

Update on parametric cost models for space telescopes

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Since the June 2010 Astronomy Conference, an independent review of our cost data base discovered some inaccuracies and inconsistencies which can modify our previously reported results. This paper will review changes to the data base, our confidence in those changes and their effect on various parametric cost models.

Update on parametric cost models for space telescopes

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ABSTRACT

Parametric cost models are used to plan missions, compare concepts and justify technology investments. This paper updates an on-going effort to develop cost models for space telescopes and summarizes how recent database changes have changed previously published preliminary results. While the models are evolving, the previously published findings are valid: telescope cost increases with aperture diameter; it costs less per square meter of collecting aperture to build a large telescope than a small telescope; lower areal density telescopes cost more than more massive telescopes.

Keywords: Space Telescope Cost Model, Parametric Cost Model

1. INTRODUCTION

Parametric cost models for space telescopes provide several benefits to designers and space system project managers. They identify major architectural cost drivers and allow high-level design trades. They enable cost-benefit analysis for technology development investment. And, they provide a basis for estimating total project cost. A survey of historical models found that there was no definitive space telescope cost model [1]. Thus, there is a need for parametric space telescopes cost models. An effort is underway to develop single variable [2] and multi-variable [3] parametric space telescope cost models based on the latest available data and applying rigorous analytical techniques.

After the single and multi-variable parametric models were published, the data base underwent an independent review. The result of that review found several data points to be incorrect. As a result, the data base has undergone a complete review: some telescopes were removed from the analysis; data for other telescopes was revised; and new telescopes were added to the data base. As a result of these changes, the cost models have changed. But the general findings remain unchanged: aperture diameter is the primary cost driver for large space telescopes; it costs less per square meter of collecting aperture to build a large telescope than a small telescope; and it costs more per kg to build a low areal density telescope than a massive telescope. One significant difference is that telescope cost is approximately 10% of total mission cost instead of 30%.

2. CHANGES TO THE DATABASE

In Sept 2010, the NRO Cost Model Office reviewed our data base and, while they did not provide us with access to their database or give us any specific data, they did identify specific missions where our databases disagreed. In response, we have systematically reviewed all missions in our database. And, as a result, some missions have been temporarily removed from the database, while others have been revised (ranging from slight to dramatic). Additionally, during the past year we have added several new missions to the database. The key to cost modeling is the data base. And the key to the data base is being very precise in all definitions.

Optical Telescope Assembly (OTA) is defined as the subsystem which collects electromagnetic radiation and focuses it (focal) or concentrates it (afocal) into the science instruments. An OTA consists of the primary mirror, secondary mirror, auxiliary optics and support structure (such as optical bench or truss structure, primary support structure, secondary support structure or spiders, mechanisms for adjusting the optical components, straylight baffles, etc.). An OTA does not include science instruments or spacecraft subsystems. A science instrument (SI) is defined as the subsystem which converts electromagnetic radiation into data. A SI includes conditioning optics (e.g. beam splitters, re-imaging optics, spectral filters, dispersive elements, etc.), mechanisms, detectors, focal planes, and electronics.

Consistency with this definition is exactly the problem with the old data base. While the cost data for large missions (Hubble, Kepler, JWST, etc.) were clearly for just the OTA, the cost data for the smaller missions (GALEX, IUE, TRACE and WIRE) were for 'instruments' where an instrument was defined to be an integrated system consisting of an OTA and a SI. Removing the science instrument costs dramatically reduced the OTA cost for these missions.

Additionally, we have chosen to exclude thermal/cryogenic control systems from the definition of an OTA. For example, the JWST OTA does not include the cost of the JWST Sunshade. Conforming to this definition resulted in another change to the database. The 'old' IRAS and Spitzer OTA costs included the cryogenic system. Removing these costs dramatically changed the old data points. Please note, in the future, we plan to review this decision. It does not seem logical that an infrared OTA has much utility without a thermal/cryogenic control system. And, while it is a small cost element, ambient OTAs also require thermal control systems.

OTA Cost is defined as prime contractor cost to design, build and integrate the OTA. OTA cost includes allocated subsystem level management and systems engineering as well as program level costs which can be allocated to the subsystem. OTA cost does include NASA labor if NASA personnel participated in these functions, as in the case of the OAO telescopes. But OTA cost does not include NASA labor if that labor is strictly insight/oversight, as in the case of JWST, Hubble, Kepler, etc. Total mission cost is defined as Phase A-D, excluding: launch cost; costs associated with NASA labor (civil servant or support contractors) for program management, technical insight/oversight; or any NASA provided ground support equipment, e.g. test facilities. Including NASA costs would add at least 10% and maybe as much as 33%.

After careful review of source CADRe Documents (Cost Analysis Data Requirements), we made the following changes to the database. We increased the cost of Kepler and Wise to include program management, systems engineering and integration and test cost. We decreased the cost of GALEX, HiRISE, HUT, OAO-3, UIT, WIRE, and WUPPE to remove science instrument costs. We decreased the cost of IRAS and Spitzer by separating cryostat and OTA cost. We decreased the cost of SOFIA by removing the cost of the gimbal structure which holds the SOFIA OTA in the 747 airframe. We added cost data for the CloudSAT, OAO-B/GEP, Herschel and Planck missions. Finally, we reduced the cost of both Hubble OTA and Total Missions costs (Table 1). Previously, we had excluded the cost of the fine guidance sensor (FGS) from the OTA cost, because we believe that this cost should be allocated to the spacecraft. But we had not properly excluded management and systems engineering costs allocated to the FGS. Also, our previous Total Mission cost probably included Phase E operations costs.

Table 1: Refinement of Hubble Cost Knowledge			
Cost Element	Old (FY11\$)	Revised (FY11\$)	Notes
Total Cost Phase A-D	\$ 4.0 B	\$2.8 B	Old: NGST Cost Model Database
Total OTA	\$ 0.9 B	\$ 0.9 B	
OTA	\$ 0.7 B	\$ 0.47 B	Old: allocated FGS and C&DH PM & SE costs to OTA
<i>Optics</i>		\$ 0.07 B	New: REDSTAR 121-4742
<i>Optics Control</i>		\$ 0.08 B	
<i>Optical Structure</i>		\$ 0.08 B	
<i>Electrical Power</i>		\$ 0.02 B	
<i>Structures, mechanisms, support equipment</i>		\$ 0.05 B	
<i>System Level 53%</i>		\$ 0.14 B	
<i>ST Level 53%</i>		\$ 0.01 B	
FGS	\$ 0.2	\$ 0.26 B	New: REDSTAR 121-4742
C&DH		\$ 0.08 B	New: REDSTAR 121-4742
Thermal Control		\$ 0.01 B	New: REDSTAR 121-4742
System Level 47%		\$ 0.12 B	New: REDSTAR 121-4742
ST Level 47%		\$ 0.01 B	New: REDSTAR 121-4742
Total SSM		\$1.14 B	New: REDSTAR 121-4742
Science Instruments		\$0.5 B	New: REDSTAR 123-1064 (page 108)
ESA Contribution		\$0.25 B	New: REDSTAR 123-1064 (page 108)
Total Cost Phase A-E	\$ 5.1 B	\$ 4.6 B	Old: NGST Cost Model
Launch		\$0.62 B	New: REDSTAR 123-1064 (page 108)
Phase E		\$ 1.2 B	New: REDSTAR 123-1064 (Page 108 & 122)

Note: Totals may not tie due to rounding

The effect of all the database changes is illustrated in Figure 1. Previously, the ratio of OTA Cost to Total Mission cost was spread from a few percent to 65%. The net effect of this spread was to make it appear that on average, the OTA was approximately 20% of total mission cost. But, with the corrections, the small missions now all cluster together with their OTA cost approximately 10% of total mission cost. A careful examination of the data shows that the OTA cost as a percentage of total mission cost increases linearly from a few percent to 25%. It is hypothesized that the cause of this increase is infrastructure and technology reuse. Smaller aperture missions tend to use existing manufacturing and testing infrastructure while larger aperture missions often require the design and fabrication of expensive custom infrastructure. Also, smaller missions tend to have higher reuse of existing designs. Finally, the data implies that for small missions, other major subsystems (such as the spacecraft) are a much larger cost for the total mission than the OTA. In fact, an analysis of detailed WBS documents for 7 missions shows that the spacecraft accounts for approximately 34% of the cost, science instruments account for 28%, OTAs account for 11%, program management and systems engineering accounts for 6% each, integration and test accounts for 4% and the balance is ‘other’.

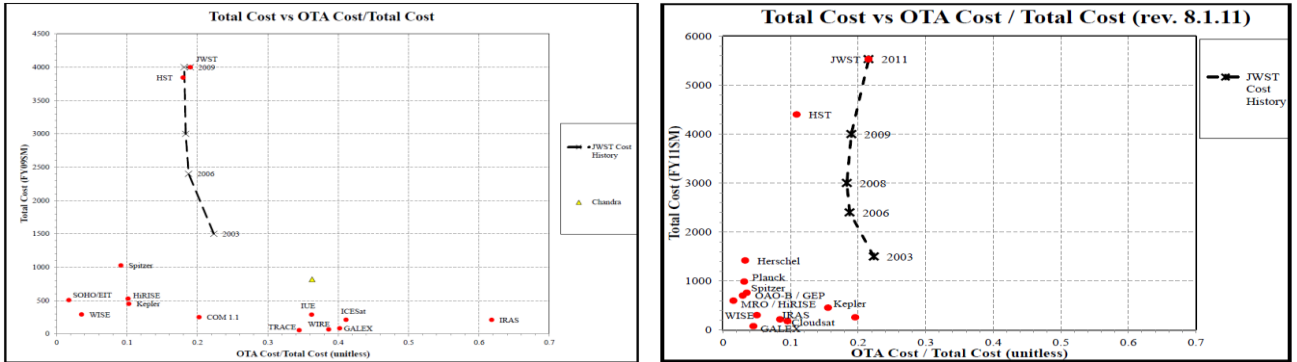


Figure 1: Correcting the database eliminates the data spread; indicates that OTA cost is approximately 10% of total mission cost; and, indicates that percentage varies from a few percent to 25%.

3. METHODOLOGY

Cost and engineering data have been collected on 59 different parameters for 45 x-ray, UV, optical, infrared, microwave and radio space telescopes. But to date, only the 33 normal-incidence UV, Optical, Infrared (UVOIR) missions have been studied for cost modeling. And, of these 33, sufficient data exists for only 20 with which to develop an OTA cost model (Table 2).

Data was collected from multiple sources, including: 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 and Retrieval System), SICM (Scientific Instrument Cost Model), project websites, and interviews.

Table 2: UV/OIR Cost Model Missions Database	
UV/Optical Telescopes	Infrared Telescopes
Cloud SAT	Herschel
Commercial #1	IRAS
Commercial #2	JWST
Copernicus	Planck
GALEX	SOFIA
HiRISE	Spitzer
HST	WIRE
HUT	WISE
Kepler	
OA0-B/GEP	
UIT	
WUPPE	

Statistical correlations are evaluated for select variables. These parameters are used to develop single and multi variable cost estimating relationships (CERs) which are evaluated for their ‘goodness’. The variables are divided between technical (Aperture Diameter, PM Focal Length, System Focal Length, Field of View, Pointing Stability, OTA Mass, Total Mass, Spectral Range Minimum, Wavelength of Diffraction Limit, Operating Temperature, Average Input Power, Data Rate, Design Life, and Orbit) and programmatic (Technology Readiness Level, Year of Development, Development Period, and Launch Year). Additionally, insight is gained by combining independent variables to form collector variables (F/#, Volume, Areal Cost or Cost Density).

Two single variable cost estimating relationships (CERs) are reported in this paper. These CERs estimate OTA cost as a function of OTA diameter and OTA mass. Additionally, two variable and three variable models are reported.

4. SINGLE VARIABLE MODEL

Single variable models are created by regressing OTA cost data versus parameters which are selected based on their correlation with OTA cost (Figure 2). Each regression is then evaluated for its ‘Goodness of Fit’ and ‘Significance’ via a range of statistical measures, including Pearson’s r^2 coefficient, Student T-Test p-value and standard percent error (SPE). Pearson’s r^2 (typically denoted as just r^2) describes the percentage of agreement between the model and the actual cost. For multi-variable models, we use Adjusted Pearson’s r^2 (or r^2_{adj}) which accounts for the number of data points and the number of variables. In general, the closer r^2 (or r^2_{adj}) is to 1.0 or 100%, the better the model. 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. Please note that since SPE is normalized, a small variation divided by a very small parameter coefficient can yield a very large SPE. The p-value is the probability that a fit or correlation would occur if the variables are independent of each other. The closer the p-value is to 0, the more significant the fit or correlation. The closer it 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 it is large, then removing the variable will have a negligible effect. Also, it is important to consider how many data points are included in a given correlation, fit or regression.

rev. 8.1.11		OTA Cost vs VI							
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

Figure 2: Single Variable Regression Analysis for OTA Cost

For the 8.1.11 database, the variables which yield a significant regression for OTA cost are: aperture diameter, primary mirror focal length, OTA volume, pointing stability and OTA mass. Of these, OTA mass has the smallest SPE. While this author does not agree, many cost models only use mass to estimate cost. Therefore, we will investigate a mass model in Section 4.2. All of the other variables are correlated with aperture. All OTAs tend to have similar F/#s. Thus, larger apertures have longer focal lengths and of course larger volumes. Also, pointing stability is proportional to resolution which is defined by aperture diameter. Therefore, in Section 4.1 we will investigate aperture models.

4.1 Single Variable Aperture Model

This section presents aperture model results for the revised database without comparison to the previous results. While the exponent of the model has changed, none of the previous conclusions have changed. From an engineering and a scientific perspective, aperture is the best parameter with which to build a space telescope cost model. Aperture defines the observatory’s science performance (sensitivity and resolution) and determines the payload’s size and mass. Since the aperture exponent is still less than 2, cost increases with Aperture at a rate less than D^2 . Thus larger telescopes cost less per area than smaller telescopes. As shown in Figure 3, for 15 free-flyer missions (excluding WIRE), we obtain the following cost estimating relationship (CER):

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

This model based only on aperture diameter accounts for 82% of the cost variation in the real data, but it is noisy.

As with the previous publications, we are regressing OTA cost versus aperture diameter for only free flying missions. Attached missions continue to have a cost relationship whose slope is parallel to the free flyer cost slope, but whose leading coefficient is lower. The implication is that attached missions, which are more massive than free flying missions, are lower cost. Changes in the database uniformly reduced the cost of small aperture missions, including the attached. Additionally, given doubt about the accuracy of WIRE, we are excluding it from the regression.

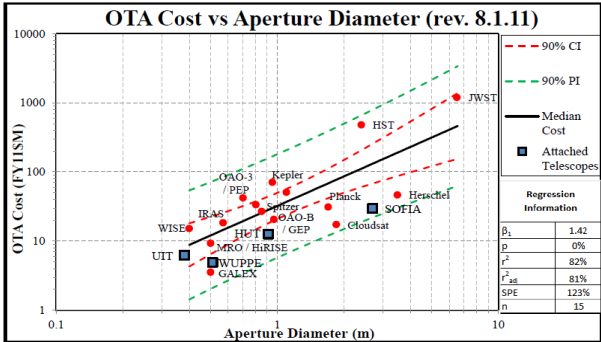


Figure 3: OTA Cost vs Aperture Diameter

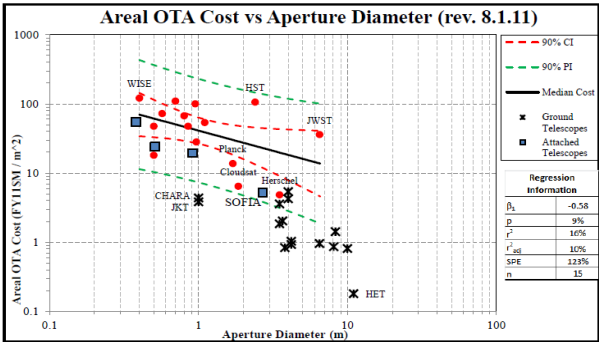


Figure 4: OTA Areal Cost vs Aperture Diameter

One concern about cost versus diameter is that JWST drives the fit. As a simple sanity check, the data was normalized by collecting area to define Areal Cost (cost per square meter) (Figure 4). We have extended this previous analysis to include ground telescopes, and the result is the same. Larger aperture telescopes cost less per square meter than smaller aperture telescopes. Given that the number of collected photons is proportional to collecting area, larger aperture telescopes have a greater return on investment (ROI) than smaller aperture telescopes.

Finally, a regression of mission total cost versus aperture diameter yields a CER of:

$$\text{Total Cost} \sim \text{Diameter}^1 \quad (N = 18; r^2 = 89\%; \text{SPE} = 79)$$

The most interesting result of this regression is that the exponent is 1. Total mission cost as a function of aperture diameter is ‘flatter’ than OTA cost. The implication is that for smaller aperture missions other costs (maybe spacecraft) dominate the mission cost. This is consistent with the earlier finding that OTA cost is only 10% of total mission cost.

4.2 Single Variable Mass Model

This section presents mass model results for the revised database without comparison to the previous results. While the exponent of the model has changed, none of the previous conclusions have changed. Although an aperture based CER is logical for an optical engineer, many believe that Mass is the more important CER. Total system mass determines what vehicle can be used to launch the mission. And, significant engineering costs are expended to keep a given payload inside of its allocated mass budget, for example: light-weighting mirrors and structure. It is factual to assert that space telescopes are designed to meet a specific mass budget. As shown in Figure 5, for 13 free-flyer mission (excluding attached OTAs), we obtain the following CER:

$$\text{OTA Cost} \sim \text{OTA Mass}^{1.1} \quad (N = 13; r^2 = 87\%; \text{SPE} = 58\%)$$

The mass model accounts for 87% of the variation in the real data. And, it is less noisy than the aperture model.

