Space Systems Cost Modeling

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Why Cost Estimation?

- Critically important part of system design
  - Too high – lose the contract award
  - Too low – over-run cost plus contracts, company loss on fixed price contracts
- Trends
  - Design to cost
  - Cost as an independent variable

Work Breakdown Structure

- Multi-level table used to organize, normalize and track costs and schedule
  - Ensures accounting of all aspects of costs
  - Each element has a start time, completion time, and all components of direct costs (labor, material, etc)
- Example shows top three levels for spacecraft systems
  - From MIL HDBK 881
  - http://www.acq.osd.mil/pm/newpolicy/wbs/mil_hdbk_881/mil_hdbk_881.htm

FLEX

1.0 MANAGEMENT

1.1 Project Planning & Schedule
- 1.1.1 Organization and Meetings
- 1.1.2 Schedule Maintenance
- 1.1.3 Implem & Work-around Plans

1.2 Financial
- 1.2.1 Budget Update & Forecast
- 1.2.2 Subcontract Monitoring

1.3 Task Manage & Tracking
- 1.3.1 Monitoring & Tracking
- 1.3.2 WBS Maintenance

1.4 Interface
- 1.4.1 Program Monitor
- 1.4.2 JSC RMS Program
- 1.4.3 Tech. Tracking Committee
- 1.4.4 Reporting

1.5 Co-I & Subcontractor Mgmt
- 1.5.1 Planning & Schedule
- 1.5.2 Technical & Task Tracking

1.6 Quality
- 1.6.1 Quality Program Plan
- 1.6.2 Nonconformance Tracking

2.0 SYSTEM ENGINEERING

2.1 Requirements
- 2.1.1 Expt Req Document
- 2.1.2 Subsystem Req. Documents

2.2 Design & Evaluation
- 2.2.1 3-D 1-g & 0-g Modeling
- 2.2.2 Feedforward Control Design
- 2.2.3 Feedback Control Design
- 2.2.4 Human-in-the-Loop Simulation
- 2.2.5 Performance Evaluation

2.3 Configuration Control
- 2.3.1 Design Documents
- 2.3.2 Processing &Tracking
- 2.3.3 Equipment List Maintenance
- 2.3.4 Test Matrix

2.4 Program Reviews
- 2.4.1 Conceptual Design Review
- 2.4.2 Requirements Review
- 2.4.3 Non-Advocate Review
- 2.4.4 Preliminary Design Review
- 2.4.5 Critical Design Review
- 2.4.6 Flight Readiness Review
- 2.4.7 Post Mission Expt Review

3.0 HARDWARE DESIGN & FAB

3.1 Arm Fabrication
- 3.1.1 Prototype (1)
- 3.1.2 Ground Test Facilities (2)
- 3.1.3 Flight Arms (2)
- 3.1.4 Motors
- 3.1.5 Payloads

3.3 Human Interface
- 3.3.1 Joystick
- 3.3.2 Grid W/S/W
- 3.3.3 Task Targets
- 3.3.4 Video Interface

3.2 Support Elec & Software
- 3.2.1 Experiment Support Module
- 3.2.2 Crew Interface
- 3.2.3 Ground Support Equipment
- 3.2.4 Software
- 3.2.5 Up/downlink Refurbishment

4.0 INTEGRATION & TEST

4.1 Engineering Model Integ
- 4.1.1 Robotic Arm Subsystem Tests
- 4.1.2 ESM Configuration
- 4.1.3 System Functional Testing
- 4.1.4 Prelim Environmental Test

4.2 Flight Model Integration
- 4.2.1 Integ Planning & Doc
- 4.2.2 Test Planning & Doc
- 4.2.3 Arm Subsystem Accept. Tests
- 4.2.4 System Integration
- 4.2.5 Functional Testing/Charact
- 4.2.6 System Accept/Cert Testing

4.3 Carrier Integration
- 4.3.1 Form 1628 Submittal
- 4.3.2 Integ Reviews (CIR, FOR,.)
- 4.3.3 Safety Reviews (0, I, II, III)
- 4.3.4 Payload Integ Plan (PIP)
- 4.3.5 Interface Control Doc (ICD)
- 4.3.6 PIP Annexes
- 4.3.7 Verification Activities
- 4.3.8 Crew Training
- 4.3.9 JSC Interface/Project Monit
- 4.3.10 Material Lists
- 4.3.11 Packing & Stowage Plans
- 4.3.12 FM Delivery & Recovery

5.0 OPERATIONS

5.1 On-Orbit
- 5.1.1 Diagnostics & error identi
- 5.1.2 Human-in-the-Loop
- 5.1.3 Protocol format

5.2 Ground
- 5.2.1 KSC
- 5.2.2 JSC
- 5.2.3 On-orbit Predictions Document

5.3 Post-Mission Activities
- 5.3.1 Flight Data Analysis
- 5.3.2 Reporting and dissemination

Software Cost Estimation

- Flight software RDT&E costs $435 / SLOC
- Ground software RDT&E $220/ SLOC

Language Factor	
Ada	1.00
UNIX-C	1.67
PASCAL	1.25
FORTRAN	0.91

SMAD Table 20-10

Technology Readiness Levels

Technology Readiness Level	Definition	Risk	Std Dev (%)
1	Basic principles observed	High	>25
2	Conceptual design formulated	High	>25
3	Conceptual design tested analytically or experimentally	Moderate	20-25
4	Critical function/characteristic demonstrated	Moderate	15-20
5	Component or breadboard tested in relevant environment	Moderate	10-15
6	Prototype/engineering model tested in relevant environment	Low	<10
7	Engineering model tested in space	Low	<10
8	Full operational capability	Low	<10

Higher Level Cost Factors

- Wraps model non-physical factors
  - Program support, system engineering, management costs, product assurance, integration and test
- Overhead is incurred in support of an activity but is not solely identifiable to that activity
  - Administration, real estate taxes, facility maintenance
- Level I taxes are allocated to headquarters
  - Defense Contract Administration Services (DCAS)
  - Small Business Innovative Research (SBIR)
  - Independent Research and Development (IR&D)

Higher Level Cost Factors (continued)

- Program Support
  - Costs activities, systems and hardware development outside the prime contract
    - Analyses
    - Govt test facilities, equipment and personnel
    - Program office support contractors for technical oversight
- Advanced development studies
- Fee

Management Reserves

- Account for cost and schedule uncertainty
  - Regression analysis
  - Complexity factor uncertainty
  - Cost driver input uncertainty
  - Time and material cost
  - Vendor ROMs
- Should be held at Management level
- Should not be used to accommodate scope changes

Development Status	Reserve Percent
Off the shelf; hardware exists; no mods required	10%
Modifications required to existing hardware	15%
New hardware but design passed CDR; vendor quotes	20%
New hardware but design passed PDR	25%
New design but within state of the art; Cost est from CERs; vendor ROMs	35%
New design; remote analogs, outside SOTA	50%

Production Costs

- Non-recurring costs include design, drafting, engineering unit integration, assembly and test, GSE, and design verification
- Recurring includes flight hardware manufacture, IA&T
- Theoretical First Unit is the basis for calculating costs for the production run
- Protoflight unit is the qualification test unit that is refurbished for flight
- Prototype units don’t fly

Annual Funding Profiles

- Total RDT&E costs must be spread across the development years
  - Typically loaded toward the earlier years
- NASA uses a Beta curve but other models exist
  - http://www.jsc.nasa.gov/bu2/beta.html
- Similar models are used for production runs

Inflation

- CERs are based on constant year dollars and must be inflated to determine the total value and year-by-year requirement
- Inflation factors for each type of money (RDT&E, Production, Operation) are published by OSD and NASA annually
- Government figures included in ACEIT cost estimation software

Cost Analysis Requirements Document

- Usually required for formal cost reviews
  - Explains the rationale used to derive cost estimates
- Documentation makes it easier to update the estimate through the duration of the program life
- Usually contains
  - Project description
  - WBS
  - Ground rules and assumptions
  - Schedule
  - Cost summaries for each WBS element
  - Cost phasing summaries

CARD Subsystem Summaries

- Overall technical description (function, components, quantities, heritage, TRL, risk)
- Schematic, picture or diagram
- CER graphs or single point analog
- Basis of estimate if not parametric (e.g., grassroots, vendor ROM
- Key assumptions
- POC

Costing References

- Space Mission Analysis and Design, Wertz and Larson
- Reducing Space Mission Cost, Wertz and Larson
- International Reference Guide to Space Launch Systems, Isakowitz, AIAA
- Jane's Space Directory
- Cost Models
  - Aerospace Corporation Small Satellite Cost Model (SSCM)
  - Air Force Unmanned Spacecraft Cost Model (USCM)
  - NASA Goddard Multivariable Instrument Cost Model (MICM)
  - NASA World Wide Web sites
    - http://www.jsc.nasa.gov/bu2/guidelines.html
    - http://www.jsc.nasa.gov/bu2/models.html

