

Update on multi-variable parametric cost models for ground and space telescopes

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ABSTRACT

Parametric cost models can be used by designers and project managers to perform relative cost comparisons between major architectural cost drivers and allow high-level design trades; enable cost-benefit analysis for technology development investment; and, provide a basis for estimating total project cost between related concepts. This paper reports on recent revisions and improvements to our ground telescope cost model and refinements of our understanding of space telescope cost models. One interesting observation is that while space telescopes are 50X to 100X more expensive than ground telescopes, their respective scaling relationships are similar. Another interesting speculation is that the role of technology development may be different between ground and space telescopes. For ground telescopes, the data indicates that technology development tends to reduce cost by approximately 50% every 20 years. But for space telescopes, there appears to be no such cost reduction because we do not tend to re-fly similar systems. Thus, instead of reducing cost, 20 years of technology development may be required to enable a doubling of space telescope capability. Other findings include: mass should not be used to estimate cost; spacecraft and science instrument costs account for approximately 50% of total mission cost; and, integration and testing accounts for only about 10% of total mission cost.

Keywords: Space Telescope Cost Model, Parametric Cost Model

1. INTRODUCTION

Parametric cost models for space telescopes provide several benefits to designers and space system project managers. They identify major architectural cost drivers and allow high-level design trades; enable cost-benefit analysis for technology development investment; and, they provide a basis for estimating total project cost. Over the past eight years, we have published several papers on cost models for both ground and space based optical telescope assemblies (OTA), where an OTA is defined as the primary mirror, secondary mirror, auxiliary optics, and support structure.^[1-10] These papers fully discuss our data collection methodology and cost model creation process. A discussion of that methodology and statistical analysis process will not be repeated in this paper. This paper provides a summary update of our recent progress in developing multi-variable parametric cost models for both ground and space telescopes.

2. GROUND OPTICAL TELESCOPE ASSEMBLY COST MODEL

In 2005, Stahl et al. published a single variable which estimated cost as a function of primary mirror diameter and a multivariable parametric cost model for ground telescopes which estimated cost as a function of primary mirror diameter, diffraction-limited wavelength, and year of development.^[2] The multi-variable model also included a factor for primary mirror segmentation and/or duplication. While the original multivariable model is still relevant an error was found and corrected in the single variable model.^[10] The single variable model published in 2005 is:

$$\text{Ground OTA Cost} \propto \text{Diameter}^{1.8}$$

The corrected model published in 2012 is:

$$\text{Ground OTA Cost} \sim \$2\text{M} \times \text{Diameter}^{1.4}$$

As discussed in Luedtke and Stahl, 2012, the reason that the diameter exponent changed is because the leading multiplier was excluded from the regression. The reason it was excluded is because cost models are inherently comparative, i.e. they should not be used to actually attempt to predict the cost of a given specific telescope architecture, but rather they should be used to compare the relative costs of two related telescopes. But, the effect of excluding the leading multiplier from the regression was to force the cost estimate of small aperture telescopes towards 1; which required a ‘steeper’ cost

curve with diameter. Also, by omitting the leading multiplier, the regression was not independent to units, i.e. a different exponent would have been returned if the regression had been done in centimeters instead of meters. By including the leading multiplier, a ‘flatter’ cost curve with diameter that is independent of units was obtained.

Another reason that the 2005 paper published the single variable model without the multiplier is because the coefficient was similar with that of the multi-variable model, but in fact it should not have matched. The reason why the single variable diameter exponent should be lower than the multivariable diameter exponent is because of the effect of year of development. Year of development and aperture diameter are positively correlated ($r=0.55$, $p=0.03$), a fact which makes sense because one tends to build the largest telescope that can be afforded at any given time. Because technology advancement tends to reduce the cost to fabricate a telescope of a given aperture diameter, when year of development is implicitly included in the single variable model, it results in a smaller diameter exponent. But, when year of telescope development is made explicit as a cost variable independent of aperture diameter, it results in a larger diameter exponent.

