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The Scaling Relationship Between Telescope Cost and Aperture Size for Very Large Telescopes

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ABSTRACT

Cost data for ground-based telescopes of the last century are analyzed for trends in the relationship between aperture size and cost. We find that for apertures built prior to 1980, costs scaled as aperture size to the 2.8 power, which is consistent with the previous finding of Meinel (1978). After 1980, 'traditional' monolithic mirror telescope costs have scaled as aperture to the 2.5 power. The large multiple mirror telescopes built or in construction during this time period (Keck, LBT, GTC) appear to deviate from this relationship with significant cost savings as a result, although it is unclear what power law such structures follow. We discuss the implications of the current cost-aperture size data on the proposed large telescope projects of the next ten to twenty years. Structures that naturally tend towards the 2.0 power in the cost-aperture relationship will be the favorable choice for future extremely large apertures; our expectation is that space-based structures will ultimately gain economic advantage over ground-based ones.

1. Introduction

The most basic parameter that can be used to describe a telescope is its primary aperture size. In many cases, that parameter is such an inseparable part of a telescope's identity, it is in fact part of the name, or at least cited in the same breath as its proper name - the 5-m Hale, the 3.5-m WIYN, etc. As first explored by Meinel (1978, 1979a,b), this parameter can be linked to another fundamental parameter - that of cost. Many additional parameterizations can be utilized to specific the capabilities and performance of a given telescope, such as moving mass, instrument suite, and site, but aperture size is matched only by choice of operational wavelength as a fundamental cost driver. As described in Meinel (1978), a proportionality of cost to aperture size that scales as the 2.8 power (cost $\propto D^{2.8}$) was found to be true to first order. In this manuscript, we will explore the impact that an entire generation of telescopes since then has had upon the aperture-cost power law.

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2. Ground-Based Telescopes

Data used in this analysis can be found in Table 1, and their online cost references & other backing information; we have made every effort to obtain the publicly published cost data that most accurately reflect the telescope construction cost. For each telescope, the cost data point was intended to be inclusive of telescope mirror, structure, enclosure, and other essential site work based on these references, and exclusive of instrumentation and operations cost. Cost data were normalized to year 2000 US dollars using the standard federal tables for inflation adjustment for the past century. There are unfortunately as many acronyms as there are telescopes, and rather than expand them all here, the reader is encouraged to reference those links he or she has an interest in.

We should note that the costs cited herein are potentially a bit ‘soft’, in that in many cases, a telescope’s initial construction is followed by a period (sometimes years) in which the operation of the aperture is optimized. In many cases this optimization is improving the performance of the telescope beyond its initial specifications, but in a few cases this commissioning phase is needed just to meet the original design goals. For that latter case, the operation costs of that extended commissioning phase should be included in the true aperture cost, but we are unable to precisely do such accounting here.

2.1. Pre-1980

Large telescopes built prior to 1980 had certain basic characteristics typically in common. These characteristics include:

- Equatorial mounts - Even the massive 5-m Hale has a equatorial mount, with an axis parallel to the Earth’s rotational axis. The period 1970-1980 saw the first breaks with tradition on this point, with the 6-m Soviet (now Russian) SAO telescope.
- Slow optical systems - F/ratios were typically greater than 3, and never less than 2.5.
- Thick mirrors - Some lightweighting was incorporated into these mirrors, but thermal inertia and the resultant mirror seeing remains a substantial problem for these apertures.

As a result of the first two points above, such designs had substantial impact upon tube length, and as a result, enclosure size and attendant expense.

2.2. Post-1980

Large telescopes built after 1980 had the following basic characteristics in common:

- Alt-az mounts - Advances in computer control and optomechanical devices now allow for the more compact mounting allowed by the alt-ax mounts
- Fast optical systems - Of the major (>2.5m) apertures built since 1980, not a single one had a f/ratio greater than 2.5, and none since 1989 have been greater than 1.8.
- Thin mirrors - Often these primaries are coupled with active control systems to dynamically compensate for changes in the angle between the pointing vector and the gravity vector.