Cost Estimating Methods

1) Detailed Bottom-Up Cost Estimating
   – Most accurate, most time consuming
   – Applied after an architecture has been selected and the design is mature

2) Analogous Estimating
   – Can be applied at any level of design
   – Inflexible for trade studies

3) Parametric Estimation
   – Cost Estimation Relationships (CERs)
   – Best for trade studies during the Conceptual Design Phase

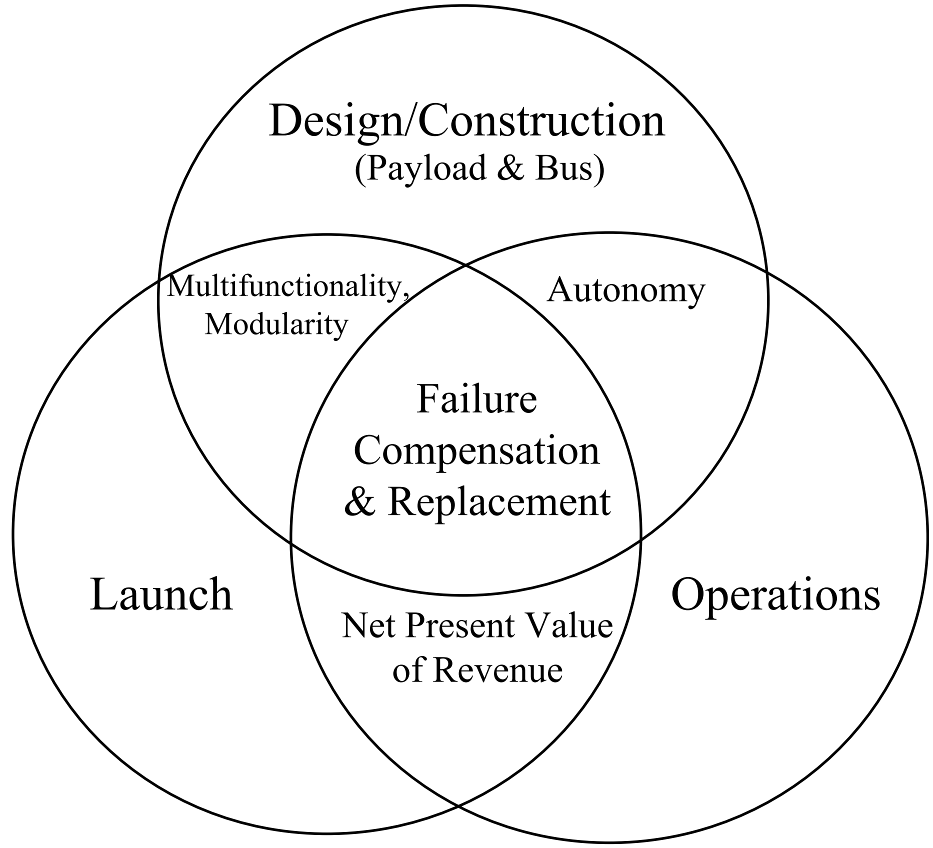
Reducing Space Mission Cost, Larson and Wertz

Graduate Student Labor Rates

- Many program costs are dominated by the labor costs of the “standing army” times the duration of the program (e.g., operations)
  - Labor costs consist of salary times wraps (e.g., overhead and employee benefits)
  - Overhead includes real estate taxes, facility maintenance, aspects of administration, etc.
  - Employee benefits include retirement fund contributions, paid vacation, continuing education, sometimes health plans
- How much does a graduate student at MIT cost per year?
  - $1,475 (PhD) or $1,335 (SM) stipend per month before taxes
  - MIT overhead is 63.5%
  - Tuition is $1,887 per month
  - Only stipend is subject to overhead $/yr=[(1475*1.635)+1887]*12=$51,584 per year
- What about staff
  - Assume a salary of $50,000 per year before taxes
  - Cost to contract is salary times overhead times employee benefits
  - $/year = $50000*1.635*1.377 = $50000*2.25 = $112,570
- Only labor is subject to employee benefits
- Travel, materials, labor, etc. are subject to overhead
  - Fabricated equipment and subcontracts beyond first $25k are exempt from overhead

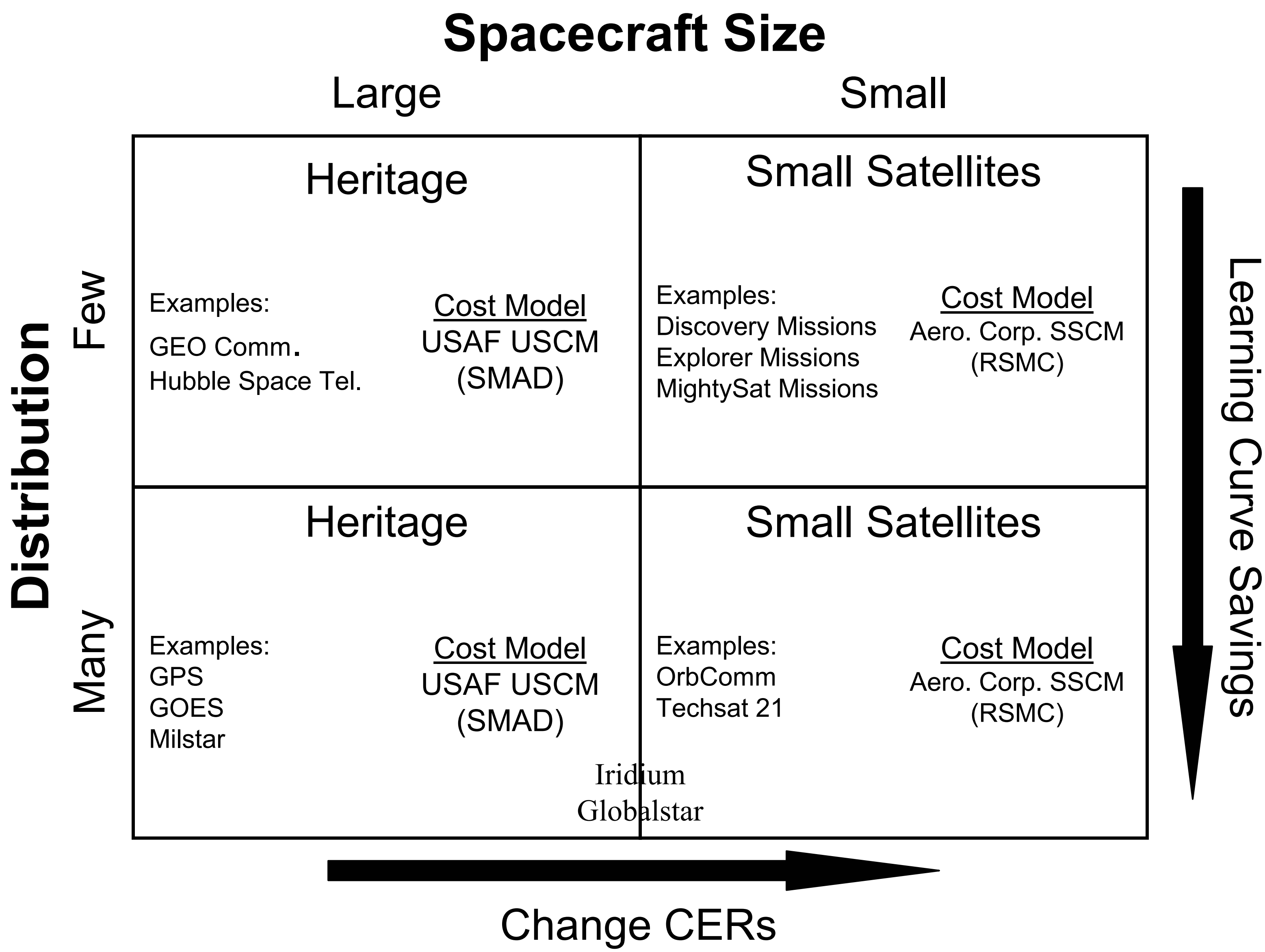
Lifecycle Cost

- Design and Construction
  - The spacecraft, Learning curve
- Launch
  - Getting the spacecraft from here to there
- Operations
  - Should not be underestimated
- Failure Compensation & Replacement
  - Failures are violations of requirements
  - Compensatory action or lost revenue incurs cost
  - Expected Value calculation
    - Cost of failure at time *t*
    - *Pr(failure)* at time *t*
- Modularity
  - Decreases design costs at the expense of Launch costs
  - Multifunctionality does the opposite
- Autonomy
  - Trade between cost of inserting autonomy during design vs. the actual savings in operations costs



- Net Present Value
  - A dollar in hand today is worth more than a dollar in hand tomorrow
  - A dollar spent tomorrow costs less than a dollar spent today

Spacecraft Size vs. Distribution



Cost Estimating Relationships (CER's)

- A *parametric cost model* is a series of mathematical relationships that relate spacecraft cost to physical, technical, and performance parameters.
- *Cost Estimation Relationships* (CERs) show how the cost properties of the system or subsystem vary with characteristic parameters.
- "Wraps" typically account for approximately 30% of the development cost for space systems.
- Requires a historical database.
- Based on regression analysis & the correlation of data.
- $Cost=a+bM^{c}P^{d}$
- To be used as a comparison tool, *not* a budgeting tool.

