# Parametric Cost Model for Ground and Space Telescopes

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## Introduction

Cost models provide several benefits to designers and project managers:

- Identify major architectural cost drivers
- Allow high-level design trades
- Enable cost-benefit analysis for technology development investment
- Provide a basis for estimating total project cost for budgetary planning and procurement activities.

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## Parametric Cost Models

- Cost Models are backward looking. They provide a statistical correlation between an item's historical cost and quantifiable technical or programmatic parameters.
- Parameters with statistically significant correlations to cost are called Cost Estimating Relationships (CERs).
- Cost Models DO NOT predict the cost of a given Mission or Component. They provide an estimate of the 50% probable cost.
- Cost Models can be used to compare a potential future mission relative to a historical mission.
- Finally, actual cost is frequently driven by non-technical issues such as managerial decisions and funding profiles.

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## Optical Telescope Assembly (OTA)

An OTA is defined as the system which collects electromagnetic radiation and focuses it (focal) or concentrates it (afocal) into the science instruments.

An OTA consists of:

- Primary Mirror
- Secondary Mirror
- Auxiliary Optics (such as Steering or Tertiary Mirrors)
- 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.).
- Assembly, Integration and Test

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## Cost

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/WYE)
- Government Furnished Equipment (GFE)
- Existing Contractor infrastructure (not 'billed' to contract)

NOTE: These are 'First Unit' Costs only – no HST Servicing

Mass includes:

- Dry mass only (no propellant)

## Database

- Cost Models are only as good as their Database.
- Inconsistencies and inaccuracies in a cost model are the results of insufficient data completeness or diversity, inconsistencies in definitions, or data errors or inaccuracies.
- The results evolve every time we add new missions to the Database, add data to or correct data in the Database.
  - When we added CALIPSO to the database the model exponents changed in the $3^{rd}$ decimal point but the p-values reduced by 2X.
- The hardest part of Cost Modeling is collecting and validating the database. Which requires engineering judgement.
- This is a 20 year work in progress.

## MSFC OTA Database

The MSFC multivariable parametric telescope cost model is based on 47 telescopes (27 space and 20 ground) out of a total database of 72 telescopes (51 space and 26 ground).

The model does not use every telescope in the database because of data completeness.

Technical, programmatic & cost information is collected from:

- Public reports,
- Project managers (via interviews and emails),
- NASA archival sources:
    - CADRe (Cost Analysis Data Requirements),
    - NAFCOM (NASA/Air Force Cost Model) database,
    - NICM (NASA Instrument Cost Model) database,
    - NSCKN (NASA Safety Center Knowledge Now),
    - RSIC (Redstone Scientific Information Center),
    - REDSTAR (Resource Data Storage and Retrieval System)
    - SICM (Scientific Instrument Cost Model) database.

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## MSFC Space OTA Database

Space OTA database contains 51 imaging and non-imaging space missions ranging from X-ray to UVOIR to FarIR. Non-imaging missions include spectroscopic, LIDAR or radio/microwave.

| Imaging | Non-Imaging | Not in Regression | Attached |
|---|---|---|---|
| AFTA | ACTS | CCOR | SOFIA |
| COM_0.7 | CALIPSO/CALIOP | Commercial SiC .35 | HUT |
| COM_1.1 | Cloudsat | Commercial SiC .5 | UIT |
| Herschel | GALEX | EO-1/ALI | WUPPE |
| HST | ICESat/GLAS | FUSE | |
| IRAS | IUE | Imaging EUV | X-Ray |
| JWST | MO / MOLA | ISO | EUVE |
| Kepler | OAO-B / GEP | LandSAT-7 | Chandra |
| MO / MOC | SWAS | SDO / AIA | HEAO-2 |
| MRO / HiRISE | | LRO / LROC NAC | HERO |
| OAO-2 / CEP | | SOHO/EIT | FOXSI |
| OAO-3 / PEP | | STEREO/SECCHI A | |
| Planck | | TDRS-1 | |
| Proprietary | | TDRS-7 | |
| Spitzer | | TRACE | |
| WIRE | | | |
| WISE | | | |
| WMAP | | | |

# Space Telescope Data Parameters

MSFC Space OTA database contains information on 47 different cost, programmatic and engineering 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 Number of Segments | # |
| PM Segment Size | meter |
| 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 | |

# MSFC Ground OTA Data Base

Ground OTA database contains 26 telescopes from optical to radio.

| In the Regression |
|---|
| AEOS |
| Commercial |
| Commercial Radio |
| DKIST |
| Gemini 1 |
| Green Bank Radio |
| HET |
| JKT |
| KECK 1 |
| KECK 1 & 2 |
| LBT |
| Magellan 1 |
| MMT 6.5m replacement |
| SOAR |
| Starfire |
| Subaru |
| SubMM Array Dish |
| UKIRT |
| WHT |
| WIYN |

| Not Included in Regression |
|---|
| ALOT |
| CHARA |
| DCT |
| IRTF |
| LAMP |
| VLA Dish |
| |
| |

## Ground Telescope Database Parameters

Data was collected on 22 parameters for Ground Telescopes

| Primary Mirror Specific Information | |
|---|---|
| PM Cost | $ FY M |
| PM Aperture Diameter | meters |
| PM Surface Figure Error | rms nm |
| PM Material | |
| PM Focal Length | meters |
| PM F/# | |
| PM Number of Segments | # |
| PM Segment Size | meter |
| PM Aspheric Departure | micrometers |
| PM Mass | kg |
| PM Lightweight Factor | % |

| Optical Telescope Assembly Information | |
|---|---|
| OTA Cost | $ FY M |
| Diffraction Limit | micrometers |
| Transmitted WFE | nm rms |
| Operating Temperature | K |
| OTA Mass | kg |
| Year of Development | |
| Development Period | months |
| Design Life | months |
| On or Off-Axis | |
| Number of Curved Optical Elements | |
| Optical Bench Material | |

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## How to Build a Model

Start with Correlation Matrix.

