Instrument Design Lab (IDL)
Cost Assumptions

Capturing Your Cost Assumptions
and
Providing a Preliminary Explanation
of your Cost Product

August 2011

What's Expected

- **Cost Input**
  - Please provide input to the following ***Cost Input*** sheets, no later than the last collaborative day of the study, at the conclusion of presentations
- **Cost Product**
  - These charts provide preliminary background information on the parametric cost estimate the IDL team will generate, based on the detailed mass model or master equipment list (MEL) created during the course of the study
  - Please ask any questions you have about the cost product during the cost sidebar, which is typically scheduled on Wednesday afternoon of a 5-day study
  - More detailed answers can also be provided when the cost results are presented, typically 10-12 business days after the study is over
- **Cost Accuracy**
  - These charts provide general background information on how an accurate cost estimate is generated, given the fidelity of the description of the conceptual instrument design, as well as its maturity

Cost Assumptions - Schedule

Instrument Life Cycle Milestones:

- **Project Start Date – Authorization to Proceed (ATP)**
  - assumed to be Phase B Initiation, unless this is a Step 2 proposal
- **CDR Date**
- **Start of Instrument Level Environmental Testing**

Please note that the instrument life cycle is typically different from the mission lifecycle as the instrument need to be delivered to the observatory on a different timeline than the observatory to the S/C. The schedule that the Mission Design Lab (MDL) works to is the mission timeline.

These additional dates would be helpful, but are not absolutely required:

- **Instrument PDR Date**
- **End Production Date**
  - when Instrument sub-assembly phase is complete and instrument-level integration commences
- **Delivery to Spacecraft Observatory Date**
- **Launch**

If the customer desires, we can recommend an instrument schedule derived from a Launch date (time permitting in the study).

Cost Assumptions – Spares Approach

Number of fully integrated instrument-level units to build and cost:
- **Flight Units**
- **Flight Spare Units (parametrically identical to the flight and prototype units)**
- **Full Prototype Unit (unique to this study)**

Please note that the Instrument Design Lab (IDL) rarely has the opportunity in a 1-week study to address component or assembly level spares. Sparing is assessed at the instrument-level. The cost for component-level spares is captured as 10% of the total instrument cost. In addition, the cost for not-fully integrated ETUs is captured as 10% of the total instrument cost.

Definition of ETU and EDU:
- **Engineering Test Units (ETU) (protoflight)**
  - Can be tested to flight levels
  - Can be flown
- **Engineering Development Units (EDU) (prototype)**
  - Not built to flight levels
  - Can <u>not</u> be flown

The IDL will automatically assume an EDU is developed for all subsystem assemblies (without an EDU, there are cost impacts to going straight to flight unit production, because more risk is incurred). We will not assume that an integrated EDU of the entire instrument is developed, rather, that EDUs for subassemblies are built and tested. If the scale of the instrument is large (e.g. a segmented telescope or multiple focal plane assemblies), we may assume only a partial EDU is developed for a portion of subsystem hardware.

Cost Assumptions - Build Approach

Build Assumptions: these conditions can be different for different subassemblies
- In-house
- Out-of-house
- For a few major assemblies, we may be able to build a hybrid model

Dollar Assumptions:
- Real year dollars
- Constant year dollars (most typical)

Class of Mission
- This will establish the class of electronics parts

‘Black Box’ Input for Lower Fidelity Assemblies

If there are ‘black box’ assemblies that cannot be described at a component level, we can still represent the control and operation of that hardware in the thermal, electrical, and mechanical subsystems in our conceptual instrument design if it the following accommodation needs are described:

- Envelope (mm x mm x mm)*
- Total mass (w/o contingency) (Kg)
- Total Power (avg/peak) (W)
- Data Rate (avg/peak) (Mbits/sec)
- Instrument Duty Cycle (%)
- List any mechanisms and mechanism Duty Cycle (%)
- Operating Temperature Range (˚C)
- Survival Temperature Range (˚C)
- Temperature Stability Requirements (˚C/minutes)
- List any hardware proximity requirements (mm) (relative to control electronics and relative to the sphere (does it need a window))
- Optical FOV Requirements (˚)
- Operating modes
- Calibration hardware/operations
- Real-time computations, including compression
- % Composition by Mass (% electrical, optical, mechanical, etc)

In some cases, we will be able to estimate the cost of black box assemblies that cannot be parametrically described at a component level. The accuracy of that estimate is vastly improved with illustrations of the hardware that speak to the complexity/simplicity of the hardware involved and the number of components that need to be integrated.