The Stahl 2005 multivariable model had a diameter exponent of 1.8:

$$\text{Ground OTA Cost} \sim 0.7 \text{ SF } D^{1.8} \lambda^{-0.5} e^{-0.04(Y)}$$

$$(R^2=95\%, \text{ adjusted } R^2=94\%, \text{ SPE} = 35\%)$$

Where:

OTA Cost in Millions of FY2000\$

D = Primary Mirror Diameter (meters)

λ = Wavelength Diffraction Limited (microns)

Y = Year of Development - 2000

SF = Segmentation Factor

$\text{SF} = P_n R_n^{0.7} (D_s/D)^{1.8}$ if the primary mirror is segmented, and

SF = 1 if the primary mirror is monolithic

Where

D_s = Diameter of the Repeated Segments (meters)

D = Diameter of the Primary Mirror (meters)

R_n = Number of Repeated Segments

P_n = Number of Unique Prescriptions

A key element of the multi-variable ground telescope mode is the Segmentation Factor. The purpose of this factor is to include cost reduction from learning while making duplicate primary mirror segments (such as for Keck or HET) or whole primary mirrors for arrays of telescopes (such as for VLT or CARA). The data base used to derive the above result contained only 5 segmented monolithic or sparse aperture telescopes. The 0.7 exponent is an 80% learning curve (where each successive unit is 80% the cost of the previous unit). And, in all cases the duplicated segments or complete OTAs were assumed to be identical. Therefore, an assumption was made that learning was confined to a given prescription or implementation. However, results from the JWST primary mirror assembly segments (PMSAs) indicate that learning transfers across prescriptions (Figure 1).

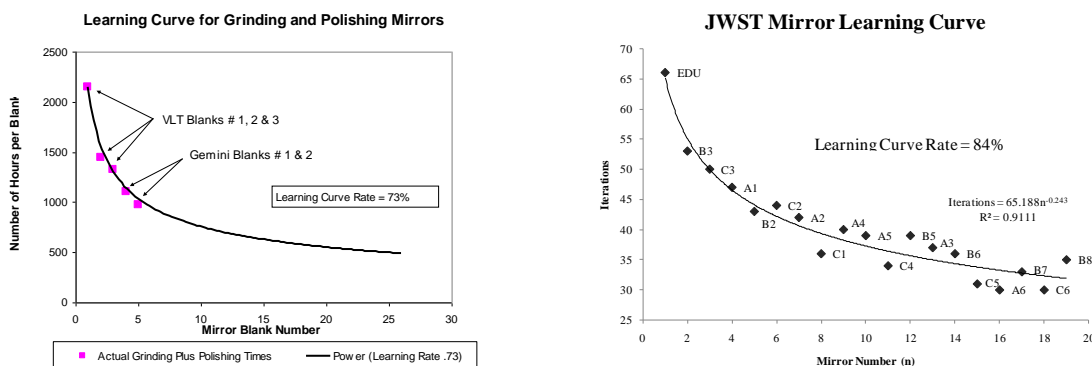


Figure 1: Learning Curve for fabricating 5 8-meter primary mirrors for VLT & Gemini is 73%; Learning curve for fabricating 19 1.5-meter segments for JWST is 84% (private communication, Ben Gallagher).

