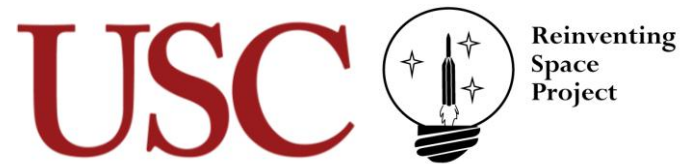# *Leveraging Performance-Based Cost Modeling*

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March 19, 2014

- Executive Summary

- Reinventing Space Project Summary

- PBCM Objectives

- PBCM Process and Assumptions

- Results for Earth Observing System

    – Physical Parameters

    – Cost vs. Altitude for Fixed Coverage
      and Resolution

- Conclusion for Earth Observing
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- Conclusions for PBCM

- Questions for the Cost Community

- Appendix

    – PBCM Process Details

    – Summary of Assumptions

    – Risk, Reliability, and Schedule

    – Cost vs. Cost Overruns

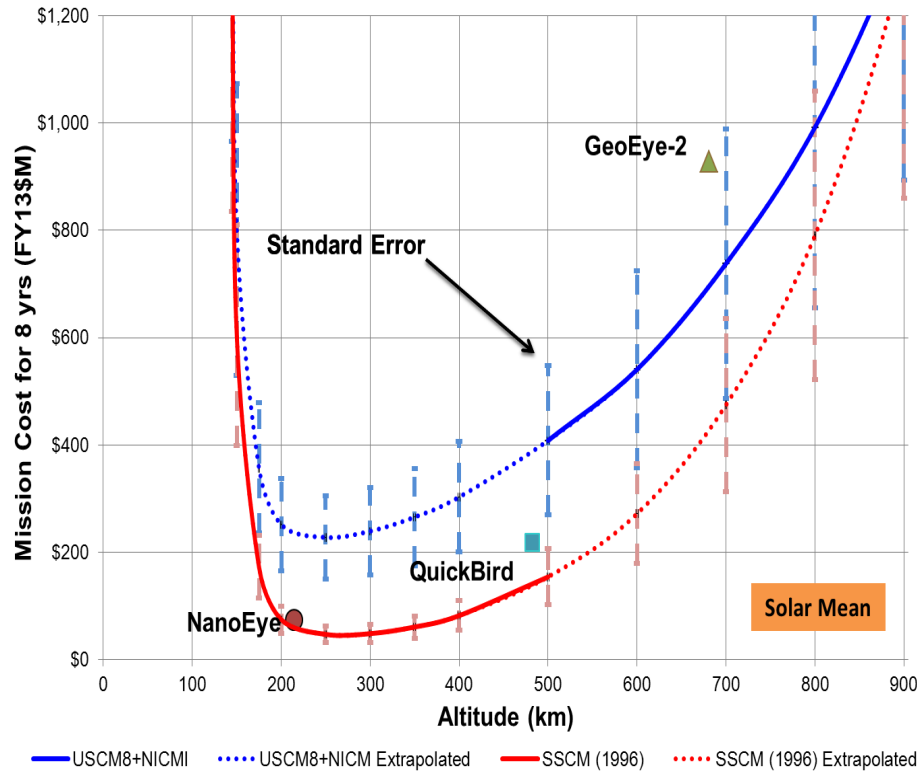   – Reinventing Space Project Overview

- **Sequestration 2013 made clear that government spending has to be reduced**

- How to reduce mission space costs is well defined, but contrary to current M.O.
  - **For Earth Observing Missions, lower the altitude**
  - **Reduce physical size of spacecraft**
  - **Launch more satellites, and more frequently (economies of scale and lower risk)**
  - Lower parts reliability, increase mission reliability
  - Larger margin
  - Use microprocessors and modern electronics
  - Reduce development schedule
  - Trade on requirements

- **We are presenting to the cost community today to determine:**
  1. Whether Performance Based Cost Modeling (PBCM) is an appropriate method to quantify cost savings.
  2. How do we convince the elephants to change how we do business in space?

- We believe the 3 highest priority problems in space systems are:

  1. **They cost too much**

  2. **They take too long**

  3. **They are not as responsive or robust as they should be**

- What do we want to achieve?
  - Reduce space mission cost — by a factor of 2 to 10
  - Reduce the schedule for new programs — from decades to months or years
  - Reduce the cost of access to space — by a factor of 2 to 5 initially, 4 to 10 in the longer term
  - Provide responsive launch (within 8–24 hours) to respond to natural or man-made disasters
  - Provide frequent, low-cost access to space for education, innovation, and testing
  - **Create evidence that these goals are attainable**

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Initial Results:

- Earth Observation Systems

Future Goals:

- Communication Satellite Systems
- Interplanetary Missions

Cost vs. Altitude for Fixed Resolution and Coverage

Number of satellites required for coverage

- **Objective: Quantify the relationship between Cost and Performance**

  - **Cost: dollar amount spent on entire program**

    - Includes costs for Non-recurring engineering, recurring, launch, operations & maintenance, production with learning curves, and amortization of costs

  - **Performance: first priority technical program objective**

    - For Earth Observation: Resolution and Coverage Rate

    - For Communication Systems: Data Rate and Coverage Rate

- Illuminate useful mission design alternatives

  - Lower cost, better performance, or both

- SmallSats are inherently lower cost than large satellites

  - PBCM aims to **quantify** cost saving methods

> **Today, most acquisition performance analysis focuses on cost overruns
> i.e., how much does the system cost relative to what we expected it to cost?**
>
> **PCBM allows us to focus on the more important questions of how much performance
> we can achieve for a given cost, or what the cost is for a given level of performance.**