A special class of telescopes in the post-1980 era are the *giant segmented mirror* (GSM) *telescopes*. Beginning with the Keck I telescope, optical systems in excess of 8.4-m have begun to be available to the astronomical community. Currently operational GSM telescopes are Keck I, Keck II, and the Hobby-Eberly telescope, with the GTC, SALT, and LBT apertures all under construction. These telescopes all have effective areas in excess of 9-m.

A second special class appearing in the post-1980 era were large telescopes that made special efforts in trading operation capability for increased aperture size. Both the Hobby-Eberly and SALT telescopes have eliminated structural elevation pointing for simplified design and reduced cost, and the liquid mercury telescope of Univ. British Columbia is restricted to zenith pointing for even greater cost savings, much like the Arecibo 305 meter radio telescope.

Table 1. Telescope data used in this analysis.

Telescope	Institute	Size (m)	Cost ($M)	Year	Adj. Cost (2000, $M)	f/ratio	Mass (tons)	Reference
Yerkes	Univ. Chicago	1.0	0.5	1897	10.0			http://www2.uchicago.edu/alumni/alumni.mag/9702/9702Yerkes.html
Hooker	Mt. Wilson	2.5	0.6	1917	9.2	5.0		http://www.sierramadre.lib.ca.us/smarchives/Exhibits_More.htm
Hale	Caltech	5.1	6.3	1928	60.0	3.3	482	http://www.astro.caltech.edu/observatories/palomar/history/ http://www.gryp.fsnet.co.uk/ast11.htm
Mayall	NOAO	4.0	10.0	1970	41.5	2.8	n/a	http://www.aura-nio.noao.edu/book/ch5/5_7.html
AAT	AAO	3.9	22.8	1973	78.8			http://www.ast.cam.ac.uk/AAO/about/aat.html; A$ 15932250
Blanco	CTIO	4.0	10.0	1976	27.1	2.8	310	http://arjournals.annualreviews.org/doi/full/10.1146/annurev.astro.39.1.1
ESO 3.6m	ESO	3.6	41.7	1977	104.3	3.0	240	http://www.eso.org/gen-fac/pubs/astclim/papers/lz-thesis/node23.html http://astrophysics.weber.edu/Correct/Astr0179.pdf
IRTF	NASA	3.0	10.0	1979	21.7	2.5		http://www.hawaii-county.com/databook_97/section13.htm
CFHT	CFHT Consortium	3.6	30.0	1979	65.1	3.8		http://www.hawaii-county.com/databook_97/section13.htm
WHT	Obs. Roque de los Muchachos	4.2	21.5	1979	46.6	2.5	210	http://www.ing.iac.es/∼crb/wht/hist.html; 10 million pounds
Faulkes	UH / UK	2.0	6.0	2001	5.9			http://www.bizjournals.com/pacific/stories/2001/03/26/focus4.html
NOT	NOTSA	2.5	4.9	1983	7.9	2.0	43	http://www.not.iac.es/
NTT	ESo	3.5	13.0	1988	17.6	2.2	110	http://astrophysics.weber.edu/Correct/Astr0179.pdf
ARC	Apache Point Obs.	3.5	11.0	1988	14.9	1.8		http://www.eurekalert.org/pub_releases/2001-09/uoca-uoc090601.php http://archives.thedaily.washington.edu/1996/012696/Star012696.html http://www.washington.edu/research/pathbreakers/1994c.html http://www.apo.nmsu.edu/Telescopes/eng.papers/performance/performance1988.html
Starfire 3.5m	AFRL	3.5	27.0	1993	30.9			http://www.de.afrl.af.mil/Factsheets/35meter.html
WIYN	WIYN Consortium	3.5	14.0	1994	15.7	1.8		http://www.noao.edu/wiyn/wiynis.html
AEOS	USAF (Maui)	3.7	18.2	2000	18.2	1.5	75	http://www.acec.org/programs/2000eeaawards.htm http://ulua.mhpcc.af.mil/AMOS/1999_AMOSTechnicalConference/Mayo_paper/Mayo.html
VISTA	ESO	4.1	51.5	2003	48.0			http://www.schott.com/english/news/press.html?NID=1417
SOAR	CTIO	4.2	28.0	2001	27.4	1.8		http://www.lna.br/soar/soar_e.html
Magellan 1	CfA	6.5	65.0	2000	65.0	1.3	150	http://www.unispace3.co.cl/inicial6_e.html
Magellan 2	CfA	6.5	72.0	2001	70.4	1.3	150	http://www.astro.lsa.umich.edu/∼rab/specjust.pdf
Gemini	NSF	8.1	88.0	1992	103.5	1.8	311	http://www.the-scientist.com/yr1992/march/let3_920316.html
VLT UTs	ESO	8.2	266.8	2000	266.8	1.8	430	http://www.phys.hawaii.edu/∼jgl/post/WGLSF_table_29Mar01.htm http://www.belspo.be/belspo/res/coord/res_euro/eso/det_en.stm
Subaru	NAOJ	8.3	170.0	2000	170.0	1.8	500	http://www.hawaii-county.com/databook_97/section13.htm http://www.phys.hawaii.edu/∼jgl/post/WGLSF_table_29Mar01.htm http://www.jinjapan.org/kidsweb/techno/subaru/history.html
Keck	CARA	10.0	94.5	1985	139.1	1.8	273	http://www.lbl.gov/Science-Articles/Archive/keck-telescope.html
GTC	Spain	10.0	90.6	1997	95.3	1.7		http://www.gtc.iac.es/home.html; 12750 MPtas (1997)
LBT	Univ. Arizona	11.9	110.0	2000	110.0	1.1	530	http://www.sdaa.org/SDAAAppli/arizona.htm&e=747 http://medusa.as.arizona.edu/lbtwww/ http://mytwobeadsworth.com/MtGraham928.html
LMT	Univ. of British Columbia	6.0	1.0	2000	1.0	1.5	n/a	
HET	McDonald Obs.	9.5	14.0	1997	14.7	1.8	n/a	
BTA	Special Astroph. Obs.	6.0		1976		4.0	850	