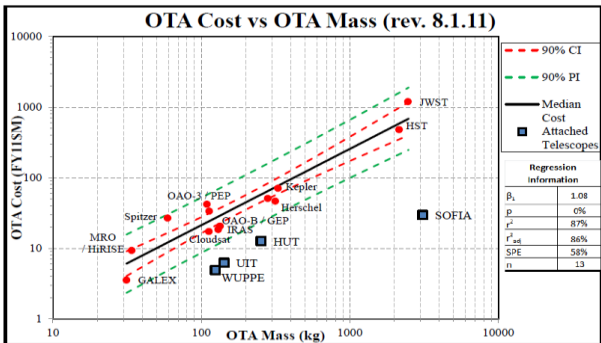


Figure 5: OTA Cost vs OTA Mass

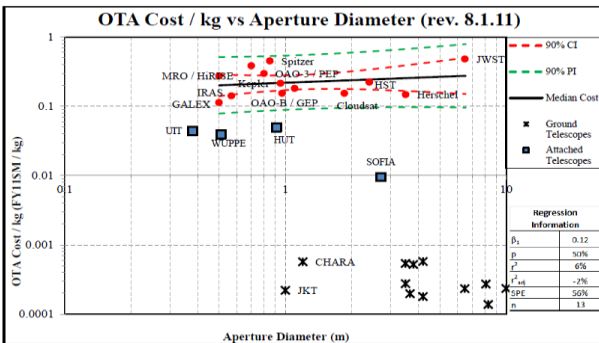


Figure 6: OTA Cost Density vs Aperture Diameter

A very interesting tool for analyzing the role of mass on cost is cost density (cost per kg). Figure 6 plots OTA cost per kg versus OTA aperture diameter. Several obvious conclusions can be drawn from Figure 6. All free flying space telescopes have approximately the same cost per kg – independent of aperture diameter. And, all ground telescopes also have approximately the same cost per kg – independent of aperture diameter. Space telescopes cost about 1000X per kg more than ground telescopes – independent of aperture diameter. Additionally, UIT, WUPPE and HIT which flew ‘attached’ to the space shuttle are 2X less expensive per kg. And, SOFIA which flies attached to a 747 is 15X less expensive. One explanation for this data might be that each of these mission ‘types’ are built to different design rules. While all three types need similar wavefront shape and pointing stabilities as a function of aperture diameter, they have different static gravity and dynamic jitter environments. And, they have different mass budgets with which to achieve the required wavefront shape and pointing stability.

Another wavelength story is Herschel and Kepler (Figure 5). Herschel and Kepler have essentially the same mass and cost, but vastly different apertures, diffraction limits and operating temperatures. Based only on aperture, Herschel should be more expensive than Kepler, but it has a significantly longer diffraction limit and lower operating temperature.

A final caution about using mass as a CER can be found by considering HST vs JWST (Figure 7). When considering OTA mass, HST and JWST OTAs have similar mass and thus should have similar cost, but JWST’s OTA is 2X more expensive than HST. And, when considering total mission mass, HST’s mass is 2X greater than JWST’s mass. Thus, from purely a mass model, HST should cost 2X more than JWST. But in fact JWST is 2X more than HST. The reason is complexity. JWST is more complex than HST.

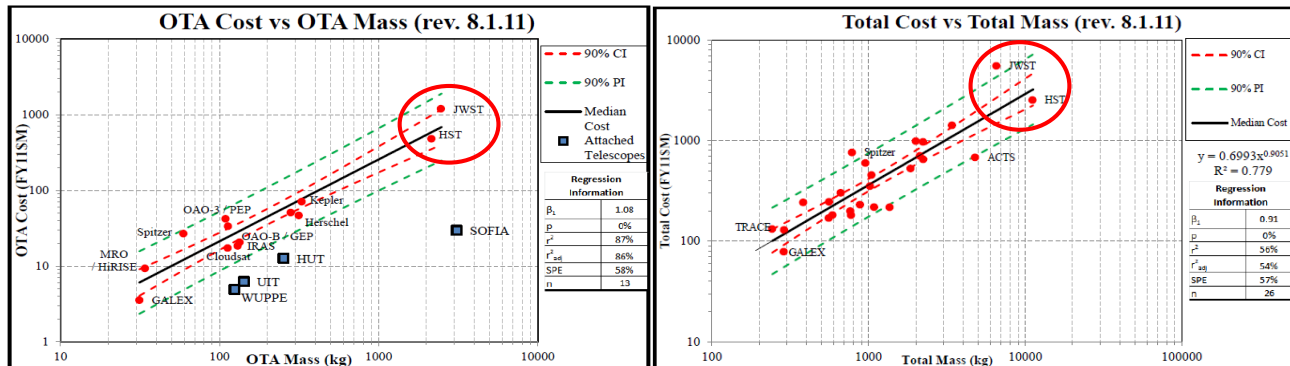


Figure 7: Comparison of OTA Cost vs OTA Mass and Total Cost vs Total Mass

Again, the problem with using mass as a CER for space telescopes is that it is not an independent parameter. It depends on aperture diameter. The bigger the aperture, the more massive the telescope must be to support the mirror, to achieve the required pointing stability, etc. Also, bigger aperture telescopes typically have bigger science instruments, require more power and have bigger spacecraft.

5. MULTI-VARIABLE MODELS

Given that the single variable aperture model accounts for only 82% of the actual OTA cost variation and is somewhat noisy, it is necessary to look at multi-variable models. To develop a multi-variable model, we regress the data for diameter and candidate second variables (Figure 8). A good two variable model is one where the second variable is not collinear with aperture diameter (this excludes OTA mass, Primary Mirror Focal Length and OTA Volume); and, where the addition of a second variable is significant and does not make the aperture variable insignificant. The variables which meet these two conditions are: Area Density, Spectral Minimum, Diffraction Limit and Design Life. Of these, the two variable model with the highest adjusted r^2 and the lowest SPE is Diffraction Limited Wavelength:

$$\text{OTA Cost} \sim \text{OTA Diameter}^{1.5} \lambda^{-0.2} \quad (N = 12; r^2 = 98\%; \text{SPE} = 60\%)$$

It is interesting to note that the Diameter exponent is slightly larger than for the single variable model. This is because for our data set, the larger aperture missions are longer wavelength missions. Thus, the cost increase for a larger aperture is compensated by a cost decrease for a longer diffraction wavelength. The -0.2 exponent on wavelength predicts that a 10X longer wavelength OTA costs 40% less.

This two-variable model is different from our previously published two-variable model. Previously, we had not found a wavelength dependency. And, previously, we had found a year of development dependency. We continue to investigate

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

Figure 8: 2 Variable OTA Cost Regression Summary

year of development as a potential 3rd variable. Additionally, we are finding that operating wavelength is a potential significant 3rd variable – this too is different from our previous results.

Finally, it is interesting to note the regression results for Design Life and also Areal Density. The authors tend to discount the areal density regression for two reasons. First, it should be collinear with aperture - since it is simply mass divided by collecting area. We don't exactly know why the regression does not report it as being collinear, but we observed a similar effect when we used F/# as a second variable. Second, the exponent violates engineering judgment – it implies that a more massive areal density will cost more. The Design Life result is confusing on two counts and requires further study. First, it is unclear why the diameter exponent dropped by such a large amount. And second, the design life exponent implies that a 10 yr mission is only 10% more expensive than a 1 year mission.

6. CONCLUSIONS

Parametric cost models for space telescopes provide several benefits to designers and space system project managers. They identify major architectural cost drivers and allow high-level design trades. They enable cost-benefit analysis for technology development investment. And, they provide a basis for estimating total project cost. Based on an independent review of our database, we undertook a one year careful review and reconciliation of our database with source documents. As a result, there have been changes to our previously published models. But our general findings remain unchanged: aperture diameter is the primary cost driver for large space telescopes; it costs less per square meter of collecting aperture to build a large telescope than a small telescope; and it costs more per kg to build a low areal density telescope than a massive telescope. One significant difference is that telescope cost is approximately 10% of total mission cost instead of 30%.

This paper reports three OTA Cost Models:

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

$$\text{OTA Cost} \sim \text{OTA Diameter}^{1.5} \lambda^{-0.2} \quad (N = 12; r^2 = 98\%; \text{SPE} = 60\%)$$

$$\text{OTA Cost} \sim \text{OTA Mass}^{1.1} \quad (N = 13; r^2 = 87\%; \text{SPE} = 58\%)$$

Of these, the diameter and wavelength model is probably the most correct. But, it is still a work in progress.

Finally, we continue to find that telescopes designed to a larger mass budget have a lower cost. Space telescopes cost about 1000X per kg more than ground telescopes – independent of aperture diameter. Additionally, UIT, WUPPE and HIT which flew ‘attached’ to the space shuttle are 2X less expensive per kg. And, SOFIA which flies attached to a 747 is 15X less expensive. One explanation might be that it requires significantly more ‘engineering’ effort to design a low areal density telescope with the required wavefront shape and pointing stability for its operational (static gravity load and dynamic jitter) environment than it does for a high areal density telescope.

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- [2] 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
- [3] Stahl, H. Philip, and Todd Henrichs, “Preliminary Multi-Variable Cost Model for Space Telescopes”, SPIE Proceedings 7731, 2010.



Update on parametric cost models for space telescopes

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Agenda

- Introduction and Summary
- Data Collection Methodology
- Statistical Analysis Methodology
- What to Model?: OTA or Total Mission Cost
- Single Variable Models: Mass and Diameter
- Multi-Variable Models
- Total Mission Cost Models
- Conclusions



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Parametric Cost Models

Parametric cost models have several 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 total project cost.



DISCLAIMER

Cost Models are only as good as their Data Base

This is a work in progress.

The results evolve as we add new missions to the Database, add data to or correct data in the Database.



Background

I have been using and developing cost models for ~15 yrs.

Developed a cost model for NGST = JWST

Published several papers, including 3 last summer:

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.07, 2010

Stahl, H. Philip, and Todd Henrichs, “Preliminary Multi-Variable Cost Model for Space Telescopes”, SPIE Proceedings 7731, 2010.

Stahl, H. Philip, Todd Henrichs and Courtnay Dollinger, “Parametric Cost Models for Space Telescopes”, ESA International Conference on Space Optics, Rhodes, 2010.



Independent Review

In Sept 2010, the NRO Cost Model Office reviewed the data base and found some discrepancies:

In some cases our data was more accurate.

In other cases, we found errors in our data.

Problem was that, for some missions, costs which were stated to be for the OTA were instead for the 'instrument'

Instrument is the OTA and Science Instrument (conditioning optics, mechanisms, detectors, electronics, etc.)

Note: the NRO did not give us access to their data base.



Research Status

Consequently, we instituted a complete review of our data base:

- Double check and validate all missions in our data base

- Eliminate missions for which data is insufficient

- Improve Documentation, and

- Add new missions



Findings

Methodology presented is (to the best of our knowledge) correct.

After much effort, individual mission source information has been translated into a common WBS.

While our previously published models are not correct, they are consistent with our new models.



OLD Findings – 9/13/10

Aperture Diameter is principle cost driver for space telescopes.

$$\text{OTA Cost} \sim \$100\text{M} \times D^{1.3} e^{-0.04(YoD-1990)}$$

Because cost varies with diameter to a power less than 2, larger diameter telescopes cost less per square meter of collecting aperture than small diameter telescopes.

Technology development reduces cost by ~50% per 17 years.

If all other parameters are held constant,
adding mass reduces cost, and
reducing mass increases cost.



Findings – 8/8/11

Aperture Diameter is principle cost driver for space telescopes.

$$\text{OTA Cost} \sim \text{Diameter}^{1.4}$$

$$\text{OTA Cost} \sim \text{Dia}^{1.6} \lambda^{-0.25}$$

Larger diameter OTAs cost less per square meter of aperture.

Longer wavelength OTAs cost less.

If all parameters are held constant, adding mass reduces cost & reducing mass increases cost.

Still examining Year of Development

Diameter coefficient increases when we add wavelength, because JWST and Herschel are large aperture and long wavelength.

Cost increase from Aperture is off-set by longer wavelength



Differences

Primary differences between 13 Sept 10 and Today:

Most of the small aperture cost missions in old database were not OTA but rather complete instrument costs.

When the cost was reduced to be OTA only, it lowered the small aperture costs and increased the slope coefficients.

Half of old database IR missions included cost of cryogenic system

Separating theses costs again reduced the cost for these infrared missions.

BUT, we need to study (OTA + Thermal System).



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- Conclusions



Methodology

Data accumulated on 59 engineering and programmatic variables

18 Variables studied for Cost Estimating Relationships (CERs)

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 and Retrieval System),

SICM (Scientific Instrument Cost Model),

project websites, and interviews.



Cost & Mass Definitions

Total Mission:

- Spacecraft
- Science Instruments
- Telescope
- Thermal System

Instrument:

- Entire payload or experiment including 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



Cost & Mass 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)



Fiscal Year 2011

All costs are inflated to fiscal year 2011 using the NASA New Start Index Inflation Calculator.

Details can be found at:

<http://cost.jsc.nasa.gov/inflation/nasa/inflateNASA.html>



Technical Variables

Aperture Diameter

PM Focal Length

System Focal Length

Field of View

Pointing Stability

OTA Mass

Total Mass

Spectral Range Minimum

Wavelength of Diffraction Limit

Operating Temperature

Average Input Power

Data Rate

Design Life

Orbit



Programmatic Variables

TRL (Technology Readiness Level)

Year of Development (or Start of Development)

Development Period

Launch Year



Missions (8.6.11 Database)

Currently 45 missions in data base

33 'normal-incidence' UVOIR and
Infrared telescopes

5 grazing incidence X-Ray

7 Radio/Microwave

Data for microwave, radio wave
& grazing incidence X-Ray/EUV
provides wavelength diversity

To date only normal-incidence
UVOIR and Microwave
telescopes used for cost modeling

Cost Model Missions Database (8.6.11)	
<u>X-Ray Telescope</u>	<u>Infrared Telescopes</u>
Chandra (AXAF)	CALIPSO
Einstein (HERO-2)	Herschel
EUVE	IRAS
FOXSI	ISO
HERO	JWST
	SOFIA
<u>UV/Optical Telescopes</u>	Spitzer (SIRTF)
Commercial #1	TRACE
Commercial #2	WIRE
Copernicus (OAO-3/PEP)	WISE
EO-1/ALI	
EUVE	<u>Microwave Telescopes</u>
FUSE	ACTS
GALEX	Cloud SAT
HST	Planck
HUT	WMAP
ICESat	
IUE	
Kepler	<u>Radio Antenna</u>
LANDSAT-7	SWAS
LRO/LROC NAC	TDRS-1
MO/MOC	TDRS-7
MO/MOLA	
MRO/HiRISE	
OAO-B/GEP	
SDO/AIA	
SOHO/EIT	
STEREO/SECCHI	
UIT	
WUPPE	



Missions (8.6.11 Database)

Of 37 ‘normal-incidence’ UVOIR
and Microwave telescopes

27 are ‘Free Flying’

4 are ‘Attached’ and

5 are ‘Planetary/Other’

Additionally, some of these are
Imaging and others are
Spectroscopic.

We have not yet investigated the
impact of this distinction, but
expect spectroscopic to be lower
cost.

Normal Incidence Database (8.6.11)	
<u>Free Flying Telescope</u>	<u>Attached Telescopes</u>
ACTS	HUT
CALIPSO	SOFIA
Cloud SAT	UIT
Commercial #1	WUPPE
Commercial #2	
Copernicus (OAO-3/PEP)	
EO-1/ALI	<u>Planetary Telescopes</u>
EUVE	LRO/LROC NAC
FUSE	MO/MOC
GALEX	MO/MOLA
Herschel	MRO/HIRISE
HST	STEREO/SECCHI
ICESat	
IRAS	
ISO	
IUE	
JWST	
Kepler	
LANDSAT-7	
OAO-B/GEP	
Planck	
SDO/AIA	
SOHO/EIT	
Spitzer (SIRTF)	
TRACE	
WIRE	
WISE	
WMAP	



Sept 10 Database Review

In Sept 2010, the NRO Cost Model Office reviewed our data base and found some discrepancies:

In some cases our data was more accurate.

In other cases, we found errors in our data.

Problem was that, for some missions, costs which were stated to be for the OTA were instead for the 'instrument'

Instrument is the OTA and Science Instrument (conditioning optics, mechanisms, detectors, electronics, etc.)

Note: the NRO did not give us access to their data base.

We removed all missions in question and added them back as we confirmed and validated their values.

Additionally, we continue to add new mission to the database.



Changes to the Database from July 10 to Aug 11

After careful review of source
CADRe Documents (Cost Analysis Data
Requirements)

Increased: Kepler & Wise to include
PM, SE and I&T costs

Decreased: GALEX, HiRISE, HUT,
OAO-3, UIT, WIRE, & WUPPE
because their cost was for complete
instrument – not just OTA.

Decreased: HST based on better data.

Decreased: IRAS and Spitzer by
removing Cryostat cost from OTA
(will explore Thermal OTA later)

And, based on new data we:

Removed SOFIA gimbal cost

Added CloudSat, OAO-B/GEP;
Herschel & Planck

We continue to seek new/better data.

