Update on Parametric Cost Model for Space Telescopes

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DISCLAIMER

This is a work in progress

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Cost Models are only as good as their Data Base

OLD #1

Last year we published in Optical Engineering the following single variable cost model:

$$\textbf{OTA Cost} \sim \textbf{\$100M x Dia}^{1.20} \quad \textit{(N = 17; } r^2 \textit{ = 75\%; SPE = 79\%)}$$

which explains 75% of the sample population cost variation.

One of the 17 sample points was a 2009 JWST ETC cost estimate (which of course is no longer valid).

OLD #2

Last year at Tech Days 2010 and SPIE Astronomy, we reported the following multi-variable cost models:

Two Variable Models provide better estimates

OTA Cost ~ $100M x $D^{1.3}$ $e^{-0.04(YoD-1960))}$ ***(N = 16, r^2 = 95%; SPE=39%)***

Potential Three Variable Model is:

OTA Cost ~ $D^{1.15}$ $\lambda^{-0.17}$ $e^{-0.03(YoD-1960))}$ ***(N = 20, r^2 = 92%; SPE = 76%)***

Both of which included 2009 JWST ETC cost.

Also, we reported OTA cost is 20 to 30% of Total Mission cost

NRO Database Review

On 13 Sept 2010, I gave a colloquium at the NRO after which the NRO Cost Office requested a copy of our Database.

While they would not give us any data, they did tell us where they disagreed with our data.

As a result, our previously published models have changed.

We are in the process of double checking the contents of our data base and adding new systems to our data base.

Findings

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

The data base is changing and as a result the previously published models may or may not be correct.

An NRO review cast doubt on some of our data. But, accepting their data without review yields ‘inconsistent’ results.

Our current results ‘bounds’ the right answer.

OLD Findings – 9/13/10

Aperture Diameter is principle cost driver for space telescopes.

$$\textbf{OTA Cost} \sim \textbf{\$100M x } \mathbf{D^{1.3}\ \ e^{-0.04(YoD-1990))}}$$

Because cost varies with diameter to a power less then 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 – 5/3/11

Aperture Diameter is principle cost driver for space telescopes.

OTA Cost ~ $D^{1.75}$

Small aperture missions have as large an effect on model slope as large aperture missions.

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

If all other parameters are held constant,

adding mass may reduce cost, and

reducing mass increases cost.

Data Base

Missions (5.3.11 Database)

Currently 42 missions in data base

- 32 'normal-incidence' UVOIR and Infrared telescopes
- 4 grazing incidence X-Ray
- 6 Radio/Microwave

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

To date only normal-incidence telescopes used for cost modeling

Cost Model Missions Database (5.3.11)

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

Missions (5.3.11 Database)

Of 32 'normal-incidence' UVOIR and Infrared telescopes

- 24 are 'Free Flying'
- 4 are 'Attached' and
- 4 are 'Planetary/Lunar'

Cost Model Missions Database (5.3.11)	
Free-Flying	Attached
CALIPSO	SOFIA (747)
Commercial	HUT (Shuttle
Copernicus (OAO-3)	UIT (Shuttle)
EO-1/ALI	WUPPE (Shuttle)
EUVE	
FUSE	Planetary/Lunar
GALEX	LRO/LROC NAC
Herschel	MRO/HiRISE
HST	MGS/MOC
ICESat	MGS/MOLA
IRAS	
ISO	
IUE	
JWST	
Kepler	
LANDSAT-7	
SDO/AIA	
SOHO/EIT	
Spitzer	
STEREO/SECCHI	
TRACE	
WIRE	
WISE	

Sept 10 Database Review

In Sept 2010 the NRO Cost Office reviewed our Database.

As a result, we updated some of our data for:

GALEX, IRAS, IUE & HiRise

And we temporarily eliminated missions from our analysis:

Free Flying: Copernicus, EUVE, ICESat, ISO, SOHO/EIT, TRACE,

Attached: HUT, UIT, WUPPE

One problem is that data which we thought was for OTA only was actually for a complete instrument, i.e. OTA and Focal Plane.

We confirmed this by comparing our database with the SICM (Science Instrument Cost Model) database.

Missions (5.3.11 Database)

These are the missions used in our cost model analysis

12 are 'Free Flying'

1 is 'Attached' and

1 is 'Planetary'

Also, JWST cost is updated.

Cost Model Missions Database	
Free-Flying	Attached
Commercial #1	SOFIA
Commercial #2	
GALEX	Planetary
Herschel	HiRise
HST	
IRAS	
IUE	
JWST	
Kepler	
Spitzer	
WIRE	
WISE	