- Determine the performance requirements

  - Sensing requirement   Visible EO Imaging for baseline mission

  - Resolution at nadir   0.5 m for baseline mission

  - Coverage   14,200 km^2/sec for baseline mission

  - Mission lifetime   8 years for baseline mission

- Estimate total mission cost from performance parameters

  1. Size the payload required to meet the desired resolution

  2. Size the spacecraft bus to support the payload

  3. Size the spacecraft wet mass (in appendix)

  4. Determine number of satellites required for coverage and lifetime requirements

  5. Input mass estimates into weight-based cost model CERs to predict WBS costs

  6. Determine launch cost (in appendix)

  7. Determine recurring and non-recurring engineering costs (in appendix)

  8. Estimate total mission costs

- Present the relationship between total mission cost and performance

  9. Total Mission Cost vs. Orbit Altitude for fixed Resolution and Coverage

- Determine the payload aperture diameter using diffraction limited optics for Earth Observation mission
  - D = Aperture diameter
  - θ = Resolution requirement
  - h = Orbital altitude
  - λ = Observation wavelength

$$D = \frac{h\,\lambda}{\theta}$$

- Spacecraft bus density is estimated empirically from 6 existing observation systems:
  - GeoEye-1
  - GeoEye-2
  - Quickbird
  - OrbView-3
  - Kestrel Eye
  - NanoEye

$$M_{dry} = 2287 D^3$$

- Less redundancy needed for systems with shorter design-life
  - Spacecraft with longer design-life typically include parts redundancy in case of failures
  - For single-string systems, we assume reduced bus mass by 30%

- Determine the initial number of satellites required in orbit

  – Based on the coverage requirement

  – Assuming circular orbits (future models will study elliptical orbits)

  – Coverage is a function of orbit altitude and minimum working elevation angle

  – At lower altitudes the coverage rate decreases, thus increasing the number of satellites required at lower altitudes

- Determine how many more satellites are required for the mission life

  – Based on the lifetime requirement

  – Assume satellite design life is proportional to the orbit altitude

    - e.g., 8 years at 800 km, 4 years at 400 km, 2 years at 200 km

    - Sizing the wet mass of the spacecraft takes this assumption into account

  – We can simply estimate number of replacement satellites needed

- Assume 10% launch failure

  – Increases the number of spacecraft needed to account for launch failures

- Traditional space system cost models can effectively predict space system cost trends

  - Empirically weight-based (adjustments for power/data rate)

  - Mass budgets available early in mission design

  - Mass historically correlates well with actual hardware costs

  - Although not a substitute for detailed engineering design

- Cost models leveraged in this PBCM analysis:

  - **Unmanned Space Vehicle Cost Model (USCM),** Version 8 – Tecolote Research/USAF SMC

  - **NASA Instrument Cost Model (NICM),** Version IIIC – NASA Jet Propulsion Laboratory

  - **Small Satellite Cost Model (SSCM),** 1996 – The Aerospace Corporation

- **This ensures that the results will be consistent with widely accepted cost models**

> **Are USCM, NICM, and SSCM valid and sufficient? Should we use more/different models?**

5. Estimating Costs using Cost Estimating Relationships (CERs)

Table 11-11. SSCM Earth Orbiting Total Non-recurring Cost (development plus one protoflight unit) CERs in FY2010 Thousands of Dollars. Useful for spacecraft weighing less than 500 kg. It is presumed that these CERs include the cost of contractor program management, systems engineering, product assurance, and I&T. See Tables 11-35 and 11-38 for application of these CERs.

SME-SMAD WBS Element	CER Y = total non-recurring cost of development plus one protoflight flight unit in FY10 \$K	Cost Driver(s)	Cost Driver Input Range	Standard Error of Estimate (absolute) FY10 \$
1.1 Spacecraft				
1.1 Spacecraft Bus (alternate CER when no component information is available)	$Y = 1,064 + 35.5\ X^{1.261}$	X = Spacecraft Bus Dry Weight (kg)	20–400 kg	3,696
1.1.1 Structure	$Y = 407 + 19.3\ X \times \ln(X)$	X = Structure Weight (kg)	5–100 kg	1,097
1.1.2 Thermal Control	$Y = 335 + 5.7\ X^2$	X = Thermal Control Weight (kg)	5–12 kg	119
1.1.3 Attitude Determination & Control System (ADCS)	$Y = 1,850 + 11.7\ X^2$	X = ADCS Dry Weight (kg)	1–25 kg	1,113
1.1.4 Electrical Power Supply (EPS)	$Y = 1,261 + 539\ X^{0.72}$	X = EPS Weight (kg)	7–70 kg	910
1.1.5 Propulsion (Reaction Control)	$Y = 89 + 3.0\ X^{1.261}$	X = Spacecraft Bus Dry Weight (kg)	20–400 kg	310
1.1.6a Telemetry, Tracking, & Command (TT&C)	$Y = 486 + 55.5\ X^{1.35}$	X = TT&C Weight (kg)	3–30 kg	629
1.1.6b Command & Data Handling (CD&H)	$Y = 658 + 75\ X^{1.35}$	X = Command & Data Handling Weight (kg)	3–30 kg	854
1.2 Payload				
1.2 Payload	$Y = 0.4\ X$	X = Spacecraft Bus Total Cost \$K	2,600–69,000 (\$K)	
1.3 Spacecraft Integration, Assembly, and Test				
1.3 Integration, Assembly, & Test (IA&T)	$Y = 0.139\ X$	X = Spacecraft Bus Total Cost (\$K)	2,600–69,000 (\$K)	
4.0 Program Level				
4.0 Program Level	$Y = 0.229\ X$	X = Spacecraft Bus Total Cost (\$K)	2,600–69,000 (\$K)	
5.0 Flight Support				
5.0 Launch & Orbital Operations Support (LOOS)	$Y = 0.061\ X$	X = Spacecraft Bus Total Cost (\$K)	2,600–69,000 (\$K)	
6.0 Aerospace Ground Equipment				
6.0 Ground Support Equipment (GSE)	$Y = 0.066\ X$	X = Spacecraft Bus Total Cost (\$K)	2,600–69,000 (\$K)	

[Wertz, Everett, and Puschell, 2011]

- Upfront cost for Theoretical First Unit (TFU) is the sum of:

  - Non-recurring engineering cost

  - Recurring engineering cost

- Standard Wright learning curve applied to multiple units after the TFU

  - Conservative 90% learning curve assumed

  - NASA Cost Estimating Handbook recommends 85% learning curve for aerospace industry

- Production of multiple units has the advantage of postponing costs

  - It is more expensive to spend money now than it is to spend money down the road when you account for the Time Value of Money

  - Amortize cost over the mission lifetime (spread payments out over time)

  - Higher altitude missions with less satellites have to be paid for up front

  - Lower altitude missions with shorter design-life and more satellites to build have more opportunities to postpone payments

- The total mission cost takes all the factors above into account and generates a final estimate of the total mission cost

Baseline Requirements and Input Assumptions for Earth Observing Systems

Assumptions	Value
Resolution (m)	0.5
Area Access Rate (AAR) at 800 km Altitude (km^2/s)	14,217
Mission Life Requirement (yrs)	8
Wavelength to Observe (nm)	550
Spacecraft/Payload Average Density (kg/m^3)	79
Propellant Density (kg/m^3)	1000
Dry Mass/ Aperture^3	2287
Payload % of Total S/C Dry Mass	31%
Spacecraft Power/Spacecraft Dry Mass (W/kg)	1.3
Payload Power Percentage of Spacecraft Power (W)	46%
Spacecraft Datarate at 800 km Altitude (kbps)	800,000
Drag Coefficient	2
Solar State (Min, Mean, Max)	Mean
Minimum Working Elevation Angle (deg)	30
Percentage of Launches that Fail	10%
Min. No. Sats for No System Redundancy	2
Spacecraft Propellant Isp	235
Learning Curve	90%
Amortization Rate	8%
Cumulative Savings Effect of Amortization	19%

Input Assumptions intended to represent a realistic mission.

	Physical Parameters	Model Predictions			Examples		
					NanoEye	Quickbird	GeoEye-2
1	Orbital Altitude (km)	200	400	800	215	482	681
2	Resolution (m)	0.5	0.5	0.5		0.65	0.32
3	Payload Aperture Diameter (m)	0.22	0.44	0.88	0.23	0.60	1.10
4	Spacecraft Dry Mass (kg)	24.4	194.8	1,558.6	23.0	995.0	2,086.0
5	Non-Redundancy Mass Reduction	30.0%	20.0%	0.0%			
6	Corrected Spacecraft Dry Mass (kg)	17.0	155.9	1,558.6			
7	Spacecraft Wet Mass (kg)	292.5	181.1	1,559.4	76.4	1,028	2,540
8	Payload Power (W)	10.2	93.5	935.2			
9	Payload Datarate (kbps)	273,345	489,309	800,000			
10	Spacecraft Area Access Rate (km²/sec)	4,858	8,696	14,217	5,177	10,034	12,819
11	Satellite Orbital Period (min)	88.5	92.6	100.9	88.8	94.2	98.4
12	Spacecraft Design Lifetime (yrs)	2	4	8	2.15	4.82	6.81
13	No. of Sats Needed for Same Coverage at Any Given Time	2.9	1.6	1.0	2.7	1.4	1.1
14	Number of Satellites Required for Entire Mission	11.7	3.3	1.0	10.2	2.4	1.3
15	Number of Redundant Satellites	1.2	0.3	0.0	1.0	0.2	0.0
16	No. of Satellites to Build w/ System Redundancy*	12.9	3.6	1.0	11.2	2.6	1.3
17	Total Launch Mass (kg)	3,767	651	1,559	859	2,659	3,309

* Note that fractions of satellites have been allowed in this model for purposes of comparison simplicity and a smoother display of results

To satisfy the baseline mission, we compare three options:

A. 1.0 (1,559-kg) traditional large satellite flown at 800 km

B. 3.6 (156-kg) satellites flown at 400 km

C. 12.9 (17-kg) SmallSats flown at 200 km

For a fixed resolution, reducing the altitude by a factor of 4 reduces the individual spacecraft bus mass by almost 2 orders of magnitude.

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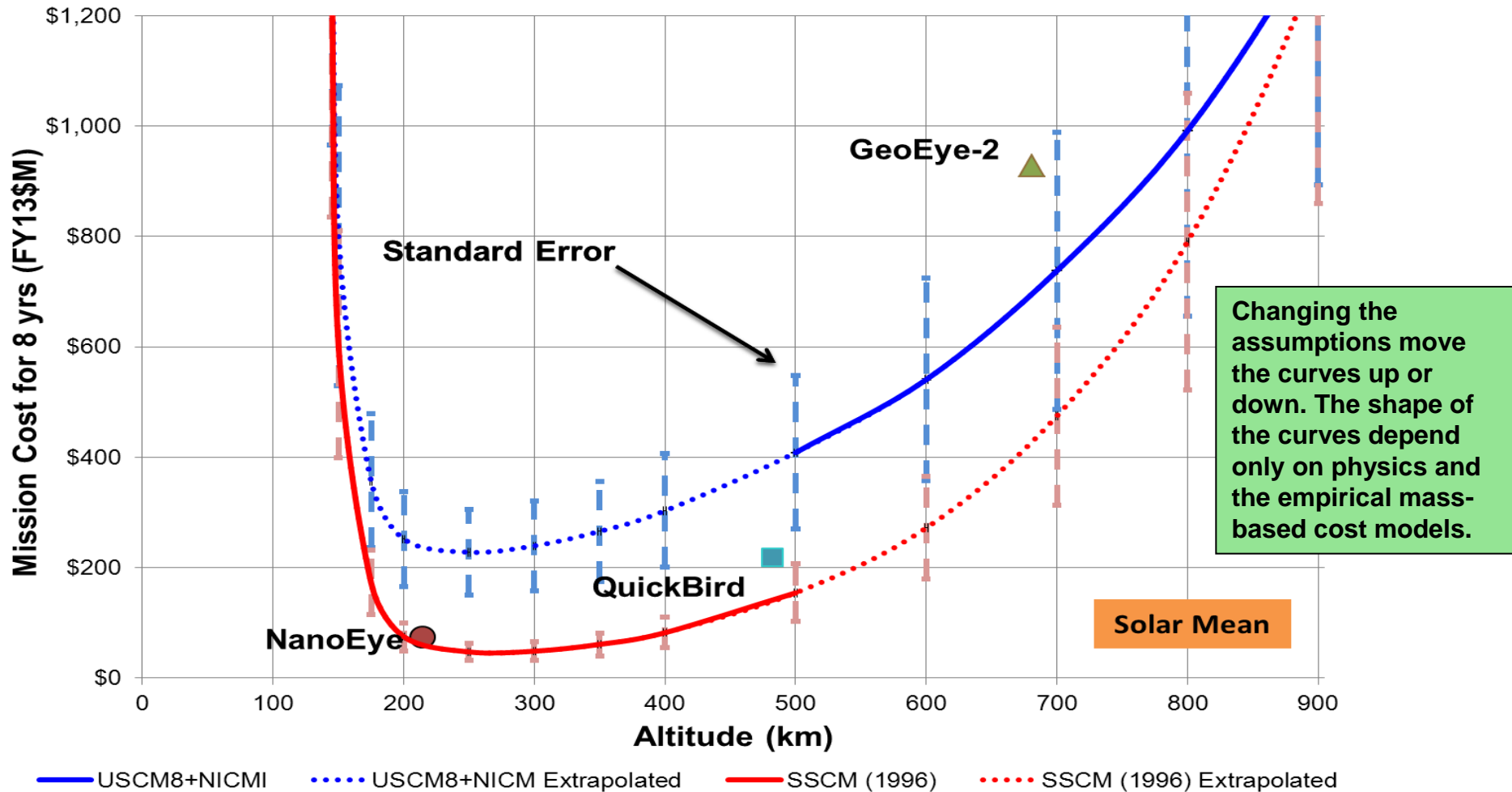| Cost Estimates - USCM8 and NICM (from SME)	Model Predictions			Examples		
				NanoEye	Quickbird	GeoEye-2
1 Orbital Altitude (km)	200	400	800	215	482	681
2 Total Upfront Cost (FY13$M)	$55.16	$220.14	$1,225.64	$15.5	$87.5	$835.0
3 Total NRE Cost (FY13$M)	$19.60	$131.93	$909.61	$10.0		
4 TFU or T1 Cost (FY13$M)	$27.94	$83.46	$278.37	$2.0	$60.0	$784.4
5 Total RE Production Cost w/ Learning Curve (FY13$M)	$243.95	$247.12	$278.37	$22.5	$134.3	$981.7
6 Remaining RE Production Cost w/ Learning Curve (FY13$M)	$216.02	$163.66	$0.00	$20.5	$74.3	$197.3
7 Average RE Unit Cost per Spacecraft (FY13$M)	$18.94	$68.70	$278.37	$2.0	$51.9	$784.4
8 Nth (Last) Unit Cost (FY13$M)	$16.37	$63.35	N/A	$2.0	$50.6	N/A
9 Equivalent Present Value of Amortized Cost (FY13$M)	$222.66	$140.08	$0.00	$36.0	$87.8	$170.1
10 Total System Cost Before Amortizing (FY13$M)	$330.10	$393.11	$1,225.64	$36.0	$161.8	$1,032.3
11 Total System Cost to be Amortized (FY13$M)	$274.94	$172.97	$0.00	$20.5	$74.3	$197.3
12 Total Adjusted System Cost After Amorizing (FY13$M)	$277.82	$360.22	$1,225.64	$51.6	$175.3	$1,005.1

Cost Estimates - SSCM (1996) (from SME)	Model Predictions			Examples		
				NanoEye	Quickbird	GeoEye-2
1 Orbital Altitude (km)	200	400	800	215	482	681
2 Total Upfront Cost (FY13$M)	$12.27	$48.05	$790.88	$15.5	$87.5	$835.0
3 NRE Cost (FY13$M)	$2.30	$26.59	$569.36	$10.0		
4 TFU or T1 (FY13$M)	$2.35	$16.71	$183.86	$2.0	$60.0	$784.4
5 Total RE Production Cost w/ Learning Curve (FY13$M)	$20.49	$49.48	$183.86	$22.5	$134.3	$981.7
6 Remaining RE Production Cost w/ Learning Curve (FY13$M)	$18.14	$32.77	$0.00	$20.5	$74.3	$197.3
7 Average RE Unit Cost per Spacecraft (FY13$M)	$1.59	$13.76	$183.86	$2.0	$51.9	$784.4
8 Nth (Last) Unit Cost (FY13$M)	$1.37	$12.68	N/A	$2.0	$50.6	N/A
9 Equivalent Present Value of Amortized Cost (FY13$M)	$62.41	$34.08	$0.00	$36.0	$87.8	$170.1
10 Total System Cost Before Amortizing (FY13$M)	$89.33	$90.13	$790.88	$36.0	$161.8	$1,032.3
11 Total System Cost to be Amortized (FY13$M)	$77.06	$42.08	$0.00	$20.5	$74.3	$197.3
12 Total Adjusted System Cost After Amorizing (FY13$M)	$74.68	$82.13	$790.88	$51.6	$175.3	$1,005.1

The tables have different results because USCM8 is developed by parametric cost modeling of traditional large satellites, and similarly, parametric cost modeling of small satellites for SSCM.

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Space
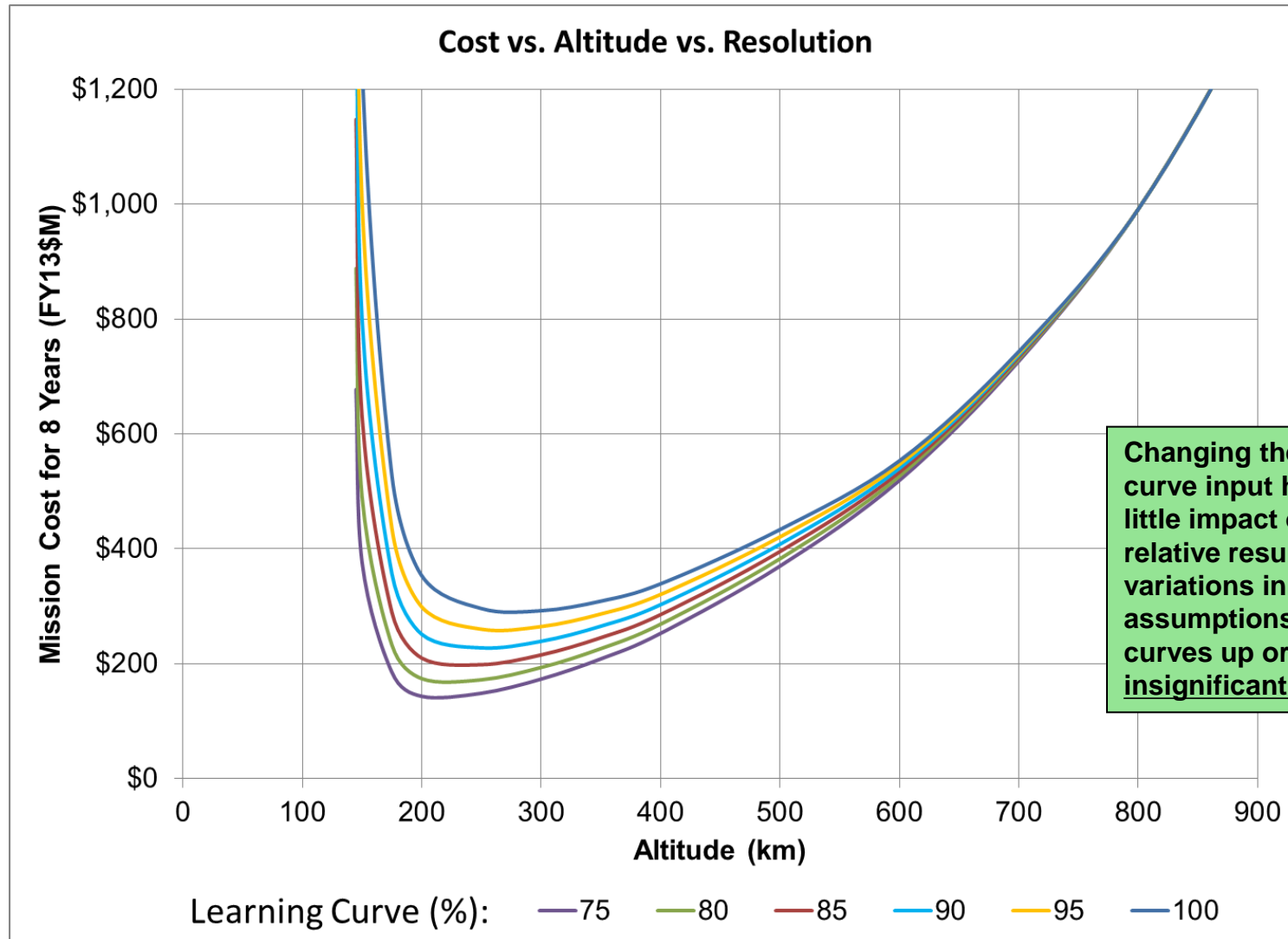Project

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Cost vs. Altitude for Fixed Resolution and Coverage

Changing the assumptions move the curves up or down. The shape of the curves depend only on physics and the empirical mass-based cost models.

For the same resolution and coverage, we can potentially dramatically reduce mission cost by using multiple smaller satellites at a lower altitude.

16

Cost vs. Altitude vs. Resolution

Changing the learning curve input has very little impact on the relative results. Other variations in inputs assumptions shift the curves up or down **insignificantly** as well.

Varying the input assumptions does not change the relative results of the study.

- Past Earth observation systems have used traditional space technology to achieve the best possible performance, but have been very expensive
  - In addition, low-cost, responsive dedicated launch has not been available for SmallSats
- Using modern microelectronics, future SmallSat observation systems at a lower altitude than traditional systems have the potential for:
  - **Much Lower Overall Mission Cost**
  - **Comparable or Better Performance (Resolution and Coverage)**
  - **Lower Risk (both Implementation and Operations)**
  - **Shorter Schedule**
- Relevant secondary advantages for the low-altitude SmallSats include:
  - Lower up-front development cost
  - More sustainable business model
  - More flexible and resilient
  - More responsive to both new technology and changing needs
  - Mitigates the problem of orbital debris
- The principal disadvantages of the SmallSat observation system are:
  - Needs greater FoV agility than larger, higher altitude systems
    - Needed agility is inversely proportional to altitude, but moments of inertia are also much less
  - **Needs responsive, low-cost, small launch system for operational missions**
  - **Requires changing the way we do business in space and how we think about using space systems (the biggest challenge)**

For Earth observing, a major increase in performance, reduction in cost, or both is possible by using multiple SmallSats at significantly lower altitudes for future missions.

- Is this technique valid from a cost modeling perspective? Are our assumptions valid? Is there anything wrong with this method?

- Are USCM, NICM, and SSCM valid? Should we use more/different models?

- Would this technique provide adequate justification to influence design decisions?

- Are there similar techniques being used? What have their conclusions been?

- What can we do better?

What must be done to convince the elephants?

APPENDIX

- The wet mass, $M_{wet} = M_{prop} + M_{dry}$ is calculated iteratively using the following formulas:

$$M_{launch} = M_{dry} + M_{prop}$$

$$\beta = \frac{C_D A}{M}$$

$$M_{prop} = M_{dry} \left[1 - \exp\left(\frac{-\Delta V}{I_{sp} g_o}\right) \right]$$

$$\Delta V = \frac{\pi \rho r v}{\beta T}$$

I_{sp} : specific impulse of the propellant (A liquid monopropellant)

g_o : gravitational acceleration at the Earth's surface

β : ballistic coefficient

C_D : satellite drag coefficient, assumed to be the same for every spacecraft in this model

A : satellite cross-sectional area along the velocity vector, assuming a spherical spacecraft

M : mass of the satellite (average of the satellite launch and dry masses)

ΔV : total delta V required to maintain the mission altitude for the design life of the satellite

ρ : local atmospheric density

r : distance of the satellite from the central body (Earth)

v : orbital velocity of the satellite

T : orbital period of the satellite

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Table 11-8. USCM8 Non-recurring Subsystem CERs in FY2010 Thousand s of Dollars. These CERs predict the cost of development plus one qualification unit. See Tables 11-34 and 11-37 for application of these CERs.

Live Calc

SME-SMAD WBS Element (Non-recurring subsystem)	CER Y = non-recurring cost in FY2010 thousands of dollars for development plus one qualification unit.	Cost Driver(s)	Cost Driver Input Range	SEE
1.1 Spacecraft				
1.1 Spacecraft Bus (alternate CER when no component information is available)	$Y = 110.2 X1$	X1 = Spacecraft Weight (kg)	114–5,127 kg	47%
1.1.1/1.1.2 Structure and Thermal Control	$Y = 646 X1^{0.684}$	X1 = Structure + Thermal Weight (kg)	59–501 kg	22%
1.1.3 Attitude Determination & Control System (ADCS)	$Y = 324 X1$	X1 = ADCS Weight (kg)	35–524 kg	44%
1.1.4 Electrical Power System (EPS)	$Y = 64.3 X1$	X1 = EPS Weight (kg)	47–1,065 kg	41%
1.1.5 Propulsion (Reaction Control)	$Y = 20.0 X1^{0.485}$	X1 = Total RCS tank volume (cubic centimeters)	Not given	35%
1.1.6 Telemetry, Tracking, & Command (TT&C)	$Y = 26,916$	Y = Average TT&C Cost (since there is no statistical CER for this element)	CER based on S-Band telemetry	Not given
1.2 Payload				
1.2 Communications Payload (based on weight and number of channels)	$Y = 339 X1 + 5,127 X2$	X1 = Communications Subsystem Weight (kg) X2 = Number of Communication Channels	160–395 kg 2–32 channels	40%
1.2 Communications Payload (alternate CER based on weight alone)	$Y = 618 X1$	X1 = Communications Subsystem Weight (kg)	160-395 kg	38%
1.3 Spacecraft Integration, Assembly, and Test				
1.3 Integration, Assembly, & Test (of bus and payload into spacecraft)	$Y = 0.195 X1$	X1 = Spacecraft Bus + Payload Non-recurring Cost ($K)	3,600–545,000 $K	42%
4.0 Program Level				
4.0 Program Level (for a Communications Satellite)	$Y = 0.236 X1$	X1 = Space Vehicle and IA&T Non-recurring Cost ($K)	7,850–353,804 $K	23%
4.0 Program Level (for an other than Communications Satellite)	$Y = 0.414 X1$	X1 = Space Vehicle and IA&T Non-recurring Cost ($K)	7,850–353,804 $K	40%
6.0 Aerospace Ground Equipment (AGE)				
6.0 Aerospace Ground Equipment (AGE)	$Y = 0.421 X1^{0.907} \times 2.244^{X2}$	X1 = Spacecraft Bus Non-recurring Cost ($K); X2 = 0 for comm sats and X2 = 1 for non-comm sats	7,850–353,804 $K	37%

The Payload CER is omitted for Earth Observation System and replaced with CERs found in NICM

[Wertz, Everett, and Puschell, 2011]

Table 11-9. USCM8 Spacecraft Bus Recurring T1 CERs in FY2010 Thousands of Dollars. These CERs predict the manufacturing cost of the first flight unit. See Tables 11-34 and 11-37 for application of these CERs.

SME-SMAD WBS Element (Recurring subsystem T1)	CER Y = Recurring T1 cost in FY2010 thousands of dollars	Cost Drivers	Cost Driver Input Range	SEE
1.1 Spacecraft				
1.1 Spacecraft Bus (alternate CER when no component information is available)	$Y = 289.5\,X1^{0.716}$	X1 = Spacecraft Weight (kg)	288–7,398 kg	21%
1.1.1/1.1.2 Structure and Thermal Control (a)	$Y = 22.6\,X1$	X1 = Structure + Thermal Weight (kg)	59–501 kg	21%
1.1.3 Attitude Determination & Control System (ADCS)	$Y = 795\,X1^{0.593}$	X1 = ADCS Weight (kg)	27–524 kg	36%
1.1.4 Electrical Power Supply (EPS)	$Y = 32.4\,X1$	X1 = EPS Weight (kg)	111–1,479 kg	31%
1.1.5 Propulsion Apogee Kick Motor (AKM)	$Y = 29\,X1 + 0.024\,X2$	X1 = AKM Weight (kg) X2 = Burn-time (seconds)	81–966 kg	22%
1.1.6 Telemetry, Tracking, & Command (TT&C)	$Y = 883.7\,X1^{0.491} \times 1.13^{X2}$	X1 = TT&C weight (kg) X2 = Geosynchronous Transfer Orbit (1 = yes; 0 = no)	12–76 kg for S-band	18%
1.2 Payload				
1.2 Communications Payload	$Y = 189\,X1$	X1 = Communications Payload Weight (kg)	38–928 kg	39%
1.3 Spacecraft Integration, Assembly, and Test				
1.3 Integration, Assembly, & Test (IA&T) of bus and payload into space vehicle	$Y = 0.124\,X1$	X1 = Spacecraft Bus + Payload Recurring Cost ($K)	35,367–142,044 $K	34%
4.0 Program Level				
4.0 Program Level (for a Communication Satellite)	$Y = 0.234\,X1$	X1 = Space Vehicle (Spacecraft Bus + Payload + IA&T) Recurring Cost ($K)	13,287–268,225 $K	13%
4. Program Level (for an other than communication satellite)	$Y = 0.320\,X1$	X1 = Spacecraft (Spacecraft Bus + Payload + IA&T) Recurring Cost ($K)	13,287–268,225 $K	28%
5.0 Flight Support				
5.0 Launch Operations & Orbital Support (LOOS)	$Y = 5,850$	Y= Average LOOS cost in $K	Not given	Not given
(a) Current version of USCM8 provides a combined structure/thermal CER.				

The Payload CER is omitted for Earth Observation System and replaced with CERs found in NICM

[Wertz, Everett, and Puschell, 2011]

Table 11-14. NICM Non-recurring Hardware Development Plus One Protoflight Unit Cost for Remote Sensing Instrument Payload in FY2010 Thousands of Dollars. These are alternative instrument (non-communications) payloads; select one CER from the table. See Table 11-34 (item 1.2) for application of CER 1.2.2.

SMAD WBS Element	CER Y in FY2010 thousands of dollars for development plus production of one protoflight unit	Cost Drivers [plus Data Range]
1.2.2 Optical Planetary (for instruments visiting planets other than Earth) Payload (e.g. cameras, spectrometers, interferometers)	$Y = 328 \times M^{0.426} \times P^{0.414} \times DL^{0.375}$ $R^2 = 0.76$ SEE = 39%	M = Instrument Total Mass in kilograms (kg). [1–75 kg] P = Maximum Instrument Power in watts (W). [1–75 W] DL = Design Life in months [10–150 months]
1.2.2 Optical Earth-Orbiting (instruments on spacecraft in geocentric orbits) Payload (e.g., cameras, spectrometers, interferometers)	$Y = 1{,}163 \times M^{0.328} \times P^{0.357} \times DR^{0.092}$ $R^2 = 0.89$ SEE = 35%	M = Instrument Total Mass in kilograms (kg). [10–350 kg] P = Maximum Instrument Power in watts (W) [0. 5–400 W] DR = Total Data Rate in kilo bits per second (kbps). [0.1–30,000 kpbs]
1.2.2 Active and Passive Microwave Payload (e.g., radars, altimeters, scatter meters, sounders, GPS receivers)	$Y = 23{,}620 \times M^{0.284} \times P^{0.325} \times DR^{0.090} \times T^{-1.296}$ $R^2 = 0.88$ SEE = 37%	M = Instrument Total Mass in kilograms (kg). [10–50 kg] P = Maximum Instrument Power in watts (W). [10–600 W] DR = Total Data Rate in kilo bits per second (kbps). [0.1–1,000 kbps] T = Instrument Technology Readiness Level (TRL) [4–9]
1.2.2 Particles Payload (e.g., plasma detectors, plasma wave detectors)	$Y = 980 \times M^{0.327} \times P^{0.525} \times DL^{0.171}$ $R^2 = 0.65$ SEE = 29%	M = Instrument Total Mass in kilograms (kg). [1–40 kg] P = Maximum Instrument Power in watts (W). [1–40 W] DL = Design Life in months. [10–150 months]
1.2.2 Fields Payload (e.g., electric field detectors, magnetic field detectors)	$Y = 1{,}130 \times M^{0.184} \times P^{0.238} \times DL^{0.274}$ $R^2 = 0.87$ SEE = 28%	M = Instrument Total Mass in kilograms (kg). [0.1–35 kg] P = Maximum Instrument Power in watts (W). [0.1–25 W] DL = Design Life in months. [1–100 months]

[Wertz, Everett, and Puschell, 2011]

The Optical Earth-Orbiting Payload Element was used for this study, and replaces the payload CERs found in USCM8.

- Assumes single satellite launches

- Assumes 10% learning curve and amortizing cost

- Derived empirically using cost data from existing launch vehicles

$$Cost_{launch} = 26.489 - 0.0015 M_{launch}$$

Vehicle	Capacity to LEO (kg)	Launch to LEO Cost/kg (FY13$K)
Pegasus XL	443	$43.64
Taurus	1,380	$19.77
Minotaur IV	1,650	$13.99
Athena	2,065	$16.61
Atlas 2AS	8,618	$16.19
Ariane 44L	10,200	$15.77
Falcon 9	10,450	$5.68

[Wertz, Everett, and Puschell, 2011]

Reinventing Space Project

USC University of Southern California

	Cost Estimates (FY$13M) - USCM8 (from Manual) and NICM (from SME)	Model Predictions		
1	**Orbital Altitude (km)**	200	400	800
2	**Spacecraft Bus (Fabrication) Cost**	$3.1	$20.7	$166.3
3	**Spacecraft Bus NRE Cost**	$1.34	$12.21	$122.11
4	**Spacecraft Bus RE Cost**	$1.7	$8.5	$44.2
5	**Fraction of Spacecraft Bus RE/(RE+NRE)**	57%	41%	27%
6	**Payload (Fabrication) Cost**	$15.3	$73.5	$372.4
7	**Payload NRE Cost**	$6.6	$43.4	$273.5
8	**Payload RE Cost**	$8.7	$30.2	$98.9
9	**Payload Wrap Factor Costs**	$11.1	$47.8	$219.4
10	**Management**	$1.2	$6.3	$33.7
11	**Systems Engineering**	$5.5	$21.3	$86.6
12	**Product Assurance**	$2.0	$8.6	$39.7
13	**Integration and Test**	$2.4	$11.6	$59.5
14	**Total Payload Cost**	$26.4	$121.3	$591.8
15	**Payload NRE Cost**	$11.5	$71.6	$434.6
16	**Payload RE Cost**	$14.9	$49.8	$157.2
17	**Other NRE**	$2.10	$17.02	$152.04
18	**Spacecraft Bus Integration, Assembly, and Test**	$0.26	$2.38	$23.81
19	**Program Level**	$0.57	$5.21	$52.10
20	**Aerospace Ground Equipment**	$1.27	$9.43	$76.14
21	**Other RE**	$8.27	$15.06	$43.56
22	**Spacecraft Bus Integration, Assembly, and Test**	$1.29	$4.79	$17.74
23	**Program Level**	$0.97	$4.25	$19.81
24	**Launch Operations & Orbital Support**	$6.01	$6.01	$6.01
25	**Fraction of Spacecraft Bus Cost RE/(RE+NRE)**	52.6%	41.0%	24.7%
26	**Total Upfront Cost**	$47.45	$178.85	$991.29
27	**Total NRE Cost**	$14.89	$100.79	$708.75
28	**TFU or T1 Cost**	$24.95	$73.31	$244.88
29	**Launch Cost**	$7.62	$4.75	$37.66

The model predictions are derived from the Performance Requirements and Cost Model CERs

- The optical payload assumes diffraction limited optics

- Space system mass is proportional to the cube of the linear dimensions

  – Equivalent to saying that most spacecraft have about the same density

- Non-redundancy mass reduction factor

  – 5% reduction in estimated mass for every year the design life is reduced starting at 8 years (e.g., 10% for 6 yrs, 20% for 4 yrs, 30% at 2 yrs)

- All systems are designed using liquid propellant

- All missions are flown in a circular orbit

- All missions work at the same minimum working elevation angle of 30 deg

- Design life is proportional to altitude (e.g., 8 yrs at 800 km, 2 yrs at 200 km)

- Wright learning curve for multiple units after the TFU

- Costs postponed due to spacecraft being built and launched later are reduced to Present Value to account for the value of delayed spending

- *SmallSat Schedules* are much shorter than for traditional large satellites

  - Traditional major defense programs take 8.8 years in development (Milestone B) and well over 10 years from Milestone A to implementation [DoD Procurement Study]

- *Reliability* **of SmallSats** (including single string SmallSats) is essentially similar to that of traditional large satellites according to a Goddard study of over 1,500 spacecraft launched from 1995 to 2007

- *Risk* = the probability of a negative event times the impact/consequences of that event

  - Non-recurring cost for SmallSats is 1-2 orders of magnitude less than for traditional satellites

  - *Implementation Risk* is low due to low non-recurring cost and short schedule, i.e., the consequences of failing to implement a SmallSat system will not endanger the larger, more traditional system

  - *Operational Risk* of SmallSats is also much lower than traditional systems due to shorter operational life and the availability of spares (on orbit or on the ground) or back-up

- SmallSats also support the DoD objective of disaggregation

SmallSat missions provide much shorter schedules, comparable reliability, and significantly less risk (both implementation and operational) than traditional large satellite missions.

- *Cost overruns* are typically the primary concern for government acquisition
  - Cost overruns are a management problem associated with cost performance relative to expectations
  - Most easily resolved by reducing expectations
  - Makes sense programmatically, but not from the perspective of the end user
- **From the perspective of the end user, it is really cost vs. performance that matters**
  - How much performance can I get for how much money?
  - Equivalently, given the constraint of a limited total budget, how much performance am I able to achieve?
  - From this perspective, cost overruns are only relevant to the extent that they impact the overall cost vs. performance of the system
- **For operational programs on a system that is well understood (such as GEO communications), cost overruns are both important and bad**
  - For these systems costs should be well understood and well controlled
- **For R&D programs, some amount of cost overrun should be acceptable and expected**
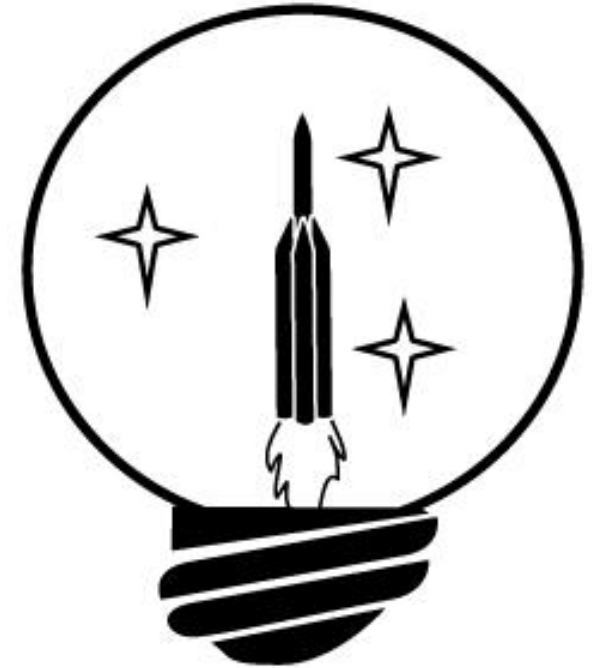 - If there are never any cost overruns, we're not pushing hard enough on cost reduction

For purpose of creating much lower cost, high utility missions, cost (and schedule) for a given level of performance should be our measure of success, NOT cost overruns. This is a major purpose of creating Performance-Based Cost Modeling.

- Near-term projects

  – Support 3 USC graduate students doing fundamental research

    - **We want to transform the current disaggregation/smallsat debate from a vague philosophical discussion to a quantitative discussion of costs and benefits**

      – Extend traditional weight-based cost models to have mission utility factors to quantify, for example, the impact of microelectronics or composite materials

  – Provide seminars on Reinventing Space to anyone willing to listen

- Longer-term projects

  – More extensive basic technical research in cost reduction

  – Expand considerably the data base of cost reduction alternatives, based so far as possible on real experience throughout the community

  – Work with other universities to contribute to the solution of this long-term problem

  – Restart the *Journal of Reducing Space Mission Cost* for peer-reviewed contributions

Our goal is to start a more informed discussion of an inherently complex issue, starting today!

- Currently teaching a USC graduate course, ASTE-523, in "Reinventing Space: the Design of Low-Cost Space Missions"

    – Have taught it every other year since 1998

- **Have developed approximately 100 specific recommendations on dramatically reducing cost and schedule and preventing cost and schedule overruns**

    – Process and programmatic

        - Attitude
        - Government/Customer
        - Personnel
        - Programmatic

    – Technology and Systems

        - Mission Design
        - Systems Engineering
        - Launch
        - Spacecraft Technology
        - Operations

- Are in the process of revising and expanding our database of approaches and methods and how they are presented

Dramatically reducing cost with high utility and robustness is not a simple process of discovering unobtainium. It is a complex mix of technology and processes tuned to the organization, the mission, and the needs of the end user – but history has shown that it can be done!

- **Significantly reducing overall mission cost and schedule typically requires using multiple techniques that complement each other**
  - Unless there is a single large cost or schedule driver, making a change in only one part of the system is unlikely to have a major impact on the system as a whole

- **Reducing cost and schedule is not just a matter of finding a low-cost spacecraft bus or payload**
  - It is a mission problem involving the full range of mission engineering issues in order to provide the end user the data they need, when they need it, at low cost and with high reliability

- **Truly reducing overall space mission cost significantly will require at least some investment in, and development of both low-cost small spacecraft and low-cost, small, responsive launch systems**

- **The greatest impact comes from mission diversity**
  - Small spacecraft used for some operational activities and as a test-bed to rapidly and economically develop low-cost processes and technology for larger missions

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1. **We want to reinvent space, but with the advantages of both modern technology and the experience base of 50 years of space exploration.**

2. **It takes real engineering to make it work, and that implies the need to start a proactive program that, in turn, needs to have support at the highest levels of management.**