Changes in Database from July 10 to Aug 11

Mission	Change	Mission	Change
CloudSat	+	OAO-B/GEP	+
GALEX	↓	OAO-3/PEP	↓
Herschel	+	Planck	+
HST	↓	SOHO/EIT	×
ICESat	×	Spitzer	↓
IRAS	↓	TRACE	×
ISO	×	WIRE	↓
IUE	×	WISE	↑
JWST	↑	SOFIA	↓
Kepler	↑	HUT	↓
MRO/HiRISE	↓	UIT	↓
		WUPPE	↓



Refinement of Hubble Cost Knowledge

Hubble Cost Knowledge			
Cost Element	Old (FY11\$)	Revised (FY11\$)	Notes
Total Cost Phase A-D	\$ 4.0 B	\$2.8 B	Old: NGST Cost Model Database
Total OTA	\$ 0.9 B	\$ 0.9 B	
OTA	\$ 0.7 B	\$ 0.47 B	Old: allocated too much FGS/C&DH cost to OTA (should be spacecraft costs)
<i>Optics</i>		\$ 0.07 B	New: REDSTAR 121-4742
<i>Optics Control</i>		\$ 0.08 B	
<i>Optical Structure</i>		\$ 0.08 B	
<i>Electrical Power</i>		\$ 0.02 B	
<i>Structures, mechanisms, support equipment</i>		\$ 0.05 B	
<i>System Level 53%</i>		\$ 0.14 B	
<i>ST Level 53%</i>		\$ 0.01 B	
FGS	\$ 0.2	\$ 0.26 B	New: REDSTAR 121-4742
C&DH		\$ 0.08 B	New: REDSTAR 121-4742
Thermal Control		\$ 0.01 B	New: REDSTAR 121-4742
System Level 47%		\$ 0.12 B	New: REDSTAR 121-4742
ST Level 47%		\$ 0.01 B	New: REDSTAR 121-4742
Total SSM		\$1.14 B	New: REDSTAR 121-4742
Science Instruments		\$0.5 B	New: REDSTAR 123-1064 (page 108)
ESA Contribution		\$0.25 B	New: REDSTAR 123-1064 (page 108)
Total Cost Phase A-E	\$ 5.1 B	\$ 4.6 B	Old: NGST Cost Model Database
Launch		\$0.62 B	New: REDSTAR 123-1064 (page 108)
Phase E		\$ 1.2 B	New: REDSTAR 123-1064 (Page 108 & 122)

Note: Totals may not tie due to rounding



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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.



Agenda

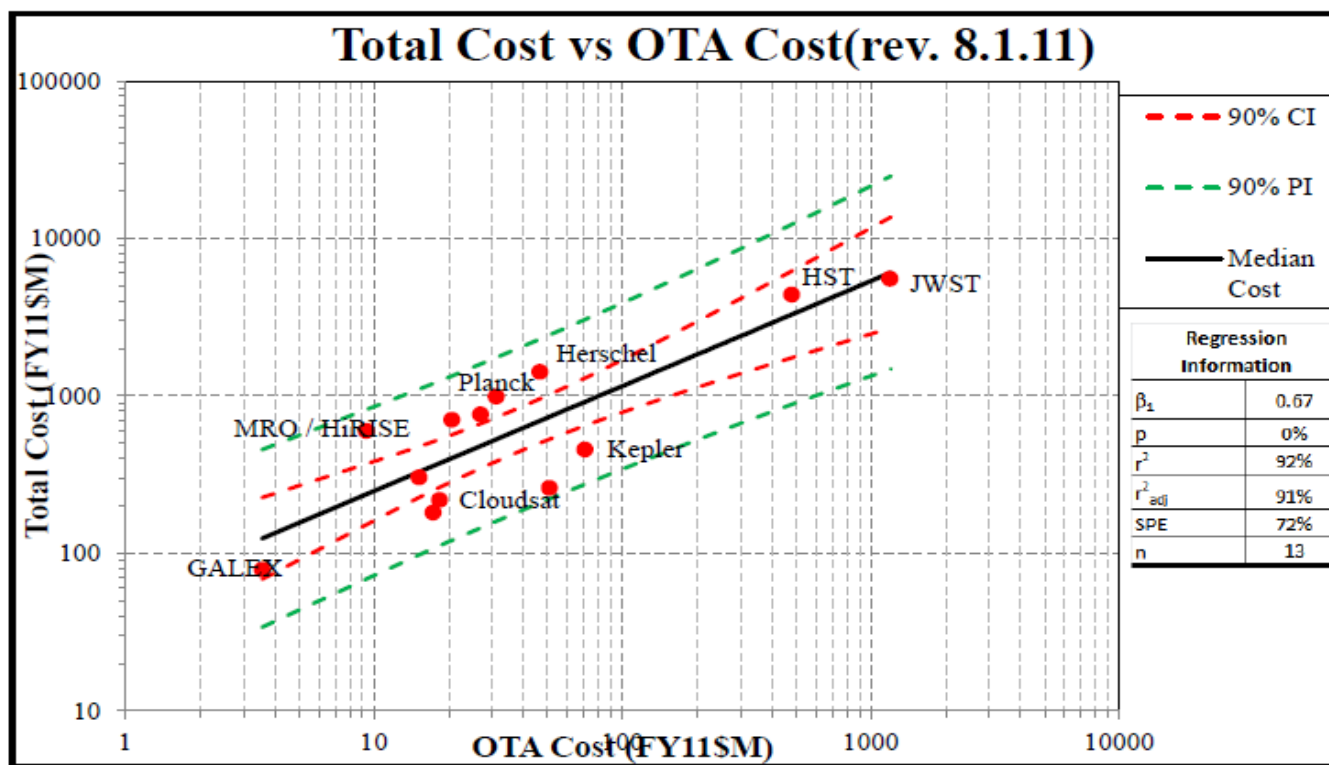
- Introduction and Summary
- Data Collection Methodology
- Statistical Analysis Methodology
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OTA Cost or Total Cost

To date we have focused on OTA Cost Model.

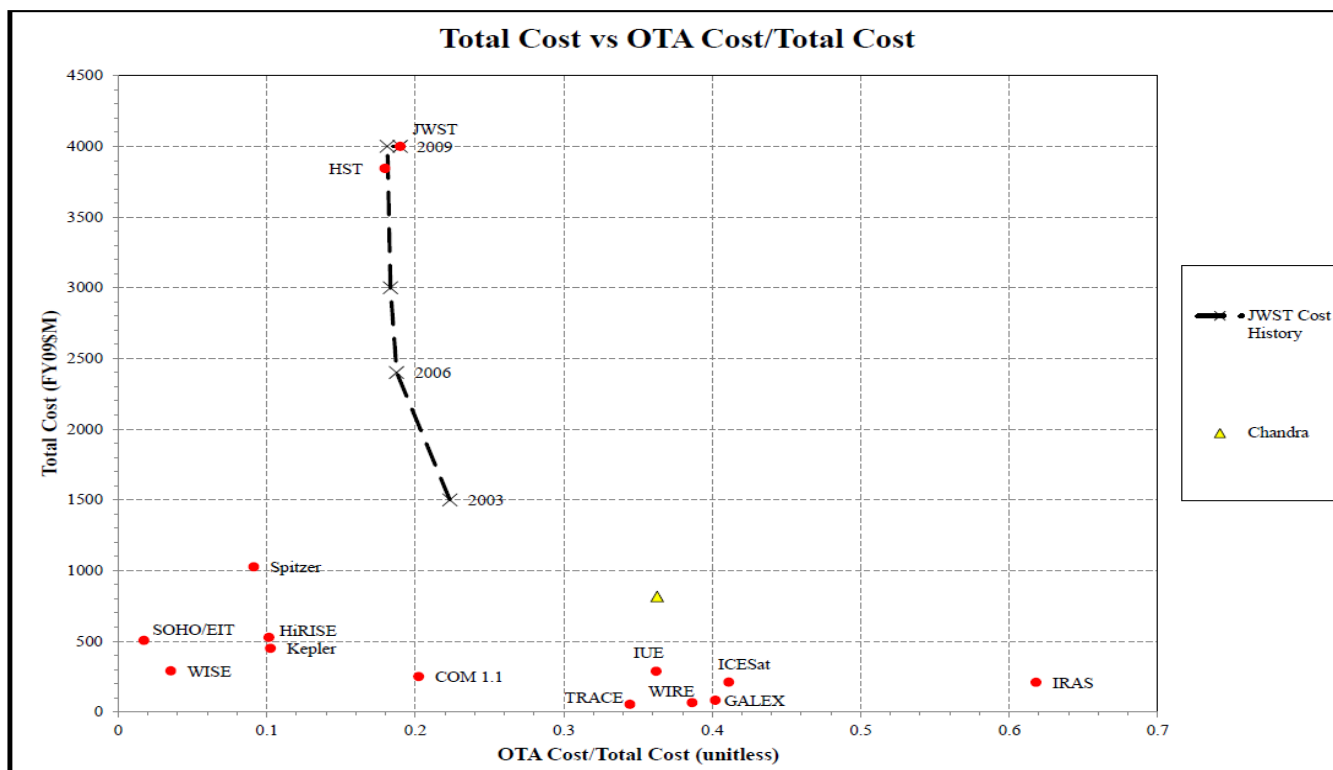
Given that OTA and Total Mission Costs appear to have a linear relationship, can the cost of one predict the cost of the other, i.e. is OTA cost a fixed percentage of Total Mission Cost?





Old Database % of Total

The 'old' data base was flawed such that the ratio of OTA Cost to Total Mission Cost appeared to be a constant 20%

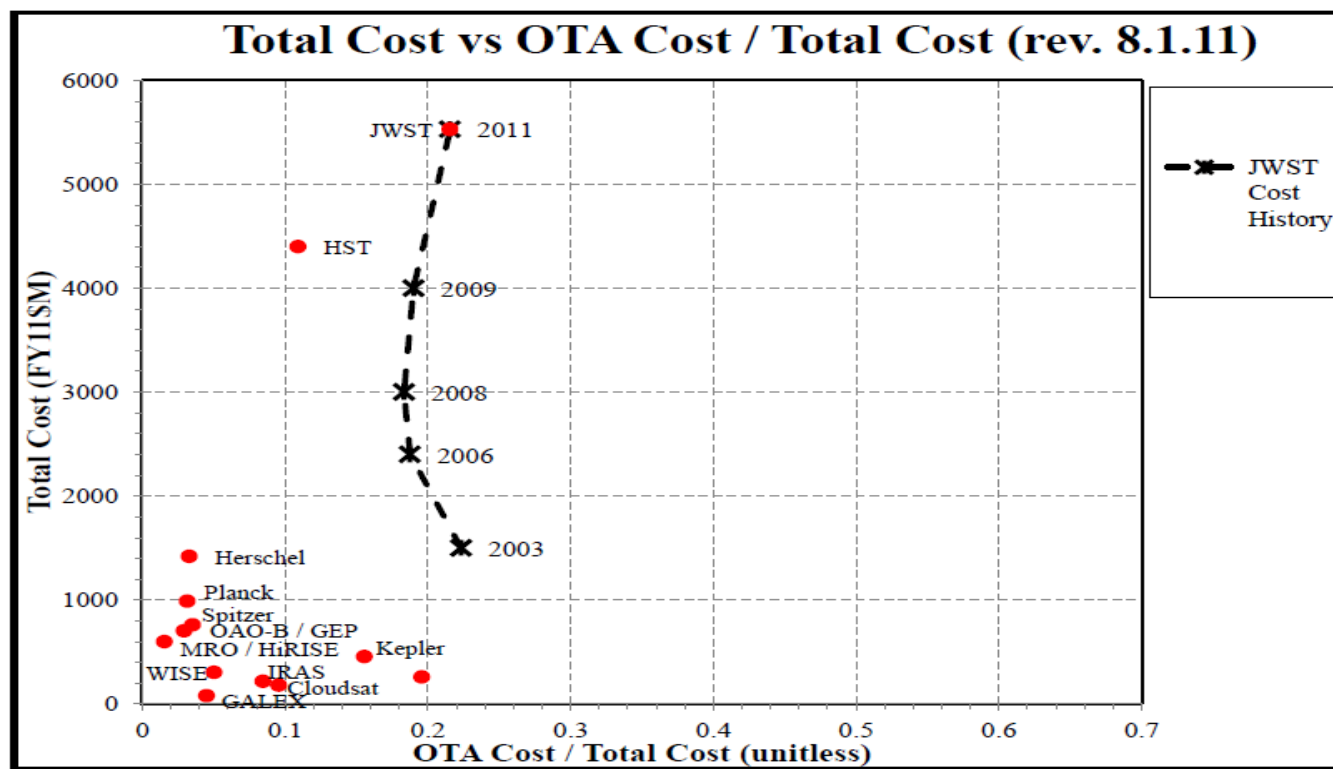




New Database % of Total

Corrections to the data base clustered the percentage of OTA Cost as a function of the Total mission cost for the small missions.

JWST cost info is preliminary until JWST launches.

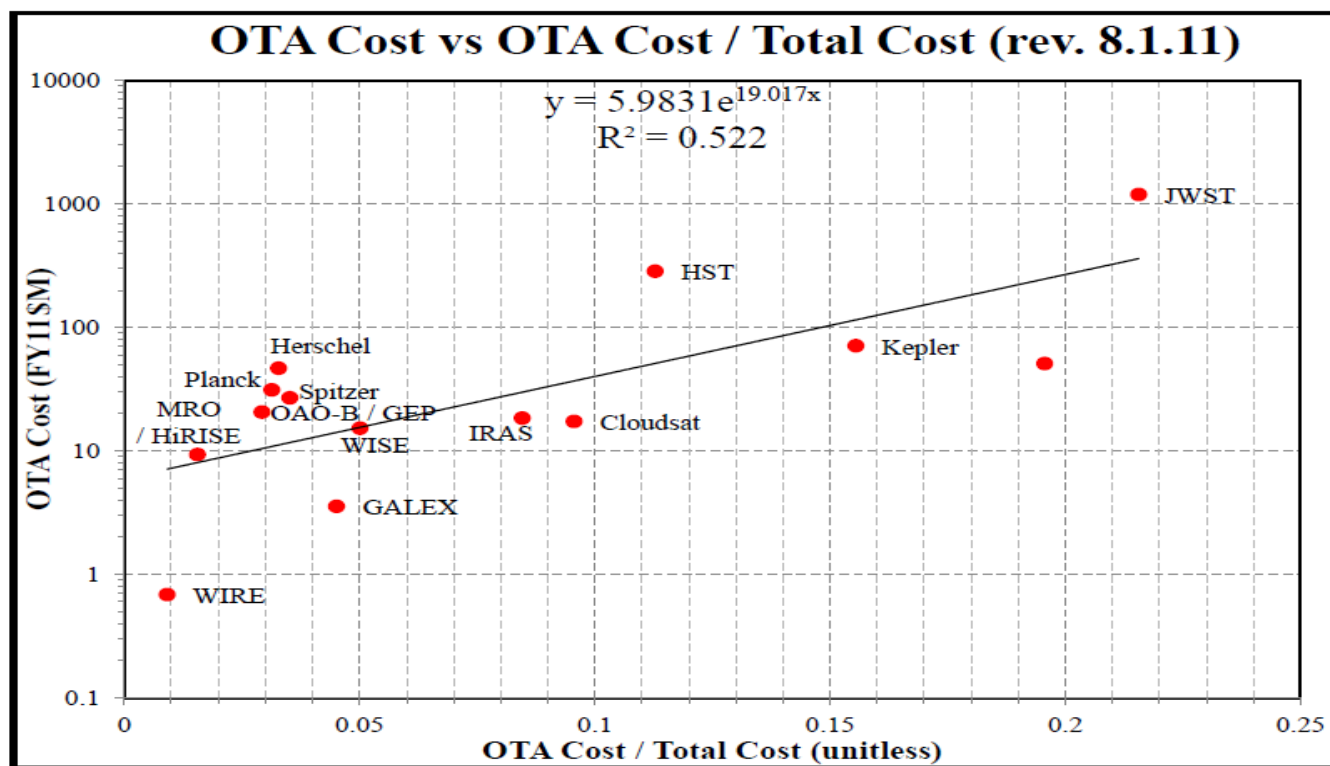




OTA Cost is NOT a fixed % of Total Mission Cost

OTA's cost as % of Total depends upon need to develop custom tooling or infrastructure – or use existing.

WIRE is clearly questionable & under review. Also, have asked GALEX to clarify their CADRe cost (missing Structure cost)





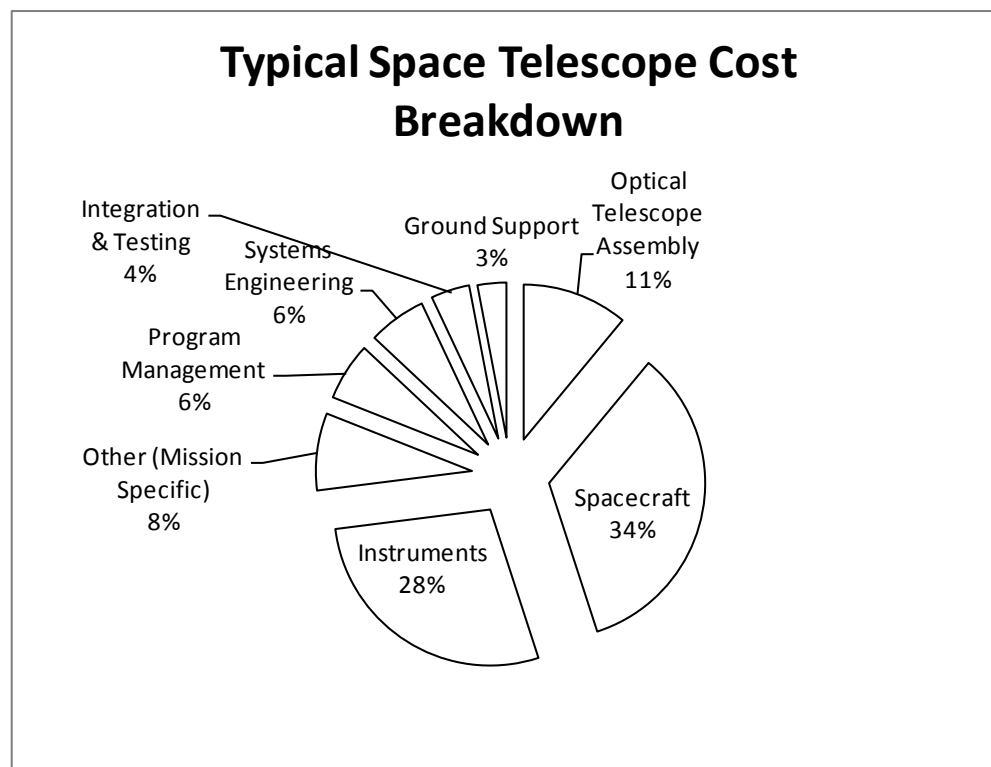
OTA Cost as a % of Total Mission Cost

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

Mapping these on to a common WBS gives OTA ~10% of Total

Some say that Power System is 20% of total mission Cost and Mass

For 1960/1970 missions, electronics costs are greater than OTA costs.

