Parametric Cost Models for Space Telescopes

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Parametric Cost Models

Parametric cost models have several uses:

- identify major architectural cost drivers,
- allow high-level design trades,
- enable cost-benefit analysis for technology development investment, and
- provide a basis for estimating total project cost.

In the past 12 months

Added JWST cost information for 2003, 2006, 2008 and 2009.

Published two peer reviewed cost model papers:

Stahl, H. Philip, Kyle Stephens, Todd Henrichs, Christian Smart, and Frank A. Prince, "Single Variable Parametric Cost Models for Space Telescopes", Optical Engineering Vol.49, No.06, 2010

Stahl, H. Philip, "Survey of Cost Models for Space Telescopes", Optical Engineering, Vol.49, No.05, 2010

And, will publish a paper at the SPIE Astronomy conference:

Preliminary Multi-Variable Parametric Cost Model for Space Telescopes

Methodology

Data on 59 different variables (19 studied) was acquired for **30** NASA, ESA, & commercial space telescopes using:

NAFCOM (NASA/ Air Force Cost Model) database,
RSIC (Redstone Scientific Information Center),
REDSTAR (Resource Data Storage and Retrieval System),
project websites, and interviews.

Table 1: Cost Model Missions Database

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

Table 2: Cost Model Variables Study and the completeness of data knowledge

Parameters	% of Data
OTA Cost	89%
Total Phase A-D Cost w/o LV	84%
Aperture Diameter	100%
Avg. Input Power	95%
Total Mass	89%
OTA Mass	89%
Spectral Range	100%
Wavelength Diffraction Limit	63%
Primary Mirror Focal Length	79%
Design Life	100%
Data Rate	74%
Launch Date	100%
Year of Development	95%
Technology Readiness Level	47%
Operating Temperature	95%
Field of View	79%
Pointing Accuracy	95%
Orbit	89%
Development Period	95%
Average	88%

