Preliminary Cost Model for Space Telescopes

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ABSTRACT

Parametric cost models are routinely used to plan missions, compare concepts and justify technology investments. However, great care is required. Some space telescope cost models, such as those based only on mass, lack sufficient detail to support such analysis and may lead to inaccurate conclusions. Similarly, using ground based telescope models which include the dome cost will also lead to inaccurate conclusions. This paper reviews current and historical models. Then, based on data from 22 different NASA space telescopes, this paper tests those models and presents preliminary analysis of single and multi-variable space telescope cost models.

Keywords: Space Telescope Cost Model, Parametric Cost Model

1. INTRODUCTION

Multivariable parametric cost models for space telescopes have several uses. 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. Cost models for ground based telescopes have been published since the 1960's. But, until recently, there was an insufficient data base to generate cost models for space telescopes. This lack of data has resulted in unfounded extrapolation of ground telescope models to space telescope and creation of 'rule of thumb' scaling laws. In the mid 1990s, after the launch of the Hubble Space Telescope, Horak, et. al. developed a detailed parametric cost model for space telescopes based on 17 DoD and NASA missions. [1 – 3] In the last 15 years several more space telescopes have been developed and launched (including Kepler and Spitzer) or are under development with relatively mature cost knowledge (i.e. JWST). Therefore, now there is a sufficiently detailed cost data base to study cost estimating relationships for space telescopes.

This paper presents a parametric space telescope cost model developed using statistical methods with data collected from 22 different NASA space telescope missions. The study examines single and multi-variable cost estimating relationship (CER) models and identifies cross-dependencies between CERs.

2. HISTORICAL COST MODELS

2.1 Ground Telescope Cost Models

Ground telescope cost models have historically focused on primary mirror diameter as the principle cost driver. A detailed discussion of ground cost models can be found in Stahl, 2005. [4] Starting in the 1960's, models scaled cost as a function of primary mirror diameter raised to the power of 3.0. Since that time, many different scaling laws have been proposed by different and, in some cases, even the same author. In his 1979 paper Meinel [5] found a "scaling law exponent close to the 2.0 power, in contrast to the often cited 2.7 exponent." However, in later papers [6,7] he reported scaling laws ranging from 2.5 to 2.75. Of all these laws, the one which seems to have gained the most acceptance is the 2.7 factor. In 2000, Bely indicated that a scaling law of 2.7 is considered the standard for ground-based observatories [8] and in 2002 Stepp stated that the consensus traditional scaling law appears to be 2.7. [9]

While these laws are technically correct, they should not be extended to space telescopes because they all include the ground observatory building and/or dome (the cost of the dome is driven by the volume of the telescope which is proportional to D raised to the 3^{rd} power). And, space telescopes do not have domes. Therefore, any use of a 2.7 scaling law for space telescopes will result in unfounded conclusions. Meinel actually made the dome distinction in his 1979 paper but then failed to repeat it in his later papers.

In 2005, Stahl [4] published a multivariable parametric cost model for ground telescope assemblies where the cost scales with primary mirror diameter to the 1.8th power:

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

Where: D = Primary Mirror Diameter
λ = Wavelength Diffraction Limited Performance
Y = Year of Development for reduction in technology cost over time
SF = Segmentation Factor

The segmentation factor estimates the cost reduction that can be gained by incorporating replication and serial processing learning into the fabrication of large telescopes. However, please note that this cost efficiency is not fully obtained if multiple parallel manufacturing lines are used.

$SF = P_n\, R_n^{0.7}\, (Ds/D)^{1.8}$ if the primary mirror is segmented and
$= 1$ if the primary mirror is monolithic
Ds = Segment Diameter
P_n = Number of Unique Segment Prescriptions
R_n = Number of Repeated Segments

It was hoped that the cost relationships for ground optical telescope assemblies without their domes would be indicative of space telescope assemblies. But, as the analysis of this paper indicates, that hope is not substantiated.

2.2 Space Telescope Cost Models

Parametric cost models for space telescopes have not been discussed as much as ground. Partly because of the lack of an extensive data base, i.e. there are not as many space telescopes, and partly because cost information for space telescopes is difficult to obtain either for proprietary or national security reasons. But, there have been some published models.

2.2.1 Meinel Models

In 1986, Meinel and Meinel asserted that "Space telescopes are intrinsically 2 orders of magnitude more expensive for a given aperture than are terrestrial ones and are likely to remain at least 1 order of magnitude more expensive." [10] However, it does not appear that such cost reduction has occurred. 10 years later in 1997, Schmidt-Kaler and Rucks assert that space telescopes are still more expensive than ground telescopes by a factor of almost 100. [11] These assertions would imply that space telescope costs scale with aperture diameter to either the 2.0 or 2.7 power.