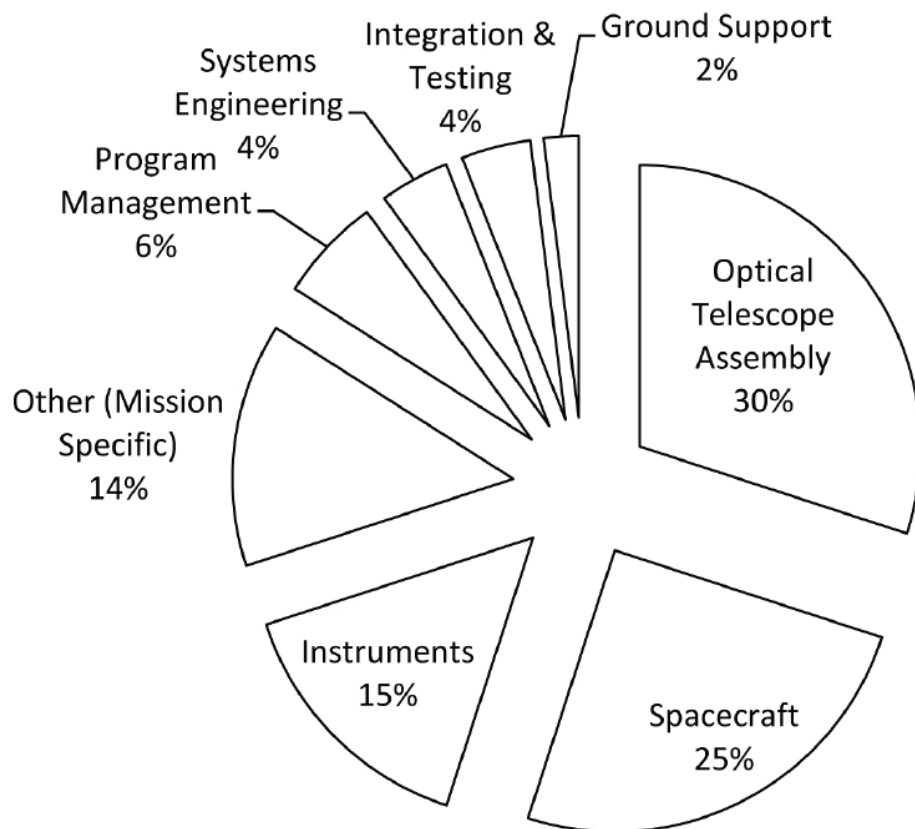




OTA Cost as a % of Total Mission Cost (OLD)

The 'flawed' data base yielded an OTA cost ~ 30% of Total

Typical Space Telescope Cost Breakdown





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OTA Cost Regression

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

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

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

Volume & FL have acceptable R^2_{adj} & SPE (but they are all just Dia)

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	



Mass Model



Mass Model

While the exponent of the Mass Model may have changed, none of the previous Mass Model conclusions have changed:

Different Classes of Missions have Different Costs per Kilogram

More Massive Missions still cost Less than Less Massive Missions

Cost per Kilogram is driven by Launch Vehicle Constraints

Space Telescopes are designed to mass

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

Such as light-weighting mirrors and structure.

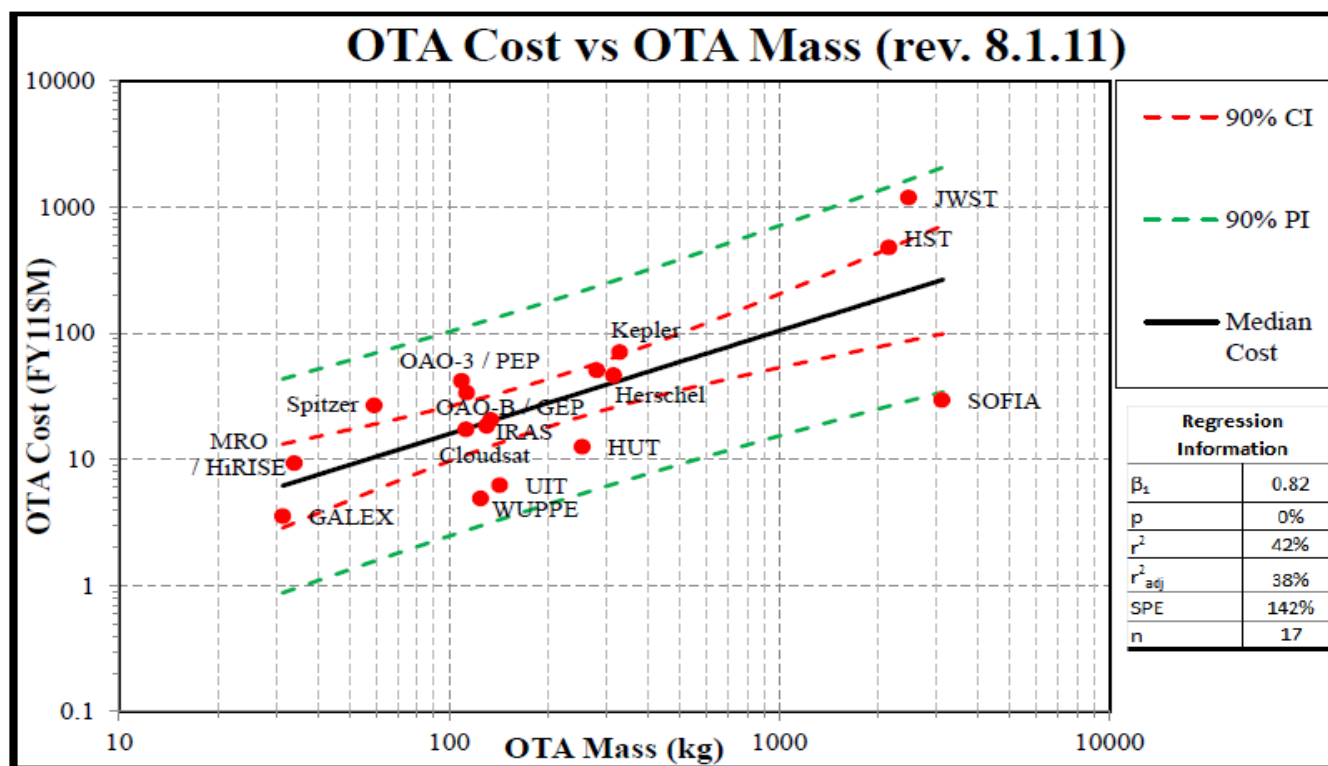


OTA Cost Mass Model #1

Regressing on all OTAs in the data base:

$$\text{OTA Cost} \sim \text{OTA Mass}^{0.8} \quad (N = 17; r^2 = 42\%; SPE = 142\%)$$

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



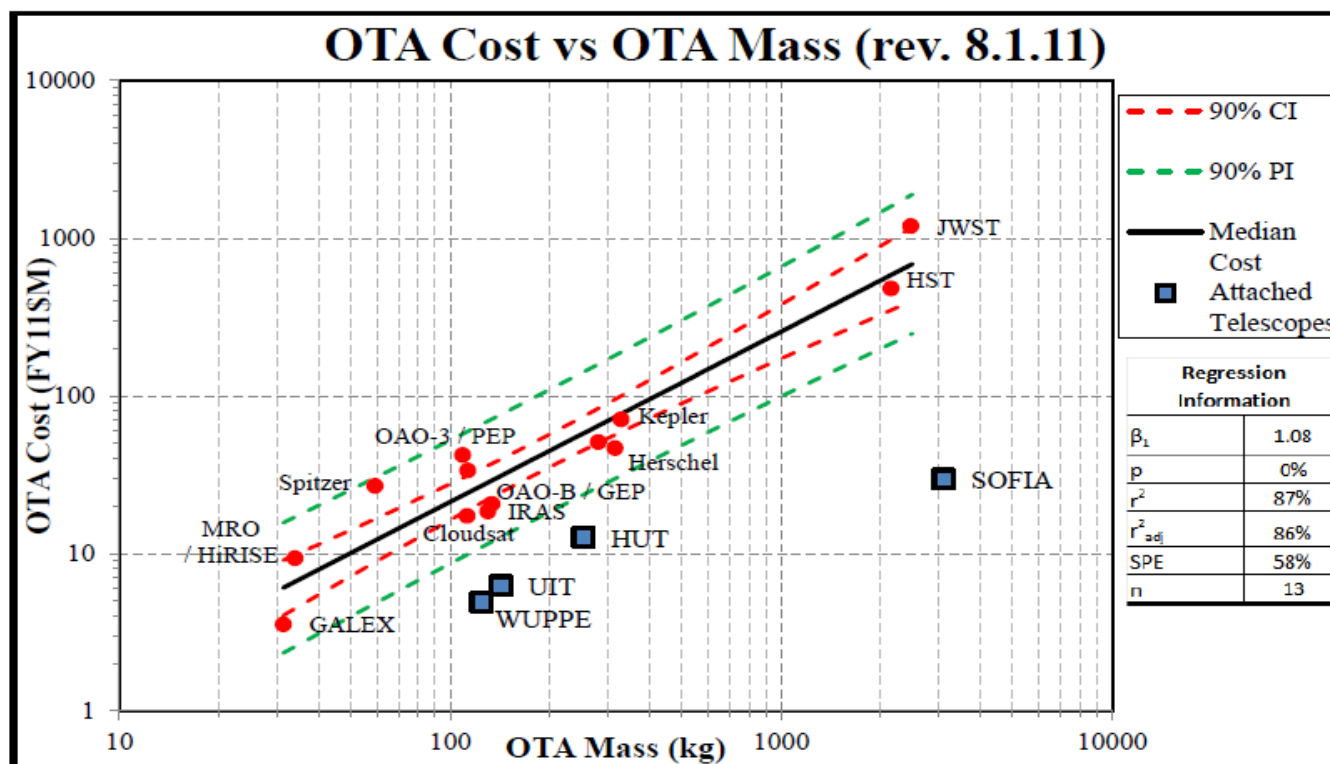


OTA Cost Mass Model #2

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

$$\text{OTA Cost} \sim \text{OTA Mass}^{1.1} \quad (N = 13; r^2 = 87\%; \text{SPE} = 58\%)$$

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

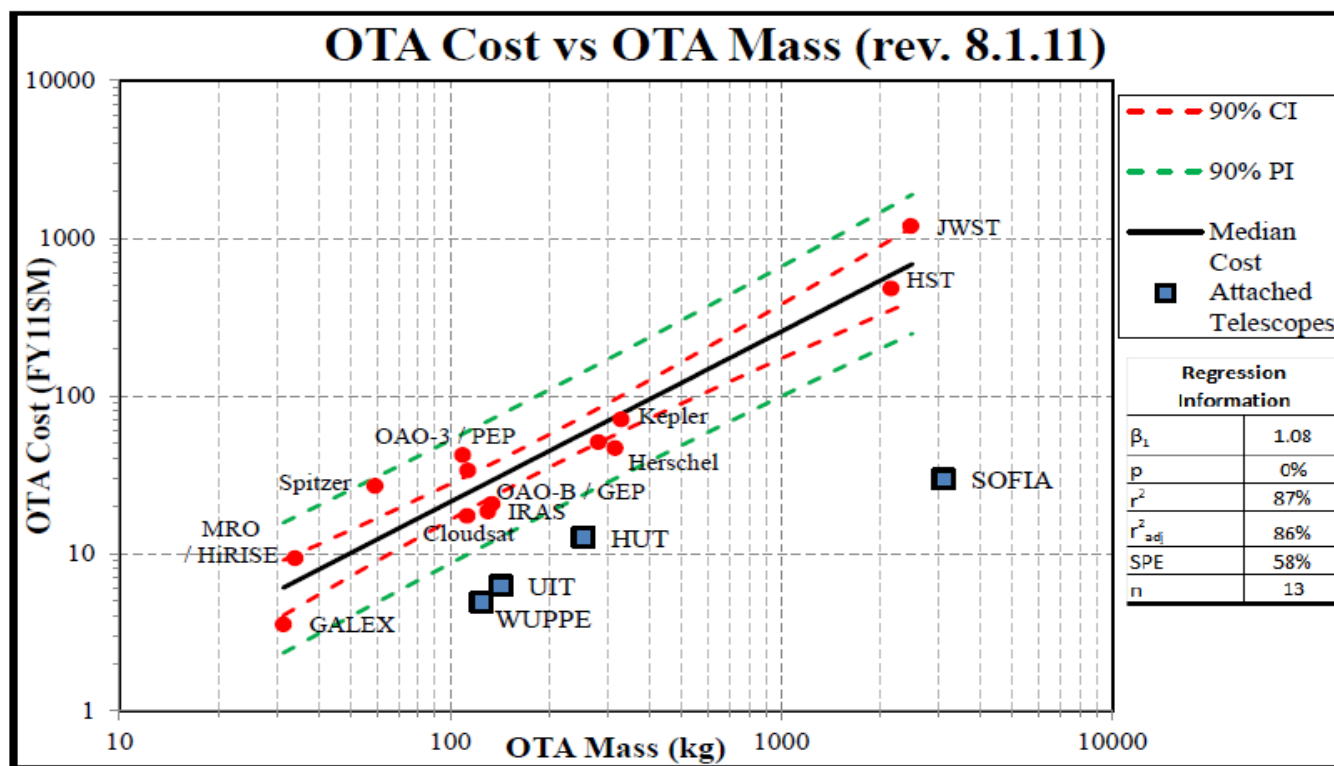




OTA Cost Mass Model #2

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

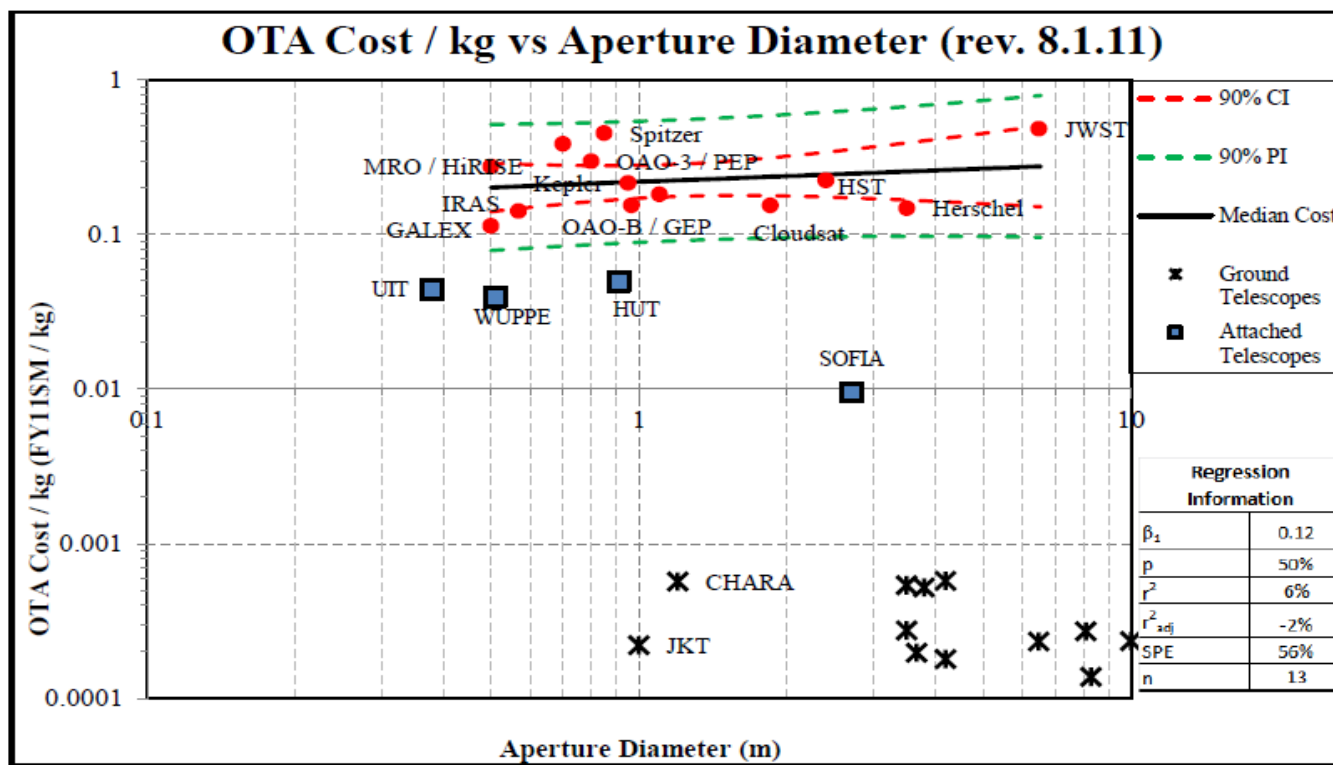
It costs more to design & build a low mass OTA than a high mass OTA