Cross Correlation Matrix

	Total Phase A-D Cost	OTA Cost	Areal Total Cost	Areal OTA Cost	Total Cost / Total Mass	OTA Cost / OTA Mass	Aperture Diameter	PM F Len.	PM F/N	OTA Volume	FOV	Pointing Accuracy	Total Mass	OTA Mass	OTA Areal Density	Spectral Range minimum	Wavelength Diffraction Limit	Operating Temperature	Avg. Input Power	Data Rate	Design Life	Technology Readiness Level	Year of Development	Development Period	Launch Date	Orbit
units	(FY09$M)	(FY09$M)	(FY09$M)	(FY09$M/ m^2)	(FY09$M/ kg)	(FY09$M/ kg)	(m)	(m)	unitless	(m^3)	(°)	(Arc-Sec)	(kg)	(kg)	(kg/m^2)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
Total Phase A-D Cost	1.00	0.70	0.09	-0.36	0.59	-0.05	0.64	0.80	0.36	0.83	0.26	-0.52	0.92	0.72	-0.48	-0.02	-0.40	-0.04	0.59	0.44	0.65	-0.41	-0.11	0.78	0.11	0.54
OTA Cost		1.00	-0.53	-0.30	0.32	0.21	0.87	0.82	0.39	0.84	0.00	-0.58	0.68	0.82	0.41	0.07	-0.23	0.01	0.14	0.15	0.46	-0.68	-0.31	0.45	-0.16	0.17
Areal Total Cost			1.00	0.68	0.20	0.22	-0.71	-0.40	0.03	-0.50	0.26	0.34	0.00	-0.47	0.38	-0.23	-0.18	-0.07	-0.05	-0.07	-0.20	-0.29	-0.28	0.14	-0.34	0.40
Areal OTA Cost				1.00	-0.34	0.58	-0.74	-0.62	-0.16	-0.71	-0.56	0.30	-0.34	-0.48	0.59	-0.20	-0.07	-0.03	-0.48	-0.48	-0.41	-0.43	-0.56	-0.22	-0.68	0.04
Total Cost / Total Mass					1.00	-0.16	0.27	0.18	-0.02	0.23	0.19	-0.24	0.22	0.13	-0.30	0.31	-0.12	-0.35	0.03	0.45	0.26	0.26	0.10	0.67	0.24	0.69
OTA Cost / OTA Mass						1.00	-0.15	-0.20	0.03	-0.26	-0.30	0.26	-0.03	-0.39	-0.31	-0.19	-0.42	0.26	-0.49	-0.01	0.11	-0.64	-0.26	-0.35	-0.37	-0.19
Aperture Diameter							1.00	0.88	0.27	0.98	-0.09	-0.58	0.63	0.86	-0.60	0.14	-0.11	0.05	0.42	0.38	0.53	-0.29	0.09	0.37	0.26	0.08
PM F Len.								1.00	0.69	0.96	0.34	-0.66	0.84	0.78	-0.44	-0.50	-0.19	0.28	0.49	0.31	0.50	-0.38	-0.07	0.50	0.10	0.28
PM F/N									1.00	0.45	0.57	-0.41	0.48	0.33	-0.02	-0.61	-0.43	0.32	0.06	0.20	0.25	-0.37	-0.32	0.21	-0.29	0.08
OTA Volume										1.00	0.08	-0.65	0.84	0.84	-0.54	-0.36	-0.08	0.21	0.65	0.34	0.52	-0.31	0.06	0.54	0.26	0.31
FOV											1.00	0.12	0.16	-0.05	0.01	0.05	-0.38	-0.06	-0.02	0.18	0.09	-0.27	0.08	-0.01	0.09	0.09
Pointing Accuracy												1.00	-0.48	-0.71	0.14	0.31	0.08	-0.38	-0.37	-0.29	-0.35	-0.15	0.13	-0.55	-0.02	-0.32
Total Mass													1.00	0.82	-0.42	-0.15	-0.49	0.03	0.55	0.17	0.65	-0.56	-0.27	0.64	-0.10	0.33
OTA Mass														1.00	-0.11	-0.06	0.06	-0.03	0.60	0.09	0.40	-0.29	-0.16	0.57	0.02	0.47
OTA Areal Density															1.00	0.05	0.28	-0.31	-0.16	-0.39	-0.55	0.07	-0.36	-0.20	-0.46	-0.09
Spectral Range minimum																1.00	0.76	-0.79	-0.09	-0.12	-0.25	-0.09	0.21	0.20	0.23	0.01
Wavelength Diffraction Limit																	1.00	-0.55	-0.07	-0.25	-0.75	0.51	0.35	0.31	0.28	0.14
Operating Temperature																		1.00	0.09	0.31	0.31	0.11	-0.01	-0.30	0.00	-0.30
Avg. Input Power																			1.00	0.34	0.64	0.05	0.35	0.27	0.45	0.04
Data Rate																				1.00	0.54	0.51	0.49	-0.06	0.52	0.21
Design Life																					1.00	-0.15	0.12	0.12	0.24	0.14
Technology Readiness Level																						1.00	0.68	-0.24	0.64	0.33
Year of Development																							1.00	-0.23	0.97	-0.05
Development Period																								1.00	-0.02	0.51
Launch Date																									1.00	0.04
Orbit																										1.00

Goodness of Fit

Goodness of Single & Multivariable fits are evaluated via Pearson's R^2 and Student's T p-value

Pearson's R^2 coefficient describes the percentage of variation in the estimated cost that is explained by the actual model.

- The closer R^2 is to 1, the better the fit.

p-value is the probability that a better model exists.

- The closer p-value is to 0, the better the fit.
- 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.

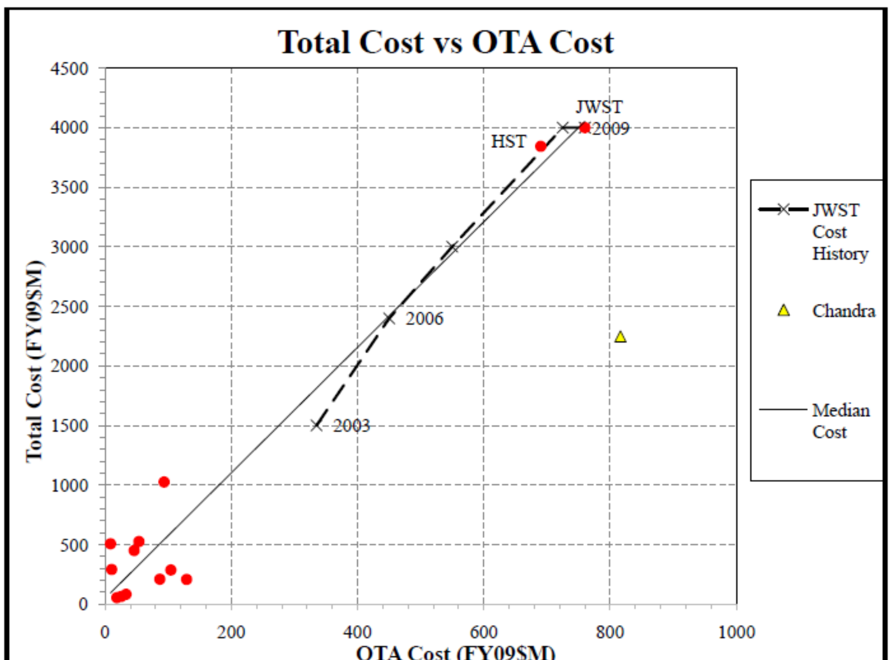
Also important is the Number of Data Points (N) in the Fit.