The Meinel's revisited cost models for space telescopes in 2004 with lead author Bellea. [12] At one point in the paper they assert that "no general inference can be drawn from the relationship between telescope cost and aperture size … telescope size is independent of cost. Instead, our assessment is that the predominant phenomenon at play is rapid technological development." But, later in the paper and in the conclusion they assert that it is their expectation that the scaling law for space-based telescopes is close to $D^{2.0}$. They make this argument based upon a scaling of the structure necessary to maintain optical surface figure in a zero-gravity environment and the scaling of structure necessary to protect a space telescope from space weather.

2.2.2 Bely Models

In 2000, Bely asserted that from his experience with "mostly classified systems cost data", that the scaling law for space telescopes based on primary mirror diameter is "on the order of 1.8th power." [13] In his 2003 book, Bely justified this assertion based on the argument that space telescopes do not have a dome or large structure which scales with volume and that the cost to design and test a telescope is larger for a space than a ground telescope. [14] But most importantly, Bely provided an equation with a citation: "For space telescopes, one model developed by Technomics [6], based for the most part on military and surveillance missions, is of the form:"

$$Cost \propto \frac{D^{1.6}\, M_f\, D_f\, D_f'}{\lambda^{1.8}\, T^{0.2}\, e^{0.033(Y-1960)}}$$

The Technomics citation provided by Bely is identical to this paper's reference [1] Horak et al, 1993. The Horak cost model will be summarized later in this paper and thus will not be discussed here. However, the cost relationship reported by Bely is not the same as reported by Horak. There are three specific differences. Missing from the Bely equation is a term for number of curved elements included in the Horak model. The Horak model exponent for wavelength is 0.178 not 1.8 – obviously a typo on the part of Bely. And, the exponent for aperture diameter in the cited Horak publication is 0.705 not 1.6. It is this last discrepancy which is of most interest to the primary author, because during his tenure in industry, he saw several proprietary cost models which claimed to have been derived from the Horak model with the same 1.6th power aperture diameter exponent.

2.2.3 Mass Models

In the space industry, mass as been found to be a key cost driver. Thus, the NASA Air Force Cost Model (NAFCOM) estimates space missions cost based on mass. NAFCOM has an extensive data base containing parametric cost data and technical information at the group, subsystem and component level for many historical NASA programs. This data is normalized and separated by mission type. In addition, NAFCOM contains data from the Scientific Instrument Cost Model (SICM). NAFCOM and SICM are computer software applications which calculate cost predictions based on user parameter inputs. Mass is the primary variable used to estimate telescope cost. Additional inputs are available to account for the complexity of the telescope being estimated.

An example of a space telescope cost versus mass model is available from the JSC cost model website: [15]

$$\text{Cost} = \$2.25\text{B } (\text{Mass}/10000 \text{ kg})^{0.654} \times (1.555^{\text{Difficulty Level}}) \times (N^{-0.406})$$

Where: N = number of flight systems
Difficulty Level = 0 Average
= 1 High
= 2 Very High

2.2.4 PRC Cost Models

PRC Systems Services has generated several telescope cost models. In 1985, PRC published a model which predicts cost of telescopes for unmanned and manned spacecraft [16]. The paper reports two cost estimating relationships: Telescope Design and Development and Telescope Flight Hardware. These “represent the cost of second unit following the manufacture and assembly of a prototype article. System level costs are included (for example: Systems Test Hardware (prototype); Systems Test Operations, GSE, Systems Engineering and Integration and Program Management).” PRC studied the parameters of weight, volume, primary mirror diameter, and minimum temperature. The PRC diameter only CER reported below estimates 58% of total space telescope D&D and Flight cost:

For all space telescopes in their database (UV, visible, IR):
Design and Development Cost is proportional to $D^{0.276}$,
Flight Unit Cost is proportional to $D^{0.286}$, and
D&D cost is approximately 3X the flight unit cost.

For just the infrared telescopes in their database
Design and Development Cost is proportional to $D^{0.4782}$,
Flight Unit Cost is proportional to $D^{0.5576}$, and
D&D cost is approximately 4X the flight unit cost.

