Parametric Cost Model for Ground and Space Telescopes

H. Philip Stahl, Michael Allison
NASA MSFC, Huntsville, AL 35821

ABSTRACT

Parametric cost models can be used by designers and project managers to compare cost 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. The NASA Marshall Space Flight Center has developed a 5-parameter first-article optical telescope assembly cost model

$$\mathbf{OTA\$\ (FY17) = \$20M\ \ x\ \ 30^{(S/G)}\ \ x\ \ D^{(1.7)}\ \ x\ \ \lambda^{(-0.5)}\ \ x\ \ T^{(-0.25)}\ \ x\ \ e^{(-0.028)\ (Y-1960)}}$$

Where S/G = 1 for space and 0 for ground telescopes, D = diameter, λ = diffraction limited wavelength, T = operating temperature and Y = year of development. The model explains 92% (Adjusted R2) of the cost variation in a database of 47 total ground and space telescope assemblies (OTA). The MSFC model estimates the most likely cost for only the OTA. Where an OTA is defined as the subsystem which collects electromagnetic radiation and focuses it (focal) or concentrates it (afocal) into the science instruments. An OTA consists of the primary mirror, secondary mirror, auxiliary optics and support structure (such as optical bench or truss structure, primary support structure, secondary support structure or spiders, straylight baffles, mechanisms for adjusting the optical components, electronics or power systems for operating these mechanisms, etc.). Finally, duplication only reduces cost for the manufacture of identical systems (i.e. multiple aperture sparse arrays or interferometers). And, while duplication does reduce the cost of manufacturing the mirrors of segmented primary mirror, this cost savings does not appear to manifest itself in the final primary mirror assembly (presumably because the structure for a segmented mirror is more complicated than for a monolithic mirror).

Keywords: Space Telescope Cost Model, Parametric Cost Model

1. INTRODUCTION

Parametric cost models provide several benefits to designers and project managers. They identify major architectural cost drivers and allow high-level design trades. They enable cost-benefit analysis for technology development investment. And, they provide a basis for estimating total project cost for budgetary planning and procurement activities. In November 1999, NASA MSFC began an independent cost and schedule analysis of the Optical Telescope Element (OTE) for what would become the Webb Space Telescope. This effort consisted of two thrusts: bottoms-up estimating and top-down parametric modeling. This effort culminated in the November 2000 Re-Scope meeting that changed the JWST mirror collecting area from 50 to 25 square meters, and helped define the procurement "should-cost" estimate. Subsequently, MSFC continued developing parametric cost models for ground and space telescope assemblies. [1-15]

Our effort is data driven, mathematically rigorous, and consistent with engineering practice. Our papers fully discuss methodology, including what telescopes are in the data base, what programmatic and engineering data is collected and data completeness. As well as the model creation process, including parameter cross-correlation analysis, sequential variable regression and statistical confidence. This paper publishes a single model for both ground and space telescopes and discusses cost reduction via duplication.

But first, please understand that a parametric cost model is a statistical correlation between an item's historical cost (dependent variable) and quantifiable technical or programmatic parameters (independent variables). Statistically significant correlations are called Cost Estimating Relationships (CERs). Furthermore, parametric cost models cannot predict the cost of a specific future system. They are backward looking. At best, they can be used to compare a potential future mission relative to a historical mission. And, they provide an estimate of systems most probable cost and the uncertainty of that estimate. The fact that a cost model is a probabilistic estimation is important because non-technical issues such as managerial decisions and funding profiles can have profound impacts on cost.

Finally, while there is a tendency to focus on the OTA cost, in reality OTA cost is a small portion of any given mission – only about 10 to 15%. Instruments and spacecraft are each typically a larger portion of the total mission cost than the telescope.

2. DATABASE

A parametric cost model is only as good as its database. Inconsistencies and inaccuracies in a cost model are the results of insufficient data completeness or diversity, inconsistencies in definitions, or data errors or inaccuracies. In our own research, every time the database was changed, the cost model changed slightly. For example, after the AURA "Space Astrophysics Landscape for the 2020s and Beyond" meeting, we added the CALIPSO telescope to the database. This one change resulted in small increases to all the exponents in the 3rd decimal place and reduced the p-values for all exponents by a factor of 2. For this reasons, no one should ever use or accept the output of a cost estimating tool without understanding the tool's underlying database. Thus, the fundamental challenge of cost modeling is developing a parametric model that includes the most important parameters. To do this requires a database with sufficient samples and data diversity to yield statistically meaningful results. And, engineering judgment to interpret the results.

The MSFC multivariable parametric telescope cost model is based on 47 telescopes (27 space and 20 ground) out of a total database of 72 telescopes (46 space and 26 ground). The MSFC Space OTA database contains information on over 47 different cost, programmatic and engineering parameters (Table 1) for 51 imaging and non-imaging space missions ranging from X-ray to UVOIR to FarIR (Table 2). The non-imaging missions include spectroscopic, LIDAR or radio/microwave systems.

