Multivariable Parametric Cost Model for Ground AND Space Telescope

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Executive Summary

Based on a 46 telescope database, MSFC cost office has developed a parametric cost model:

$$\mathbf{OTA\$\ (FY17) = \$20M \times 30^{(S/G)}\ D^{(1.7)}\ \lambda^{(-0.5)} * T^{(-0.25)}\ e^{(-0.027)\,(Y-1960)}}$$

where:

- Space Telescopes are approx. 30X more expensive than Ground
- Cost increases with Aperture Diameter to power of 1.7
- Cost decreases with Diffraction Limit to power of -0.5
- Cost decreases with Operating Temperature to power of -0.25
- Cost decreases 50% approx. every 25 years.

Statistical Quality is: R2 = 92%, Data SE=21%, Predictive SE=45%

- R2 = % of data variation described by model
- Data SE = Standard Deviation of Fit Residual Error
- Predictive SE = Standard Deviation Uncertainty of Prediction

Introduction, Disclaimers and Definitions

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 total project cost.

However

All Cost Models are Wrong!

But Some are Useful.

The Rest will get you into Trouble.

Expectations

- Cost Models CANNOT predict the cost of a specific mission or any component of that mission.
    - They provide an estimate of the most probable cost and an estimate of the uncertainty of that cost.
- Cost Models are backward looking.
    - They develop Cost Estimating Relationships (CERs) between the cost of historical missions and quantifiable technical/programmatic parameters.
- Cost Models are a RELATIVE tool.
    - They use CERs to estimate a potential cost relative to a historical cost.

Database

- Cost Models are only as good as their Database.
- The hardest part of Cost Modeling is collecting and validating the database.
- This is a 20 year work in progress.
- The results evolve as we add new missions to the Database, add data to or correct data in the Database.

Cost Estimating Relationships (CERs)

- A Cost Model is a statistical correlation between an item's Historical Cost (dependent variable) & quantifiable technical or programmatic parameters (independent variables).

- Correlations are called Cost Estimating Relationships (CERs).

- Based on experience, we have chosen 4 CERs:
  - Primary Mirror Diameter
  - Wavelength of Diffraction Limited Performance (WDLP)
  - Operating Temperature
  - Year of Development (YOD)

- We believe that Mass is not a valid CER.

Limitations

- Cost Model interpretation must be consistent with laws of physics, engineering practice and program management.
- Blindly using a Cost Model CER without understanding its assumptions and constraints will lead to wrong conclusions and potentially very expensive decisions.

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)

Database Status

Significant Changes

Over the last few years, made significant changes to the Ground Telescope Database:

- Diffraction Limited Wavelength Performance (2017)
- Year of Development (2018)

While putting together the integrated model, realized that we were using different definitions for Year of Development.

- Ground Telescopes were using First Light (this is wrong)
- Space Telescopes were using start of Phase C

The integrated model is so good that and examination of outliers frequently uncovers database errors.

MSFC Cost Database (2018)

MSFC Cost Database collects data on over 45 potential CERs.

Currently have 100% completeness of OTA Cost and 4 key CERs for 46 telescopes:

- 20 Ground Telescopes
    - Diameter ranges from 1 meter to 100 meters
    - WDLP ranges from 500 nm to 21 centimeters
    - YOD ranges from 1979 to Present
    - 14 Monolithic and 6 Segmented

- 26 Space Telescopes
    - Diameter ranges from 30 cm to 6.35 meter
    - WDLP ranges from 400 nm to 2 mm
    - Operating Temperature ranges from 4 to 300K
    - YOD ranges from 1962 to Present
    - 22 Monolithic and 4 Segmented
    - 18 Imaging and 8 Non-Imaging

Database significantly updated after 2010 NRO Cost Office review.

Database Parameters

Primary Mirror Specific Information	
PM Cost	$ FY M
PM Aperture Diameter	meters
PM Thickness	cm
PM Surface Figure Error	rms nm
PM Material	
PM Focal Length	meters
PM F/#	
PM Mass	kg
PM First Mode Frequency	Hz
Optical Telescope Assembly Information	
OTA Cost	$ FY M
Diffraction Limit	micrometers
Transmitted WFE	nm rms
OTA Structure First Mode	Hz
OTA Mass	kg
System Focal Length	meters
System F/#	
FOV	degrees
Spatial Resolution	arc-seconds
Year of Development	
Development Period	months
Design Life	months
TRL	

Total System Information	
Total Cost	$ FY M
OTA + Thermal Cost	$ FY M
Instrument Cost	$ FY M
Operating Temperature	K
Total Mass	kg
OTA + Thermal Mass	kg
Instrument Mass	kg
Spectral Range Minimum	micrometers
Spectral Range Maximum	micrometers
Total Avg Input Power	Watt
Instrument Avg Power	Watt
Data Rate	Kbps
Start Date	
Date of Launch	
Orbit	km
Launch Vehicle	
Pointing Knowledge	arc-second
Pointing Accuracy	arc-second
Pointing Stability/Jitter	arc-sec/sec
# of Primary Mirrors	
# of Instruments	
# of Curved Optics	
Coating	

Ground Telescope Data Base – excluding Cost

rev. 11.01.2018	Effective Diameter	Diffraction Limit	Temp	Year of Dev.
	(m)	(µm)	K	(year)
JKT	1.00	1.00	270.00	1977
Commercial	1.00	0.50	300.00	2013
Starfire	3.50	0.53	273.00	1989
WIYN	3.50	0.42	263.00	1988
AEOS	3.67	0.85	273.00	1991
UKIRT	3.80	2.20	273.00	1974
SOAR	4.20	1.00	263.00	1997
WHT	4.20	6.10	270.00	1981
DKIST	4.20	0.90	300.00	2011
MMT 6.5m replacement	6.50	1.60	262.00	1992
Magellan 1	6.50	1.00	280.00	1994
Gemini 1	8.10	0.80	270.00	1994
Subaru	8.30	0.60	273.00	1988
KECK 1	10.00	1.00	273.00	1986
LBT	11.88	0.65	273.00	1997
KECK-I&II	14.14	1.00	273.00	1986
HET	9.20	20.00	264.00	1994
Commercial Radio	5.00	210000.00	300.00	2012
SubMM Array Dish	6.00	300.00	300.00	1998
Green Bank Radio	100.00	6500.00	300.00	1991