Given the JWST results, Luedtke and Stahl 2012, published a new ground telescope cost model. The model is derived from a data set of from only 5 segmented or sparse aperture telescopes and assumes that learning transfers across prescriptions:

$$\text{Ground OTA Cost} \sim 0.8 \text{ SF } D^{1.7} \lambda^{-0.7} e^{-0.04(Y)}$$

$$(R^2=91\%, \text{ adjusted } R^2=88\%, \text{ SPE} = 37\%)$$

where $\text{SF} = [S^{0.7} (D_s/D)^{1.7}]$ and S represents the total number of segments. While the duplication and diameter exponents are nearly identical, the wavelength exponent is significantly different. However, given the size and similarity of the current data base, the new -0.7 exponent may or may not be more correct than the old -0.5 exponent. The problem is one of insufficient wavelength diversity in the data base. While multiple authors have given rules of thumb for how cost varies with wavelength, only Meinel's papers contain quantitative data.^[4] A comparison of optical and radio wavelength telescopes indicates approximately a 100X to 1000X difference in cost.^[11,12] Assuming that an optical telescope operates at a wavelength of 1 micrometer and that radio telescopes operate from 10 mm to 10 meters, an exponent of -0.5 implies that a radio telescope will cost 100X to 3000X less while an exponent of -0.7 implies a 600 to 80,000X cost reduction. Similarly, a comparison of optical and submillimeter telescopes indicates a 10X cost difference.^[13] Assuming that the submillimeter wavelength is 100 micrometers to 1 mm, then a -0.5 exponent indicates a 10X to 30X cost reduction while a -0.7 exponent indicates a 25 to 125X reduction.

3. SPACE OPTICAL TELESCOPE ASSEMBLY COST MODEL

While some of the space telescope data base has changed slightly since 2011, there is no change to any of the model regressions. However, we continue to refine our interpretations of the data and try to clarify mis-conceptions.

3.1 Optical Telescope Assembly Cost as a percentage of Total Mission Cost

During the past year, this author has been in several meetings where some have asserted, quite forcefully, that one must reduce the size of a telescope aperture to make a given mission affordable. Or, that integration and test (I&T) accounts for 60% of the total mission cost and that all one needs to do is reduce the need for I&T. The problem is that the data does not support these assertions. Based on an analysis of detailed work breakdown structures for 7 of the 14 free flying UVOIR space telescope missions in the data base for which we have both OTA and Total Mission cost, the average OTA cost is only 12% of total mission cost (Figure 2). For these missions, the spacecraft and science instruments account for half of the total mission cost, and the OTA cost is comparable with Program Management and Systems Engineering cost. It must be stated that the 12% OTA cost is an average. The actual costs of OTA as a function of Total, for all 14 missions for which we have data, varies from 2 to 20% (Figure 3). Based on this analysis, one might conclude that the best way to reduce total mission cost is to reduce the cost (and or capability) of the Science Instruments or Spacecraft. But, maybe the better question to ask is What is right balance of cost between major subsystems? And, which subsystem's cost is out of proportion?

Furthermore, Observatory level I&T cost is only 10% of total mission cost. However, in this accounting, mission I&T cost excludes sub-system level I&T cost. Given that sub-system I&T costs might be 10 to 25% of their individual costs, it is plausible that total I&T costs might be as large as 25% of total mission cost but certainly not 60%.

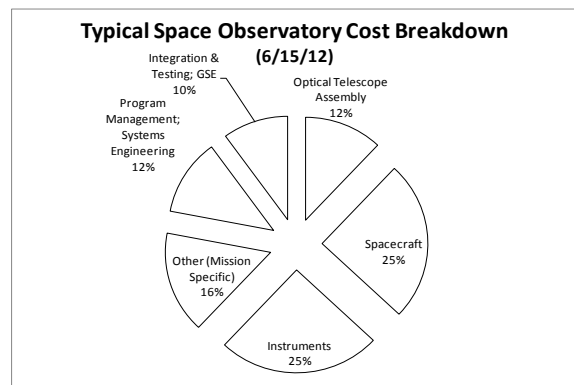


Figure 2: Average Percentage of Total Mission Cost for Major Cost Elements and/or Sub-Systems.

