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Headquarters U.S. Air Force

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New Challenges for Cost Analysts:

Creating Technical Baselines for Point Estimates

SCEA National Conference
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- We would like to thank the NCG for the use of their Demonstration Satellite Bus and Payload CERs

Background

- "I don't know the inputs"
  - As a means to control costs, Government and Contractors often ask cost analysts to estimate system costs much earlier in their life cycle
  - At the concept phase, **many inputs** required to complete a high fidelity estimate are **not available** . . . ***but high level technical parameters and requirements or budget are known***
  - What do you do? Determine the relationship between known parameters and typical cost model inputs and the technical baseline

- Purpose of this presentation is to describe one such method of using Technical parameters along with target performance (or cost) to determine system cost (or performance)

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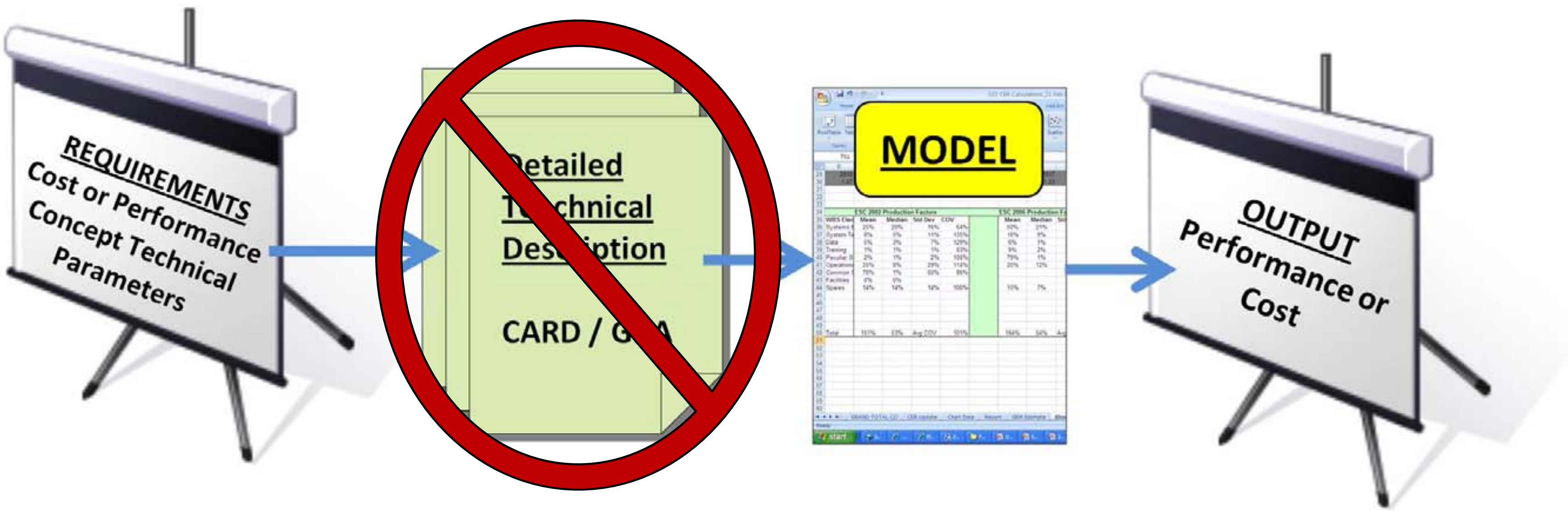
Description of Problem

- Operationally Responsive Space (ORS) Program Office approached AFCAA to determine methods to estimate small satellites in Summer 2007
- At the time, ORS program office did not have a technical baseline
  - Known: Mission Types (UHF Communications, SSA, and EO)
  - Known: Target Recurring Cost of $40M BY06
  - Known: Limited Technical Specifications (Orbit, Design Life, Materials)
  - Unknown: Size, Weight, Power



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Process

- Basic goal was to develop model that could determine typical inputs needed for satellite CERS and also determine performance given target cost
  - Typically Weight and Power
  - Driving Dimensions (e.g. Aperture)
  - Performance (e.g. Resolution)

- Step 1: Determine trade space
- Step 2: Determine applicable WBS and CERs
- Step 3: Research drivers or sizing methods
- Step 4: Determine interaction between subsystems
- Step 5: Develop Sizing and Cost Model
- Step 6: Validate Sizing with external systems

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Step 1: Determine Trade Space

- Goal is to focus the model development on areas of interest and gain agreement from all interested parties