Reducing Space Mission Cost, Larson and Wertz

RDT&E & Production CER's for Large Satellites

RDT&E Cost Component	Parameter, X (unit)	Applicable Range	CER (FY92$k)	Standard Error
IR Payload	Aperture dia. (m)	0.2-1.2	$c = 306892x^{0.562}$	46,061
Comm Antenna	Wt. (kg)	1-87	$c = 1015x^{0.59}$	1793
Comm Electronics	Wt. (kg)	14-144	$c = 917x^{0.7}$	6466
Spacecraft Bus	Dry Wt. (kg)	26-897	$c = 16253 + 110x$	14,586
Structure/Thermal	Wt (kg)	7-428	$c = 2640 + 416x^{0.66}$	4773
TT&C	Wt (kg)	4-112	$c = 1955 + 199x$	3010
Att Deter	Dry Wt. (kg)	6-97	$c = 3330x^{0.46}$	5665
Att & Reac Ctrl	Dry Wt. (kg)	25-170	$c = 935 + 153x$	1895
Power	EPS Wt. x BOL Pwr (kg-W)	104-414,920	$c = 5303 + 0.108x^{0.97}$	5743

Prod. Cost Component	Parameter, X (unit)	Applicable Range	CER (FY92$k)	Standard Error
IR Payload	Aperture dis. (m)	0.2-1.2	$c = 122{,}758x^{0.562}$	18,425
Comm Antenna	Wt. (kg)	1-87	$c = 20 + 230x^{0.59}$	476
Comm Electronics	Wt. (kg)	13-156	$c = 179x$	8235
Spacecraft Bus	Dry Wt. (kg)	26-1237	$c = 185x^{0.77}$	6655
Structure/Thermal	Wt. (kg)	7-777	$c = 86x^{0.65}$	1247
TT&C	Wt. (kg)	4-112	$c = 93 + 164x^{0.93}$	1565
Att Deter	Dry Wt. (kg)	6-97	$c = 1244x^{0.39}$	1912
Att & Reac Ctrl	Dry Wt. (kg)	9-167	$c = -364 + 186x^{0.73}$	999
Power	EPS Wt. x BOL Pwr (kg-W)	104-414,920	$183x^{0.29}$	2254

SSCM Version 7.4 CER's for Small Satellites

Independent Variable	**# Data Points**	**CER for Total Bus Cost (FY94$M)**	**Applicable Range**	**Standard Error (FY94$M)**
Satellite volume (in3)	12	$c \equiv -34.84 + 4.66\ln(x)$	2,000-80,000	4.27
Satellite bus dry mass (kg)	20	$c \equiv 0.704 + 0.0235x^{1.261}$	20-400	3.33
ACS dry mass (kg)	14	$c \equiv 6.65 + 0.042x^{2}$	1-25	5.45
TT&C subsystem mass (kg)	13	$c \equiv 2.55 + 0.29x^{1.35}$	3-30	4.50
Power system mass (kg)	14	$c \equiv -3.58 + 1.53x^{0.702}$	7-70	3.52
Thermal control mass (kg)	9	$c \equiv 11.06 + 0.19x^{2}$	5-12	5.37
Structures mass (kg)	14	$c \equiv 1.47 + 0.07x\ln(x)$	5-100	5.40
Number of thrusters	5	$c \equiv 46.16 - 41.86x^{-0.5}$	1-8	8.95
Pointing accuracy (deg)	16	$c \equiv 1.67 + 12.98x^{-0.5}$	0.25-12	7.37
Pointing knowledge (deg)	10	$c \equiv 12.94 - 6.681x\ln(x)$	0.1-3	8.79
BOL power (W)	16	$c \equiv -22.62 + 17.9x^{0.15}$	20-480	6.13
Average power (W)	17	$c \equiv -8.23 + 8.14x^{0.22}$	5-10	5.71
EOL power (W)	14	$c \equiv 0.507 + 1.55x^{0.452}$	5-440	6.20
Solar array area (m2)	13	$c \equiv -814.5 + 825.7x^{0.0066}$	0.3-11	6.37
Battery capacity (A-hr)	12	$c \equiv 1.45 + 1.91x^{0.754}$	5-32	6.01
Data storage cap (MB)	14	$c \equiv -143.5 + 154.85x^{0.0079}$	0.02-100	8.46
Downlink data rate (kbps)	18	$c \equiv 26.0 - 21.86x^{-0.23}$	1-1000	8.91

Reducing Space Mission Cost, Larson and Wertz

SSCM Version 8.0 CER's for Small Satellites

Independent Variable(s)	# Data Points	CER for Total Bus Cost (FY94$M)	Applicable Range	Std. Error (%)
r: EOL power (W) s: Pointing accuracy (deg)	17	$c = 6.47 r^{0.1599} s^{-0.356}$	r: 5-500 s: 0.05-5	29.55
r: TT&C mass (kg) s: Payload power (W)	18	$c = 0.702 r^{0.554} s^{0.0363}$	r: 3-50 s: 10-120	35.68
r: Downlink data rate (kbps) s: Average power (W) p: Prop system dry mass (kg)	21	$c = 1.44 r^{0.0107} s^{0.509} 1.0096^{p}$	r: 1-2000 s: 5-410 p:-35	35.66
r: Spacecraft dry mass (kg) s: Pointing accuracy (deg)	26	$c = 0.6416 r^{0.661} - 1.5117 s^{0.289}$	r: 20-400 s: 0.05-5	37.19
r: Solar array area (m2) s: ACS type (3-axis or other)	20	$c = 4.291 r^{0.255} 1.989^{s}$	r: 0.3-11 s: 0=other, 1=3-axis	38.53
r: Power subsys mass (kg)	25	$c = 0.602 r^{0.839}$	r: 7-70	37.07

Reducing Space Mission Cost, Larson and Wertz

Can estimate cost using individual CER's or can create a weighted average where weights are inversely proportional to errors

$$C = \frac{\sum {c_i}/{\sigma_i^2}}{\sum {1}/{\sigma_i^2}}$$

Learning Curve

- CERs calculate the Theoretical First Unit Cost (TFU)
- The *learning curve* is a mathematical technique to account for productivity improvements as a larger number of units are produced.
  - Economies of scale
  - Set up time
  - Human learning
- Calculation:
  - 1) $B = 1 - \dfrac{\ln((100\%)/S)}{\ln 2}$
  - 2) $L = N^B$
  - 3) Production Cost = TFU x L

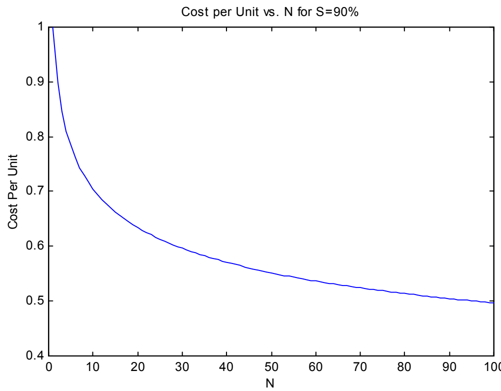
    where

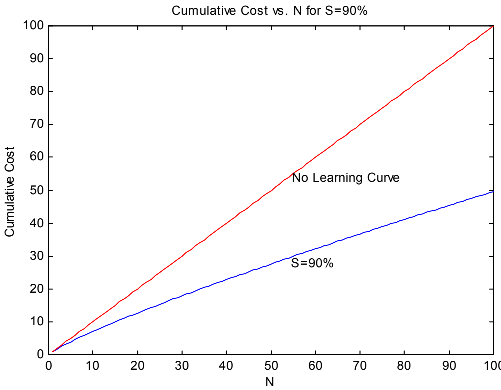
    S= Learning Curve slope

    N= Number of units produced

    L= Learning Curve Factor
- For the Aerospace Industry

N	S
<10	95%
10-50	90%
>50	85%





Adapted from SMAD, Larson & Wertz

Impact of Technological Risk on Cost

State of Technology Development	Team Familiarity				
	(A)	(B)	(C)	(D)	(E)
Well within existing state-of-the-art; familiar technology	0.6	0.7	0.8	0.9	1.0
Slightly advancing state-of-the-art; minor amounts of new technology	0.7	0.8	0.9	1.0	1.1
Nominal aerospace project using some new technology	0.8	0.9	1.0	1.1	1.2
Significant amounts of new technology	1.0	1.1	1.2	1.3	1.4
Major new technology; requires breakthroughs in state-of-the-art	1.2	1.3	1.4	1.5	1.6

(A) Team is totally familiar with the project and has completed several identical projects. Team's technical expertise is superior.
(B) Team is very familiar with the type of project and has completed similar projects. Team's technical expertise is very good.
(C) Nominal team has related but not identical project experience. Team's technical expertise is average.
(D) Project introduces many new aspects with which team is unfamiliar. Team's technical expertise is below average.
(E) Team is totally unfamiliar with this type of project. Team's technical expertise is poor.