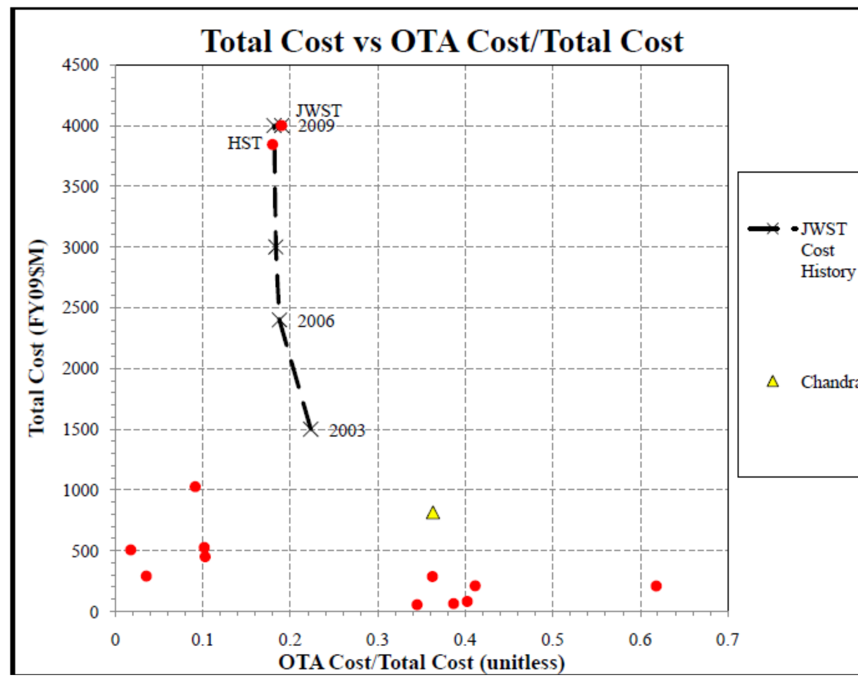
OTA Cost or Total Cost

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.

Total cost is defined as all mission contract costs excluding government costs, launch costs, mission operations and data analysis.

For 14 missions free flying missions, OTA cost is ~20% of Phase A-D total cost (R^2 = 96%) with a model residual standard deviation of approximately $300M.