Table 1: Space Telescope Database Cost, Programmatic and Engineering Parameters

Primary Mirror Specific Information	
PM Cost	$ FY M
PM Aperture Diameter	meters
PM Thickness	cm
PM Surface Figure Error	rms nm
PM Material	
PM Focal Length	meters
PM F/#	
PM Number of Segments	#
PM Segment Size	meter
PM Mass	kg
PM First Mode Frequency	Hz
Optical Telescope Assembly Information	
OTA Cost	$ FY M
Diffraction Limit	micrometers
Transmitted WFE	nm rms
OTA Structure First Mode	Hz
OTA Mass	kg
System Focal Length	meters
System F/#	
FOV	degrees
Spatial Resolution	arc-seconds
Year of Development	
Development Period	months
Design Life	months
TRL	

Total System Information	
Total Cost	$ FY M
OTA + Thermal Cost	$ FY M
Instrument Cost	$ FY M
Operating Temperature	K
Total Mass	kg
OTA + Thermal Mass	kg
Instrument Mass	kg
Spectral Range Minimum	micrometers
Spectral Range Maximum	micrometers
Total Avg Input Power	Watt
Instrument Avg Power	Watt
Data Rate	Kbps
Start Date	
Date of Launch	
Orbit	km
Launch Vehicle	
Pointing Knowledge	arc-second
Pointing Accuracy	arc-second
Pointing Stability/Jitter	arc-sec/sec
# of Primary Mirrors	
# of Instruments	
# of Curved Optics	
Coating	

Table 2: Missions in Space Telescope Database

Imaging	Non-Imaging	Not in Regression	Attached
AFTA	ACTS	CCOR	SOFIA
COM_0.7	CALIPSO/CALIOP	Commercial SiC .35	HUT
COM_1.1	Cloudsat	Commercial SiC .5	UIT
Herschel	GALEX	EO-1/ALI	WUPPE
HST	ICESat/GLAS	FUSE	
IRAS	IUE	Imaging EUV	X-Ray
JWST	MO / MOLA	ISO	EUVE
Kepler	OAO-B / GEP	LandSAT-7	Chandra
MO / MOC	SWAS	SDO / AIA	HEAO-2
MRO / HiRISE		LRO / LROC NAC	HERO
OAO-2 / CEP		SOHO/EIT	FOXSI
OAO-3 / PEP		STEREO/SECCHI A	
Planck		TDRS-1	
Proprietary		TDRS-7	
Spitzer		TRACE	
WIRE			
WISE			
WMAP			

The MSFC ground OTA database contains information on 22 potential CERs (Table 3) for 26 telescopes from optical to radio (Table 4).

Table 3: Ground Telescope Database Cost, Programmatic and Engineering Parameters

Primary Mirror Specific Information	
PM Cost	$ FY M
PM Aperture Diameter	meters
PM Surface Figure Error	rms nm
PM Material	
PM Focal Length	meters
PM F/#	
PM Number of Segments	#
PM Segment Size	meter
PM Aspheric Departure	micrometers
PM Mass	kg
PM Lightweight Factor	%

Optical Telescope Assembly Information	
OTA Cost	$ FY M
Diffraction Limit	micrometers
Transmitted WFE	nm rms
Operating Temperature	K
OTA Mass	kg
Year of Development	
Development Period	months
Design Life	months
On or Off-Axis	
Number of Curved Optical Elements	
Optical Bench Material	

Table 4: Observatories in Ground Telescope Database

In the Regression		Not Included in Regression
AEOS	LBT	ALOT
Commercial	Magellan 1	CHARA
Commercial Radio	MMT 6.5m replacement	DCT
DKIST	SOAR	IRTF
Gemini 1	Starfire	LAMP
Green Bank Radio	Subaru	VLA Dish
HET	SubMM Array Dish	
JKT	UKIRT	
KECK 1	WHT	
KECK 1 & 2	WIYN	

Technical, programmatic and cost information for the database was collected from public reports, direct contact with project managers (via interviews and emails), and NASA archival sources:

- CADRe (Cost Analysis Data Requirements),
- NAFCOM (NASA/Air Force Cost Model) database,
- NICM (NASA Instrument Cost Model) database,
- NSCKN (NASA Safety Center Knowledge Now),
- RSIC (Redstone Scientific Information Center),
- REDSTAR (Resource Data Storage and Retrieval System) and
- SICM (Scientific Instrument Cost Model) database.

3. STATISTICAL ANALYSIS

Of the 45 potential space CERs, there is sufficient data completeness to do pairwise cross-correlation (Table 5) for 15 potential variables. The purpose of this analysis is to identify CERs that are both correlated with cost and not correlated with each other. For example, cost is mostly highly correlated with 'size' parameters such as diameter, focal length and volume. This is logical, larger telescopes cost more than smaller telescopes. And, cost is highly correlated with launch date, which implies that more recent telescopes have been more expensive. But, launch date is also highly correlated with 'size' parameters, which implies that more recent telescopes have been larger. Thus, launch date is not an independent variable. The same applies to mass. Cost is correlated with mass, but mass is correlated with size, i.e. larger diameter telescopes have higher mass. It is, however, interesting to note that mass is correlated with design life. An example of an obvious engineering relationship is the negative correlation between wavelength and operating temperature, i.e. longer wavelength systems operate at colder temperatures.