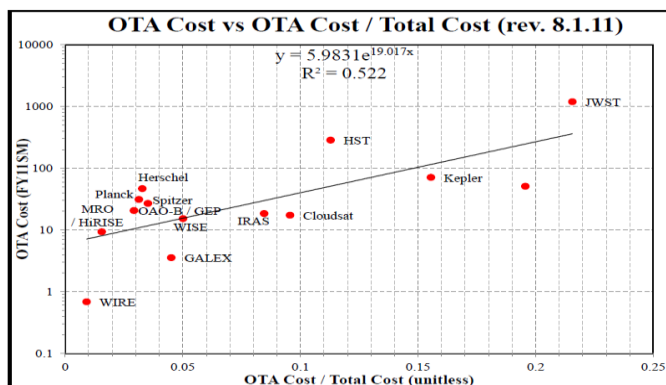


Figure 3: OTA Cost as a function of Total Mission Cost

3.2 Optical Telescope Assembly Cost as a function of Mass

Many believe that mass is the single most important cost driver for space telescopes. They assert that to reduce cost, all one need do is to reduce mass. But, it is simply not true. A comparison of JWST and HST proves the point. If mass determined cost, then the JWST OTA would cost approximately the same as the HST OTA instead of twice as much. And, if mass determined cost, then the total mission cost of JWST would be half the total mission cost of HST instead of the reverse (Figure 4).

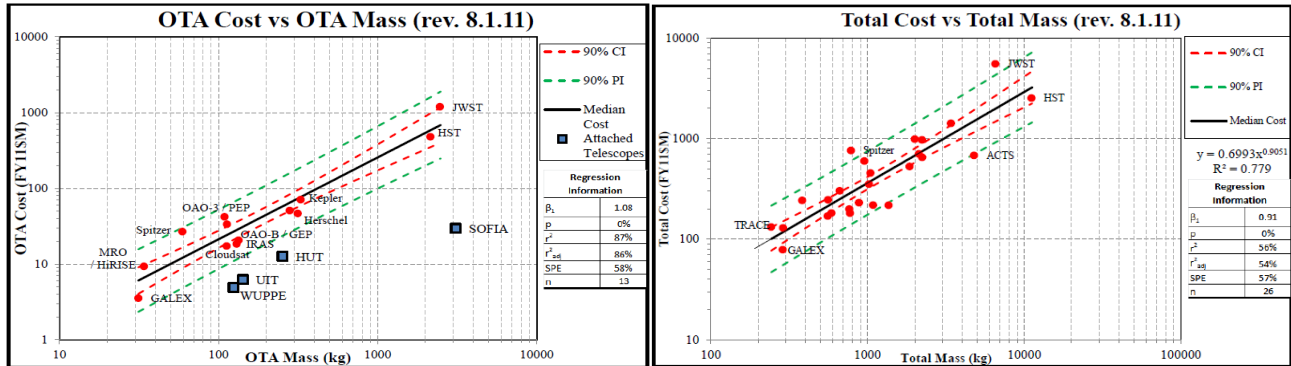


Figure 4: Mass of the JWST and HST OTAs are nearly identical, but the cost of the JWST OTA is twice the cost of the HST OTA; Total mass of HST is nearly twice that of JWST, but the cost of JWST is nearly twice that of HST.

What is true is that space missions are constrained by the mass capacity of their launch vehicle. All space missions are designed to a constrained mass budget. Thus, mass is not a free variable. And, it is a fact that ground telescopes cost less than space telescopes. What is interesting is that all ground telescopes have approximately the same cost per kg. And, all space telescopes also have approximately the same cost per kg (Figure 5). But the cost per kg for ground and space differ by 1000X. Additionally, SOFIA which is attached to a 747 airframe is 15X less expensive per kg than free-flying space telescopes. And, space telescopes which were attached to the Space Shuttle were 2X less expensive than free-flying space telescopes. One conclusion is that design rules drive OTA cost more than mass: complex, smart mass with tight design rules costs more per kg than simple, dumb mass with generous design rules. Thus, the best way to reduce cost is to change the design rules by using larger capacity launch vehicles and increasing the mass margins.