In 2000, Smart developed a multi-variable parametric cost model:

$$\text{Cost} = \$521.967\text{M} * MD^{1.120} * TRL^{-0.881} * AP^{0.187} * YT^{-0.330}$$

Where: MD = Mirror Diameter [meters]
TRL = Technology Readiness Level
AP = Average Power [watt]
YT = Year of Technology

using 13 space telescopes: EUVE, HEAO-2, HST, SIRTF, TRACE, WIRE, IRAS, IUE, OAO-2, OAO-3, Skylab 1, and two Spacelab-2 missions. The regression statistics for this model explained 89% of the cost variation of these missions (Figure 1) [17].

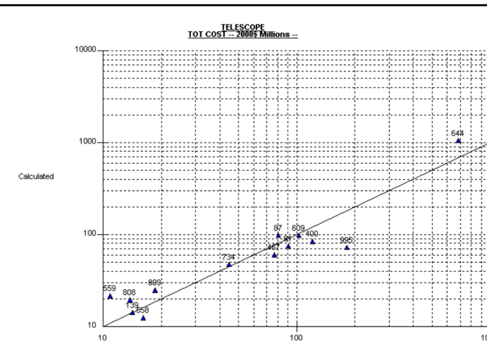

Figure 1. Estimated cost versus actual cost of Smart Model for 13 space telescope missions.

2.2.5 Horak Cost Models

Of all the historical models, the Horak model is the most detailed and best documented. The complete model was published via two reports in 1993 [1] and 1994 [2]. An updated model was published in 1996 [3]. The purpose of the model was to estimate the total cost of IR sensor payloads operating in geosynchronous and non-geosynchronous orbits or on aircrafts. The database consisted of strategic and experimental IR sensor programs (Table 1). The cost methodology developed consisted of 7 cost estimating relationships (CERs) that estimate the costs of IR sensor assemblies (i.e. Optical Telescope Assembly/Structure, focal plane arrays, etc.). The study also developed a CER for integration, assembly and calibration of the subsystems into a complete system.

Table 1. Horak Cost Model Data Base of Strategic and Experimental IR Sensor Programs used in the development of CERs for Optical Telescope Assembly/Structure
Homing Overlay Experiment (HOE
Forward Acquisition Sensor (FAS)
Airborne Optical Adjunct (AOA)
Optical Airborne Measurements Program (OAMP)
Anti-Satellite Program (ASAT)
Teal Ruby Experiment (TRE)
Defense Support Program (DSP 14-17)
Landsat Thematic Mapper (TM-4, TM-5, TM-6)
Infrared Astronomical Satellite (IRAS)
Hubble Space Telescope Optical Telescope Assembly (OTA)
Space Infrared Experiment (SIRE)
High Endo-atmospheric Defense Interceptor (HEDI)
Exo-atmospheric Reentry Intercept System (ERIS)
Ground-based Surveillance & Tracking System (GSTS)
Midcourse Sensor Experiment (MSX)
Spectrographic Imaging Reflective Telescope (SPIRIT III-MSX)
Space Based Visible Sensor (SBVS – MSX)

The 1993 study developed CERs to estimate the manufacturing cost of the first flight unit of 7 IR sensor subsystems including the optical telescope assembly/structure. If a qualification unit was developed, its cost was considered as non-recurring and was included in the developing engineering costs. The manufacturing cost included fabrication, assembly, inspection and test of the hardware subsystem and did not include any program level costs (e.g. system engineering, program management, etc.). Cost of money, G&A and fee for the subsystem component are included. The OTA subsystem includes the telescope optics, mounting hardware, and optical bench support structure. It also included baffles, shroud, and any structure associated with housing the telescope, cryostat and shroud. Figure 2 shows the CER and its statistics for the OTA subsystem. With a regression R^2=97.8%, the study found that the CER explains 97.8% of the cost variation of the 16 telescopes in the study.

The 1993 study also developed a CER for the labor and material costs associated with integrating and assembling the subsystem hardware into the complete system. With a regression R^2=96.6%, the study found that:

Integration and Assembly Cost = 27% x Total Subsystem Hardware Costs

The 1994 report developed CERs to estimate the non-recurring development engineering costs for the Demonstrate and Validation (D&V) and the Engineering Manufacturing Development (EMD) phases of a program. With a regression R^2=97.8%, the study found that:

Design Cost of the OTA = 125% of the Manufacturing Cost of the First Flight Unit

If more than one flight unit are manufactured, then the design cost increases with quantity – but not linearly. The increase factors in a learning curve of 76%.