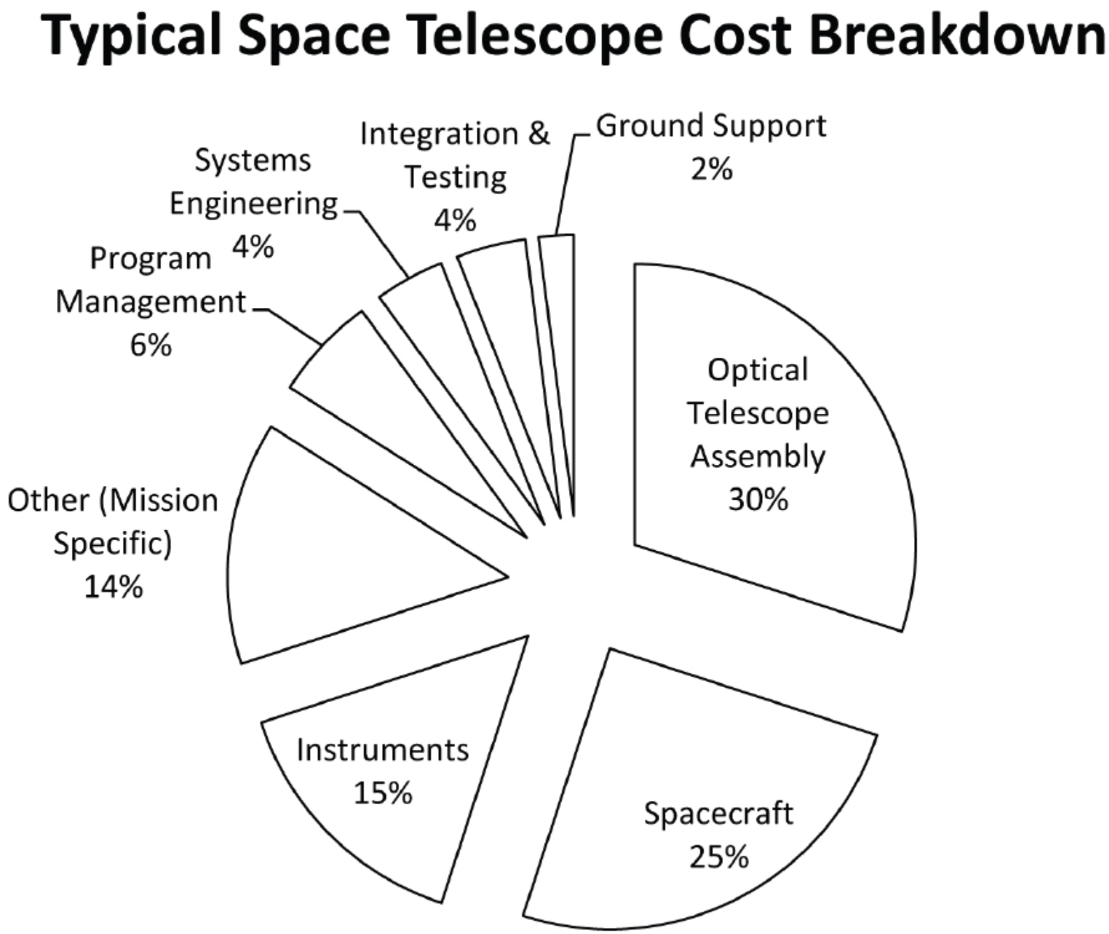




OTA Cost or Total Cost

We have detailed WBS data for 7 of the 14 free flying missions.