2.3. Discussion on Ground-Based Apertures

As seen in Figure 1, there appears to be a clear progression of cost with telescope size. An examination of the aperture built prior to 1980 shows cost $\propto D^{2.77}$, which as would be expected is consistent with Meinel (1978). For those monolithic apertures built since 1980, the cost-aperture power law is slightly shallower, with cost $\propto D^{2.46}$, but still significantly greater than merely scaling with telescope area, D^2. The GSM telescopes that have been built appear to drop below the post-1980 line, just as the post-1980 line drops below the pre-1980 line.

Our interpretation of this offset in the power law intercept is the cost reducing impact of fundamentally new technologies. At the ∼1980 turning point, the improvement was a combination of telescope mounting and faster optical systems, reducing the overall size of the telescopes. For the advance associated with GSMs, the improvement is the cost reduction associated with fabrication of segmented versus monolithic primary mirrors. There are unfortunately not enough data points to determine if the GSMs will also follow a cost $\propto D^{2.46}$ power law; however, we naively expect for the cost-aperture relationship to generally adhere to this slope.

As such, we may easily predict general costs for future apertures built using technology associated with the current family of GSMs. We expect a 30-m telescope to cost roughly \$1.4 billion, and a 100-m telescope is expected to be roughly \$26 billion, *using current GSM technology.* If, as can be reasonably postulated, advances in telescope construction technology can be applied to the next generation of large apertures, reductions of 2-3× can be expected with each new family of technology, as seen in the progression from pre-1980 to post-1980 to GSMs. A \$600M, 30-m telescope can be reasonably argued to be only a single technology generation away. However, following this same reasoning, a \$2B, 100-m telescope is probably a full three technology generations away from being realized.