Look for Variables which are Highly Correlated with Cost.

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

Important for Multi-Variable Models:

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

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## Goodness of Correlation, Fits and Regressions

A variable's 'Goodness' is evaluated via Pearson's Adjusted $r^2$, standard percent error (SPE), and Student's T-Test p-value.

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.

## Statistical Analysis

Of the 47 space parameters, there is sufficient completeness to do cross-correlation for 15 variables to identify CERs that are correlated with cost and not correlated with each other.

All Variable Pairwise Correlation Matrix for Space Imaging System Dataset (N=18) — Rev 12.05.2017

| | OTA$ | Eff Dia | Volume | PM FL | Sys FL | FOV | WDLP | Temp | OTA Mass | Design Life | e^(YOD -1960) | Dev Period | Launch Date | Orbit | Point Stab |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OTA $ | 1.00 | 0.85 | 0.94 | 0.98 | 0.98 | -0.22 | -0.15 | -0.07 | 0.78 | 0.59 | 0.00 | 0.59 | 0.93 | -0.18 | -0.27 |
| Eff Diameter | 0.85 | 1.00 | 0.81 | 0.86 | 0.89 | 0.04 | 0.15 | 0.02 | 0.65 | 0.63 | 0.08 | 0.24 | 0.46 | -0.19 | -0.39 |
| Volume | 0.94 | 0.81 | 1.00 | 0.94 | 0.92 | -0.11 | -0.06 | -0.22 | 0.54 | 0.36 | -0.03 | 0.53 | 1.00 | -0.11 | -0.31 |
| PM Focal Length | 0.98 | 0.86 | 0.94 | 1.00 | 0.96 | -0.08 | -0.12 | -0.05 | 0.73 | 0.56 | 0.04 | 0.54 | 0.94 | -0.16 | -0.32 |
| Sys Focal Length | 0.98 | 0.89 | 0.92 | 0.96 | 1.00 | -0.22 | -0.12 | -0.13 | 0.78 | 0.63 | 0.29 | 0.63 | 0.90 | -0.11 | -0.30 |
| FOV | -0.22 | 0.04 | -0.11 | -0.08 | -0.22 | 1.00 | 0.68 | -0.13 | -0.18 | -0.21 | -0.03 | 0.09 | -0.12 | -0.18 | -0.32 |
| WDLP | -0.15 | 0.15 | -0.06 | -0.12 | -0.12 | 0.68 | 1.00 | -0.30 | -0.14 | -0.20 | -0.07 | 0.16 | -0.08 | -0.14 | -0.58 |
| Operate Temp | -0.07 | 0.02 | -0.22 | -0.05 | -0.13 | -0.13 | -0.30 | 1.00 | 0.14 | 0.36 | 0.19 | -0.46 | -0.23 | 0.26 | 0.77 |
| OTA Mass | 0.78 | 0.65 | 0.54 | 0.73 | 0.78 | -0.18 | -0.14 | 0.14 | 1.00 | 0.82 | 0.11 | 0.59 | 0.51 | -0.24 | -0.31 |
| Design Life | 0.59 | 0.63 | 0.36 | 0.56 | 0.63 | -0.21 | -0.20 | 0.36 | 0.82 | 1.00 | 0.27 | 0.13 | 0.32 | 0.13 | -0.10 |
| e^(YOD-1960) | 0.00 | 0.08 | -0.03 | 0.04 | 0.29 | -0.03 | -0.07 | 0.19 | 0.11 | 0.27 | 1.00 | -0.19 | 0.31 | -0.09 | -0.32 |
| Develop Period | 0.59 | 0.24 | 0.53 | 0.54 | 0.63 | 0.09 | 0.16 | -0.46 | 0.59 | 0.13 | -0.19 | 1.00 | 0.50 | -0.19 | -0.75 |
| Launch Date | 0.93 | 0.46 | 1.00 | 0.94 | 0.90 | -0.12 | -0.08 | -0.23 | 0.51 | 0.32 | 0.31 | 0.50 | 1.00 | -0.09 | -0.31 |
| Orbit | -0.18 | -0.19 | -0.11 | -0.16 | -0.11 | -0.18 | -0.14 | 0.26 | -0.24 | 0.13 | -0.09 | -0.19 | -0.09 | 1.00 | 0.70 |
| Point Stability | -0.27 | -0.39 | -0.31 | -0.32 | -0.30 | -0.32 | -0.58 | 0.77 | -0.31 | -0.10 | -0.32 | -0.75 | -0.31 | 0.70 | 1.00 |

## Statistical Analysis

Cost is highly correlated with Diameter, Focal Length, Volume, Mass and Launch Date

But Volume, Focal Length and Mass are Cross-Correlated with Diameter.