Design Cost of the OTA = 125% x (Cost of the First Flight Unit) x (Number of Flight Units)$^{0.613}$

The breadboard or engineering unit was found to cost 68% of the manufacturing cost of the first fight unit and the qualification unit was found to cost 106% of the manufacturing cost of the first flight unit.

CER: $T1 = 0.357\,(Matl)(Dsn)(Apr)^{0.705}(\#Elem)^{0.473}(\lambda)^{-0.178}(K^{\circ})^{-0.191}\,e^{-0.033(Yr-80)}$

T Statistics: (1.74) (8.80) (2.55) (-2.04) (-2.61) (-2.31)

Statistics R^2 = 97.0%
s = 0.212 (17 Data Points)
(11 Degrees of Freedom)

Where
T1 = The Prototype T1 manufacturing cost in FY88 $M.
Apr = The optical aperture (diameter) of the telescope in centimeters.
#Elem = The number of <u>curved</u> optical elements in the telescope.
λ = Lowest wave length in spectral band (μm) processed by telescope.
K° = Coldest operating temperature of optics in degrees Kelvin.
Yr-80 = Year development complete minus 1980.
Matl = Two material factors which are multiplied together.

Optical Bench/Structure factor:

Aluminum	=	1.00
Invar	=	1.30
Graphite-Epoxy	=	1.50
Beryllium	=	1.50

Optical elements factor:

Aluminum	=	1.00
Steel	=	1.00
ULE Glass	=	1.50
Beryllium	=	1.30

Dsn = Three design factors which are multiplied together.

On-axis versus off-axis factor:

On-axis	=	1.00
Off-axis (with Al mirrors)	=	1.00
Off-axis	=	1.33

Degree of Optical element light weighting factor:

None	=	1.00
Small (70-40% left)	=	1.00
Med. (40-20% left)	=	1.20
Large (20-10 % left)	=	1.40

Scan/Dither mirror factor:

None	=	1.00
Yes	=	1.25

Figure 2. Horak 1993 Cost Estimating Relationship for the Optical Telescope Assembly/Structure

In 1996, Horak published a set of charts with a cost model for Optical Telescope Assembly [3] which combined design, programmatic, and manufacturing costs (Figure 3). Unfortunately, there is no commentary discussion in the report.

CER: $\text{Lot \$} = 716.8 \times \text{Programmatics} \times \text{Technical} \times \text{Design}$
T Statistics: (1.59)

$\text{Programmatics} = (Qty)^{0.879}\,e^{-0.665(Tech)}\,e^{-0.034(Yr-80)}$
T Statistics: (8.78) (-2.38) (-2.11)

$\text{Technical} = (Aper)^{0.673}\,(\text{Curved Elem})^{0.500}\,(^{\circ}K)^{-0.273}(\lambda_{min})^{-0.257}$
T Statistics: (5.05) (fixed) (-2.62) (-2.24)

$\text{Design} = (Matl \times Dsn)\,e^{-0.500(\text{No Baffle})}$
T Statistics: (fixed)

Statistics R^2 = 97.10% (16 Data Points)
s = 0.217 (9 Degrees of Freedom)

Figure 3. Horak 1996 Cost Estimating Relationship for the Optical Telescope Assembly

3.0 METHODS

3.1 Database Collection

For the current study, cost and parametric data has been acquired for 22 NASA, ESA, and commercial space telescopes (Table 2). Data was acquired from the NAFCOM (NASA/ Air Force Cost Model) database, RSIC (Redstone Scientific Information Center) and REDSTAR (Resource Data Storage and Retrieval System) Libraries, project websites, and interviews with project engineers, managers and principal investigators. While not a traditional space telescope, TDRS system data was deliberately added to the study in an effort to obtain wavelength diversity.

Table 2. Cost Model Data Base

X-Ray Telescopes	UV/Optical Telescopes
AXAF	CALIPSO
HEAO-2	EUVE
	FUSE
Infrared Telescopes	GALEX
Herschel	HST
IRAS	HUT
ISO	ICESat
JWST	IUE
SOFIA	Kepler
Spitzer	OAO-3
TRACE	SOHO/EIT
WIRE	UIT
WISE	WUPPE
Radio Wave Antenna	Microwave Telescopes
TDRS-1	WMAP
TDRS-7	

3.2 Variables Studied

Data has been accumulated on 59 different variables for the above programs. Of these, 19 variables were selected for study. Table 3 lists these variables and the percentage of programs for which data has been recorded. Cost values are represented in millions of US dollars adjusted for inflation to year 2009 dollars.