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



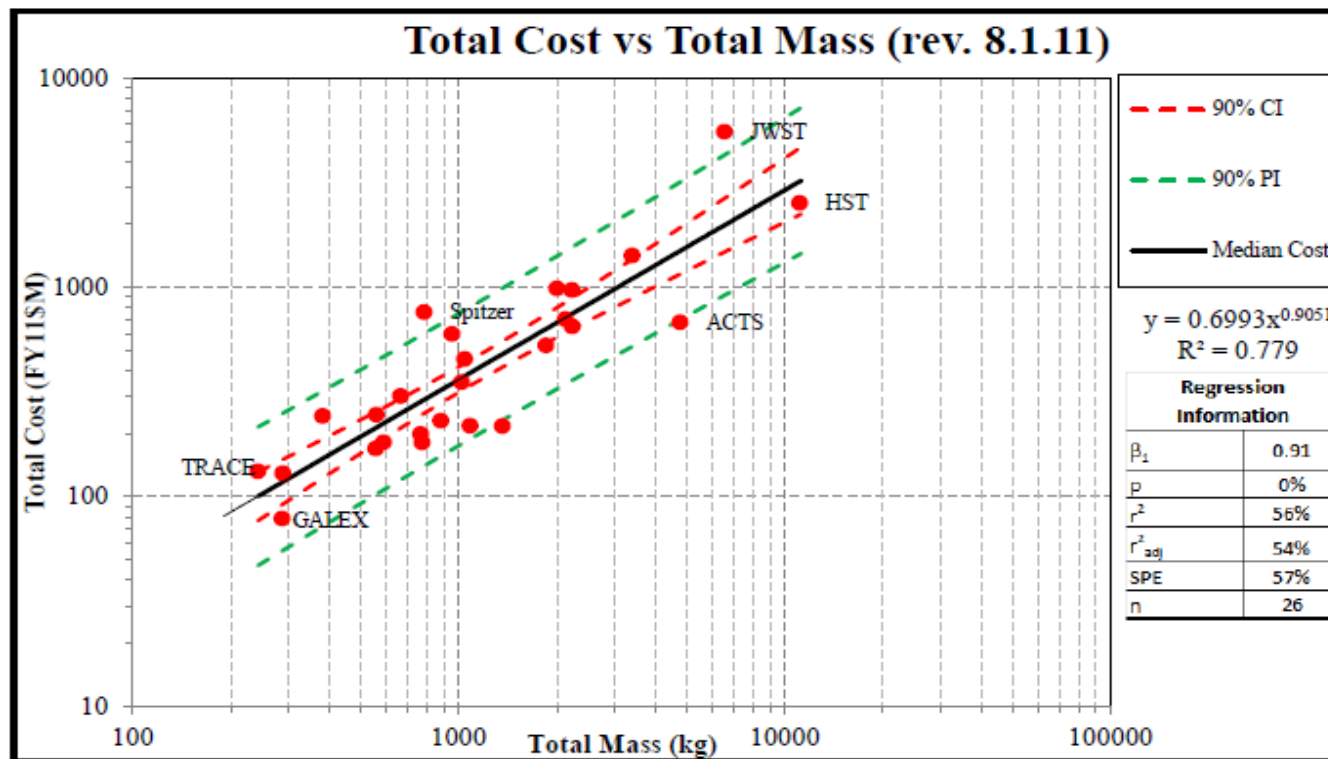


Mission Total Cost Mass Model

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

$$\text{Total Cost} \sim \text{Total Mass}^{0.9} \quad (N = 26; r^2 = 56\%; SPE = 57\%)$$

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



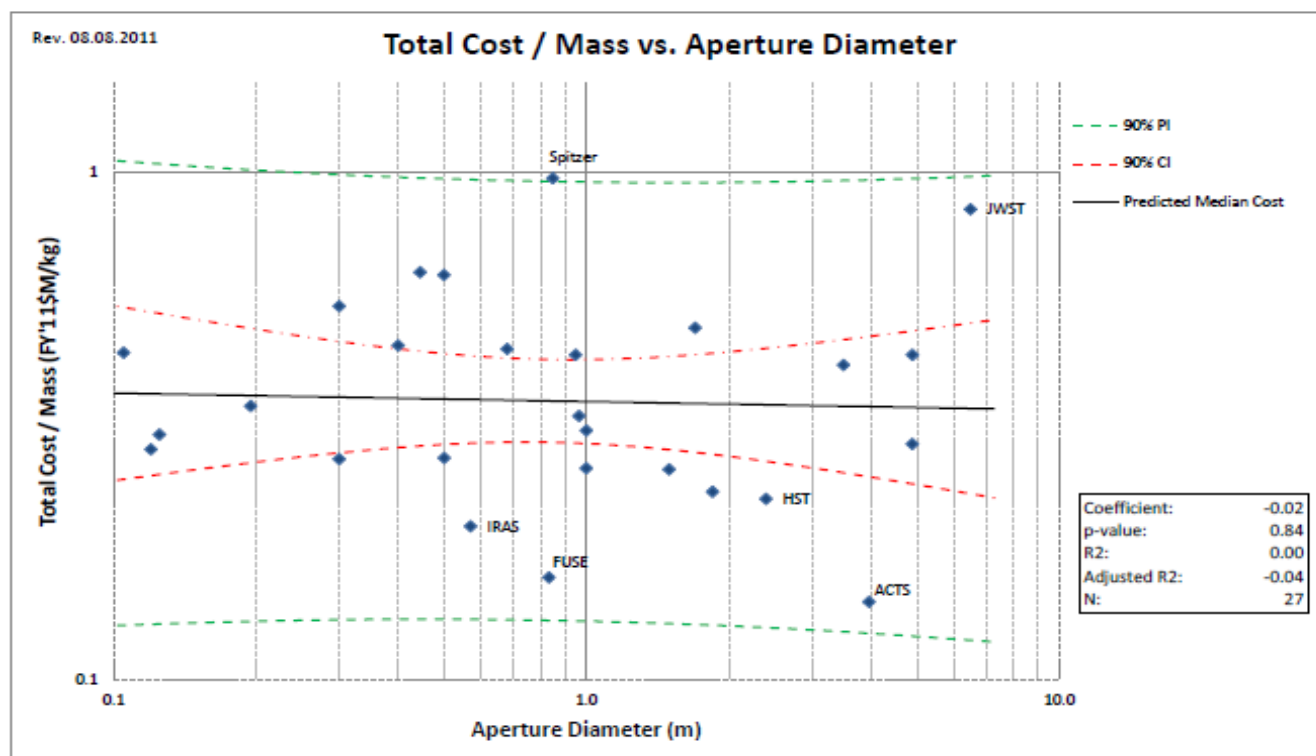


Total Mission Cost Density

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





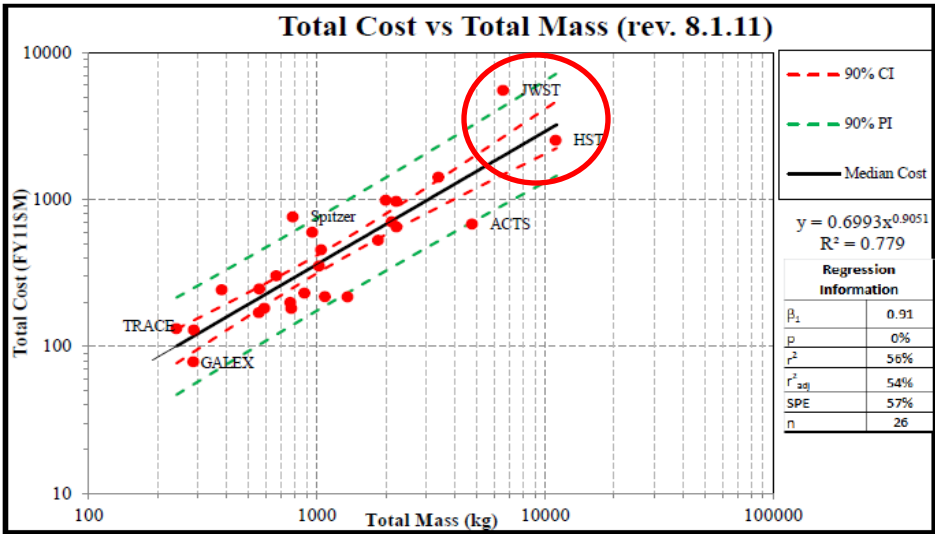
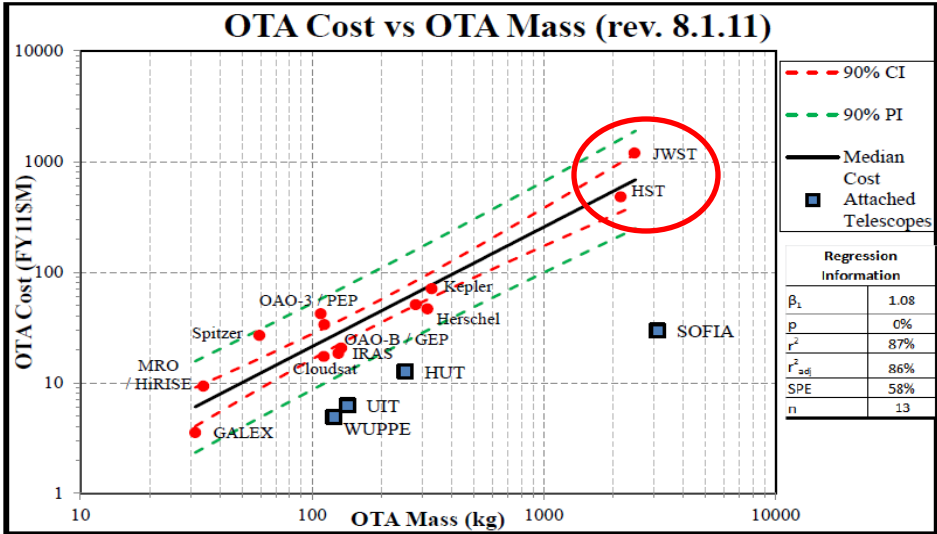
Mass is not a Good CER

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.



Aperture Model



Aperture Model

While the exponent of the Aperture Model may have changed,
none of the previous conclusions have changed:

Cost increases with Aperture at a rate less than D^2

Thus larger telescopes cost less per area than smaller telescopes.

This is 'magnified' for Missions

Different Mission Classes have different \$/kg – Independent of
Aperture

Our regressions improve as we improve our data knowledge.

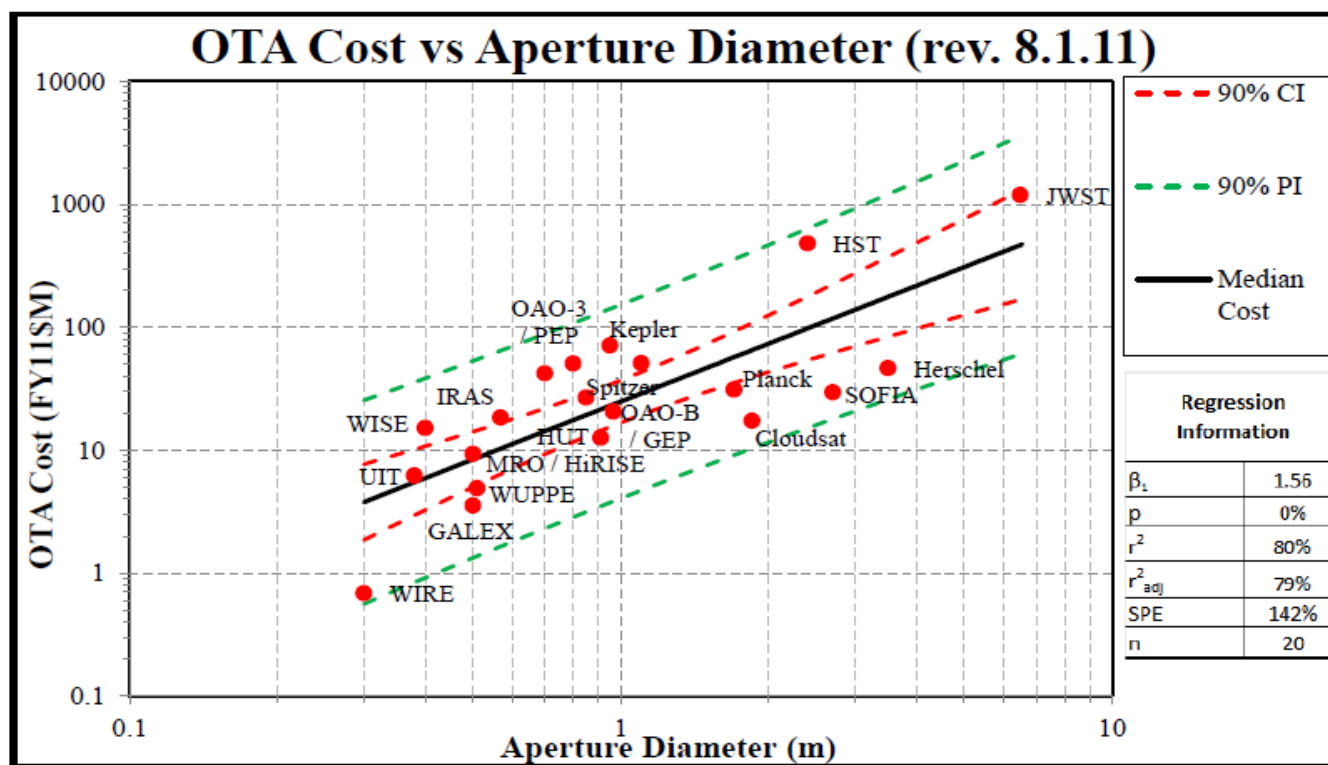


OTA Cost vs Aperture Model #1

Regressing OTA Cost vs Aperture for all missions in database:

$$\text{OTA Cost} \sim \text{Diameter}^{1.6} \quad (N = 20; r^2 = 80\%; SPE = 142)$$

Diameter accounts for 80% of the cost variation, but is noisy



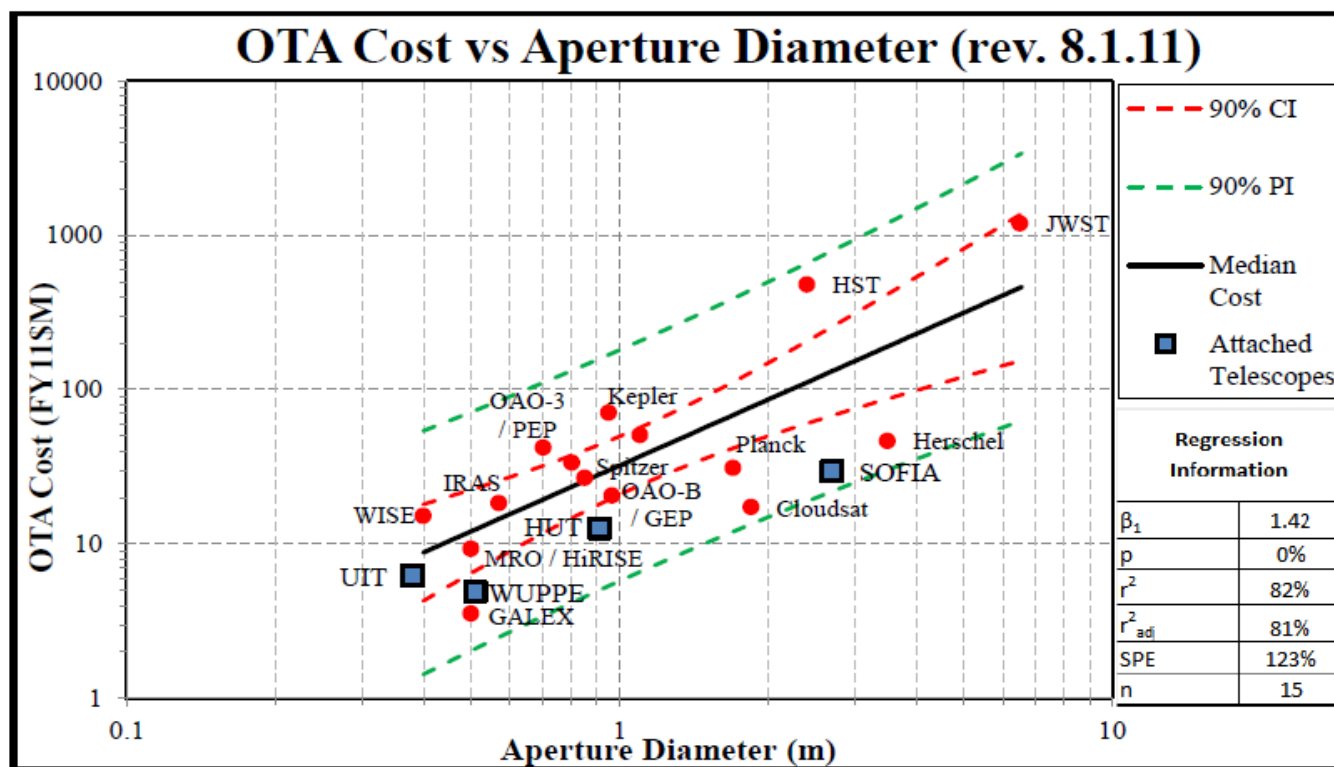


OTA Cost vs Aperture Model #2

Regressing OTA Cost vs Aperture for just Free-Flyer missions
(and excluding WIRE):