Space Telescope Data Base – excluding Cost

rev. 11.01.18	Aperture Diameter	Total Effective Aperture Diameter	Diff. Lim. λ	Operating Temp.	Year of Development
Imaging	(m)	(m)	(μ)	(K)	(year)
AFTA	2.40	2.40	0.78	284	1992
COM_0.7	0.70	0.70	0.50	283	1996
COM_1.1	1.10	1.10	0.65	283	2007
Herschel	3.50	3.50	80.00	80	2001
HST	2.40	2.40	0.50	294	1973
IRAS	0.57	0.57	8.00	4	1977
JWST	6.35	6.20	2.00	50	2006
Kepler	0.95	1.40	1.00	213	2001
MO / MOC	0.35	0.35	0.53	283	1986
MRO / HiRISE	0.50	0.50	0.40	293	2001
OAO-2 / CEP	0.31	0.61	1.50	300	1962
OAO-3 / PEP	0.80	0.80	2.40	288.5	1963
Planck	1.70	1.70	300.00	40	2001
Proprietary	2.40	2.40	0.60	300	2012
Spitzer	0.85	0.85	6.50	5.5	1995
WIRE	0.30	0.30	24.00	12	1995
WISE	0.40	0.40	2.75	17	2002
WMAP	1.40	2.10	1300.00	60	1996
Non-Imaging					
ACTS	3.97	3.97	1950.00	263	1984
Cloudsat	1.85	1.85	1300.00	250	2000
GALEX	0.50	0.50	8.00	273	1998
ICESat	1.00	1.00	8.00	283	1998
IUE	0.45	0.45	3.50	273	1973
MO / MOLA	0.50	0.50	15.00	283	1986
OAO-B / GEP	0.97	0.97	5.00	289	1964
SWAS	0.68	0.68	286.00	170	1993

Telescope Cost Model

MSFC Multivariable Telescope Cost Model

Based on a 46 telescope database, MSFC cost office has developed a parametric cost model:

$$\textbf{OTA\$ (FY17)} = \$20M \times 30^{(S/G)} D^{(1.7)} \lambda^{(-0.5)} T^{(-0.25)} e^{(-0.027)(Y-1960)}$$

where:

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Application Examples

Model can be used as a direct equation or as a relative comparator.

For example, as a direct calculation, assume HabEx:

- 4 m diameter
- 0.4 µm diffraction limited telescope
- 270K operating temperature
- 2025 year of development

Most likely cost estimate (50% probability) < $0.5 B

$$\$20M \times 30 \times (4)^{(1.7)} \times (.4)^{(-0.5)} \times (270)^{(-0.25)} \times e^{(-0.027)(2025-1960)}$$

$$\$20M \times 30 \times 10.6 \times 1.6 \times 0.25 \times 0.17 = \$\ 430\ M$$

NOTE: recommend rounding up to 1 significant digit.

84% probable cost (estimate + SE_{pred}) < $0.7B (actually $ 0.62B)

Application Examples

Or, as a comparison to another telescope such as JWST or HST.

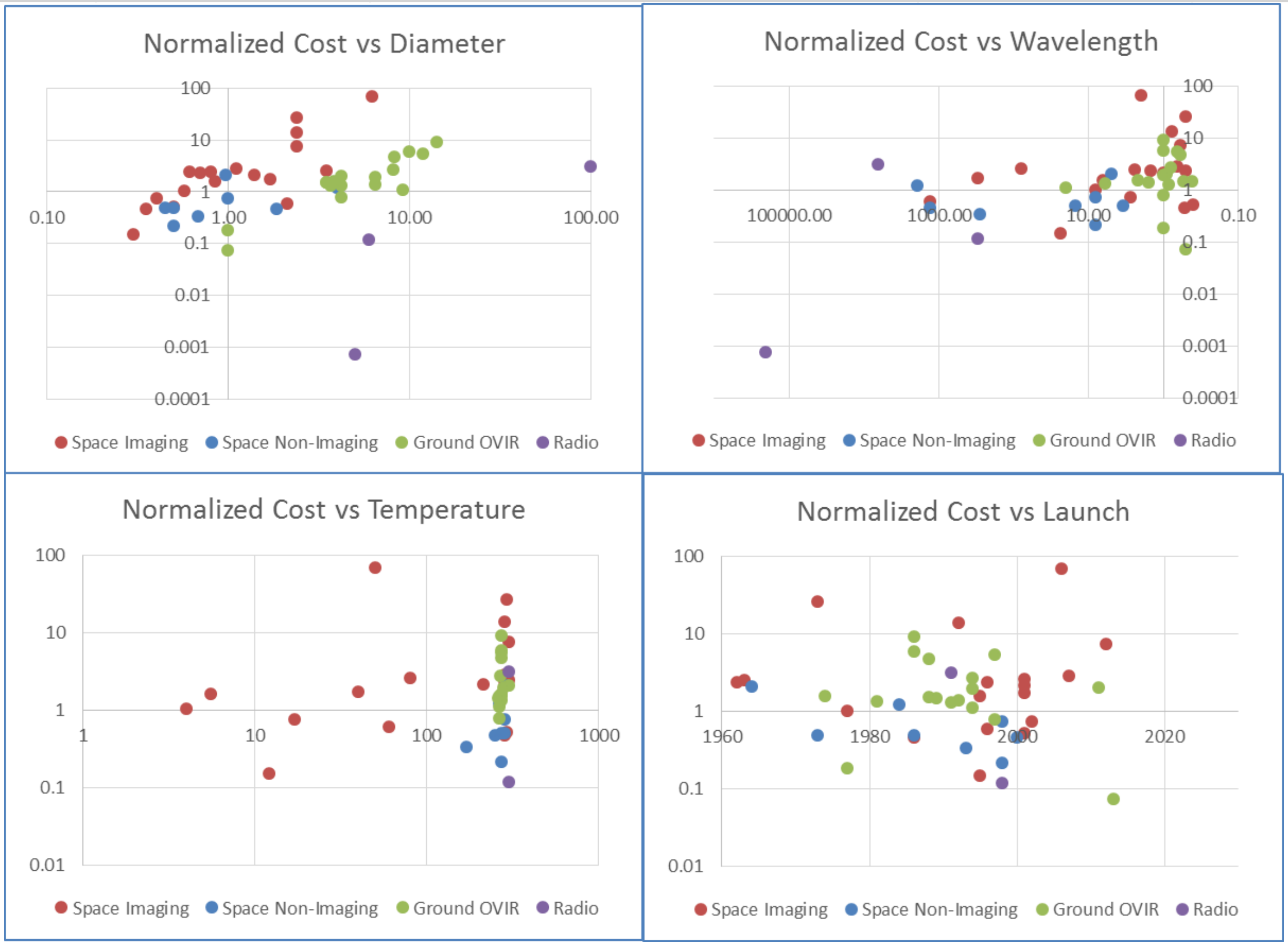
		JWST	HabEx	Ratio
Total Cost [FY17 $M]		$1,380		
Diameter [meter]	1.7	6.35	4	0.46
WDLP [micrometer]	-0.5	2	0.4	2.24
Temperature [K]	-0.25	50	270	0.66
exp(YOD)	-0.027	2006	2025	0.60
50% Predicted Cost [FY17 $M]			$552	0.40
85% Predicted Cost [FY17 $M]			$801	