3. Space-Based Telescopes

Unfortunately, there are only a few operational examples of space-based telescopes. The obvious candidate is the Hubble Space Telescope (HST). Of NASA's other three 'Great Observatories', only the Space Infrared Telescope Facility (SIRTF) has a mirror design that lends itself to comparison within this context. A full accounting of flight designs is appropriate within the context of categorizing the approaches to space telescopes:

- Delivery to orbit - Both HST and SIRTF are examples of this category of space-based mission.
- Assembly in orbit - Given the payload shroud constraints of a ∼5m diameter on even the largest of launch vehicles, a number of spacecraft that have flown or are in the planning stages take advantage of a ground-based construction, with a space-based assembly stage. This can be as simple as an autonomous unfurling, or a more complicated and drawn out assembly phase prior to operations. It is worth noting that there are two obvious classes of telescope in this category - those that benefit from *robotic* assembly, and (particularly within the context of the space station) those that would be the product of *human* assembly. Of surprise to many, there are three clear examples of at least the robotic assembly approach to date: the 8-m VSOP and 12-m commercial MBSat radio antennas, both of which have flown, and the 6.5-m near-infrared JWST, which has not flown but is clearly committed to this approach and will be orbited within the next ten years.

Table 1—Continued

Telescope	Institute	Size (m)	Cost ($M)	Year	Adj. Cost (2000, $M)	f/ratio	Mass (tons)	Reference
UKIRT	UK	3.8	5.0	1979	10.9			http://www.hawaii-county.com/databook_97/section13.htm
UH 88”	UH	2.2	5.0	1970	20.8			http://www.hawaii-county.com/databook_97/section13.htm
MMT	Univ. Arizona	6.5	49.4	2000	49.4	1.3	118	$11m for original 6 elements in 1977, $20m conversion in 1995
CFHT Upgrade	CFHT Consortium	8.0	108.0	1999	110.5			http://www.casca.ca/lrp/vol2/wf8m/node5.html
Swedish ELT	Lund Obs.	50.0	876.0	2003	816.8			http://www.astro.lu.se/∼torben/euro50/publications/swedish50m99.pdf; 750 million Euros
GSMT / CELT	NOAO / Caltech	30.0	600.0	2000	600.0			http://www.aura-nio.noao.edu/book/ch5/5_7.html