Table 5: Pair-Wise Cross-Correlation of 15 potential CERs for 18 space imaging missions.

All Variable Pairwise Correlation Matrix for Space Imaging System Dataset (N=18)															Rev 12.05.2017
	OTA$	**Eff Dia**	**Volume**	**PM FL**	**Sys FL**	**FOV**	**WDLP**	**Temp**	**OTA Mass**	**Design Life**	**e^(YOD -1960)**	**Dev Period**	**Launch Date**	**Orbit**	**Point Stab**
OTA $	1.00	**0.85**	**0.94**	**0.98**	**0.98**	-0.22	-0.15	-0.07	0.78	0.59	0.00	0.59	**0.93**	-0.18	-0.27
Eff Diameter	0.85	1.00	0.81	0.86	0.89	0.04	0.15	0.02	0.65	0.63	0.08	0.24	0.46	-0.19	-0.39
Volume	0.94	0.81	1.00	0.94	0.92	-0.11	-0.06	-0.22	0.54	0.36	-0.03	0.53	1.00	-0.11	-0.31
PM Focal Length	0.98	0.86	0.94	1.00	0.96	-0.08	-0.12	-0.05	0.73	0.56	0.04	0.54	0.94	-0.16	-0.32
Sys Focal Length	0.98	0.89	0.92	0.96	1.00	-0.22	-0.12	-0.13	0.78	0.63	0.29	0.63	0.90	-0.11	-0.30
FOV	-0.22	0.04	-0.11	-0.08	-0.22	1.00	0.68	-0.13	-0.18	-0.21	-0.03	0.09	-0.12	-0.18	-0.32
WDLP	-0.15	0.15	-0.06	-0.12	-0.12	0.68	1.00	-0.30	-0.14	-0.20	-0.07	0.16	-0.08	-0.14	-0.58
Operate Temp	-0.07	0.02	-0.22	-0.05	-0.13	-0.13	-0.30	1.00	0.14	0.36	0.19	-0.46	-0.23	0.26	0.77
OTA Mass	0.78	0.65	0.54	0.73	0.78	-0.18	-0.14	0.14	1.00	0.82	0.11	0.59	0.51	-0.24	-0.31
Design Life	0.59	0.63	0.36	0.56	0.63	-0.21	-0.20	0.36	0.82	1.00	0.27	0.13	0.32	0.13	-0.10
e^(YOD-1960)	0.00	0.08	-0.03	0.04	0.29	-0.03	-0.07	0.19	0.11	0.27	1.00	-0.19	0.31	-0.09	-0.32
Develop Period	0.59	0.24	0.53	0.54	0.63	0.09	0.16	-0.46	0.59	0.13	-0.19	1.00	0.50	-0.19	-0.75
Launch Date	0.93	0.46	1.00	0.94	0.90	-0.12	-0.08	-0.23	0.51	0.32	0.31	0.50	1.00	-0.09	-0.31
Orbit	-0.18	-0.19	-0.11	-0.16	-0.11	-0.18	-0.14	0.26	-0.24	0.13	-0.09	-0.19	-0.09	1.00	0.70
Point Stability	-0.27	-0.39	-0.31	-0.32	-0.30	-0.32	-0.58	0.77	-0.31	-0.10	-0.32	-0.75	-0.31	0.70	1.00

The pairwise cross-correlation analysis identified eight potential CERs: aperture diameter, wavelength of diffraction limited performance (WDLP), operating temperature, year of development (YOD), primary mirror focal length, field of view, total mass and development period. Eighteen different combinations of these eight potential CERs were evaluated. And only four had a statistically significant (i.e. $p < 10\%$) correlation with cost: effective aperture diameter, WDLP, operating temperature and YOD.

The MSFC telescope database has 100% completeness of these four CERs for 47 OTAs – 27 space and 20 ground. Table 6 gives the CER values for each of these OTAs. Cost data is not published, Cost data is NASA proprietary.