All Variable Pairwise Correlation Matrix for Space Imaging System Dataset (N=18) — Rev 12.05.2017

| | OTA$ | Eff Dia | Volume | PM FL | Sys FL | FOV | WDLP | Temp | OTA Mass | Design Life | e^(YOD -1960) | Dev Period | Launch Date | Orbit | Point Stab |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OTA $ | 1.00 | 0.85 | 0.94 | 0.98 | 0.98 | -0.22 | -0.15 | -0.07 | 0.78 | 0.59 | 0.00 | 0.59 | 0.93 | -0.18 | -0.27 |
| Eff Diameter | 0.85 | 1.00 | 0.81 | 0.86 | 0.89 | 0.04 | 0.15 | 0.02 | 0.65 | 0.63 | 0.08 | 0.24 | 0.46 | -0.19 | -0.39 |
| Volume | 0.94 | 0.81 | 1.00 | 0.94 | 0.92 | -0.11 | -0.06 | -0.22 | 0.54 | 0.36 | -0.03 | 0.53 | 1.00 | -0.11 | -0.31 |
| PM Focal Length | 0.98 | 0.86 | 0.94 | 1.00 | 0.96 | -0.08 | -0.12 | -0.05 | 0.73 | 0.56 | 0.04 | 0.54 | 0.94 | -0.16 | -0.32 |
| Sys Focal Length | 0.98 | 0.89 | 0.92 | 0.96 | 1.00 | -0.22 | -0.12 | -0.13 | 0.78 | 0.63 | 0.29 | 0.63 | 0.90 | -0.11 | -0.30 |
| FOV | -0.22 | 0.04 | -0.11 | -0.08 | -0.22 | 1.00 | 0.68 | -0.13 | -0.18 | -0.21 | -0.03 | 0.09 | -0.12 | -0.18 | -0.32 |
| WDLP | -0.15 | 0.15 | -0.06 | -0.12 | -0.12 | 0.68 | 1.00 | -0.30 | -0.14 | -0.20 | -0.07 | 0.16 | -0.08 | -0.14 | -0.58 |
| Operate Temp | -0.07 | 0.02 | -0.22 | -0.05 | -0.13 | -0.13 | -0.30 | 1.00 | 0.14 | 0.36 | 0.19 | -0.46 | -0.23 | 0.26 | 0.77 |
| OTA Mass | 0.78 | 0.65 | 0.54 | 0.73 | 0.78 | -0.18 | -0.14 | 0.14 | 1.00 | 0.82 | 0.11 | 0.59 | 0.51 | -0.24 | -0.31 |
| Design Life | 0.59 | 0.63 | 0.36 | 0.56 | 0.63 | -0.21 | -0.20 | 0.36 | 0.82 | 1.00 | 0.27 | 0.13 | 0.32 | 0.13 | -0.10 |
| e^(YOD-1960) | 0.00 | 0.08 | -0.03 | 0.04 | 0.29 | -0.03 | -0.07 | 0.19 | 0.11 | 0.27 | 1.00 | -0.19 | 0.31 | -0.09 | -0.32 |
| Develop Period | 0.59 | 0.24 | 0.53 | 0.54 | 0.63 | 0.09 | 0.16 | -0.46 | 0.59 | 0.13 | -0.19 | 1.00 | 0.50 | -0.19 | -0.75 |
| Launch Date | 0.93 | 0.46 | 1.00 | 0.94 | 0.90 | -0.12 | -0.08 | -0.23 | 0.51 | 0.32 | 0.31 | 0.50 | 1.00 | -0.09 | -0.31 |
| Orbit | -0.18 | -0.19 | -0.11 | -0.16 | -0.11 | -0.18 | -0.14 | 0.26 | -0.24 | 0.13 | -0.09 | -0.19 | -0.09 | 1.00 | 0.70 |
| Point Stability | -0.27 | -0.39 | -0.31 | -0.32 | -0.30 | -0.32 | -0.58 | 0.77 | -0.31 | -0.10 | -0.32 | -0.75 | -0.31 | 0.70 | 1.00 |

## Statistical Analysis

The pairwise cross-correlation analysis identified eight potential CERs:

- Aperture Diameter,
- Wavelength of Diffraction Limited Performance (WDLP),
- Operating Temperature,
- Year of Development (YOD) – start of Phase C or Award of Contract
- Primary Mirror Focal Length,
- Field of View,
- Total Mass
- Development Period

18 combinations of these CERs were evaluated.

And only four had a statistically significant (i.e. $p < 10\%$) correlation with cost: effective aperture diameter, WDLP, operating temperature and YOD.

Database has 100% completeness of these 4 CERs for 47 OTAs (27 space & 20 ground)

## MSFC Cost Database – Recent Changes

Much effort has been expended to compile a database with wide data diversity.

For wavelength diversity, we included radio and sub-millimeter telescopes.

For YOD diversity we located cost and technical information for the 1960 era OAO-2 Celeste Experiment Package and OAO-3 Princeton Experiment Package; and recent CALIPSO and DKIST telescopes.