Flight Software & Firmware

Flight Software (FSW)

- FSW will be estimated parametrically using SEER-SEM if source lines of code (SLOC) are provided by the customer or can be estimated by the IDL team based on heritage mission references from Code 580
- IDL FSW assumptions will be based on in-house developments for FSW re-use and labor, which may not apply to out of house developments
- If SLOC cannot be estimated, the IDL can provide a grassroots estimate of labor which can be costed with either in-house or out-of-house labor estimates

FPGA Firmware:

- Costs for FPGA firmware development is estimated using a grassroots scheme based on in-house developments on previous flight projects
- The methodology for this estimate will be shown in the electrical presentation

Your Parametric Cost Estimate is a Complete Lifecycle Estimate

- **Your parametric cost estimate is provided in a powerpoint presentation as a summary**
- **It is also included as a static spreadsheet in MS Excel format**
  - By static, we mean it is not encoded to re-sum any changes you may enter
  - This spreadsheet is saved to the Cost Model folder in the final report
- **Line item costs for individual components in the cost product spreadsheet are lifecycle cost estimates of the total financial burden to the government to fully develop and qualify that component from 'cradle to grave'**
- **Line item costs for individual components in the PRICE H report:**
  - Not only include the cost to <u>fabricate</u> (or procure) the component
  - But also include all the non-technical and technical systems engineering and project management labor to
    - design the part
    - analyze it
    - derive and document the specifications for the part
    - produce the engineering drawing
    - track the part specification in configuration management
    - procure and receive the part
    - validate the performance
    - support the design process with design reviews, ECN/ECRs, etc.
    - Data management, QA, Reliability, etc.

Your Parametric Cost Estimate is a Complete Lifecycle Estimate

- **There are some items in the mass model of your conceptual instrument that the IDL team will indicate as purchased components**
  - Purchased components include such devices as temperature sensors, thermal paint, and mechanism motors, for example
  - These are assumed to be commercial off the shelf (COTS) purchases of heritage flight components
- **There is a design and engineering 'wrap' that the cost modeling software will add to purchased components to ensure that a full lifecycle estimate is produced**
  - The cost to the government is not limited to merely the purchase price
  - Technical labor is required to perform analysis and modeling to ensure that this specific COTS part is sufficient, and to document the performance specifications, as well as to receive, test, and integrate the part
- **Lifecycle expenses related to purchased components:**
  - When a component is assumed to be purchased from a vendor (i.e. a vendor quote has been provided), an additional line item is added to the parametric cost model to account for the design and engineering effort to
    - The most significant technical labor related to purchased elements is the performance analysis and modeling to verify that the COTS specifications for that part will meet the overall system performance requirements
    - document the specifications for the part in a fabrication drawing
    - track the part specification in configuration management
    - procure and receive the part
    - validate the performance
    - support the design process with design reviews, ECN/ECRs, etc.
    - Data management, QA, Reliability, etc.

Accounting for I&T Costs

- **All SubAssembly-Level I&T Costs are included in the Parametric Lifecycle Cost Estimate**
  - The final cost product will include I&T line items for each subassembly and assembly to account for the labor and hardware to accomplish the following tasks associated with instrument development:
    - write and execute procedures to integrate two or more subsystems/elements
    - write and execute procedures to verify electrical and structural interfaces and specification compliance
    - design and procure or fabricate GSE for the I&T sequence (e.g. power supplies, o-scopes, logic analyzers), but not the instrument-specific MGSE or EGSE which most instruments eventually require
    - these are sub-instrument I&T events, not the instrument-level I&T event

- **Instrument-Level I&T**
  - Instrument-level I&T is not estimated directly with PRICE H
  - It is typically assumed to be a percentage of the total parametric (PRICE H) instrument cost, and is broken down into the categories shown on the following page, which can be scaled based on the complexity and maturity of the instrument

Instrument Level Cost 'Wraps'