Table 6: Space & Ground Telescope Database CERs

SPACE TELESCOPES						
rev. 11.17.20	Effective PM Diameter	Diff. Lim. λ	Operating Temp.	Year of Development	# of PM Segments	PM Segment Diameter
Imaging	(m)	(μ)	(K)	(year)	#	(m)
AFTA	2.40	0.78	284	1992	1	2.40
COM_0.7	0.70	0.50	283	1996	1	0.70
COM_1.1	1.10	0.65	283	2007	1	1.10
Herschel	3.50	80.00	80	2001	1	6.50
HST	2.40	0.50	294	1977	1	2.40
IRAS	0.57	8.00	4	1977	1	0.57
JWST	5.64	2.00	30	2006	18	1.40
Kepler	1.40	1.00	213	2001	1	1.40
MO / MOC	0.35	0.53	283	1986	1	0.35
MRO / HiRISE	0.50	0.40	293	2001	1	0.50
OAO-2 / CEP	0.61	1.50	300	1962	4	0.31
OAO-3 / PEP	0.80	2.40	288.5	1963	1	0.80
Planck	1.70	300.00	40	2001	1	1.70
Proprietary						
Spitzer	0.85	6.50	5.5	1995	1	0.85
WIRE	0.30	24.00	12	1995	1	0.30
WISE	0.40	2.75	17	2002	1	0.40
WMAP	2.10	1300.00	60	1996	2	1.50
Non-Imaging						
ACTS	3.97	1950.00	263	1984	2	2.80
CALIPSO	1.00	6.60	283	2000	1	1.00
Cloudsat	1.85	1300.00	250	2000	1	1.85
GALEX	0.50	8.00	273	1998	1	0.50
ICESat	1.00	8.00	283	1998	1	1.00
IUE	0.45	3.50	273	1973	1	0.45
MO / MOLA	0.50	15.00	283	1986	1	0.50
OAO-B / GEP	0.97	5.00	289	1964	1	0.97
SWAS	0.68	286.00	170	1993	1	0.68

GROUND TELESCOPES						
rev. 11.01.2018	Effective Diameter	Diffraction Limit	Temp	Year of Dev.	Total Segments	Seg Size
	(m)	(μm)	K	(year)	#	(m)
JKT	1.00	1.00	270.00	1977	1	1
Commercial	1.00	0.50	300.00	2013	1	1
Starfire	3.50	0.53	273.00	1989	1	3.5
WIYN	3.50	0.42	263.00	1988	1	3.5
AEOS	3.67	0.85	273.00	1991	1	3.67
UKIRT	3.80	2.20	273.00	1974	1	3.8
SOAR	4.20	1.00	263.00	1997	1	4.2
WHT	4.20	6.10	270.00	1981	1	4.2
DKIST	4.20	0.90	300.00	2011	1	4.2
MMT Replace	6.50	1.60	262.00	1992	1	6.5
Magellan 1	6.50	1.00	280.00	1994	1	6.5
Gemini 1	8.10	0.80	270.00	1994	1	8.1
Subaru	8.30	0.60	273.00	1988	1	8.3
KECK 1	10.00	1.00	273.00	1986	36	1.8
LBT	11.88	0.65	273.00	1997	2	8.4
KECK-I&II	14.14	1.00	273.00	1986	72	1.8
HET	9.20	20.00	264.00	1994	91	1
Commercial Radio	5.00	210000.00	300.00	2012	1	5
SubMM Array Dish	6.00	300.00	300.00	1998	72	1
Green Bank Radio	100.00	6500.00	300.00	1991	2004	3

To enable a meaningful statistical regression, much effort has been expended to compile a database with wide data diversity. To provide wavelength diversity, we included radio and sub-millimeter telescopes. For year of development diversity we located cost and technical information for the 1960 era Orbiting Astronomical Observatory #2 Celeste Experiment Package (OAO-2/CEP) and the OAO-3 Princeton Experiment Package (OAO-3/PEP), and we added the recent CALIPSO and DKIST telescopes. JWST is in the data base because, while it has not launched, its OTA is complete and its cost known.

For the 20 Ground Telescopes:

- Diameter ranges from 1 meter to 100 meters
- WDLP ranges from 500 nm to 21 centimeters
- YOD ranges from 1979 to Present
- 14 Monolithic and 6 Segmented

27 Space Telescopes

- Diameter ranges from 30 cm to 5.6 meter
- WDLP ranges from 400 nm to 2 mm
- Operating Temperature ranges from 4 to 300K
- YOD ranges from 1962 to Present
- 23 Monolithic and 4 Segmented
- 18 Imaging and 9 Non-Imaging

Please note that effective Diameter may not be the same as the telescope's aperture stop diameter. For example, the Kepler PM is larger than the stop defined by the Schmidt corrector. And, WMAP, LBT and Keck I&II all have two telescopes. Their effective PM diameter is the size of a circular aperture with the same total collecting area.

Also, in compiling the database, it was discovered that we were using different YOD definitions for space and ground. When we started the cost modeling effort in 1999, we defined YOD to be 'first light' for ground telescopes. We considered defining YOD to be 'launch date' for space telescopes but used start of Phase C instead – because launch dates can be delayed for no fault of the missions, i.e. Hubble's launch date was delayed due to the Challenger accident. But, when we combined the two databases, we discovered that there was approximately a 6 year effective difference between these two definitions and that difference resulted in a difference in the Ground-to-Space scale factor. Thus, we changed the ground telescope database to the date for when each telescope contract was issued.