Mapping on common WBS indicates that OTA is ~30% of Total,

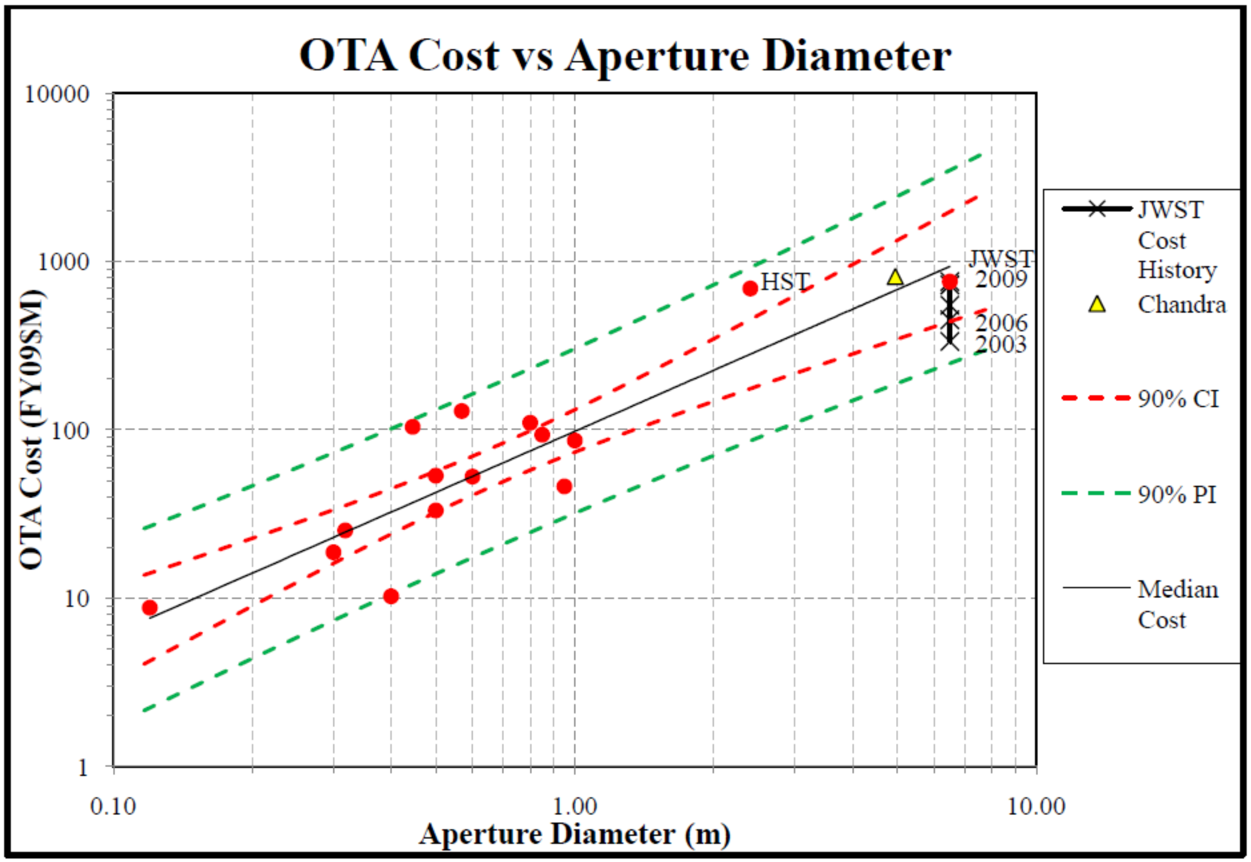


OTA Cost vs Aperture Diameter

For free-flying space telescopes:

OTA Cost ~ Aperture Diameter$^{1.28}$ **(N = 16; r2 = 84%) without JWST**

OTA Cost ~ Aperture Diameter$^{1.2}$ **(N = 17; r2 = 75%) with 2009 JWST**

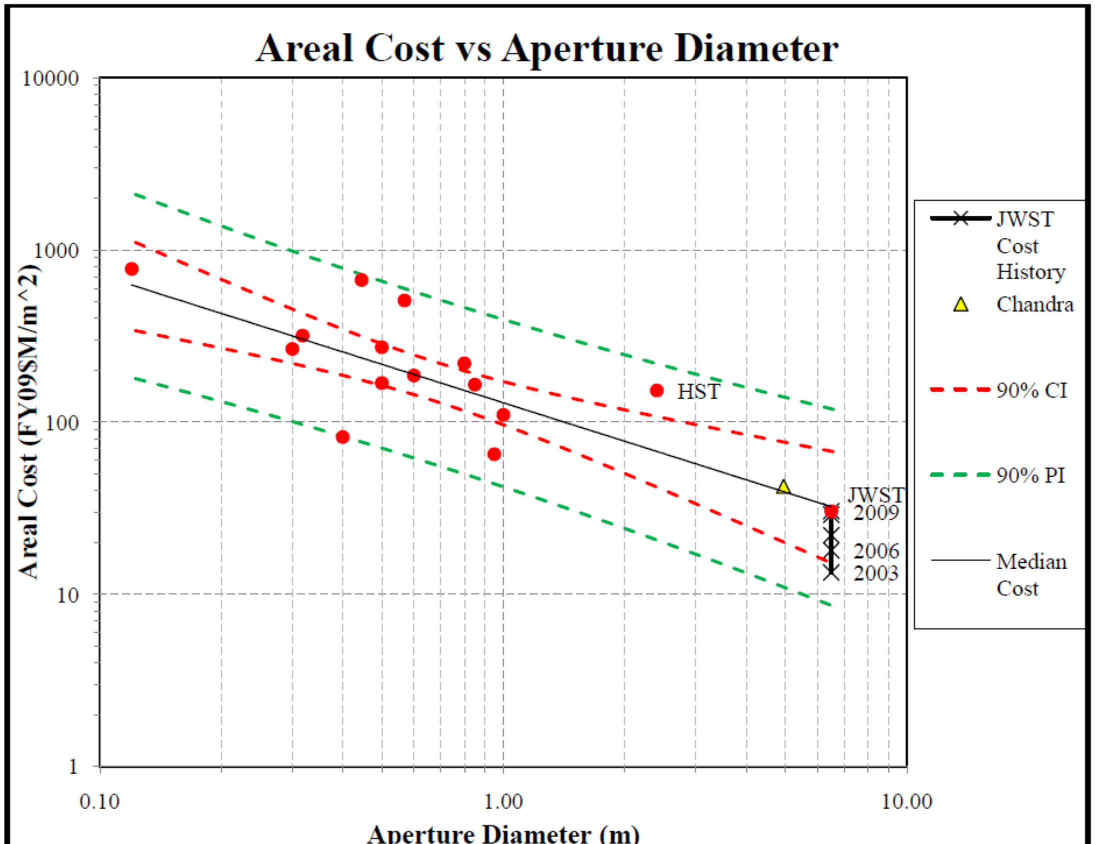


Area Cost

Total Cost is important, but Areal Cost might be more relevant.