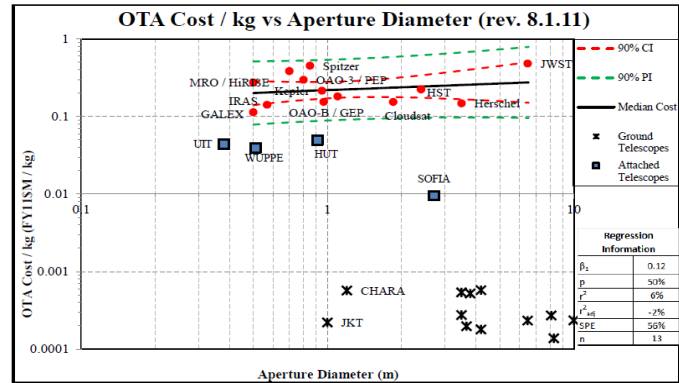


Figure 5: Cost per kg of Space Free-Flying, Space Attached, Airborne and Ground indicates that different design rules apply for each class of telescope.

3.3 Single Variable Space Optical Telescope Assembly Cost Model

While the single variable space OTA model is unchanged, it is interesting to note that its diameter exponent is now identical to the ground OTA model.

$$\text{Space OTA Cost} \sim \$100M D^{1.4} \quad (N = 15; r^2 = 82\%; SPE = 123)$$

$$\text{Ground OTA Cost} \sim \$2M D^{1.4}$$

Based on 15 free-flying space telescopes, the aperture diameter model accounts for 82% of the cost variation in the real data and it is noisy. Therefore, a multi-variable model is indicated.

3.4 Multivariable Space Optical Telescope Assembly Cost Models

Given that the single variable aperture model accounts for only 82% of the actual OTA cost variation and is somewhat noisy, it is necessary to look at multi-variable models. To develop a multi-variable model, we regress cost against diameter and candidate second variables (Figure 6). A good two variable model is one where the second variable

| rev. 8.1.11 | | OTA Cost vs Aperture Diameter and V2 | | | | | | | | | | | | | |
|-------------------------|---------|--------------------------------------|------|--------------------------------|------|-----------------------|------|-------------------|------|--------------------|------|-------------------|------|----------------------|------|
| Variable 2 | | Aperture Diameter | | PM F Len. | | OTA Volume | | FOV | | Pointing Stability | | OTA Mass | | OTA Areal Density | |
| Diam. | p-value | 1.42 | 0.00 | 0.73 | 0.19 | -1.28 | 0.38 | 1.26 | 0.02 | 1.64 | 0.01 | 0.02 | 0.94 | 2.05 | 0.00 |
| Var. 2 | p-value | - | - | 1.00 | 0.06 | 1.00 | 0.06 | 0.00 | 1.00 | -0.21 | 0.32 | 1.07 | 0.00 | 1.01 | 0.00 |
| Adjusted r ² | | 81% | | 93% | | 93% | | 4% | | 95% | | 85% | | 84% | |
| SPE | | 123% | | 84% | | 84% | | 142% | | 66% | | 58% | | 54% | |
| n | | 15 | | 11 | | 11 | | 12 | | 8 | | 13 | | 12 | |
| Multicollinearity? | | N/A | | Yes | | Yes | | No | | No | | Yes | | No | |
| Variable 2 | | Spectral Range minimum | | Diffraction Limited Wavelength | | Operating Temperature | | Design Life (exp) | | Year of Dev. (exp) | | Dev. Period (exp) | | Date of Launch (exp) | |
| Diam. | p-value | 1.62 | 0.00 | 1.54 | 0.00 | 1.49 | 0.00 | 0.83 | 0.02 | 1.45 | 0.00 | 1.14 | 0.04 | 1.46 | 0.00 |
| Var. 2 | p-value | -0.18 | 0.02 | -0.22 | 0.02 | -0.08 | 0.64 | 0.01 | 0.01 | -0.01 | 0.46 | 0.01 | 0.17 | -0.01 | 0.70 |
| Adjusted r ² | | 96% | | 98% | | 81% | | 99% | | 84% | | 91% | | 82% | |
| SPE | | 74% | | 60% | | 136% | | 71% | | 124% | | 128% | | 120% | |
| n | | 15 | | 12 | | 14 | | 15 | | 14 | | 13 | | 15 | |
| Multicollinearity? | | No | | No | | No | | No | | No | | No | | No | |