- The following 'wraps' are added to the parametric cost estimate of the instrument to account for the full instrument-level lifecycle costs to the center
- These placeholders are based on historic data to ensure that the final cost estimate is a complete lifecycle cost estimate to fully qualify and integrate at the instrument level
- The IDL will work with the customer team to tailor these wraps to capture instrument-specific drivers or handicaps that may increase or decrease these expenses

Instrument Level Considerations	Typical Wrap
Ground Support Equipment (GSE) that is instrument-specific (that is, cannot be readily adapted from general purpose GSE)	5%
Environmental testing at the Instrument Level	5%
Component level flight spare components	10%
Engineering Test Unit (ETU)	10%
Instrument to S/C Integration and Test (typically included in WBS 10.0)	5%
FSW GSE (this is taken from the FSW estimate, not the total instrument cost)	5%
Center Management & Overhead (CM&O), although this may not apply to developments or AOs	Is specific to each NASA Center

Key Input Parameters in the Parametric Cost Model
Global Parameters

- **Labor Rates are set to the build approach indicated by the customer**
  - GSFC bid rates used for in-house build of spacecraft/instrument
    - G&A part of Center Management & Operations (CM&O)
  - GSFC Typical Contractor Rates
    - Used for GSFC vendor provided hardware
    - Used when actual rates are not available
    - Accounts for vendor's G&A and Fee
  - PRICE H Industry Labor Rates
    - Default labor rates provided by Price Systems, Ic. that include vendor G&A and Fee
- **Inflation (NASA escalation rates)**
- **Engineering Environment (Defined for NASA by PRICE Systems, Inc. calibration study)**
  - Emphasizes: System Engineering, Project Management, Automated design capabilities

Key Input Parameters in the Parametric Cost Model
Individual Component Parameters

- **Complexity Factors**
  - Table driven, defined by Price Systems from industry experience
- **Modification Level/Remaining Design Factor**
  - This is the way TRL is encoded into several factors that include
    - % design that exists
    - % design modification
    - % design complexity (e.g. how many different engineering disciplines are involved)
    - % fabrication complexity
- **Quantity and Design Repeat**
  - This captures any efficiency from a learning curve for multiple builds
- **Composition**
  - The material composition of the components, as well as the engineering discipline category (electrical, structure)
- **Mass**
- **Operating Platform**
  - Varies from Manned Spaceflight to Aircraft platforms
  - Is typically set to Unmanned Space – High Reliability

IDL Cost Product

Cost Estimating Output from Price H

Basic Estimate (Metric)

Cost Summary | LM Totals | LM Production | LM Development

Spacecraft Bus
Thu March 18 2010 2:17 PM (PRICE Estimating Suite 2009 SR1)
Assembly Cost — Costs in ($1000 Constant 2010)

Program Cost	Development	Production	Total Cost
Engineering			
Draft	1624.8	381.8	2006.6
Design	9279.6	2083.1	11362.7
System	6111.2	-	6111.2
Proj. Mgmt.	3807.1	5399.6	9206.7
Data	67.1	116.2	183.3
SubTotal(ENG)	20889.8	7980.7	28870.5
Des Int Cost	[9473.2]		
Manufacturing			
Production	-	9113.7	9113.7
Prototype	694.1	-	694.1
Tool Test Eq.	277.0	191.5	468.5
Purchased	0.0	31937.2	31937.2
SubTotal(MFG)	971.1	41242.3	42213.4
G & A / CoM	3228.6	2322.7	5551.3
Fee / Profit	3763.4	7731.9	11495.3
Total Cost	28853.0	59277.6	88130.5
Total (Thruput)	0.0	100.0	100.0
Total w/Thruput	28853.0	59377.6	88230.5
Schedule Start	Jan 05 [51]	Jan 07 [22]	
First Item	Mar 09	Oct 08 [15]	
Finish	Mar 09 [51]	Jan 10 [37]	

Assy Weight	498.26	Assy WS	457.96
Assy Series MTBF Hrs	468.914	Unit Assy Cost	48513.63
Assy Quantity	1	Avg Assy Cost	59324.77