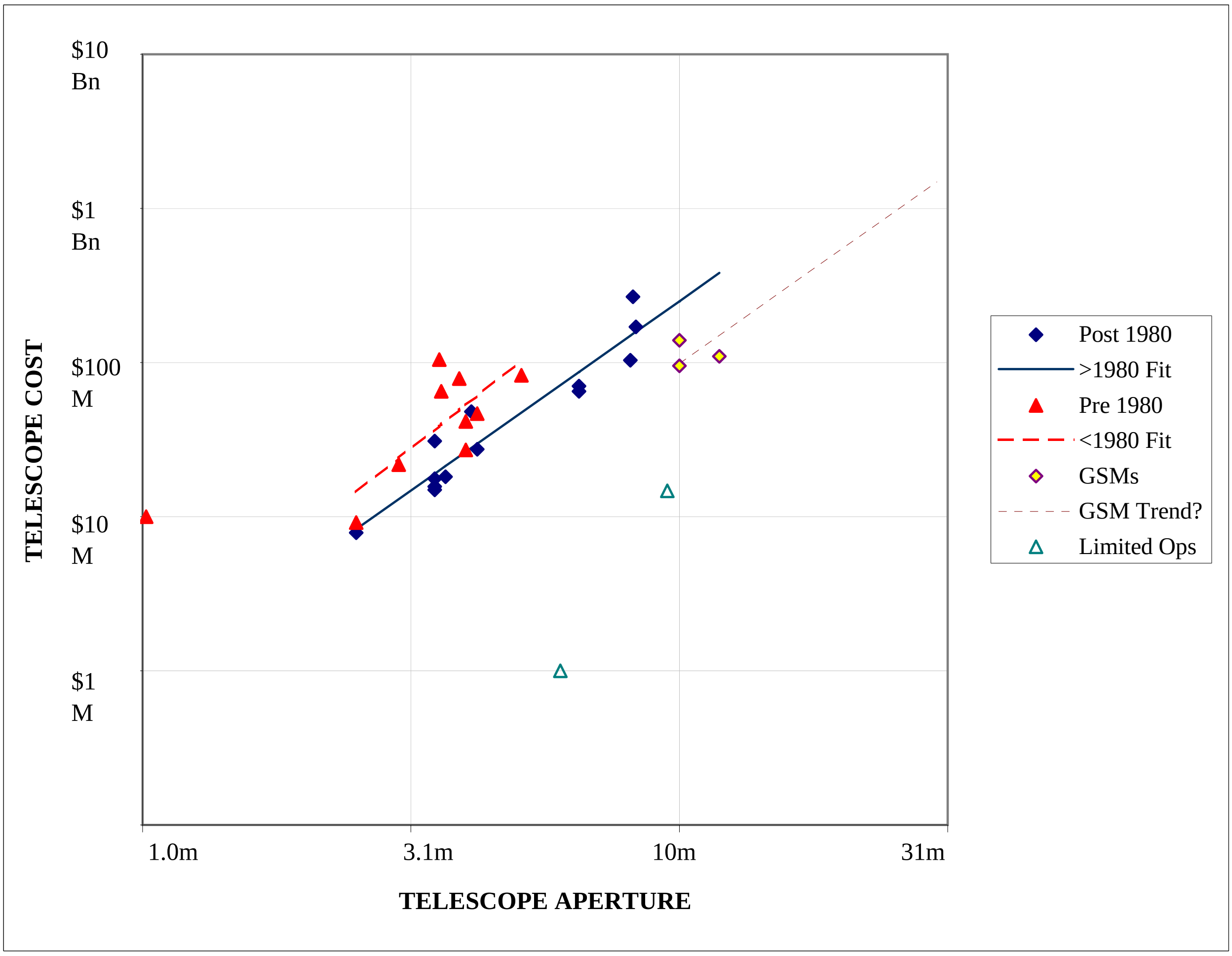

Fig. 1.— Cost versus aperture diameter for optical telescopes built before and after 1980. For the pre-1980 fit, cost $\propto D^{2.77}$, and for the post-1980 fit (exclusive of the giant segmented mirrors), cost $\propto D^{2.45}$. The two limited operations telescopes plotted are the UBC 6-m liquid mecury telescope and the 9-m (effective) HET.

- Fabrication in orbit - This approach is, at present, somewhat more fanciful than the previous two, potentially making using of some sort of *in situ* resource utilization (and as a result, bypassing the limitations of launch vehicle lift restrictions). Although the most promising in terms of ultimate aperture size, we will only mention this approach here in passing, for the sake of completeness, due to its gross technical immaturity.

A further complication worth considering is the prospect of *on-orbit servicing*, which can be applied equally to all three categories above.

Given the small number of examples to date for space-based telescopes, no general inference can be drawn from the relationship between telescope cost and aperture size for these apertures. Indeed, the similar relative cost between Hubble and JWST - on the order of \$1 to \$2 billion dollars for each - would indicate within the simple confines of the rough analysis presented herein for ground-based apertures that telescope size is independent of cost. Instead, our assessment is that the predominant phenomenon at play is rapid technological development as it impacts aperture size, rather than simple scaling of a single family of technology.

4. General Discussion

Ground-based Telescopes. There are two key factors that affect the aperture-cost scaling law for ground-based telescopes:

- Environment - Environment manifests itself in two significant ways for ground-based telescopes. Inclement weather is the first of these two ways - the telescope must be protected from precipitation and other hazards associated with being open to the air. For all major optical telescopes to date, this is accomplished by construction of a telescope enclosure, typically a dome. The second weather factor is wind - acceptably low wind velocities do not preclude operation under transparent conditions, but wind shake can significantly degrade telescope performance. For most optical telescopes, an enclosure can also mitigate the effect of wind upon the telescope structure, typically a co-rotating dome.