20 Ground Telescopes

- Diameter ranges from 1 to 100 m
- WDLP from 500 nm to 21 cm
- Temperature from 262 to 300K
- YOD from 1979 to 2011
- 14 Monolithic and 6 Segmented

27 Space Telescopes

- Diameter ranges from 0.3 to 5.6 m
- WDLP from 400 nm to 2 mm
- Temperature from 4 to 300K
- YOD from 1962 to 2021
- 23 Monolithic and 4 Segmented
- 18 Imaging and 9 Non-Imaging

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# Ground Telescope Database

| rev. 11.01.2018 | Effective Diameter | Diffraction Limit | Operating Temperature | Year of Dev. | Total Segments | Seg Size |
|---|---|---|---|---|---|---|
| | (m) | (µm) | (K) | (year) | # | (m) |
| JKT | 1.00 | 1.00 | 270 | 1977 | 1 | 1 |
| Commercial | 1.00 | 0.50 | 300 | 2013 | 1 | 1 |
| Starfire | 3.50 | 0.53 | 273 | 1989 | 1 | 3.5 |
| WIYN | 3.50 | 0.42 | 263 | 1988 | 1 | 3.5 |
| AEOS | 3.67 | 0.85 | 273 | 1991 | 1 | 3.67 |
| UKIRT | 3.80 | 2.20 | 273 | 1974 | 1 | 3.8 |
| SOAR | 4.20 | 1.00 | 263 | 1997 | 1 | 4.2 |
| WHT | 4.20 | 6.11 | 270 | 1981 | 1 | 4.2 |
| DKIST | 4.20 | 0.90 | 300 | 2011 | 1 | 4.2 |
| Commercial Radio | 5.00 | 210000.00 | 300 | 2012 | 1 | 5 |
| SubMM Array Dish | 6.00 | 300.00 | 300 | 1998 | 72 | 1 |
| MMT 6.5m replacement | 6.50 | 1.60 | 262 | 1992 | 1 | 6.5 |
| Magellan 1 | 6.50 | 1.00 | 280 | 1994 | 1 | 6.5 |
| Gemini 1 | 8.10 | 0.80 | 270 | 1994 | 1 | 8.1 |
| Subaru | 8.30 | 0.60 | 273 | 1988 | 1 | 8.3 |
| HET | 9.20 | 20.00 | 264 | 1994 | 91 | 1 |
| KECK 1 | 10.00 | 1.00 | 273 | 1986 | 36 | 1.8 |
| LBT | 11.88 | 0.65 | 273 | 1997 | 2 | 8.4 |
| KECK-I&II | 14.14 | 1.00 | 273 | 1986 | 72 | 1.8 |
| Green Bank Radio | 100.00 | 6500.00 | 300 | 1991 | 2004 | 3 |

# Space Telescope Database

| rev. 11.17.20 | Effective PM Diameter | Diff. Lim. λ | Operating Temp. | Year of Development | # of PM Segments | PM Segment Diameter |
|---|---|---|---|---|---|---|
| Imaging | (m) | (µ) | (K) | (year) | # | (m) |
| AFTA | 2.40 | 0.78 | 284 | 1992 | 1 | 2.40 |
| COM_0.7 | 0.70 | 0.50 | 283 | 1996 | 1 | 0.70 |
| COM_1.1 | 1.10 | 0.65 | 283 | 2007 | 1 | 1.10 |
| Herschel | 3.50 | 80.00 | 80 | 2001 | 1 | 6.50 |
| HST | 2.40 | 0.50 | 294 | 1977 | 1 | 2.40 |
| IRAS | 0.57 | 8.00 | 4 | 1977 | 1 | 0.57 |
| JWST | 5.64 | 2.00 | 30 | 2006 | 18 | 1.40 |
| Kepler | 1.40 | 1.00 | 213 | 2001 | 1 | 1.40 |
| MO / MOC | 0.35 | 0.53 | 283 | 1986 | 1 | 0.35 |
| MRO / HiRISE | 0.50 | 0.40 | 293 | 2001 | 1 | 0.50 |
| OAO-2 / CEP | 0.61 | 1.50 | 300 | 1962 | 4 | 0.31 |
| OAO-3 / PEP | 0.80 | 2.40 | 288.5 | 1963 | 1 | 0.80 |
| Planck | 1.70 | 300.00 | 40 | 2001 | 1 | 1.70 |
| Proprietary | | | | | | |
| Spitzer | 0.85 | 6.50 | 5.5 | 1995 | 1 | 0.85 |
| WIRE | 0.30 | 24.00 | 12 | 1995 | 1 | 0.30 |
| WISE | 0.40 | 2.75 | 17 | 2002 | 1 | 0.40 |
| WMAP | 2.10 | 1300.00 | 60 | 1996 | 2 | 1.50 |
| Non-Imaging | | | | | | |
| ACTS | 3.97 | 1950.00 | 263 | 1984 | 2 | 2.80 |
| CALIPSO | 1.00 | 6.60 | 283 | 2000 | 1 | 1.00 |
| Cloudsat | 1.85 | 1300.00 | 250 | 2000 | 1 | 1.85 |
| GALEX | 0.50 | 8.00 | 273 | 1998 | 1 | 0.50 |
| ICESat | 1.00 | 8.00 | 283 | 1998 | 1 | 1.00 |
| IUE | 0.45 | 3.50 | 273 | 1973 | 1 | 0.45 |
| MO / MOLA | 0.50 | 15.00 | 283 | 1986 | 1 | 0.50 |
| OAO-B / GEP | 0.97 | 5.00 | 289 | 1964 | 1 | 0.97 |
| SWAS | 0.68 | 286.00 | 170 | 1993 | 1 | 0.68 |