Areal Cost decreases with aperture size, therefore, larger telescopes provide a better ROI

OTA Areal Cost ~ Aperture Diameter $^{-0.74}$ ***(N = 17; r^2 = 55%) with JWST***



Mass Models

While aperture diameter is the single most important parameter driving science performance.

Total system mass determines what vehicle can be used to launch.

Significant engineering costs are expended to keep a given payload inside of its allocated mass budget.

Space telescopes are designed to mass

Mass Models

Our data shows that

Total Mass is ~ 3.3X OTA mass (R2 = 92%), and

Total Cost is ~3.3X to 5X OTA Cost.

3.3X comes from WBS analysis

5X comes from regression analysis

Mission	Mass Ratio	Cost Ratio
JWST	~2.6X	~5.3X
Hubble	4.6X	5.5X
Chandra	6.2X	2.8X

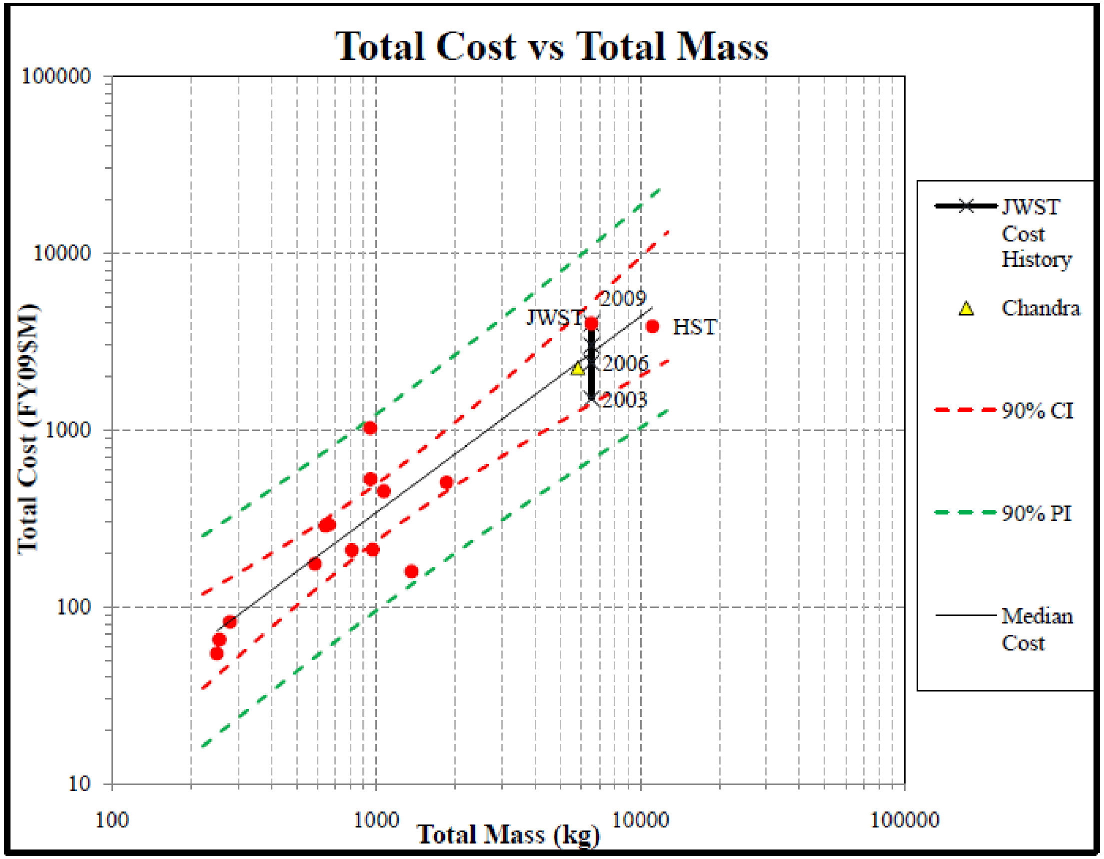
For Chandra, science instruments were massive and optics expensive