4. COST MODEL REGRESSION

The NASA MSFC OTA database was regressed against the 4 CERs plus a Space/Ground multiplier factor to yield a 5-parameter cost model that explains 92% (Adjusted R2) of the cost variation in a database of 47 total ground and space telescope assemblies.

$$\mathbf{OTA\$\ (FY17) = \$20M\ \times\ 30^{(S/G)}\ \times\ D^{(1.7)}\ \times\ \lambda^{(-0.5)}\ \times\ T^{(-0.25)}\ \times\ e^{(-0.028)\,(Y-1960)}}$$

Parameter	Intercept	S/G	D	λ	T	YOD
Model Value	20	30	1.7	-0.5	-0.25	-0.028
Actual Value	21.3	28.2	1.697	-0.467	-0.262	-0.0282
SE	1.6	1.2	0.09	0.03	0.07	0.006
p-value	2E-07	1E-18	9E-22	6E-21	9E-4	3E-05

where: (S/G) = 1 for Space OTAs
= 0 for Ground OTAs
D = Effective Telescope Aperture Diameter
λ = Wavelength of Diffraction Limited Performance
T = Operating Temperature
YOD = Year of Development, i.e. start of Phase C/D or Issue of Contracts.

SE is the ‘standard error’. It reports the average distance that the parameter varies from the regression line. It reports how ‘wrong’ the model is on average. The p-value term is the null result correlation. It is the probability that the parameter’s value is equal to zero. For example, a p-value of 0.001 indicates that the probability of temperature not being correlated with cost is 0.1%.

It is important to stress that the model estimates the ‘first-unit’ ‘most-likely’ (i.e. 50% probable) cost for ONLY an Optical Telescope Assembly (OTA). Where an OTA is defined as the mission subsystem that collects electromagnetic radiation and focuses it (focal) or concentrates it (afocal) into the science instruments. An OTA consists of the primary mirror, secondary mirror, auxiliary optics and support structure (such as optical bench or truss structure, primary support structure, secondary support structure or spiders, straylight baffles, mechanisms for adjusting the optical components, electronics or power systems for operating these mechanisms, etc.). An OTA does not include science instruments or spacecraft.

Using NASA terminology, the model estimates ONLY Contractor Cost for Phase A to D, i.e. design, development, integration and test. The model’s cost estimate does not include Pre-Phase A (i.e. formulation) costs, Phase E (launch/operation) costs, government labor costs, government furnished equipment (GFE) or existing contractor infrastructure or other non-contracted costs.

And, given that the current model’s uncertainty is nearly 50%, to be conservative, use the 84% probably cost – multiply the 50% estimate from the model by 1.5.

Please note that regressions with different combinations of variables and dataset (i.e. ground or space only, or monolithic or segmented only) yields different exponent values for the model parameters. It is for this reason, that one should never blindly use a cost model without understanding the database from which it is constructed. For example, if one regresses only on effective diameter for the entire MSFC database, its exponent is close to 1.0. The reason is because the largest apertures in the database are radio and sub-mm wave telescope, which cost less. Adding WDLP to the regression increases the aperture exponent into the 1.6 range. Alternatively, you can get the same aperture exponent by restricting the regression to only optical wavelength telescopes. Temperature only has an impact for space telescopes – because ground telescopes operate close to ambient. Finally, there is an interesting relationship between aperture diameter and YOD. Adding YOD increases the aperture diameter exponent. The reason is because more recent telescope tend to be larger and – because of technology advance – they tend to have a lower cost per area. Thus, without the YOD term, one gets a ‘flatter’ trend line for cost versus aperture diameter. This effect is particularly noticeable if you create a database subset of the first occurrence of each aperture ‘size’ for ground telescopes; without YOD the diameter exponent is 1.3 and with YOD the diameter exponent is 1.5.

5. RESIDUAL ANALYSIS

The ‘goodness’ of the model was evaluated via residual and outlier analysis. Each column in Figure 1 shows cost versus CER (diameter, wavelength, temperature and YOD). The top row plots ‘raw’ database cost vs each CER. At best one can say that there is a slight diameter trend line and that cost per diameter shows a slight space vs ground clustering. Row two plots the raw data normalized by diameter. Once the data is normalized for diameter, there is an obvious wavelength dependency. And, there are obviously two trend lines in wavelength, temperature and YOD (for ground and space). Row three adds wavelength normalization. At this point, a clear diameter trend emerges and the ground vs space clusters are solidified. Normalizing by temperature and YOD in row four tightens the groupings. And, scaling by Space/Ground in row five pulls the two datasets into a single model.

The model is so good, that when tested using the residual analysis technique, it was possible to identify data points that did not lie on the trend lines. Upon inspection, the causes of these outliers were typically typos in the database or inaccurate values. For example, in the YOD analysis, we accidentally entered UKIRT’s YOD as 1997 when it was built in 1979. Similarly there was a discrepancy in HST’s YOD between 1973 and 1977. Other examples are in WDLP. While CLOUDSAT was specified to have a performance of 3.19-mm, the telescope was actually built with a WDLP of 1.3-mm. Similarly, we found a better citation for Planck and changed its WDLP from 700 to 300 micrometers.