  For optical telescopes, as the aperture grows, the dome grows as $\sim (\mathrm{f/ratio} \times D)^3$. Reduction of telescope f/ratios over time have improved the situation over the past twenty years, but this factor ultimately can be no smaller than $\sim D^3$. A common mistake at many observatories is the assumption that the dome is a simple element of the overall observatory, not worth a great deal of thought or investment; the result is often years of expensive maintenance headaches and/or operational limitations.

  Recent illustrations accompanying proposals for a 30m-class telescope compare the aperture size to that of a baseball diamond; this is a particularly illustrative example, noting that recent retractable roof baseball stadiums have been built and are worthwhile enclosures to consider when trying to approximate price. While larger than the enclosure for a 30m telescope (in that they have to enclose an outfield and grandstands), they are also significantly simpler in that they only retract, and do not have to rotate. A recent example of this sort of venue in Seattle was built for \$600M (telescope not included).

- Gravity - Observational pointing access to the sky is typically achieved through orienting the telescope structure in two axes, frequently elevation & azimuth or right ascension & declination. (The Hobey-Eberly and Liquid Mercury Telescope are notable exceptions to this observation, and have traded significant operational flexibility for economic advantage, as seen in Figure 1.) Changing a telescope's elevation or declination alters the angle between the telescope's pointing vector and the local gravity vector. Since the telescope must maintain its alignments throughout all pointings, the structure must be tolerant of this variable angle. As such, the telescope structure often grows as a hemisphere behind the aperture it supports - the growth, and cost, of this structure will scale as $\sim D^3$. Clever design of this structure can reduce the power law to something closer to the square of the aperture diameter, but consistency of the $D^{2.7}$ aperture-cost scaling law indicates there are perhaps limits to cleverness dictated by modern construction materials and techniques.

Both of these factors affect the relevant power law for ground-based telescopes. Elimination of the telescope dome for the largest of the new telescopes is certainly an option (and actively under consideration for some of the larger apertures proposed), although it will clearly multiply the deleterious effect of wind shake on the telescope backing structure and push the cost of the backing structure back towards $\sim D^3$. These two ever present ground-based factors will push the aperture-cost scaling law away from $\sim D^2$ and towards $\sim D^3$.

Space-based Telescopes. As with ground-based apertures, there are two key factors that affect the aperture-cost scaling law for space-based telescopes:

- Structural stability - As with ground-based telescopes, a space-based telescope's backing structure will be responsible for maintaining the unique shape of the primary mirror, regardless of pointing. However, given the absence of a significant gravitational field, the structure may be designed primarily for aperture alignment rather than support against an external field. There will be no changing external force to cope with as the aperture points to different portions of the sky. As such, it is our expectation that the structure will be primarily 2-dimensional assembly and that the aperture-cost law associated with maintaining optical figure will scale as $\sim D^2$.
- Environment - For structures of significant size in space, an important consideration that begins to impact operational considerations is the space 'weather', primarily due to the sun. Particulate solar wind, radiation pressure, and heating effects of the solar environment will all have to be accounted for. It is likely that large telescopes in space will need a shield between the primary aperture and the sun. This shield, while notionally as large or even larger than the aperture itself, will also manifest itself as a primarily 2-dimensional structure. Also, given the substantially relaxed requirements for such a shield to maintain a given shape, it can be a fairly gossamer structure. Such a shield provides the additional benefit of cooling of the telescope; this type of structure is already a part of the baseline JWST design and is not considered to be a significant cost driver. The cost of this structure should also scale as $\sim D^2$.

It is also worth noting that certain expensive design drivers for ground-based telescopes are not necessarily present in punitive space-based designs. For example, since a dome is no longer enclosing the telescope structure, a driver for relatively fast focal ratios (and difficult to fabricate parabolas) is removed.