- ORS Trade space
  - Small Satellite (Bus and Payload) < 1000 lbs
  - Design Life of 1-3 years
  - One mission type per satellite
  - Programmatically and Technologically similar to TACSAT like missions and procurement
  - LEO Orbits
  - 3-axis stabilized
  - No State of the art technology

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Step 2: Determine Applicable WBS and CERs

- **As with any estimate, the WBS drives the structure of the model and the inputs required**
- **Given the details and program description available at concept phase, a high level WBS is appropriate and in some cases**
- **After WBS is determined, CERs should be identified to focus the technological sizing (weight, power, etc) on the appropriate variables – We need the inputs to the CERs**
  - **Although they may be of some value to the analysis, determining satellite parameters that do not feed CERs less useful**
- **ORS CERs**
  - **Subsystem Level WBS chosen (Structure, Power, Optical assembly, electronics, etc)**
  - **Demonstration Satellite CERs applicable**
    - Based on smaller buses and experimental payloads, similar to TACSATs
    - Total Cost relationships dependent on weight, power, resolution, mission type, and other drivers

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Step 3: Research Drivers and Sizing Methods

- **Goal is to determine how to get from what you know to what you need to estimate costs**
- **In some cases the customer supplied known values or drivers may be very limited – This was the case with ORS**
  - **Workaround – Conduct research to determine what minimum drivers are required to specify a technical baseline that feeds the CERs**
    - **Create relationships between drivers and required CER inputs**
      - Engineering Calculations
      - Weight estimating relationship – WERs
      - Power estimating relationships – PERs
  - **Create a flexible model where the users can vary the drivers within the trade space**
    - **The drivers should be independent of one another to not over-constrain the model**

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Step 3: Research Drivers and Sizing Methods

- AFCAA had several good resources and databases for determining weight and power drivers along with experience in reviewing satellite designs

Subsystem	Drivers
EPS	EOL Power, Design Life, Solar Array Type & Efficiency, Orbit, Battery Type, Bus Voltage
ADCS	Stabilization Method, Vehicle Weight, # Sensors, Orbit Type
Propulsion	Satellite Mass, Delta V, ISP, Propulsion Margins
C&DH	Simple / Typical / Complex Characterization, Data Storate Requirement
TT&C	Ku - Band, S-Band, X-Band
STR	Total Satellite Weight, Orbit
TCS	Total Satellite Weight, Orbit, BOL Power
Telescope Assembly	Target Range, Resolution, Detection Wavelength, FOV, Limiting Magnitude, Target Velocity

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Step 3: Research Drivers and Sizing Methods

- In some cases, drivers can be used to estimate required weights and powers via engineering calculations
- Example: Calculation of Solar Array Area
  - Can be calculated with max required power output, efficiency, manufacturing degradation, design life, and annual efficiency reduction factor

Description	Value	Units
Day Power	7,276	Watts
Eclipse Power	7,276	Watts
Bus Voltage	28	V
Te	35.49	minutes
Solar Cell Efficiency	28%	
Inherent Degradation	66%	
Sun Incidence Angle	-	
P_o	378.8	W/m2
P_{bol}	250.0	W/m2
Degradation	2.75%	per year
Design Life	1.0	Year
P_{eol}	243.2	W/m2
A_{sa}	331	ft2
BOL	7482	W
Solar Array Weight	331	lbs
DoD	50%	
Efficiency	90%	
Battery Capcity	4303.4	W-hr
Battery Weight	438	lbs
NiH	21.8	W-hr/lb
Li-Ion	40.9	W-hr/lb
NiCd	12.5	W-hr/lb
Power Reg	485	lbs
Total EPS	1254	lbs

Numbers for reference only

Step 3: Research Drivers and Sizing Methods

- **In some cases, drivers can be tested against existing databases to create WERs or PERs**
- **Example: ADACs weight**
  - Statistically significant relationship exists between ADACs weight and total satellite weight, number of ADACs sensors, and Orbit Type

Log Linear Analysis for Dataset ADCS_Data, Case 10
Wednesday, September 12, 10:26 am

I. Model Form and Equation Table

Model Form:	Unweighted Log-Linear model
Number of Observations Used:	25
Equation in Unit Space:	ADACS_Weight = 0.286 * #Sensors ^ 0.3122 * SV ^ 0.7036 * 1.617 ^ LEO