IDL Cost Output includes Instrument Wraps

Example SC Bus 18-Mar-2010	Cost Estimate ($FY10) Flight Units = 1, EDU = 1 Point Estimate CBE Dry Mass (kg) 498	
Parametric Cost Model Summary (Development and Production Costs)		
PRICE H Spacecraft Bus	$88,230,544	
Structure		$2,057,638
Mechanisms		$4,022,157
Power		$9,667,581
ACS		$17,380,631
Telecomm		$17,339,900
Command and Data Handling (C&DH) (Dual-String)		$7,474,576
Thermal Control		$1,878,218
Propulsion		$18,989,283
Harness		$7,012,358
Spacecraft Bus Integration & Test		$2,408,203
PRICE H Payload to S/C Bus Integration & Test (assumed captured in WBS 10.0)		
Total Parametric Estimate	$88,230,544	
The following are NOT PRICE-H estimates but are derived from PRICE H estimates. These estimates are included for completeness and are considered ROM estimates. Consult the Grass-roots estimating organization for more accurate estimates of these items.		
Flight Software (10% of Parametric Estimate)	$8,823,054	
Ground Support Equipment (GSE) (5% of Parametric Estimate)	$4,411,527	
Environmental Testing Labor (5% of Parametric Estimate)	$4,411,527	
Engineering Test Unit (ETU) (10% of Parametric Estimate)	$8,823,054	
H/W Spares (10% of Parametric Estimate)	$8,823,054	
Launch Vehicle Integration & Test (assumed captured in WBS 10.0)		
SC Bus Subtotal	$123,522,762	

IDL Mass Model (a.k.a. MEL)

- In a 1-week study, the IDL captures a parametric description of the conceptual instrument design in a mass model, also known as the Master Equipment List (MEL) that becomes the basis for the cost model
- The components described represent the Current Best Estimate (CBE) of the mass and materials in that solution
- Recommended mass margins are noted in the systems summary, but the cost estimate is based on the CBE mass, and that is what is shown in the MEL
- The IDL will provide a MEL that is arranged in a hierarchy that reflects the true nature of the assemblies so that the calculated I&T costs are accurate
- The MEL includes these parameters
  - Component and assembly nomenclature consistent with the systems level block diagram
  - Flown quantity of components, indicating any redundancy
    - It is important to break down large components into pieces if it is anticipated that it will not be fabricated from a monolithic piece – again this will capture the true labor to design, build, and integrate the multiple pieces
  - Composition
  - CBE mass, and the source of that mass estimate
    - Calculated from a model (C)
    - Engineering judgment (EJ)
    - Weighed (W)
  - Purchase price, if applicable
  - Component level TRL
  - Any heritage mission references