Table 3. Cost Model Variables

Parameters	% of Data
OTA Cost	89%
Phase A-D Cost w/o LV	82%
Primary Diameter (m)	86%
Avg. Input Power (Watts)	79%
Total Mass (kg)	93%
OTA Mass (kg)	82%
Spectral Range (μ)	100%
Wavelength Diffraction Limit (μ)	43%
Primary Mirror Focal Length (m)	46%
Primary Mirror f/#	46%
Design Life (months)	100%
Data Rate (Kbps)	68%
Launch Date	100%
Year of Development	46%
Technology Readiness Level (TRL)	29%
Operating Temperature (K)	79%
Field of View (degrees)	64%
Pointing Accuracy (Arc-Sec)	43%
Orbit (km)	82%
Average	72%

3.3 Statistical Methods

For this paper, the data set is limited to normal incidence UV/visible and IR telescopes. Cost data is analyzed via the statistical parametric method of single and multiple variable regressions. The purpose of this analysis is to model past trends, construct cost estimating relationships (CERs), and predict the cost of future telescopes. Once the data is verified, it is studied for initial relationships between the trade variables. Figure 4 shows the cross-correlation matrix. This is an important step for isolating key CERs for the cost model, for identifying linkages between CERs, and for verifying that correlations and their 'signs' are consistent with engineering judgment.

	Areal OTA Cost (FY09$M/m^2)	OTA Cost (FY09$M)	Phase A - D w/o Launch Costs (FY09$M)	Primary Diameter (m)	Avg. Input Power (Watts)	Total Mass (kg)	OTA Mass (kg)	Spectral Range Min (u)	WDL (µ)	diam^2*Prim F. Length	Primary Mirror Focal Length (m)	Primary Mirror f/#	Design Life (months)	Data Rate (Kbps)	Launch Date	Year of Dev.	Technology Readiness Level (TRL)	Operating Temp. (K)	FOV (degrees)	Pointing Accuracy (Arc-Sec)	Orbit (km)
Areal OTA Cost (FY09$M/m^2)	**1.00**	-0.32	-0.31	**-0.79**	-0.45	-0.50	-0.58	-0.10	-0.16	**-0.64**	-0.53	0.34	-0.24	**-0.62**	-0.56	-0.44	-0.33	-0.15	-0.02	0.40	0.19
OTA Cost (FY09$M)		**1.00**	**0.71**	**0.83**	0.21	**0.63**	**0.69**	0.13	-0.02	**0.70**	0.58	-0.40	0.51	0.43	-0.10	-0.37	**-0.64**	-0.05	0.13	-0.53	0.13
Phase A - D w/o Launch Costs			**1.00**	**0.63**	**0.65**	**0.81**	**0.61**	0.15	0.37	**0.71**	0.50	**-0.64**	**0.83**	0.44	0.29	0.04	-0.32	-0.17	0.15	**-0.68**	0.45
Primary Diameter (m)				**1.00**	0.42	**0.68**	**0.82**	0.14	0.09	**0.98**	**0.81**	-0.54	0.48	0.59	0.27	0.03	-0.40	0.05	0.09	-0.57	-0.03
Avg. Input Power (Watts)					**1.00**	0.55	**0.64**	-0.10	-0.24	**0.66**	0.52	-0.35	**0.72**	0.58	0.54	0.19	-0.20	0.18	0.46	-0.52	0.05
Total Mass (kg)						**1.00**	**0.86**	-0.06	0.21	**0.91**	**0.78**	-0.41	**0.65**	0.24	0.04	-0.05	-0.49	0.03	-0.18	-0.50	0.12
OTA Mass (kg)							**1.00**	-0.16	-0.07	**0.91**	**0.81**	-0.39	0.27	0.55	0.07	0.04	-0.31	0.18	-0.18	**-0.64**	0.14
Spectral Range Min (u)								**1.00**	**0.87**	-0.37	-0.57	-0.33	0.10	-0.15	0.26	0.31	-0.05	**-0.84**	0.20	0.42	0.09
WDL (µ)									**1.00**	0.03	-0.33	**-0.80**	0.38	-0.07	0.45	0.58	0.39	**-0.73**	0.05	**0.73**	0.22
diam^2*Prim F. Length										**1.00**	**0.90**	-0.38	0.56	0.54	0.09	0.05	-0.32	0.33	**-0.73**	**-0.69**	-0.25
Primary Mirror Focal Length (m)											**1.00**	0.06	0.36	0.39	-0.09	-0.19	-0.33	0.55	**-0.72**	**-0.65**	-0.40
Primary Mirror f/#												**1.00**	0.36	0.39	-0.09	-0.19	-0.33	0.55	**-0.72**	**-0.65**	-0.40
Design Life (months)													**1.00**	0.50	0.32	0.11	-0.35	-0.04	0.14	**-0.66**	0.19
Data Rate (Kbps)														**1.00**	0.40	0.22	0.44	0.29	0.49	**-0.66**	0.21
Launch Date															**1.00**	**0.96**	0.35	-0.04	0.38	0.18	0.00
Year of Dev.																**1.00**	0.58	-0.24	-0.15	0.34	0.04
Technology Readiness Level																	**1.00**	-0.18	-0.15	0.01	0.59
Operating Temp. (K)																		**1.00**	0.06	-0.50	-0.37
FOV (degrees)																			**1.00**	-0.22	0.12
Pointing Accuracy (Arc-																				**1.00**	-0.20
Orbit (km)																					**1.00**

