Reinventing Space Conference
BIS-RS-2014-40

Quantifying the Cost Reduction Potential for Earth Observation Satellites

Anthony Shao
Microcosm/University of Southern California

Elizabeth A. Koltz
University of Southern California

James R. Wertz
Microcosm/University of Southern California

12th Reinventing Space Conference
18-20 November 2014
London, UK

BIS-RS-2014-40

Quantifying the Cost Reduction Potential for Earth Observation Satellites

Anthony Shao and James R. Wertz
Microcosm/USC, 4940 W. 147th Street, Hawthorne CA 90250; 1-310-219-2700
ashao@microcosminc.com; jwertz@microcosminc.com

Elizabeth A. Koltz
University of Southern California (USC), 854B Downey Way, Los Angeles, CA, 90089; 1-310-968-0452
chapman@usc.edu

ABSTRACT

In the present budget environment, there is a strong need to dramatically drive down the cost of space missions. There is the perception that SmallSats are inherently much lower cost than more traditional larger satellites and can play a central role in reducing overall space mission cost, but this effect has been difficult to quantify. Without quantifiable evidence of their value, SmallSats are under-utilized as a method for reducing space mission cost. The purpose of this study is to quantify the relationship between cost and performance for space systems, by creating a *Performance-Based Cost Model (PBCM)*. Today, most acquisition performance analyses focus on cost overruns, or how much the system costs relative to what it is expected to cost. Instead, PBCM allows us to focus on more important questions, such as, how much performance we can achieve for a given cost, or what the cost is for a given level of performance. In this paper, we present the relationship between cost vs. orbit altitude for a fixed resolution and coverage requirement, cost vs. resolution, and cost vs. coverage. Traditional cost models for space systems are typically weight-based, primarily because mass allocation is determined early in mission design and has historically correlated well with actual hardware cost. To provide the underlying cost data for this study, we apply 3 cost models widely used throughout the aerospace cost modeling community: the Unmanned Space Vehicle Cost Model (USCM), the Aerospace Corp. Small Satellite Cost Model (SSCM), and the NASA Instrument Cost Model (NICM).

Our first application of the PBCM is for Earth observation systems. 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. Space system mass is proportional to the cube of the linear dimensions—equivalent to saying that most spacecraft have about the same density. This means that by flying at lower altitudes, satellites can reduce their payload size and therefore the entire mass of the satellite, thus reducing the cost of the system dramatically. We conclude that for an Earth observation system, an increase in performance, reduction in cost, or both, is possible by using multiple SmallSats at lower altitudes when compared to traditional systems. Specifically,

- By using modern microelectronics and light-weight materials such as composite structures, future SmallSats observation systems, **operating at a lower altitude than traditional systems**, have the potential for:
  - Comparable or better performance (resolution and coverage)
  - Much lower overall mission cost (by a factor of 2 to 10)
  - Lower risk (both implementation and operations)
  - Shorter schedules
- 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 technologies and changing needs
  - Mitigates the problem of orbital debris

The principal demerits of the approach are the lack of low-cost launch vehicles, the need for a new way of doing business, and changing the way we think about the use of space assets. This paper provides the basis for this assessment, estimates for the level of cost reduction, and reports on additional results since the 2013 Reinventing Space Conference and AIAA Space 2014 Conference.

KEYWORDS: Reinventing Space, Cost Reduction, Observation Satellites, Low-altitude, SmallSats, Cost Estimation, Cost Modeling

I. Background

At the start of the space program in the 1960s, spacecraft were inevitably massive and large given the technology constraints at the time. As a result, spacecraft were very heavy and flew in a higher altitude regime due to the dense atmosphere at lower altitudes. Above approximately 500 km altitude, it is relatively easy for a satellite to stay in a circular orbit above Earth for many years to several hundred or even thousands of years [Wertz, Everett, Puschell, 2011]. This capability allowed engineers to design spacecraft for long on-orbit lifetimes, typically in the range of 5 – 15 years. Because spacecraft had to last this long, many processes and requirements were put in place to ensure that the spacecraft, its subsystems and parts were above certain reliabilities (i.e., > 99.99%). Parts redundancy and testing was a method utilized to increase reliability. However, this further increased the cost of the spacecraft, and thus the overall cost of the mission. In turn, schedules were elongated due to all the processes, testing, and design reviews. The ever-increasing cost of space missions leads to longer schedules and fewer missions. This leads to a demand for higher reliability, which, in turn, leads to higher cost, longer schedules, and fewer missions. This current mentality is represented by Fig. 1. We believe that space systems today have the following major problems: (1) they cost too much, (2) they take too long to build and launch, and (3) they are not as responsive or robust as they should be. It is often assumed that in order to reduce cost, you must chose to reduce performance or reliability, for example. This research on SmallSats will show how the claim "faster, better, cheaper—pick any two" is flawed.