Technology Readiness Level	Definition of Space Readiness Status	Added Cost (%)
1	Basic principle observed	>25%
2	Conceptual design formulated	>25%
3	Conceptual design tested	20-25%
4	Critical function demonstrated	15-20%
5	Breadboard model tested in environment	10-15%
6	Engineering model tested in environment	<10%
7	Engineering model tested in space	<10%
8	Fully operational	<5%

What are the TRL's for TPF Technology?

Technology	TRL	What Will it Change	When Will This Occur	New TRL
Formation Flying				
Deployable Structures				
Interferometry Optics				
Tethers				
Cryogenic Optics				
Deployable Primaries				
Autonomy				
White Light Nulling				
High Speed Controls				

Operations Costs

- What makes up operations costs?
  - Ground Station(s)
  - Personnel
- Ground Stations
  - Facilities (The Operations Control Center)
  - Equipment (Antenna, Computers, etc.)
  - Software (Usually the most difficult & most expensive)
- Personnel
  - Maintenance Costs
  - Contractor Labor (~$140K/Staff Year)
  - Government Labor (~$95K/Staff Year)
- Please see SMAD for Operations CERs
- Does anyone here have hands-on operations experience?

Adapted from SMAD, Larson & Wertz

The Time Value of Money

Adapted from:
• Applied Systems Analysis - de Neufville
•Aerospace Product Design Course Notes - C. Boppe

- Plays a major role in the allocation of resources for *expensive, long-term* space projects.
- Why will an organization incur debt?

  The benefit of using the money now is greater than the interest paid.
- Why is a given amount of $ today worth more than the same amount of $ in the future?

  1) Inflation

  2) $ can be used to increase productivity *now*.
- Compound Interest Formula

$$F = P(1+i)^{t}$$

where: F= future value of money; P= present value of money; i= interest rate; t= investment/project lifetime

- Present Value Formula

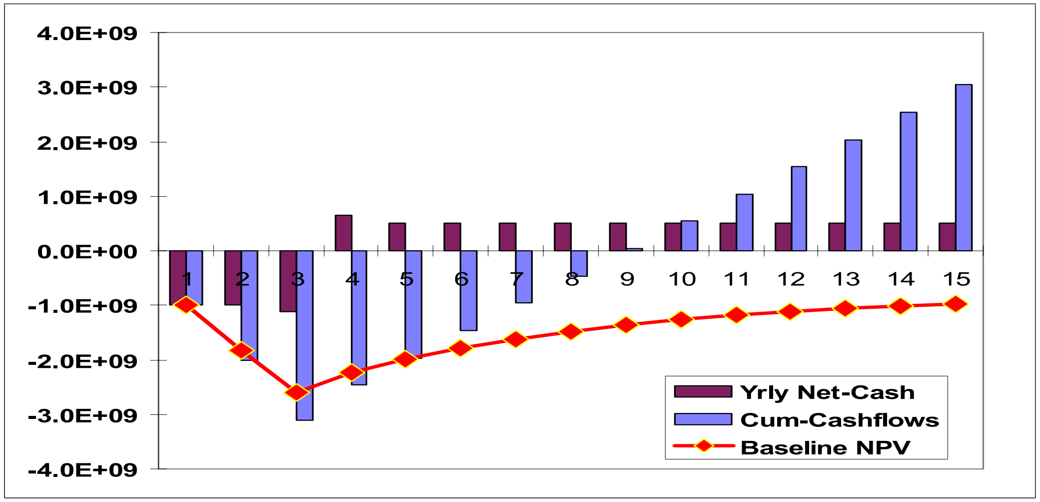
$$P = F(1+r)^{-N}$$

where: r= discount rate (~3% greater than the interest rate)

Cash Flow Analysis

Adapted from:
• Applied Systems Analysis - de Neufville
•Aerospace Product Design Course Notes - C. Boppe

- When doing a cash flow analysis for a large, long-term space project, it is important to compare all revenues and expenditures in *constant* dollars.
- Commercial Space Projects
  - When does it make sense to invest in a space project?
    - When the expected return on investment in the project is greater than the return from investing the same amount of capital at the interest rate.
    - Determined through a cash flow analysis.
- Present Value of Profit
  - PVP= $\text{Revenue}(1+r)^{-t} - \text{Cost}(1+i)^{t}(1+r)^{-t}$
    - Assumes "Cost" requires borrowing money at i to cover investments



Costing References

- Space Mission Analysis and Design, Larson and Wertz, Ch. 20.
- Reducing Space Mission Cost, Wertz and Larson, Entire Book
  - see reference list in Ch. 8
- International Reference Guide to Space Launch Systems, Isakowitz, AIAA
- Jane's Space Directory
- Cost Models
  - Aerospace Corporation Small Satellite Cost Model (SSCM)
  - Air Force Unmanned Spacecraft Cost Model (USCM)
  - NASA Goddard Multivariable Instrument Cost Model (MICM)
  - NASA World Wide Web sites.

Mars Rover Engineering Costs (JPL)

- Rover development costs without instruments and instrument structure (i.e., payload).

$$\$ = 222.3645 M^{0.19652} \rho^{-1} e^{0.014638\rho} \qquad \rho = \frac{M}{V_{effective}}$$

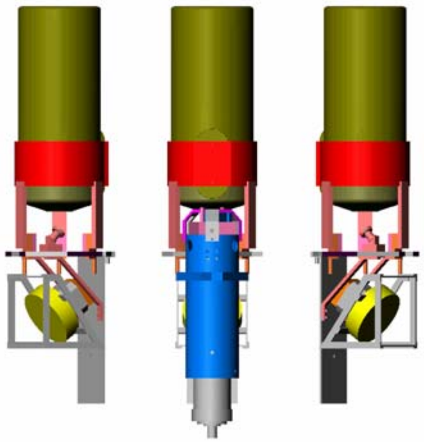
  - M is the rover mass [kg] without payload
  - $V_{effective}$ is the stowed rover envelope
  - $ is in FY02$M
  - Needing to retract the MER wheels for stowage drove up cost

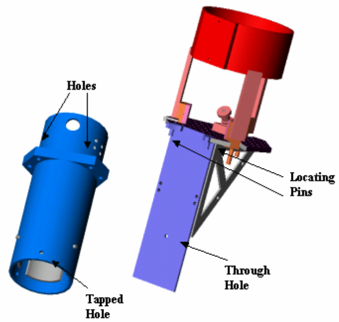
- Effective volume is estimated from launch vehicle fairing

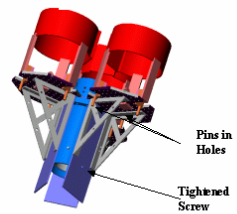
$$V_{effective} = 0.038766\left(F_{av} - 0.6\right)^{3}$$

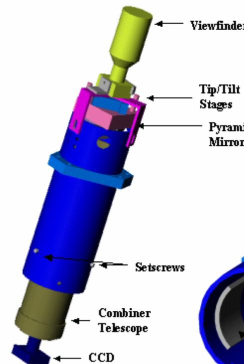
  - F_{av} is available fairing diameter [m]
  - 3.749m for Delta IV-4240