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

Diameter accounts for 82% of the cost variation, is less noisy



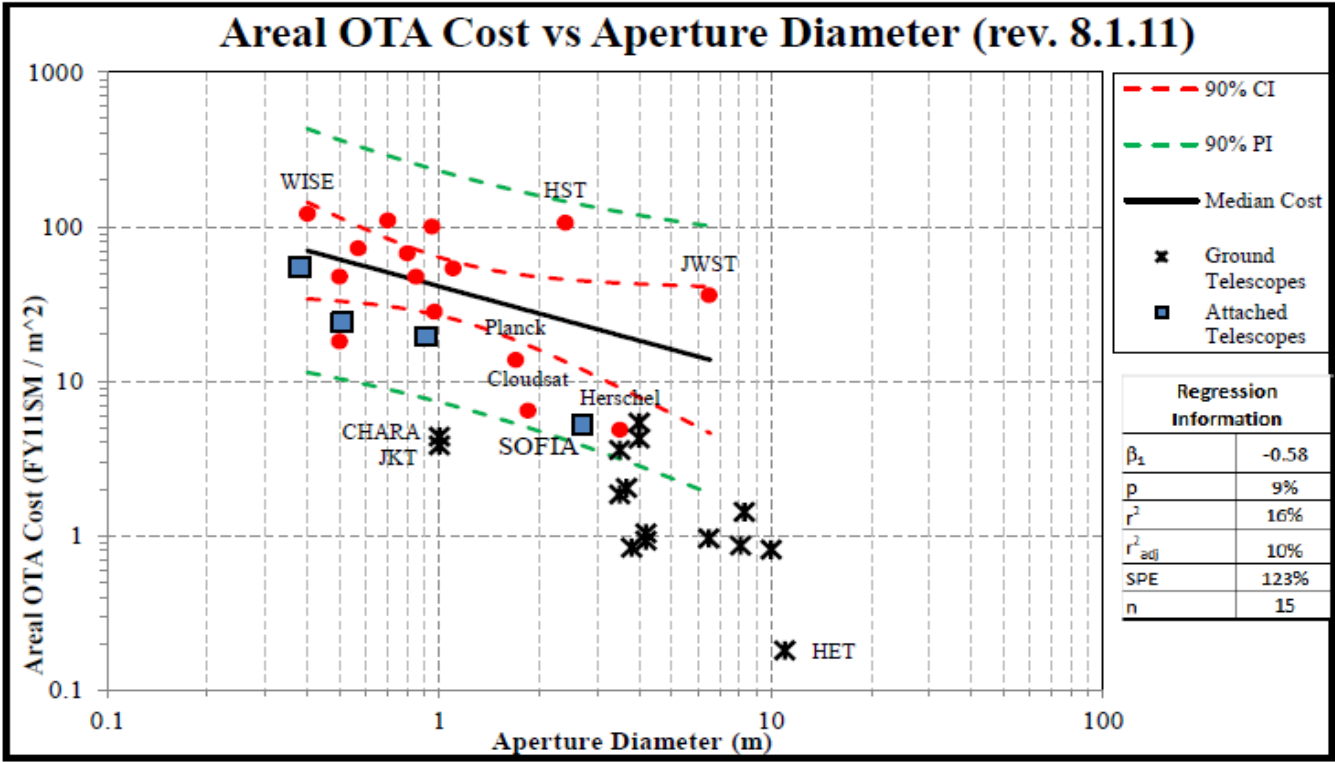


OTA Areal Cost

Because coefficient for diameter is less than ‘2’, the areal cost (cost per area) decreases as telescopes become larger.

Larger OTAs provide a higher ROI, less \$ per photon.

Also, more massive ‘attached’ and ‘ground’ have lower areal cost





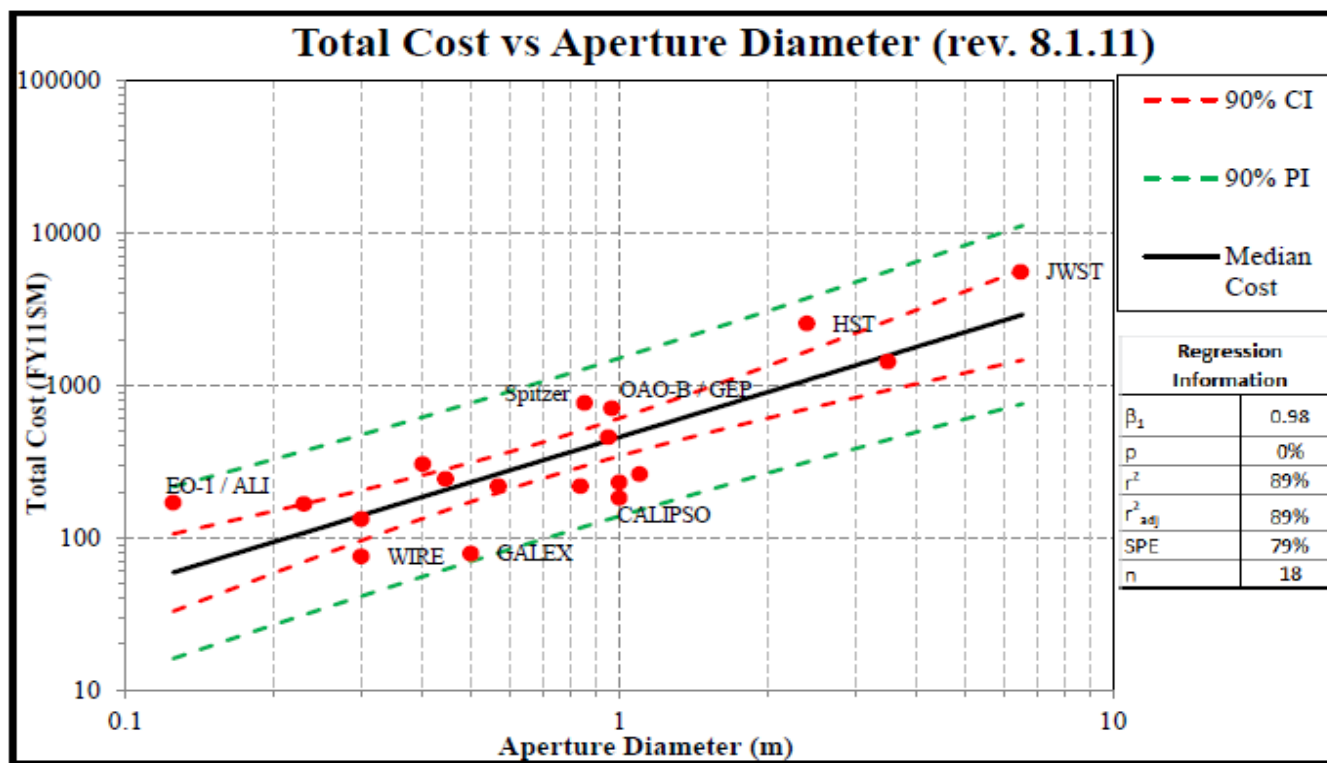
Total Mission Cost vs Aperture Model

Regressing Total Cost vs Aperture for free-flying UVOIR:

$$\text{Total Cost} \sim \text{Diameter}^1 \quad (N = 18; r^2 = 89\%; SPE = 79)$$

Diameter accounts for 89% of the cost variation

Because Total is 'flatter' than OTA, larger aperture are even more cost effective. Other costs (spacecraft, power, etc.) drive smaller aperture.





Consequences of Incorrect Data

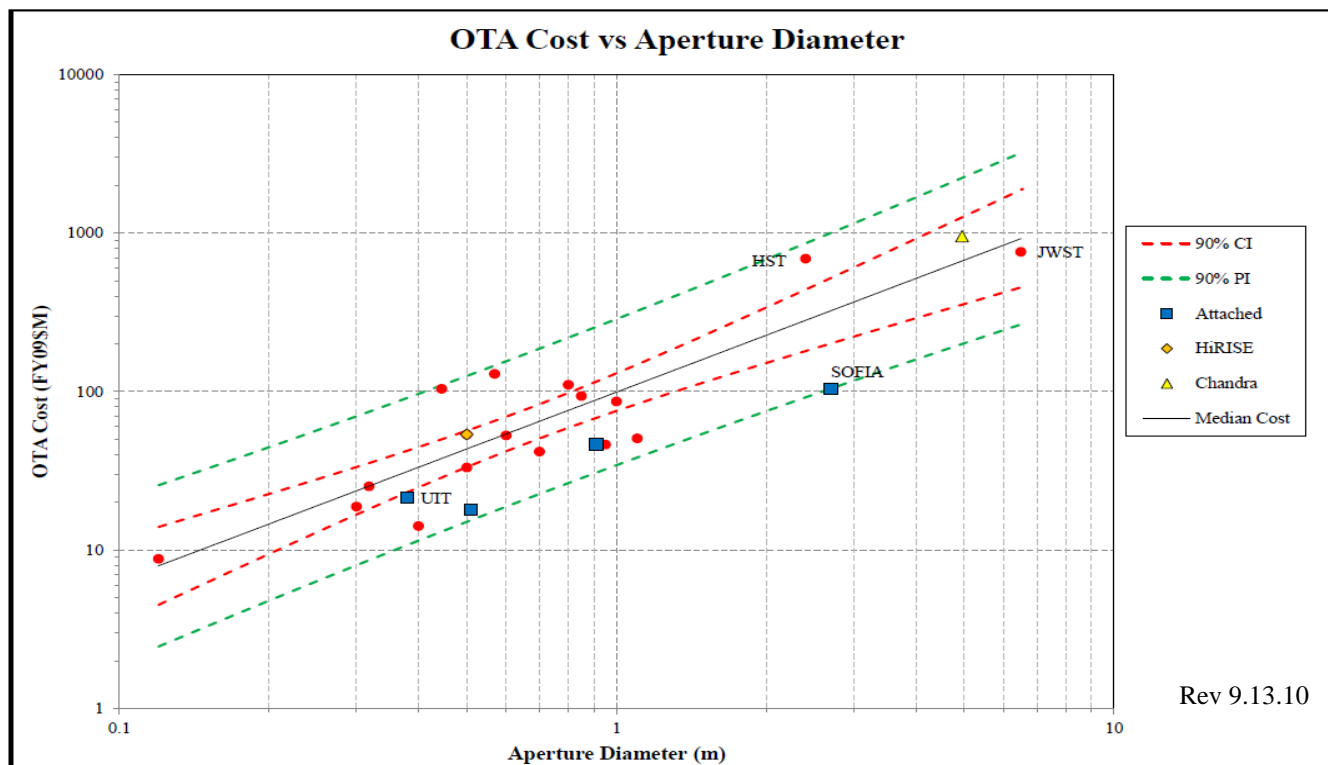


Aperture Model – 9/13/10

Including 2009 JWST; Excluding SOFIA & ‘attached’

$$\text{OTA Cost} \sim \text{Dia}^{1.2} \quad (N = 16; r^2 = 73\%; SPE = 81\%)$$

Small aperture missions are wrong, costs too high, instrument \$
This made the slope too flat.

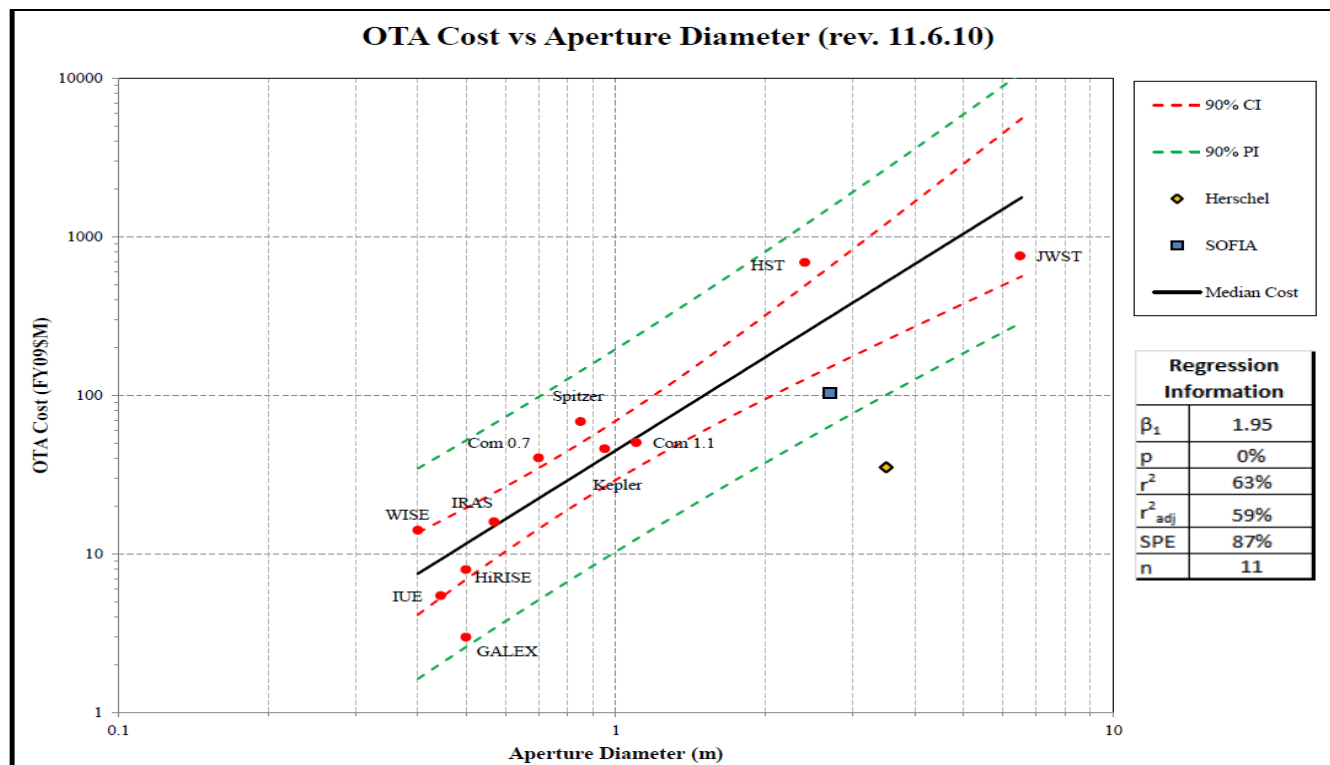




Aperture Model – 11/6/10

Deleting several small missions & reducing cost of others, lowers starting point and dramatically increases slope (including 2009 JWST; Excluding SOFIA & Herschel):

$$\text{OTA Cost} \sim \text{Dia}^{1.95} \quad (N = 11; r^2 = 63\%; \text{SPE} = 87\%)$$





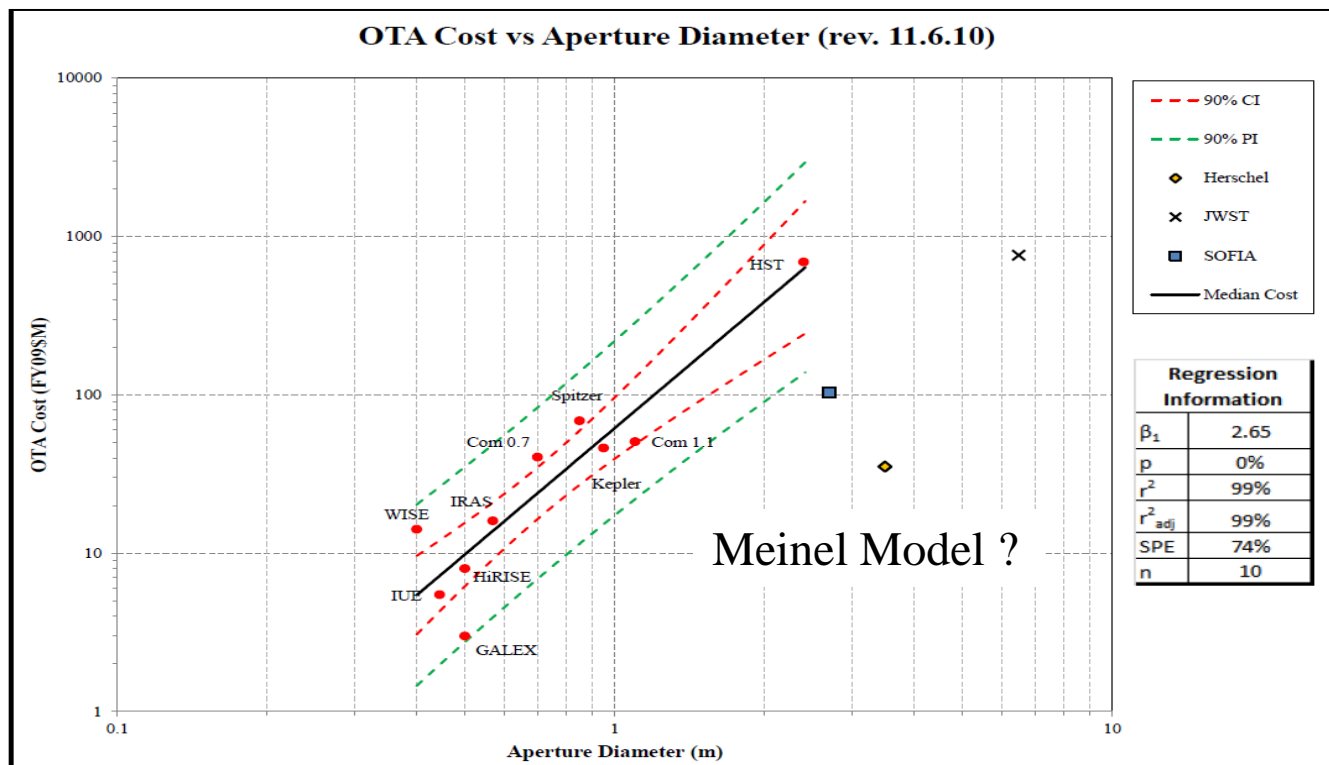
Aperture Model – 11/6/10

Excluding JWST, SOFIA & Herschel:

$$\text{OTA Cost} \sim \text{Dia}^{2.65} \quad (N = 10; r^2 = 99\%; \text{SPE} = 74\%)$$

This regression is only for fielded free-flying UVOIR OTAs.

Slope is close to Meinel & JPL 2.7 model.





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Need for a second variable

Assuming that Mass is not the right CER and that Aperture is

Aperture Model only accounts for 70% of the cost variation.