Figure 1: Residual Error Analysis

6. SEGMENTED APERTURE COST MODEL

Given that telescope cost is primarily driven by aperture diameter. And, that there is a practical limit to how large of a monolithic mirror one can make. The question of mirror segmentation must be addressed.

Historically, segmentation has always been the solution for when technology did not allow a monolithic mirror. But as soon as technology permitted, segmented mirrors were replaced with monoliths. The original 'Large Space Telescope' (i.e. Hubble) was a segmented mirror. Then NASA funded the development of lightweight high-temperature-fused ULE mirrors. The Multi-Mirrored Telescope has been replaced by a 6.5m monolith. And, 10-m class segmented telescopes such as Keck gave way to 8-m class monoliths such as VLT and Subaru. Finally, JWST's 6.2-m aperture was segmented because it had to fit inside a 4.5-m launch fairing. If the Space Launch System (SLS) had existed at the time that JWST was being developed, it may well have had a monolithic mirror.

The MSFC database as a total of 10 segmented telescope (6 ground and 4 space). Because the segmented telescope database is small, it is difficult to perform meaningful regressions. Potentially a 'trick' is to consider the 36 monolithic telescopes as 'one' segment apertures. Replacing the Effective Diameter (D) parameter with a segmentation parameter (Nseg x Dseg, where Nseg = the number of segments in the aperture and Dseg = the segment circumscribed diameter) and regressing on the 47 telescope MSFC database yields a potential 6-variable ground and space segmented telescope cost model.

$$\textbf{OTA\$ (FY17)} = \$20\text{M} \times 30^{(S/G)} \times \text{Nseg}^{(0.8)} \times \text{Dseg}^{(1.7)} \times \lambda^{(-0.5)} \times T^{(-0.25)} \times e^{(-0.028)\,(Y-1960)}$$

Parameter	Intercept	S/G	Nseg	Dseg	λ	T	YOD
Model Value	20	30	0.8	1.7	-0.5	-0.25	-0.028
Actual Value	23.0	25.1	0.78	1.63	-0.473	-0.252	-0.0291
SE	1.7	1.3	0.06	0.12	0.03	0.08	0.007
p-value	1E-06	2E-16	2E-16	4E-17	4E-19	0.003	9E-05

Analysis with different database combinations indicates a correlation between the exponents for Nseg and Dseg. Their solutions range from $\text{Nseg}^{(0.78)}$ $\text{Dseg}^{(1.61)}$ to $\text{Nseg}^{(0.84)}$ $\text{Dseg}^{(1.73)}$. For the segmented aperture cost model, we choose $\text{Nseg}^{(0.8)}$ $\text{Dseg}^{(1.7)}$. The Dseg exponent should be the same value as for D in the monolithic model. The cost to make a single mirror should be the same in both model. And the 0.8 exponent for Nseg is consistent with empirical data from the manufacture of 8-m monolithic mirrors by REOSC and 1.4-m JWST mirror segments (Figure 2).

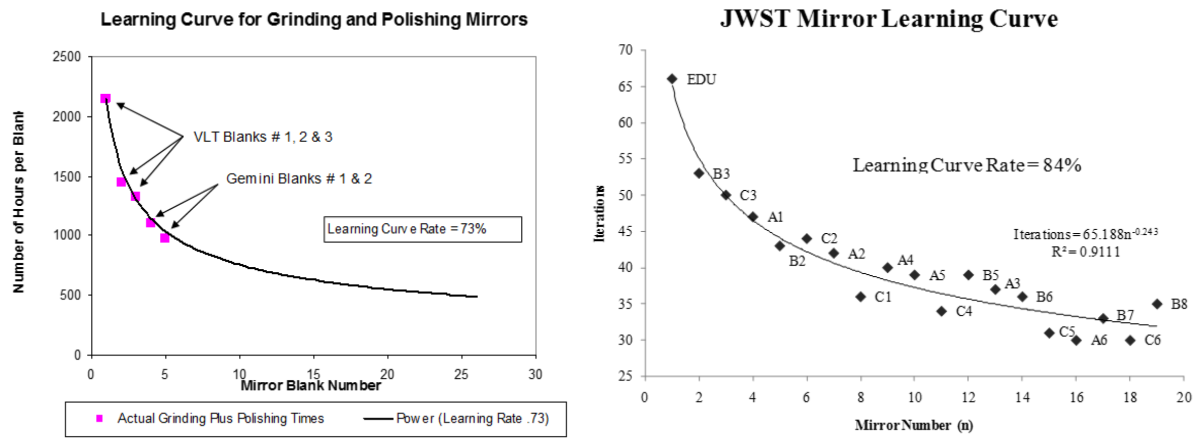


Figure 2: Learning curve for multiple fabrication of similar mirrors: (left) is 8.2-m mirrors manufactured by REOSC, (right) is JWST primary mirror segments.

Finally, just as regression analysis identified the S/G scale factor, we investigated if there was a scale factor between monolithic and segmented mirrors. The regression 'indicates' that segmented aperture telescopes are approximately 15% more expensive than monolithic telescopes. BUT, the regression result is not significant. It has a p-value = 30%. So the segmented cost model assumes no difference.