Figure 4 Pearson's Cross-Correlation Matrix for the Variables

For example, CERs with the most significant statistical correlation to OTA cost are: primary mirror diameter (83%) and OTA mass (69%). Another function of the correlation matrix is to identify CERs which are connected via engineering principles or programmatic logic or even just current practice. For example, there is a strong statistical correlation which can be explained by sound engineering principles between diffraction limited wavelength and primary mirror F/#, operating temperature and pointing stability; between OTA mass and primary mirror diameter, primary mirror focal length, and, to a lesser degree, pointing stability and average power. However, care must be taken when considering two independent variables that are strongly correlated with one another. This can lead to the well-known problem of multicolinearity, such as coefficients with non intuitive or "wrong" signs. There are several methods for dealing with this issue, including only incorporating one of the variables, or combining similar variables via a collector variable. Highly correlated independent variable candidates in the data set include for example, total system mass and OTA mass. An example of a collector variable is volume.

Based on experience and theory, cost is modeled by a power model. Once a model is generated, it is diagnosed, refined and assessed for effectiveness. Models are tested for 'goodness' via a range of statistical methods. For single variable models, R^2 describes the percentage of variation in the dependent variable (e.g. cost) which can be attributed to the independent variable (e.g. diameter). When multi-variable models are generated, it is necessary to use 'adjusted' R^2. There is also a 'predicted' R^2 which quantifies how well the model predicts each point in the data set. For all of these tests, the closer the value is to 1.0, the better the model. While doing multi-variable regressions, the Student's T test generates t- and p-values. The p-value is the probability that a better model exists, so, for a p-value, the closer it is to zero the better. If a p-value for a given variable is small, then removing it from the model would cause a large change to the model. If the p-value for a given variable is large, then it has negligible effect on the model.

4.0 COST MODELS

4.1 OTA Cost versus Total Cost

A fundamental question is whether to model OTA cost or total cost. Engineering judgment says that OTA cost is most closely related to OTA engineering parameters. But, managers and mission planners are really more interested in total Phase A-D cost. For this study, total cost is defined as all mission costs excluding launch, mission operations and data analysis. Analysis of the 22 missions in the data base indicates that there is a linear relationship between OTA cost and total cost (Figure 5). OTA cost is ~15% of Phase A-D total cost (R^2 = 85%). From the graph, it is clear that HST and JWST are strong influences on this relationship. If the analysis is repeated without JWST, then OTA cost is 18.5% of total cost (R^2 = 91%). Without JWST, the standard deviation of the model residual is ~\$340M. With JWST, the standard deviation is ~\$600M. So, either JWST has truly broken the cost barrier, or…

As a cross check, the WBS cost elements of 8 missions was analyzed: GALEX, HEAO-2, HST, IRAS, IUE, JWST, Kepler and Spitzer. A common WBS was defined for all 8 missions. The percentage of each WBS element as a function of total cost was calculated and then averaged to produce a generic WBS cost allocation. This analysis indicates that the OTA cost is approximately 30% of the total mission cost.

