Technologies for Affordable SEC Missions

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Abstract—The influence of technology in reducing spacecraft costs was evaluated by analyzing historical trend data for spacecraft subsystems. The analysis is based on several dozen spacecraft and has lead us to the conclusion that, on average, the use of technologies that reduce spacecraft power will reduce spacecraft mass and cost. These conclusions are particularly important for NASA's SEC (Sun-Earth Connection) missions where 43,300 kg is projected to be launched over a 19-year period. An example is given where the use of ultra-lower power electronics in spacecraft subsystems significantly reduces spacecraft costs by permitting smaller and cheaper subsystems.

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1. PROBLEM STATEMENT

The number of spacecraft listed on NASA's Sun Earth Connection (SEC) Roadmap is double digit per year after 2011. As seen in Fig. 1, the number of roadmapped spacecraft in orbit is greater than 8 per year for the years between 2011 and 2017. It is anticipated that the number count will be maintained in the double-digit range for the years beyond 2015.

SEC has identified 38 missions and these are listed in Table A1 found in the Appendix. Also included are the mass of each spacecraft, the number of spacecraft needed for each mission, mission launch date and mission duration where known.

The mass of the individual spacecraft including payload for each mission is plotted in Fig. 2. It indicates that the spacecraft mass spans from 10 to over 3,000 kg. This range is due to the nature of the payload. The heavier-weight spacecraft have imager-type payloads; whereas, the lighter-weight spacecraft have payloads with small instruments and detectors for characterizing the local space environment.

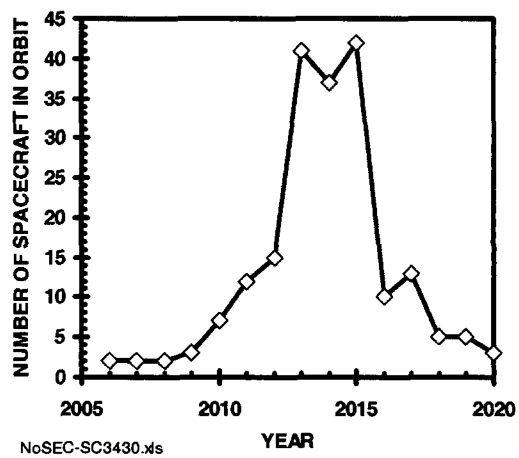

Figure 1. Estimated number of spacecraft needed by SEC in the next 15 years.

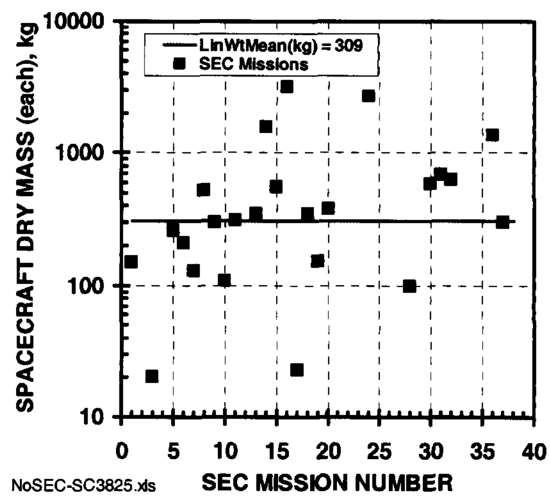

Figure 2. SEC spacecraft mass.

As seen in Fig. 2 the linear-weighted-mean (LinWtMean) mass for the spacecraft listed in Table A1 is about 310 kg. There are a total of 140 units to be launched over a 19-year period. The total spacecraft wet mass is 43,300 kg.

To afford these missions, SEC has set a goal where the average cost of the spacecraft should be well below \$20M/unit. As will be shown (in Fig. 3), this is not an unreasonable goal. *The objectives of this study are to determine if judicious use of technology can reduce spacecraft costs and by how much.*

2. APPROACH

Spacecraft costs are driven by a number of factors as seen in Fig. 3. The cost domain is subdivided into three factors: Technology, Architecture, and Manufacturing.