Therefore, other variables must account for the remaining 30% of the cost variation.

Thus, a multi-variable model is required.

First step is a residual analysis.



How to develop a Multi-Variable Model

Perform multi-variable regression to add a second variable.

Select two variable model based on:

- Change in Significance of Diameter to Fit

- Significance of Variable #2 to Fit

- Increase in r^2_{adj}

- Decrease in SPE

- Multi-Collinearity

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.



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		Yes		Yes		No		No		Yes		No	
Variable 2		Spectral Range minimum		Diffraction Limited Wavelength		Operating Temperature		Design Life (exp)		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)	
Diam.	p-value	1.62	0.00	1.54	0.00	1.49	0.00	0.83	0.02	1.45	0.00	1.14	0.04	1.46	0.00
Var. 2	p-value	-0.18	0.02	-0.22	0.02	-0.08	0.64	0.01	0.01	-0.01	0.46	0.01	0.17	-0.01	0.70
Adjusted r ²		96%		98%		81%		99%		84%		91%		82%	
SPE		74%		60%		136%		71%		124%		128%		120%	
n		15		12		14		15		14		13		15	
Multicollinearity?		No		No		No		No		No		No		No	

Diffraction Limit & Spectral Min are most significant, both increase R2 & decrease SPE
 OTA Mass increases R2 to 85%, but is multi-collinear with Aperture Diameter.
 Other multi-collinear variables are FL and Volume
 Don't understand impact of Design Life on Diameter.

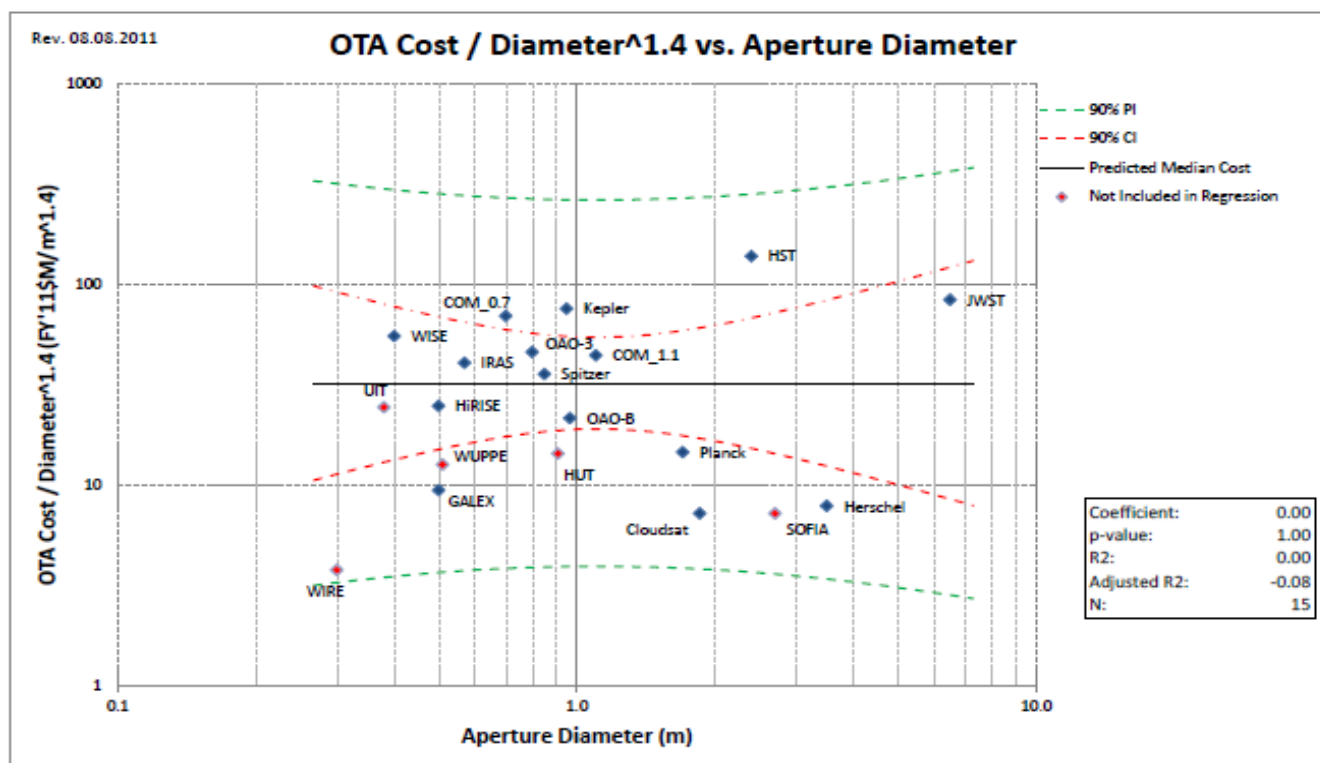


Aperture Residual Error Analysis

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

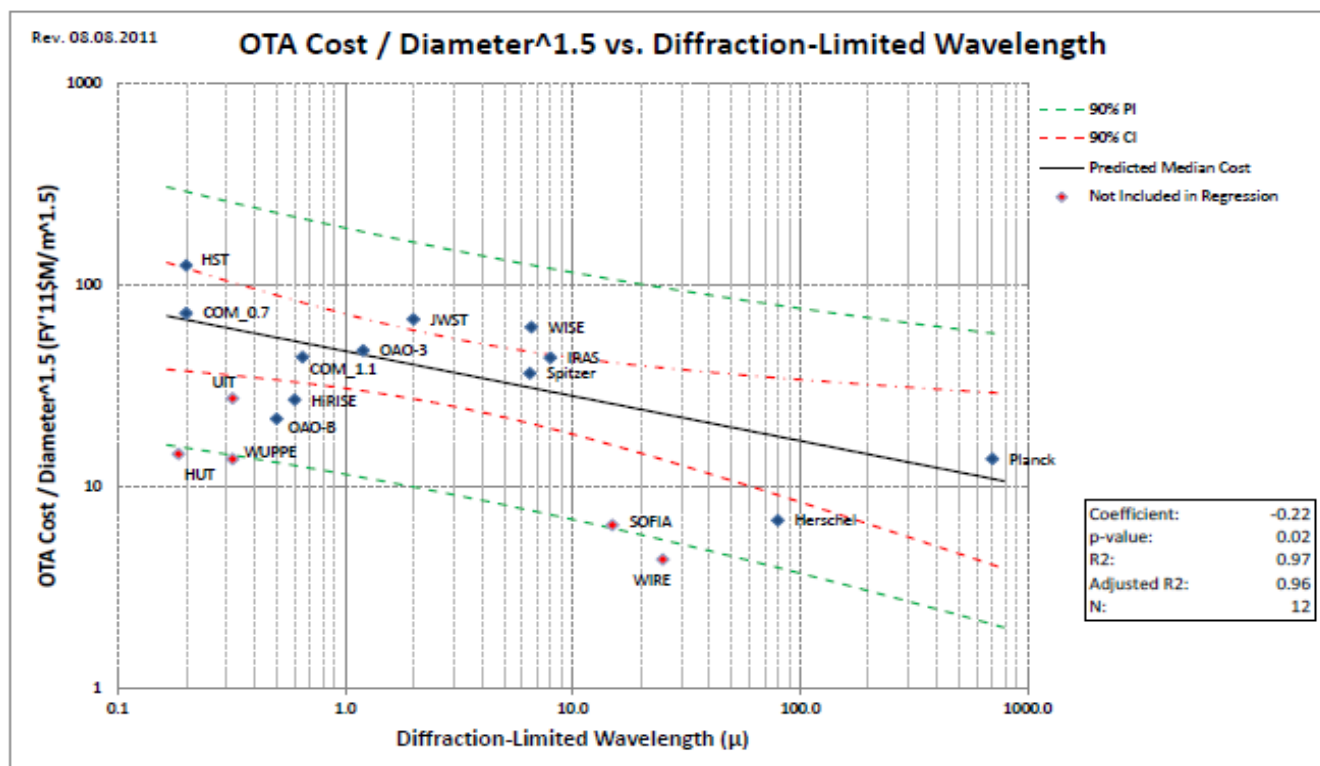




Aperture Residual Error Analysis: Wavelength

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.

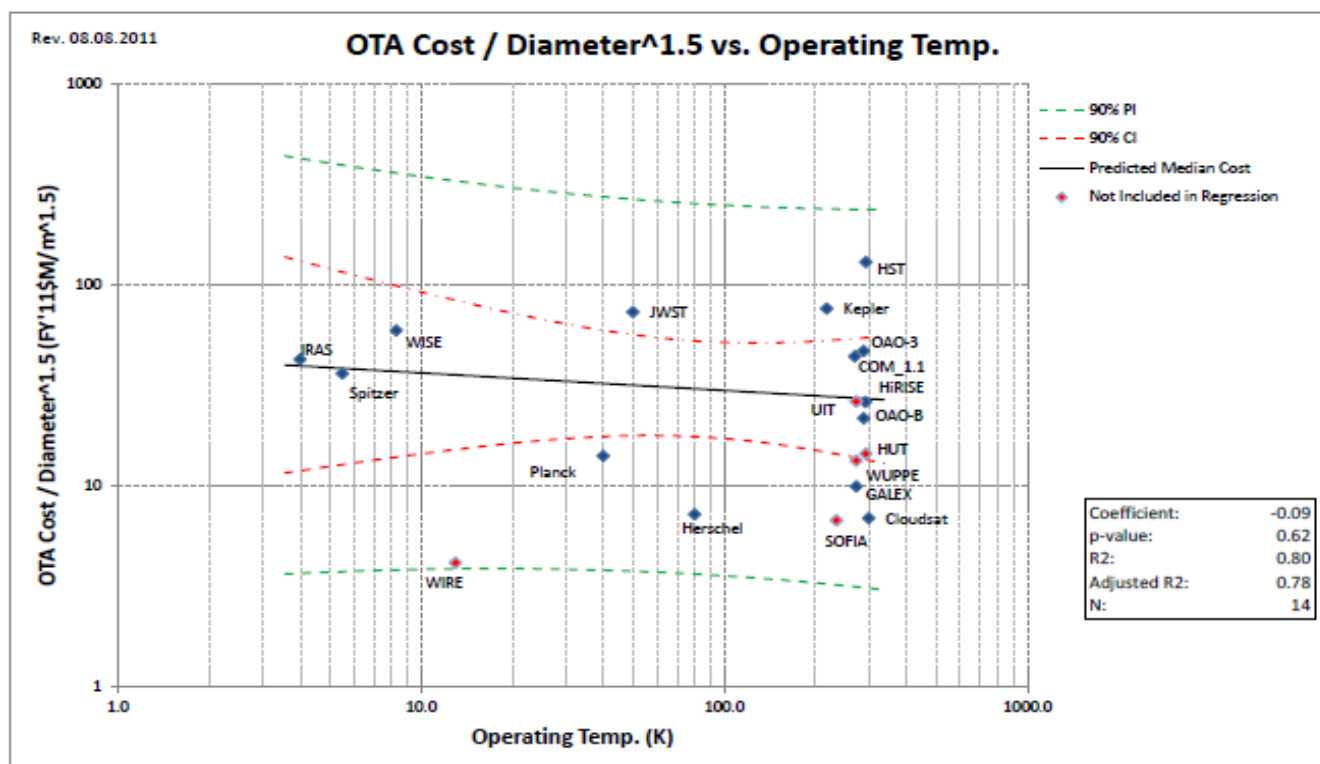




Aperture Residual Error Analysis: Temperature

Operating Temperature does not significantly explain residual aperture variation

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





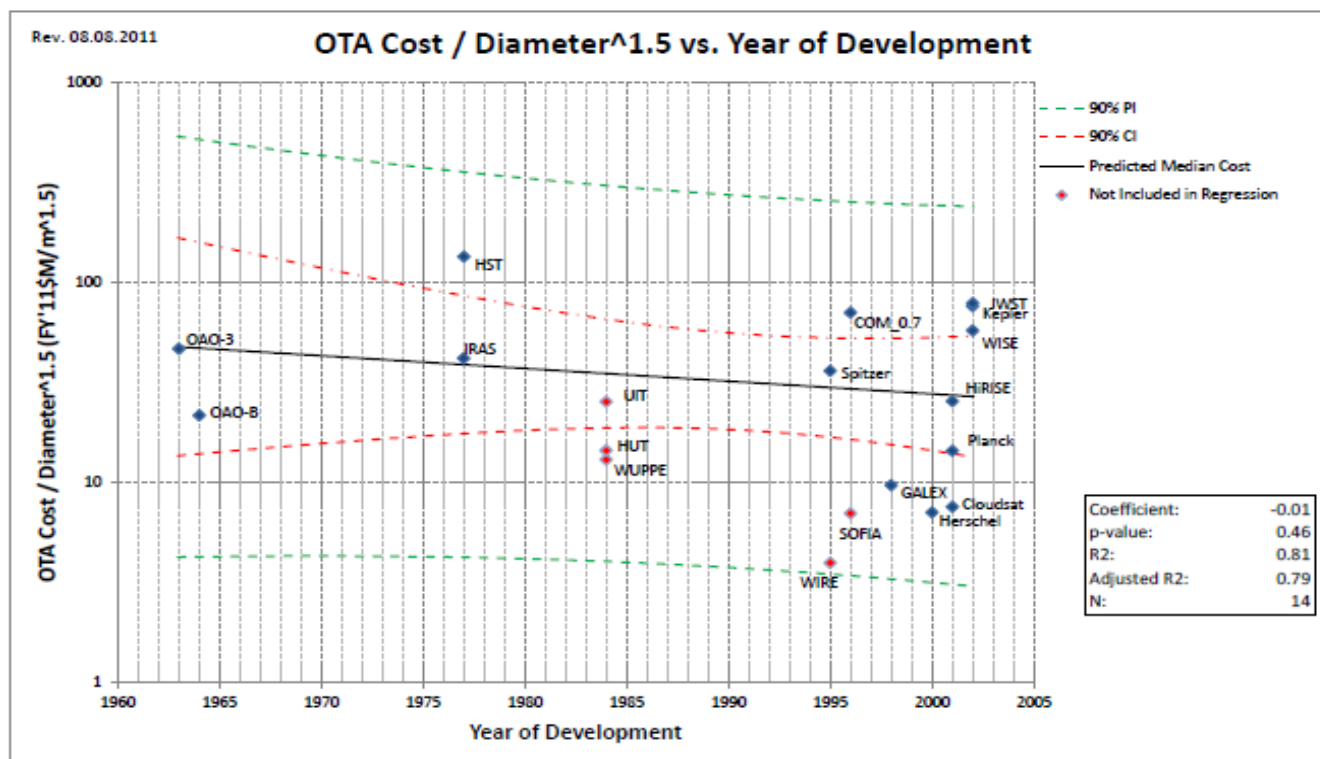
Aperture Residual Error Analysis: YOD

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.



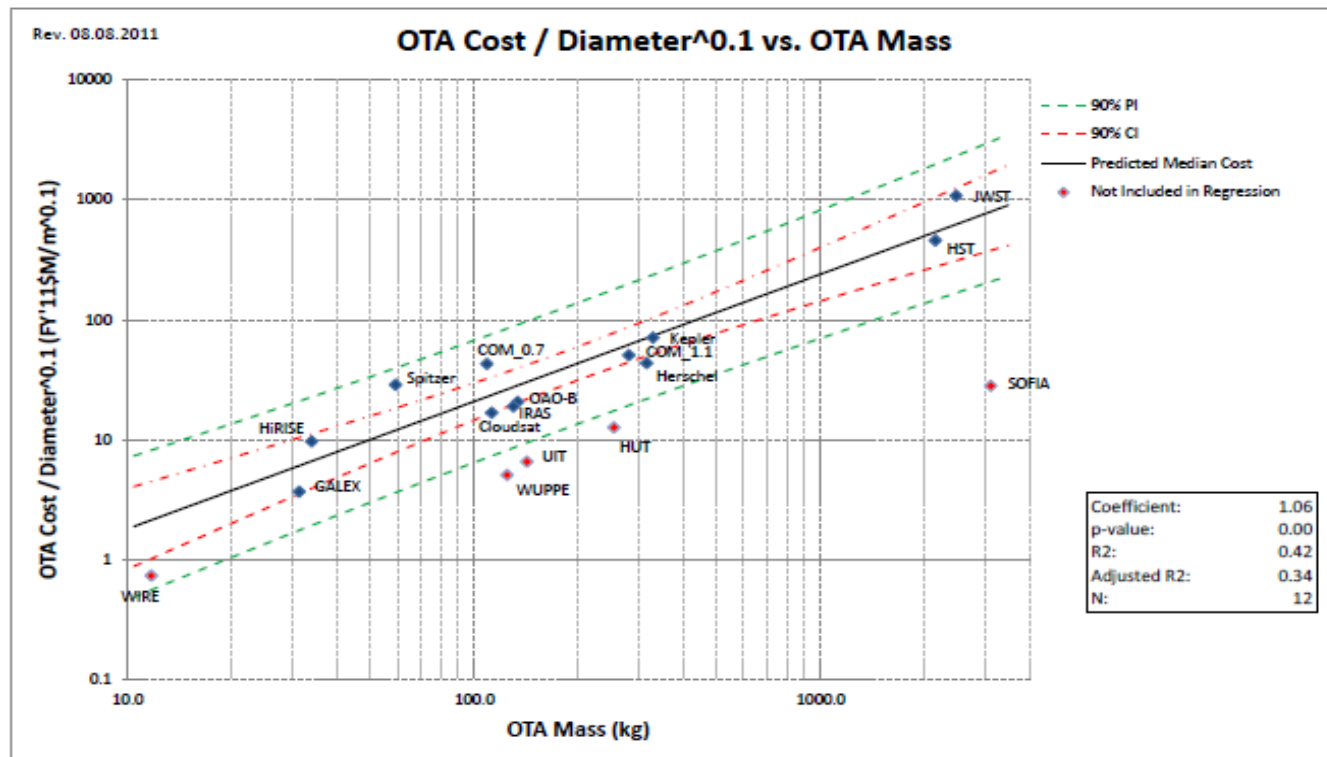


Aperture Residual Error Analysis: Mass

Mass explains some residual aperture variation

($p = 0.0$; $R^2 = 0.42$)