## Cost Model Regression

47 OTA Database was regressed against 4 CERs plus a Space/Ground multiplier factor to yield a cost model that explains 92% (Adjusted R2) of Database cost variation.

$$\mathbf{OTA\$\ (FY17) = \$20M \times 30^{(S/G)} \times D^{(1.7)} \times \lambda^{(-0.5)} \times T^{(-0.25)} \times e^{(-0.028)\,(Y-1960)}}$$

| Parameter | Intercept | S/G | D | λ | T | YOD |
|---|---|---|---|---|---|---|
| Model Value | 20 | 30 | 1.7 | -0.5 | -0.25 | -0.028 |
| Actual Value | 21.3 | 28.2 | 1.697 | -0.467 | -0.262 | -0.0282 |
| SE | 1.6 | 1.2 | 0.09 | 0.03 | 0.07 | 0.006 |
| p-value | 2E-07 | 1E-18 | 9E-22 | 6E-21 | 9E-4 | 3E-05 |

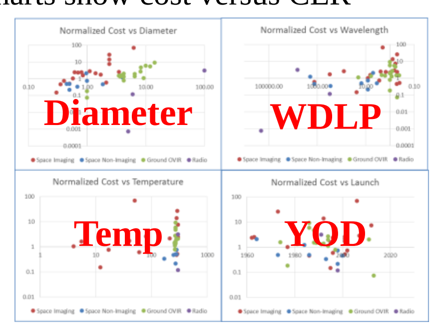
where:
(S/G) = 1 for Space OTAs
= 0 for Ground OTAs
D = Effective Telescope Aperture Diameter
λ = Wavelength of Diffraction Limited Performance
T = Operating Temperature
YOD = Year of Development

Note: to get 84% probable estimate multiple 50% estimate by 1.5X.

## Model Evaluation

The ‘goodness’ of the model was evaluated via residual and outlier analysis.

Each graph in the follow charts show cost versus CER



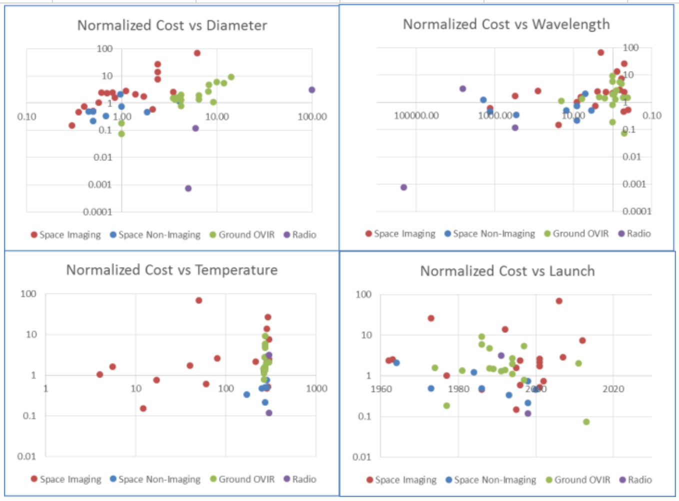

First Chart plots Raw OTA cost vs each CER.

Subsequent Charts normalize the OTA cost as a function of each CER.

When the data is normalize for each CER, the graphic for that CER is unaffected. So, when we normalize for diameter, that residual plot does not change.

# Raw OTA$ Data: Ground & Space Combined

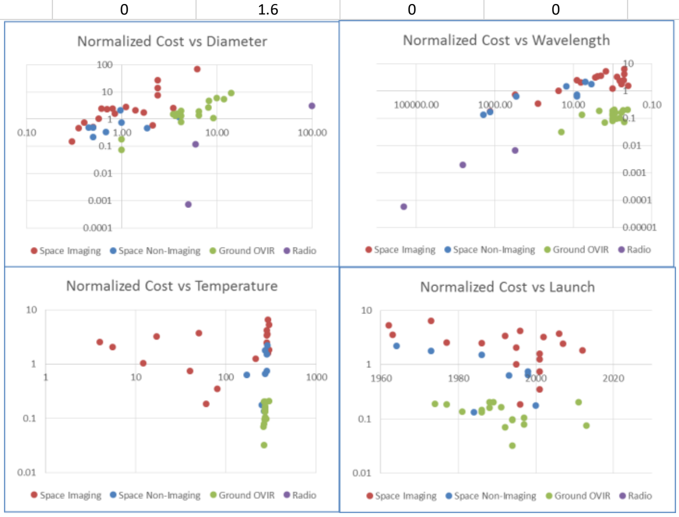
| OTA Cost | Scale Factor | Eff Aperture Dia | Diff. Lim. λ | Operating Temp. | Year of Dev. |
|---|---|---|---|---|---|
| (FY17$M) | | (m) | (μ) | (K) | (year) |
| 20 | 0 | 0 | 0 | 0 | 0 |