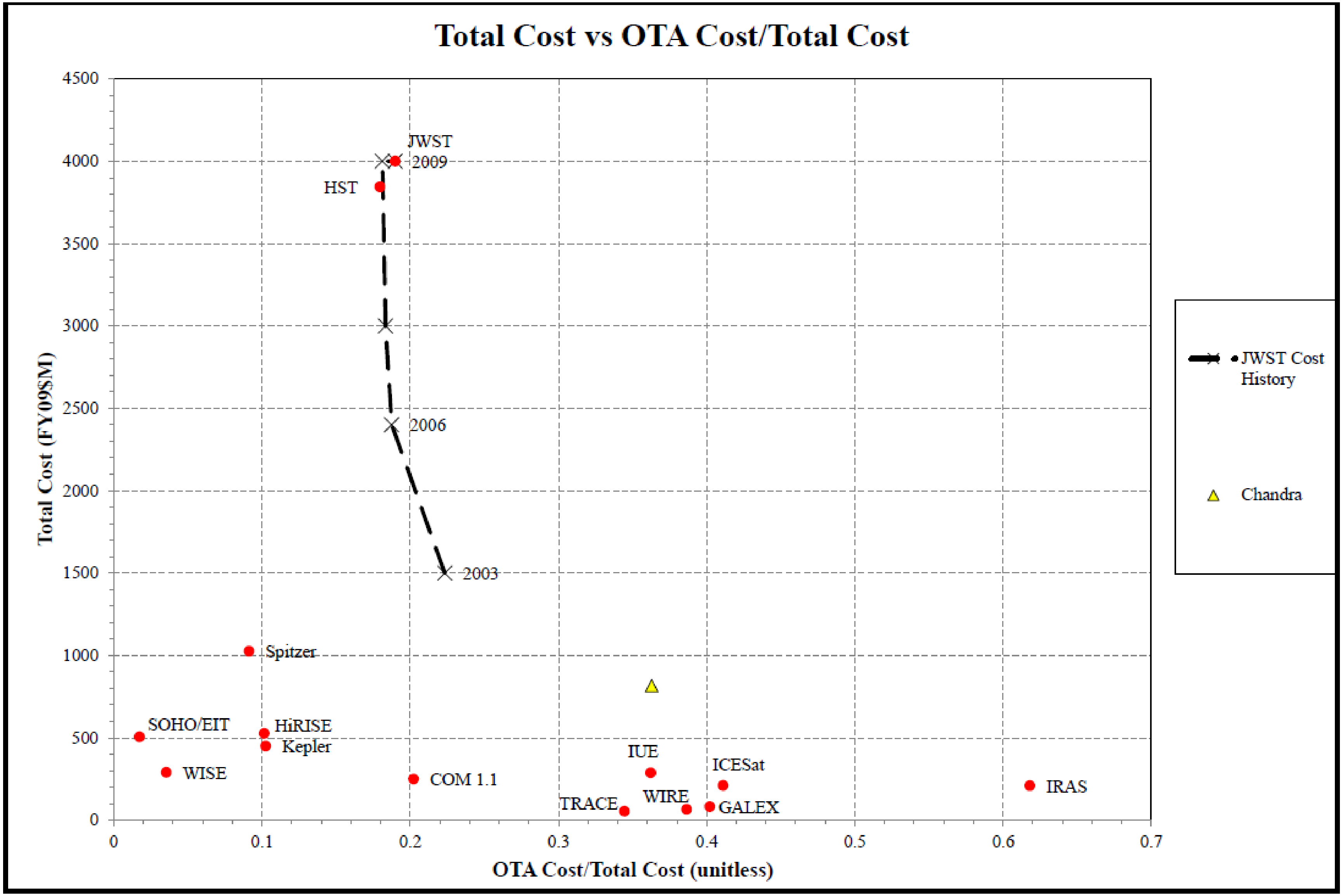
Need Data on Missions (5.3.11 Database)

We need data on missions.

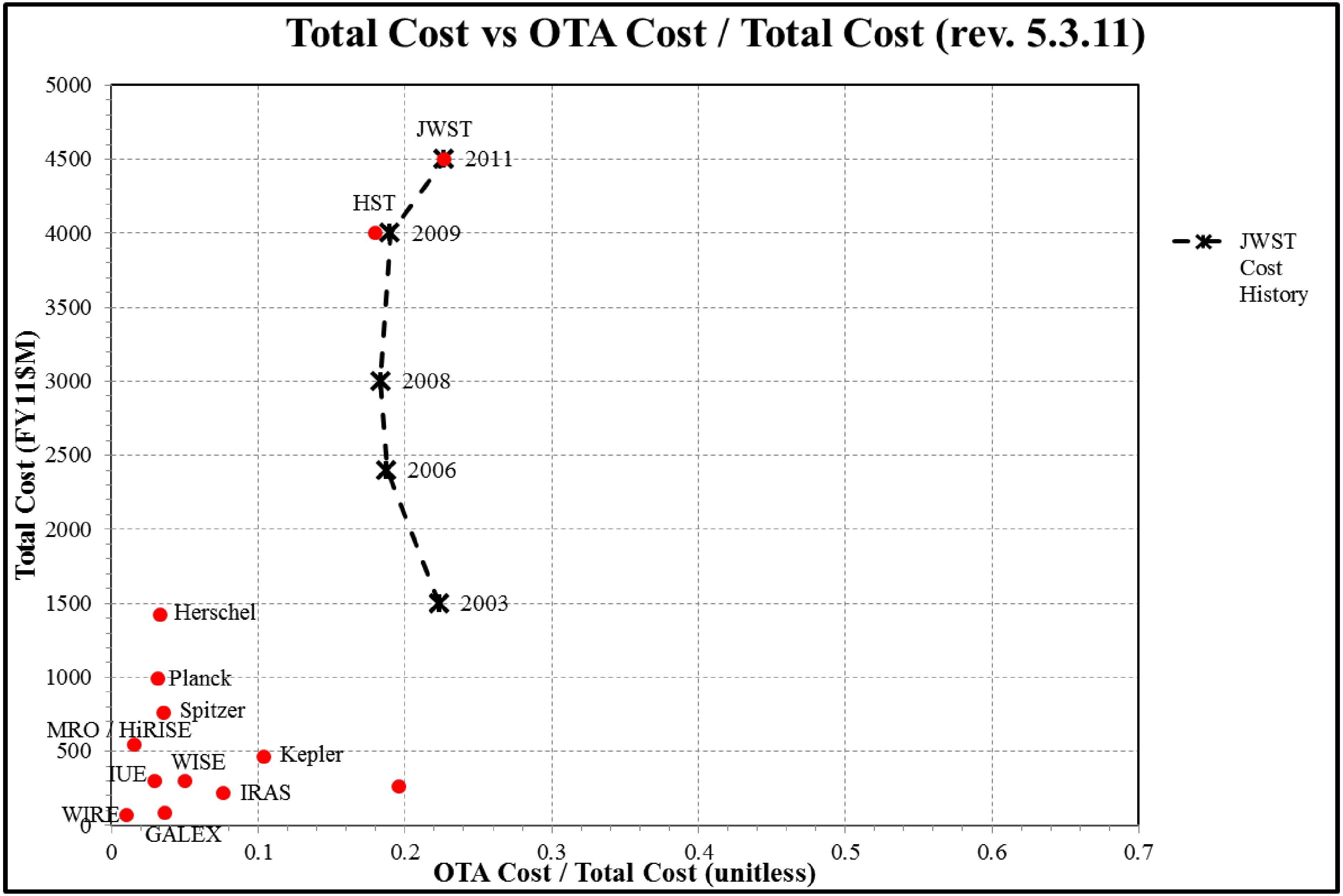
Cost Model Missions Database	
<u>Free-Flying</u>	<u>Attached</u>
CALIPSO	HUT (Shuttle
Copernicus (OAO-3)	UIT (Shuttle)
EO-1/ALI	WUPPE (Shuttle)
EUVE	
FUSE	<u>Planetary</u>
ICESat	LRO/LROC NAC
ISO	MGS/MOC
LANDSAT-7	MGS/MOLA
SDO/AIA	
SOHO/EIT	
STEREO/SECCHI	
TRACE	

Effects of Changes to Database

OTA $ vs % of Total (old)



OTA $ vs % of Total (new)



OTA Cost versus Total Cost

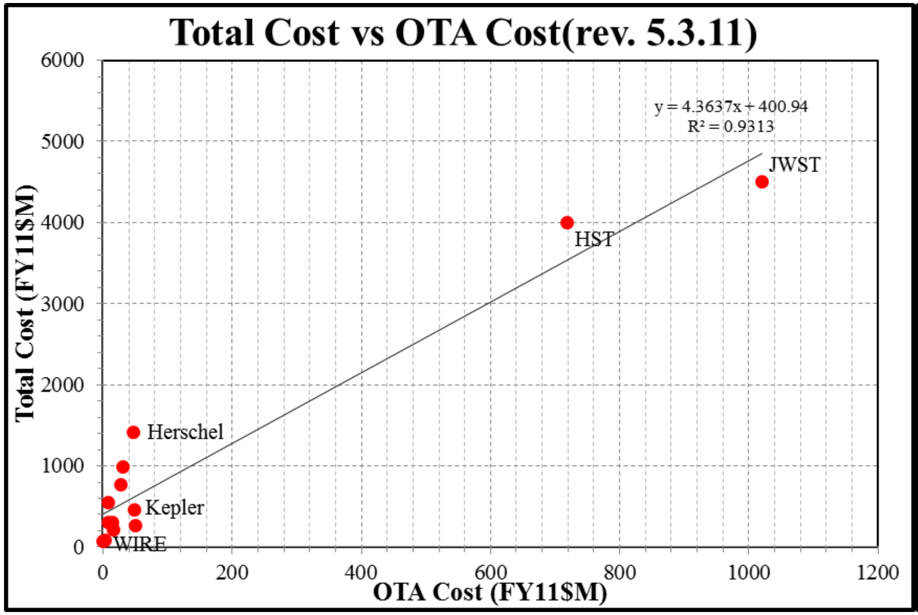
Previously, assumed that OTA cost was fixed percentage of Total mission cost

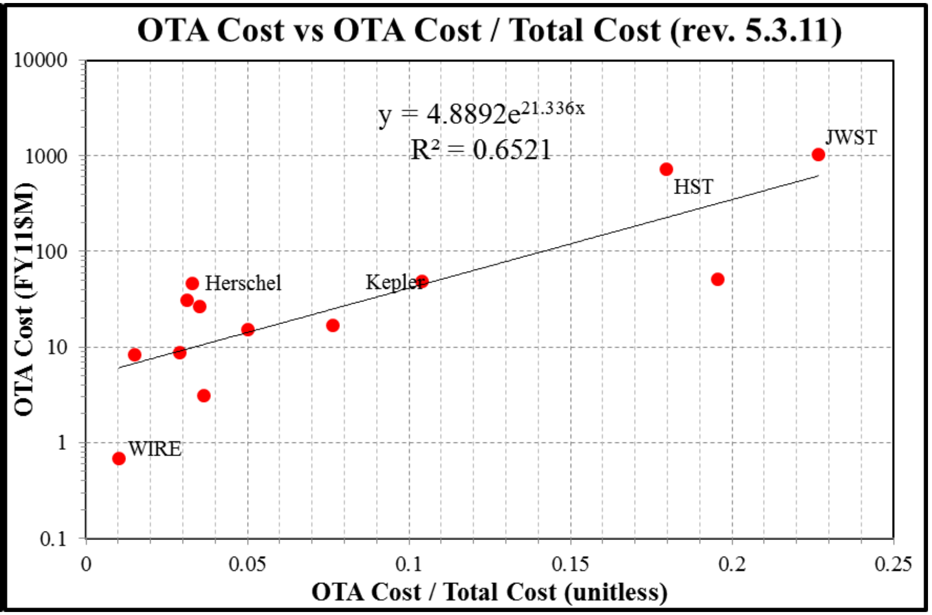
Reported that OTA accounted for 20% to 30% of Total Mission Cost

But, current data indicates that OTA cost varies from 5% to 25%.

More expensive (larger aperture) OTAs are a larger percentage of total mission cost than less expensive (smaller aperture) OTAs

One explanation is that smaller OTAs can be manufactured using existing infrastructure, but larger OTAs require new, 'expensive' infrastructure





Single Variable Results

OTA Cost Regression – without SOFIA

Regressing on 14 normal incidence, 'free-flying' UVOIR OTAs :

- Significant Variables: Diameter, Focal Length, Volume, Pointing & Mass
- Mass has the highest R^2_{adj} and lowest SPE
- Volume, PM FL and Aperture Diameter have acceptable R^2_{adj} & SPE

rev. 5.3.10		OTA Cost vs V1													
Variable Name		Aperture Diameter		PM F Len.		PM f/#		OTA Volume		FOV		Pointing Stability		OTA Mass	
Var.	p-value	1.79	0.00	1.74	0.00	1.15	0.32	0.66	0.00	-0.02	0.96	-0.76	0.01	1.10	0.00
Adjusted r^2		67%		74%		0%		72%		2%		33%		96%	
SPE		142%		123%		835%		114%		1002%		205%		78%	
n		14		12		12		12		13		8		11	

Variable Name		OTA Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.		Year of Dev. (exp)		Date of Launch (exp)	
Var.	p-value	0.05	0.95	-0.14	0.54	-0.20	0.40	0.23	0.53	-0.01	0.93	0.04	0.49
Adjusted r^2		-11%		2%		-2%		-8%		-8%		-4%	
SPE		1186%		1041%		974%		1316%		1422%		1300%	
n		11		14		12		13		13		14	

OTA Cost Regression – with SOFIA

Regressing on 15 normal incidence, UVOIR OTAs:

- Significant Variables: Diameter, Focal Length, Volume Pointing & Mass
- Aperture Diameter and Focal Length have the highest R^2_{adj}
- Mass has the lowest SPE

rev. 5.3.10		OTA Cost vs V1													
Variable Name		Aperture Diameter		PM F Len.		PM f/#		OTA Volume		FOV		Pointing Stability		OTA Mass	
Var.	p-value	1.75	0.00	1.74	0.00	1.08	0.34	0.65	0.00	-0.15	0.68	-0.76	0.01	0.97	0.00
Adjusted r^2		67%		75%		2%		72%		4%		33%		56%	
SPE		146%		117%		729%		116%		719%		205%		88%	
n		15		13		13		13		14		8		12	

Variable Name		OTA Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.		Year of Dev. (exp)		Date of Launch (exp)	
Var.	p-value	0.16	0.83	-0.16	0.46	-0.19	0.42	0.27	0.43	0.00	0.98	0.04	0.42
Adjusted r^2		-9%		2%		-1%		-7%		-8%		-3%	
SPE		1084%		900%		845%		1162%		1225%		1183%	
n		12		15		13		14		14		15	

Mass Model

As an optical engineer, my preference is to develop a model based on an optical parameter, i.e. Aperture Diameter.

Aperture Diameter is what most interests 'users' of space telescopes because it is directly proportional to sensitivity and resolution.

But, many believe that Mass is the most important CER parameter.

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.

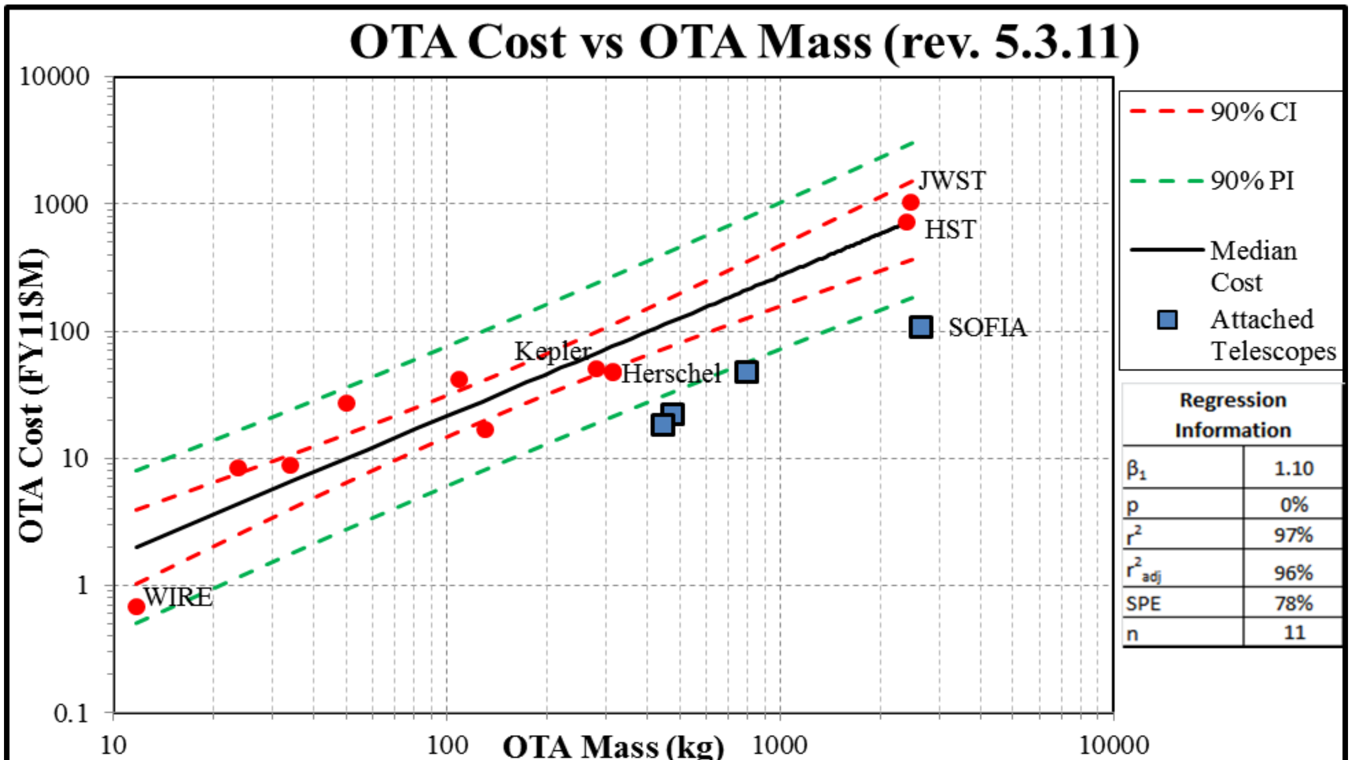
<u>Space telescopes are designed to mass</u>

Mass Model

Regressing OTA Cost vs OTA Mass for just free-flying missions in data base (excluding ‘attached’):

OTA Cost ~ OTA Mass $^{1.1}$ ***(N = 11; r^2 = 96%; SPE = 78%)***

Mass explains 96% of the cost variation

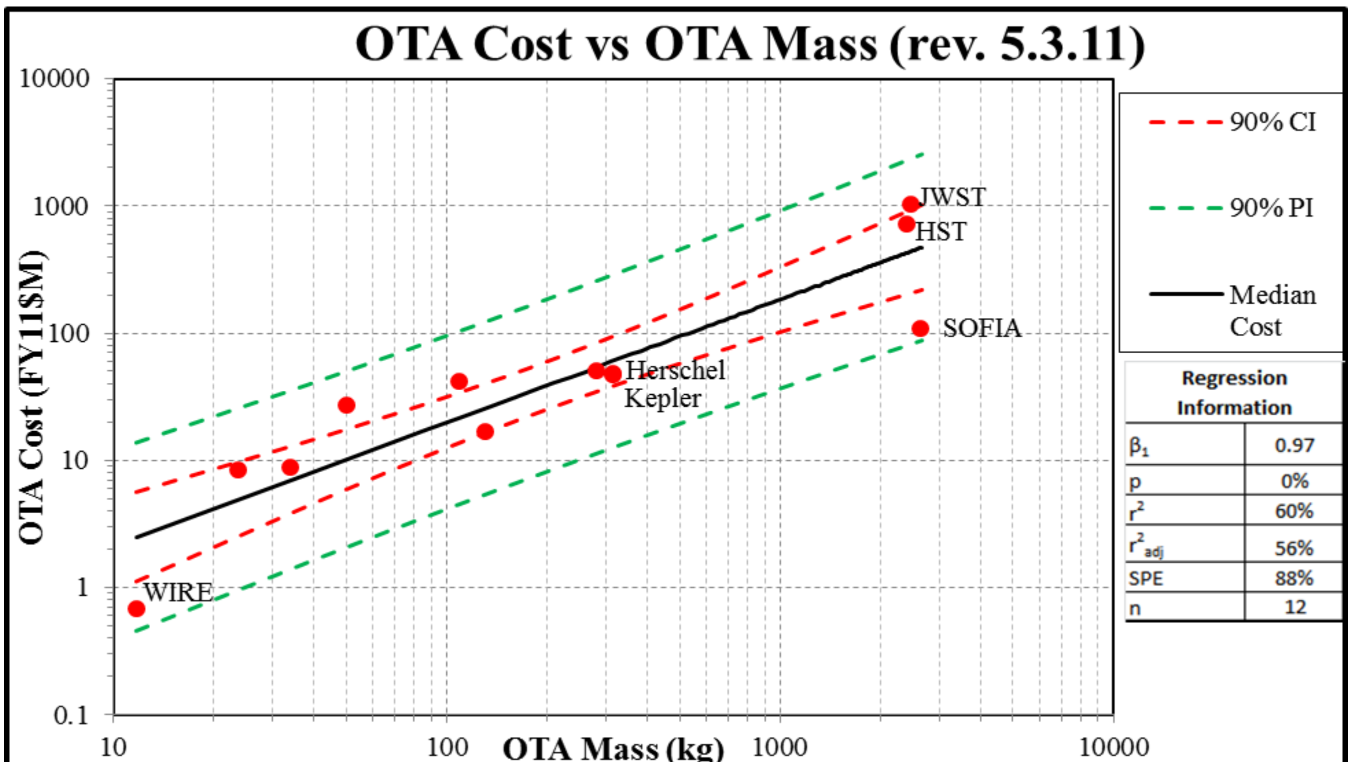


Mass Model

Adding SOFIA (but not other attached because they are Instruments and not OTAs) to the regression:

OTA Cost ~ OTA Mass $^{0.97}$ ***(N = 12; r^2 = 56%; SPE = 88%)***

Mass accounts for 56% of the cost variation

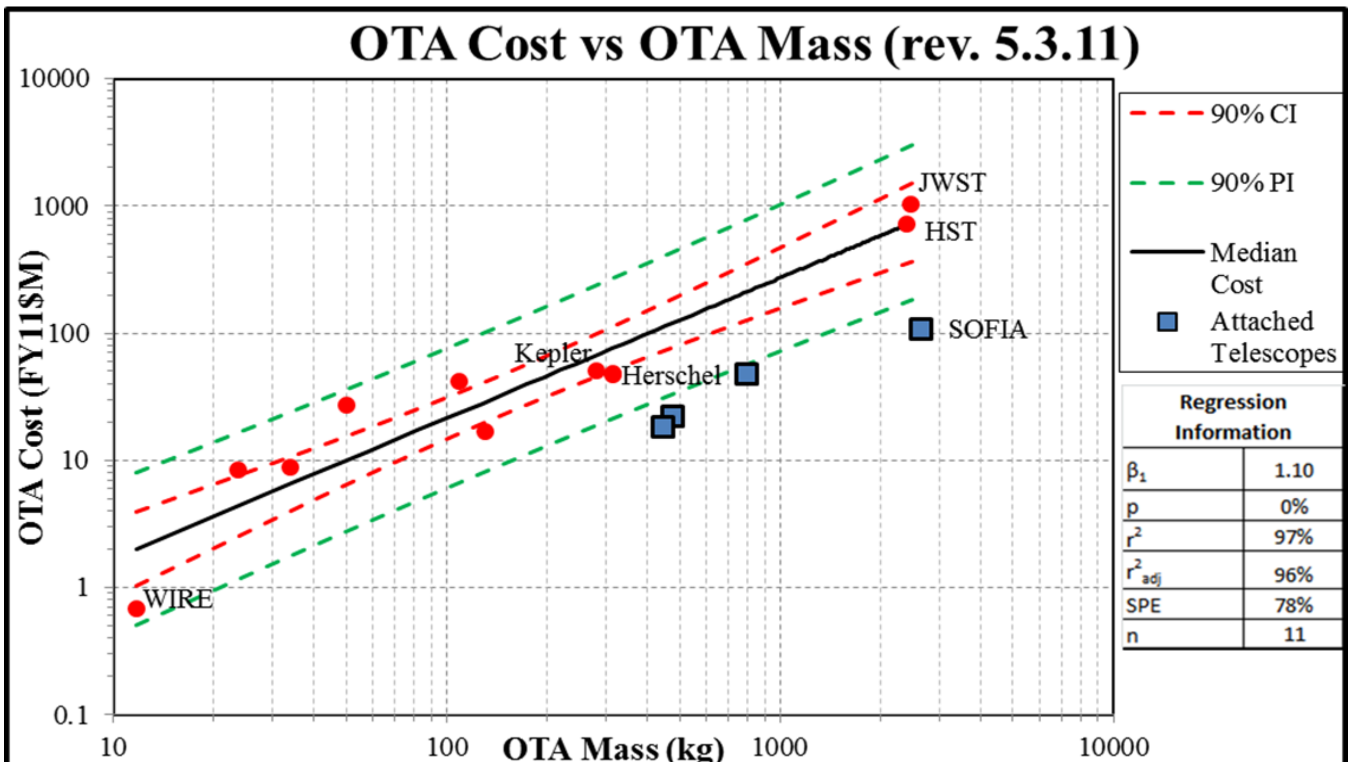


Mass Model

Key question is what is meaning of this plot?

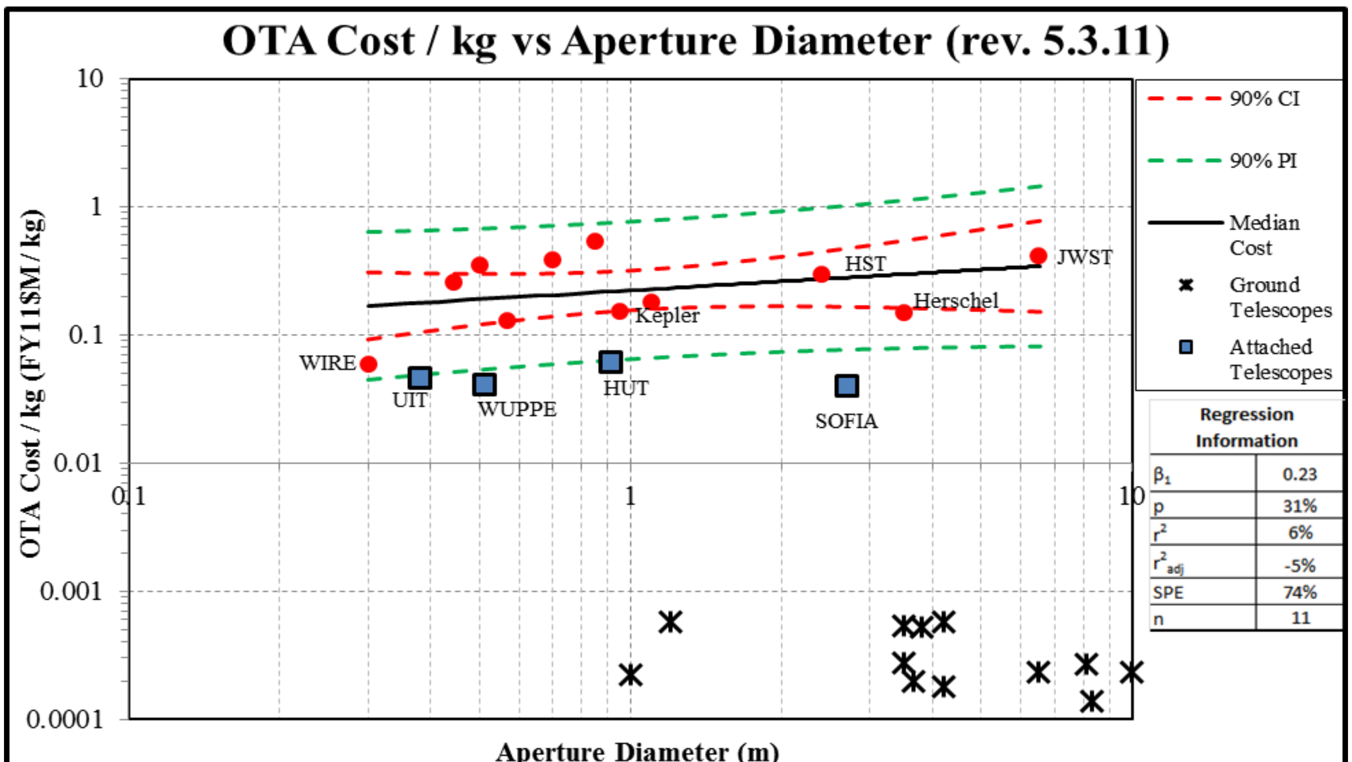
Are ‘attached’ missions lower cost than ‘free-flying’?

Initially we thought yes, that ‘attached’ were lower cost because they were higher mass.



It Costs more to make a Low Mass OTA

- Cost per kg depends on mission ‘type’; is independent of aperture size
- Free-Flying OTAs are ~5.5X more expensive per kg than Attached OTAs
- Ground OTAs are 1000X less expensive per kg than Free-Flying OTAs
- However, ‘Attached’ UIT, WUPPE and HUT are Instruments not OTAs, we do not know the OTA cost or mass.



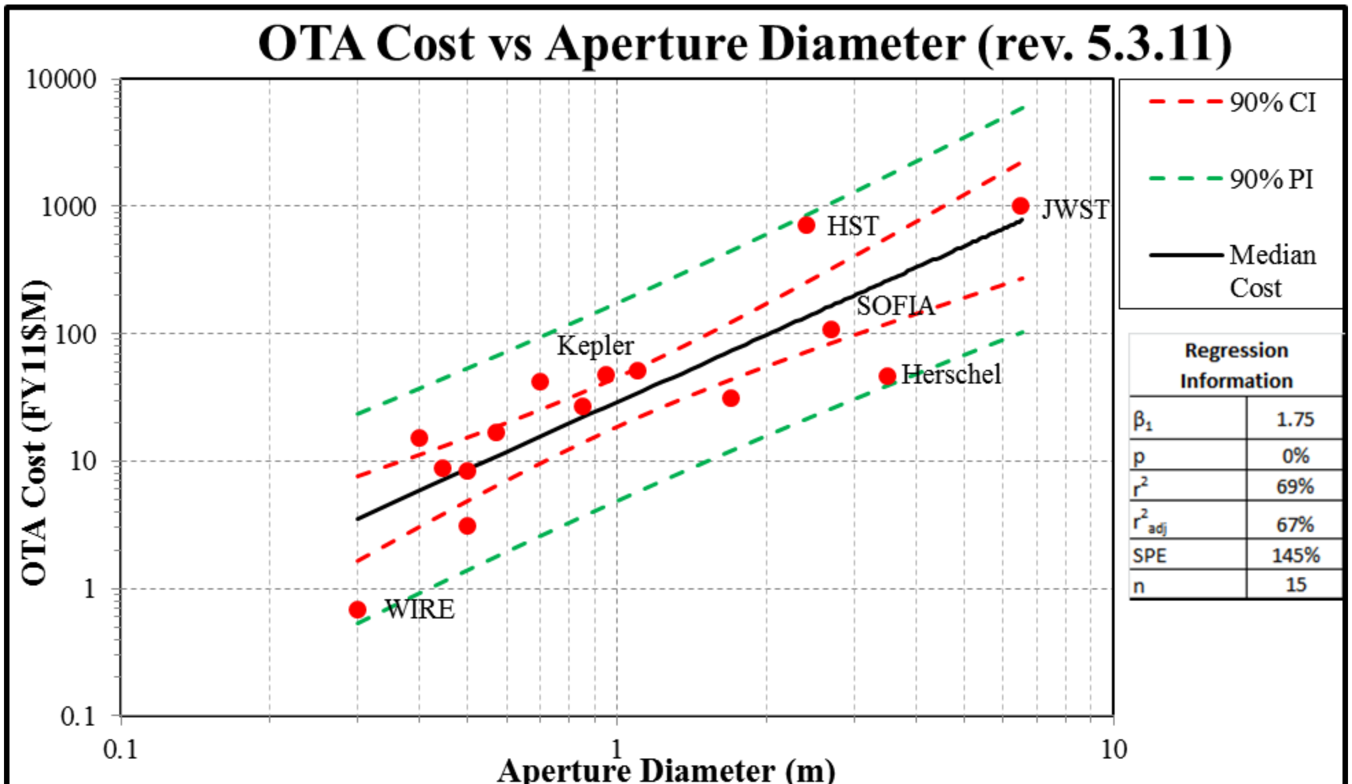
Considering SOFIA

Looking at Aperture Data, SOFIA's OTA Cost is 'in-family'.

HST & SOFIA have similar apertures (also Herschel) but different cost

To confuse matters more, Herschel & Kepler have similar mass & cost but different apertures

Maybe there is a wavelength effect?



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

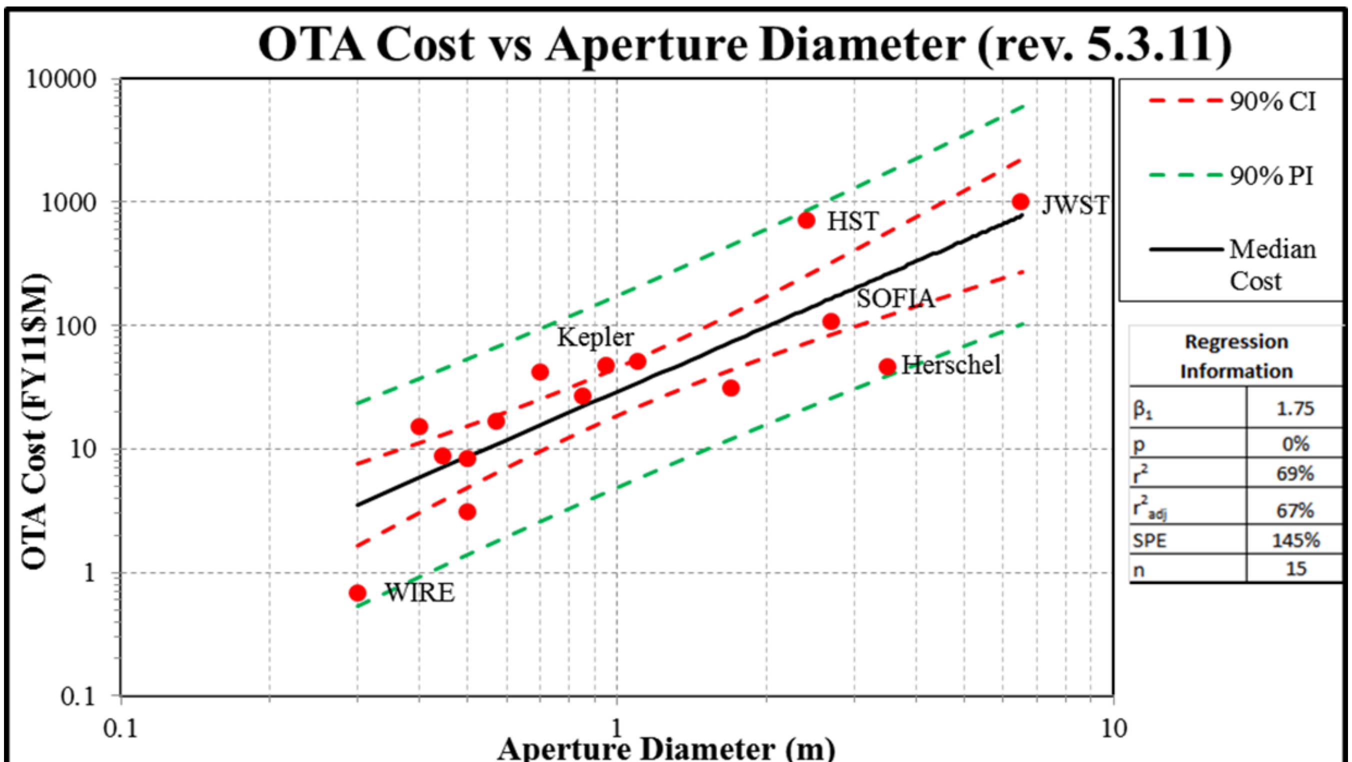
<u>But in reality it is all Aperture, the others depend on aperture.</u>

Aperture Model

Regressing OTA Cost vs Aperture for all missions in database:

OTA Cost ~ Diameter $^{1.75}$ ***($N = 15$; $r^2 = 67\%$; $SPE = 145$)***

Diameter accounts for 67% of the cost variation, but is noisy



Need for a second variable

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

Aperture Model only accounts for 67% of the cost variation.

Therefore, other variables must account for the remaining 33% of the cost variation.

Thus, a multi-variable model is required.

Conclusions

Conclusions

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

The data base is changing and as a result the previously published models may or may not be correct.

Aperture Diameter is principle cost driver for space telescopes.

$$\textbf{OTA Cost} \sim \textbf{D}^{1.75}$$

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

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