MEL Example

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	Subsystem/Component Description	Composition	Quantity		Mass		If the Part is available Commercially		Maturity		
		(i.e. AL, composite, analog, digital, special surface prep, cabling, machined	Total Flown Quantity	Flown Flight Spares	Mass (kg)	Subtotal Mass (kg)	COTS Purchase Price (if TRL >6) ($)	Break the Composition down to % by mass if necessary (e.g. 5% optics, 20%	List Heritage Spaceflight Missions	TRL	Mass Confidence: Model (c), Eng Jud (EJ)
IR Instrument Assembly						164.16					
Cold Top						70.18					
Cal Target Assembly						24.26					
Cal Target						10.05					
	cal target back plate	aluminum	1		1.50	1.50			ARCADE	6	EJ
	cal target tile plate	aluminum	34		0.05	1.70			ARCADE	6	EJ
	cal target absorber, per cone, density 4g/cm^3	steel cast	646		0.01	6.46			ARCADE	6	EJ
	tile fasteners	steel	37		0.01	0.37			ARCADE	6	EJ
	cal target skirt ring	aluminum	1		0.02	0.02			ARCADE	6	EJ
Cal Target Mechanism						12.65					
	Target counter weight	Steel	1		8.85	8.85				8	EJ
	drive system		1		1.00	1.00	3 (Flight, E	Different ratio gear box		7/8	EJ
	Launch lock mechanism	alum, steel, wax	1		0.50	0.50	3 (Flight, EM, Lifetest)			8	EJ
	target drive motor		1		0.50	0.50	3 (Flight, E	70%mechical and 30% electrical		7	EJ
	target system bearings, brackets, fasteners,	steel	1		1.50	1.50	3 (Flight, EM, Lifetest)			7/8	EJ
	target harnesses, sheared conductive wire		1		0.30	0.30	3 (Flight, EM, Lifetest)			7/8	EJ
						1.56					
	cal target cover MLI		1		0.06	0.06					EJ
	2.7K ADR Stage	mag wire	1		0.20	0.20		wire mag	XRS	4	EJ
	Calibrator Target Pivot Arm	aluminum	1		1.30	1.30				6	C
Structure & Misc						15.90					
	Moon Baffles		1		0.08	0.08					
	Instrument enclosure shell	aluminum	1		2.34	2.34				6	C
	instrument coating -partial	steel cast	1		2.50	2.50				6	C
	instrument enclosure septum,	aluminum	1		0.95	0.95				6	C
	Instrument enclosure Top panel,	aluminum	1		2.30	2.30				6	C
	Instrument enclosure bottom panel,	aluminum	1		2.60	2.60				6	C
	Instrument Mounting Bracket,	aluminum	2		0.65	1.30				6	C
	ADR mount bracket,	aluminum	1		1.41	1.41				6	C
	Optics Box Front cover,	aluminum	1		1.16	1.16				6	C
	Optics Box bottom cover,	aluminum	1		0.34	0.34				6	C
	Optics box rear cover,	aluminum	2		0.46	0.92				6	C
Detector Assembly						0.36					
	detector bolometer assembly (include 2 detectors)		2		0.07	0.14	$3.4M through put	10g ceramic	XRS	4/5	EJ
	Wiring Cable	Tension wire for each signal (in 3 segments)	6		0.01	0.03	cost is included above		XRS	7	EJ
	JFET preamplifiers	Aluminum	2		0.03	0.06	cost is included above		XRS	7	EJ
	detector heat strap,	26" of 24 AWG copper, each	2		0.01	0.01			XRS	7	EJ
	Winston cones/concentrator, 63 long x 36mm diameter, hog out 7/8	Al lathe-turn	2		0.02	0.04			COBE	7	EJ
	detector- cone brackets	aluminum with Kevlar supports to 2.7K optics box	2		0.04	0.08				8	EJ

IDL Point Design Estimate & Cost Risk

- The IDL Cost Estimate is a Point Estimate based on the single point design of the instrument
- The point design that the IDL derives in a 1-week study is An engineering solution, but not necessarily THE solution that will be implemented for flight
- The point estimate is described by the IDL in the MEL in terms of Current Best Estimate (CBE) of mass and materials, and represents a single estimate among a range of feasible possibilities
- Cost risk analysis attempts to address the risk that the eventual outcome of the parameters may differ from the CBE selections made at the conceptual design phase of pre-formulation
- Cost risk capabilities within the parametric cost modeling tool allow a range of input values to be entered to generate a range of cost outcomes
- Cost risk simulation is performed using well known sampling techniques (e.g. Monte Carlo simulation) of the parameter ranges resulting in a Probability Distribution Function (PDF) of possible outcomes, also known as a Density Curve
- PDF can also be represented as a Cumulative Distribution Function (CDF), also known as an S-Curve to provide a graphical representation of the possibilities of various cost outcomes
- Cost risk analysis takes additional labor and is beyond a 1-week IDL study, and is not recommended for the initial instrument conceptual design, but will be necessary for proposal development

Using your Point Design Estimate

- Often, early formulation Managers must get their designs into a cost box during IDC studies, before cost risk analysis can be performed
- Doing this requires trades and descopes against science performance, so descopes should be minimized whenever possible
- However, failure to fully understand the difference between a point design cost estimate and a probabilistic cost estimate can result in unexpected sticker shock later
- NASA desires probabilistic cost estimates at the 70% Confidence Level (CL) so that our endeavors have a 70% chance of succeeding without a cost overrun
- The point design cost estimate is ALWAYS well below the 70% CL, so Managers should realize this when working with a point estimate and use a rule of thumb multiplier to act as a placeholder for the extra money that will be required for a 70% CL price
- A reasonable multiplier is 1.5 X CBE point design cost, to use as a placeholder until you can complete the full cost risk analysis, when checking to see if your price is “in-the-box”
- This will allow Managers to make trades/descopes during very early engineering formulation, such as IDC studies, AND avoid sticker shock when the eventual cost risk analysis is completed, which requires a fair amount of design maturity to be developed first