7. COST ESTIMATING EXAMPLES

OTA cost can be estimated via two methods: using the model directly (Figure 3) or using the model to compare relative cost with other OTAs (i.e. Hubble & JWST) (Figure 4). Please remember that segmented aperture telescopes ‘may be’ 15% more expensive than monolithic, but such a scaling factor was not included in the model because its regression was statistically uncertain. Thus, it is possible that the model estimates for segmented aperture telescopes are low. And, maybe the estimates based on relative ratios of JWST are more correct.

		Equation Method			
Effective Aperture		4-m	4-m Seg	8-m	8-m Seg
Architecture		off-axis	on-axis	off-axis	off-axis
Starting Space Cost [FY17 $M]	$ 600				
Number of Segments	0.8	1	6	1	35
Circumscribed Diameter [meter]	1.7	4	1.8	8	1.5
WDLP [micrometer]	-0.5	0.5	0.5	0.5	0.5
Temperature [K]	-0.25	270	270	270	270
exp(YOD)	-0.028	2025	2025	2025	2025
50% Predicted Cost [FY17 $M]		$ 358	$ 386	$ 1,163	$ 1,161
85% Predicted Cost [FY17 $M]		$ 519	$ 560	$ 1,687	$ 1,684

Figure 3: Examples of 50% and 85% predicted telescope cost estimates using parametric model.

In Figure 4, the ratio column indicates whether the telescope whose cost is being estimated is more or less expensive than the basis of estimate telescope. For example. A 4-m monolithic aperture telescope is 2.4X more expensive than HST – based on aperture – but half as expensive as JWST. A UVO telescope will be approx. 2X more expensive than JWST but an ambient temperature telescope will be approximately half as expensive, so those parameters tend to cancel. Finally regarding YOD, technology has advanced since HST was started in 1977 that an identical telescope should cost only 25% of the original in 2025 and if a second JWST telescope were made in 2025, it should cost only 60%.

			Relative Cost Method									
Aperture			4-m Mono				4-m Mono			JWST	8-m Seg	
Architecture		HST	off-axis	Ratio		JWST	off-axis	Ratio			off-axis	Ratio
Total Cost [FY17 $M]		$530				$1,380				$1,380		
Number of Segments	0.8	1	1	1.00		1	1	1.00		18	37	1.78
Diameter [meter]	1.7	2.4	4	2.38		6.35	4	0.46		1.4	1.4	1.00
WDLP [micrometer]	-0.5	0.5	0.4	1.12		2	0.4	2.24		2	0.4	2.24
Temperature [K]	-0.25	294	270	1.02		50	270	0.66		50	270	0.66
exp(YOD)	-0.028	1977	2025	0.26		2006	2025	0.59		2006	2025	0.59
50% Predicted Cost [FY17 $M]			$376	0.71			$ 542	0.39			$ 2,116	1.53
85% Predicted Cost [FY17 $M]			$546				$ 786				$ 3,069	

Figure 4: Examples predicted telescope cost estimates using model to ratio relative to HST and JWST.

8. MASS COST MODELS

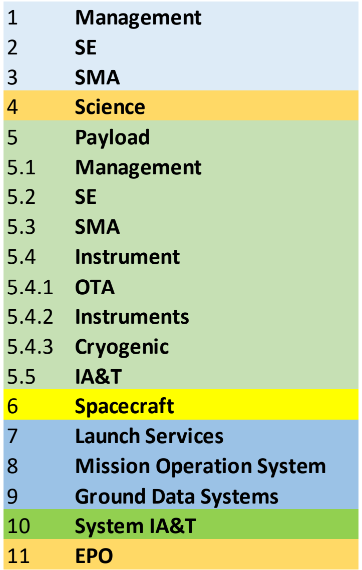
While many cost models use mass as a CER, our research finds that mass is not a good CER. The problem with mass is that it is not an independent variable. It is correlated with aperture. The best example of the inappropriateness of mass is the fact that at 3180 kg HST’s OTA is 1.5X more massive than JWST’s 2170 kg OTA. Thus, a mass-based cost model would estimate JWST to be 66% the cost of HST when in reality JWST was approximately 2.6X more expensive than HST.

While the following is supposition on the part of the author and cannot be tested, one reason for the difference between HST and JWST cost relative to their mass may be launch vehicle mass capacity and design margin. Because the space shuttle had a launch mass of 16,000 kg to LEO while the Ariane-5 can only launch 6600 kg to SE-L2, JWST had to be designed to a lower mass than HST. The advantage of having extra mass available is that it enables stiffer, more robust and stable optical components and structure – which are easier to manufacture with less risk and lower total cost.