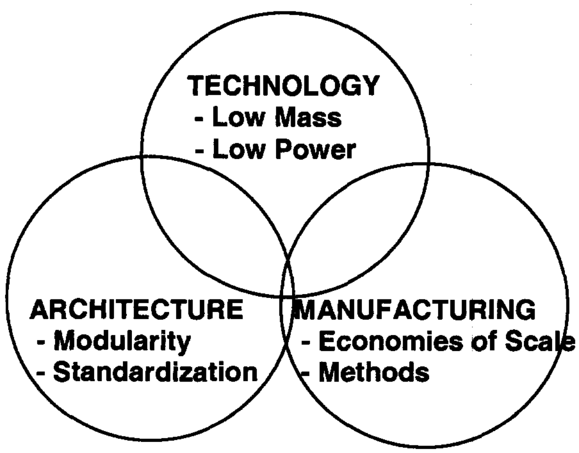

Figure 3. Spacecraft affordable domains.

At first blush, the solution to reducing spacecraft cost is one of *economies of scale*. Manufacturing a lot of something brings the cost down over the cost of the initial unit. The small numbers seen in Fig. 1 make estimating the economies of scale difficult. However, Bearden [1, p. 258] suggests that on average the Nth unit will cost between 87% and 96% of the previous unit starting after the second unit. The first unit includes non-recurring engineering costs; thus, cost of the second unit is substantially less than the first unit. Also important to lowering spacecraft cost is implementing cost effective *manufacturing disciplines*. N. Dennehy [2], GSFC, developed a list of disciplines and technologies needed for the spacecraft "Factory of the Future" as seen in Table A2 given in the Appendix. Finally, the architecture of the design plays a role. By calling for the use of standard-off-the-shelf and modular parts, testing and documentation costs are reduced. This effort is focused on developing insight into procedure for identifying which technologies have the highest likelihood of affecting spacecraft cost.

In this study we focused on identifying parameters that influence the spacecraft costs and then related them to technologies and their relationship to cost. As will be seen, the most important parameters are spacecraft mass and power. The main sources for the data used in this study are Wertz and Larson [3], [4], Sarsfield [5] and the Small Satellite Data Base (SSDB) from The Aerospace Corporation (Aerospace).

3. SYSTEM COST/MASS RATIO

It is well know that spacecraft costs are highly correlated with the dry mass of the spacecraft. Bearden [1, p. 254] provided the following cost/mass ratio estimates listed in Table 1. In round numbers, the cost/mass ratio is about 100 k\$/kg.

Table 1. Spacecraft cost per unit mass

Space System	Cost (k\$/kg)
Communication	70-150
Surveillance	50-150
Metrology	50-150
Interplanetary	>130

Further evidence for this trend was obtained as seen in Fig. 4 from the data of Wertz and Larson [4, p. 808] and Sarsfield [5, p. 111] where their costs were inflated to the year 2002. The span of this data ranges from 80.4 k\$/kg to 299 k\$/kg. The fitting points for these numbers is given by the data marked by the + sign.

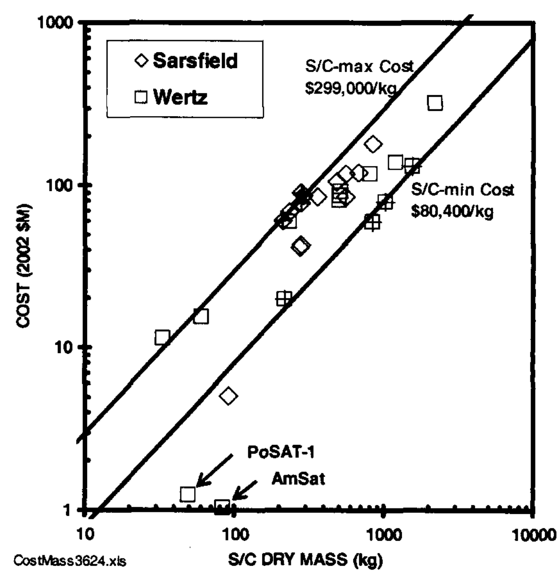

Figure 4. Historical spacecraft cost/mass ratios from Sarsfield [5, p. 111] and Wertz and Larson [4, Appendix A].