		HST	HabEx	Ratio
Total Cost [FY17 $M]		$530		
Diameter [meter]	1.7	2.4	4	2.38
WDLP [micrometer]	-0.5	0.5	0.4	1.12
Temperature [K]	-0.25	294	270	1.02
exp(YOD)	-0.027	1973	2025	0.25
50% Predicted Cost [FY17 $M]			$354	0.67
85% Predicted Cost [FY17 $M]			$514	

Graphical Residual Analysis

Raw OTA$ Data: Ground & Space Combined

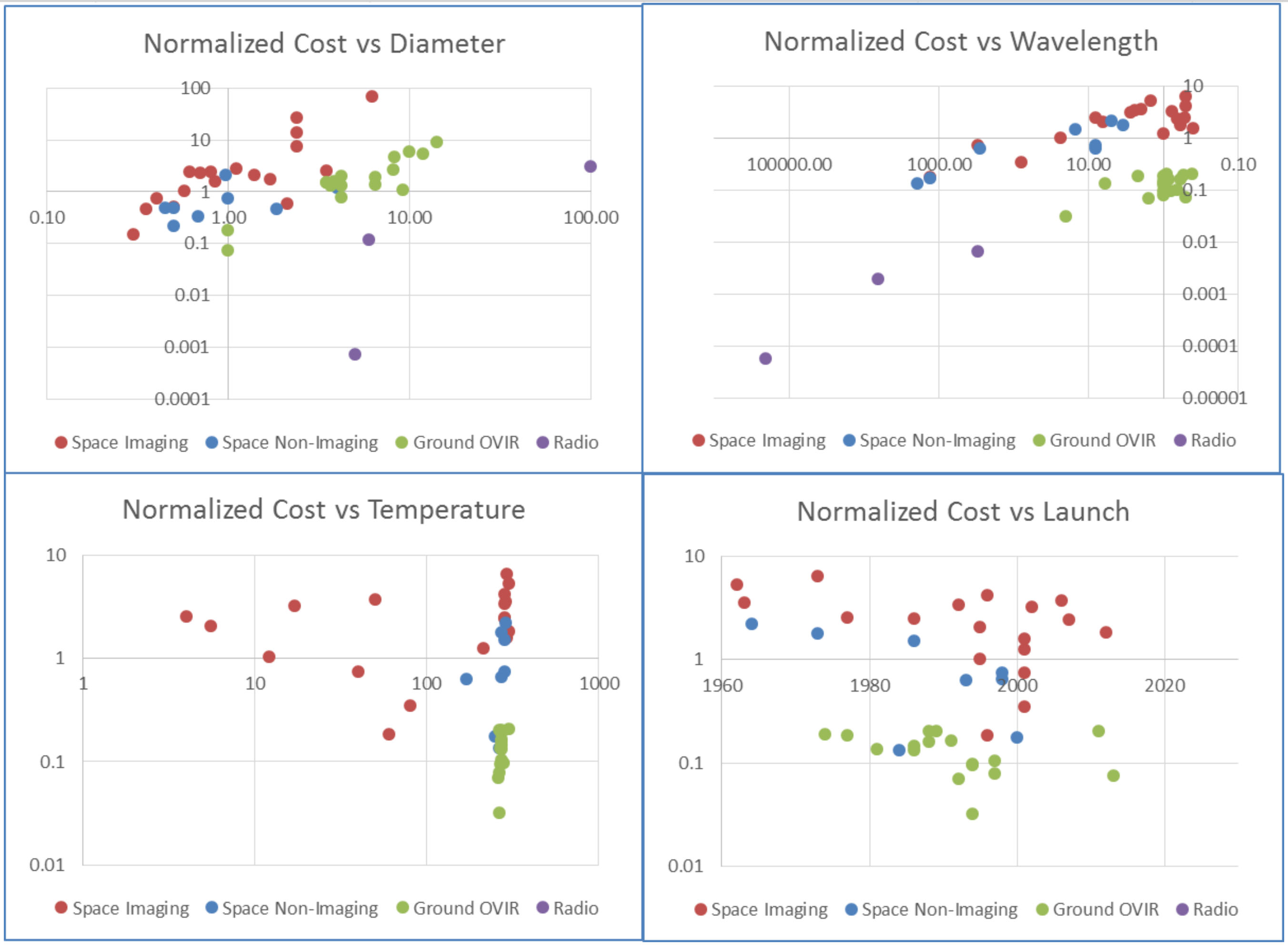
OTA Cost	Scale Factor	Eff Aperture Dia	Diff. Lim. λ	Operating Temp.	Year of Dev.
(FY17$M)		(m)	(μ)	(K)	(year)
20	0	0	0	0	0



First normalize for Diameter – will effect all but Cost vs Dia Plot

OTA$ / (Dia)

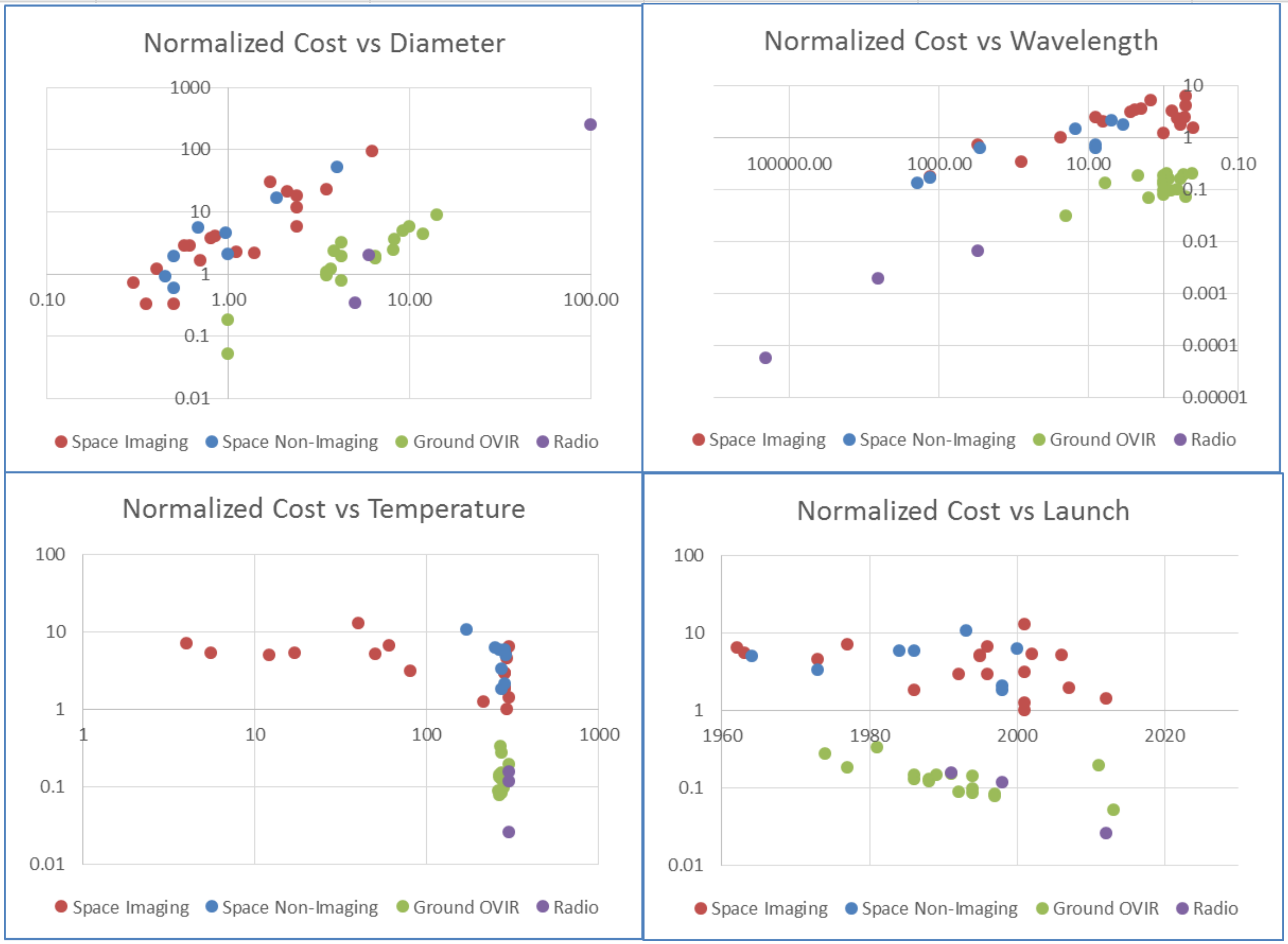
OTA Cost	Scale Factor	Eff Aperture Dia	Diff. Lim. λ	Operating Temp.	Year of Dev.
(FY17$M)		(m)	(μ)	(K)	(year)
20	0	1.6	0	0	0



Next normalize for Wavelength – will effect all but WDLP

OTA$ / (Dia, WDLP)

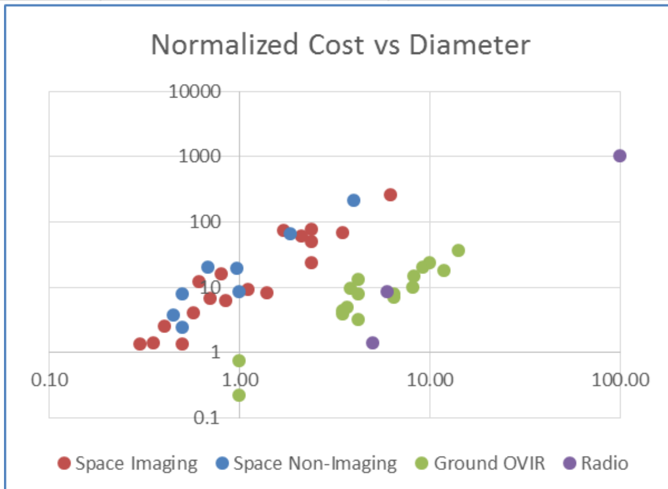
OTA Cost	Scale Factor	Eff Aperture Dia	Diff. Lim. λ	Operating Temp.	Year of Dev.
(FY17$M)		(m)	(μ)	(K)	(year)
20	0	1.6	-0.5	0	0

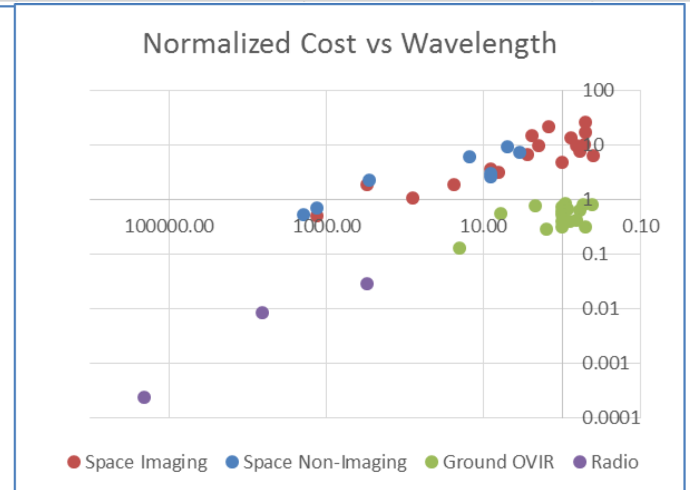


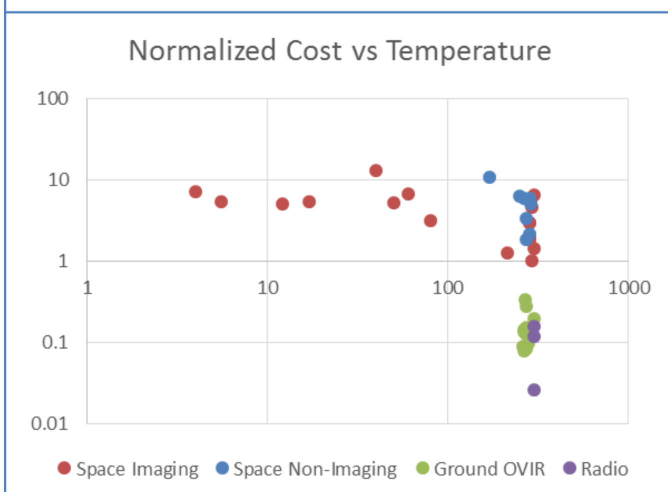
Next normalize for Temperature – will effect all but Temp

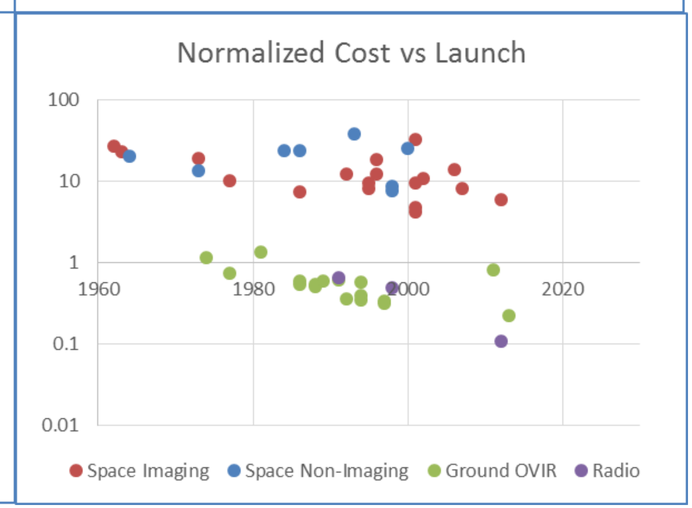
OTA$ / (Dia, WDLP, T)

OTA Cost	Scale Factor	Eff Aperture Dia	Diff. Lim. λ	Operating Temp.	Year of Dev.
(FY17$M)		(m)	(μ)	(K)	(year)
20	0	1.6	-0.5	-0.25	0





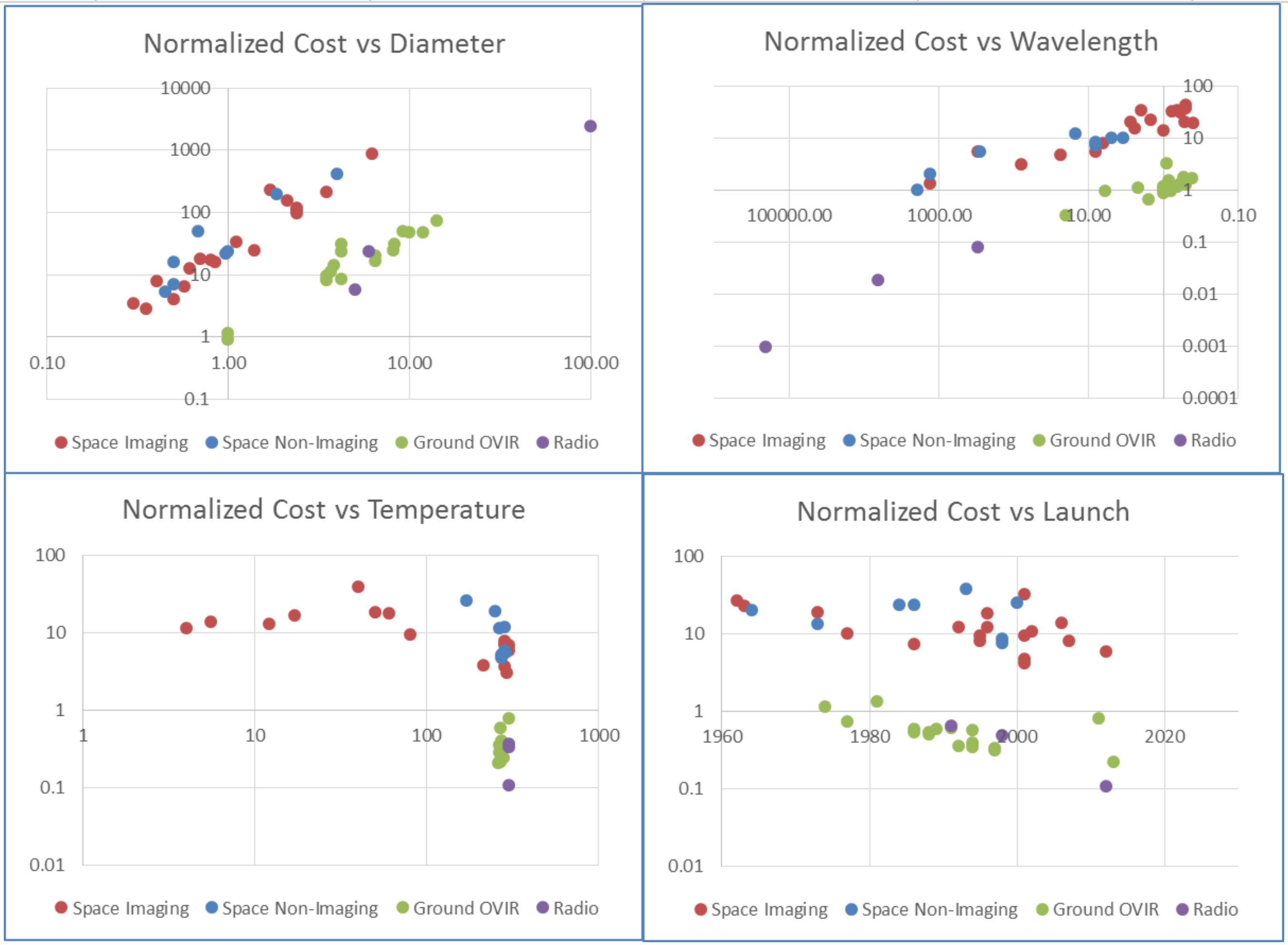




Next normalize for YOD – will effect all but YOD

OTA$ / (Dia, WDLP, T, YOD)

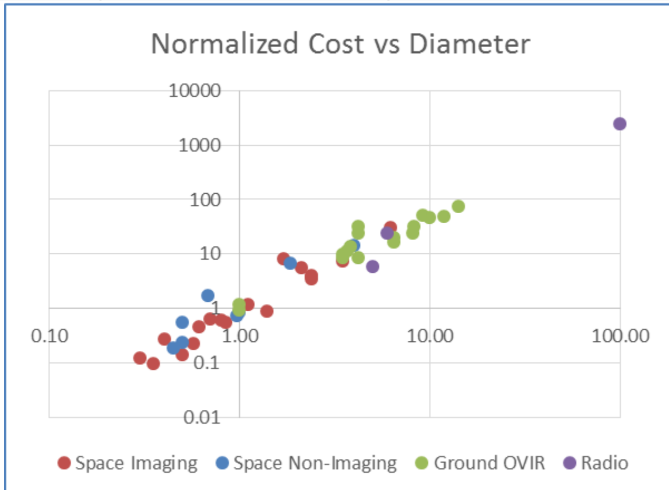
OTA Cost	Scale Factor	Eff Aperture Dia	Diff. Lim. λ	Operating Temp.	Year of Dev.
(FY17$M)		(m)	(μ)	(K)	(year)
20	0	1.6	-0.5	-0.25	-0.027

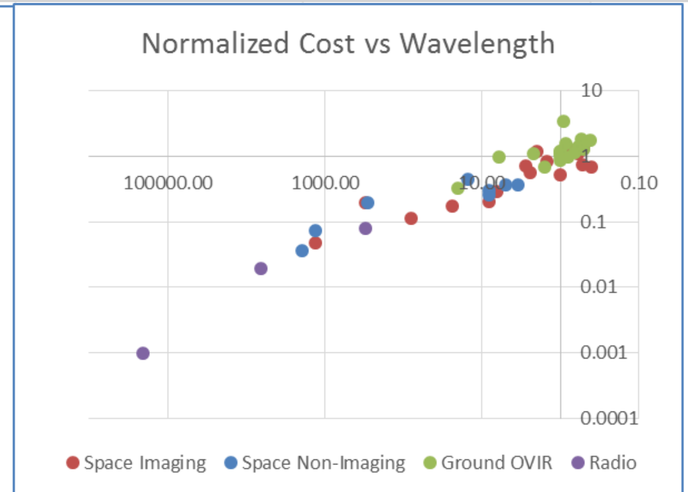


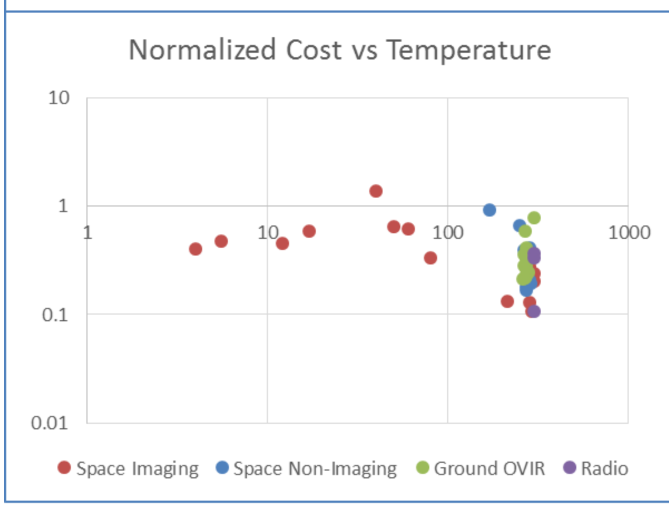
Finally add Ground vs Space Scale Factor

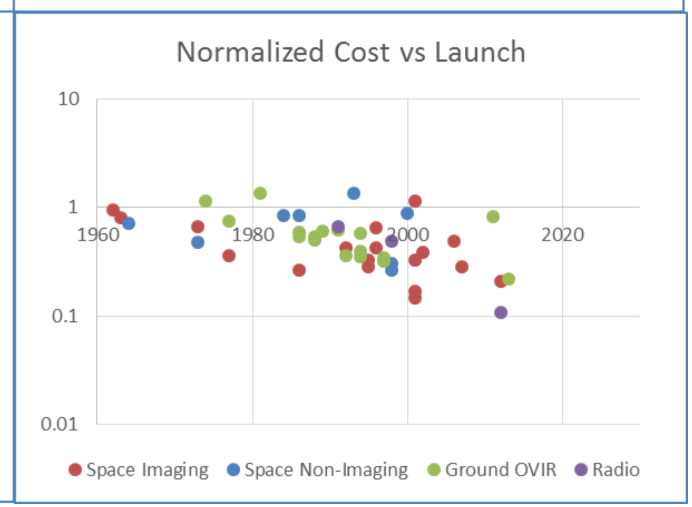
Finally, apply the Space/Ground Scale Factor

OTA Cost	Scale Factor	Eff Aperture Dia	Diff. Lim. λ	Operating Temp.	Year of Dev.
(FY17$M)		(m)	(μ)	(K)	(year)
20	1	1.6	-0.5	-0.25	-0.027









Sub-System Analysis

NASA WBS

NASA has a highly detailed WBS for categorizing cost. (Unfortunately, most of the detail is for the spacecraft).

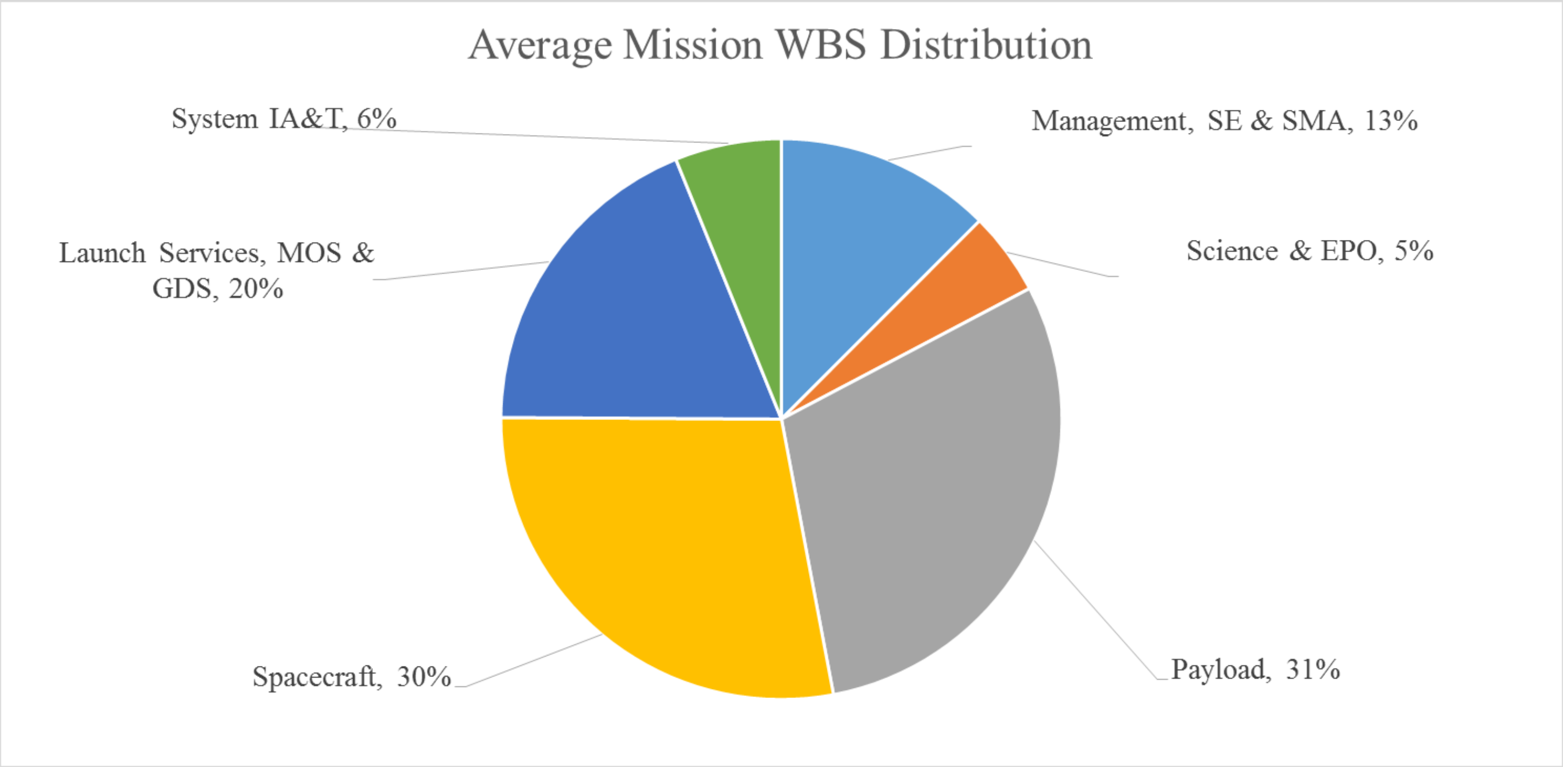
We accumulate cost data for only the level 1 categories except for the Payload.

Then combine into broader groups.

1	**Management**
2	**SE**
3	**SMA**
4	**Science**
5	**Payload**
5.1	**Management**
5.2	**SE**
5.3	**SMA**
5.4	**Instrument**
5.4.1	**OTA**
5.4.2	**Instruments**
5.4.3	**Cryogenic**
5.5	**IA&T**
6	**Spacecraft**
7	**Launch Services**
8	**Mission Operation System**
9	**Ground Data Systems**
10	**System IA&T**
11	**EPO**

Sub-System Cost Analysis

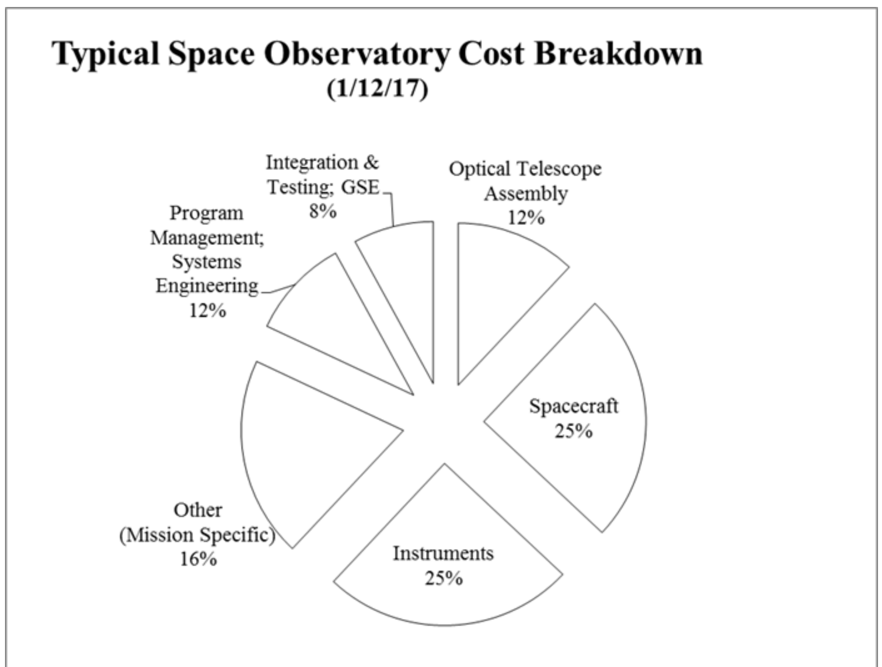
Based on Cost Analysis Data Requirements (CADRe) reports for 14 missions: CALIPSO, CLOUDSAT, GALEX, ICESAT, JWST, Kepler, LANDSAT-7, Spitzer, STEREO, SWAS, TRACE WIRE, WISE and WMAP. (CADRe reports are incomplete on many older missions).



OTA Cost as a % of Total Mission Cost

Based on 7 space missions in 1.12.17 database (whose data may not be current):

- OTA ~12% of Total Mission Cost
- Spacecraft and Instruments account for 50% of Total
- Mission I&T is ~ 8%.
- OTA I&T is ~15% of OTA Cost (< 2% of Total Mission Cost)
- Program Management and Systems Engineering equals OTA

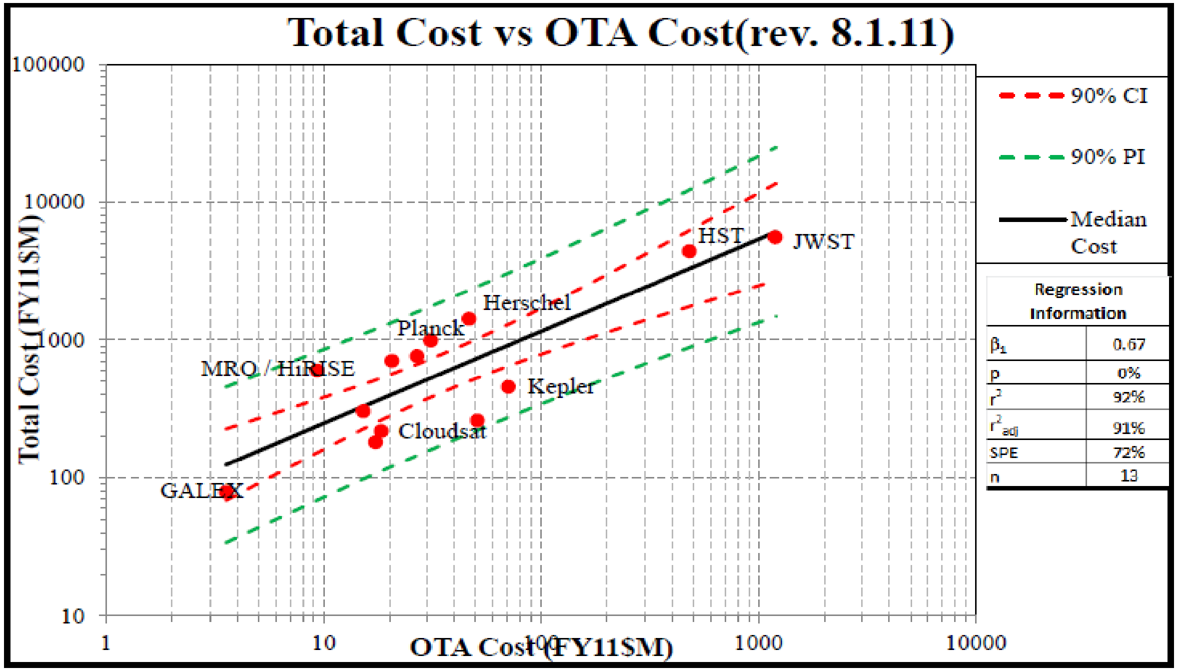


Analysis needs to be repeated for current database

OTA Cost vs Total Cost

Based on 13 space mission in 8.1.11 database (whose data may not be current):

- There is a relationship between OTA cost & Total Mission Cost
- Expensive missions tend to have expensive telescopes