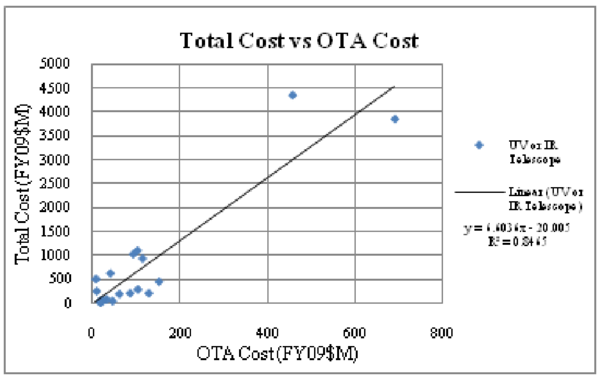

Figure 5 Relationship between OTA Cost and Total Cost

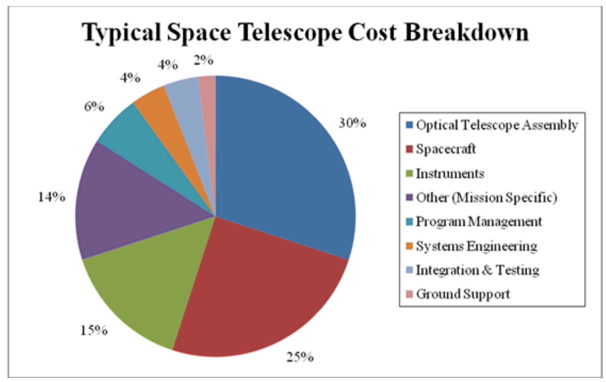

Figure 6 Major Elements of Total Cost

The 15% to 30% scale factor is consistent with both the PRC and Horak models. If one defines total payload cost as the sum of design and development and flight unit manufacturing cost, the PRC model predicts that the cost of the flight unit is 20% to 25% of the total cost. And, if one assumes that the flight unit quantity is one (which is often the case for NASA telescopes) and that there is both an engineering and qualification unit, then the flight unit cost is 33% of the total design cost and 25% of the total mission cost.

For the purpose of this paper, we will confine ourselves to deriving cost estimating relationships for OTA Cost. However, this convenience does miss some variables, such as average power and design life, which have a high correlation with total cost and a small correlation with OTA cost. These variables influence spacecraft and instrument costs with a minimal impact on OTA cost.

4.2 Single Variable Cost Models

OTA Cost Estimating Relationships were examined for aperture diameter, mass, primary mirror focal length, F/#, average power, data rate, design life and wavelength. But of these, only aperture diameter and mass resulted in CERs which could statistically explain more than 70% of the cost variation. Variables such as focal length, power, wavelength, operating temperature and design life will be considered as secondary variables in a multi-variable analysis.

4.2.1 Cost as a Function of Aperture Diameter CER

Based on a sample size of 18 free-flying space telescopes, a single variable cost estimating relationship was developed for OTA cost as a function of primary mirror diameter (Figure 7):

OTA Cost ~ Aperture Diameter $^{1.14}$

(R^2 = 74%) with JWST

OTA Cost ~ Aperture Diameter $^{1.32}$

(R^2 = 71.5%) without JWST

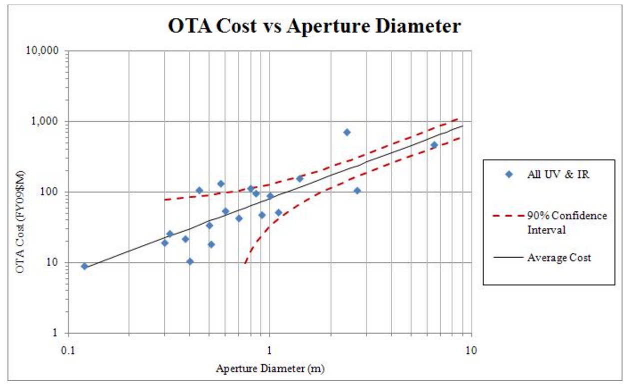

Figure 7 OTA Cost vs Aperture Diameter Scaling Law, 90% Confidence Intervals, and Data

Of all the historical cost models, this result is closest to the 2000 Smart Model. And, it is clearly different from any model which suggests that space telescope costs scale with aperture to the power of 1.6X to 2.0X. Furthermore, it is interesting to note that areal cost (cost/m^2) of collecting aperture actually decreases for increasing diameter. Larger telescopes provide a higher return on investment as well as better science.

4.2.2 Cost as a Function of Mass

While for astrophysicists, telescope aperture diameter is the single most important parameter because it drives system level observatory performance, for engineers and mission planners, mass (and volume) is of equal if not greater importance. Total system mass determines what vehicle can or cannot be used to launch the payload. Significant engineering costs are expended to keep a given payload inside of its allocated mass budget. Space telescopes could be described as being designed to mass.

