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Assuring Space Mission Success

Review of Three Small-Satellite Cost Models

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Presentation to the 2010 ISPA/SCEA Conference
San Diego, CA
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SmallSat Costing Must Adapt a Different Model

Technical Parameters	SmallSat Range	Design Impact	Cost Impact
Size	<8 cu meters	✓	✓
Weight	< 500 kg	✓✓✓	✓✓✓
Power	< 1000 w	✓✓✓	✓✓
Pointing Accuracy	> 1 degree	✓✓	✓
Total Impulse (Delta V)	0 to < 300 m/sec	✓	✓
Down Link Rate	< 10 Mbits/sec	✓	✓
Programmatic Parameters			
Orbit Regime	LEO (or MEO)	✓✓✓	✓
Satellite Class (A to D)	C or D	✓✓✓	✓✓
Design Life	< 3 years	✓	✓
Redundancy	Single String	✓	✓
Qualification Testing	None	✓✓	✓✓

Small Satellite Cost Models Covered in this Paper have Different Approaches to the Issues

1. The Small Satellite Cost Model (SSCM)
   – *Eric Mahr, The Aerospace Corporation*

2. The Demonstration System Cost Model (DSCM)
   – *Dan Barkmeyer, The NRO Cost Analysis Improvement Group*

3. Parametric Sizing and CAIV Cost Model
   – *Sam Toas, Air Force Cost Analysis Agency and the Operationally Responsive Space Program Office*

There are underlying data points that are in the "DNA" of all three models

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Small Satellite Cost Model (SSCM)

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Presentation to the AIAA Space 2009 Conference
Pasadena Convention Center
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SSCM Small Satellite Cost Model

Motivation

- Paradigm shift in early 1990's saw a move from traditional large satellites to small satellites
  - *NASA Faster, Better, Cheaper (FBC)*
  - *Commercial communications*
  - *Universities*
  - *Technology demonstrations*

- Parametric weight-based cost models based on traditional large satellites do not accurately predict the costs of small satellites
  - *Overlook strategies that are an integral part of the small satellite design process*
    - Highly focused missions
    - Streamlined development process and reduced programmatic oversight
    - Shorter design lifetimes and lower reliabilities

- Need existed for a model that could credibly estimate costs of small satellites

SSCM Description

- Parametric cost model
- Estimates development and production cost of a spacecraft bus for small (<1000 kg total wet mass) Earth-orbiting or near-Earth planetary missions
- Subsystem-level Cost Estimating Relationships (CERs) derived from technical and cost database of historical small spacecraft
- CERs include cost drivers that are not strictly weight-based
  - *Performance*
  - *Configuration*
  - *Technology*
  - *Programmatics*
- Applies to civil, commercial and military missions

SSCM Small Satellite Cost Model

Small Satellite Characteristics

Characteristic	Cost Related Observation
Physical	
Light (Mass)	Reduced spacecraft cost
Small (Volume)	Simplified systems engineering
Functional	
Specialized design	Reduce interface requirements, complexity
Dedicated mission	Fewer users, shorter lifetimes
Procedural	
Short project schedule	Focused design effort, minimize optimization
Streamlined organization	Less management structure
Developmental	
Existing components/facilities	No development of new parts or technologies
Software advances	Extensive software reuse
Risk Acceptance	
Low to moderate mission value	Rely on existing technology
Higher tolerance for mission risk	Reduced redundancy, complexity
Launch	
Small vehicle or piggyback	Avoid launch date slips, stand-downs
Ground Terminals	
Simplified/autonomous	Need fewer personnel

SSCM
Small Satellite Cost Model

Elements Estimated

- Satellite Program
  - Satellite
    - **Spacecraft Bus**
      - **Attitude Determination and Control Subsystem (ADCS)**
      - **Propulsion**
      - **Power**
      - **Telemetry, Tracking and Command (TT&C)**
      - **Command and Data Handling (C&DH)**
      - **Structure**
      - **Thermal**
    - Payload
    - **Integration, Assembly and Test (IA&T)**
    - **Program Management (PM)/Systems Engineering (SE)**
    - **Launch and Orbital Operations Support (LOOS)**
  - Launch Service
  - Ground Segment