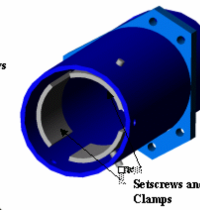
ARGOS Cost Model

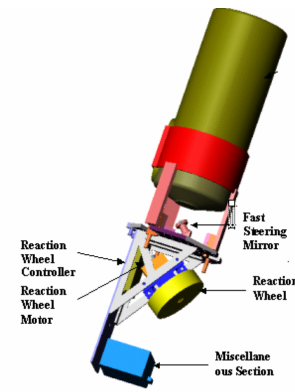


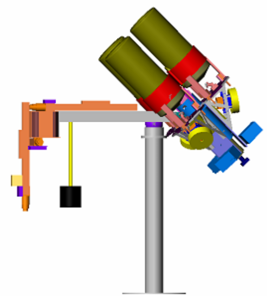


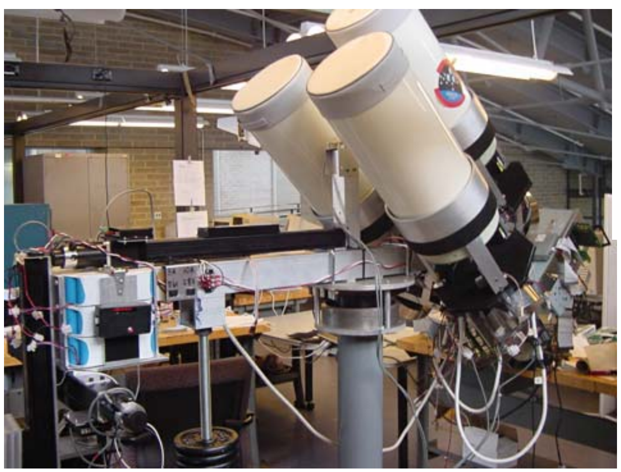












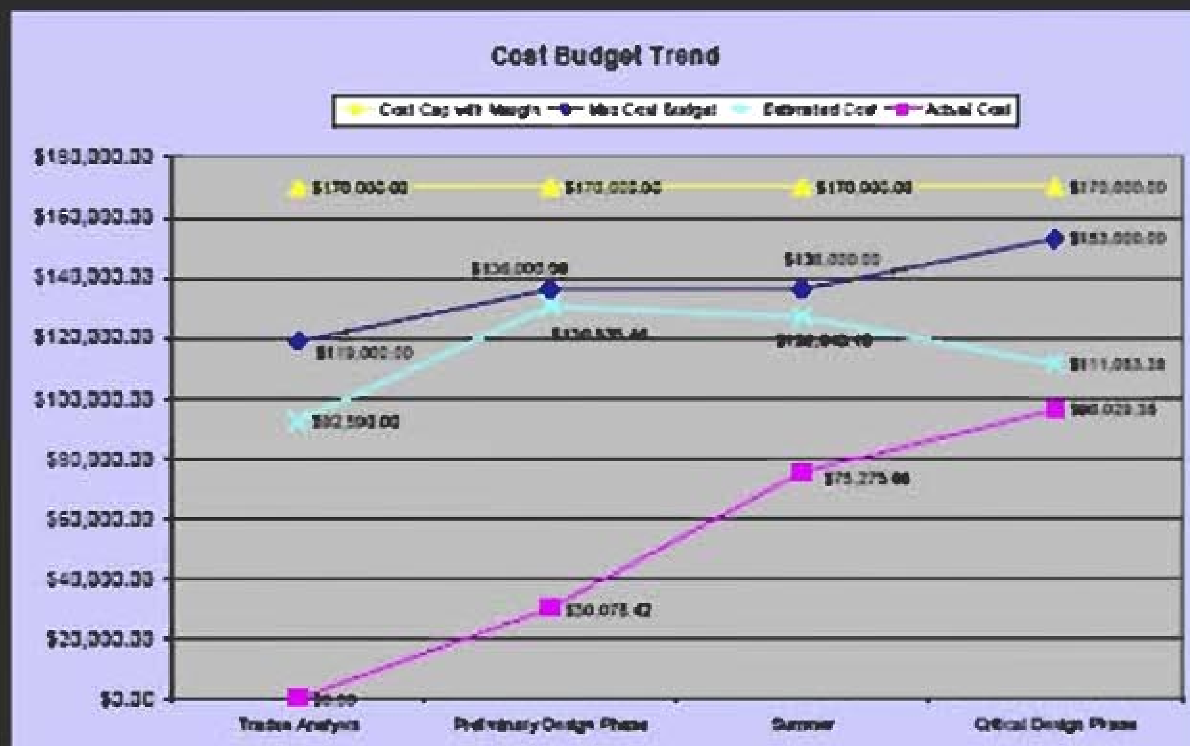
MIT ASTRO AERO

Budget Overview

Introduction
Optics
ACS
Structures
PAS
SOC
Systems
- *Budgets*
- Risk Management
- Schedules
- Integration

Conclusion

- Since PDR, costs have been cut, resulting in a lower estimated cost



Literature Search

Kahan, Targrove, “Cost modeling of large spaceborne optical systems”, SPIE, Kona, 1998

Humphries, Reddish, Walshaw,”Cost scaling laws and their origin: design strategy for an optical array telescope”, IAU, 1984

Meinel, “Cost-scaling laws applicable to very large optical telescopes”, SPIE, 1979

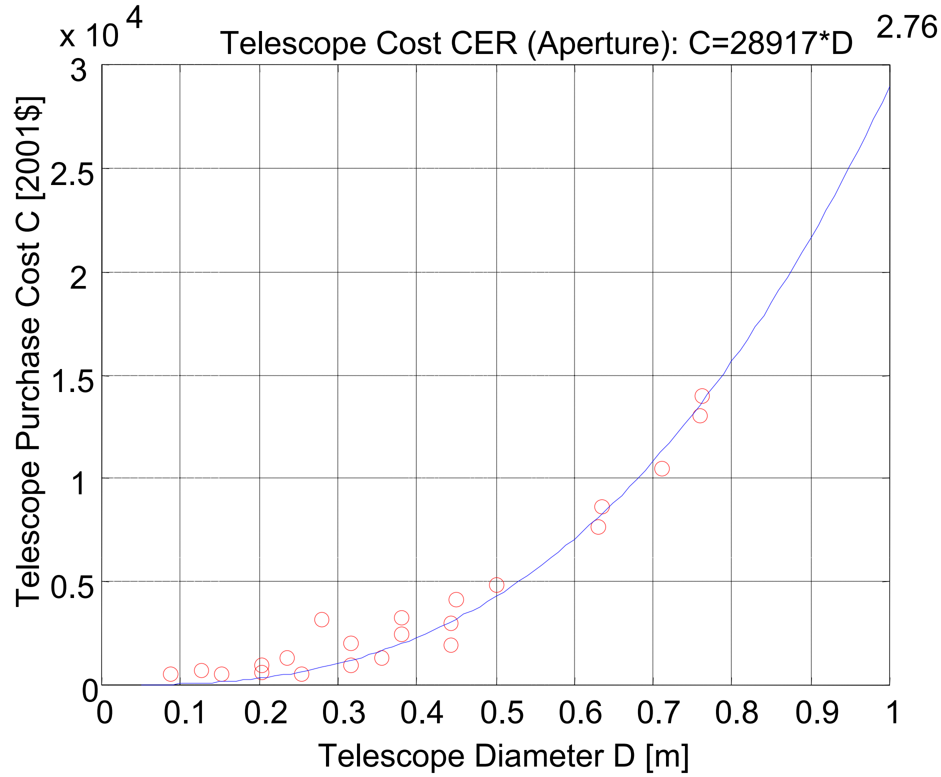
Meinel’s law: $S = 0.37 \cdot D^{2.58}$ [M$] (1980)

Small Amateur Telescopes

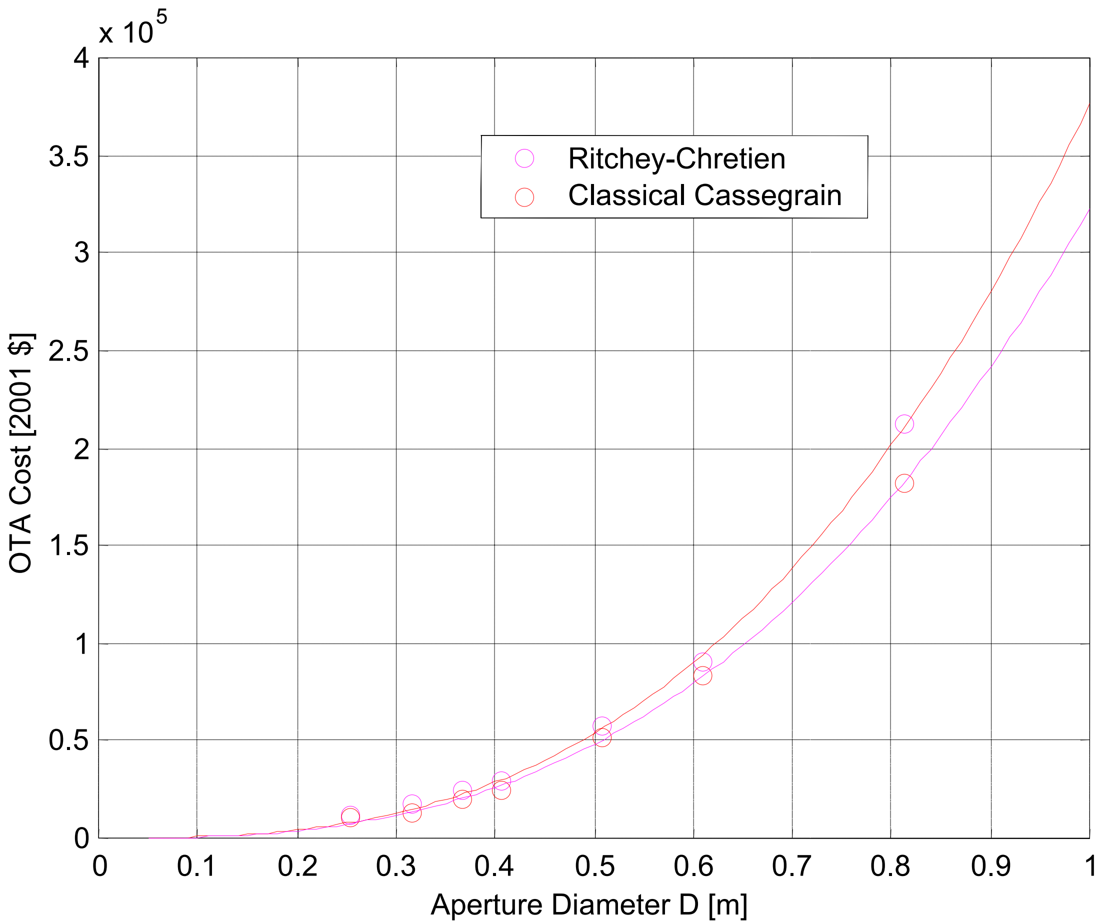
- Priced various amateur telescopes
  - DHQ f/5
  - DHQ f/4.5
  - D Truss f/5
  - Obsession f/4.5
  - Celestron G-f/10
- Fit power law

- Exponent surprisingly similar to Meinel's Law

$$C = 28917 D^{2.76}$$



Professional Telescope OTA cost



Company: Optical Guidance Systems
(http:www.opticalguidancesystems.com)

CERs for Ritchey-Chretien

$$C_{RC} = 376000 \cdot D^{2.80}$$

Classical Cassegrain

$$C_{CC} = 322840 \cdot D^{2.75}$$

Remarkable Result: virtually identical power law across completely different product lines.

