OPTICAL TELESCOPE ASSEMBLY COST ESTIMATING MODEL

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INTRODUCTION

Parametric cost models can be used by designers and project managers to compare cost between major architectural cost drivers and allow high-level design trades; enable cost-benefit analysis for technology development investment; and, provide a basis for estimating total project cost between related concepts. The NASA Marshall Space Flight Center has developed a 5-parameter cost model that explains 93% (Adjusted R2) of the cost variation in a database of 46 total ground and space telescope assemblies. This model can be used to estimate the most probably cost for the Habitable Exoplanet Telescope Assembly.

DISCLAIMERS

Parametric cost models cannot predict the cost of a future system. They are backward looking. They describe how historical system costs vary as a function of cost estimating relations (CERs) - the most important factors that drive cost. The only forward prediction that a cost model can make is to provide guidance as to how the cost of a potential future system might scale relative to an existing historical system. Furthermore, a parametric cost model is only as good as its database. The fundamental challenge of cost modeling is developing a parametric model that includes the most important CERs. To do this requires a database with sufficient samples and data diversity to yield statistically meaningful results, and engineering judgment to interpret the results. Finally, cost models are statistical. They only provide an estimate of the most likely or 50% probable cost +/- an uncertainty.

DEFINITIONS

The MSFC multivariable model estimates the most likely cost for ONLY an Optical Telescope Assembly (OTA). Where an 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, straylight baffles, mechanisms for adjusting the optical components, electronics or power systems for operating these mechanisms, etc.). An OTA does not include science instruments or spacecraft.

DATABASE

The MSFC OTA database contains information on 46 different cost, programmatic and engineering parameters for 35 space missions with normal incidence optical telescopes or antenna; and 26 ground telescopes or radio antenna. The database consists of both conventional imaging telescopes and non-imaging systems such as spectroscopic missions, LIDAR or radio antenna.

The cost model is developed by regressing over 18 combinations of 8 cost estimating relations (CERs) for 46 OTAs (26 Space and 20 Ground). Four CERs were identified as key: Aperture Diameter, Wavelength of Diffraction Limited Performance, Operating Temperature and Year of Development.

SPACE TELESCOPES

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

GROUND TELESCOPES

rev. 11.01.2018	Effective Diameter [m]	Diffraction Limit λ [μ]	Operating Temperature [K]	Year of Development [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

COST MODEL

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

Fit value	19.0	30.4	1.69	-0.47	-0.24	-0.0274
SE	1.6	6.0	0.09	0.03	0.07	0.006
p-value	5E-7	2E-18	2E-21	1E-20	0.002	4E-5

Model explains 93% (Adjusted R2) of the cost variation in the OTA database

where:

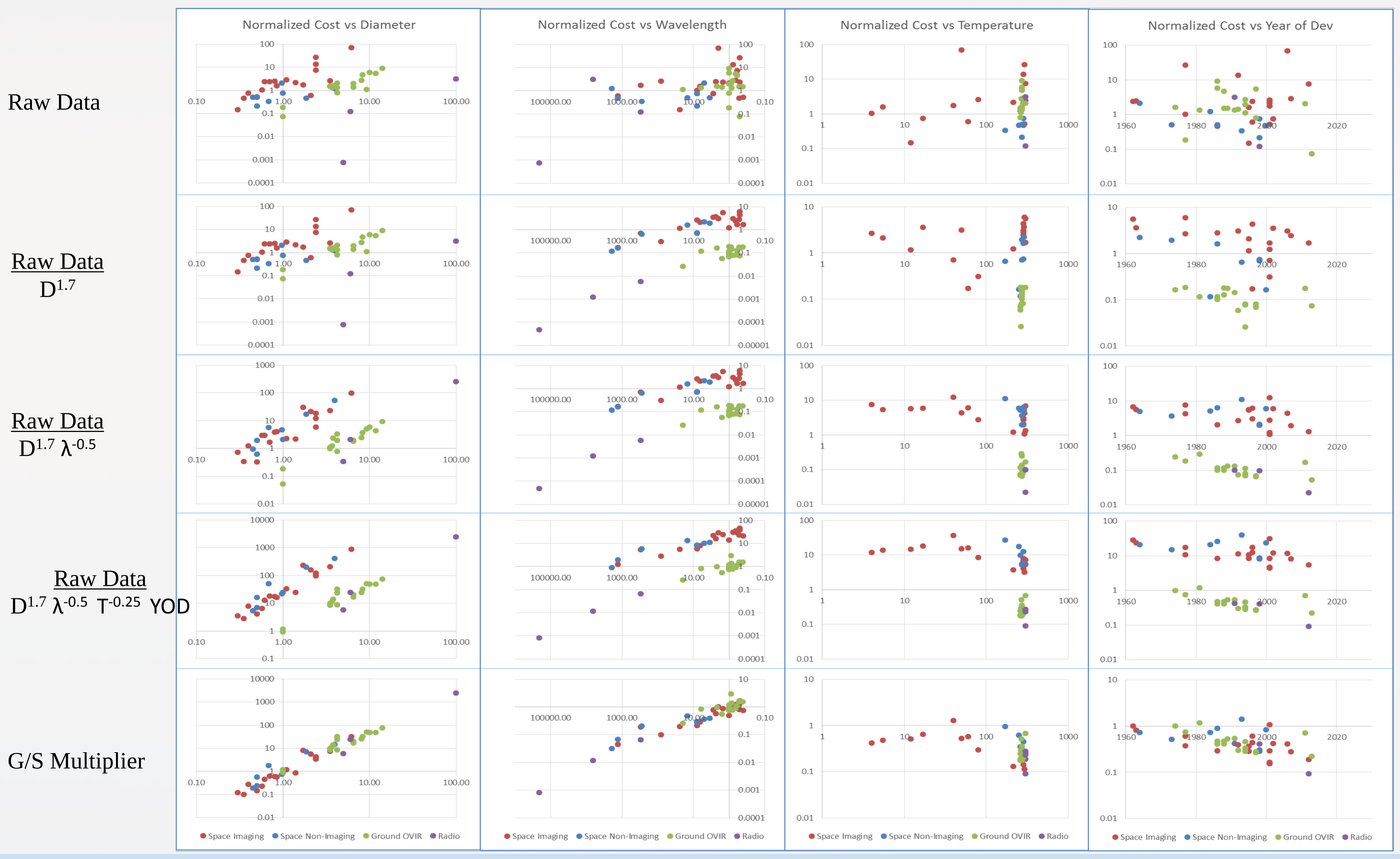
S/G = 1 for Space Missions and 0 for Ground Telescopes.
D = Aperture Diameter
λ = Wavelength of Diffraction Limited Performance (UV is more expensive)
T = Operating Temperature (Cryo is more expensive)
Y = Year of Development (Cost reduces by 50% approx. every 25 years)

NOTE:

- Model predicts ONLY the MOST PROBABLE or 50% cost.
- The prediction uncertainty is 45%.
- Thus to get the 84% most probably cost, multiply by 1.45X.

Residual Analysis

The below graphic illustrates the residual error of the model. Each column shows cost versus CER. The top row is the 'raw' database date. Row two is after normalizing cost by diameter. Row three is after normalizing cost by wavelength. Row four is after including temperature and YOD normalization. And, row five is after invoking ground to space multiplier.



OTA COST ESTIMATION EXAMPLE

OTA cost can be estimated via two methods: using the model directly or using model to compare relative cost with other OTAs (i.e. Hubble & JWST).

For an OTA with:

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

Direct Model Method

OTA$ (50% probable) = $430M

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

OTA$ (84% probable) = $620M

Relative Comparison Method

		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	

SUB-SYSTEM COST

Average cost breakdown for 14 missions is: payload ~33%, spacecraft ~33%, labor ~25%; (Instruments + Spacecraft ~ 50%).

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.