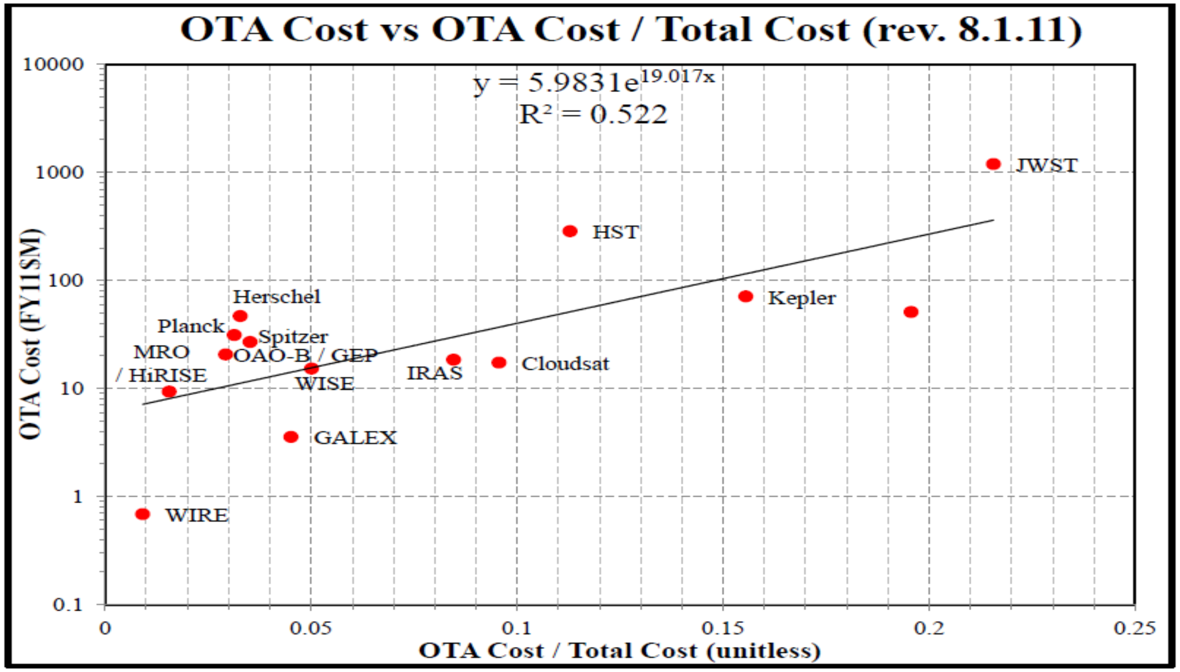


Analysis needs to be repeated for current database

OTA Cost as a % of Total Mission Cost

Based on 13 space mission in 8.1.11 database (whose data may not be current):

- BUT, there is not a linear relationship between OTA & Mission Cost
- OTA Cost varies from 1% to 25% of Total Mission Cost.
- JWST is largest diameter and largest %. But Herschel is also large and has a very small %. Maybe Herschel's longer wavelength is important.
- HST is a large UVOIR telescope, but Kepler – with its smaller aperture and lower WDLP – was a higher %.



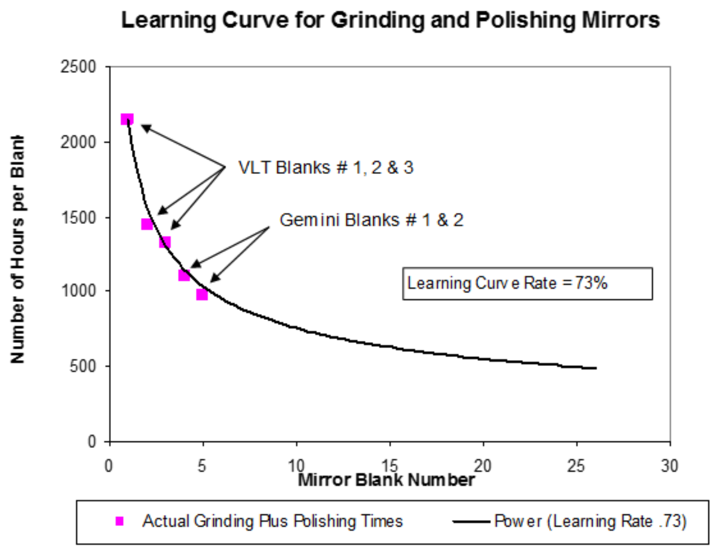
Analysis needs to be repeated for current database

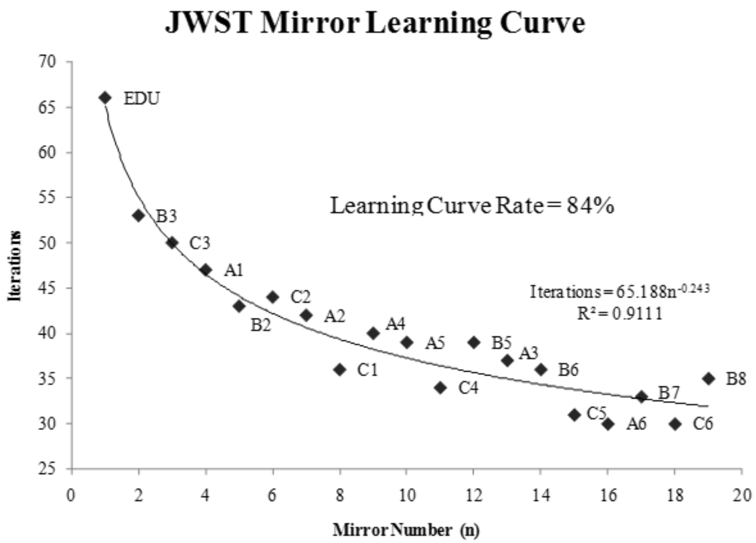
Segmentation does not decrease Cost

FINDING:

Segmentation does not reduces cost

Learning from duplication is approximately 80%





BUT, <u>only</u> for the components that are duplicated.

There is NO cost savings for primary mirrors because the cost of the backplane to hold the segments is higher – complexity.

Segmentation Increases Cost

Regressing on the 46 telescope database:

- Cost of the 10 segmented aperture telescopes database are ~13% higher than what the model predicts their cost to be if they were monolithic.
- BUT, this is smaller than the Data Standard Error of 20%.
- Thus, while it may be statistically correct, it is not significant.

Adding Segmentation to the Cost Model:

$$\mathbf{OTA\$\ (FY17) = \$20M \times 30^{(S/G)}\ N_{seg}^{(0.84)}\ D_{seg}^{(1.75)}\ \lambda^{(-0.5)} * T^{(-0.25)}\ e^{(-0.028)\ (Y-1960)}}$$

(R2 = 96%, Data SE=20%)

Where:

Nseg = number of segments in aperture

Dseg = circumscribed diameter of segments (= Dia for Monolithic)

<u>However, in simulations actual cost impact depends on segment architecture.</u>

Conclusion

Summary

A multivariable parametric model has been developed that explain 92% of the cost variation of a 46 mission dataset.

$$\textbf{OTA\$ (FY17) = \$20M x } 30^{(S/G)}\, D^{(1.7)}\ \lambda^{(-0.5)} * T^{(-0.25)}\, e^{(-0.027)\,(Y-1960)}$$

Space Telescopes are approx. 30X more expensive than Ground

Technology Maturation reduces cost by approx. 50% every 25 years.

Model predicts the most likely (50% probable) cost.

Multiplying Model by 1.45X yields the 84% probable cost.

Analysis of Sub-System Costs are on-going.

Segmentation does not decrease cost, but its predicted cost increase is within model uncertainty.