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Cost Estimating Challenges for the Constellation Program

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Disclaimers

- The work described in this presentation was conducted while the author was employed at Science Applications International Corporation supporting Marshall Space Flight Center and other NASA centers
- The author has been involved in the development and use of cost estimating models for parts of the Constellation program, including the Ares launch vehicle and to a lesser extent, Orion
  – The author is only presenting work on those portions of Constellation in which he has direct experience
  – The material presented represents the author's opinion and in no way does he purport to act as an official representative or spokesperson for the Constellation program

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Acknowledgements

- The author would like to thank David Cowart, Paradigm Technologies, for his contributions to the Technology Maturity Index research discussed in this presentation

Introduction

- NASA has encountered several challenges in developing credible cost estimates for Constellation, including
  - Similar, analogous missions were developed more than 40 years ago
    - Proper hardware analogies may not exist
    - Systems-level activities have also changed substantially
      - e.g., GSE/Tooling
  - New launch vehicle development presents new communication challenges with technical personnel (e.g., hardware engineers)
  - Risk-based estimates are still a recent innovation at NASA
    - Need a basis for providing realistic and believable risk estimates
- The focus of this presentation is on these particular challenges and the proactive way in which the NASA estimating community is acting to meet them

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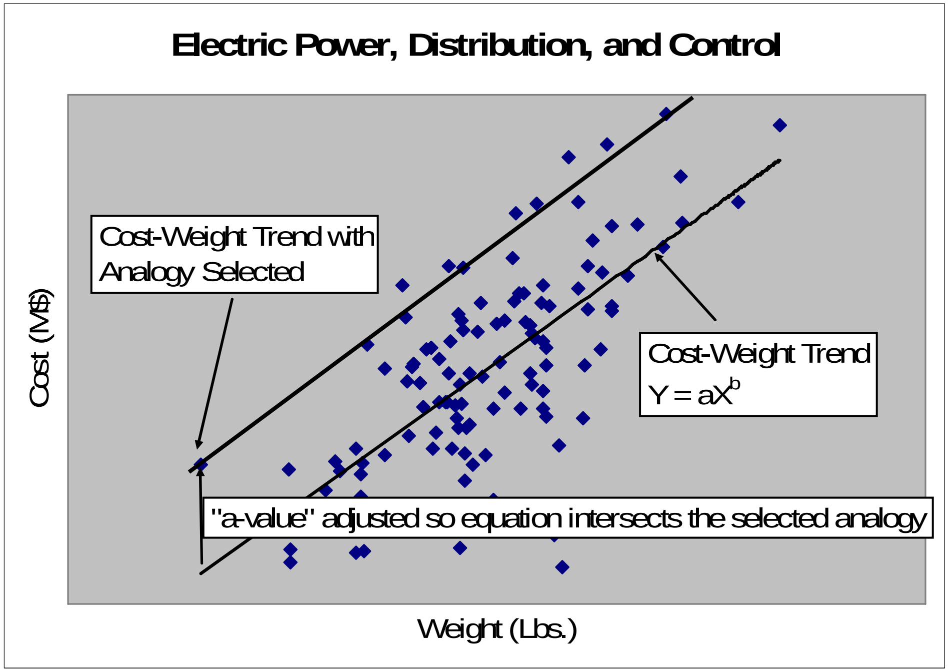
Challenge #1: Lack of Proper Analogies

- Analogy-based (aka "first-pound") estimating methods are well established and have a long track record



- Analogy-based estimating methods are useful when a close analogy exists
  - In these cases it may be the best estimating method available

Challenge #1: Lack of Proper Analogies

- The best hardware analogies for much of the Constellation program are Apollo and Saturn
  - Began development over 40 years ago
    - Hardware design, materials, and manufacturing methods have changed
      - Productivity enhancements have reduced cost over time
        - » Engineers have gone from using drafting tools and mainframes to personal computers with CAD/CAM software
      - Ground support equipment for launch vehicles has changed substantially
  - Budget environment is substantially different
    - As a result of Sputnik and the ensuing "space race, " Apollo was schedule-driven
    - Constellation is cost-driven
      - Has already suffered a one-year planned schedule slip due to a $500 million budget cut
  - Apollo was highly dependent on advances in technology
    - Not the case with Constellation

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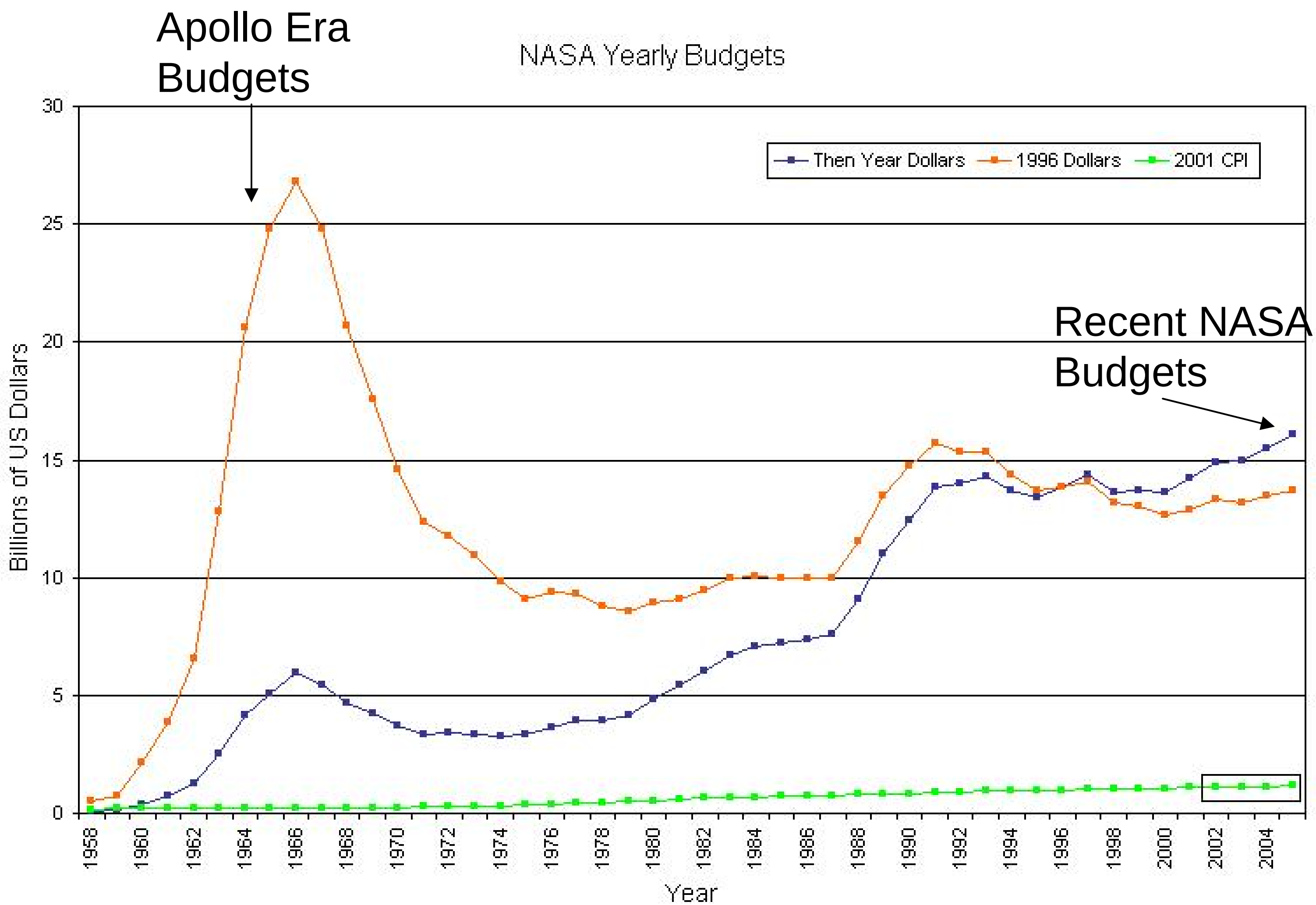
Challenge #1: Lack of Proper Analogies



Challenge #1: Lack of Proper Analogies

- As a result of these differences analogy-based methods may be of limited use
  - May lead to overestimation due to lack of consideration for cost reductions due to
    - Less technology development/use of more mature technologies
    - Not accounting for improvements in productivity over time
    - Substantial differences in ground support equipment and tooling

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Solution to Challenge #1: Develop and Use Multivariate CERs

- While analogy-based methods may be useful, multivariate CERs can take into account:
  - Productivity effects over time
  - Technology maturity
  - Heritage
  - Manufacturing automation
  - Programmatic factors such as funding and requirements stability
  - And other factors
- For several years the NASA/Air Force Cost Model (NAFCOM) has included multivariate CERs
  - Development has undergone several improvement cycles, including 2006-2007

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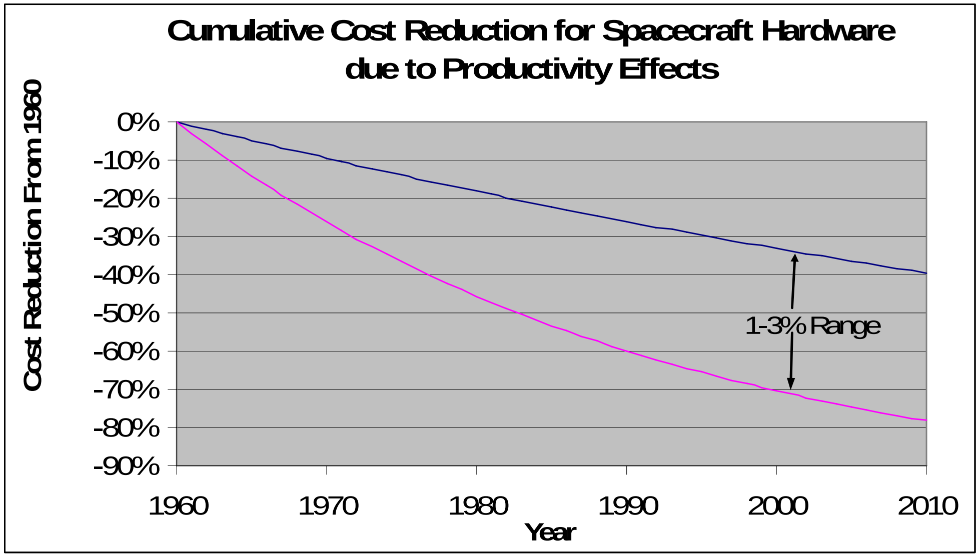
Multivariate CERs: Accounting for Productivity Effects

- One simple way to incorporate productivity effects is to directly include launch year as a variable in a multivariate CERs:

$$Cost = aX_1^{b_1} \ldots LY^{b} \ldots X_n^{b_n}$$

- Implemented in NAFCOM as an independent variable in the subsystem-level multivariate CERs
  - Based on recent research by the author and others (including Darryl Webb of the Aerospace Corpotation), productivity improvements have reduced cost by 1-3% per year (holding everything else constant)



Multivariate CERs: Accounting for Technology Maturity

- Substantial investments in design and development are required when immature technologies are selected for use in a space program
  - May also affect manufacturing cost (e.g., Shuttle Orbiter thermal tiles)
- Technology maturity or “readiness” is thus an important cost driver
- Technology Readiness Level (TRL) is one way to assess technology maturity

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Accounting for Technology Maturity – Technology Readiness Levels

- One option is to apply Technology Readiness Level (TRL) scale strictly to technology
- TRL uses an integer ordinal scale, 1-9
  - Level 1 Basic principles observed and reported
  - Level 2 Technology concept and/or application formulated
  - Level 3 Analytical and experimental critical function and/or characteristic proof of concept
  - Level 4 Component and/or breadboard validation in laboratory environment
  - Level 5 Component and/or breadboard validation in relevant environment
  - Level 6 System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
  - Level 7 System prototype demonstration in an operational (space) environment
  - Level 8 Actual system completed and (flight) qualified through test and demonstration (Ground and Space)
  - Level 9 Actual system (flight) proven through successful mission operations

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Accounting for Technology Maturity – Issues with TRL

- The problem with TRL is that any technology that has been successfully used in flight would automatically be assigned a value equal to 9
  - For example, the first time a composite structural material was used successfully in a space program, composite structural material would be assigned a value of 9 for all subsequent flights of that technology
  - Using TRL scale will result in too many high value TRLs and some very low value TRLs

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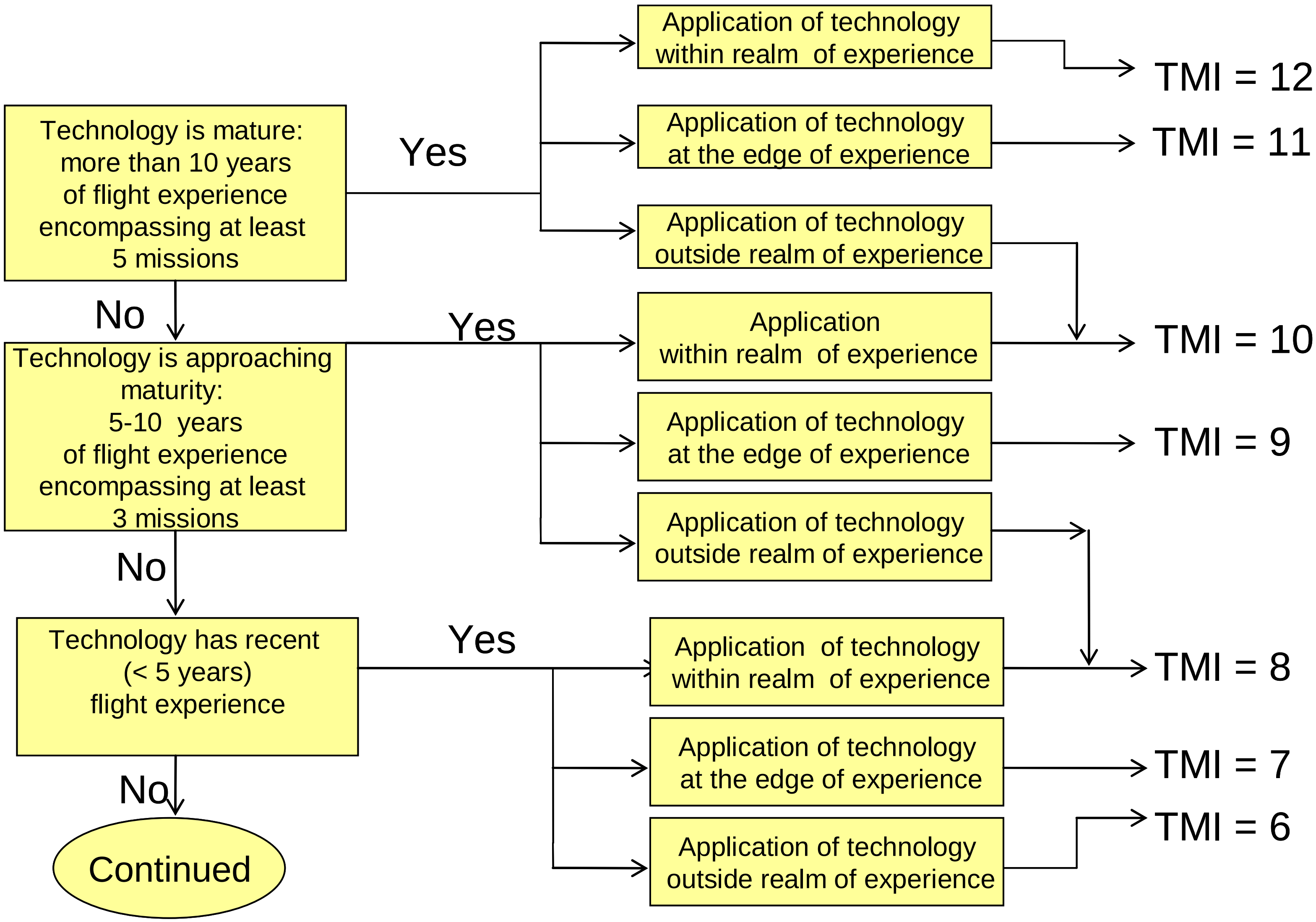
Accounting for Technology Maturity – TMI, the TRL Alternative

- Developed a new technology maturity index (TMI) as an alternative to TRL
- TMI is based on TRL
  - Uses 1-12 scale
  - TRL as defined is a little vague, so we sharpen some of the definitions
  - Considers amount of experience with the technology
    - Flight experience
    - Test experience
  - Also considers application of the technology (configuration, space, etc.)

TMI Flowchart



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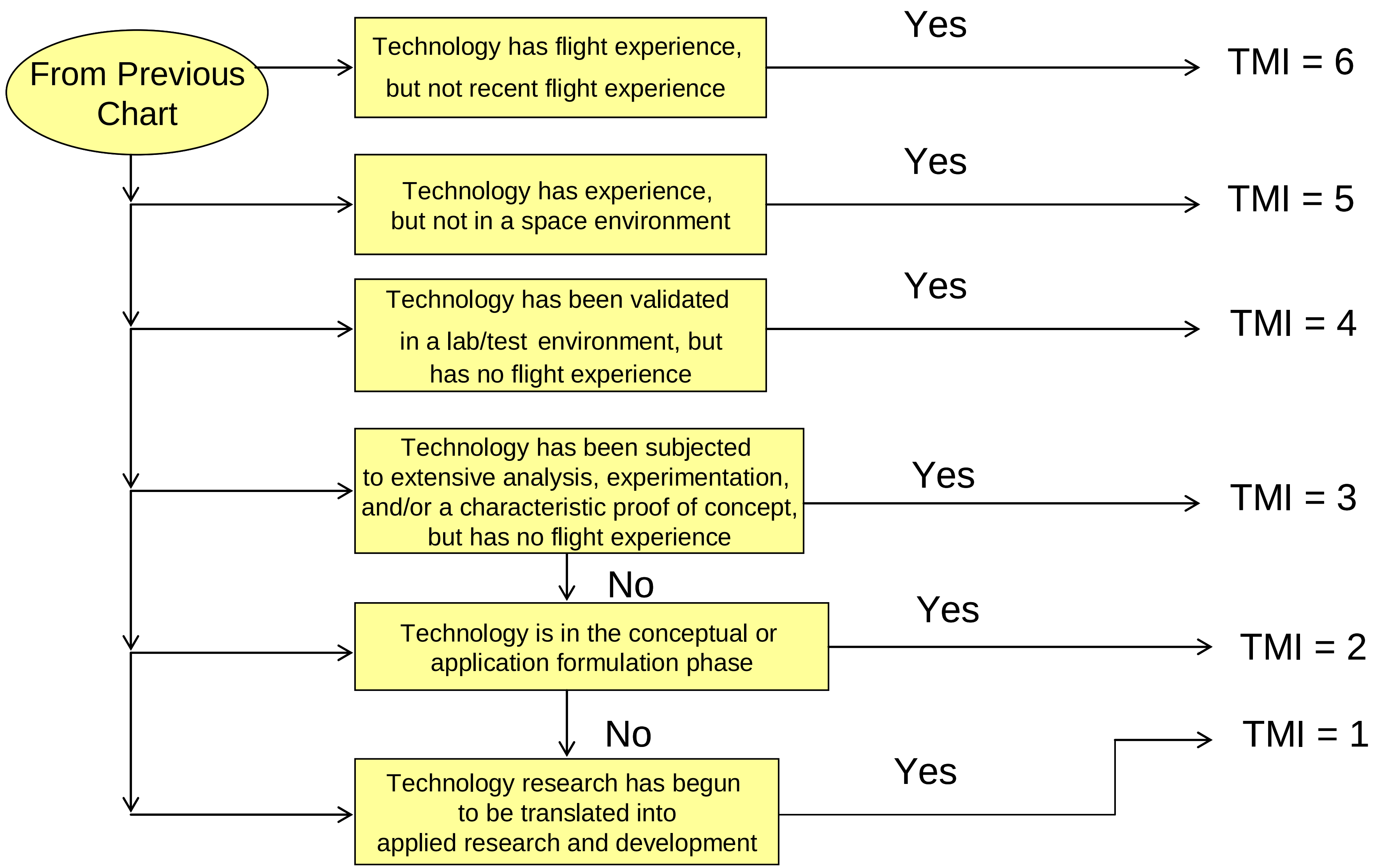
TMI Flowchart



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TMI Research

- TMI was assessed for individual NASA missions and other spacecraft
  - Identified key technologies for components used in attitude control and communications, command and data handling subsystems
    - Memory – Tape Recorders, Solid State
    - Processors
    - Antenna Bands and Configurations
    - Gyros
    - Momentum Wheels
    - Sensors
    - Star Trackers
    - And Many, Many Others
  - Developed timelines tracing the development of each technology, beginning in the 1950s and earlier
  - Collected and searched literally thousands of documents on spacecraft technologies

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Timeline Example: Ka-band Technology

- Ka-band technology development began in the early 1970s at MIT's Lincoln Labs
- Beginning with ACTS (launched in 1993), nine NASA satellites encompassing seven distinct development programs have successfully deployed Ka-band technology
  - ACTS, Cassini, Deep Space 1, Mars Global Surveyor, Mars Observer, Mars Reconnaissance Orbiter, and TDRS-8, -9, and -10
- Ka-band technology has also been deployed in commercial satellites, military satellites, and numerous foreign satellites

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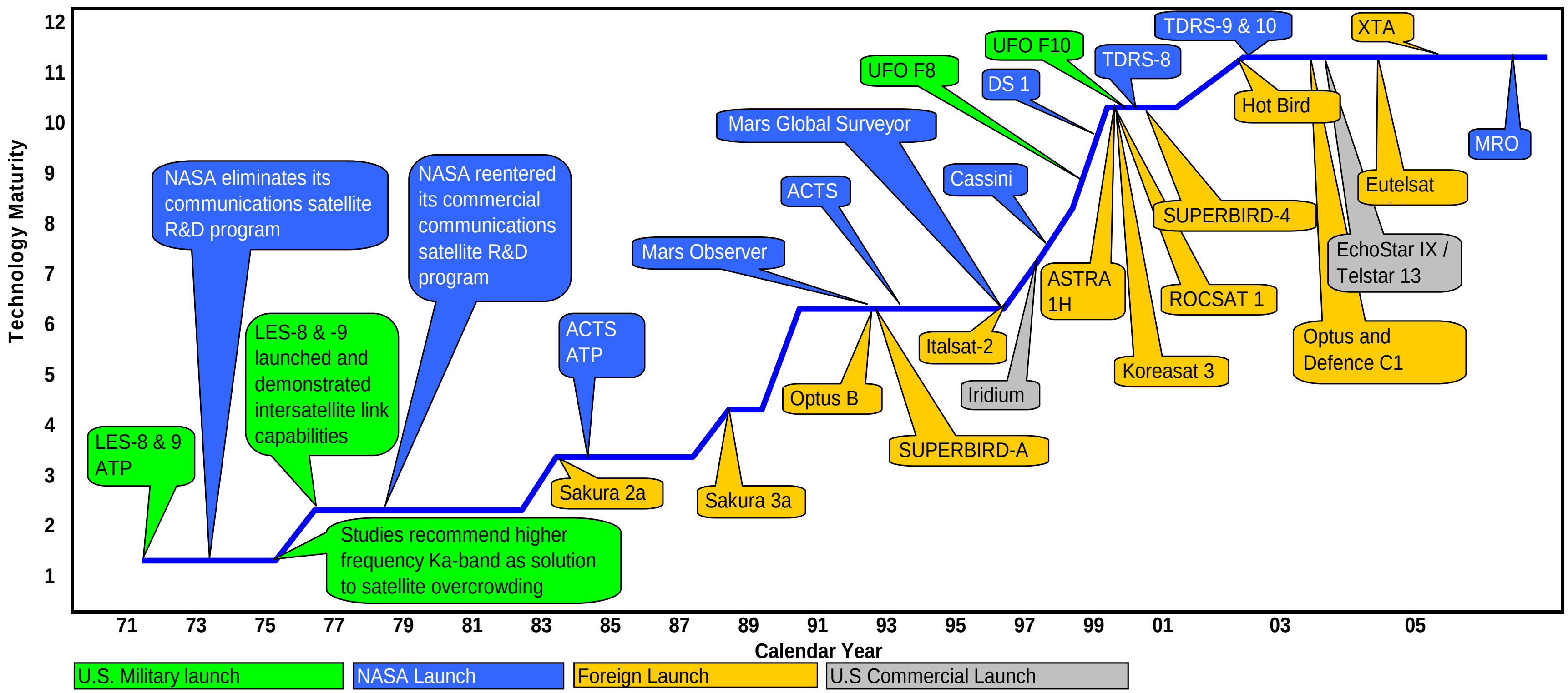
Ka-band TMI Levels and Milestones

- Timelines such as this have been developed for all salient avionics technologies used in spacecraft



- TMI has been incorporated in the multivariate CERs for avionics

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Challenge #2: Changes in Tooling/GSE

- Tooling and other ground support equipment (GSE) for launch vehicles have evolved dramatically since the Apollo era
- The image below is a Douglas booster tooling tower used in the manufacture of the S-IVB Saturn stage

(source http://history.nasa.gov)

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Challenge #2: Changes in Tooling/GSE

- Much of the manually intensive fixed infrastructure and labor-intensive tooling have been replaced by laser-aligned tooling that is highly automated
- The image below is of a computer-controlled tooling fixture with laser-aligned rails that allow the fixture to be positioned without mechanical intervention

(Source http://www.apexdt.com/images/computer_controlled_handlin.jpg)

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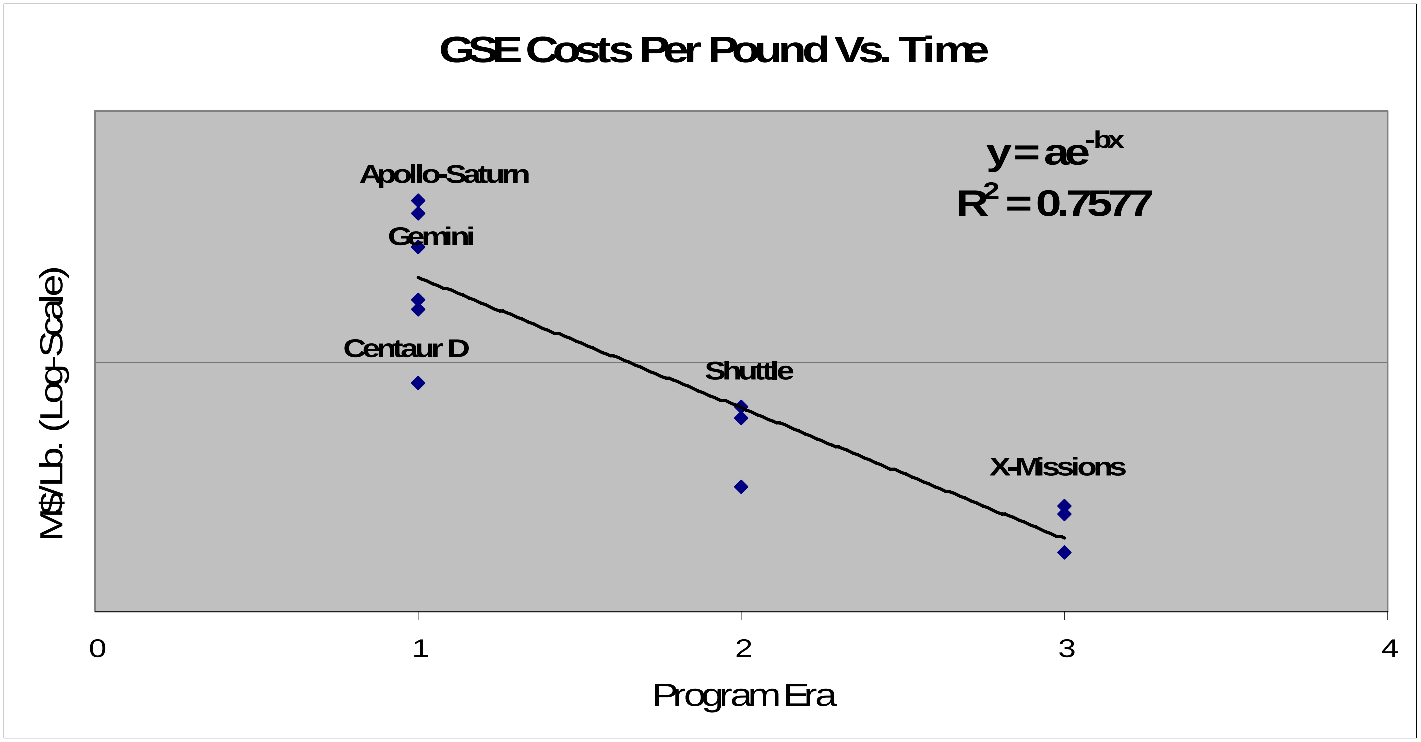
Challenge #2: Changes in Tooling/GSE

- Advances in GSE and tooling technologies have resulted in dramatic reductions in per-pound GSE cost over time
- Note that in the graph below, each of the three eras resulted in a reduction in per-pound cost approximately equal to **an order of magnitude** (y-axis is log-scale)



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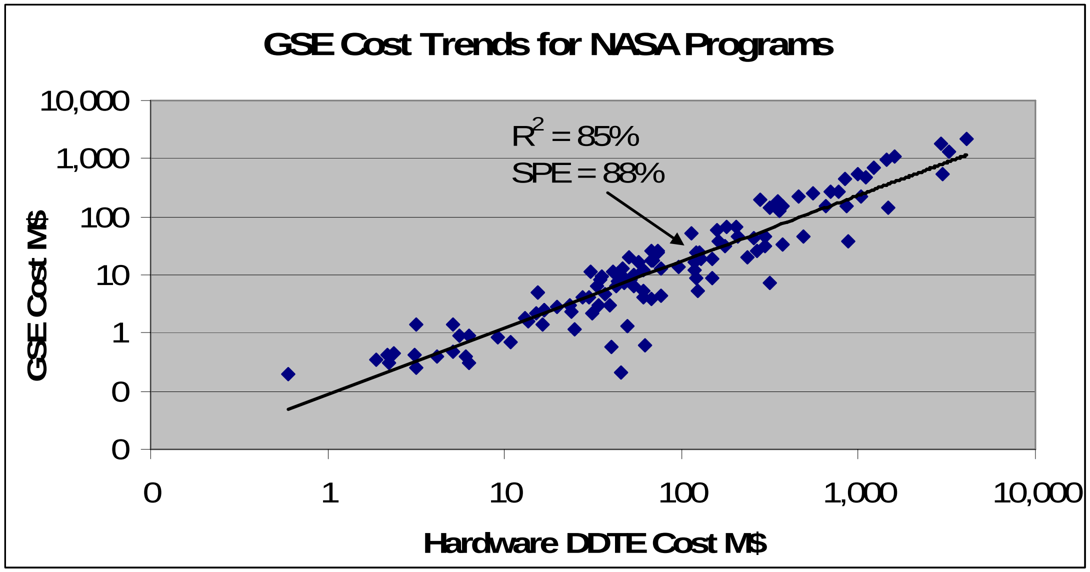
Challenge #2: Changes in Tooling/GSE

- One caveat with the previous graph is that the latest era (in the graph) is ground support equipment for X-vehicles, which may not reflect full GSE/tooling environment due to several reasons, one of which is the strict imposition of cost-cutting measures due to budget constraints and the “faster, better, cheaper” policy of the 1990s

Challenge #2: Changes in GSE/Tooling

- A traditional way to model systems-level (aka "below the line") costs is as a function of hardware cost



- This is often combined with an analogy-based approach described in detail earlier in this presentation
  - For this approach we again have the challenge of finding the right analogy
  - Example: Ares I Upper Stage – what is the right analogy? S-IVB may be most similar but GSE for the two are drastically different

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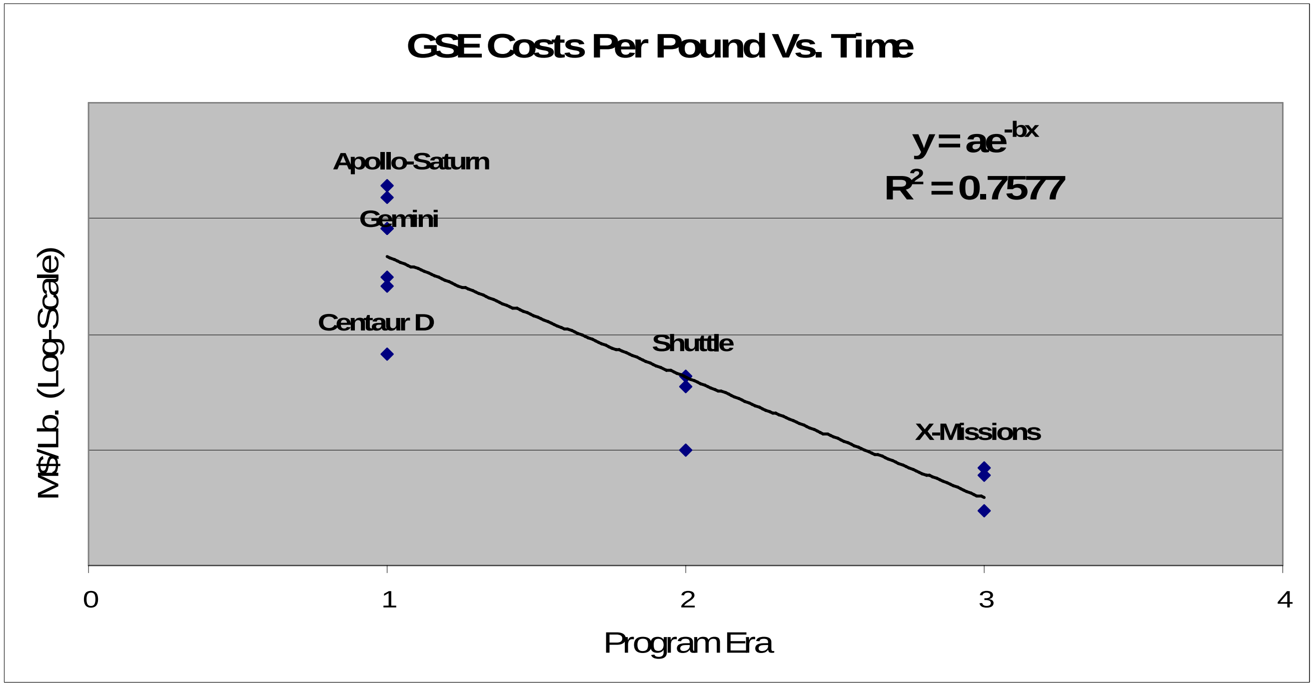
Solution to Challenge #2: Develop Multivariate Systems-Level CERs

- The graph below is a simple multi-variate GSE CER for launch vehicles and manned spacecraft:



$$\frac{Cost}{Weight} = a \cdot e^{-Era \cdot b} \quad \text{or} \quad Cost = a \cdot Weight \cdot e^{-Era \cdot b}$$

- Takes into account changes in GSE over time

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Multivariate Systems-Level Cost Drivers

- The changes that have affected GSE costs over the years have also had an effect on costs for other systems-level activities, such as integration and assembly, systems test operations, program management, systems engineering, and launch operations
- In order to more accurately assess systems-level costs, multivariate systems-level CERs were developed for all systems-level activities that take place during design and development
- Numerous cost drivers were analyzed and many significant cost drivers for systems-level cost were found in addition to hardware cost, including:

Bus Weight	Development Schedule	Launch Year	Requirement Stability	Design Life
Funding Stability	Average Hardware New Design	Amount of In-House Systems-Level Activities	Mission Type	University Contractor
Multiple Prime Contractors	Tooling Heritage	Mechanical Complexity	Shuttle Launch	

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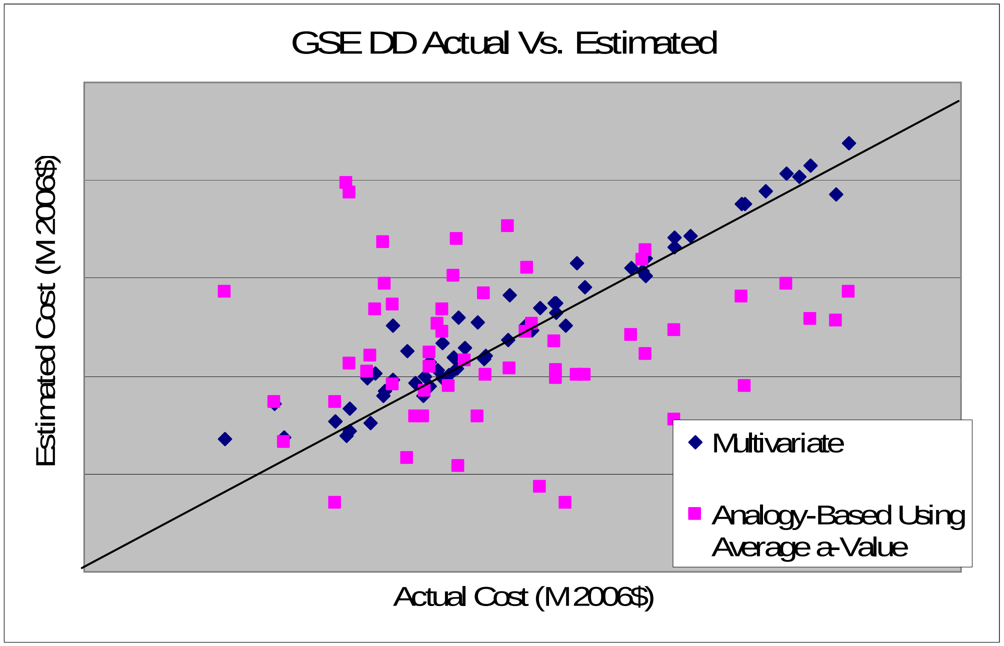
Multivariate Systems-Level CERs

- Multivariate Systems-Level CERs take into account numerous factors that influence "below-the-line" costs
- Allow accurate estimation without relying upon an appropriate analogy, which may not always exist



Challenge #3: Communicating Cost Estimates with Systems Personnel

- Some existing cost models are designed to estimate at the subsystem level
  - But many engineers work at a lower level
  - Subsystem-level estimates can be difficult to reconcile with bottoms-up estimates
    - Cannot accurately determine specific sources of differences
  - Subsystem-level estimates based on spacecraft can be misleading when applied to launch vehicles
    - Example – electric power subsystem estimate for Ares V
      - Large amount of cables (a ton of cabling, literally!), not typical of most EPD&C subsystems in NASA databases
  - Subsystem-level multivariate CERs should **not** be applied to component-level estimates
    - Results in overestimation

Subsystem-Level CERs and Their Application to the Component Level

- Assume a CER equal to the square-root function (i.e., $\sqrt{\ }$), subsystem weight equal to 100 lbs., and two components that each weigh 50 lbs
- If we estimate the subsystem cost at the subsystem level using the CER, the estimate is $\sqrt{100} = \$10$
- But if we apply the same CER to the two components, we obtain for each component $\sqrt{50} \approx \$7.14$
- Adding these two components together results in a subsystem-level roll-up estimate equal to \$14.14, which is 41% higher than the subsystem-level application of the CER

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Subsystem-Level CERs and Their Application to the Component Level

- Suppose for the subsystem-level CER Cost = aW^b, that there are N distinct components, and the CER is applied to each of these N components
- Also suppose that the subsystem weight is W_0, and the weight of each component is equal to W_0/N
- Then the estimate for each component is $a(W_0/N)^b$ and the subsystem-level roll-up is the sum of these component estimates, i.e., $N(a(W_0/N)^b)$
- The ratio of the component-based estimate to the subsystem-based estimate is

$$\frac{N \cdot a\left(\frac{W_0}{N}\right)^b}{aW_0^b} = N^{1-b}$$

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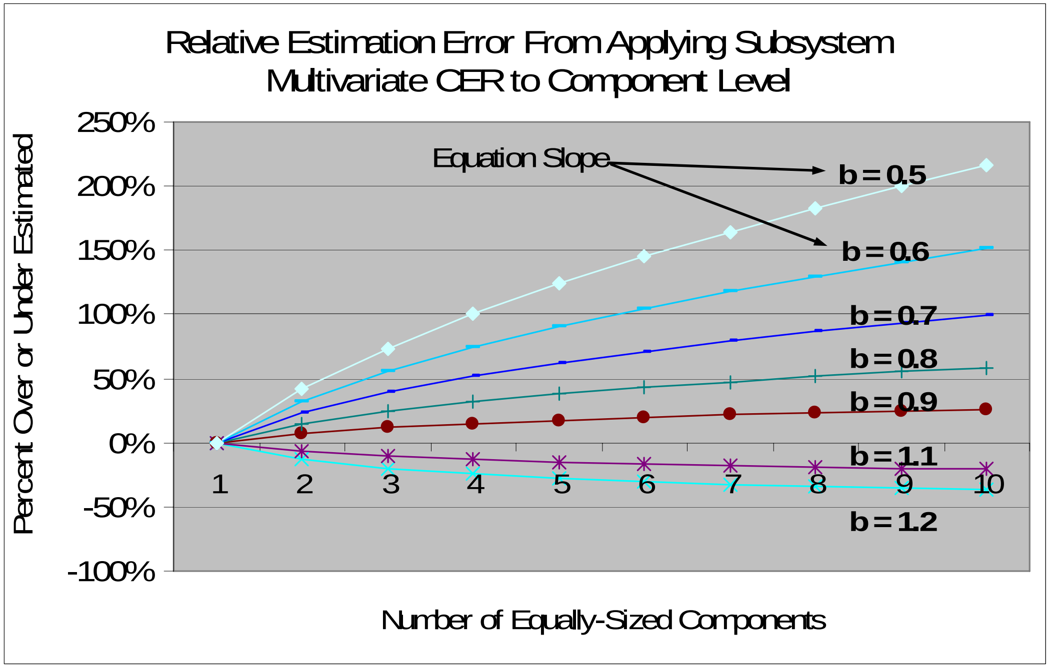
Subsystem-Level CERs and Their Application to the Component Level

- Three cases
  - $b > 1 \Rightarrow N^{1-b} < 1$
    - *A*pplication of a subsystem multivariate CER to a lower level **underestimates** the cost relative the subsystem-level CER
  - $b < 1 \Rightarrow N^{1-b} > 1$
    - Application of a subsystem-level multivariate CER to a lower level **overestimates** the cost relative to the subsystem-level CER
  - $b = 1 \Rightarrow N^{1-b}=1$ (linear case)
    - The application to the lower level has **no effect**
- "Most" CERs have b-values less than 1, so the main concern with applying multivariate subsystem-level CERs at the component-level is overestimation
  - Subsystem-level CER coefficients are calculated based on subsystem-level data which means applying subsystem-level multivariate CERs will result in systematic overestimation of actual costs

Subsystem-Level CERs and Their Application to the Component Level



- Note that
  - The greater the number of components, the greater the overestimation
  - The lower the equation slope, or “b-value”, the greater the overestimation

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Correction Factor for Subsystem-Based Component-Level Estimates

- Consider the general case in which a subsystem-level CER is applied at the component-level. Assume N components. Let p_i represent the percentage that the i^{th} component contributes to the total subsystem weight, where

$$\sum_{i=1}^{N} p_i = 1$$

- The subsystem-level rollup of the N component-level estimates is then

$$\sum_{i=1}^{N} a(p_i W_0)^b = aW_0^b \sum_{i=1}^{N} p_i^b$$

- Apply a correction factor of p_i^{1-b} to each estimate since the sum of all the percentages is equal to 1

- This correction factor can be applied to multivariate CERs if there is one single dominant cost driver as an *approximation*

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Subsystem-Level CERs and Their Application to the Component Level

- Note that application of subsystem-level CER is NOT a problem when the analogy method is used
- For the analogy method, suppose there are N components, all with equal weights and equal costs, and that the weight of the subsystem is W_0. Then the a-value for the subsystem-level CER is

$$a' = \frac{Actual\,Cost}{W_0^b}$$

- Since all weights and costs are equal, the a-value for each component is

$$a'' = \frac{\frac{Actual\,Cost}{N}}{\left(\frac{W_0}{N}\right)^b} = \frac{Actual\,Cost}{W_0^b} N^{b-1} = a' N^{b-1}$$

- Thus the subsystem-level roll-up of the component-level estimates is

$$Na''\left(\frac{W_0}{N}\right)^b = Na' N^{b-1}\left(\frac{W_0}{N}\right)^b = a' W_0^b$$

which is the same as the subsystem-level estimate

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Solution to Challenge #3: Develop Component-Level CERs

- To keep from mis-applying the subsystem-level multivariate CERs, there are three choices
  - Apply a correction factor to the subsystem-level multivariate CERs
  - Calibrate subsystem-level multivariate CERs to component-level data (i.e., adjust the "a-value" using the analogy method technique)
  - Develop CERs at the component-level, i.e., develop CERs using component-level data
- In 2006, MSFC embarked upon the development of component-level estimates for Ares launch vehicles
  - Developed component-level estimates for thrust vector control and avionics
    - Where sufficient data were available, developed component-level CERs
    - Where 2-3 data points were available, calibrated existing subsystem-level multivariate CER
    - Where no data were available, applied subsystem-level multivariate CER with a correction factor (as described)

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Development of Component-Level Estimates

- Developed specific spreadsheet models that enable component-level estimates for Ares I and Ares V launch vehicles
- Simple user interface, incorporated risk directly in the spreadsheet using the method of moments
- Developed 17 component-level CERs for this effort

Amplifier	Antenna	Battery	Camera	Controller
Diplexer-Multiplexer	Gyro	Instrumentation	Power Cables	Power Distribution and Control
Processor	Receiver	Solar Array	Tank	Transmitter
Transponder				

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Example of Spreadsheet-Based Model: Screenshot

WBS - Component Level Avionics for Ares I Upper Stage

Model Inputs

Model Outputs

Component	QNHA	Unit Wt	Total Wt	New Design	Mfg. Meth.	Eng. Mgt.	Test App.	Int. Comp.	Fund. Avail.	Pre-Dev	TMI	Launch Year	DD 2006$M
LAUNCH VEHICLE AVIONICS			6,584.5										$1,319.363
UPPER STAGE AVIONICS			3,195.9										$633.670
UPPER STAGE AVIONICS H/W			3,195.9										$298.468
Command & Data Handling System (C&DHS)			**588.6**										$188.698
Flight Computer (FC)	4	60	240.0	0.79	25	50	75	75	25	25	9	2012	$112.575
Command & Telemetry Computer (CTC)	2	25	50.0	0.79	25	50	75	75	25	25	9	2012	$33.129
Data Acquisition Unit (DAU)	6	25	150.0	0.79	25	50	75	75	25	25	9	2012	$33.129
Operational Instrumentation Electronics (OIE)	4	25	100.0	0.79	25	50	75	75	25	25	9	2012	$9.129
J2 Engine Control Unit (ECU) (Book kept with USE)													
Data Bus Isolation Amplifiers (DBIA)	9	5.4	48.6	0.79	25	50	75	75	25	25	8		$0.735
Bus Interface Adaptor (BIA)	0	17	0.0	0.79	25	50	75	75	25	25	9	2012	$0.000
Radio Freq Communication System (RFCS)			**42.8**										$3.433
S-band Transponder	2	6.5	13.0	0.79	25	50	75	75	25	25	9		$1.320
S Band Power Amp (PA) (Includes TWT & EPC power & weight)	2	4.6	9.2	0.79	25	50	75	75	25	25	8		$0.631
Traveling Wave Tube (TWT)													
Electronic Power Conditioner													
S Band Antennas	4	0.7	2.8	0.79	25	50	75	75	25	25	8		$0.610
S-band Diplexer	2	2	4.0	0.79	25	50	75	75	25	25			$0.291
S-band Bandreject Filter (BRF)	2	0.44	0.9	0.79	25	50	75	75	25	25	9	2012	$0.008
S-band Bandpass Filter (BPF)	2	0.44	0.9	0.79	25	50	75	75	25	25	9	2012	$0.008
RF Switch	2	0.5	1.0	0.79	25	50	75	75	25	25	9	2012	$0.013
Forward / Reflected Power Sensor	2	2.5	5.0	0.79	25	50	75	75	25	25			$0.506
Coax	60	0.101	6.1	0.79	25	50	75	75	25	25			$0.045
Flight Safety System (FSS)			**127.1**										$13.550
FSS RF Subsystem			**78.0**										$6.844
Command Receiver/Decoder (CRD)	2	10.22	20.4	0.79	25	50	75	75	25	25	8	2012	$1.606
Antenna	2	7.68	15.4	0.79	25	50	75	75	25	25	8		$2.207

Note – All inputs and outputs in this screenshots are completely notional.
Any resemblance to actual costs for current or past programs is purely coincidental

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Challenge #4: Providing Realistic and Comprehensive Risk Estimates

- It can be easy for an analyst to overlook sources of risk and possibly underestimate risk
- On the other hand, it is also tempting to attempt to add every possible source of error, possibly leading to double- and even triple-counting error so that risk is grossly overestimated
- For these reasons, it is desirable to have some way to check risk results against reality
  - How much risk is enough?
  - How much is too much?

Solution to Challenge #4: Use Recent Cost Growth Data

- Cost risk growth data can be used as a means to check the results of risk analyses against reality
- These checks can be used to determine if the amount of risk in the cost risk analyses is too high or too low
- In 2004 Matt Schaffer of NASA HQ collected and analyzed budget data on cost growth for NASA missions
  - Comprised 50 missions from the 1990s – present
  - Cost growth ranged from -25% to +193%
  - Average cost growth was 35%
  - 76% of the missions had budget overruns
    - Similar to studies by Goddard and GAO
  - Data are conservative
    - Does not completely account for changes in requirements and scope before ATP (accounting for this would reduce the reported cost growth for some missions, e.g., Rossi XTE)

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Cost Growth And Its Relationship to Cost Risk

- Cost risk is the probability of exceeding the initial estimate
- Cost growth is the actual amount that the initial estimate is exceeded
- Assumption - the initial budgets in the cost growth database are point estimates (no risk is included)
- By assuming that the initial estimates are point estimates, we can relate cost risk to cost growth
  - For example, if the point estimate represents the 30th percentile of a cost risk distribution, then the ratio of the 70th percentile to the 30th percentile represents potential cost growth
- For A, B two points of a cost risk distribution (A > B), with B as an initial reference point, the following formula relates cost growth to cost risk
  - Cost growth = A/B
- A cost growth distribution is simply the ratio of various percentiles on a cost risk distribution relative to an initial reference point, such as the 30th percentile

Cost Risk Rule of Thumb

- Assume that the 30th percentile on a cost risk S-curve represents the point estimate (initial estimate)
  - From experience, the point estimate is typically at or below the 30th percentile
- Assume that the risk distribution is Lognormal
- For NAFCOM estimates, the ratio of the standard deviation to the mean is typically between 1/3 and 1/2 of the mean
- The ratio of the 70th percentile to the 30th percentile of a lognormal is

$$\frac{e^{P+0.5244Q}}{e^{P-0.5244Q}} = e^{1.0488Q}$$

- When $\sigma = a\mu$, it follows that

$$Q = \sqrt{\ln(1+\frac{(a\mu)^2}{\mu^2})} = \sqrt{\ln(1+a^2)}$$

- When a = 1/3, the 70th percentile is 41% higher than the 30th percentile
- Thus, a reasonable rule of thumb for the ratio of the 70th percentile to the point estimate is 1.4

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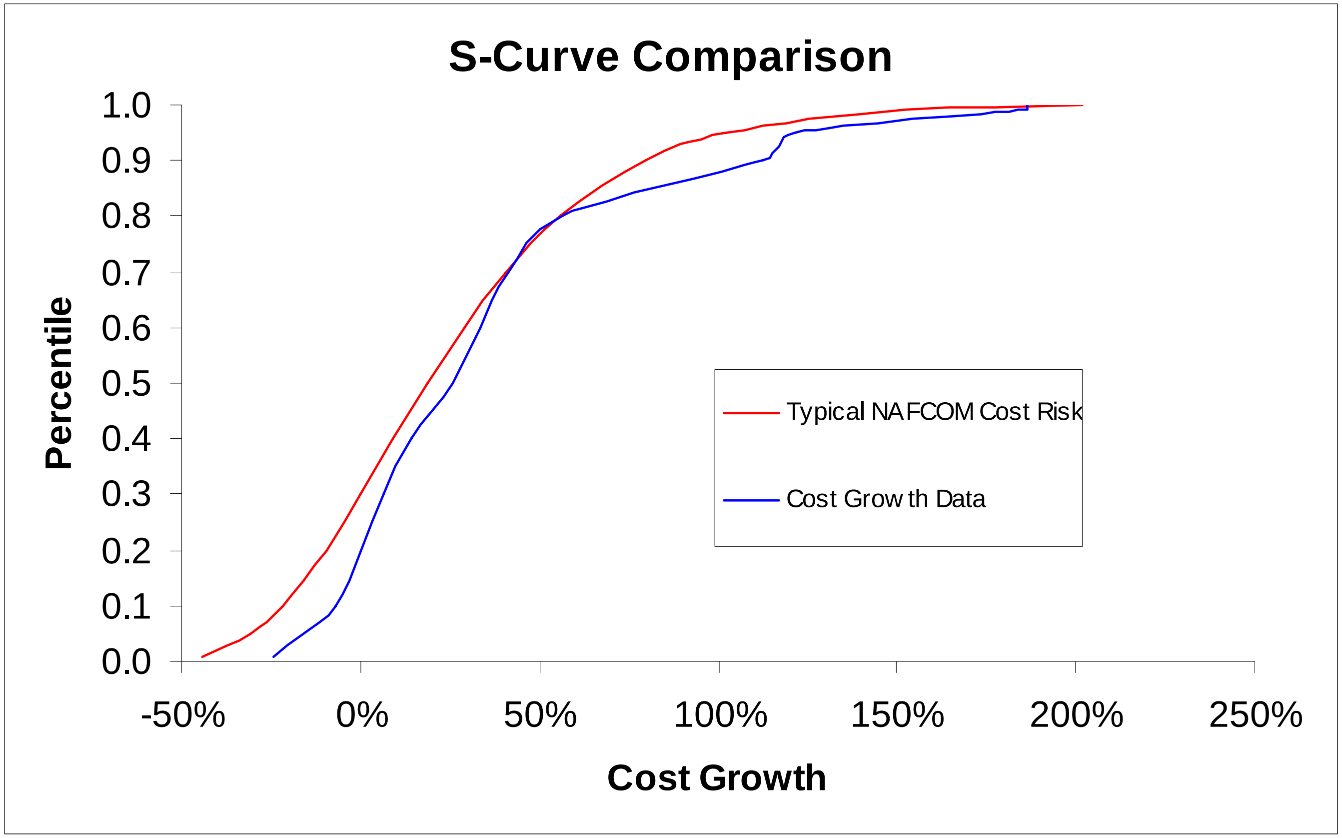
Converting Cost Risk to Cost Growth

- The derivation of the rule of thumb on the previous chart provides a method to convert cost risk into cost growth
  - Select a reference point, and divide each percentile by the initial reference point
  - In this analysis, it is assumed that the 30^{th} percentile is the reference point
  - Once the cost risk has been normalized to a cost growth curve, it can be directly compared to the cost growth data
  - Assume that a = 1/3 for "typical" risk

Cost Risk Reality Check S-Curves



- Notice how closely a “typical” NAFCOM risk distribution fits the bulk of the actual cost growth data
  - Provides confidence that cost risk estimates produced by NAFCOM are realistic