ACS Mass and Cost

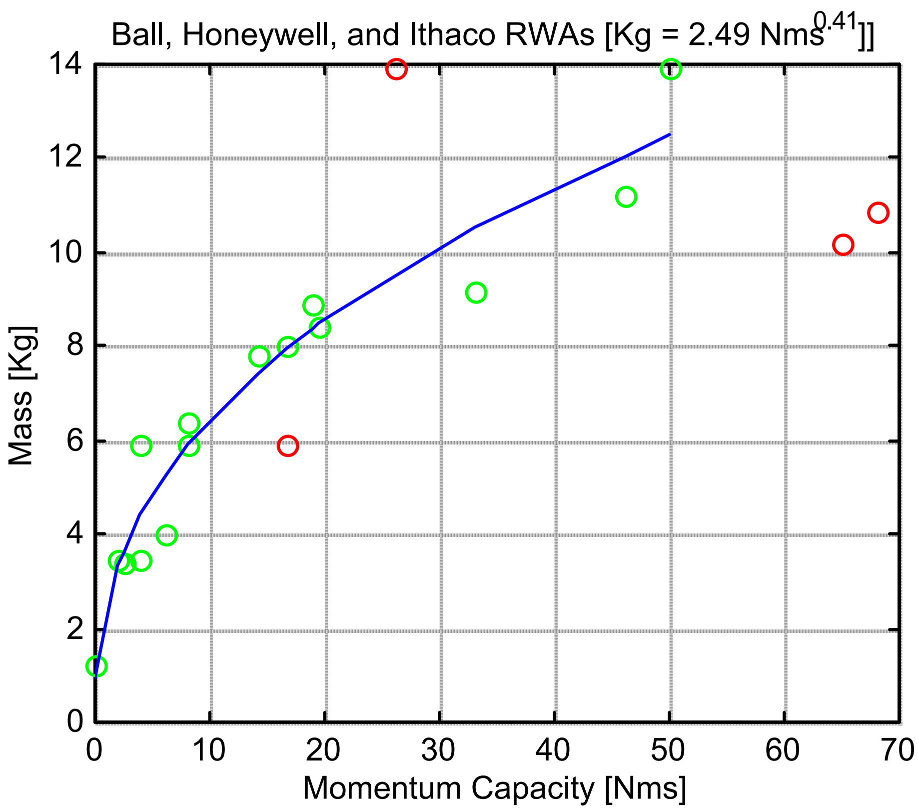
- Reaction wheel mass scales w/ momentum capacity

$$Kg = 2.49\,Nms^{0.41}$$

- Reaction wheels dominate ACS mass
- ACS cost is function of mass

$$\$_{ACS} = c_o Kg_{ACS}^{0.8}$$

- Scale using ARGOS ACS mass and cost
- Inertia depends on sub-aperture masses and geometry
- Assumed 1.5 deg/sec slew rate



Sub-System Cost Tables

Passive Optics

Item	Unit Cost (US$)	Quantity Bought	Actual Cost (US$)	Monolith Quantity	Monolith Cost	Golay-3 Quantity	Golay-3 Cost	Golay-6 Quantity	Golay-6 Cost	Golay-9 Quantity	Golay-9 Cost	Golay-12 Quantity	Golay-12 Cost
Takahashi Telescope (Used)	$2,339	1	$2,339	0	$0	0	$0	0	$0	0	$0	0	$0
Takahashi Telescope	$2,800	2	$5,600	0	$0	3	$8,400	0	$0	0	$0	0	$0
Sub-Aperture (D=0.4169m)	$18,140	0	$0	1	$18,140	0	$0	0	$0	0	$0	0	$0
Sub-Aperture (D=0.09393m)	$377	0	$0	0	$0	0	$0	6	$2,259	0	$0	0	$0
Sub-Aperture (D=0.0618m)	$127	0	$0	0	$0	0	$0	0	$0	9	$1,141	0	$0
Sub-Aperture (D=0.0463m)	$60	0	$0	0	$0	0	$0	0	$0	0	$0	12	$718
Beam Combiner	$3,624	1	$3,624	1	$3,624	1	$3,624	1	$3,624	1	$3,624	1	$3,624
Collimator	$2,300	4	$9,200	0	$0	3	$6,900	6	$13,800	9	$20,700	12	$27,600
Collimator Engineering	$2,500	1	$2,500	0	$0	0	$0	0	$0	0	$0	0	$0
Collimnator Mounting	$500	3	$1,500	0	$0	3	$1,500	6	$3,000	9	$4,500	12	$6,000
Pyramidal Mirror	$3,000	1	$3,000	0	$0	1	$3,000	1	$3,000	1	$3,000	1	$3,000
Optical Instruments (Fold Mirrors etc.)	$1,948	1	$1,948	0	$0	1	$1,948	2	$3,896	3	$5,844	4	$7,792
Charged Coupled Device (CCD) Dragonfly	$1,495	3	$4,485	2	$2,990	2	$2,990	2	$2,990	2	$2,990	2	$2,990
Firewire Card	$90	2	$180	2	$180	2	$180	2	$180	2	$180	2	$180
Flock Paper/Adhesive	$106	1	$106	1	$106	1	$106	1	$106	1	$106	1	$106
Compression Ring/Adapter Sleeve	$132	1	$132	1	$132	1	$132	1	$132	1	$132	1	$132
Optical Posts/Shear Plate	$1,617	1	$1,617	0	$0	0	$0	0	$0	0	$0	0	$0
Telephoto Lens	$500	1	$500	1	$500	1	$500	1	$500	1	$500	1	$500
Total			$36,730		$25,171		$28,779		$32,986		$42,216		$52,141

Active Optics

Item	Unit Cost (US$)	Quantity Bought	Actual Cost (US$)	Monolith Quantity	Monolith Cost	Golay-3 Quantity	Golay-3 Cost	Golay-6 Quantity	Golay-6 Cost	Golay-9 Quantity	Golay-9 Cost	Golay-12 Quantity	Golay-12 Cost
Fast Steering Mirror (FSM)	$2,575	3	7,725	1	$2,575	3	$7,725	6	$15,450	9	$23,175	12	$30,900
Precision Mount For Combiner	$3,000	1	3,000	0	$0	1	$3,000	1	$3,000	1	$3,000	1	$3,000
1 Channel PZT Amplifier	$515	9	4,635	3	$1,545	9	$4,635	18	$9,270	27	$13,905	36	$18,540
Mirror Mounts w/ High Precision screws	$177	4	708	1	$177	3	$531	6	$1,062	9	$1,593	12	$2,124
Pyramidal Mirror Mount Combo	$1,048	1	1,048	0	$0	1	$1,048	1	$1,048	1	$1,048	1	$1,048
Test PC	$842	1	842	0	$0	0	$0	0	$0	0	$0	0	$0
Optics Electronics	$584	1	584	1	$584	1	$584	1	$584	1	$584	1	$584
Amplifier Boards	$45	6	270	1	$45	3	$135	6	$270	9	$405	12	$540
Cleaning Materials	$55	1	55	0	$0	0	$0	0	$0	0	$0	0	$0
Electronic Focuser and Adapter	$684	1	684	1	$684	1	$684	1	$684	1	$684	1	$684
Optics Hardware	$13	1	13	1	$13	1	$13	1	$13	1	$13	1	$13
Large Knobs	$4	10	40	3	$12	9	$36	18	$72	27	$108	36	$144
DAC Channels	$259	12	3,113	3	$778	9	$2,334	18	$4,669	27	$7,003	36	$9,338
Total			22,716		$6,413		$20,725		$36,122		$51,518		$66,914

Sub-System Cost Tables

Attitide Control System

Item	Unit Cost (US$)	Quantity Bought	Actual Cost (US$)	Monolith Quantity	Monolith Cost	Golay-3 Quantity	Golay-3 Cost	Golay-6 Quantity	Golay-6 Cost	Golay-9 Quantity	Golay-9 Cost	Golay-12 Quantity	Golay-12 Cost
Fly Wheels	$300	3	$900	3	$900	3	$900	3	$900	3	$900	3	$900
Rate Gyros	$3,000	0	$0	1	$3,000	1	$3,000	1	$3,000	1	$3,000	1	$3,000
Motor, Tachometers, Amplifiers	$802	3	$2,406	3	$2,406	3	$2,406	3	$2,406	3	$2,406	3	$2,406
TCM-2-50 (Tilt Inclinometer/Magnetometer)	$769	1	$769	1	$769	1	$769	1	$769	1	$769	1	$769
TCM-2-20 (Tilt Inclinomter/Magnetometer)	$699	1	$699	0	$0	0	$0	0	$0	0	$0	0	$0
Active Balancer	$2,163	3	$6,490	3	$6,490	3	$6,490	3	$6,490	3	$6,490	3	$6,490
Lab/Power Supplies	$442	1	$442	0	$0	0	$0	0	$0	0	$0	0	$0
DAC Channels	$259	3	$778	3	$778	3	$778	3	$778	3	$778	3	$778
ADC Channels	$281	6	$1,688	6	$1,688	6	$1,688	6	$1,688	6	$1,688	6	$1,688
Filters for Rate Gyros	$283	1	$283	1	$283	1	$283	1	$283	1	$283	1	$283
Balancing Fly Wheels	$250	0	$0	3	$750	3	$750	3	$750	3	$750	3	$750
Total			$14,455		$17,064		$17,064		$17,064		$17,064		$17,064

Structures

Item	Unit Cost (US$)	Quantity Bought	Actual Cost (US$)	Monolith Quantity	Monolith Cost	Golay-3 Quantity	Golay-3 Cost	Golay-6 Quantity	Golay-6 Cost	Golay-9 Quantity	Golay-9 Cost	Golay-12 Quantity	Golay-12 Cost
Collar	$583	3	$1,750	2	$1,167	3	$1,750	5	$2,917	7	$4,083	9	$5,250
Translation Stages	$234	9	$2,106	0	$0	9	$2,106	18	$4,212	27	$6,318	36	$8,424
Bread Boards	$176	4	$706	1	$176	3	$529	6	$1,058	9	$1,588	12	$2,117
Adapter Plates	$38	10	$380	0	$0	9	$342	18	$684	27	$1,026	36	$1,368
Nuts, Bolts, Tools, Cables, Connections etc.	$378	1	$378	0.5	$189	1	$378	2	$755	3	$1,133	4	$1,510
Model SRA250 Spherical Air Bearing	$12,900	1	$12,900	0	$0	0	$0	0	$0	0	$0	0	$0
Pedestal for Spherical Air Bearing	$980	1	$980	0	$0	0	$0	0	$0	0	$0	0	$0
Air Supply Filter	$1,870	1	$1,870	0	$0	0	$0	0	$0	0	$0	0	$0
Vibration Suppression Mounts	$2	15	$36	12	$29	12	$29	12	$29	12	$29	12	$29
Angle Braces	$199	6	$1,194	0	$0	6	$1,194	12	$2,388	18	$3,582	24	$4,776
Machine Shop	$7,059	1	$7,059	1	$7,059	1	$7,059	1	$7,059	1	$7,059	1	$7,059
Center Structure Assembly	$700	1	$700	1	$700	1	$700	1	$700	1	$700	1	$700
Total			$30,058		$9,320		$14,087		$19,802		$25,518		$31,233

Science, Operations, & Communications

Item	Unit Cost (US$)	Quantity Bought	Actual Cost (US$)	Monolith Quantity	Monolith Cost	Golay-3 Quantity	Golay-3 Cost	Golay-6 Quantity	Golay-6 Cost	Golay-9 Quantity	Golay-9 Cost	Golay-12 Quantity	Golay-12 Cost
WLS LAN PCI Cards 11 Mbps	$230	1	$230	1	$230	1	$230	1	$230	1	$230	1	$230
Wireless Broadband Gateway	$250	1	$250	0	$0	0	$0	0	$0	0	$0	0	$0
Wireless LAN card	$131	1	$131	0	$0	0	$0	0	$0	0	$0	0	$0
Portable Computer	$1,697	1	$1,697	0	$0	0	$0	0	$0	0	$0	0	$0
Total			$2,307		$230		$230		$230		$230		$230

Sub-System Cost Tables

Power, Avionics, & Software

Item	Unit Cost (US$)	Quantity Bought	Actual Cost (US$)	Monolith Quantity	Monolith Cost	Golay-3 Quantity	Golay-3 Cost	Golay-6 Quantity	Golay-6 Cost	Golay-9 Quantity	Golay-9 Cost	Golay-12 Quantity	Golay-12 Cost
PC Power Supply	$165	2	$331	1	$165	1	$165	1	$165	1	$165	1	$165
Batteries	$165	10	$1,651	6	$991	6	$991	6	$991	6	$991	6	$991
Chargers	$130	6	$782	0	$0	0	$0	0	$0	0	$0	0	$0
Power Electronics	$413	1	$413	1	$413	1	$413	1	$413	1	$413	1	$413
Gas Gauge Chip Circuit Boards	$44	10	$439	6	$263	6	$263	6	$263	6	$263	6	$263
Misc PC Parts for test computer	$528	1	$528	0	$0	0	$0	0	$0	0	$0	0	$0
Shuttle AK31 Motherboard	$102	1	$102	1	$102	1	$102	1	$102	1	$102	1	$102
AMD 1.4 GHz Athlon CPU	$139	1	$139	1	$139	1	$139	1	$139	1	$139	1	$139
Mushkin 512 MB DDR RAM	$274	3	$821	2	$547	2	$547	2	$547	2	$547	2	$547
Simpletech 512 MB Compact Flash Card	$353	1	$353	0	$0	0	$0	0	$0	0	$0	0	$0
I Code Composer Studio: TMD S324685C-07	$999	0.5	$500	0	$0	0	$0	0	$0	0	$0	0	$0
TI 6701 EVM: TMD X32006701	$1,495	2	$2,990	0	$0	0	$0	0	$0	0	$0	0	$0
SMT 320 4 SLOT PCI MOTHERBOARD	$1,436	1	$1,436	1	$1,436	1	$1,436	1	$1,436	1	$1,436	1	$1,436
SMT 6012 Drivers for 6701	$383	1	$383	0	$0	0	$0	0	$0	0	$0	0	$0
HEPC8 Module Carrier	$3,125	1	$3,125	1	$3,125	1	$3,125	1	$3,125	1	$3,125	1	$3,125
HEGD14 DAC	$2,075	2	$4,150	0	$0	0	$0	0	$0	0	$0	0	$0
HEGD2 ADC	$2,250	1	$2,250	0	$0	0	$0	0	$0	0	$0	0	$0
Cables/Connectors	$200	1	$200	0.5	$100	1	$200	1.5	$300	3	$600	4.5	$900
MagicRAM Internal IDE Compact Flash Adapter	$90	1	$90	1	$90	1	$90	1	$90	1	$90	1	$90
DSP Board Repair	$450	1	$450	0	$0	0	$0	0	$0	0	$0	0	$0
HESDP Software Developers Pack	$1,600	1	$1,600	0	$0	0	$0	0	$0	0	$0	0	$0
Heron4 (6701)	$2,000	1	$2,000	1	$2,000	1	$2,000	1	$2,000	1	$2,000	1	$2,000
RTX Training	$3,000	1	$3,000	0	$0	0	$0	0	$0	0	$0	0	$0
Total			$27,730		$9,370		$9,470		$9,570		$9,870		$10,170

Miscellaneous

Item	Unit Cost (US$)	Quantity Bought	Actual Cost (US$)	Monolith Quantity	Monolith Cost	Golay-3 Quantity	Golay-3 Cost	Golay-6 Quantity	Golay-6 Cost	Golay-9 Quantity	Golay-9 Cost	Golay-12 Quantity	Golay-12 Cost
Office Tools	$427	1	$427	0	$0	0	$0	0	$0	0	$0	0	$0
Dspace board	$1,945	1	$1,945	0	$0	0	$0	0	$0	0	$0	0	$0
Summer '01 Supplies	$258	1	$258	0	$0	0	$0	0	$0	0	$0	0	$0
Air Compressor	$305	1	$305	0	$0	0	$0	0	$0	0	$0	0	$0
Total			$2,934		$0		$0		$0		$0		$0

			ARGOS		Monolith		Golay-3		Golay-6		Golay-9		Golay-12
Total			$136,930		$67,568		$90,355		$115,774		$146,416		$177,752

Labor Cost Table

Sub-System		Yearly	Hours					ARGOS	
		Rate	Spring	Summer	Fall	Spring	Total	Total	Recurring
Passive Optics	Soon-Jo Chung	$70,000	200	200	200	200	800	$61,833	$15,458
	Janaki Wickrema	$50,000	260	0	260	130	650	$35,885	$7,177
	Erik Iglesias	$50,000	260	360	260	130	1010	$55,760	$7,177
	David Ngo	$50,000	260	360	260	130	1010	$55,760	$7,177
Active Optics	Soon-Jo Chung	$70,000	150	160	150	150	610	$47,148	$11,594
	Abran Alaniz	$50,000	260	360	260	130	1010	$55,760	$7,177
	Praxedis Flores III	$50,000	260	0	260	130	650	$35,885	$7,177
ACS	Carl Blaurock	$70,000	0	0	78	78	156	$12,058	$6,029
	Ayanna Samuels	$50,000	260	0	260	130	650	$35,885	$7,177
	Susan Kim	$50,000	260	0	260	130	650	$35,885	$7,177
	Paul Wooster	$50,000	260	0	260	130	650	$35,885	$7,177
Structures	Marc dos Santos	$50,000	260	0	260	130	650	$35,885	$7,177
	David LoBosco	$50,000	260	0	260	130	650	$35,885	$7,177
PAS	Raymond Sedwick	$70,000	104	96	104	104	408	$31,535	$8,038
	Soon-Jo Chung	$70,000	0	0	0	104	104	$8,038	$8,038
	Carolina Tortora	$50,000	260	0	260	130	650	$35,885	$7,177
	Christopher Rakowski	$50,000	260	360	260	130	1010	$55,760	$7,177
	Dustin Berkovitz	$50,000	260	360	260	130	1010	$55,760	$7,177
SOC	John Keesee	$90,000	104	96	104	104	408	$40,545	$10,335
	Eric Coulter	$50,000	260	0	260	130	650	$35,885	$7,177
	Daniel Kwon/Lisa Girerd	$50,000	260	0	260	130	650	$35,885	$7,177
Management	Paul Bauer	$70,000	104	96	104	104	408	$31,535	$8,038
	David Miller	$90,000	104	48	104	104	360	$35,775	$10,335
	Raymond Sedwick	$70,000	26	0	26	26	78	$6,029	$2,010
	John Keesee	$90,000	26	0	26	26	78	$7,751	$2,584
Total								$919,903	$190,115

EB/OHD Wrap
2.12
Student
$50,000
Staff
$70,000
Management
$90,000

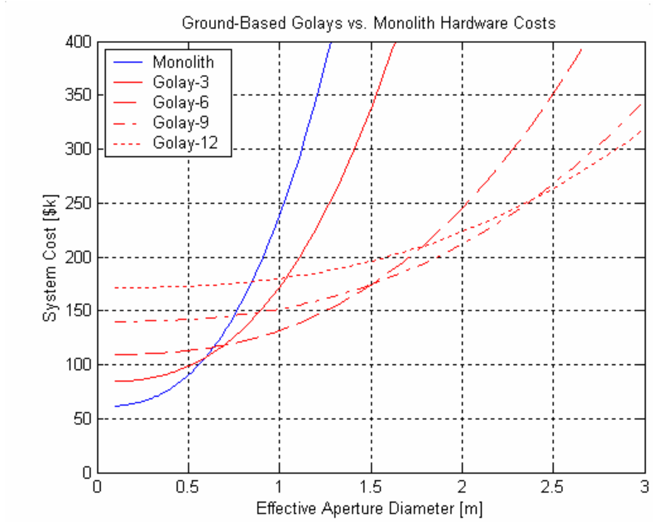
Labor Cost Table

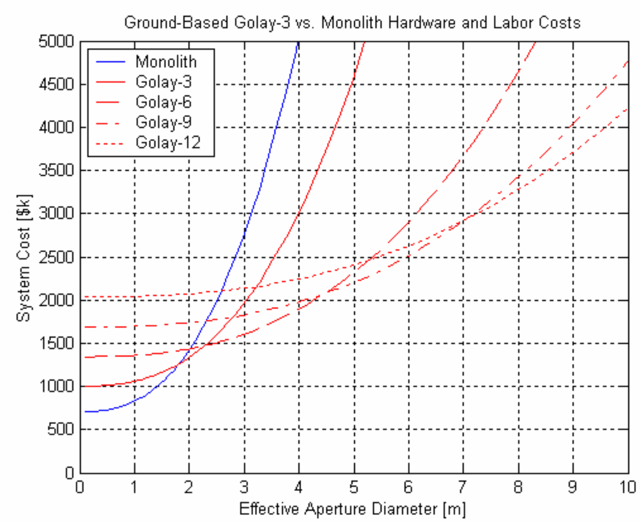
Sub-System	ARGOS			Monolith			Golay-3		
	mult	Total	Recurring	mult	Total	Recurring	mult	Total	Recurring
Passive Optics	1	$209,240	$36,990	0.3	$62,772	$11,096.88	1	$209,240	$36,990
Active Optics	1	$138,794	$25,948	0.3	$41,638	$7,784.38	1	$138,794	$25,948
ACS	1	$119,714	$27,560	1	$119,714	$27,560.00	1	$119,714	$27,560
Structures	1	$71,771	$14,354	0.6	$43,063	$8,612.50	1	$71,771	$14,354
PAS	1	$186,980	$37,608	1	$186,980	$37,607.92	1	$186,980	$37,608
SOC	1	$112,316	$24,689	1	$112,316	$24,689.17	1	$112,316	$24,689
Management	1	$81,090	$22,967	1	$81,090	$22,966.67	1	$81,090	$22,967
Total		$919,903	$190,115		$647,572	$140,318		$919,903	$190,115

Sub-System	Golay-6			Golay-9			Golay-12		
	mult	Total	Recurring	mult	Total	Recurring	mult	Total	Recurring
Passive Optics	1.5	$313,859	$55,484	2	$418,479	$73,979	2.5	$523,099	$92,474
Active Optics	2	$277,588	$51,896	3	$416,381	$77,844	4	$555,175	$103,792
ACS	1	$119,714	$27,560	1	$119,714	$27,560	1	$119,714	$27,560
Structures	2	$143,542	$28,708	3	$215,313	$43,063	4	$287,083	$57,417
PAS	1	$186,980	$37,608	1	$186,980	$37,608	1	$186,980	$37,608
SOC	1	$112,316	$24,689	1	$112,316	$24,689	1	$112,316	$24,689
Management	1	$81,090	$22,967	1	$81,090	$22,967	1	$81,090	$22,967
Total		$1,235,088	$248,912		$1,550,272	$307,709		$1,865,456	$366,506

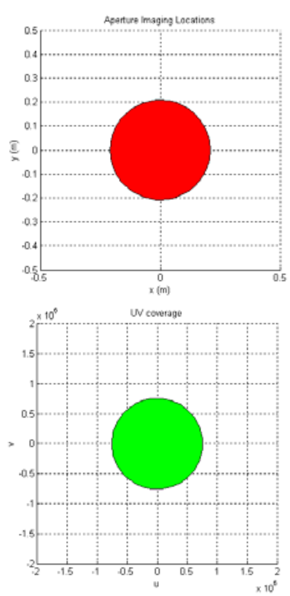
Golay System Costs

- Optimum Golay is D_{eff}-dependent
- Labor moves Golay benefits to larger D_{eff}
- Golay's sacrifice Encircled Energy

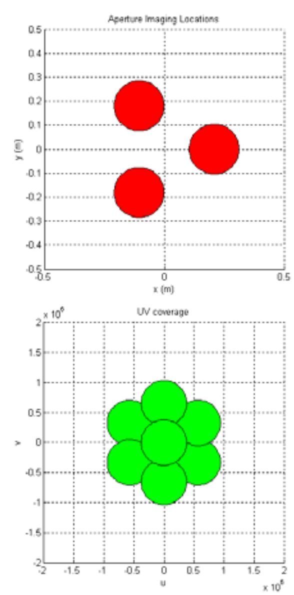




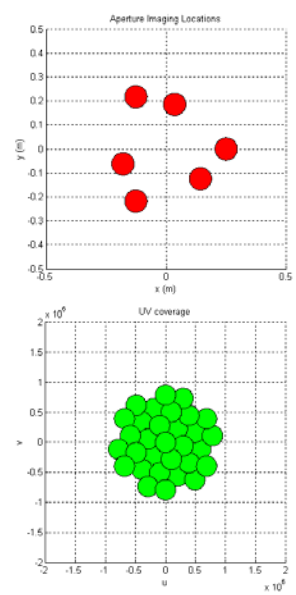
EE=83.5%



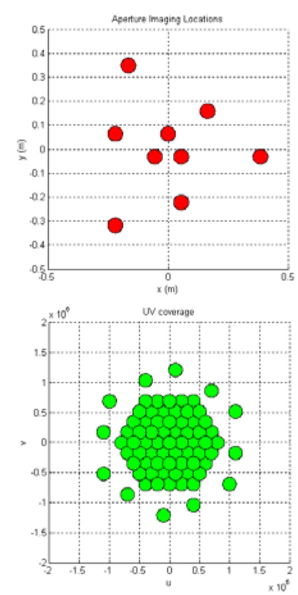
EE=26.4%



EE=9.3%



EE=3.6%



EE=2.2%