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

# OTA$ / (Dia)

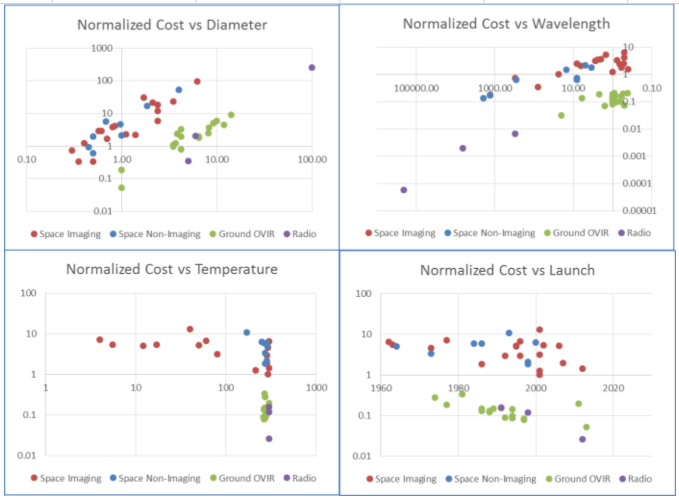
| OTA Cost | Scale Factor | Eff Aperture Dia | Diff. Lim. λ | Operating Temp. | Year of Dev. |
|---|---|---|---|---|---|
| (FY17$M) | | (m) | (μ) | (K) | (year) |
| 20 | 0 | 1.6 | 0 | 0 | 0 |




Next normalize for Wavelength – will effect all but WDLP

# OTA$ / (Dia, WDLP)

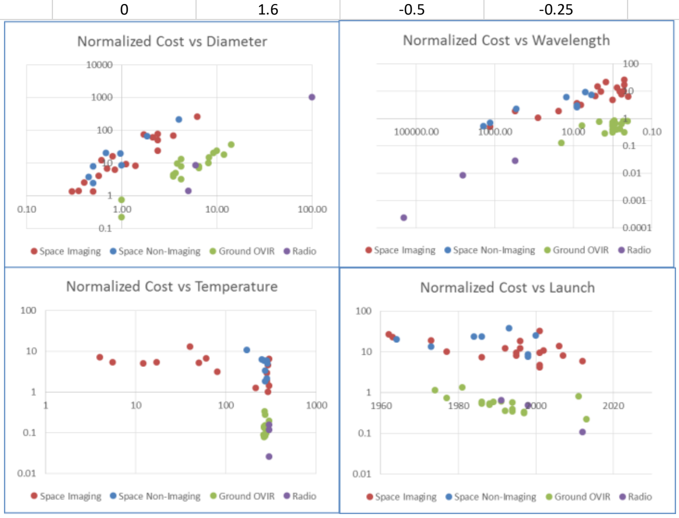
| OTA Cost | Scale Factor | Eff Aperture Dia | Diff. Lim. λ | Operating Temp. | Year of Dev. |
|---|---|---|---|---|---|
| (FY17$M) | | (m) | (µ) | (K) | (year) |
| 20 | 0 | 1.6 | -0.5 | 0 | 0 |




Next normalize for Temperature – will effect all but Temp

# OTA$ / (Dia, WDLP, T)

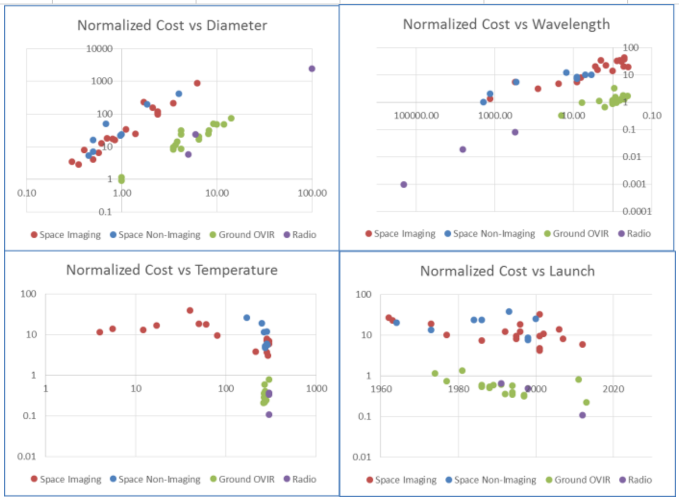
| OTA Cost | Scale Factor | Eff Aperture Dia | Diff. Lim. λ | Operating Temp. | Year of Dev. |
|---|---|---|---|---|---|
| (FY17$M) | | (m) | (µ) | (K) | (year) |
| 20 | 0 | 1.6 | -0.5 | -0.25 | 0 |




Next normalize for YOD – will effect all but YOD

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

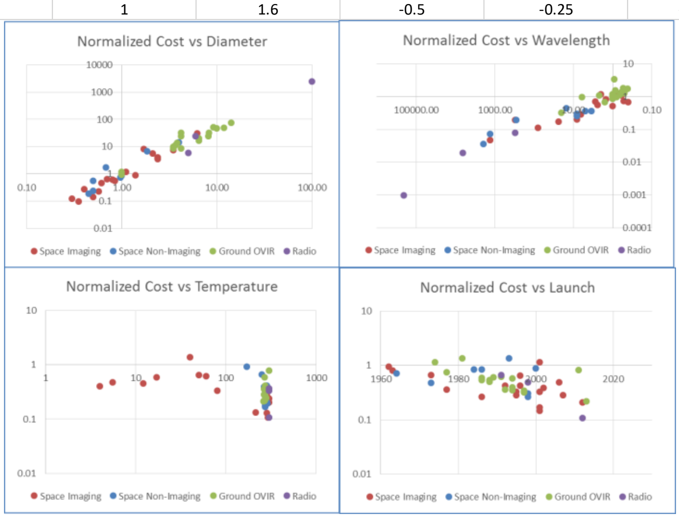
| OTA Cost | Scale Factor | Eff Aperture Dia | Diff. Lim. λ | Operating Temp. | Year of Dev. |
|---|---|---|---|---|---|
| (FY17$M) | | (m) | (μ) | (K) | (year) |
| 20 | 0 | 1.6 | -0.5 | -0.25 | -0.027 |




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 |



## Model Predictive Power

The model is so good, that when tested using the residual analysis technique, it was possible to identify data points that did not lie on the trend lines.

The causes of these outliers were typos or inaccurate values.

For example, in YOD:

- We accidentally entered UKIRT's YOD as 1997 when it was built in 1979.
- Similarly there was a discrepancy in HST's YOD between 1973 and 1977.

And for WDLP.

- While CLOUDSAT was specified to have a performance of 3.19-mm, the telescope was actually built with a WDLP of 1.3-mm.
- We found a better citation for Planck and changed its WDLP from 700 to 300 micrometers.



## Does Aperture Segmentation Lower Cost?

Historically, segmentation has always been the solution for when technology did not allow a monolithic mirror. But as soon as technology permitted, segmented mirrors were replaced with monoliths.

- The original 'Large Space Telescope' (i.e. Hubble) was a segmented mirror. Then NASA funded the development of lightweight high-temperature-fused ULE mirrors.
- The Multi-Mirrored Telescope has been replaced by a 6.5m monolith.
- And, 10-m class segmented telescopes such as Keck gave way to 8-m class monoliths such as VLT and Subaru.

But the question is – given that telescope cost is driven by aperture diameter – does segmentation reduce cost.

Or, is it simply an engineering solution to an engineering problem.

## Segmented Aperture Cost Model

The MSFC database has a total of 10 segmented telescope (6 ground and 4 space).

With so few segmented telescope, it is difficult to perform meaningful regressions.

So, … we consider the 36 monolithic telescopes as ‘one’ segment apertures.

And, replaced the Effective Diameter (D) parameter with a segmentation parameter

**Nseg x Dseg**

Where:

Nseg = number of segments in the aperture

Dseg = segment circumscribed diameter

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## Segmented Aperture Cost Model

Regressing on the 47 telescope MSFC database yields a potential 6-variable ground and space segmented telescope cost model.

**$OTA\$ (FY17) = \$20M \times 30^{(S/G)} \times Nseg^{(0.8)} \times Dseg^{(1.7)} \times \lambda^{(-0.5)} \times T^{(-0.25)} \times e^{(-0.028)(Y-1960)}$**

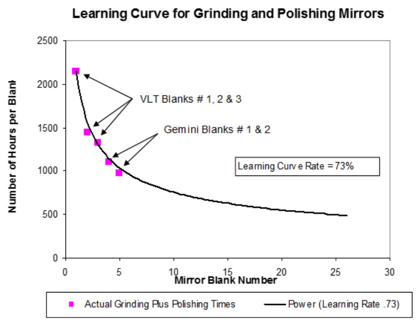
| Parameter | Intercept | S/G | Nseg | Dseg | λ | T | YOD |
|---|---|---|---|---|---|---|---|
| Model Value | 20 | 30 | 0.8 | 1.7 | -0.5 | -0.25 | -0.028 |
| Actual Value | 23.0 | 25.1 | 0.78 | 1.63 | -0.473 | -0.252 | -0.0291 |
| SE | 1.7 | 1.3 | 0.06 | 0.12 | 0.03 | 0.08 | 0.007 |
| p-value | 1E-06 | 2E-16 | 2E-16 | 4E-17 | 4E-19 | 0.003 | 9E-05 |

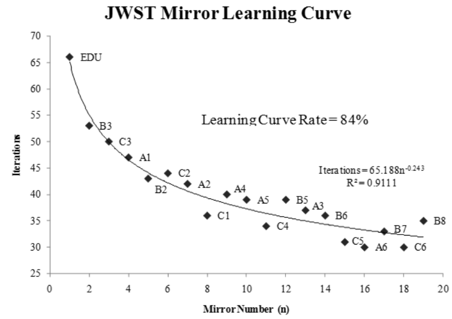
Please note that the Dseg exponent has same value as for D in the monolithic model.

The cost to make a single mirror should be the same in both model.

# Segmented Cost Reduction

Nseg 0.8 exponent is consistent with empirical data from the manufacture of 8-m monolithic mirrors by REOSC and 1.4-m JWST mirror segments.




But, cost reduction applies ONLY to component being duplicated. Complexity of assembling and aligning a segmented mirror actually increases cost.

Regressing on a seg/mono scale factor ‘hints’ that segmented telescopes cost ~ 15% more than monolithic telescopes. BUT, the result is not significant (p-value = 30%).