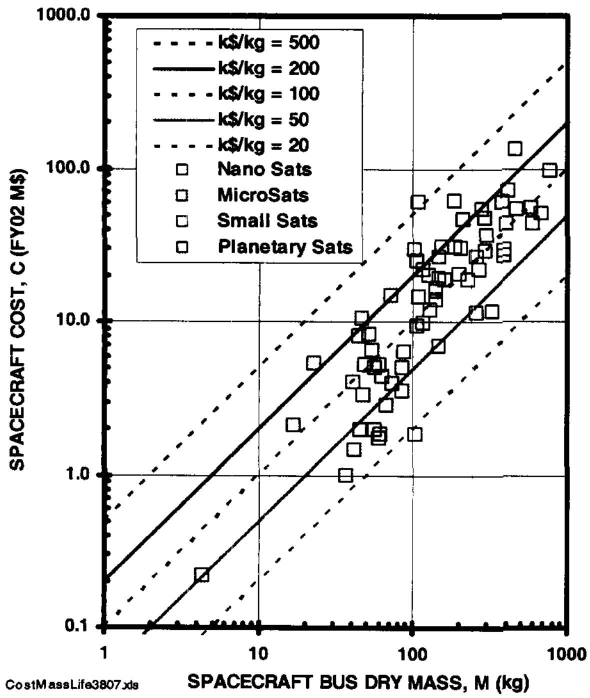

Figure 5. Historical spacecraft cost/mass ratio from Aerospace's small satellite database.

More recent date analysis from Aerospace is shown in Fig. 5. In this figure the cost/mass ratio spans from 20 k$/kg to 500 k$/kg. The data in this chart is segregated into categories for nanosats (1 to 10 kg), microsats (10 to 100 kg), and smallsats (100 to 1000 kg). The caveat in the use of this data is that the costs were derived from one-of-a-kind spacecraft and not from a fleet or constellation.

Conclusions from Figs. 4 and 5 are:

1. Cost/mass ratio varies by more than an order of magnitude and is centered about 120 k$/kg. This is in agreement with the estimate of Bearden [1, p. 254].
2. Cost/mass ratio is lower for microsats than higher mass spacecraft as seen in Fig. 3
3. Lowest cost spacecrafts are produced by the AmSat and PoSat (Surrey) as seen in Fig. 2.

The low cost of the AmSat and PoSat (Surrey) spacecrafts is due to several factors [3]. The AmSat cost reduction factors are:

- Almost no paid labor.
- Small integration facilities.
- Numerous donations of both hardware and software.

The PoSat (Surrey) cost reduction factors are:

- Subsystem reuse and modularity reduces test and analysis costs.
- LEO space environment allows the use of low-cost COTS components that require little radiation shielding, which reduces weight hence cost.
- Manufacturing efficiency such as common schedules and team members across projects reduces cost.

4. Subsystem Costs

Considering the costs of satellite subsystems further refined the identification of cost drivers. Using data from Wertz and Larson [4, Appendix A] and the cost models from Bearden [1, p. 271], subsystem cost distributions are shown in Fig.6. From the distribution, it can be seen that the power subsystem cost is the biggest percentage and the propulsion and thermal subsystem costs are the smallest percentage.

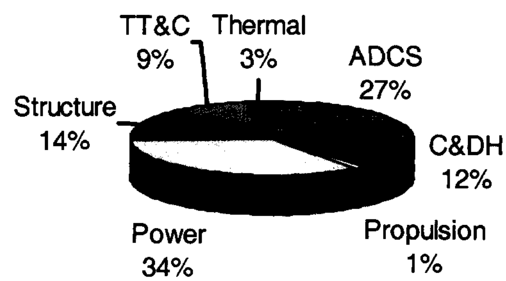

Figure 6. Light satellite sub-system costs [4, Appendix A]

Another view of subsystem costs is given by the data from the Aerospace small satellite database; see Fig. 7. In this figure the largest cost fraction is again found for the power subsystem and the smallest cost fraction for the thermal control subsystem for this class of missions.