Total Cost vs Total Mass

Based on 15 free-flying OTAs

Total Cost ~ Total Mass $^{1.12}$ ***(N = 15; r^2 = 86%) with JWST***

Total Cost ~ Total Mass $^{1.04}$ ***(N = 14; r^2 = 95%) without JWST***

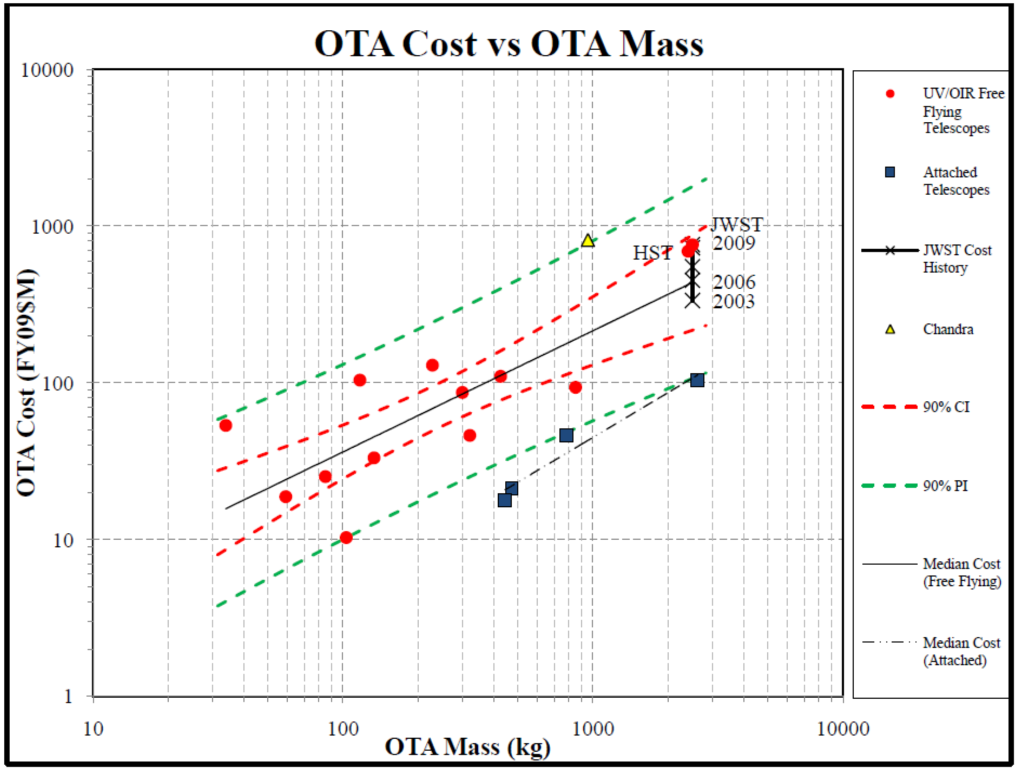


OTA Cost vs OTA Mass

Based on 15 free-flying OTAs

OTA Cost ~ OTA Mass $^{0.69}$ ***(N = 14; r^2 = 84%) without JWST***

OTA Cost ~ OTA Mass $^{0.72}$ ***(N = 15; r^2 = 92%) with JWST***



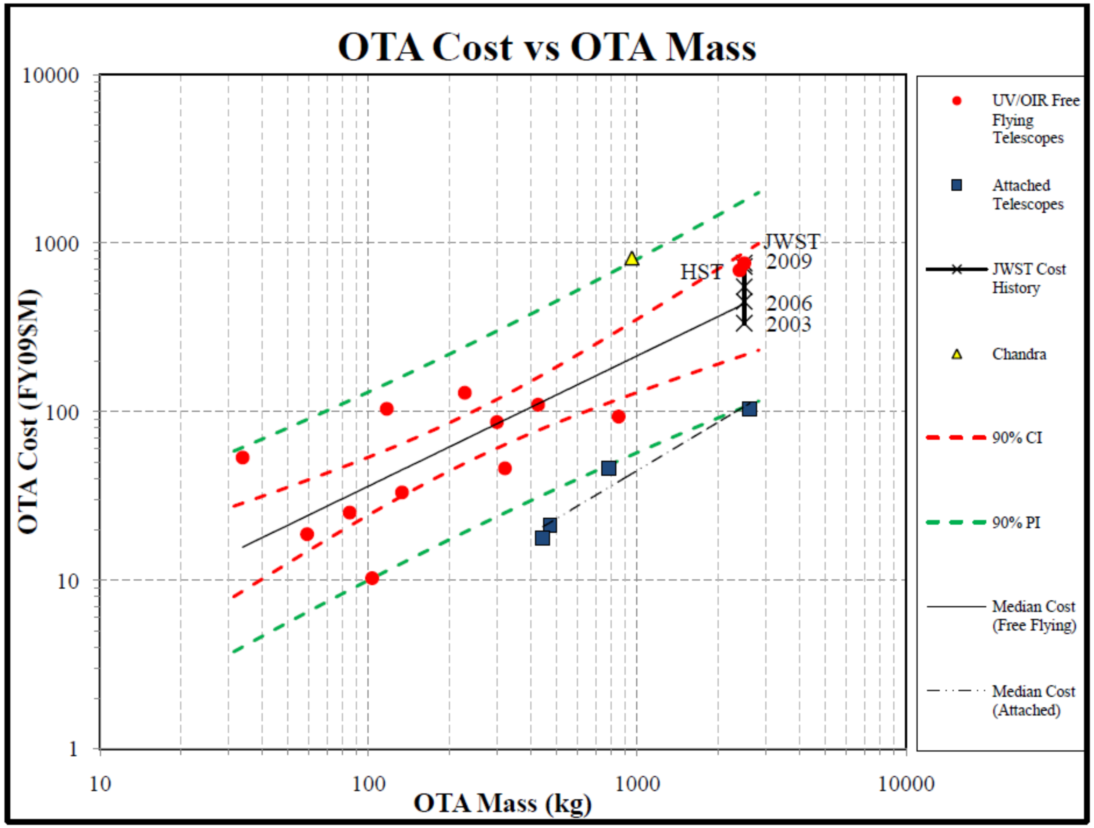
It costs more to make a Lightweight Telescope

For 15 free-flying and 4 attached missions

(3 to Space Shuttle Orbiter and SOFIA to Boeing 747)

‘Attached’ OTAs are ~10X more massive than ‘free-flying’

‘Attached’ OTAs cost ~60% less than ‘free-flying’



Problem with Mass

Mass may have a high correlation to Cost.

And, Mass may be convenient to quantify.

But, Mass is not an independent variable.

Mass depends upon the size of the telescope.

Bigger telescopes have more mass and Aperture drives size.

And, bigger telescopes typically require bigger spacecraft.

The correlation matrix says that Mass is highly correlated with:

Aperture Diameter, Focal Length, F/# ,Volume, Pointing and Power

But in reality it is all Aperture, the others all depend on aperture.

Statistical Summary

While Mass regression has the highest correlation (Pearson's r^2), it also has the highest uncertainty (SPE).

Table 4: Summary of Single Variable Cost Model Statistics								
	OTA Cost		OTA Areal Cost		OTA Cost		Total Cost	
Variable	OTA Diameter		OTA Diameter		OTA Mass		Total Mass	
includes JWST	yes	no	yes	no	yes	no	yes	no
Exponent	1.2	1.28	-0.74	-0.72	0.72	0.69	1.12	1.04
Coefficient	98.5	103.5	122.0	133.6	1.03	1.58	0.16	0.24
$s_{log\$}$	0.62	0.64	0.62	0.64	0.70	0.70	0.53	0.54
Pearson's r^2	75%	84%	55%	52%	92%	84%	86%	95%
SPE	79%	79%	78%	79%	93%	91%	71%	77%
n	17	16	17	16	15	14	15	14

Multi-Variable Models

From engineering & science perspective, Aperture Diameter is the best parameter for a space telescope cost model.

But, the single variable model:

$$\textbf{OTA Cost} \sim \mathbf{D^{1.3}}$$

(excluding JWST because it is not complete) only predicts 84%.

So, other factors must influence cost. The best result thus far is:

$$\textbf{OTA Cost} \sim \mathbf{D^{1.37}\ e^{-0.042(LYr-1960))}} \qquad \textit{(N = 15, } R^2 \textit{ = 90\%)}$$

where D = Aperture Diameter and LYr = Launch Year

Finally, launch year is problematic, launches can be delayed for no fault of the project. A better date might be Start of Development.

Conclusion

A study is in-process to develop a multivariable parametric cost model for space telescopes.

Cost and engineering parametric data has been collected on 30 different space telescopes.

Statistical correlations have been developed between 19 variables of 59 variables sampled.

Single Variable and Multi-Variable Cost Estimating Relationships have been developed.

Results are being published.