Figure 6: 2 Variable OTA Cost Regression Summary

most space telescopes are not. Most space telescopes are unique, one of a kind designs which require the invention of new technology just to exist. Technology advance is most effective when making a second or duplicate system.

Ignoring areal density because diameter is in both variables, the best second variables which yield a significant exponent without invalidating the diameter exponent are spectral range, diffraction limited wavelength and design life. While design life has the highest adjusted- r^2 its exponent is has no value. Thus, the best two variable cost model is:

$$\text{OTA Cost} \sim \text{Dia}^{1.6} \lambda^{-0.2} \quad (N = 12, r^2 = 98\%; \text{SPE} = 60\%)$$

Repeating the regression analysis for a third variable yields:

$$\text{OTA Cost} \sim D^{1.7} \lambda^{-0.3} T^{-0.25} \quad (N = 11, r^2 = 96\%; \text{SPE} = 54\%)$$

It is obvious why temperature is the next variable. Just as aperture diameter and year of development are inversely correlated for ground telescopes, wavelength and temperature are negatively correlated for space telescopes. For space telescopes, the longer the operating wavelength, the lower the operating temperature. Two additional observations, the sign and magnitudes of the wavelength and temperature exponents tend to balance each other; and adding the second and third parameters has moved the diameter exponent closer to the ground model.

4. CONCLUSIONS

Parametric cost models provide several benefits to designers and space system project managers. They identify major architectural cost drivers and allow high-level design trades; enable cost-benefit analysis for technology development investment; and, they provide a basis for estimating total project cost. As part of our continuing research, we have revised and improved our ground telescope cost model and refined our understanding of space telescope cost models.

Parametric Cost Models should not be used to predict the cost of a specific architecture, but rather estimate the cost difference between similar architectures. For example, for ground based telescopes aperture diameter is the most significant cost driver and technology development tends to reduce cost by ~50% every 20 years. Also, longer wavelength telescopes are less expensive to build than shorter wavelength telescopes. Because all ground telescopes operate at approximately the same temperature, there is no statistical cost dependency for operating temperature. For space telescopes, aperture diameter is also the most significant cost driver, and, while space telescopes cost more than

ground telescopes, the relative scaling of cost with aperture diameter is similar for the two classes of telescopes. One explanation for why space telescopes cost more than ground telescopes is the design rules, i.e. the requirement to design space telescopes to a constrained mass budget with tight safety margins. Mass is not a good (or maybe even valid) cost estimating parameter. While in our data base larger aperture telescopes always cost more than smaller aperture telescopes, this relationship does not always hold true for mass. Additionally, for space telescopes, we are not finding a statistically significant cost reduction with year of development. One explanation may be because space telescopes tend to be unique, one-of-a-kind systems which rather than taking advantage of technology development to reduce their costs, actually take advantage of technology development to enable their existence. Therefore, instead of reducing cost by ~50% every 20 years, maybe 20 years of technology development is required to enable a doubling of a given mission capability. For both ground and space telescopes, when manufacturing duplicative components, the data indicates ~80% learning curve cost reduction.

Finally, analysis of detailed work breakdown structures for 7 space missions indicates that, on average, the optical telescope assembly is approximately 12% of total mission cost. By comparison, spacecraft and science instrument costs account for approximately 50% of total mission cost. And, depending upon how the costs are accounted, integration and testing costs are only 10% to maybe 25% of total mission cost.

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