While developing the mass CER, an obvious cost versus mass relationship was identified. It costs more to make a light weight telescope than it costs to make a heavy telescope. In the 22 mission data set there are 18 free flying telescopes and 4 that are attached to the Space Shuttle or, as in the case of SOFIA, a 747. As shown in Figure 8, the 4 'attached' missions have a significantly higher mass and lower OTA cost than the free flying missions. This is because they have significantly different design rules. Granted, the attached missions obviously have a different total cost than the free flier because the Shuttle or 747 replaces the spacecraft costs, but the OTA cost comparison should be valid.

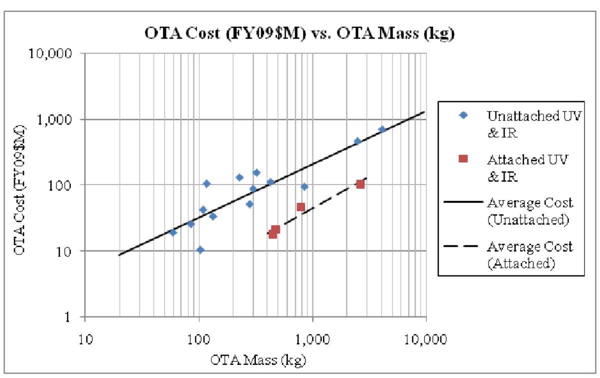

Figure 8 OTA Cost vs OTA Mass for Free-Flying Space Telescopes and Attached Telescopes

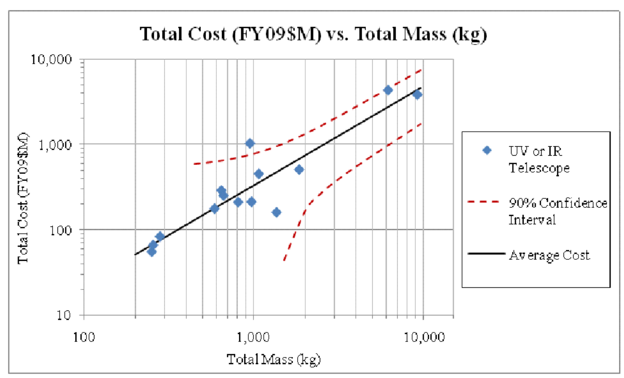

Figure 9 Total Cost vs Total Mass Scaling Law, 90% Confidence Intervals, and Data

Based on a sample size of 14 free-flying space telescopes, a single variable cost estimating relationship was developed for OTA cost as a function of OTA mass (Figure 8):

$$\textbf{OTA Cost} \sim \textbf{OTA Mass}^{\,0.8} \quad (R^2 = 77\%)$$

As one might surmise from looking at Figure 8, there is no difference in the cost model with or without JWST. The JWST cost per mass lines almost exactly on the model line. It is interesting to observe that this result is close to the JSC mass based cost model with its coefficient of 0.65.

Additional analysis was performed to examine total payload cost as a function of total payload mass. Using the same 14 free-flying space telescopes, a CER was developed for Total Phase A-D Cost as a function of Total Mass (Figure 9):

$$\textbf{Total Cost} \sim \textbf{Total Mass}^{\,1.16} \quad (R^2 = 85\%)$$

In this case, repeating the analysis without JWST reduces the coefficient to 1.1. So, while JWST's OTA cost is consistent with its mass, the overall JWST mission cost is higher than the model indicates.

Finally, while it is probably obvious, there is a very good correlation (with a statistical confidence of 90%) between total mass and OTA mass (Figure 8). Total mass is approximately 2.15X that of the OTA mass.

4.0 CONCLUSION

A study has begun to develop a multivariable parametric cost model for space telescopes. Cost models have several uses. 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. Cost and engineering parametric data has been collected on 22 different NASA space telescopes. Statistical correlations have been developed between 19 variables of 59 variables sampled. Two single variable cost estimating relationships were developed: one for primary mirror diameter and one for mass. Key findings for the preliminary study are:

$$\textbf{OTA Cost} \sim \textbf{Aperture Diameter}^{\,1.2}$$

OTA Cost ~ 15% to 30% of Total Phase A-D Cost

$$\textbf{OTA Cost} \sim \textbf{OTA Mass}^{\,0.8}$$

$$\textbf{Total Phase A-D Cost} \sim \textbf{Total Mass}^{\,1.2}$$

OTA Mass ~ 50% of Total Mass

OTA Mass ~ Aperture Diameter

While some of the results are consistent with historical models, the Diameter findings invalidate long held 'intuitions'.

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