

In force of previous arguments, however, in addition to the impact of the diameter of the primary mirror on the OTA cost, one may guess a multiparametric relationship with some additional dependence also on the telescope f-number. A 'faster' optical design requires, in general, a more elaborated manufacturing with a larger departure from the straight flat surface of the blank. In addition, a Wynne (1972, 1974) field corrector is often to be considered, to flatten the curved image plane.

As sketched in Fig. 2, the amount of glass to be removed for reducing the curvature radius of the primary mirror scales with the diameter (D) and the sagittal depth (S) of the primary mirror through the quantity SD^2. Fig. 3 actually shows that a correlation holds among the different telescope providers leading to conclude, in force of equation (16), that

$$C \propto D^{2.10\pm0.24} f^{-0.70\pm0.08} \quad (20)$$

In line with original considerations as in the few pioneering works dating back to the 80's (Johnson 1981 is an important, though underrated, contribution in this sense), even considering the supplementary addition of modern CCD/CMOS detectors for a telescope array, a general saving scheme confirms that any array solution with $N \geq 4$ telescopes, each with a diameter in excess to 30–40 cm, could be a competitive alternative to a bigger monolithic instrument of metric class, mainly aimed at wide-field surveys, and up to exceedingly larger apertures for unusual applications, like for a striking concept of a synthetic 12 m telescope for deep-space communications (Romanofsky 2019).

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DATA AVAILABILITY

This study made use of the data supplied by the Ackermann et al. (2015) study and of public price listing of commercial telescopes, as provided by the Astroshop internet portal at the URL: https://www.astroshop.eu/. Copy of these data can be made available on reasonable personal request to the author.

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