Currently, there is a clear and present budget problem that must be addressed. Arati Prabhakar, DARPA's Director, was quoted in Space News [2014a] saying there is "something going on inside the national security community in space that's actually quite troubling, that has to do with how slow and costly it is for us today to do anything we need to do on orbit for national security purposes." The USAF has announced a series of studies to determine the future of its big satellite programs. General Shelton was quoted in Space News [2014b] stating, "Do we want to continue with the military dedicated constellation? Can we turn either a portion or all of this over to a commercial provider and contract for a service?" To add context to these remarks, the commercial providers Gen. Shelton refers to have offered the same technologies but at less cost. Mark Valerio, VP of Lockheed Martin's Military Space business, quoted in Space News [2014b] saying, "We're looking at innovative options for hosting payloads, and we are suggesting ways to reduce costs while maintaining our technology edge to address evolving threats." Google has also demonstrated that the demand for low cost satellite imagery is high by announcing plans to buy Skybox, a company that makes Earth imaging microsatellites [Space News, 2014c].

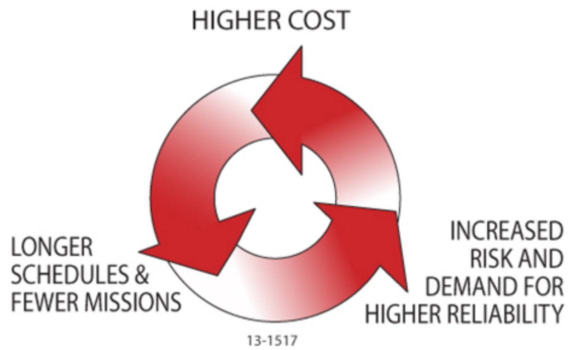

Figure 1. The Space Spiral [Wertz, Everett, Puschell, 2011].

In the present budget environment, likely extending into the future, there is a strong need to drive down the cost of space missions. The main goal of this paper is to quantify the relationship between cost and performance, or measures of effectiveness (MoEs) and determine ways to reduce space mission cost for Earth Observation systems. This cost and performance relationship can ultimately allow us to pursue potentially useful mission design alternatives, such as systems that are lower cost, have better performance, or both. Questions that would be useful to ask when designing a system are:

- What is the cost per level of performance (e.g., cost/resolution, cost/coverage rate, cost/photo)?
- What is the best performance that can be achieved for a fixed cost?
- What is the lowest cost option for a mission with fixed requirements?

Performance-Based Cost Modeling (PBCM) is a mission engineering approach to enable programs to be able to ask these questions early in the design phase in order to drive down cost from the outset. In this paper, we will explore how various factors such as satellite size and orbit altitude affect the cost of space mission. In Sec. II, we introduce the PBCM approach, discuss the technique used to perform the study, and show how we can quantify the relationship between cost and performance. The results are then presented in Sec. III.

II. Performance-Based Cost Modeling (PBCM)

Today, most acquisition performance analysis focuses on cost overruns, or how much the system cost relative to what it is expected to cost. PBCM allows us to instead 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. The goal of PBCM is not to create a new cost model, but to use existing and widely used cost models to find new ways to reduce space mission cost. Our first application of the PBCM is for Earth observation systems. In this paper, we present the relationship between cost vs. altitude (for a fixed resolution and coverage requirement), cost vs. resolution, and cost vs. coverage.

Traditional cost models for space systems are typically weight-based, primarily because mass is determined or assigned early in mission design and has historically correlated well with actual hardware cost. To provide the underlying cost data for this study, we use three cost models widely used throughout the aerospace cost modeling community [Apgar, 2011]:

- Unmanned Space Vehicle Cost Model (USCM8) [Tecolote Research, 2002]
- SmallSats Cost Model (SSCM) [Aerospace Corp., 1996]
- NASA Instrument Cost Model (NICM) [Habib-agahi, 2010]

Our goal is to determine cost as a function of performance for an Earth Observing (EO) system. To do this, we predict the life-cycle costs by using the models listed above (USCM8, SSCM, and NICM) and define the performance as measured by two parameters: (i) the resolution at nadir, and (ii) the area coverage rate. For a baseline mission, we will assume the following performance:

- Imaging in the visible
- Resolution = 0.5 meter (at nadir)
- Area Access Rate = 14,200 km^2/sec
- Mission Duration = 8 years

Cost can then be measured by the cost per year to achieve this level of performance.

The coverage rate of 14,200 km^2/sec corresponds to the area access rate (AAR) of a system in a circular orbit at 800 km with a minimum working elevation angle of 30 deg. In order for a satellite at this altitude to meet the 0.5 m resolution requirement, a system with diffraction-limited optics will have a 0.88 m aperture telescope. We will define this system with an 8-year design life as our baseline. If the satellite life at a particular altitude is, for example, 4 years, then we will need twice as many satellites to cover the full 8-year mission duration. Similarly, if the coverage at a given altitude is one third of the baseline value, then we will need triple the number of satellites to provide the baseline coverage.

In order to achieve the same resolution with diffraction-limited optics, we vary the aperture size in direct proportion to the altitude. Thus, at 400 km, we use an aperture of 0.44 m to achieve the same 0.5 m resolution. We assume that mass is proportional to the cube of the linear dimensions, which translates to assuming that the spacecraft dimensions scale linearly with the aperture and that the density of the various spacecraft are approximately the same (validated by Reeves [1999]). Our baseline spacecraft dry mass at 800 km is then estimated to be 1,559 kg, corresponding to a typical observing satellite at that altitude. (The actual value has very little effect on the results when comparing costs, since it is the ratio of the masses that matters.)

At lower altitudes, we assume a shorter satellite design life. To make the model simple, we assume a design life proportional to the altitude, such that the design life is 8 years at 800 km, 4 years at 400 km, and 2 years at 200 km. Therefore, we will need more satellites at lower altitudes due to the shorter design life and the reduced coverage. Because the design life is shorter, we can assume less redundancy, and therefore lower mass at lower altitudes. We essentially reduced the mass per satellite as a function of altitude and also required 10% more satellites to cover potential launch failures.

Finally, there are financial issues associated with the satellite lifetime and the number of satellites required for the mission. We have defined an upfront cost equal to the non-recurring development cost plus the first production unit, often called the *theoretical first unit* (*TFU*). The remainder of the spacecraft are built assuming a 90% learning curve, which is conservative for space systems [NASA, 2008a]. An advantage to building multiple satellites is that they don't all have to be built prior to the first launch. The production of the satellites can be spread out over time and, therefore, paid for over time. For this effect, we have initially used an 8% interest rate and an impact of amortization of a 19% reduction in cost for units built after the first one, based on the results of a 90% learning curve analysis over the 8 year mission duration [Shao and Koltz, 2013]. The list of numerical assumptions is shown in Table 1.

In summary, the steps for PBCM are as follows:

1. Identify the numerical performance requirements
2. Size the payload required to meet the desired resolution
3. Size the spacecraft bus to support the payload

4. Determine the spacecraft wet mass
5. Determine the number of satellites required for coverage and lifetime requirements
6. Input mass estimates into weight-based cost model Cost Estimating Relationships (CERs) to predict costs
7. Determine launch cost
8. Determine recurring and non-recurring engineering (NRE) costs
9. Estimate total mission cost

A more detailed description of each of these steps can be found in Shao et al. [2013] and Koltz et al. [2013].

We have not taken into account any variations in ground system performance on cost. To first order, we do not anticipate any major changes due to the ground system. Recall that the initial assumption was that the resolution and coverage rate were both held constant as the altitude changed. This implies that the data rate will also remain constant. Changing the altitude and the satellite lifetime will have three principal secondary effects:

- At lower altitudes the time in view of a single ground station will be less, but there will be more satellites viewing more ground stations
- At lower altitudes the same power-aperture on the spacecraft will result in higher data rates
- With shorter lifetimes and newer technology, the ability to store data on board the spacecraft becomes much higher (and will be effectively unlimited in the future)

The net effect is that we do not anticipate a substantive impact on the cost or performance results of the study due to the ground station, although it could result in a somewhat further reduction in cost for the lower altitude system.

III. Results for Earth Observing Systems

We selected three mission altitudes of 200 km, 400 km, and 800 km and applied the technique and assumptions described Sec. II. We also have provided three real observation system examples for reference, which include NanoEye [Wertz, Van Allen, and Barcley, 2010], Quickbird [Digital Globe, 2013; Spaceflight Now, 2000], and GeoEye-2 [GeoEye, 2013; Space News, 2012]. We start off by determining the payload aperture diameters using diffraction-limited optics and we see that the aperture is linearly proportional to the mission altitude (i.e., 0.22 m at 200 km, 0.44 m at 400 km, and 0.88 m at 800 km). As can be seen in Table 2, the payload power and datarate scale proportionally to the mission altitude as well. **For a fixed resolution, the spacecraft mass required at 200 km is 17 kg, but is almost 2 orders of magnitude larger (1,559 kg) at 800 km.** This is a very significant difference in mass and will generate a substantial difference in mission cost, as will be seen in Table 3a and 3b.

Table 1. List of numerical input assumptions.

Assumptions	Value
Resolution (m)	0.5
Area Access Rate (AAR) at 800 km Altitude (km^2/s)	14,217
Mission Duration (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 I_{sp}	235
Learning Curve	90%
Interest Rate	8%
Cumulative Savings Effect of Amortization	19%

The area access rate (AAR) is less at lower altitudes, and therefore will require additional satellites to satisfy the coverage rate requirement of 14,200 km^2/sec. To support the same coverage rate a single satellite at 800 km, requires 2.9 satellites at 200 km and 1.6 satellites at 400 km. Then, based on the design life of each spacecraft and accounting for launch failures, we determine the number of satellites required for the entire 8-year mission. For the baseline mission providing 0.5 m resolution in the visible at 14,200 km^2/sec, for 8 years, our 3 options are:

1. 1 traditional large satellite (1,559 kg) flown at 800 km
2. 3.6 moderate-size satellites (156 kg each) flown at 400 km
3. 12.9 SmallSats (17 kg each) flown at 200 km

The projected cost values, in constant year dollars, for several cost items using USCM8 and NICM are displayed in Table 3a, and for comparison using SSCM in Table 3b. The key cost values here are:

- The total upfront cost (line 2)
- The remaining recurring cost with learning curve (line 6)
- The total adjusted system cost after amortization (line 12)

Table 2. Physical Parameters of 3 Select Mission Altitudes and 3 Example Observation Systems.

	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	181.2	1,559.4	76.4	1,028	2,540
8	Payload Power (W)	10.2	93.2	932.0			
9	Payload Datarate (kbps)	273,345	489,309	800,000			
10	Spacecraft Area Access Rate (km^2/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	652	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

Table 3a. Cost Predictions for the 3 Selected Altitudes using USCM8 [Tecolote Research, 2002] and NICM [Apgar, 2011], and 3 Example Observation Systems.

	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)	$47.45	$178.85	$991.29	$15.5	$87.5	$835.0
3	Total NRE Cost (FY13$M)	$14.89	$100.79	$708.75	$10.0		
4	TFU or T1 Cost (FY13$M)	$24.95	$73.31	$244.88	$2.0	$60.0	$784.4
5	Total RE Production Cost w/ Learning Curve (FY13$M)	$217.84	$217.07	$244.88	$22.5	$134.3	$981.7
6	Remaining RE Production Cost w/ Learning Curve (FY13$M)	$192.90	$143.76	$0.00	$20.5	$74.3	$197.3
7	Average RE Unit Cost per Spacecraft (FY13$M)	$16.92	$60.35	$244.88	$2.0	$51.9	$784.4
8	Nth (Last) Unit Cost (FY13$M)	$14.62	$55.65	N/A	$2.0	$50.6	N/A
9	Equivalent Present Value of Amortized Cost (FY13$M)	$203.94	$123.97	$0.00	$36.0	$87.8	$170.1
10	Total System Cost Before Amortizing (FY13$M)	$299.27	$331.93	$991.29	$36.0	$161.8	$1,032.3
11	Total System Cost to be Amortized (FY13$M)	$251.82	$153.07	$0.00	$20.5	$74.3	$197.3
12	Total Adjusted System Cost After Amorizing (FY13$M)	$251.39	$302.82	$991.29	$51.6	$175.3	$1,005.1

Table 3a. Cost Predictions for the 3 Selected Altitudes using SSCM [Aerospace Corporation, 1996], and 3 Example Observation Systems.

	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	$569.37	$10.0		
4	TFU or T1 (FY13$M)	$2.35	$16.71	$183.84	$2.0	$60.0	$784.4
5	Total RE Production Cost w/ Learning Curve (FY13$M)	$20.49	$49.48	$183.84	$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	$183.84	$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)	$77.07	$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 total upfront cost for both the 200 and 400 km mission are much less than the upfront cost for the 800 km mission. However, both missions at the lower altitude have additional costs associated with the mission (i.e. the remaining production cost). **Even without adjusting the cost due to advantages of amortization, the total system cost (Table 3, line 10) shows that at lower altitudes the life-cycle costs are much less, even with many more satellites to build.** (Again, the life-cycle cost does not include operations cost. Section V describes how adding operations cost will not impact the relative results of the study.) Results from Table 3b have notably different values because USCM8 is developed by parametric cost modeling of traditional large satellite systems, and the SSCM is derived from parametric cost modeling of SmallSats [Apgar, 2011].

Our model estimates the required mass to operate at each altitude for a given resolution and coverage rate, and then inserts them into separate costs models (USCM8 & NICM, and SSCM). We run the model twice over a range of altitudes: first with projections from USCM and NICM, and again with projections from SSCM, and then plot them on the same graph for comparison. This means the missions are compared within the same class each time. In a sense, what we are doing is comparing apple to apples and oranges to oranges at the same time.

Performance vs. Cost

A. Cost vs. Coverage

Figure 2 shows the relationship between cost and coverage for two mission altitudes at a fixed resolution of 0.5 m. In order to have twice the coverage at a given altitude, it takes twice as many satellites, which increases the cost by approximately 1.8 times. (Recall that we introduced a 90% learning curve in this model to account for the production of multiple units.) **Flying high increases cost because it is more expensive to achieve a given resolution**.

B. Cost vs. Resolution

Figure 3 shows a sample relationship between cost and resolution for two mission altitudes. For a given mission altitude, if a higher resolution is desired, you must build a larger satellite and, therefore, spend more money. **At any altitude, twice the resolution increases the spacecraft mass by 8 times and increases the cost by up to 4.5 times.**

C. Cost vs. Altitude for Fixed Resolution and Coverage

The relationship between total mission life-cycle cost and altitude for a fixed resolution and fixed coverage requirement is shown in Fig. 4 over a range of altitudes in LEO. In the figure, the blue lines represent predictions using USCM8 and NICM, and the red lines represent predictions using SSCM. The solid lines represent the cost predictions using spacecraft bus mass values that fall within the range specified by the cost models. Extrapolated predictions based on values that are outside these specified mass ranges are indicated by the dotted lines in Fig. 4, which according to Aerospace Corporation [Mahr and Richardson, 2002] is less certain but not an unreasonable estimate. Beardon [1996] gives an in-depth analysis of this using the planetary spacecraft NEAR (Near Earth Asteroid Rendezvous), which went beyond the SSCM database range in several cases, and provided decent correlation between the model results and the actual spacecraft costs.

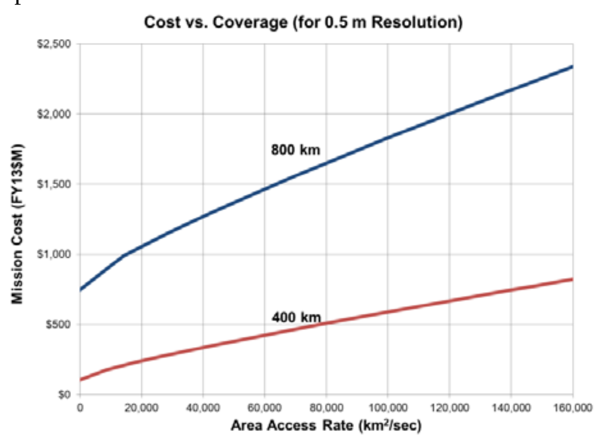

Figure 2. Cost vs. Coverage for a 0.5 m Resolution Requirement at 400 km and 800 km.

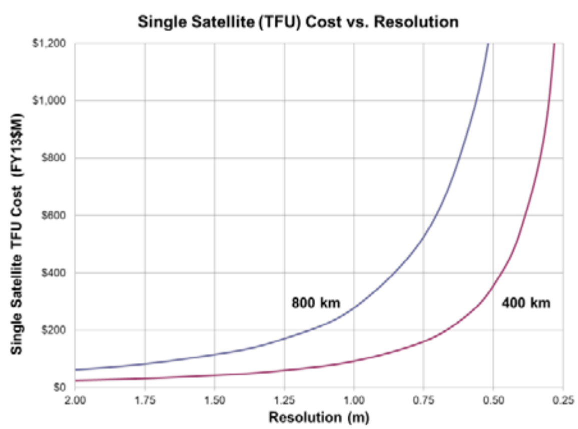

Figure 3. Single Satellite Theoretical First Unit Cost vs. Resolution at 400 km and 800 km.

As can be seen, the results from the two sets of models correlate very well with each other. (Note that the shapes of the two curves are essentially the same, suggesting that the extrapolation is reasonable.) The

Standard Error of the Estimate (SEE) of 34% has been added to the plot as vertical dashed bars.

IV. Impact of Altitude and Size on Cost and Performance

By reducing the altitude, you can reduce the size of the spacecraft, and this has a significant impact on cost. This can be seen in Fig. 4. The results clearly show that using smaller satellites at lower altitudes can provide much lower cost missions for an observation system while achieving the same performance requirements in terms of both resolution and coverage. We have also included three real observation systems as examples for comparison against this model. There have been many assumptions made to produce the results of this PBCM. However, changing the values of these assumptions, does not change the shape of the curves in Fig. 4. That is, **the relationship between mission cost and altitude remained the same over a very wide range of assumed inputs** because the shape of these curves depends only on physics and the empirical mass-based cost models.

Our most substantive conclusion is that **by significantly reducing the altitude of an Earth observation system, we can achieve the same performance in terms of resolution and coverage, but at dramatically lower cost**. Why is that the case? Basically, if we reduce the altitude by a factor of 2, we will also reduce the sensor aperture and linear dimensions of the spacecraft by a factor of 2. This reduces the volume and mass of the spacecraft by a factor of 8, which, according to the traditional mass-based cost models, reduces the cost by a factor up to 4.5. There will likely be the need of more spacecraft at the lower altitude because of reduced coverage per satellite and possibly a shorter design life, or greater atmospheric drag, but even with more spacecraft, it will be a much lower cost and more robust system that is less sensitive to spacecraft or launch failures. In addition, schedules are shorter, spending is spread out over time, and the problem of orbital debris essentially goes away below roughly 500 km [Wertz, et al. 2012]. This path has the potential to be an important option for Earth observing systems, particularly in times of critical budget problems.

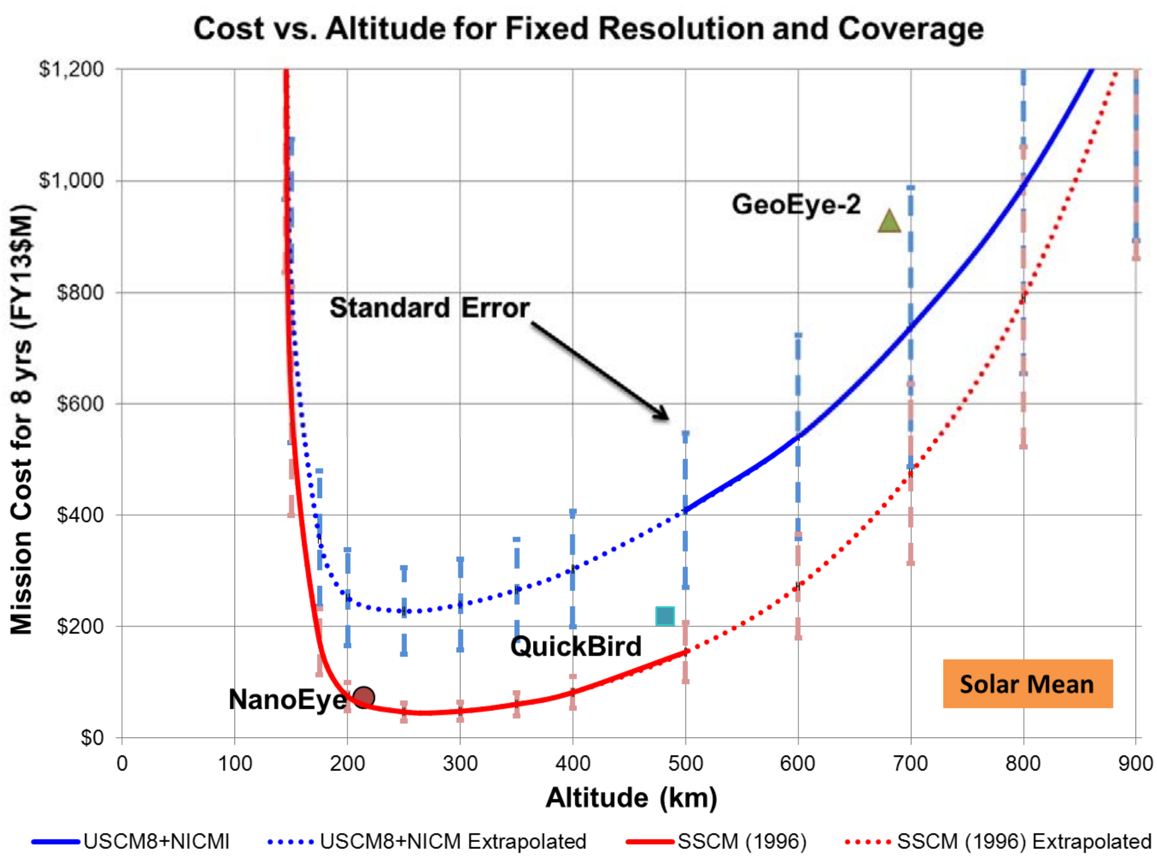

Figure 4. Cost vs. Altitude for a Fixed Resolution (0.5 m) and Coverage Rate (14,200 km²/sec). The total mission cost includes launch, but excludes cost associated with operations.

The primary disadvantage of low altitude is that there is higher drag, which can result in a short mission lifetime. However, compared to traditional large satellites, there are many advantages to SmallSats at lower altitudes. Below is a list of advantages of low-altitude SmallSats over traditional satellites:

- Shorter development schedules
- Lower implementation and operations risk
- More flexible and resilient
- More responsive to new technologies and changing needs
- More sustainable business models
- Greater attitude agility due to smaller moments of inertia

The specific advantages of low altitude systems as identified by Eves [2013] are:

1. If the resolution of the required system is already adequate, a reduction in orbit height potentially allows a smaller, lower cost, and lighter sensor to be used.
2. The lower the satellite orbit, the greater the mass of hardware and/or payload that can be placed into orbit.
3. For a given (passive or active) imaging sensor, the resolution or performance improves proportionally as you lower the altitude.
4. A shorter path length makes it easier to establish an adequate communications link budget to a terminal on the ground.
5. For a given aperture size, the effective surveillance footprint size of the mission actually increases as the orbit altitude decreases, so the timeliness of revisit is better.
6. Flying lower permits the collection of unique data sets that would not otherwise be possible (e.g., the gravity map resolution of the GRACE mission [Tapley, et al. 2004]).
7. There is no need to perform de-orbit maneuvers since atmospheric drag can bring the satellite down “for free.”
8. The problem of long-term orbital debris environment is mitigated since spacecraft below approximately 500 km will decay within a few days to several months.

V. Operations Cost

The relationship between cost and performance in Fig. 4 does not include operations costs. So far as we are aware, none of the publicly available space cost models that include operations cost break that cost down into elements that reflect the size, cost, or complexity of the spacecraft that is being operated. Nonetheless, it is reasonable to assume that we won't use the same Ops Concept for a $200 million spacecraft with a 10-year intended life as we would with a $2 million spacecraft with a 2-year intended life. There is also empirical evidence that this difference is real, as discussed below. Creating an operations cost model that is a function of the spacecraft size or complexity will likely be a challenging task. Adding operations cost to the current model will likely either move the model vertically, without changing the shape of the curve or possible tilt it a bit further in the in the direction of favoring SmallSats. We do not expect the change to be substantial in either case, but would welcome any data that others may have that reflects the impact of spacecraft size and complexity on operations cost.

Typically, operations cost depends on the following factors [Apgar, 2014]:

1. The number, complexity, and location of control and other ground stations and whether the control stations are dedicated to a single program (e.g., GPS) or allocated to multiple programs (e.g., JPL robotic missions)
2. The number of operators and hours per day required, the requirement for data recovery or additional data processing, and the level of automation (See Chap. 28 of Wertz, Everett, and Puschell [2011])
3. The amount of on-going R&D required (e.g., the need to upgrade operating software)
4. The amount of contactor support during the early years of the mission

In addition, small satellites naturally have lower operating cost. NEAR, Clementine, SAMPEX, ALEXIS, UoSat-05 are all examples of low cost small satellite programs with low operations costs. Operations costs for these specific missions were approximately 5-10% of their total mission cost, and their associated data can be found in Wertz and Larson [1996]. Therefore, multiple SmallSats flying at lower altitudes can have comparable operations cost to a single traditional satellite mission. Chapter 6 of Wertz and Larson [1996] gives detailed methods and concepts for reducing the cost of mission operations.

VI. Schedules, Reliability, and Risk

SmallSat missions provide much shorter schedules, comparable reliability, and significantly less risk than traditional large satellite missions. SmallSat schedules are much shorter than for traditional satellites. For instance, according to the Performance of Defense

Acquisition System Annual Report [DoD, 2013a], traditional major defense programs take 8.8 years in development (Milestone B) and well over 10 years from Milestone A to implementation. Reliability of SmallSats (including single-string SmallSats) is essentially similar to that of traditional large satellites according to a Goddard study [NASA, 2008b] of over 1,500 spacecraft launched between 1995 and 2007.

Risk is defined as the probability of a negative event times the impact or consequences of that event. Non-recurring cost for SmallSats is 1 to 2 orders of magnitude less than for traditional satellites [NASA, 2008b]. Therefore, implementation risk is low due to low non-recurring cost and short schedules. 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. An immediate result of having shorter schedules, reduced risk, and increased reliability is that SmallSats support the DoD objective of disaggregation [DoD, 2013b].

SmallSat missions are developed in less than 3.5 years while more traditional, large satellites an average of 10 years to develop. SmallSats have comparable reliability to larger satellite programs, despite often having single-string configuration and using COTS products. SmallSats poses significantly less risk (both implementation and operational) than traditional large satellite missions because failure rate is comparable to that of large satellites and consequence of failure is reduced due to low development cost. In addition, a paper by Hurley and Purdy at NRL "Designing and Managing for a Reliability of Zero" [2010], points out that most of today's space systems are designed for a reliability of zero, in the sense that for every day that the system is not operational or the data available to the end user, it has a reliability of zero. If the data isn't there, it doesn't matter to the warfighter who was killed or the scientist who's data was lost whether it wasn't there because of a parts failure or because the program was delayed or canceled due to more reviews or a lack of funding.

VII. Conclusions for Earth Observation Systems

The United States has more missions that need to be done than there is time and money available to do them. If the U.S. continues with the traditional way of doing business, there is the potential of physical gaps between missions that need continuity, such as weather and climate data and surveillance. Additionally, the U.S. does not have and has never had launch on demand, other than for ICBMs. Without responsive dedicated launch vehicles, it is impossible for the U.S. to respond to emergencies. This is a capability that Russia/Soviet Union has had for the past 3 decades. SmallSats can never replace traditional large satellites, but it is reasonable to believe there should be some sort of mix of both large and SmallSats in order to fill in mission gaps and increase the number of missions without added cost.

SmallSats are under-utilized as a method to dramatically reduce space mission cost. Without quantifiable evidence of their value, SmallSats will continue to be overlooked and under-recognized for their potential. By space mission cost, we mean the total mission cost from design and fabrication of a spacecraft, through launch and operations for the entire duration of the mission. Traditional (large) satellites have been used since the start of the space program, in the 1960s. These programs have done a tremendous job in terms of engineering and meeting the goals of NASA, DoD, and the United States. However, the U.S. has gotten to the point where there are many more missions that we need to or would like to accomplish, than there is funding available for them. If there are methods to dramatically reduce space mission cost, then it is clearly a benefit to implement them, or at least consider them.

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.

Due to advancements in technology and modern microelectronics, SmallSats at lower altitudes now have the potential for much lower overall mission cost, comparable or better performance, lower implementation and operations risk, and shorter schedules.

SmallSat observation systems need greater field of view (FoV) agility than larger, higher altitude systems. The needed agility is inversely proportional to altitude, but moments of inertia are also much smaller. Responsive, low-cost, small launch systems are needed for operational missions. All of this requires changing the way we do business in space and how we think about using space systems. This culture change is probably the most challenging thing, and the USC/Microcosm *Reinventing Space Project* [2014] is directed at continuing to find ways to make progress in this direction.

VIII. Future Work

While the PBCM provides sufficient detail to draw significant conclusions about the use of LEO satellites for Earth observation, there are several areas that should be researched in the future to broaden and strengthen the model. The current cost model is based solely on circular LEO Earth Observation satellites, but other constellation configurations such as LEO Elliptical Orbits and other types of missions such as communications or interplanetary science missions can be studied. Also, there are significant characteristics of LEO missions that require adaptation from more traditional, large missions, such as using autonomous orbit control, propulsion systems, checkout time and calibration process, and the responsive capabilities of SmallSats.

IX. Acknowledgements

We would like to acknowledge the California Space Grant Consortium for providing seed funding to the Microcosm/USC Reinventing Space Project. We would like to thank Azad Madni from the Astronautical Engineering Department at USC for his academic advisement and guidance on this research. We would also like to acknowledge the assistance of International Cost Estimating and Analysis Association (ICEAA) which was kind enough to let us present our results at their March 19, 2014 Workshop [Koltz, Shao, and Wertz, 2014]. Participants at the meeting asked a number of penetrating and useful questions that substantially improved the results. These questions and answers are available on the Reinventing Space Project website [2014].

X. References

1. Aerospace Corporation. 1996. *SmallSats Cost Model (SSCM)*. El Segundo, CA: The Aerospace Corporation.
2. Apgar, Henry. 2011. “Cost Estimating.” Wertz, J., Everett, D., and Puschell, J. *Space Mission Engineering: The New SMAD,* (SME) Chap. 11. Microcosm Press: Hawthorne, CA.
3. Bearden, David, A., et al. 1996. “Comparison of NEAR Costs with a Small-Spacecraft Cost Model.” AIAA/USU Conference on Small Satellites, September 16-19.
4. Department of Defense. 2013a. “Performance of the Defense Acquisition System,” 2013 Annual Report. Washington, DC: Office of the Under Secretary of Defense, Acquisition, Technology and Logistics, June 28.
5. Department of Defense. 2013b. “Resiliency and Disaggregated Space Architectures.” Air Force Space Command, White Paper, AFD-130821-034.
6. Digital Globe. 2013. Quickbird Datasheet. DS-QB 07/13.
7. Eves, Stuart. 2013. “Very Low Orbits.” 2013 Reinventing Space Conference. International Panel – Presentation, El Segundo, CA.
8. GeoEye. 2012. GeoEye-2 Fact Sheet, Rev 03/12.
9. Habib-agahi, Hamid. 2010. *NASA Instrument Cost Model (NICM) Version IV*. Pasadena, CA: NASA JPL.
10. Hurley, Mike and Bill Purdy. 2010. "Designing and Managing for a Reliability of Zero." ESA 4S Symposium, Funchal, Portugal, Paper No. 1885505, May 31–June 4.
11. Mahr, Eric, and Greg Richardson. 2002. “Development of the Small Satellite Cost Model (SSCM) Edition 2002.” IEEEAC paper #1159, Updated December 19, 2002.
12. NASA. 2008a. *2008 Cost Estimating Handbook (CEH)*. National Aeronautics and Space Administration, NASA HQ, Cost Analysis Division, Washington, DC.
13. NASA. 2008b. NASA Small Explorers Office SmallSat Study, Final Report. JHU/APL Space Department, June.
14. Reeves, Emery I. 1999. “Spacecraft Design and Sizing.” Wertz, J. R. and W. J. Larson. 1999. *Space Mission Analysis and Design. 3rd ed*., Chap. 10. Hawthorne, CA and New York: Microcosm Press and Springer.
15. Spaceflight Now. 2000. “Commercial Eye-in-the-sky Appears Lost in Launch Failure.” Nov. 21.
16. Space News. 2012. “NGA Letters Cast Cloud Over GeoEye’s Enhanced View Funding.” June 23.
17. Space News. 2014a. “DARPA Chief Says Space Programs Are Too Slow and Costly.” January 15.
18. Space News. 2014b. “Thule Air Base USAF Examining Alternative for All of Its Big Satellite Programs.” February 17, page 14.
19. Space News. 2014c. “Google to Buy SkyBox for $500 Million.” June 10.
20. Shao, Anthony, Elizabeth A. Koltz, and James R. Wertz. 2013. “Performance Based Cost Modeling: Quantifying the Cost Reduction Potential of Small Observation Satellties.” AIAA Reinventing Space Conference, AIAA-RS-2013-1003, Los Angeles, CA, Oct. 14–17.
21. Shao, Anthony, and Elizabeth A. Koltz. 2013. Microcosm Technical Report, PBCM Detailed Analysis. Microcosm: Hawthorne, CA.
22. Tapley, B.D., S. Bettadpur, M. Watkins, C. Reiger. 2004, “The Gravity Recovery and

Climate Experiment: Mission Overview and Early Results." American Geophysical Union.
23. Tecolote Research. 2002. *Unmanned Space Vehicle Cost Model (USCM)*. El Segundo, CA: US Air Force, Space and Missile Systems Center.
24. *The Reinventing Space Project*. 2014. Website: http://www.smad.com/ReinventingSpace.html
25. Wertz, James R., David F. Everett, and Jeffery J. Puschell. 2011. Space Missions Engineering: The New SMAD. Microcosm Press: Hawthorne, CA.
26. Wertz, James R., Nicola Sarzi-Amade, Anthony Shao, Christianna Taylor, and Richard E. Van Allen. 2012. "Moderately Elliptical Very Low Orbits (MEVLOs) as a Long-Term Solution to Orbital Debris." 26th Annual AIAA/USU Conference on SmallSats, SSC12-IV-6, Utah State University, Logan, UT, Aug. 13–16.
27. Wertz, James R., Richard R. Van Allen, and Tina Barcley. 2010. "NanoEye—Military Relevant Surveillance for Less Than $5 Million Total Recurring Mission Cost." 8th Responsive Space Conference, RS8-2010-1008, Los Angeles, CA, Mar. 8–11.
28. Wertz, James R., and Wiley J. Larson. 1996. *Reducing Space Mission Cost*. El Segundo, CA: Microcosm Press and Springer.