Overall, our expectation is that ground-based telescope costs will continue to scale as $\sim D^{2.5}$. Improvements in technology will provide one-time shifts in the zero-point of the aperture-cost relationship, with no impact upon slope. In contrast to the ground-based case, we expect space-based apertures to have a much slower aperture-cost relationship, growing as slowly as $\sim D^{2.0}$. The difference in slopes has a striking consequence: **At some given aperture size, it will be just as expensive to deliver an operational**

space-based or ground-based telescope. This equality is *independent* of the obvious advantages a space-based aperture has over its ground-based counterpart. Isolating the cross-over point of the two power laws will be of particular interest, in that it points to the size domain that will be exclusively inhabited by space-based apertures.

At the present, using these putative values for the power law slopes, and starting from the points established by the current generation of GSMs for the ground-based case, and JWST for the space-based case, the cross-over point appears to appear at the 300m filled aperture size, at a cost of $100 billion dollars. This is a completely unrealistic sum for any telescope. However, if we advance from this starting point and move forward two technology generations for both space-based and ground-based telescopes - with the attendant shift in power law intercepts - our cross-over location shifts to a 120m filled aperture at a cost of $10 billion dollars. This is still quite a speculative sum, but getting to be significantly more realistic. If there is a more rapid advance in space technology than in ground-based telescope technology (which these authors do not think untenable given the relative levels of investment), and two generations of space-based observatory technology evolve for every one of on the ground, our cross-over shifts to 70-m, $3 billion dollars. Given these sorts of possible scenarios, it is our expectation that the largest aperture built upon the ground will be in the region of 100-m.

Above and beyond the initial cost of an observational facility, there are two additional aspects of telescope finances that are not being examined in great detail in this simple analysis, but they bear mentioning here:

- Instrumentation - A substantial portion of the cost of any operational observatory is its instrumentation. For ground-based apertures, this can be an evolving suite of instruments with various specialized specifications and design goals. For these facilities, and for those space-based observatories with on-orbit servicing, ongoing instrumentation upgrades represent an ongoing cost of the facility.
- Operational Costs - For ground-based observatories, this number can run annually from 5% to 30% of the overall initial construction cost. There are two aspects of this cost that can be specifically identified here: first, that of ongoing maintenance, and second, that of the actual observing done with the facility.

For those space-based observatories that do not benefit from on-orbit servicing, some of these costs simply do not appear - new instrumentation does not need to be developed, nor does daily maintenance need to be physically performed upon the spacecraft(s). However, this potentially translates into limitations in terms of instrument capability and mission lifetime, particularly in relation to ground-based facilities, so the actual benefit or penalty of these considerations is not entirely clear.

5. Conclusions

We have shown the telescope cost growth scaling law of $\sim D^{2.77}$ that was first noted in Meinel (1978) for ground-based telescopes is slightly shallower for the apertures that have been built since 1980, at $\sim D^{2.46}$, but remains generally true. We have also presented arguments in support of a similar, but notably shallower, scaling law for space-based telescopes, closer to $\sim D^{2.0}$. An important implication of these two power laws is their intersection - this point defines a telescope that will be equally expensive to build on the ground or in space. This point is independent of the advantages to be gained in siting the aperture in space versus on the ground.

This is particularly interesting as the astronomical community contemplates construction of ground-based apertures that are up to 100m in size. Given the limits of public and private support for construction of new telescopes, it would be prudent for the community to carefully consider the directions they take their more ambitious technology development efforts. These investments should be directed with consideration regarding if those efforts eventually will dead end, as in the ground-based case, or have substantial growth options. Current thinking in terms of ‘overwhelmingly’ large apertures will of course eventually give way to thoughts about even larger instruments capable of achieving science goals with fundamental implications for astrophysical discovery. These goals include continental mapping of nearby exosolar terrestrial planets, a complete sub-pc catalog of star formation within the local group, and surveys of the early universe at $z > 10$.

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