9. SUBSYSTEM COST

A final topic is the connection between telescope cost and total mission cost. Many believe that telescope cost drives mission cost. To test this belief, cost data was collected in the standard NASA work breakdown structure (WBS) (Figure 5) from Cost Analysis Data Requirements (CADRe) reports for 14 missions:

- CALIPSO
- CLOUDSAT
- GALEX
- ICESAT
- JWST
- Kepler
- LANDSAT-7
- Spitzer
- STEREO
- SWAS
- TRACE
- WIRE
- WISE
- WMAP



1	**Management**
2	**SE**
3	**SMA**
4	**Science**
5	**Payload**
5.1	**Management**
5.2	**SE**
5.3	**SMA**
5.4	**Instrument**
5.4.1	**OTA**
5.4.2	**Instruments**
5.4.3	**Cryogenic**
5.5	**IA&T**
6	**Spacecraft**
7	**Launch Services**
8	**Mission Operation System**
9	**Ground Data Systems**
10	**System IA&T**
11	**EPO**

Figure 5: NASA Mission WBS

As summarized in Figure 6, the telescope is only about 5 to 15% of the total mission cost. And this percentage is highly dependent on the telescope's aperture diameter (Figure 7). For the 14 missions for which we have complete WBS cost data, the science instruments and spacecraft are each a larger percentage of the total mission cost. Furthermore, management, systems engineering and safety and mission assurance are a larger percentage of total mission cost than the telescope.

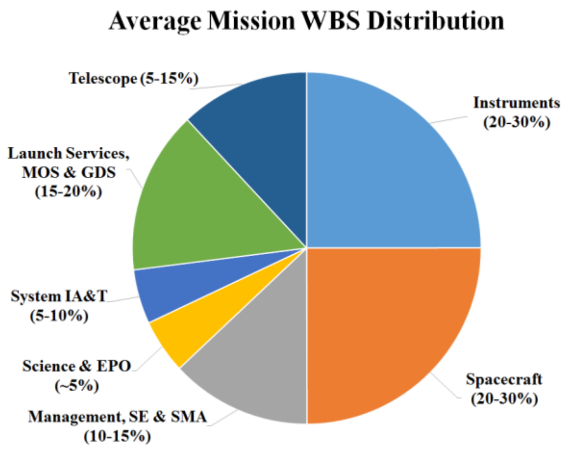


Figure 6: Average WBS for 14 missions.

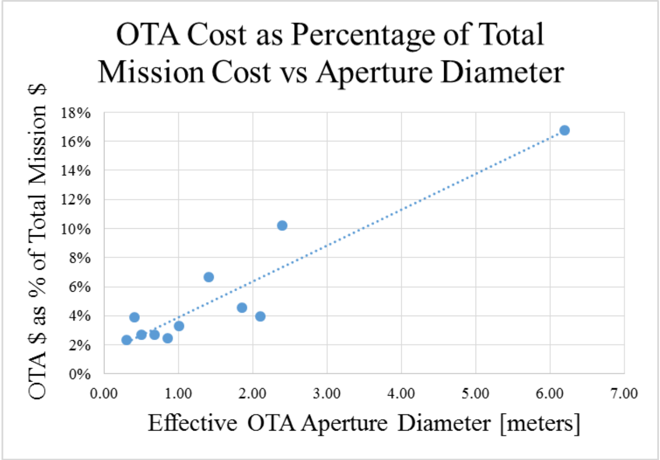


Figure 7: Larger telescopes are a larger % mission cost.

10. CONCLUSIONS

After 20 years assembling and vetting a database for ground and space telescopes containing cost, programmatic and technical data, we have sufficient quantity of telescopes with sufficient data diversity to develop a multivariable parametric cost model that explains 92% of the cost variation for the ground and space telescopes in the data base. This model can be used to provide a basis of estimate for a given telescope concept, compare between major architectural cost drivers, and justify technology development investment. This paper summarizes the MSFC database and presents the cost model it supports. It also – for the first time – presents a potential extension to the model for segmented aperture telescopes. Examples of how the model can be used to estimate telescope concept costs via either direct application or relative comparison to historical exemplars were presented. The authors wishes to reiterate that mass is not a good cost estimating relationship for telescopes. Instead, telescope cost is driven by its effective diameter, wavelength of diffraction limited performance, operating temperature and year of development. Finally, telescope cost is not the driving cost for mission in our database. Instead, science instruments and spacecraft are a larger cost driver. Furthermore, management is typically a larger cost driver than the telescope.

Finally, several implications can be drawn from the model. Space telescopes are approximately 30X more expensive than ground telescopes with the same aperture diameter and diffraction limited performance. Larger telescopes are more expensive than smaller telescopes. UV diffraction limited telescopes are more expensive than IR telescopes. Cryogenic telescopes are more expensive than warm telescopes. And, telescope cost has historically decreased by approximately 50% every 25 years – presumably due to technology advances.

11. ACKNOWLEDGEMENTS

I would like to acknowledge the contributions of all my collaborations over the past 20 years: Michael Allison, Alicia Byberg, Courtnay Dollinger, Todd Hendrichs, Alex Luedtke, Andy Prince, Gayle Reese, Ginger Holmes Rowell, Kyle Stephens, and Miranda West.

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