Cost Confidence Level

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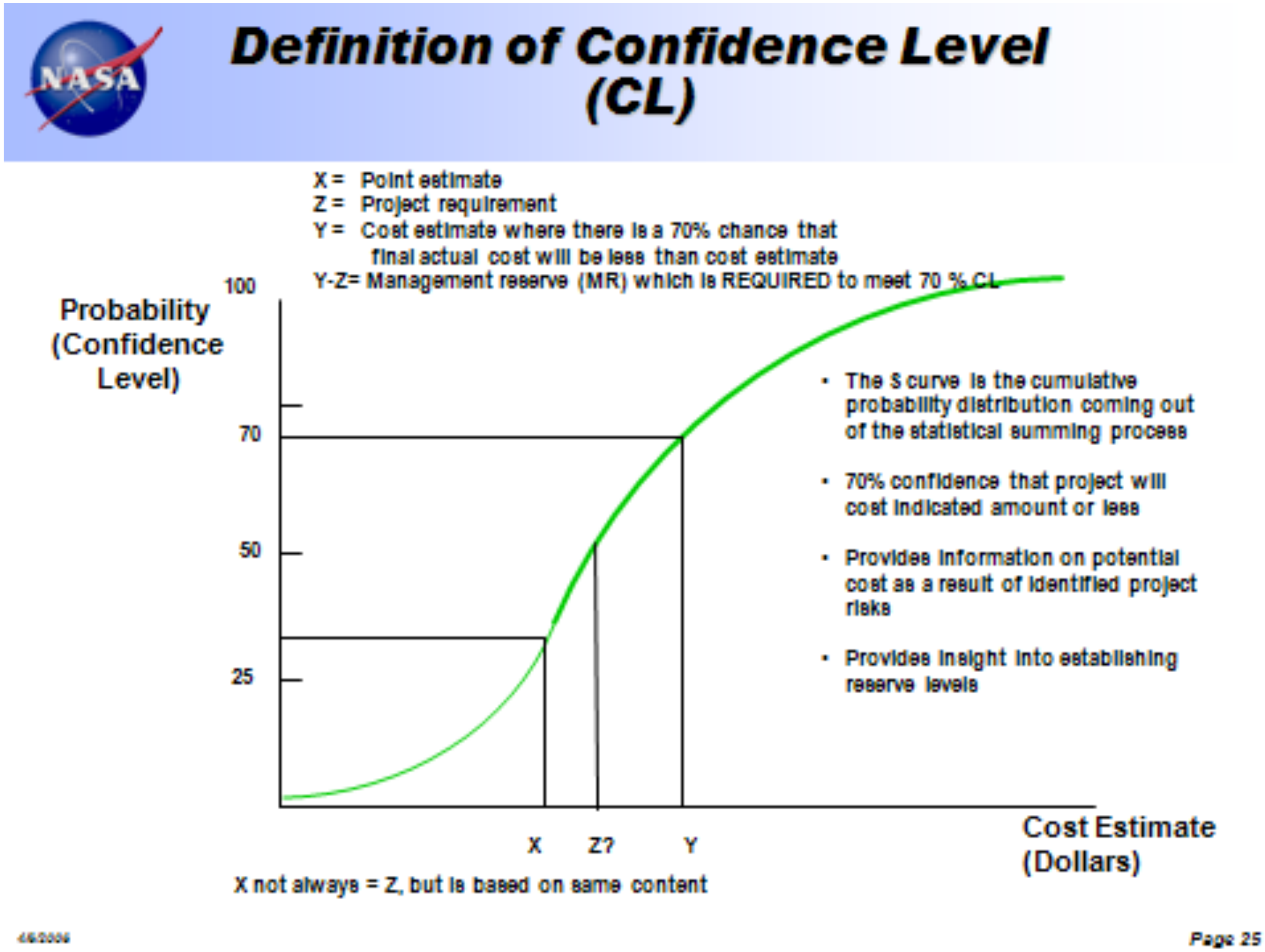

Selected Slide, Definition of Confidence Level (CL), from “NASA Cost Risk Workshop at GSFC”.