BUT it is multi-colinear with Aperture Diameter





Two Variable Aperture Model

Two second variables best meet all the criteria:

Wavelength Diffraction Limit and
Spectral Minimum

Diffraction Limited Wavelength yields the best model:

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



OTA Cost versus Diameter, Wavelength and V3

Operating Temperature is the only significant 3rd variable

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

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

More effort is required to understand issues related to:

Design Life

Year of Development

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	



Three Variable Aperture Model

Three variable which best meet all the criteria:

Wavelength Diffraction Limit

Spectral Minimum and

Operating Temperature

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

More effort is required to understand issues related to:

Design Life

Year of Development



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- Introduction and Summary
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- **Total Mission Cost Models**
- Conclusions



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:

$$\text{Mission Cost} \sim \text{OTA Cost} + \text{Other Costs}$$

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.	p-value	0.52	0.00	0.48	0.01	-0.21	0.31	-0.38	0.05	0.86	0.00	-0.11	0.36	0.00	0.92	-0.02	0.83	-0.06	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	

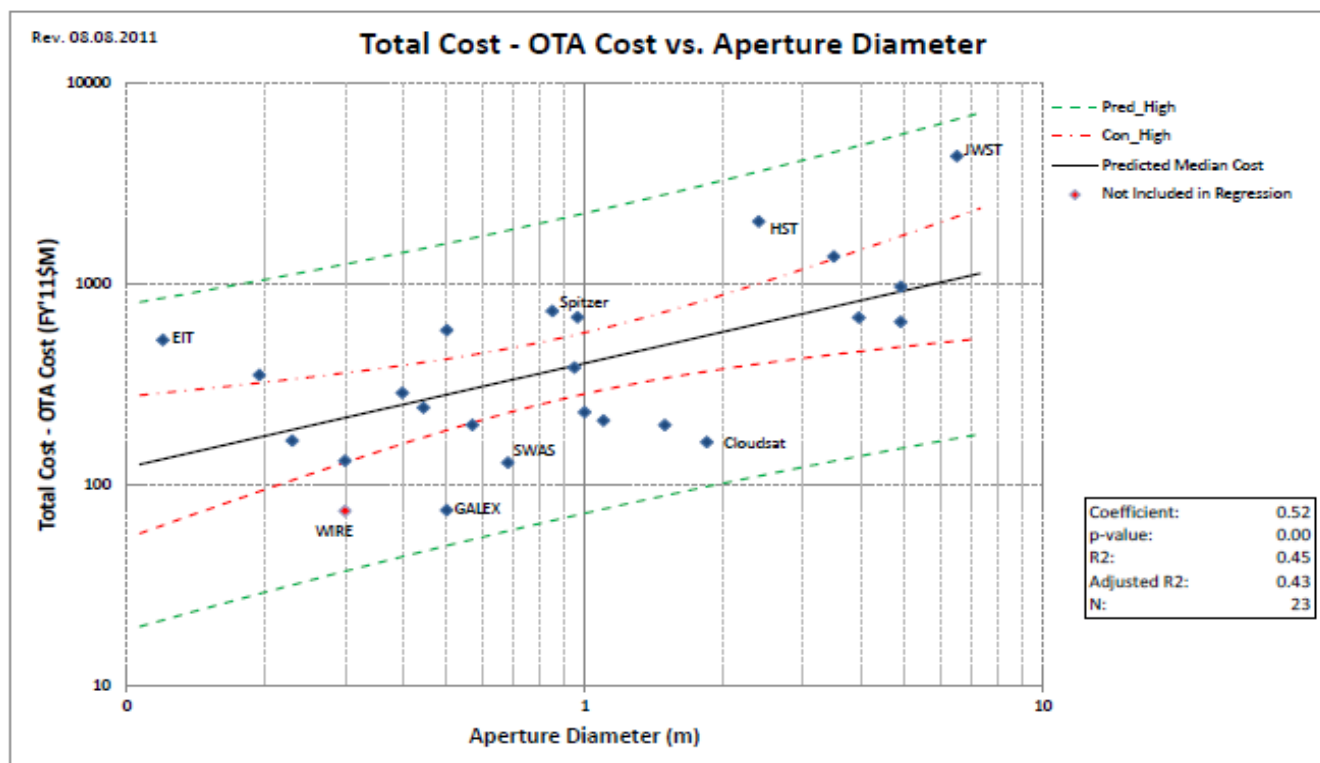
Variable Name		Total Avg. Input Power		Data Rate		Design Life (exp)		TRL		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)		Orbit	
Var.	p-value	0.34	0.04	0.01	0.83	0.01	0.00	-0.90	0.43	-0.01	0.64	0.02	0.00	0.00	0.87	0.10	0.06
Adjusted r^2		0.23		-0.03		0.71		0.04		-0.05		0.89		0.00		-0.01	
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 telescopes require larger spacecraft, power, communications, etc:

$$(\text{Total} - \text{OTA}) \text{ Cost} \sim \text{Dia}^{0.5} \quad (N = 23; r^2 = 45\%; SPE = 119\%)$$

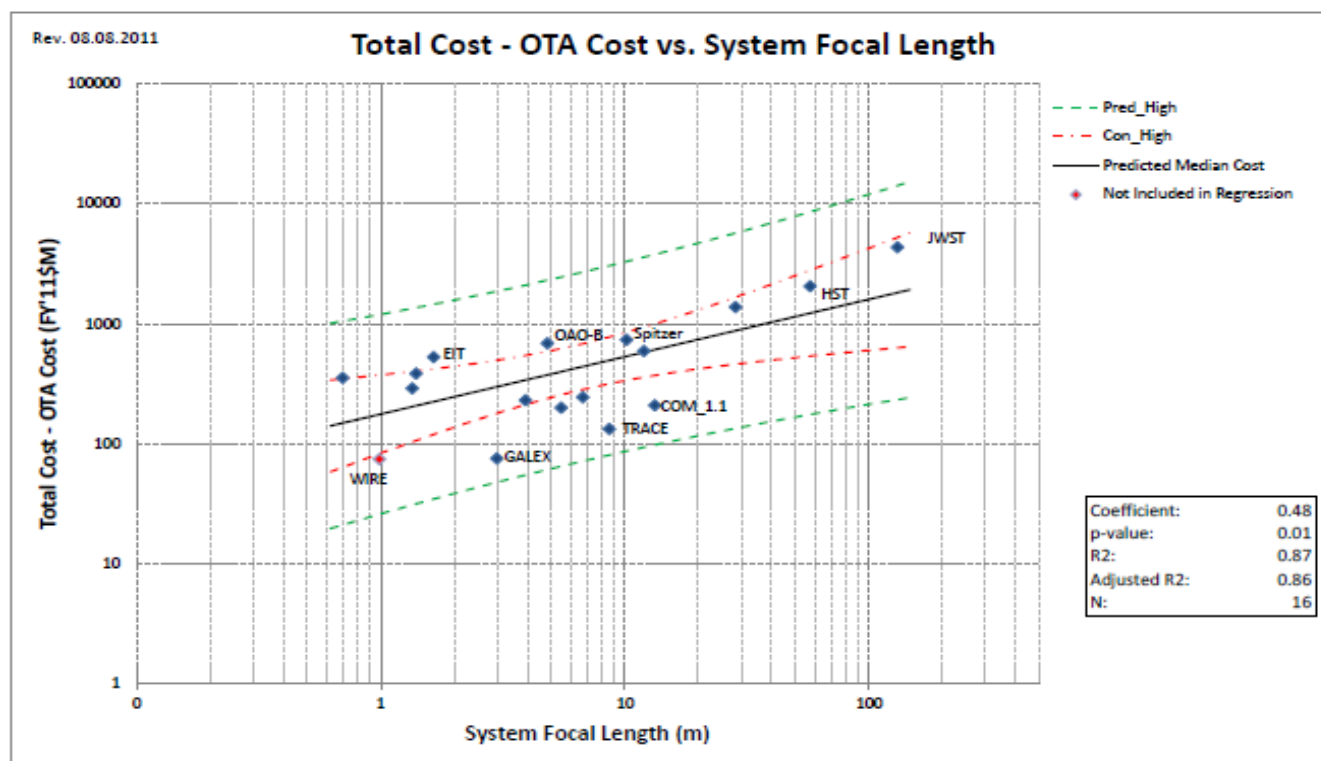




(Total – OTA) Cost vs System Focal Length

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

$$(\text{Total} - \text{OTA}) \text{ Cost} \sim \text{SFL}^{0.5} \quad (N = 16; r^2 = 87\%; \text{SPE} = 85\%)$$

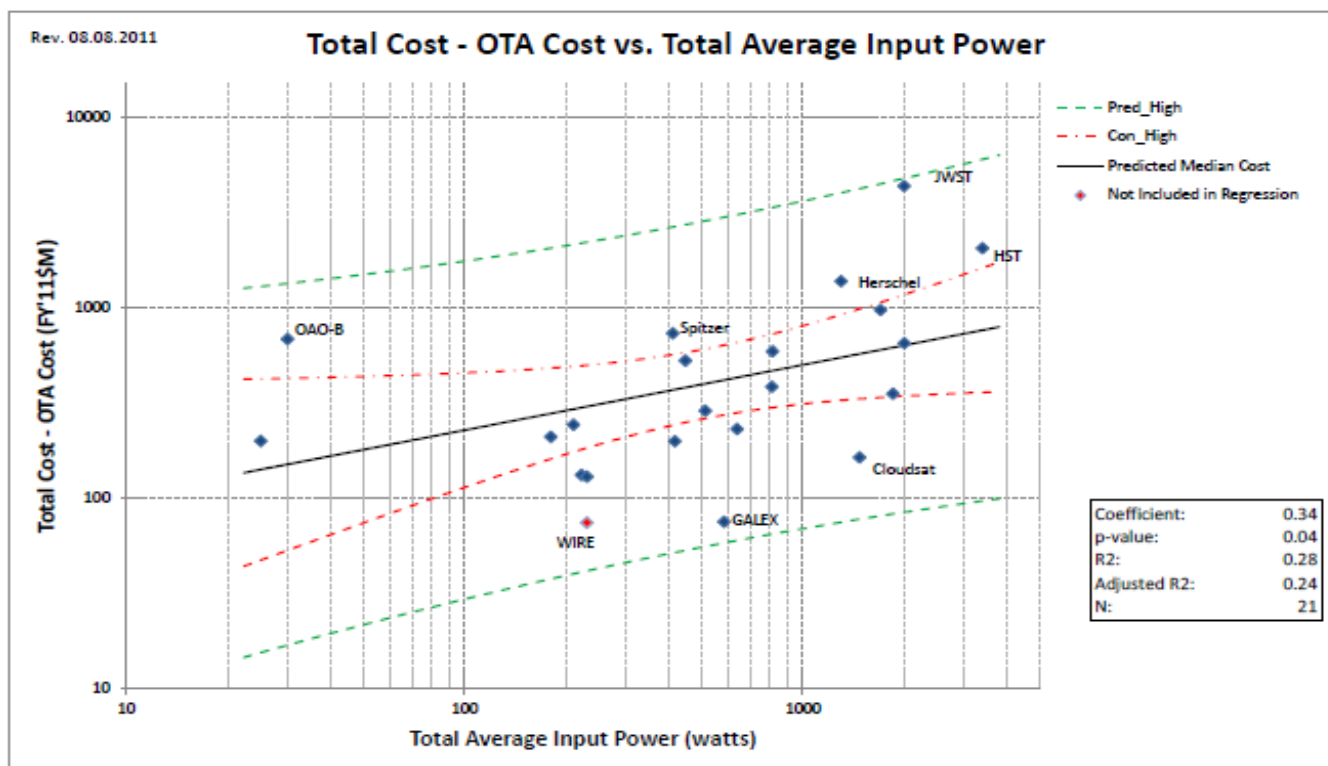




(Total – OTA) Cost vs Power

Mission Cost increases with Average Power requirement:

$$(\text{Total} - \text{OTA}) \text{ Cost} \sim \text{Power}^{0.3} \quad (N = 23; r^2 = 28\%; SPE = 173\%)$$

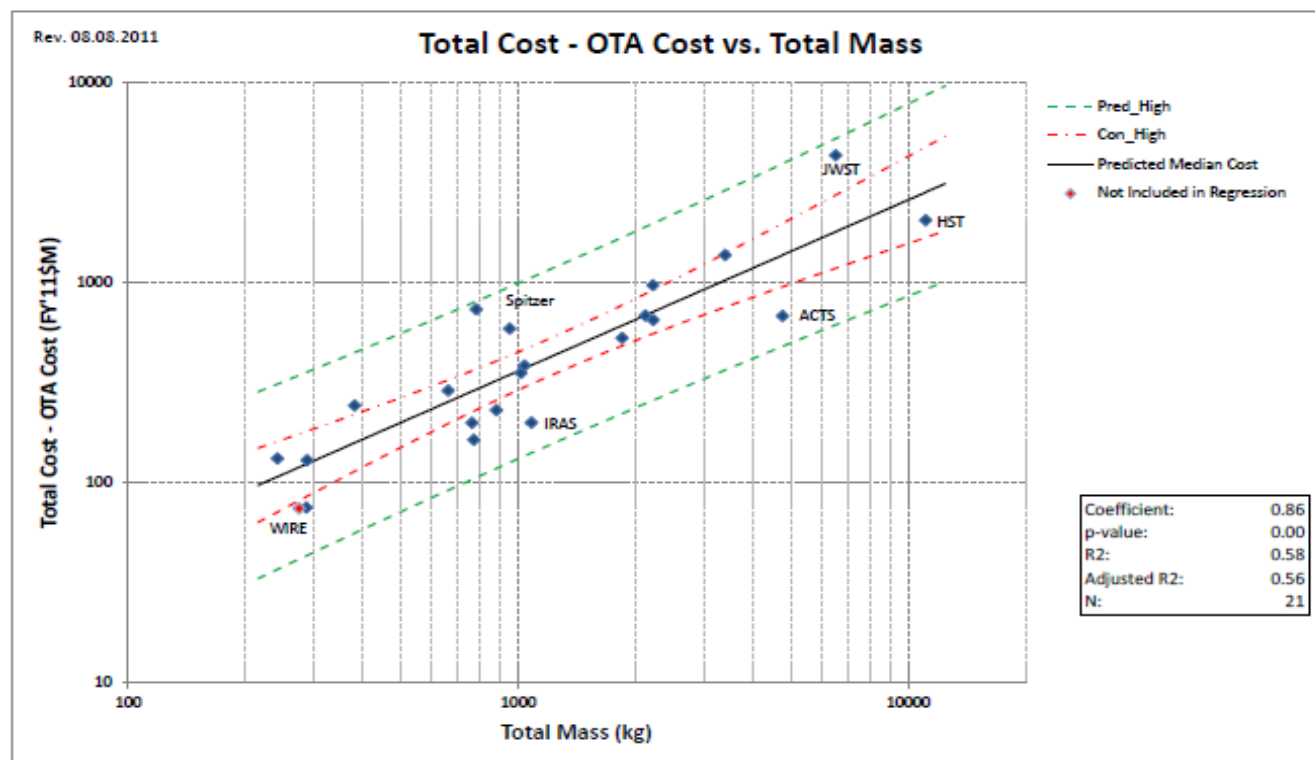




(Total – OTA) Cost vs Mass

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

$$(\text{Total} - \text{OTA}) \text{ Cost} \sim \text{Mass}^{0.9} \quad (N = 21; r^2 = 58\%; SPE = 58\%)$$





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Conclusions

Methodology developed for deriving parametric cost models based on engineering parameters using engineering judgment.

Validity of Cost models (this and historical) depend on database



Conclusions: Aperture

Consistent with Engineering Judgment Aperture Diameter is a good CER for OTA Cost:

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

1 variable only explains 82%, thus a 2 variable model is needed

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

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

In all cases, Areal Cost (\$/m²) is less for larger telescopes



Comparison with Historical Models

This study has identified a potential 3 variable model

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

Bely Model (corrected):

$$\text{OTA Cost} \sim D^{1.6} \lambda^{-0.18} T^{-0.2} e^{-0.033(YOD - 1960)}$$

Horak Model:

$$\text{OTA Cost} \sim D^{0.7} \lambda^{-0.18} T^{-0.2} e^{-0.033(YOD - 1960)}$$

But Horak had a different data base.



Three Variable Aperture Model

No three variable model yields a 'good' result, partly because we lack sufficient data.

Operating Temperature gives a statistically significant result

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

More effort is required to understand issues related to:

Design Life

Year of Development



Conclusions: Mass

OTA mass is not a good CER

OTA mass is multi-collinear with diameter, and
more massive telescopes actually cost less to make.

For a given aperture diameter,

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

Bottom line: using Mass as an OTA CER could easily lead one to
make inappropriate programmatic decisions.



General Conclusions

Larger Diameter OTAs cost more than Smaller, but Larger Diameter OTAs actually cost less per square meter of Collecting Aperture.

Longer Wavelength OTAs cost less than Shorter.

Cryogenic OTAs may cost less than Ambient.

There appears to be a cost reduction with year, but requires more study.

If all parameters are held constant, adding mass reduces cost & reducing mass increases cost.



Future Work

Get more Data

Investigate Operating Temperature.

Investigate Year of Development and Mission Duration.

Study OTA + Thermal System.

Get more Data