# Cost can be Estimated Two Different Ways

Two ways to estimate cost:

- use model directly
- use model to compare cost with other OTAs

| | | Equation Method | | | |
|---|---|---|---|---|---|
| Effective Aperture | | 4-m | 4-m Seg | 8-m | 8-m Seg |
| Architecture | | off-axis | on-axis | off-axis | off-axis |
| Starting Space Cost [FY17 $M] | $ 600 | | | | |
| Number of Segments | 0.8 | 1 | 6 | 1 | 35 |
| Circumscribed Diameter [meter] | 1.7 | 4 | 1.8 | 8 | 1.5 |
| WDLP [micrometer] | -0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Temperature [K] | -0.25 | 270 | 270 | 270 | 270 |
| exp(YOD) | -0.028 | 2025 | 2025 | 2025 | 2025 |
| 50% Predicted Cost [FY17 $M] | | $ 358 | $ 386 | $ 1,163 | $ 1,161 |
| 85% Predicted Cost [FY17 $M] | | $ 519 | $ 560 | $ 1,687 | $ 1,684 |

| | | | Relative Cost Method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Effective Aperture | | | 4-m Mono | | | 4-m Mono | | | 8-m Segmented | |
| Architecture | | HST | off-axis | Ratio | JWST | off-axis | Ratio | JWST | off-axis | Ratio |
| Total Cost [FY17 $M] | | $530 | | | $1,380 | | | $1,380 | | |
| Number of Segments | 0.8 | 1 | 1 | 1.00 | 1 | 1 | 1.00 | 18 | 35 | 1.70 |
| Diameter [meter] | 1.7 | 2.4 | 4 | 2.38 | 5.6 | 4 | 0.56 | 1.4 | 1.5 | 1.12 |
| WDLP [micrometer] | -0.5 | 0.5 | 0.5 | 1.00 | 2 | 0.5 | 2.00 | 2 | 0.5 | 2.00 |
| Temperature [K] | -0.25 | 294 | 270 | 1.02 | 30 | 270 | 0.58 | 30 | 270 | 0.58 |
| exp(YOD) | -0.028 | 1977 | 2025 | 0.26 | 2006 | 2025 | 0.59 | 2006 | 2025 | 0.59 |
| 50% Predicted Cost [FY17 $M] | | | $336 | 0.63 | | $ 528 | 0.38 | | $1,792 | 1.30 |
| 85% Predicted Cost [FY17 $M] | | | $488 | | | $ 766 | | | $2,598 | |

## Subsystem Cost

Many believe that telescope cost drives mission cost.

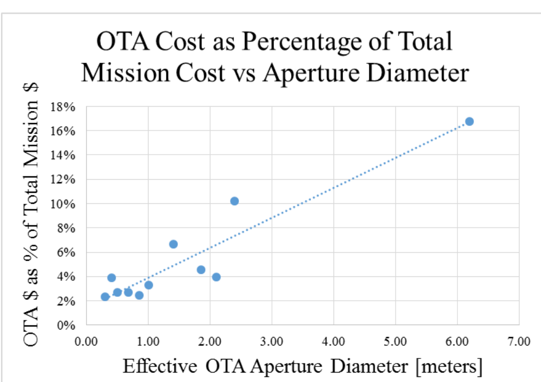
To test this, cost data was collected in the standard NASA work breakdown structure (WBS) from Cost Analysis Data Requirements (CADRe) reports for 14 missions

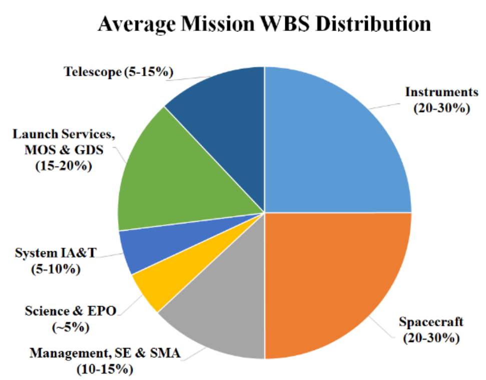
| | |
|---|---|
| CALIPSO | CLOUDSAT |
| GALEX | ICESAT |
| JWST | Kepler |
| LANDSAT-7 | Spitzer |
| STEREO | SWAS |
| TRACE | WIRE |
| WISE | WMAP |

| | |
|---|---|
| 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** |

## Subsystem Cost

While mission cost does depend on aperture size, Telescope is only 5 to 15% of total.




Science instruments and spacecraft are the largest percentage of total mission cost.

And, management, systems engineering and safety and mission assurance are larger than the telescope.

# Conclusions

After 20 years assembling/vetting a database with sufficient data diversity, we have a multivariable parametric 'first-unit' cost model for Ground and Space Telescopes:

$$\textbf{OTA\\$ (FY17)} = \\$20M \times 30^{(S/G)}\, D^{(1.7)}\ \lambda^{(-0.5)} * T^{(-0.25)}\, e^{(-0.028)\,(Y-1960)}$$

Implications of the model:

- Space Telescopes are ~ 30X more expensive than Ground
- Larger telescopes are more expensive than smaller telescopes
- UVO diffraction limited telescopes are more expensive than IR telescopes
- Cryogenic telescopes are more expensive than warm telescopes.
- Cost decreases ~ 50% every 25 years – probably due to technology advance

Also,

- Segmentation – while an engineering necessity – does not appear to reduce cost.
- Telescopes are only 10 to 15% of Total Mission Cost.
- Mass is not a good CER

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