Elements estimated shown in **bold**

SSCM
Small Satellite Cost Model

Element Definitions

ADCS	Control electronics, attitude sensors (earth, sun, star, magnetometers, gyroscopes), actuators (torque coils, reaction/momentum wheels) and gravity gradient booms
Propulsion	Tanks, thrusters, servo electronics and propellant feed plumbing
Power	Batteries, power control electronics, power converters, wire harness and solar arrays
TT&C/C&DH	Antennas, transponders, baseband units, receivers, transmitters, telemetry encoders/decoders, command processors, power amplifiers, signal and data processing equipment and magnetic or solid state data recorders
Structure	Support structure for spacecraft and payload, launch adapter or deployment mechanism, other deployment mechanisms and miscellaneous minor parts
Thermal	Thermostats, heaters, insulation (tape, blankets), special conductors and heat pipes. Does not include payload-specific cooling equipment.
IA&T	Research/requirements specification, design and scheduling of IA&T procedures, ground support equipment, spacecraft bus and payload-to-bus integration, systems test and evaluation and test data analyses. Typical tests include thermal vacuum and cycle, electrical and mechanical functional, acoustic, vibration, electromagnetic compatibility/interference and pyroshock.
PM/SE	Systems engineering (quality assurance, reliability, requirements activities), program management, data/report generation, and special studies not covered by or associated with specific satellite subsystems
LOOS	Prelaunch planning, trajectory analysis, launch site support, launch-vehicle integration (spacecraft portion) and initial on-orbit operations before ownership is turned over to the operational user (typically 30 days)

SSCM
Small Satellite Cost Model

CER Development

- Identification of cost drivers in each subsystem
  - *Technical database contains 100+ technical parameters*
  - *Narrowed field of potential cost drivers using statistics, sound engineering judgment and common sense*
- Several forms of CER were considered for each set of inputs
  - *One-variable linear and non-linear*
  - *Multi-variable, using non-correlated cost drivers*
- Data from a particular subsystem was segregated if it made engineering sense
  - *e.g., Spin-stabilized vs. 3-axis stabilized attitude control subsystems*

SSCM
Small Satellite Cost Model

SSCM07 User Interface

Technical Parameter	Value	Notes
Programmatic		
Development Time (months)	36	
Fiscal Year for Estimate (yyyy)	2007	
Inflation Methodology	NASA	
System		
Destination	Earth-Orbiting	
Maximum Distance from Sun (AU)		
Design Life (months)	48	
Satellite Wet Mass (kg)	450	
Bus Dry Mass (kg)	350	
Number of Instruments		
Power		
Solar Array Mounting Type	Deployed – Fixed	
Solar Cell Material	Gallium Arsenide	
Battery Type	NH2	
Power Subsystem Mass (kg)		
BOL Power (W)	750	
Structure		
Primary Structure Material	Aluminum	
Structure Subsystem Mass (kg)	125	
ADCS		
Stabilization Type	3-axis	
Star Tracker?	Yes	
ADCS Subsystem Mass (kg)	50	
Pointing Control (deg)	0.05	
Propulsion		
Propellant Type	Hydrazine	
Monopropellant or Bipropellant?	Monopropellant	
Propulsion Subsystem Dry Mass (kg)	20	
TT&C/C&DH		
Communications Band	S-band	
TT&C/C&DH Subsystem Mass (kg)	45	
Transmit Power (W)	10	
Thermal		
Thermal Subsystem Mass (kg)	20	

Technical Parameter	Range				
	Low	Minimum	Value	Maximum	High
Development Time		22		48	
Maximum Distance from Sun		1		2.7	
Design Life		6	48	96	
Satellite Wet Mass		165	450	787.8	
Bus Dry Mass		101	350	674	
Number of Instruments		2		7	
Power Subsystem Mass		19.3		96	
BOL Power		150	750	1760	
Structure Subsystem Mass		19.96	125	236	
ADCS Subsystem Mass		2.8	50	58.5	
Pointing Control		0.017	0.05	3	
Propulsion Subsystem Dry Mass		8.7	20	118.2	
TT&C/C&DH Subsystem Mass		8.7	45	48.98	
Transmit Power		1	10	15	
Thermal Subsystem Mass		2	20	53	

Comparison to CER Data

1

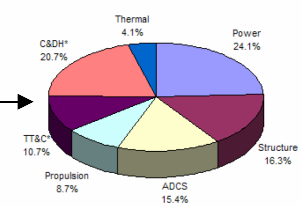
Subsystem Cost Estimates

	Estimate (FY07$K)				% of	% of	
	Non-rec	Rec	Total	Std Error	Sub-level	Sys-level	Range
Spacecraft Bus Subsystems							
Power	3,008	4,328	7,336	2,978	24.1%		
Structure	2,730	2,234	4,965	1,862	16.3%		
ADCS	2,354	2,354	4,707	1,243	15.4%		
Propulsion	899	1,746	2,045	942	8.7%		
TT&C*	1,693	1,562	3,255	3,600	10.7%		
C&DH*	3,286	3,033	6,319		20.7%		
Thermal	677	576	1,253	556	4.1%		
Spacecraft Bus	14,646	15,833	30,479	5,295	100%	62.5%	
IA&T*	3,467	2,998	6,465	3,982		13.3%	
PM/SE	4,272	4,628	8,900	3,729		18.3%	
LOOS*	0	2,905	2,905			6.0%	
S/C Development & First Unit	22,385	26,364	48,749	7,603		100%	

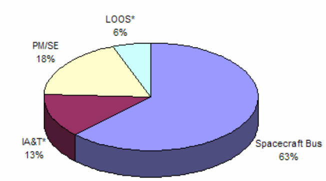
*TT&C/C&DH and IA&T/LOOS costs are generated from single CERs and standard error is presented as such. Per subsystem cost presented is based on database data.

2

Subystem-Level Cost Breakdown



System-Level Cost Breakdown



Input Data

Cost Breakdown

NATIONAL RECONNAISSANCE OFFICE

Demonstration Satellite Cost Model (DSCM)

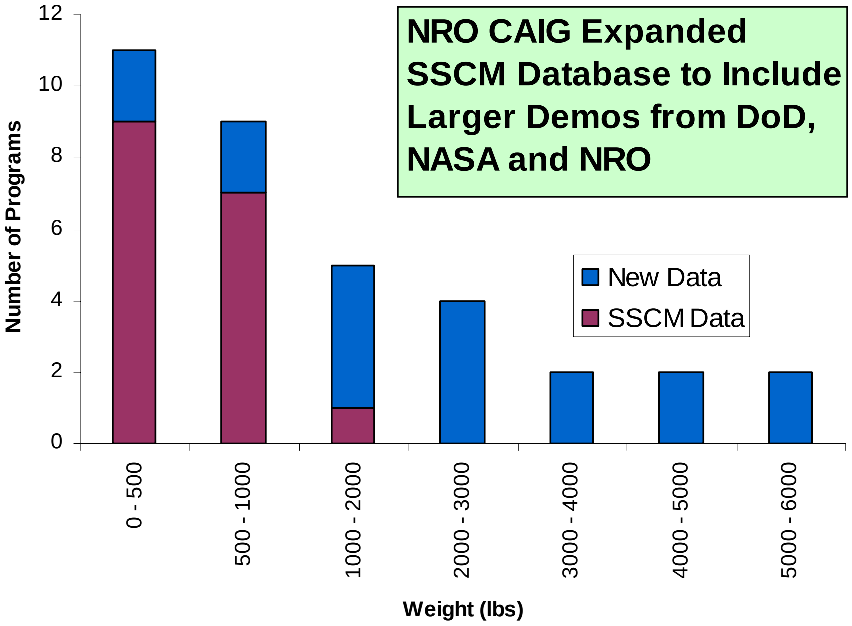
Presented at: AIAA Space 2009
Pasadena, CA

VIGILANCE FROM ABOVE

Background

- Costs of small satellites for demonstration or short-term scientific missions do not follow trends of operational satellites
- Recent tendency to develop larger, more operational-like demos
- NRO CAIG wants to know:

  How successfully can cost-reduction strategies employed for small demo satellites be extended to larger ones?
- Approach
  - Develop cost model based on SSCM database expanded to include large demonstration-type satellites
  - Compare against established cost model for operational satellites



What is a Demo?

- One-of-a-kind satellites
- Short design lives
- Not designed for a JROC-validated or pre-existing mission need
- Not designed to deliver sustained science product (e.g., Hubble, IRAS, GRO, AXAF)
- Stand-alone communication, control, and processing ground segment
- Government sponsored
- Earth-orbiting

DSCM Cost Estimating Relationships

Subsystem	CER / SER Form
SE / PM	$[\text{Cost (FY06\$K)}] = 0.26\,[\text{Base (FY06\$K)}]^{1.03}$
I&T	$[\text{Cost (FY06\$K)}] = 33.0\,[\text{S/C Dry Weight (lb)}]^{0.66} * 1.32^{[\text{Contract Includes Payload Integration}]} * 1.40^{[\text{Optical Payload}]} * 1.70^{[\text{Propulsion}]}$
Structure	$[\text{Cost (FY06\$K)}] = 45.1\,[\text{Subsystem Weight (lb)}]^{0.77} * 1.34^{[\text{Solar Array Mechanics}]}$
Thermal	$[\text{Cost (FY06\$K)}] = 62.7\,[\text{Subsystem Weight (lb)}]^{0.70} * 1.63^{[\text{Optical Payload}]} + 144$
EPS	$[\text{Cost (FY06\$K)}] = 37.1\,[\text{Subsystem Weight (lb)}]^{0.89} * 1.44^{[\text{Nickel-Hydrogen Battery}]}$
ADCS	$[\text{Cost (FY06\$K)}] = 288\,[\text{Subsystem Weight (lb)}]^{0.59} * [\text{Number of Attitude Sensors}]^{0.23}$
Propulsion	$[\text{Cost (FY06\$K)}] = 398\,[\text{Propellant Weight (lb)}]^{0.22} * [\text{Number of Thrusters}]^{0.37}$

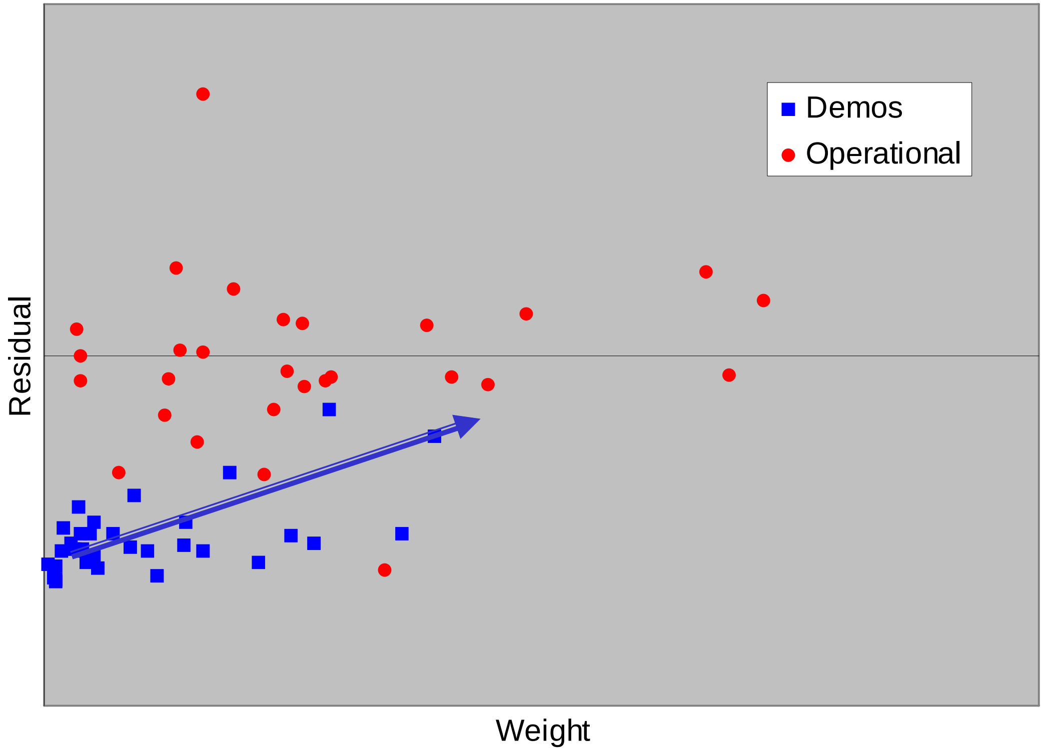
Subsystem	CER / SER Form
TTC&DH	$[\text{Cost (FY06\$K)}] = 15.5[\text{Subsystem Weight (lb)}]^{0.86} * [\text{Vehicle End of Life Power (W)}]^{0.41}$
Software	$[\text{Cost (FY06\$K)}] = 16.8[\text{TT\&C Subsystem Weight (lb)}]^{1.18}$
Launch Support	$[\text{Cost (FY06\$K)}] = 82.3[\text{Base (FY06\$K)}]^{0.22} * [\text{Number of Payloads}]^{0.51} * 1.60^{[\text{Hydrazine Propellant}]}$
Optical Payload	$[\text{Cost (FY06\$K)}] = 760\,[\text{Payload Weight (lb)}]^{0.69} * (\log[\text{Spectral Range (A)}])^{0.37} * 0.28^{[\text{Cryostat}]}$
RF Payload	$[\text{Cost (FY06\$K)}] = 119\,[\text{Payload Weight (lb)}]^{0.97} * [\text{Design Life (mo)}]^{0.28}$
Schedule	$[\text{Time to First Launch (mo)}] = 9.4\,[\text{S/C Dry Weight (lb)}]^{0.14} * [\text{Design Life (mo)}]^{0.19} * 1.13^{[\text{Optical Payload}]} - 5.6^{[\text{Option on Extant Contract}]}$

* CERs based on a mixture of NASA, DoD, and NRO data

- CERs/SERs based on technical inputs
- Determined through regression analysis supported by engineering judgment
- Selected based on accuracy across entire dataset

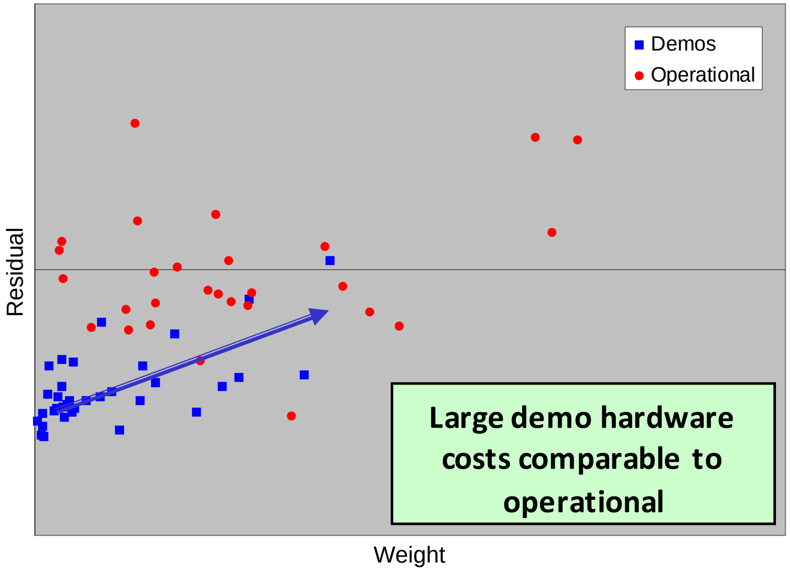
Comparison Against Operational Satellites

- Operational satellites (red) and demos (blue) estimated using cost model designed for operational satellites
- Behavior of residuals ($R = \frac{\text{Actual - Estimate}}{\text{Estimate}}$) shows trend with weight in demo satellite cost relative to operational satellites
- As weight increases, demo satellites are more accurately modeled by operational satellite model
  - Implies cost reduction due to demo-like practices becomes less effective as satellite approaches operational-like scale

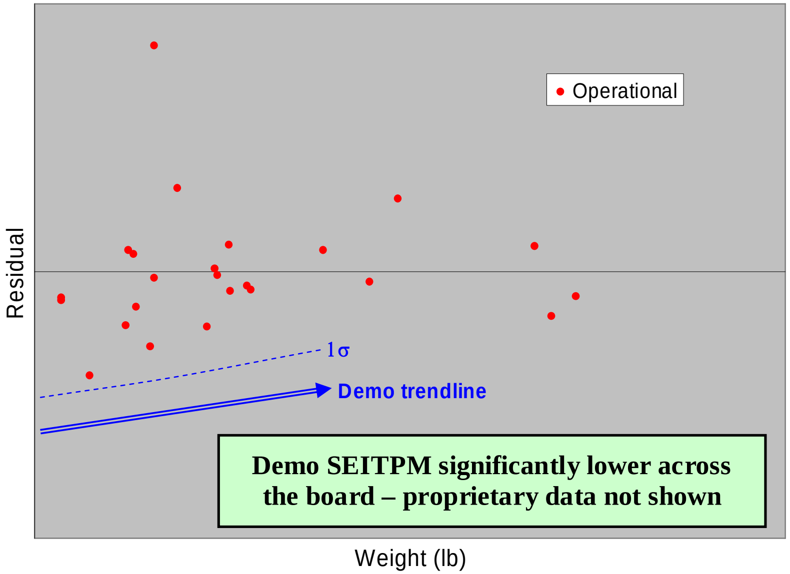


Comparison Against Operational Satellites

- Trend is more pronounced when examining only hardware cost
- Largest (most complex) demos have hardware cost in line with operational systems



- Systems engineering, integration & test, and program management (SEITPM) shows a significant savings for demos across the dataset
  - Streamlined, more risk-tolerant design and I&T is where the payoff is for demo-like development



Conclusions

- Costs of demonstration satellites can be modeled similarly to those of operational satellites, but trend differently with technical drivers
- Demonstration satellites approach the cost of operational satellites as they increase in size
  - Hardware costs only able to achieve efficiency if the scope of the program is less ambitious
  - SEITPM costs responsible for the bulk of savings associated with more risk-accepting programs

Headquarters U.S. Air Force

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AFCAA Parametric Sizing Model

AIAA Conference & Exposition

Sept 2009

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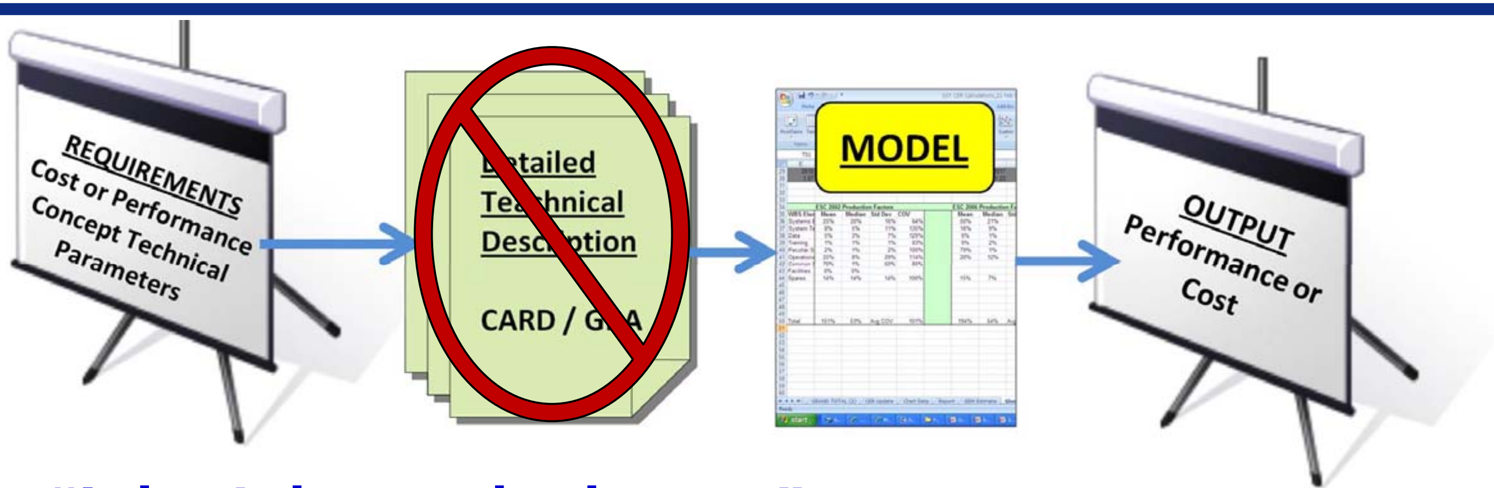
Background



- **"I don't know the inputs"**
  - Streamlined Acquisition strategy for Small Sats requires Government and Contractors to complete detailed cost estimates much earlier in the life cycle than Large Sats
  - At the concept phase, **many inputs** required to complete a high fidelity estimate are **not available** . . . ***but general mission requirements and/or target budget are known***
- **"Now what should I do?"**
  - Determine the relationship between known parameters and typical cost model inputs for the technical baseline

Weight and Power Drivers

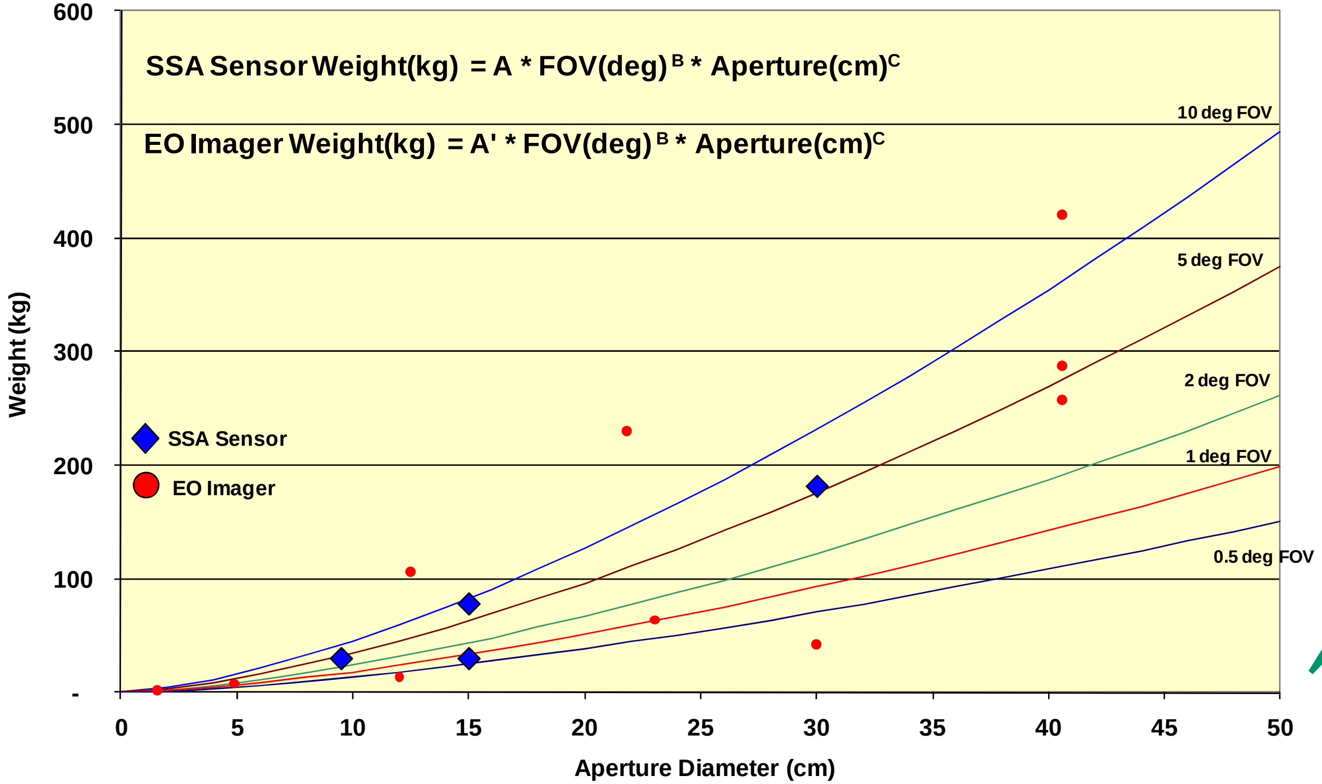
- Determine set of design parameters that could be used to estimate CER inputs (e.g., weight and power)
  - Gathered through existing literature (e.g., SMAD[1]), interviews with design engineers, and in-house knowledge
  - Drivers do not have to be fixed → Trade studies

Subsystem	Drivers
EPS	EOL Power, Design Life, Solar Array Type and Efficiency, Orbit, Battery Type, Bus Voltage
ADCS	Stabilization Method, Satellite Mass, No. Sensors, Orbit Type
Propulsion	Satellite Mass, Delta V, ISP, Propulsion Type (XIP vs. Mono)
CDH/TTC	Processing Capability, Data Storage Requirement, Frequency Band
STR	Satellite Weight, Orbit Type
TCS	Satellite Weight, Orbit Type, BOL Power
Optical Assembly	Target Range, Resolution, Wavelength, FOV, Limiting Magnitude, Target Velocity
Simple Comm Link	Range, Frequency, No. Channels, Data Rate, Required Margin

[1] Wertz, J.R., and Larson, W.J. (Eds). (1999). Space Mission Analysis and Design (3rd ed.). Microcosm Press, El Segundo, CA.

Weight Estimating Relationships

- Example below shows a weight estimating relationship developed for an optical sensor
  - Direct link from requirement (resolution, FOV) to weight / cost



Aperture diameter calculated with theoretical optics calculations (diffraction limited, limiting magnitude

Based on historical data / Quick calculation / Useful for concept level trades

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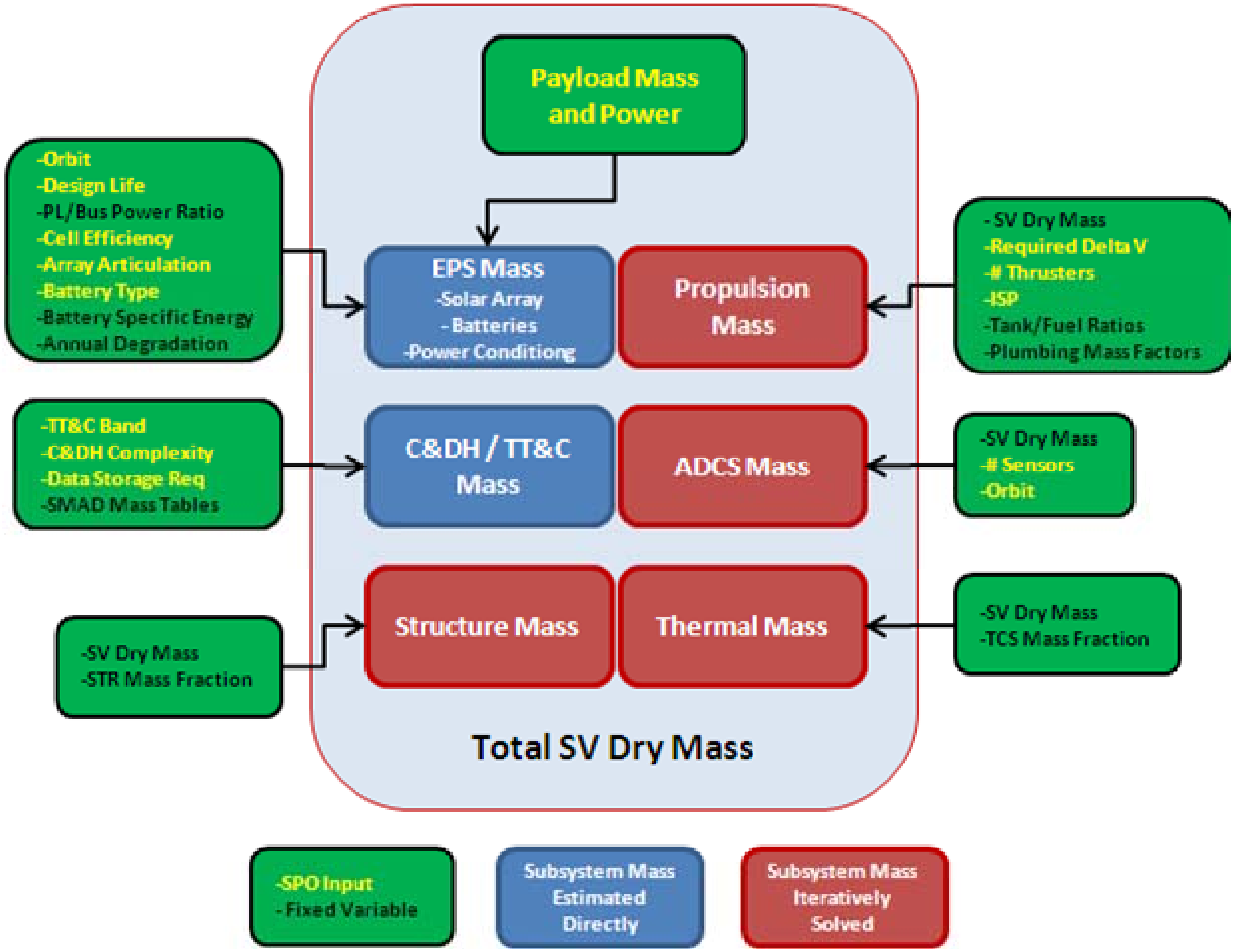
Sizing Model Interactions

Ensures the Design Closes



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