II. Fit Measures (in Fit Space)

Coefficient Statistics Summary

Variable	Coefficient	Std Dev of Coef	Beta Value	T-Statistic (Coef/SD)	Prob Not Zero
Intercept	-1.2517	0.8310		-1.5062	0.8532
#Sensors	0.3122	0.1794	0.2475	1.7404	0.9037
SV	0.7036	0.1346	0.6950	5.2261	1.0000
EXP_LEO	0.4803	0.1654	0.3006	2.9045	0.9915

Goodness-of-Fit Statistics

Std Error (SE)	R-Squared	R-Squared (Adj)	Pearson's Corr Coef
0.2897	84.86%	82.69%	0.9212

SPE	ZING	Coefficient
0.27	1.04	0.296

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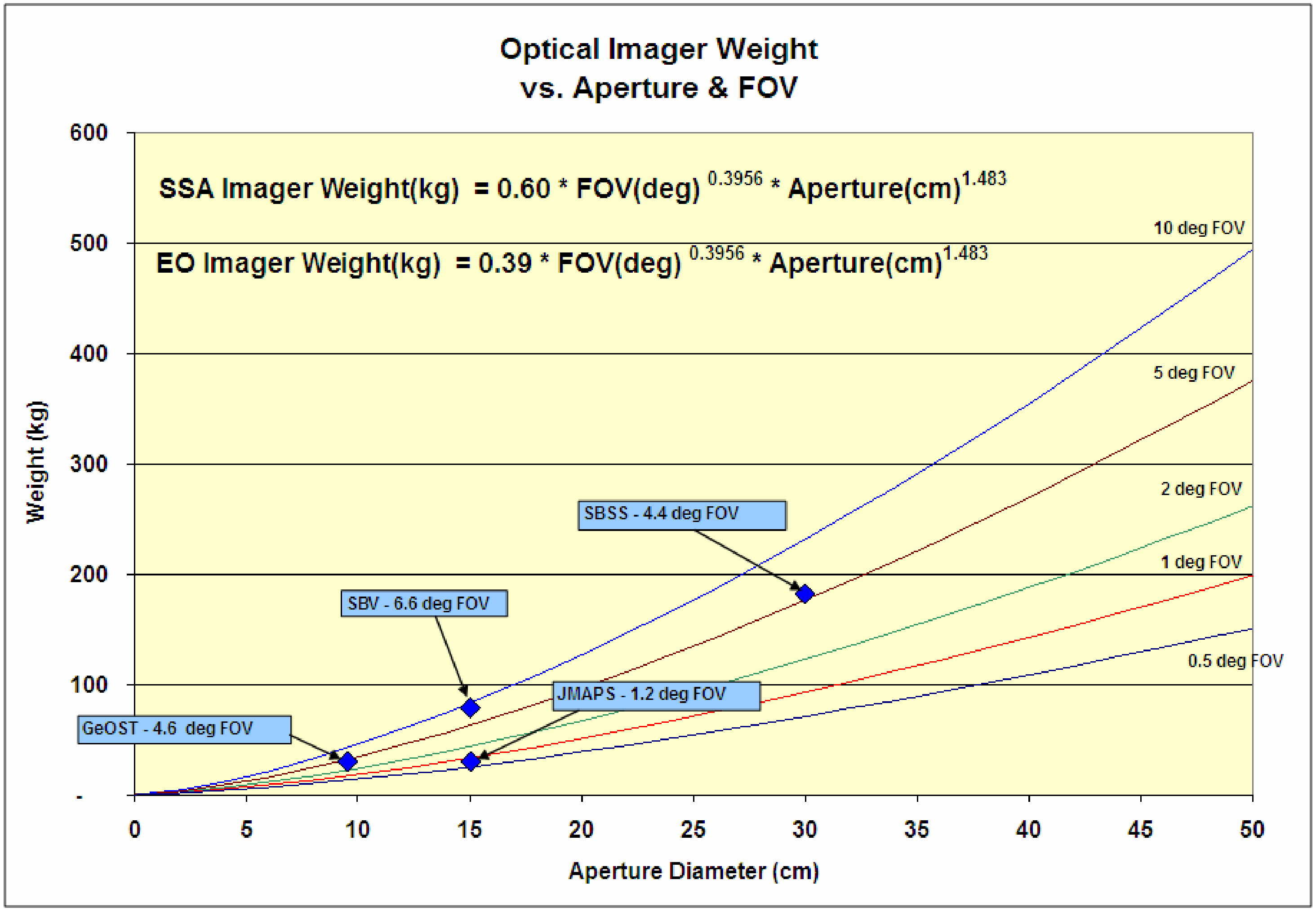
Step 3: Research Drivers and Sizing Methods

- **Additional example of Weight Estimating Relationship for Optical Imager**



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Step 3: Research Drivers and Sizing Methods

- **In some cases weights and powers can be estimated by stratifying existing databases using technical descriptions**

- **Example: C&DH Subsystem**

C&DH Complexity	Simple	Typical	Complex
Weight (lbs)			
Command only	3.3 to 5.5	3.3 to 6.6	8.8 to 11
Telemetry Only	3.3 to 5.5	5.5 to 8.8	14.3 to 16.5
Combined	6 to 12	9.9 to 14.3	20.9 to 23.1
Average	9	12.1	22
Power (Watts)			
Command only	2	2	2
Telemetry Only	5 to 10	10 to 16	13 to 20
Combined	7 to 12	13 to 18	15 to 25

Source: Space Mission Analysis and Design (Third Edition) [James R. Wertz and Wiley J. Larson, eds. - 1999]

Step 3: Research Drivers and Sizing Methods

- **Resultant Model may use a variety of sizing methods**

Subsystem	Drivers	Sizing Methodology
EPS	EOL Power, Design Life, Solar Array Type & Efficiency, Orbit, Battery Type, Bus Voltage	Engineering Relationships, Array weight data, battery capacity data
ADCS	Stabilization Method, Vehicle Weight, # Sensors, Orbit Type	Weight Estimating Relationship
Propulsion	Satellite Mass, Delta V, ISP, Propulsion Margins	Engineering Relationship
C&DH	Simple / Typical / Complex Characterization, Data Storate Requirement	Lookup Table
TT&C	Ku - Band, S-Band, X-Band	Lookup Table
STR	Total Satellite Weight, Orbit	Factor Relationship
TCS	Total Satellite Weight, Orbit, BOL Power	Factor Relationship
Telescope Assembly	Target Range, Resolution, Detection Wavelength, FOV, Limiting Magnitude, Target Velocity	Engineering Calculation, Weight Estimating Relationship

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Step 4: Determine interaction between subsystems

- **In most cases, changes in one subsystem will result in changes in other subsystems**
- **This must be modeled correctly so that the output does not result in an unrealistic technical baseline**
  - **Example: Increase in resolution (all others inputs constant) will drive payload weight, which drives ADACs, Structure, Thermal, Propulsion, etc.**
- **These interactions are how trade-offs can be modeled**
  - **Example: Increase resolution may be accomplished by reduction in orbit which may required an increase in propulsion capability**

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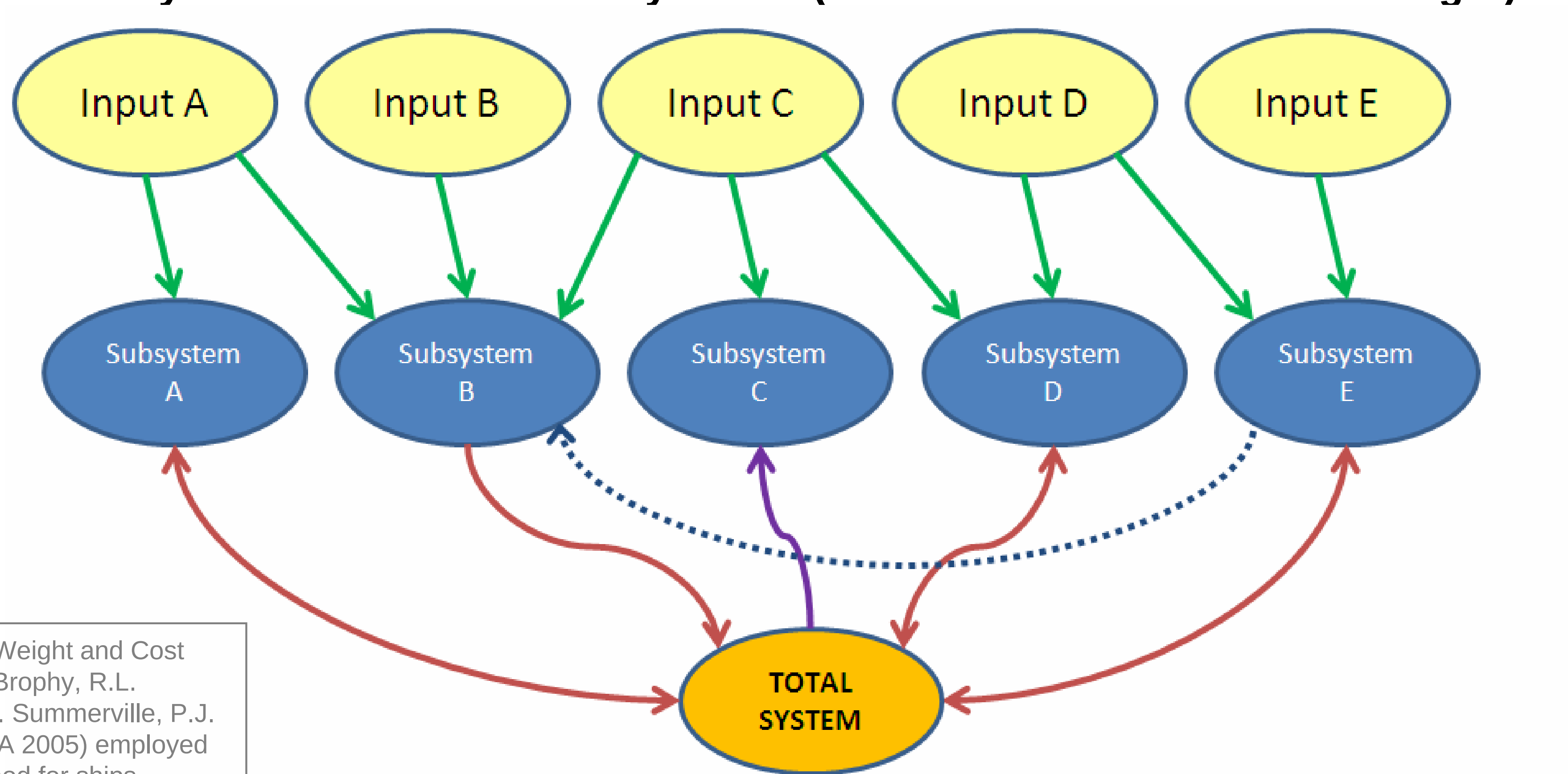
Step 4: Determine interaction between subsystems

- Some inputs drive single / multiple subsystems (Solar Array Efficiency / Design life)
- Some subsystems directly drive other subsystems (Payload -> Power)
- All subsystems drive total System
- Total System drives some subsystems (Structure function of Total Weight)



"Incremental Weight and Cost Model" (B.A. Brophy, R.L. Coleman, J.R. Summerville, P.J. Braxton, SCEA 2005) employed a similar method for ships

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Step 5: Develop Sizing and Cost Model

- **Model designed and built similar to how actual system would be designed – Given initial set of design constraints (orbit, cost or resolution, etc)**
  1. Determine payload size and power requirements
  2. Determine required bus power to support payload
  3. Size Power subsystem
  4. Size Propulsion subsystem
  5. Size TT&C and C&DH subsystems
  6. Utilize Solver to converge on single ADCS, Structure, and Thermal subsystems that can support other subsystems and total weight of satellite → TECH BASELINE
  7. Calculate total cost of system via subsystem CERs
  8. If total cost exceeds target, user can specify which variable SOLVER can modify to meet target cost
     - ORS – Resolution was variable
     - Could also use design life, target range, etc.

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ORS Model Input Sheet – Bus Drivers

TARGET REC COST	**$ 40,000**	FY06$K
Enable Target Cost	**YES**	
Orbit Inputs		
Orbit Apogee	600	km
Orbit Perigee	600	km
Inclication	90	degrees
# Thrusters	4	
Delta V	500	m/s
ISP	200	s
EPS Inputs		
Eclipse Power % of Daylight Pow	100%	%
Bus Voltage	28.00	V
Cell Efficiency	28%	
Worst Case Incidence Angle	0.00	degrees
Articulated Arrays	1	(1=Y, 0=N)
Design Life	1.00	Year
Battery Type	NiH	
Bus Ratio Inputs		
STR Ratio	24.6%	
TCS Ratio	2.2%	
TT&C CDH Inputs		
TT&C Type	S-Band	Pick One
C&DH Complexity	Complex	Complexity Scale
Solid State Recorder Required	Y	(Y or N)
ADCS Inputs		
# ADACS Sensors	8	

- **Minimum amount of information (in addition to payload parameters) required to determine bus technical baseline**

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ORS Model Input Sheet – Bus Drivers

- **Minimum amount of information (in addition to bus parameters) required to determine simple Optical Payload technical baseline**

General Payload Inputs		
Payload Integration Required	1	(1=Y, 0=N)
Optical Payload	1	(1=Y, 0=N)
COMM Payload	0	(1=Y, 0=N)
Imaging Payload	1	(1=Y, 0=N)
Optical Payload Inputs	**Value**	**Units**
Type of mission	ISR	Pick One
Range	600	km
Wavelength	0.52	microns (µm)
Field of View	1.0	deg
Target Velocity (Does Not Apply)	5.0	arc-s/sec
CDL Required	1	(1=Y, 0=N)
CDL Data Rate (Assumes X-Band)	10,000	Kbps

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ORS Model Calculations

- **Separate sheets utilized for each subsystem to calculate weight and power**
- **SOLVER guesses at initial solution for each subsystem weight**
- **Utilize Solver constraints set-up such that all subsystems meet their technical and cost requirements**
  - Example – For each iteration ADACs guess is checked against ADACS WER. If ADACs undersized, ADACs weight increased, which in turn increases structure and propulsion weights
  - Example - For each iteration, total cost of system is checked against Target Cost. If too high, resolution is increased or decreased and entire baseline recalculated
  - If all SOLVE guesses meet all model constraints, then solution has converged
- **User must not over or under-constrain model**
  - Will result in no solution or multiple solutions
- **Any parameter can be maximized or minimized in SOLVER**
  - Example – Maximize resolution for given cost
  - Example – Minimize cost for given resolution
  - Endless alternatives

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ORS Model Output

- **Weight and Cost by WBS presented on Output Sheet**
- **Performance metrics shown for each solution (Resolution and FOV)**

ALL DOLLARS ARE IN FY06 $K

Note: The estimates produced using this model are not appropriate for establishing a budget baseline for any selected alternative, but rather are appropriate for rough order of magnitude comparisons. Please note that no risk analysis has been performed on the estimate as well. We recommend the estimate for the selected alternative be updated and refined before establishing the budget baseline.

TARGET RECURRING COST	40,000	FY06 $K
APERTURE SIZE	9.93	in
RESOLUTION	3.0	m
FOV	1.00	deg

	Dry Weight		Total $K	NR $K	R $K		R $K/lb
Total	**468**	**lbs**	**91,022**	**51,022**	**40,000**		**85.49**
SV SEPM			8,593	4,296	4,296		
SV IA&T			5,072	-	5,072		
Total Payload	**105**		**58,021**	**35,196**	**22,825**		**217.61**
Optical Imager	103	lbs	56,838	34,103	22,735	$	221.04
Optical CDL	2	lbs	224	134	90	$	44.06
COMM Antenna	0	lbs	-	-	-	$	-
COMM RF/Electronics	0	lbs	-	-	-	$	-
Payload Software			959	959	-		
Total Bus	**363**		**19,336**	**11,529**	**7,807**	**$**	**21.51**
STR	115	lbs	2,335	1,635	701	$	6.09
TCS	10	lbs	667	333	333	$	32.38
EPS	82	lbs	2,710	1,680	1,030	$	12.50
ADACS	69	lbs	5,667	2,097	3,570	$	51.48
TT&C	12	lbs		-	-	$	-
C&DH	40	lbs		-	-	$	-
TT&C + C&DH	51		3,588	2,547	1,040	$	20.34
Prop	35	lbs	2,096	1,048	1,048	$	30.23
Bus Software			2,274	2,189	85		
Propellant	**185**			Not Estimated			
Total SV Dry	468	lbs					
Total SV Wet	**653**						

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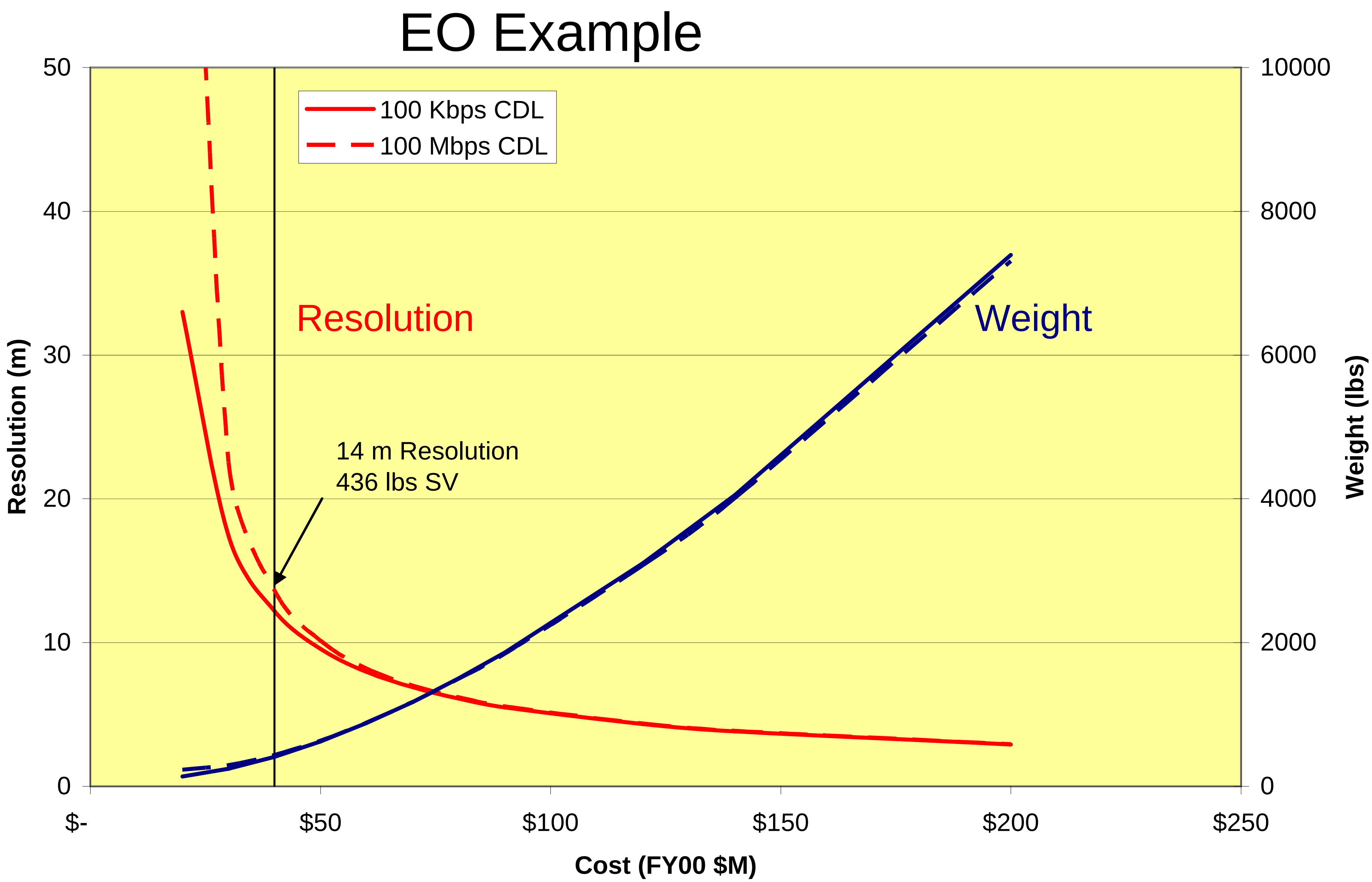
Notional Trade Results (Performance vs. Cost)



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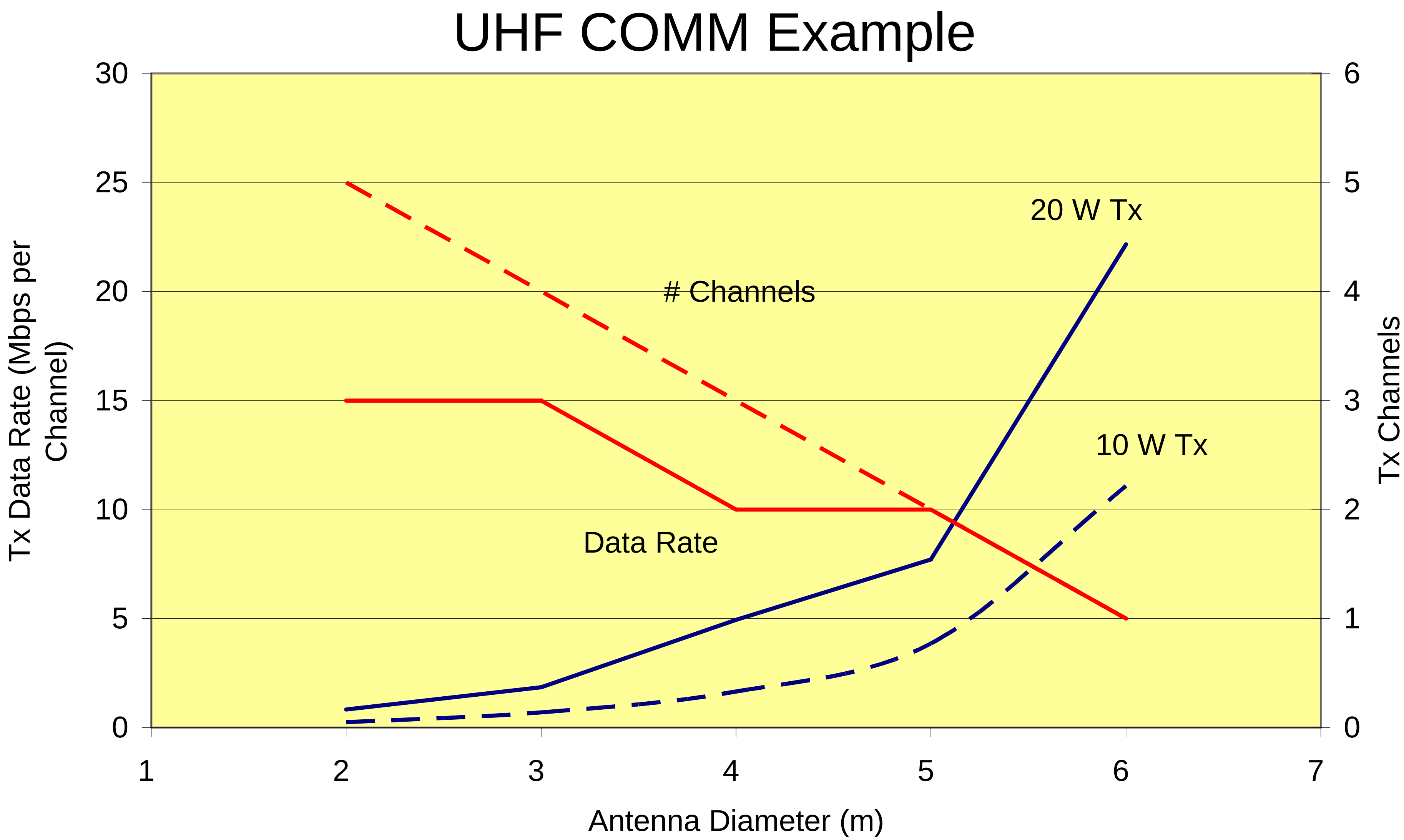
Notional Trade Results (Performance vs. Requirement)



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Step 6: Model Validation

- **No model is complete without validation using systems external to model**
  - AFCAA in initial stages of validating ORS model
- **Utilized model to verify bus sizing methodology given payload weight and power**
  - Satellite parameters from CARDs or technical documents input into ORS model
  - Payload Power and Weight directly input into ORS model
  - SOLVER utilized to calculate bus subsystem weights
  - *ORS Model has predicted total bus weights within 10% for several medium and large satellites*
- **Further bus sizing methodology would include utilizing all in house AFCAA actuals, independently sizing buses, and comparing to actuals buses**
- **Payload validation slightly more difficult given lack of detailed payload data and variation in optical payload designs (gimbals, filter designs, etc.)**

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Conclusion

- As we are asked to complete estimates earlier in life cycles, we can find ourselves faced with a lack of details
- Parametric analysis and basic engineering design principles can be utilized to determine a rough technical baseline useful for concept phase cost estimates
- Steps applicable not just to Satellites, but other commodities
- Hard (Fun) part is in determining minimum technical drivers and relationships between systems
- Technical analysis opens dialog between cost analysts and engineers and results in model that is useful to both for trade studies, either CAIV or maximum performance

Cost Analysts' job is not only related to Cost Estimation

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Future Enhancements

- Model Validation
- SIGINT / SAR Missions
- More calibration data for WERs and CERs
- Heritage adjustment for Non-Recurring cost
- Crosschecks or replacements for all SMAD assumptions
  - NR/R splits (Good comparison to NRL std Bus proposals)
  - STR / TCS ratio (Good comparison to Demo-Sat Database)
  - Specific Energy for Batteries (Published SAFT information)
  - Enhance methodology for TT&C / C&DH
- Cryocooler adjustment for optical payload
  - Investigating relationship between cooling capacity / wavelength / resolution
- Additional drop-downs or default values
- Warning pop-ups if out of estimation range (Max weight, Aperture Size, RF Power, etc).
- Risk Methodology
- Full Instructions (In progress)

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Questions?