Technology Development is a Recognized Risk

- **One of the 5 Contributing Factors to Cost Overruns and Schedule Delays from the NASA Instrument Capability Study (NICS) report is that Technology development is risky and unpredictable**
  - When programs optimistically assess the technology readiness level, they are underestimating the labor and time to complete the design and analysis of component specifications, as well as to qualify that new component or subsystem to all aspects of the relevant flight environment
- **A Technology Readiness Level (TRL) assessment applies to new and existing technology capability**
- **New Technology**
  - When developing new technology, you will encounter unknown unknowns that may change the materials, the electrical or mechanical interface, or the overall implementation approach – these changes impact other subsystems, and cost time and money
  - To defend the performance benefits of implementing new technology, not only should the science traceability justify the resource investment, but a thorough and accurate technology development plan will retire perceived risks
- **Existing Technology**
  - When developing a custom build of previously flown functionality of technology is not new, there is still a considerable amount of labor involved to derive the performance and operational requirements for the new design
  - The aerospace technology and capability utilized in a new configuration will require custom hardware, procedures, and GSE, so again, an accurate estimate of the current state of development is necessary to capture the labor required to fully mature the custom design to flight readiness

Lifecycle Cost

- **Authentically estimating the TRL of your instrument's components and assemblies will produce a more credible, realistic cost estimate and minimize overruns during implementation**
- **Life-Cycle Cost (LCC) is the total of the direct, indirect, recurring, nonrecurring, and other related expenses incurred in the design, development, verification, production, operation, maintenance, support, and disposal of a project**
- **LCC can also be defined as the total cost of ownership over the project or system's life cycle from formulation through implementation - it includes all design, development, deployment, operation and maintenance, and disposal costs**
- **The LCC for technology development of <TRL 6 hardware will include more nonrecurring engineering (NRE) for hardware demonstration units to be assembled, as well as for the development of GSE and procedures to accomplish functional and environmental testing**
- **Technology development expenses may also include new facility construction and institutional support**
  - The IDL does not make any assessment of the current state of GSFC (or industry) facilities, but a lower TRL will include the additional funding that may need to be applied to infrastructure
- **Your parametric cost estimate is a complete lifecycle estimate that includes all the labor, hardware, facilities, and procedures to integrate and test each component described in the mass model into subassemblies and assemblies**

TRL Definitions from NPR 7120.8 Appendix J

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	**Basic principles observed and reported.**	Scientific knowledge generated underpinning hardware technology concepts/ applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	**Technology concept and/or application formulated.**	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	**Analytical and experimental critical function and/or characteristic proof of concept.**	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experi-mental results validating predictions of key parameters.

TRL Definitions from NPR 7120.8 Appendix J

TRL	Definition	Hardware Description	Software Description	Exit Criteria
4	**Component and/or breadboard validation in laboratory environment.**	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	**Component and/or breadboard validation in relevant environment.**	A medium fidelity system/ component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/ simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.

TRL Definitions from NPR 7120.8 Appendix J

TRL	Definition	Hardware Description	Software Description	Exit Criteria
6	**System/sub-system model or prototype demonstration in a relevant environment.**	A high fidelity system/ component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	**System prototype demonstration in an operational environment.**	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.

TRL Definitions from NPR 7120.8 Appendix J

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TRL	Definition	Hardware Description	Software Description	Exit Criteria
8	**Actual system completed and "flight qualified" through test and demonstration.**	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	**Actual system flight proven through successful mission operations.**	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/ software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

Hardware Distinctions

- Proof of Concept - Analytical and experimental demonstration of hardware/software concepts that may or may not be incorporated into subsequent development and/or operational units.
- Breadboard - A low fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.
- Brassboard - A medium fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects, but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.
- Proto-type Unit - The proto-type unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment
- Engineering Unit - A high fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the final product, assuming proper traceability has been exercised over the components and hardware handling.

Hardware Configurations

- Mission Configuration - The final architecture/system design of the product that will be used in the operational environment. If the product is a subsystem/component, then it is embedded in the actual system in the actual configuration used in operation.
- Laboratory Environment - An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions), without respect to the impact of environment.
- Relevant Environment- Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "at risk" aspects of the final product performance in an operational environment. It is an environment that focuses specifically on "stressing" the technology advance in question.
- Operational Environment - The environment in which the final product will be operated. In the case of space flight hardware/software, it is space. In the case of ground-based or airborne systems that are not directed toward space flight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform.