Multivariable Parametric Cost Models for Space and Ground Telescopes

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All Cost Models are Wrong!

But Some are Useful.

The Rest will get you into Trouble.

Parametric Cost Models

Parametric cost models have uses:

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

HPS Intuitive Supposition

While space telescopes cost more than ground telescopes, the underlying physics & engineering principles of how one makes a telescope are common.

Thus, independent of Ground or Space:

Scaling laws related to engineering are common

For example:

- Cost versus Diameter depends on substrate manufacture, grind and polish methods; e.g. large tool versus small tool polishing.
- Cost difference between ground and space relates to mirror stiffness from lightweighting – but processing steps are similar for both.

This is important because ground dataset has better wavelength diversity (optical to Radio) and space dataset has better temperature diversity (to 5K)

Program Management practice is different and impacts cost.

Telescope Cost Model

Potential 'generic' model (combination of Ground and Space):

OTA Cost ~ (A) SF $^{0.7}$ D $^{(1.65 \pm 0.05)}$ $\lambda^{(-0.5 \pm 0.2)}$ $T^{-0.25}$ e $^{(-0.035 \pm 0.05)\,Y}$

OTA Cost in Millions of FY2000$

A =	**$1M**	**Ground**
	$100M	**Space**
D =	**Primary Mirror Diameter (meters)**	
λ =	**Wavelength Diffraction Limited (microns)**	
Y =	**Year of Development – 2000**	
SF =	**(#of Segments)$^{0.7}$ (Ds/D)$^{1.7}$**	

Note: SF fits the data but is not very predictive. Is missing something, probably difficulty of making the backplane.

DISCLAIMERS

- Cost Models CANNOT predict the cost of a specific mission.
- Cost Models are a RELATIVE tool. They estimate a potential mission's cost relative to known missions in the Data Base.
- Cost Model interpretation must be consistent with laws of physics, engineering practice and program management.
- Blindly using an incorrect and unjustified cost estimating relationship without understanding its assumptions & limitations will lead to wrong conclusions and potentially very expensive decisions.

DISCLAIMER

Cost Models are only as good as their databases

Ground Database

- 10 monolithic and 5 segmented telescopes since 1979
- Data on 18 Programmatic and Engineering parameters
- Data sources:
  - Interviews
  - REDSTAR Library (Research Data Storage and Retrieval System)
  - RSIC (Redstone Scientific Information Center)

Space Database

- 33 UVOIR & IR, 5 X-Ray, 7-Radio;
- Completeness for 15 'free-flying', 4 'attached', 1 'planet'; 8 Spectroscopic
- 59 Programmatic & Engineering parameters
- Detailed WBS data on 7 Mission.
- Data sources:
  - NAFCOM (NASA/ Air Force Cost Model) database
  - NICM (NASA Instrument Cost Model)
  - NSCKN (NASA Safety Center Knowledge Now)
  - RSIC (Redstone Scientific Information Center)
  - REDSTAR (Resource Data Storage & Retrieval System)
  - SICM (Scientific Instrument Cost Model)
  - project websites, and interviews

Normal Incidence Database (8.6.11)	
Free Flying Telescope	Attached Telescopes
Cloud SAT	HUT
Commercial #1	SOFIA
Commercial #2	UIT
Copernicus (OAO-3/PEP)	WUPPE
GALEX	
Herschel	
HST	Planetary Telescopes
IRAS	MRO/HiRISE
JWST	
Kepler	
OAO-B/GEP	
Planck	
Spitzer (SIRTF)	
WIRE	
WISE	

Definitions

Total Mission:

- Spacecraft
- Science Instruments
- Telescope

Optical Telescope Assembly (OTA):

- Primary mirror
- Secondary (and tertiary if appropriate) mirror(s)
- Support structure
- Mechanisms (actuators, etc.), Electronics, Software, etc.
- Assembly, Integration & Test

Definitions (2)

Cost includes:

- Phase A-D (design, development, integration and test)

Cost excludes:

- Pre-phase A (formulation)
- Phase E (launch/post-launch)
- Government labor costs (NASA employees: CS or support contractors)
- Government Furnished Equipment (GFE)
- Existing Contractor infrastructure which is not 'billed' to contract.
- These are 'First Unit' Costs only – no HST Servicing & there are no 2nd Systems.

Mass includes:

- Dry mass only (no propellant)

FINDING

OTA is not Largest Mission Cost Element

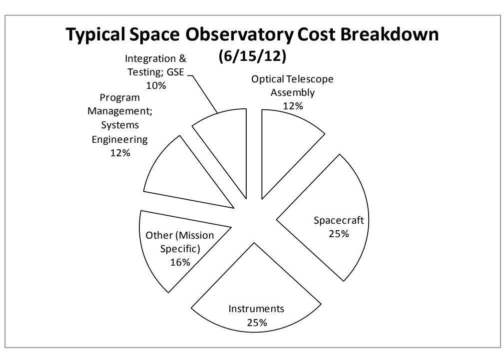
OTA ~12%

Spacecraft and Instruments ~ 50% (**Invest here to reduce $**)

Program Management & Systems Engineering equals OTA ($$$)

I&T ~ 10% (maybe another 10 to 15% of Subsystems)

Example of Mission Specific is Sun Shade for JWST



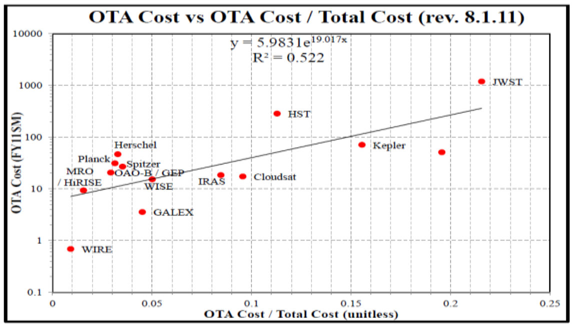
Composite WBS for 7 of 14 free flying missions.

FINDING

Mission Cost is not Proportional to OTA Cost

OTA Cost varies from ~ 1% to ~ 25% of the Total.

OTA's cost as % of Total may depend on infrastructure cost.



Notes:

WIRE is clearly questionable.

GALEX CADRe cost may be missing Structure cost.

Want to Build a Cost Model?

Model Creation

Start with Correlation Matrix.

Look for Variables which are Highly Correlated with Cost.

- The higher the correlation the greater the Cost Variation which is explained by a given Variable.
- Sign of correlation is important and must be consistent with Engineering Judgment.

Important for Multi-Variable Models:

- We want Variables which Independently effect Cost.
- When Variables ‘cross-talk’ with each other it is called Multi-Collinearity.
- Thus, avoid Variables which are highly correlated with each other.

Goodness of Correlation, Fits and Regressions

‘Correlation’ between variables and ‘Goodness’ of single variable models is evaluated via Pearson’s r^2 standard percent error (SPE), and Student’s T-Test p-value.

‘Goodness’ of multivariable fits are evaluated via Pearson’s Adjusted r^2 which accounts for number of data points and number of variables.

Pearson’s r^2 coefficient describes the percentage of agreement between the fitted values and the actual data.

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

SPE is a normalized standard deviation of the fit residual (difference between data and fit) to the fit.

- The closer SPE is to 0, the better the fit

Significance

The final issue is whether or not a correlation or fit is significant.

p-value is the probability that the fit or correlation would occur if the variables are independent of each other.

- The closer p-value is to 0, the more significant the fit or correlation.
- The closer p-value is to 1, the less significant.
- If the p-value for a given variable is small, then removing it from the model would cause a large change to the model.
- If p-value is large, then removing the variable will have a negligible effect

It is only possible to 'test' if the correlation between two variables is significant.

It is not possible to 'test' if two variables are independent.

Cross-Correlation Matrix

rev. 8.1.11	Total Cost	OTA Cost	Aperture Diameter	PM F Len.	System F Len.	FOV	Pointing Stability	Total Mass	OTA Mass	Spectral Range minimum	Diff. Lim. λ	Operating Temp.	Total Avg. Input Power	Data Rate	Design Life	TRL	Year of Dev.	Dev. Period	Date of Launch	Orbit
units	(FY11$M)	(FY11$M)	(m)	(m)	(m)	(°)	(Arc-Sec / Sec)	(kg)	(kg)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
Total Cost	**1.00**	**0.85**	**0.69**	0.21	0.52	0.13	**-0.72**	**0.68**	**0.85**	0.21	-0.05	-0.11	0.57	0.05	0.30	-0.45	-0.15	**0.70**	0.03	0.46
OTA Cost		**1.00**	**0.78**	**0.88**	**0.72**	-0.13	**-0.80**	**0.84**	**0.95**	-0.16	-0.20	0.04	0.37	0.22	**0.64**	**-0.61**	-0.03	**0.62**	0.16	0.07
Aperture Diameter			**1.00**	0.36	**0.72**	-0.04	**-0.71**	0.59	**0.84**	0.51	0.46	-0.05	0.44	-0.10	0.43	-0.28	-0.08	0.45	0.05	0.05
PM F Len.				**1.00**	**0.70**	0.13	**-0.77**	**0.69**	**0.89**	-0.48	-0.38	0.18	0.21	0.04	0.56	-0.35	-0.11	0.41	0.11	0.00
System F Len.					**1.00**	-0.29	-0.47	**0.61**	**0.70**	0.02	-0.13	-0.04	0.13	-0.16	0.60	-0.38	-0.22	0.43	-0.03	0.18
FOV						**1.00**	-0.33	0.03	0.27	0.24	0.26	-0.12	0.10	0.19	-0.15	-0.31	0.19	-0.01	0.18	0.06
Pointing Stability							**1.00**	**-0.62**	**-0.87**	0.16	0.18	-0.13	-0.46	-0.03	-0.54	0.26	-0.04	**-0.63**	-0.24	-0.03
Total Mass								**1.00**	**0.92**	-0.10	0.10	0.01	0.39	-0.19	0.46	-0.54	-0.31	0.51	-0.16	0.24
OTA Mass									**1.00**	-0.22	-0.22	0.00	0.27	-0.17	0.41	**-0.62**	-0.04	**0.69**	0.18	-0.35
Spectral Range minimum										**1.00**	**0.96**	-0.24	0.16	0.10	0.06	-0.09	0.19	0.17	0.19	0.12
Diff. Lim. λ											**1.00**	-0.28	0.10	0.15	-0.20	0.12	0.35	0.23	0.32	0.26
Operating Temp.												**1.00**	0.12	-0.05	0.27	0.11	-0.06	-0.39	-0.09	-0.06
Total Avg. Input Power													**1.00**	0.50	0.57	0.13	0.59	0.06	0.57	0.25
Data Rate														**1.00**	0.14	**0.63**	**0.72**	-0.09	**0.70**	0.28
Design Life															**1.00**	-0.15	0.12	0.15	0.25	0.33
TRL																**1.00**	**0.67**	-0.17	**0.64**	0.32
Year of Dev.																	**1.00**	-0.13	**0.97**	0.22
Dev. Period																		**1.00**	0.09	0.36
Date of Launch																			**1.00**	0.28
Orbit																				**1.00**

Cross-Correlation Matrix

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PM F Len.				**1.00**	**0.70**	0.13	**-0.77**	**0.69**	**0.89**	-0.48	-0.38	0.18	0.21	0.04	0.56	-0.35	-0.11	0.41	0.11	0.00
System F Len.					**1.00**	-0.29	-0.47	**0.61**	**0.70**	0.02	-0.13	-0.04	0.13	-0.16	0.60	-0.38	-0.22	0.43	-0.03	0.18
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Diff. Lim. λ											**1.00**	-0.28	0.10	0.15	-0.20	0.12	0.35	0.23	0.32	0.26
Operating Temp.												**1.00**	0.12	-0.05	0.27	0.11	-0.06	-0.39	-0.09	-0.06
Total Avg. Input Power													**1.00**	0.50	0.57	0.13	0.59	0.06	0.57	0.25
Data Rate														**1.00**	0.14	**0.63**	**0.72**	-0.09	**0.70**	0.28
Design Life															**1.00**	-0.15	0.12	0.15	0.25	0.33
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Orbit																				**1.00**

Correlations which are at least 95% significant are **Bolded**, e.g. for 12 data points a correlation of greater than 60% is significant to better than 95%.

Cross-Correlation Matrix

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Total Cost has significant correlations with:
- Aperture Diameter
- Pointing Stability (inverse correlation)
- OTA & Total Mass
- Average Power (weak)
- Development Period

OTA Cost has significant correlations with:
- Aperture Diameter
- Primary Mirror & System Focal Length (Volume)
- Pointing Stability (inverse correlation)
- OTA Mass
- Design Life
- TRL (inverse)
- Development Period

Wavelength & Temperature correlation is weak

Not all Correlated Variables are Independent

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Correlation Matrix implies that Larger Diameter OTAs:

- have longer Focal Lengths
- have smaller Pointing Stability Requirements
- are more Massive
- require bigger spacecraft which are more Massive & require Power
- have larger instruments that are more Massive & require Power
- need a long Design Life
- take longer to Develop

Aperture Diameter is co-linear with System F/#, Pointing, OTA Mass.

Variable Linkages

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Correlation Matrix can be used to identify variable cross-linkages which should be reconciled with Engineering Judgment.

Aperture Diameter and Pointing Stability have a large negative correlation: Larger Diameter OTAs required smaller Pointing Stability.

Pointing Stability and OTA Mass have a large negative correlation: Small Pointing Stability requires a very stiff, i.e. Massive, OTA.

Wavelength and Temperature

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Total Cost	1.00	0.85	0.69	0.21	0.52	0.13	-0.72	0.68	0.85	0.21	-0.05	-0.11	0.57	0.05	0.30	-0.45	-0.15	0.70	0.03	0.46
OTA Cost		1.00	0.78	0.88	0.72	-0.13	-0.80	0.84	0.95	-0.16	-0.20	0.04	0.37	0.22	0.64	-0.61	-0.03	0.62	0.16	0.07
Aperture Diameter			1.00	0.36	0.72	-0.04	-0.71	0.59	0.84	0.51	0.46	-0.05	0.44	-0.10	0.43	-0.28	-0.08	0.45	0.05	0.05
PM F Len.				1.00	0.70	0.13	-0.77	0.69	0.89	-0.48	-0.38	0.18	0.21	0.04	0.56	-0.35	-0.11	0.41	0.11	0.00
System F Len.					1.00	-0.29	-0.47	0.61	0.70	0.02	-0.13	-0.04	0.13	-0.16	0.60	-0.38	-0.22	0.43	-0.03	0.18
FOV						1.00	-0.33	0.03	0.27	0.24	0.26	-0.12	0.10	0.19	-0.15	-0.31	0.19	-0.01	0.18	0.06
Pointing Stability							1.00	-0.62	-0.87	0.16	0.18	-0.13	-0.46	-0.03	-0.54	0.26	-0.04	-0.63	-0.24	-0.03
Total Mass								1.00	0.92	-0.10	0.10	0.01	0.39	-0.19	0.46	-0.54	-0.31	0.51	-0.16	0.24
OTA Mass									1.00	-0.22	-0.22	0.00	0.27	-0.17	0.41	-0.62	-0.04	0.69	0.18	-0.35
Spectral Range minimum										1.00	0.96	-0.24	0.16	0.10	0.06	-0.09	0.19	0.17	0.19	0.12
Diff. Lim. λ											1.00	-0.28	0.10	0.15	-0.20	0.12	0.35	0.23	0.32	0.26
Operating Temp.												1.00	0.12	-0.05	0.27	0.11	-0.06	-0.39	-0.09	-0.06
Total Avg. Input Power																			0.57	0.25
Data Rate																			0.70	0.28
Design Life																			0.25	0.33
TRL																			0.64	0.32
Year of Dev.																			0.97	0.22
Dev. Period																			0.09	0.36
Date of Launch																			1.00	0.28
Orbit																				1.00

As expected Spectral Range and
Diffraction Limit are highly correlated.
Operating Temperature are inversely correlated.

But neither are significantly correlated with Cost – because they cancel either other out.

Year and TRL

rev. 8.1.11	Total Cost	OTA Cost	Aperture Diameter	PM F Len.	System F Len.	FOV	Pointing Stability	Total Mass	OTA Mass	Spectral Range minimum	Diff. Lim. λ	Operating Temp.	Total Avg. Input Power	Data Rate	Design Life	TRL	Year of Dev.	Dev. Period	Date of Launch	Orbit
units	(FY11$M)	(FY11$M)	(m)	(m)	(m)	(°)	(Arc-Sec / Sec)	(kg)	(kg)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
Total Cost	1.00	0.85	0.69	0.21	0.52	0.13	-0.72	0.68	0.85	0.21	-0.05	-0.11	0.57	0.05	0.30	-0.45	-0.15	0.70	0.03	0.46
OTA Cost		1.00	0.78	0.88	0.72	-0.13	-0.80	0.84	0.95	-0.16	-0.20	0.04	0.37	0.22	0.64	-0.61	-0.03	0.62	0.16	0.07
Aperture Diameter			1.00	0.36	0.72	-0.04	-0.71	0.59	0.84	0.51	0.46	-0.05	0.44	-0.10	0.43	-0.28	-0.08	0.45	0.05	0.05
PM F Len.																-0.35	-0.11	0.41	0.11	0.00
System F Len.																-0.38	-0.22	0.43	-0.03	0.18
FOV																-0.31	0.19	-0.01	0.18	0.06
Pointing Stability																0.26	-0.04	-0.63	-0.24	-0.03
Total Mass																-0.54	-0.31	0.51	-0.16	0.24
OTA Mass																-0.62	-0.04	0.69	0.18	-0.35
Spectral Range minimum																-0.09	0.19	0.17	0.19	0.12
Diff. Lim. λ																0.12	0.35	0.23	0.32	0.26
Operating Temp.																0.11	-0.06	-0.39	-0.09	-0.06
Total Avg. Input Power																0.13	0.59	0.06	0.57	0.25
Data Rate														1.00	0.14	0.63	0.72	-0.09	0.70	0.28
Design Life															1.00	-0.15	0.12	0.15	0.25	0.33
TRL																1.00	0.67	-0.17	0.64	0.32
Year of Dev.																	1.00	-0.13	0.97	0.22
Dev. Period																		1.00	0.09	0.36
Date of Launch																			1.00	0.28
Orbit																				1.00

As expected, Year of Development and Launch year are highly correlated.

TRL is correlated with Year of Development – more recent missions require higher TRL

Data Rate is correlated with Date of Launch – more recent mission require higher Data Rate.

Detailed Cross Correlation Matrix: Collector Variables

rev. 11.6.10	Total Cost	OTA Cost	Total Cost - OTA Cost	Areal Total Cost	Areal OTA Cost	Total Cost / kg	OTA Cost / kg	Aperture Diameter	PM F Len.	PM f#	System F Len.	System f#	OTA Volume	FOV	Pointing Stability	Total Mass	OTA Mass	Total Areal Density	OTA Areal Density	Spectral Range	minimum Diffraction Limited Wavelength	Operating Temperature	Avg. Input Power	Data Rate	Design Life	TRL	Year of Dev.	Dev. Period	Date of Launch	Orbit
units	(FY09$M)	(FY09$M)	(FY09$M)	(FY09$M /m2)	(FY09$M /m2)	(FY09$M /kg)	(FY09$M /kg)	(m)	(m)	unitless	(m)	unitless	(m3)	(°)	(Arc-Sec / Sec)	(kg)	(kg)	(kg/m2)	(kg/m2)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
Total Cost	1.00	0.88	1.00	-0.16	0.01	0.52	0.37	0.64	0.80	0.11	0.68	0.31	0.81	0.07	-0.62	0.93	0.76	-0.29	0.11	0.08	0.12	-0.05	0.65	0.19	0.69	-0.46	-0.07	0.58	0.17	0.36
OTA Cost		1.00	0.85	-0.45	0.18	0.12	0.23	0.82	0.82	0.03	0.72	0.33	0.85	-0.25	-0.82	0.90	0.91	-0.49	-0.05	-0.05	-0.07	-0.01	0.51	-0.06	0.65	-0.38	0.04	0.61	0.26	-0.02
Total Cost - OTA Cost			1.00	-0.14	-0.01	0.54	0.38	0.68	0.81	0.19	0.65	0.31	0.87	-0.01	-0.61	0.95	0.73	-0.28	0.08	0.09	0.16	0.02	0.71	0.29	0.68	-0.46	-0.02	0.59	0.19	0.33
Areal Total Cost				1.00	0.62	0.08	0.20	-0.86	-0.42	0.52	-0.53	0.18	-0.71	0.35	0.34	-0.21	-0.70	0.97	-0.17	-0.13	-0.28	0.14	0.14	0.24	-0.29	-0.39	-0.09	-0.15	-0.21	0.22
Areal OTA Cost					1.00	0.10	0.37	-0.42	-0.11	0.44	-0.28	-0.05	-0.28	0.26	-0.53	-0.04	0.05	0.64	0.47	-0.32	-0.58	-0.31	0.04	0.06	-0.14	-0.36	-0.33	0.09	-0.28	-0.14
Total Cost / kg						1.00	0.62	0.22	0.24	0.15	0.43	0.33	0.18	0.11	-0.15	0.18	0.14	-0.18	-0.20	0.23	0.01	-0.19	0.25	0.31	0.39	0.08	-0.01	0.33	0.09	0.55
OTA Cost / kg							1.00	0.10	-0.08	-0.46	0.29	0.35	0.03	-0.35	-0.03	0.08	-0.19	-0.11	-0.65	0.13	0.20	-0.33	0.37	0.50	0.17	0.89	0.33	0.15	0.28	0.65
Aperture Diameter								1.00	0.76	-0.29	0.80	0.11	0.97	-0.30	-0.79	0.64	0.87	-0.88	0.15	0.11	0.28	-0.08	0.14	-0.16	0.60	-0.29	0.01	0.40	0.19	-0.08
PM F Len.									1.00	0.40	0.78	0.39	0.89	0.19	-0.84	0.80	0.90	-0.45	0.27	-0.41	-0.21	0.18	0.15	0.09	0.59	-0.39	-0.07	0.57	0.12	-0.13
PM f#										1.00	-0.05	0.28	-0.06	0.49	-0.53	0.11	0.65	0.49	0.50	-0.[illegible]6	-0.68	0.22	-0.16	-0.05	0.09	-0.37	-0.23	0.26	-0.21	-0.20
System F Len.											1.00	0.69	0.86	-0.33	-0.40	0.65	0.71	-0.57	0.09	-0.07	-0.16	-0.04	-0.04	-0.26	0.65	-0.39	-0.23	0.35	-0.06	0.07
System f#												1.00	0.27	-0.18	-0.01	0.28	0.28	0.13	-0.01	-0.26	-0.57	0.04	-0.19	-0.19	0.36	-0.32	-0.38	0.06	-0.32	0.20
OTA Volume													1.00	-0.08	-0.90	0.83	0.89	-0.76	0.17	-0.27	0.05	0.09	0.28	0.14	0.60	-0.31	0.05	0.53	0.24	-0.07
FOV														1.00	-0.28	0.02	0.46	0.35	0.64	0.04	-0.11	-0.08	0.04	0.26	-0.16	-0.31	0.10	0.04	0.10	0.03
Pointing Stability															1.00	-0.57	-0.86	0.49	-0.60	0.38	0.36	-0.25	-0.32	-0.24	-0.57	0.17	0.07	-0.47	-0.07	0.05
Total Mass																1.00	0.83	-0.21	0.21	-0.02	0.13	-0.06	0.39	-0.03	0.58	-0.52	-0.20	0.57	0.01	0.17
OTA Mass																	1.00	-0.70	0.61	-0.32	-0.32	-0.03	0.20	-0.26	0.48	-0.62	-0.08	0.79	0.27	-0.49
Total Areal Density																		1.00	-0.01	-0.17	-0.28	0.13	0.01	0.14	-0.32	-0.49	-0.10	-0.15	-0.19	0.08
OTA Areal Density																			1.00	-0.13	-0.33	-0.12	-0.10	-0.54	-0.0[illegible]	-0.97	-0.39	0.44	-0.18	-0.81
Spectral Range minimum																				1.00	0.84	-0.56	0.13	0.08	-0.13	-0.09	0.27	0.10	0.29	0.14
Diffraction Limited Wavelength																					1.00	-0.41	0.13	0.08	-0.14	0.12	0.29	0.46	0.30	0.09
Operating Temperature																						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.00
Avg. Input Power																							[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.23
Data Rate																								[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.34
Design Life																									[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.15
TRL																										[illegible]	[illegible]	[illegible]	[illegible]	0.33
Year of Dev.																											[illegible]	[illegible]	[illegible]	0.09
Dev. Period																												1.00	0.06	-0.18
Date of Launch																													1.00	0.06
Orbit																														1.00

Looking deeper confirms other Engineering Correlations:

Longer Wavelength OTAs have faster Primary Mirror F/#

Lower Areal Density OTAs have lower TRL (are less mature).

How to develop a Multi-Variable Model

1. Perform a single-variable regression to identify key variable.
2. Fix 1st Variable and perform a 2-variable regression to identify next key variable.
3. Select 2nd variable based on:
   - Change in 1st Variable's Significance
   - Significance of Variable #2
   - Increase in r^2_{adj}
   - Decrease in SPE
   - Multi-Collinearity
4. Repeat for 3rd Variable.

Some variables may increase r^2_{adj} and/or decrease SPE, but they are not significant or their coefficients are not consistent with engineering judgment or they are multi-collinear.

Single Variable Space OTA

Regressing on 15 normal incidence, 'free-flying' UVOIR OTAs

Significant Variables: Diameter, Focal Length, Volume, Pointing & Mass

Diameter is co-linear with Volume, Pointing & Mass.

Focal Length has the highest R^2_{adj} and Mass has the lowest SPE

Diameter is most relevant for Science and Engineering.

rev. 8.1.11	OTA Cost vs V1													
Variable Name	Aperture Diameter		PM F Len.		PM f/#		OTA Volume		FOV		Pointing Stability		OTA Mass	
Var. | p-value	1.42	0.00	1.55	0.00	0.58	0.57	0.58	0.00	-0.12	0.69	-0.76	0.02	1.08	0.00
Adjusted r^2	81%		94%		-3%		92%		4%		6%		86%	
SPE	123%		92%		707%		80%		400%		242%		58%	
n	15		11		11		11		12		8		13	

Variable Name	OTA Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.		Year of Dev. (exp)		Date of Launch (exp)	
Var. | p-value	0.06	0.90	-0.07	0.56	-0.11	0.54	0.04	0.89	0.00	0.91	0.02	0.56
Adjusted r^2	-8%		-4%		-7%		-8%		-7%		3%	
SPE	810%		830%		787%		979%		1007%		747%	
n	12		15		12		14		14		15	

Single Variable Cost Model

Diameter yields similar CER for Space & Ground OTA Cost.

Ground OTA Cost ~ $2M $D^{1.4}$

Space OTA Cost ~ $30M $D^{1.4}$

(N = 15; r^2 = 81%; SPE = 123) (2012)

While single variable model is informative, it is of limited value:

- Diameter exponent is artificial because this model does not include year of development. More recent telescopes use advances in technology to produce larger aperture diameters at a lower cost.
- Diameter model only explains 81% of Cost Variation. Need additional variables to explain cost variation.

OTA Cost versus Diameter and V2

rev. 8.1.10		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		No		Yes		No		Yes		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	

Considering variables that are not collinear with Diameter

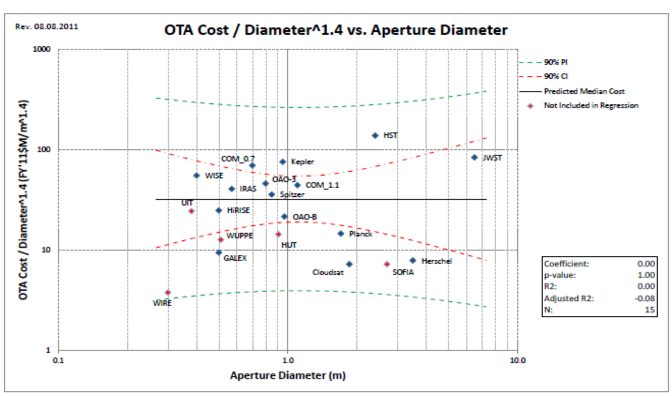
- Focal Length increases r^2 and decreases SPE but invalidates Diameter significance
- Diffraction Limit & Spectral Min are significant, both increase R^2 & decrease SPE
- YOD or DOL are 'weakly' inverse correlated, slight cost reduction with time; but for Space, each new OTA is new – limited reuse.

Residual Error Analysis: Aperture

Divide data by Diameter Model (normalize data) and plot as a function of Variables.

R^2 indicates how % of residual error explained by a 2nd Variable

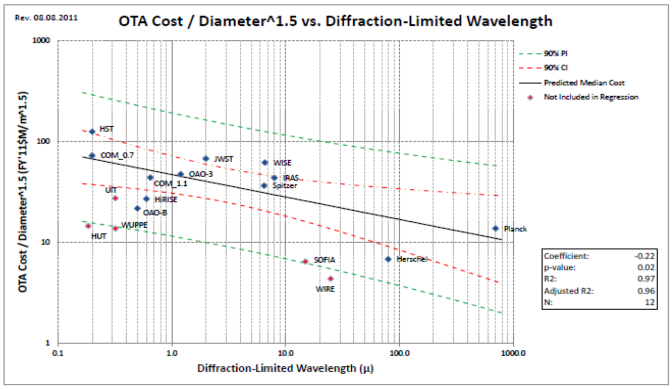
For example, as expected diameter explains 'zero' variation



Residual Error Analysis: Wavelength

Diffraction Limit Wavelength explains 97% of residual variation

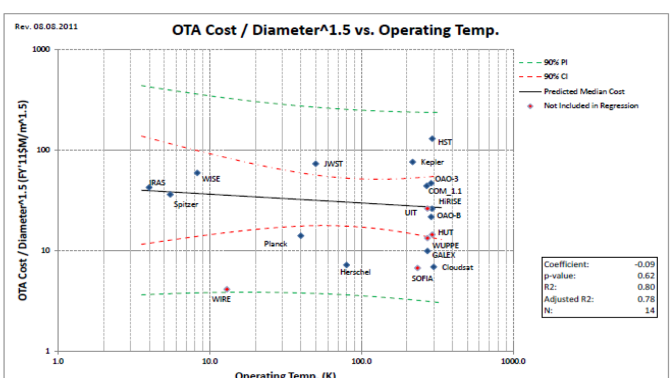
A -0.2 coefficient implies that an OTA with a 10X longer wavelength will cost 40% less.



Aperture Residual Error Analysis: Temperature

Operating Temperature does not significantly explain residual aperture variation.

But, it might be a good 3rd or 4th CER parameter

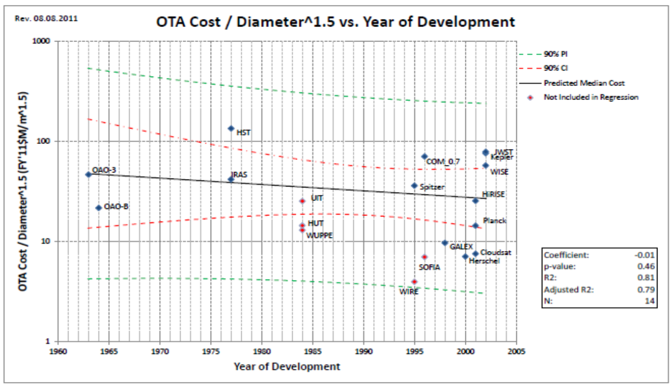


Aperture Residual Error Analysis: YOD

Year of Development does not significantly explain residual.

But, it might be a good 3rd or 4th CER parameter

Concern that YOD is correlated with Aperture and Wavelength.
Also, what is role of spectroscopic vs imaging.



Two Variable Aperture Model

Diffraction Limited Wavelength yields the best model:

$$\textbf{OTA Cost} \sim \textbf{Dia}^{1.65}\ \lambda^{-0.25} \qquad (N = 12,\ r^2 = 99\%;\ SPE = 61\%)$$

OTA Cost versus Diameter, Wavelength and V3

Operating Temperature is the only significant 3rd variable

OTA Cost ~ D $^{1.7}$ $\lambda^{-0.3}$ $T^{-0.25}$

(N = 11, r^2 = 96%; SPE= 54%)

rev. 8.1.10		OTA Cost vs Diam., Diff. Lim., and V2									
	Variable 2	Diam., Diff. Lim., & V3		FOV		Pointing Stability		OTA Mass		OTA Areal Density	
Diam.	p-value	1.54	0.00	1.37	0.01	1.48	0.10	0.66	0.24	1.97	0.00
Diff. Lim	p-value	-0.22	0.02	-0.23	0.09	-0.11	0.66	-0.16	0.22	-0.16	0.22
V3	p-value	-	-	0.13	0.66	-0.18	0.56	0.66	0.07	0.66	0.07
Adjusted r^2		98%		84%		98%		92%		92%	
SPE		60%		73%		49%		46%		46%	
n		12		10		6		10		10	
Multicollinearity?		N/A		No		Yes		Yes		No	
	Variable 2	Operating Temperature		Design Life (exp)		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)	
Diam.	p-value	1.70	0.00	0.87	0.03	1.53	0.00	1.45	0.01	1.49	0.00
Diff. Lim	p-value	-0.32	0.01	-0.05	0.66	-0.24	0.04	-0.18	0.06	-0.24	0.02
V3	p-value	-0.25	0.10	0.01	0.05	0.01	0.75	0.01	0.42	0.01	0.58
Adjusted r^2		96%		99%		97%		96%		97%	
SPE		54%		43%		60%		48%		58%	
n		11		12		11		10		12	
Multicollinearity?		No		Yes		No		No		No	

Ground Telescopes

Ground Multivariable Cost Model

Of 20 potential CER parameters, only four have statistically significant impact ($p < 10\%$):

- Primary mirror diameter (D),
- Wavelength Diffraction Limited Performance (λ),
- Reduction in Technology Cost over Time (where Y = Year of Development),
- Segmentation Factor (SF)

2012 Multi-Variable Ground Cost Model

Regressing on ground data set which contains only 5 segmented telescopes and assuming that there are NO cost differences between segment prescriptions (because 'learning' transfers between prescriptions):

$$\text{Ground OTA Cost} \sim (\$1M)\,(SF)^{0.7}\,(D)^{1.7}\,(\lambda)^{-0.7}\,e^{-0.04(Y)}$$

(R^2=91%, adjusted R^2=88%, SPE = 37%)

Where:

OTA Cost in Millions of FY2000$

D = Primary Mirror Diameter (meters)

λ = Wavelength Diffraction Limit (microns)

Y = Year of Development - 2000

SF = (#of Segments)$^{0.7}$ (Ds/D)$^{1.7}$

Luedtke, Alexander and H. Philip Stahl, "Commentary on Multivariable Parametric Cost Model for Ground Optical Telescope Assembly", Optical Engineering Vol.51, OE-111662C

Cost as a function of Diameter

An exponent coefficient for Cost vs Diameter of less than 2.0 is consistent with engineering experience.

Cost is a linear combination of diameter & diameter squared.

Some models estimate polishing cost as proportional to area.

- But, this assumes a constant tool size. It is possible for tool size to increase with mirror diameter.
- Also, ignores perimeter, which is hard to polish & varies with diameter.

Tool and fabrication machine size cost is directly proportional to mirror area.

Substrate cost also is related to Area and Areal Density.

Wavelength Diffraction Limit (WDL)

Holding variables constant, visible OTA costs more to build than an IR OTA
- It takes longer to polish a smooth UV/visible mirror than an infrared mirror.
- Stiffer OTA needed to achieve & maintain WDL in UV/visible than infrared/Radio

Ground OTA regression has WDL power of -0.5 to -0.7:
- -0.5 exponent predicts that a 2X wavelength change yields a 30% cost reduction
- -0.7 exponent predicts that a 2X wavelength change yields a 40% cost reduction

Space OTA regression has WDL power of -0.25 to -0.3:
- -0.25 exponent predicts that a 2X wavelength change yields a 15% cost reduction

-0.5 factor is consistent with published data (Meinel – optical to radio):
- 10X cost decrease for increasing WDL from 1 μm to 0.1 mm
- 1000X decrease for increasing WDL from 1 μm to 1 meter.

Cost Reduction vs WDL Model				
WDL	-0.3	-0.5	-0.7	Meinel
1 μm	na	na	na	na
0.1 mm	4	10	25	10X
1 meter	63	1000	15849	1000X

Cost as a function of Year of Development

FACT: more recent telescopes tend to cost less than older telescopes because of technology advances.

Our analysis indicates this reduction to be ~ $e^{-0.04(Y)}$

Horak published the reduction to be ~ $e^{-0.033(Y)}$

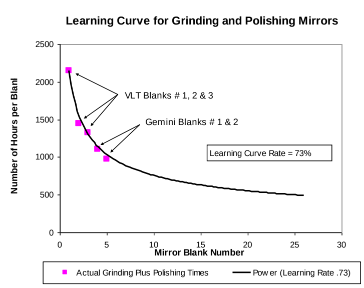
A 4% reduction is cost per year from technology development implies that cost should reduce by 50% every 17 years.

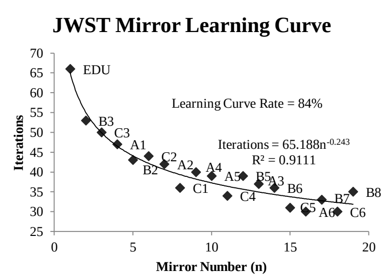
A 3.3% reduction implies a 50% reduction every 21 years.

Segmentation Factor

Segmentation Factor captures the cost reduction from 'learning'

- REOSC had ~ 73% learning curve for VLT & Gemini primary mirrors.
- JWST had ~ 84% learning curve.





Segmentation Factor

But, Segmentation Cost Model does not yield good JWST estimate.

It is missing something:

- Impact of increased Complexity of Segmented vs Monolithic
- Need to design and make a full size support structure
- Beryllium is 2X harder to fabricate than Glass
- JWST is 10X lower Aeral Density than HST
- Horak's Model has Scale Factors for Materials, Off-Axis and % Lightweighting.

Cost Model Prediction Hubble versus JWST					
Parameter	HST	JWST	Ratio	$D^{1.8} \lambda^{-0.5} T^{-0.25} e^{-0.033Y}$	$\#S^{0.7} D_s^{1.7} \lambda^{-0.5} T^{-0.25} e^{-0.033Y}$
Diameter	2.4	6.5	2.7X	6X	
Segments	1	18+spare	19X		8X
Seg Dia	2.4	1.5	0.6X		0.4X
Wavelength	0.5	2	4X	0.5X	0.5
Temperature	300	30	0.1X	2X	2X
Year of Dev	1977	2006	29	0.4X	0.4X
Total	~ \$0.5B	~ \$1.2B	2.4X	2.4X	1.2X
Estimate				\$1.2B	\$0.6B

Conclusions

Findings

Programmatically

- Largest Mission Cost drivers are Spacecraft & Instruments
- OTA cost is 10% to 15% of Total Mission Cost
- I&T cost is 10% to 25% of Total Mission Cost

Engineering OTA cost drivers are similar for Ground & Space

- Larger Diameter OTAs cost more than Smaller.
  - But Larger Diameter cost less per square meter of Collecting Aperture.
- UVO Wavelength OTAs cost more than IR OTAs.
- Cryogenic Temperature OTAs cost more than Ambient Temperature OTAs.
- Technology Advance reduces cost ~ 50% about every 20 years.
- If all parameters are held constant, adding Mass reduces cost.

Mass is NOT a good Cost Estimating Relationship

Multi-Variable Cost Models

Space OTA:

Two variable model using Wavelength Diffraction Limit explains 98% of data variation with a low SPE.

$$\textbf{OTA Cost} \sim \$100\text{M Dia}^{1.6}\ \lambda^{-0.25}$$ *(N = 12, r^2 = 98%; SPE= 60%)*

Three variable model using Wavelength & Temperature:

$$\textbf{OTA Cost} \sim \$100\text{M } D^{1.7}\ \lambda^{-0.3}\ T^{-0.25}$$ *(N = 11, r^2 = 96%; SPE= 54%)*

Ground OTA:

$$\textbf{OTA Cost} \sim \$1\text{M SF}^{0.7}\ D^{1.7}\ \lambda^{-0.5}\ e^{-0.04(YOD - 1960)}$$

Telescope Cost Model

Potential 'generic' model (combination of Ground and Space):

OTA Cost ~ (A) SF $^{0.7}$ D $^{(1.65 \pm 0.05)}$ $\lambda^{(-0.5 \pm 0.2)}$ $T^{-0.25}$ e $^{(-0.035 \pm 0.05)\,Y}$

OTA Cost in Millions of FY2000$

A =	**$1M**	**Ground**
	$100M	**Space**
D =	**Primary Mirror Diameter (meters)**	
λ =	**Wavelength Diffraction Limited (microns)**	
Y =	**Year of Development – 2000**	
SF =	**(#of Segments)$^{0.7}$ (Ds/D)$^{1.7}$**	

Note: SF fits the data but is not very predictive. Is missing something, probably difficulty of making the backplane.

Testing the Model

Using Hubble as a point of reference, it is possible to test models by predicting JWST's OTA cost.

The best prediction combines elements from Space (T), Ground (D and λ) & Historical Models (3.3% Y).

Cost Model Prediction Hubble versus JWST

Parameter	HST	JWST	Ratio	$D^{1.4}$	$D^{1.6}\ \lambda^{-0.25}$	$D^{1.7}\ \lambda^{-0.3}\ T^{-0.25}$	$D^{1.8}\ \lambda^{-0.5}\ T^{-0.25}\ e^{-0.033Y}$
Diameter	2.4	6.5	2.7X	4X	5X	5.4X	6X
Wavelength	0.5	2	4X	-	0.7X	0.66X	0.5X
Temperature	300	30	0.1X	-	-	1.8X	2X
Year of Dev	1977	2006	29	-	-	-	0.4X
Total	~ $0.5B	~ $1.2B	2.4X	4X	3.5X	6.4X	2.4X
Estimate				$2B	$1.75B	$3.2B	$1.2B

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BACKUP

Total Mission Cost Models

Mission Cost

Assume that we have a viable cost model for OTAs, the next step is models for estimating Mission Cost.

Question is whether it is better to develop a model for Total Cost, or (Total – OTA) Cost.

Regressing the two costs as a function of variables

- No statistical difference in the coefficients
- (Total-OTA) is less noisy.

Will use (Total – OTA) which assume a cost model of the form:

Mission Cost ~ OTA Cost + Other Costs

Need to remember that OTA Cost is only approx 10% of Mission Cost

Total Mission Cost Regression

For 29 normal incidence, ‘free-flying’, significant variables are:

- System Focal Length and Diameter – relates to Volume
- Total Mass and Total Power
- Design Life – relates to reliability; but the coefficient is small
- Design Period is obvious – the longer the program, the more it costs

rev. 8.8.11		Total Cost vs V1																	
Variable Name		Aperture Diameter		System F Len.		FOV		Pointing Stability		Total Mass		Total Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.	
Var.	p-value	0.53	0.00	0.55	0.00	0.04	0.72	-0.46	0.02	0.93	0.00	-0.15	0.14	0.02	0.63	-0.01	0.92	-0.03	0.82
Adjusted r^2		0.40		0.89		-0.05		0.25		0.55		0.05		-0.04		-0.05		-0.03	
SPE		126%		90%		195%		162%		60%		237%		317%		341%		310%	
n		29		20		22		11		27		27		28		19		27	

Variable Name		Total Avg. Input Power		Data Rate		Design Life (exp)		TRL		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)		Orbit	
Var.	p-value	0.40	0.02	-0.01	0.91	0.01	0.00	-1.03	0.30	-0.01	0.54	0.03	0.00	0.01	0.79	0.13	0.01
Adjusted r^2		0.25		-0.03		0.73		0.18		-0.04		0.90		0.01		0.01	
SPE		203%		300%		115%		242%		344%		102%		298%		283%	
n		27		24		27		8		26		24		27		23	

(Total Mission – OTA) Cost Regression

Regressing on 23 'free-flying' with Total & OTA cost data:

- System Focal Length and Diameter – relates to Volume
- Total Mass and Total Power
- Design Life – relates to reliability; but the coefficient is small
- Design Period is obvious – the longer the program, the more it costs

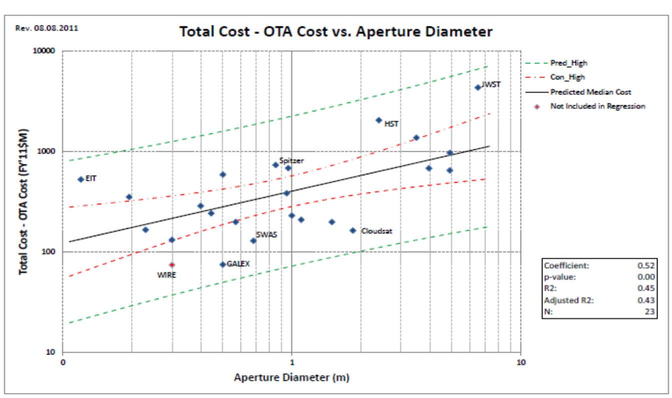
rev. 8.8.11	Total Cost - OTA Cost vs V1								
Variable Name	Aperture Diameter	System F Len.	FOV	Pointing Stability	Total Mass	Total Areal Density	Spectral Range minimum	Diff. Lim. λ	Operating Temp.
Var.	0.52	0.48	-0.21	-0.38	0.86	-0.11	0.00	-0.02	-0.06
p-value	0.00	0.01	0.31	0.05	0.00	0.36	0.92	0.83	0.74
Adjusted r^2	0.42	0.86	0.12	0.22	0.55	0.03	-0.04	-0.06	-0.04
SPE	119%	85%	126%	152%	58%	206%	247%	267%	249%
n	23	16	16	10	21	21	22	15	21

Variable Name	Total Avg. Input Power	Data Rate	Design Life (exp)	TRL	Year of Dev. (exp)	Dev. Period (exp)	Date of Launch (exp)	Orbit
Var.	0.34	0.01	0.01	-0.90	-0.01	0.02	0.00	0.10
p-value	0.04	0.83	0.00	0.43	0.64	0.00	0.87	0.06
Adjusted r^2	0.23	-0.03	0.71	0.04	-0.05	0.89	0.00	-0.01
SPE	172%	216%	103%	222%	274%	104%	247%	245%
n	21	18	21	6	20	18	21	18

(Total – OTA) Cost vs Diameter

Mission Cost increases with aperture because larger telescope require larger spacecraft, power, communications, etc:

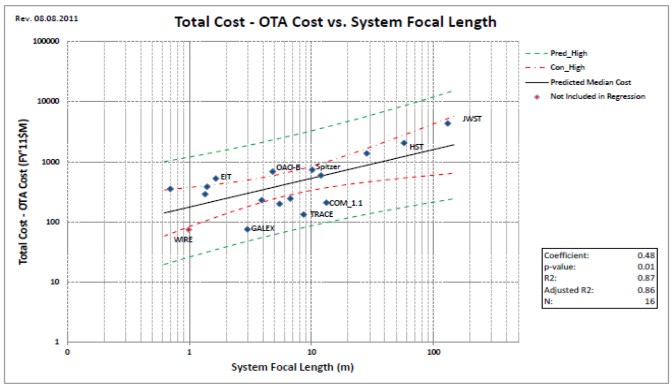
(Total – OTA) Cost ~ Dia $^{0.5}$ *(N = 23; r^2 = 45%; SPE = 119%)*



(Total – OTA) Cost vs System Focal Length

Mission Cost increases with system focal length because FL indicates total Mission Volume and larger Payloads require larger spacecraft, power, communications, etc:

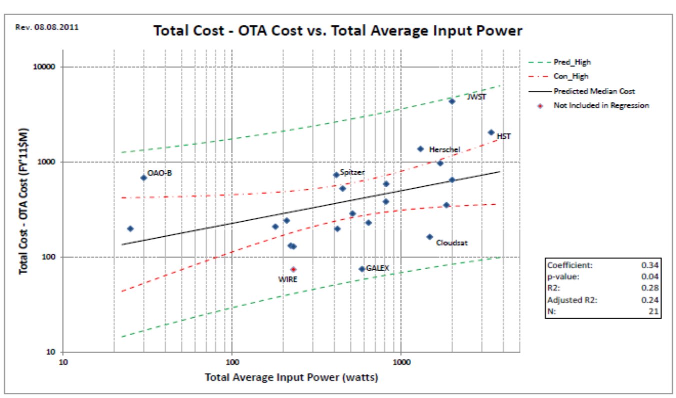
(Total – OTA) Cost ~ SFL $^{0.5}$ ***(N = 16; r^2 = 87%; SPE = 85%)***



(Total – OTA) Cost vs Power

Mission Cost increases with Average Power requirement:

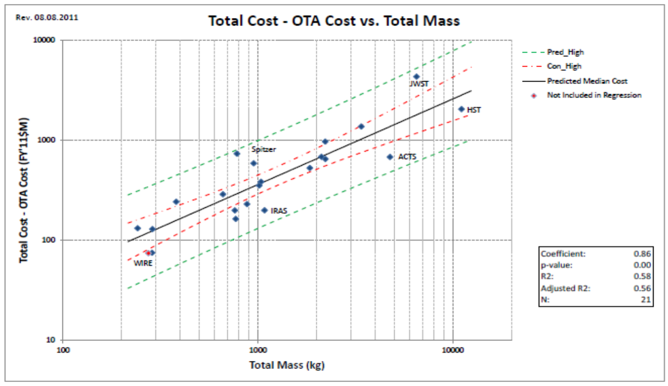
(Total – OTA) Cost ~ Power $^{0.3}$ ***(N = 23; r^2 = 28%; SPE = 173%)***



(Total – OTA) Cost vs Mass

Mission Cost increases with Mass because bigger missions are more expensive than smaller missions and bigger missions are more expensive than smaller missions:

(Total – OTA) Cost ~ Mass $^{0.9}$ ***(N = 21; r^2 = 58%; SPE = 58%)***



Total Mission Cost Regression

Regressing on the 33 normal incidence, ‘free-flying’ UVOIR:

Total Mass is significant & has good R^2_{adj} and lowest SPE

Total Cost ~ Total Mass $^{1.1}$ ***(N = 31; r^2 = 74%; SPE = 93%)***

Diameter and System Focal Length which relates to ‘Volume’ are significant
Design Life is also significant

rev. 8.1.11		Total Cost vs V1																
Variable Name		Aperture Diameter		System F Len.		FOV		Pointing Stability		Total Mass		Total Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.
Var.	p-value	0.89	0.00	0.59	0.01	0.13	0.52	-0.49	0.01	1.08	0.00	-0.39	0.00	0.06	0.26	-0.02	0.83	-0.15	0.54
Adjusted r^2		44%		84%		-4%		32%		74%		5%		-3%		-3%		-3%	
SPE		204%		142%		478%		159%		93%		345%		437%		374%		456%	
n		33		22		25		11		31		31		31		19		31	

Variable Name		Total Avg. Input Power		Data Rate		Design Life (exp)		TRL		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)		Orbit	
Var.	p-value	0.74	0.00	0.02	0.80	0.01	0.06	-1.25	0.23	-0.02	0.45	0.03	0.00	0.00	0.87	0.12	0.02
Adjusted r^2		46%		-3%		67%		25%		-3%		69%		-2%		-1%	
SPE		378%		436%		167%		276%		365%		134%		329%		398%	
n		31		28		30		9		27		26		29		24	

(Total Mission – OTA) Cost Regression

Regressing on 13 ‘free-flying’ UVOIR with Total & OTA cost data:

Total Mass is significant & has good R^2_{adj} and best SPE

(Total – OTA) Cost ~ Total Mass $^{1.1}$ ***(N = 12; r^2 = 82%; SPE = 60%)***

Diameter and System Focal Length which relates to ‘Volume’ are significant
Design Life which relates to ‘Reliability’ is significant

rev. 8.1.11		Total Cost - OTA Cost vs V1																	
Variable Name		Aperture Diameter		System F Len.		FOV		Pointing Stability		Total Mass		Total Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.	
Var.	p-value	1.04	0.01	0.68	0.00	-0.26	0.33	-0.40	0.15	1.09	0.00	-0.32	0.36	-0.05	0.63	-0.03	0.86	-0.01	0.97
Adjusted r^2		63%		87%		20%		17%		82%		8%		-1%		-5%		-8%	
SPE		103%		81%		171%		157%		60%		247%		257%		212%		290%	
n		13		11		11		7		12		12		13		10		13	

Variable Name		Total Avg. Input Power		Data Rate		Design Life (exp)		TRL		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)		Orbit	
Var.	p-value	0.35	0.13	0.04	0.55	0.01	0.01	-1.09	0.58	-0.01	0.75	0.03	0.00	0.01	0.85	0.10	0.20
Adjusted r^2		38%		-6%		90%		-9%		-9%		58%		-8%		-9%	
SPE		170%		213%		108%		306%		275%		114%		285%		317%	
n		13		11		13		4		12		11		13		12	

BACKUP

Historical Models

Historical Perspective: Diameter Models

Historically, parametric cost models for ground telescopes estimate cost as a function of primary mirror diameter.

Cost ~ Diameter $^{3.0}$	Steinbach, 1965
Cost ~ Diameter $^{2.75}$	Meinel, 2004
Cost ~ Diameter $^{2.7}$	Whitford, 1964; Beley, 2000; Stepp, 2002
Cost ~ Diameter $^{2.6}$	Lena, 1986; Lesh, 1986; Schmidt-Kaler, Rucks, 1997
Cost ~ Diameter $^{2.5}$	Meinel, 1981
Cost ~ Diameter $^{2.0}$	Meinel, 1979
Cost ~ Diameter $^{1.7**}$	Schmidt-Kaler, 1992 **modular telescopes with thin/lightweight main mirrors

Potential explanations for range of scaling factor:

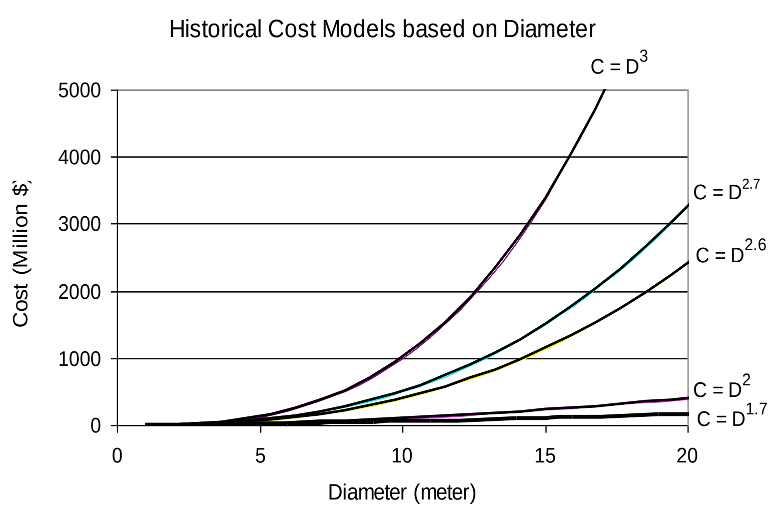
- Difference between OTA, telescope or observatory cost.
- Year of development.

A power of 2.7 for observatory cost could be consistent with Humphries

- Cost ~ K0 + K1*Diameter + K2*Diameter^2 + K3*Diameter^3+ K4*Diameter^4 + …,
- Where building costs increase to the 3rd power of diameter.

Our Model indicates OTA cost varies ~ \$2M Diameter$^{1.4}$

Scale Factor is important for Affordability of Large Diameter Telescopes



Historical Perspective: Technology Advances

Architectural and Technological Advances for Reducing Cost

- Thin and/or Lightweight Mirrors = Mounts and Buildings
- Ability to Fabrication and Polish Faster Mirrors = Smaller Buildings
- Alt-azimuth Mounts = Smaller Buildings
- Segmented Mirrors
- Multiple Telescope Arrays

Cost modeling allows testing the impact of these design concepts.

Areal density is often considered an important cost driver,

- Meinel claimed that a mass to cost scaling law with a 3.0 power slope
  - This claim has actually driven technology investments for Space Telescopes
- But this study finds that it is not significant for ground telescope OTAs.
  - Perhaps because modern OTA's are better optimized for mass

Models with no statistical support

Any Parametric Model developed to describe ground based telescopes should not be used to estimate space telescopes.

- Particularly models including dome costs which have an exponent of 2.7

Models based on Intuition

- "Space telescopes are intrinsically 2 orders of magnitude more expensive for a given aperture than are terrestrial ones" , Meinel & Meinel (1986)
- "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." Bellea & Meinel (2004)
- 'expectation that the scaling law for space-based telescopes is close to $D^{2.0}$ …. Based on 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.' Bellea & Meinel (2004)

Horak Models

Horak Model (1993, 1994) is the most detailed and best documented of the historical models.

Model estimated total cost of IR sensor payloads operating in geosynchronous and non-geosynchronous orbits or on aircrafts.

Database consisted of 17 strategic and experimental IR sensors.

7 CERs developed including for OTA & IA&T.

- Horak database is Air Force centric; Ours is NASA centric

Horak Model

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

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 curved 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

Bely Model

Bely (2000) published a model which was cited as coming from Horak.

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

But as one can see, the D exponent is different and the Wavelength exponent is off by an order of magnitude.

Horak's coefficient yields a 33% cost reduction with 10X wavelength increase.

Bely's coefficient yields a 98% cost reduction, clearly wrong.

Smart Model

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

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

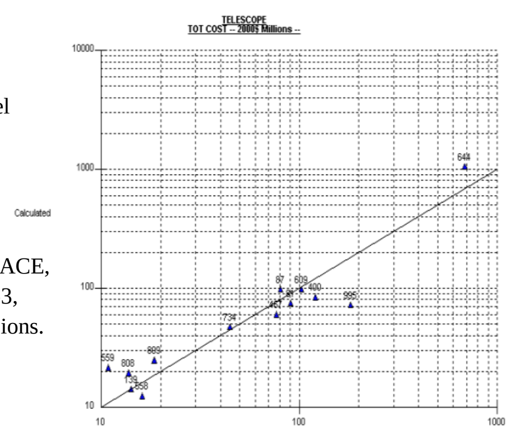
Where:

- 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.

R^2 = 89%



Planning Research Corp 1985 Model

Telescopes for unmanned and manned spacecraft:

For all space telescopes in database (UV, visible, IR):

- Design and Development Cost is proportional to $D^{0.276}$,
- Flight Unit Cost is proportional to $D^{0.286}$, and
- Flight Unit cost is approximately 33% of D&D cost.

For just the infrared telescopes in database

- Design and Development Cost is proportional to $D^{0.4782}$,
- Flight Unit Cost is proportional to $D^{0.5576}$, and
- Flight Unit Cost is approximately 25% of D&D cost.

R^2= 58%, i.e. estimates only 58% of total space telescope cost.

Wong Model, 1991

Summary of Wong Model Unmanned Spacecraft Sensor CERs					
Payload	Range	RDT&E	Error	TFU	Error
IR Sensor	0.2 to 1.2 m	$3.07\ D^{0.562}$	± 0.46	$1.23\ D^{0.562}$	± 0.18
Visible Sensor	0.2 to 1.2 m	$1.11\ D^{0.562}$	± 0.17	$0.44\ D^{0.562}$	± 0.07
GSE		11% (RDT&E + TFU)	± 0.05		
Programmatic		36% Hardware	± 0.08	33% Hardware	± 0.03

TFU = Theoretical First Unit (TFU) Cost is approximately 40% of RDT&E Cost
IR Systems cost 2.77X more than Visible Systems.

Additional interesting information:

- GSE 'wrap' = 11% of the RTD&E and TFU cost,
- Program Support 'wrap' = 36% of the hardware cost.
- Inserting new technology into a program increases RDT&E and TFU cost by 25% to 100%.
- Reuse of heritage technology requiring only moderate modifications can reduce RTD&E cost by 40% to 60%.
- Reuse of an existing design can reduce RTD&E cost by 70% to 90%.
- RTD&E cost for commercial space systems is only 80% as much as government spacecraft, because of Government Oversight.

Mass Models

In the space industry, mass has been found to be a key cost driver. Thus, the original NASA Air Force Cost Model (NAFCOM) estimated space mission cost based on mass.

Since 2002, NAFCOM has incorporated CERs of heritage, technology readiness, and other technical and programmatic parameters. However, NAFCOM still estimates space telescope cost based only on mass.

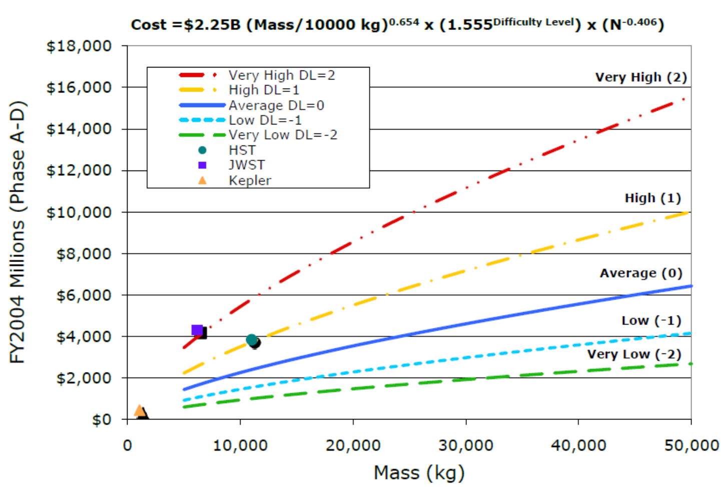
An example of cost versus mass model is the JSC Advanced Missions Cost Model for Physics and Astronomy Spacecraft Missions:

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

Where:	Cost is in 2004 $		
	N	= number of flight systems	
		= 2	Very High
		= 1	High
	Difficulty Level	= 0	Average
		= -1	Low
		= -2	Very Low

NASA JSC OTE Mass Model

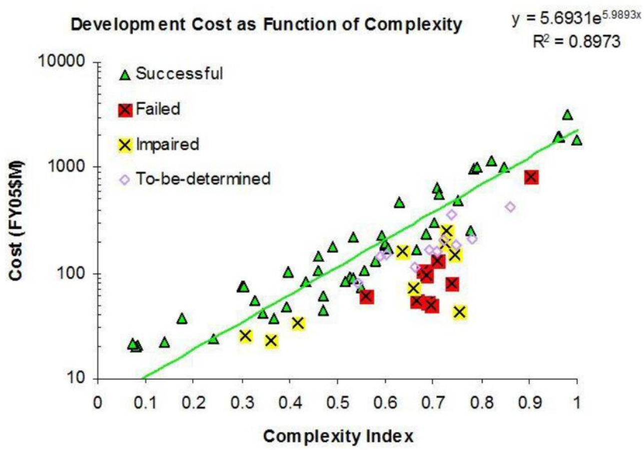
While most may view the JSC Model as asserting that mass is the most important driver of OTA Cost, a careful inspection clearly shows that Difficulty is a more significant driver of cost.



HST is nearly 2X more massive than JWST yet less expensive, because it is less Difficult.

Cost vs Complexity

Aerospace (Beardon et. al.) has published a direct correlation between payload complexity and cost & schedule growth.



Cost vs Complexity

Complexity Index

Aerospace maintains a Complexity Based Risk Assessment (CoBRA) model that can be used to assess the reasonableness of cost and schedule of a mission based on its "complexity index," which is essentially a representation of the technical and programmatic characteristics of a mission. JWST is considered to be one of the most complex science missions carried out to date and therefore falls at the high end of the range, greater than 90%, on the complexity index. JWST is consistent with being "in family" for an LCC around $6 billion–$7 billion (see Figure A.2). Like the historical growth analysis above, this should be considered a cross-check on the potential mission cost rather than an independent cost estimate.

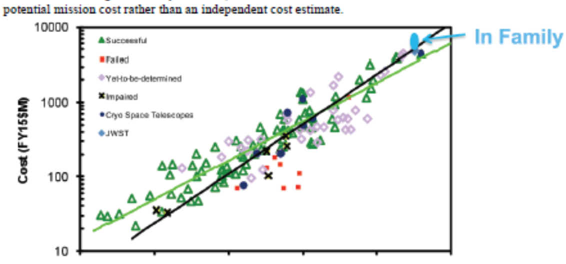


Figure A.2 Cost vs. complexity index for various missions.

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Summary of Historical Models

There is no definitive published OTA Cost Model for Space Telescopes.

- Some models are based on aperture diameter and others on mass.
- Aperture diameter scaling factor ranges from 2.7 (Meinel) to 0.27 (PRC).

Relevance of any model is depends on its data base.

Prior authors are in universal agreement that the more complex the design, the more difficult it will be to build and the more it will cost.

Predictions of historical models:

- Cost to develop a mission ranges from 1.25X to 4X cost of flight hardware
- IR ranges from either 33% less expensive to 3X more expensive than visible
- Cost drops 50% every 20 years.
- 30K OTA costs 1.5X a 300K OTA; 4K telescope costs 3X a 300K OTA.

BACKUP

Mass Models

Mass Model

Many believe that Mass is the most important CER.

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.

Such as light-weighting mirrors and structure.

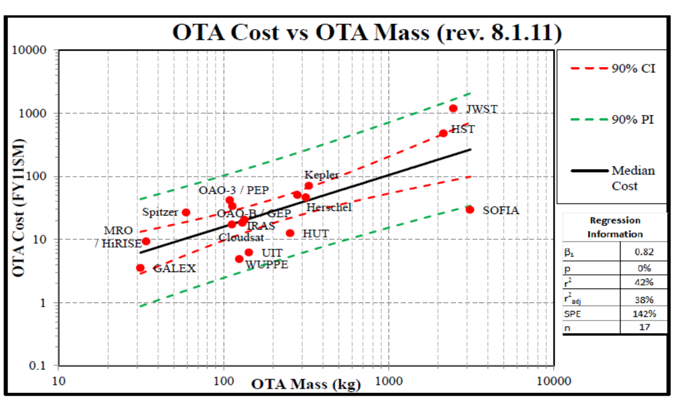
<u>Space telescopes are designed to mass</u>

OTA Cost Mass Model #1

Regressing on all OTAs in the data base:

OTA Cost ~ OTA Mass $^{0.8}$ ***(N = 17; r^2 = 42%; SPE = 142%)***

Mass accounts for only 42% of the cost variation & is noisy

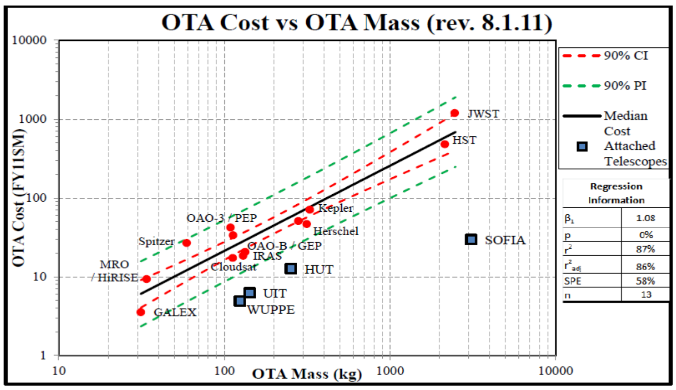


OTA Cost Mass Model #2

Regressing on only Free-Flyer (excluding ‘attached’ and SOFIA):

OTA Cost ~ OTA Mass $^{1.1}$ ***(N = 13; r^2 = 87%; SPE = 58%)***

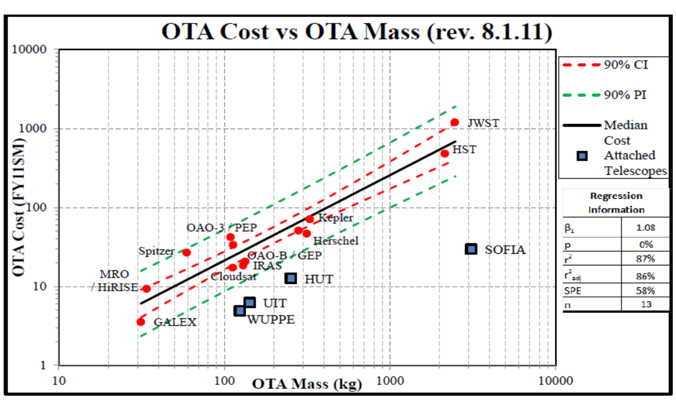
Mass accounts for 87% of the cost variation with less noise.



OTA Cost Mass Model #2

The 3 ‘attached’ missions & SOFIA clearly are a different ‘class’

They have a different set of design rules which allow them to have a lower cost for a given mass.

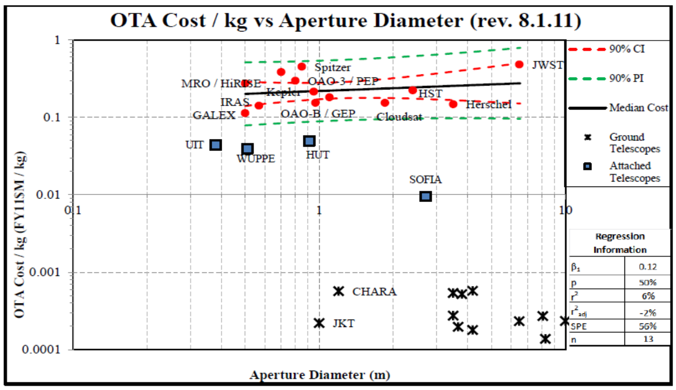


OTA Cost Density

It costs more to design & build a low mass OTA than a high mass OTA

Cost per kg depends on mission 'type'; is independent of aperture size

- Free-Flying OTAs are ~2X more expensive per kg than Attached OTAs
- Free-Flying OTAs are ~15X more expensive per kg than SOFIA
- Free-Flying OTAs are 1000X more expensive per kg than Ground

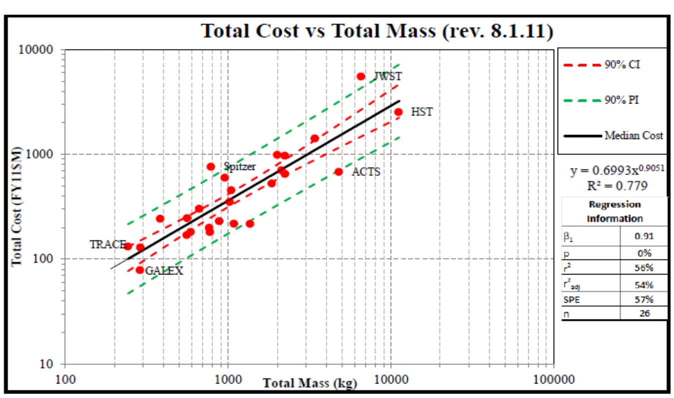


Mission Total Cost Mass Model

Regressing on only Free-Flyer (excluding 'attached' and SOFIA):

Total Cost ~ Total Mass $^{0.9}$ ***(N = 26; r^2 = 56%; SPE = 57%)***

Mass accounts for 56% of the Total Mission cost variation.

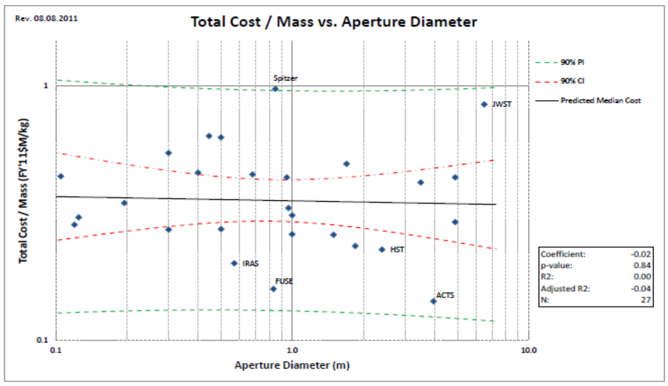


Total Mission Cost Density

Similar to OTA, all Space Mission have the same Cost/kg

Implies that all space missions have the same design rules.

Also, supports use of Mass Models



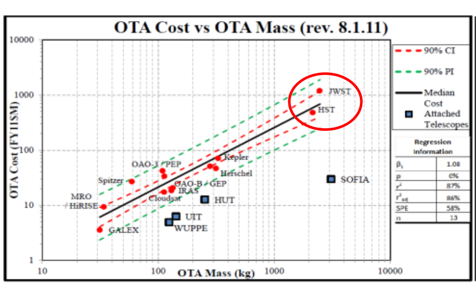
Mass is not a Good CER

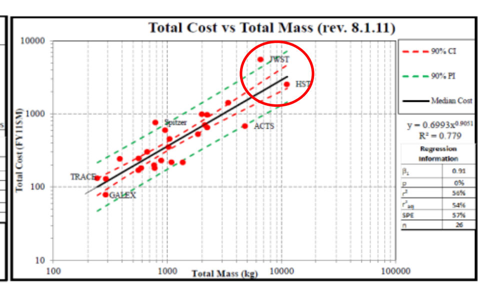
It may appear that Mass is a good CER, but it is not.

JWST & HST have same OTA mass, but JWST OTA costs is 2X HST

HST Total mass is 2X JWST, but JWST Total cost is 2X HST

The reason is complexity – JWST is more complex than HST





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 and Pointing

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