Cost models such as SSCM have developed over time to become less mass based, and increasingly power based as stronger correlations are found between power consumption and cost. For example, SSCM version 7.4 [1] is entirely mass based, whereas for the newer version, SSCM02, only four of seven subsystems use mass-based Cost Estimation Relationships (CERs) and two use power-based CERs.

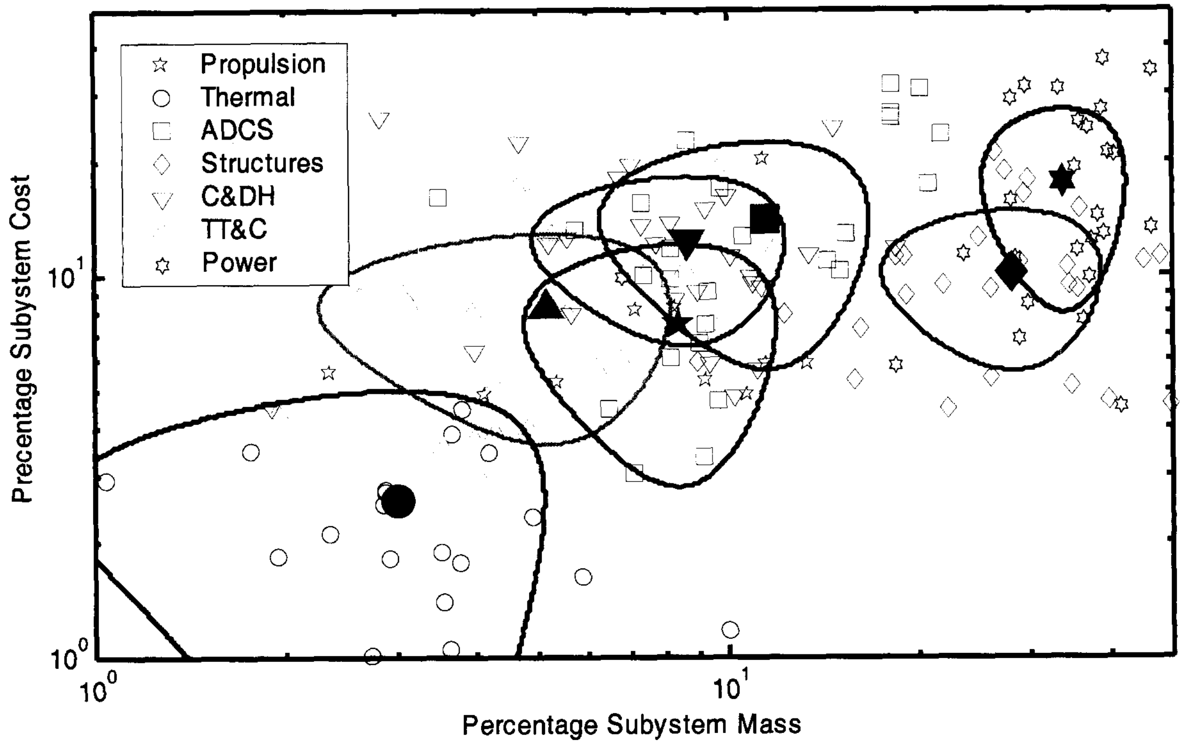

Figure 7. Historical subsystem cost-mass relationship. The mean mass and cost for the subsystem is shown as a solid symbol, with the outer ellipse indicating the standard deviation in mass and cost.

The observations from Figs. 6 and 7 lead to the conclusion that to reduce spacecraft cost, focus on technologies that reduce the load on the *power* subsystem first. Reducing power consumption provides the greatest cost reduction as opposed to *thermal control* technologies, which have a relatively minor impact on cost.

This conclusion must be applied with care. For instance, "Miniature Energy-Saving Thermal Control Subsystem" technology has a high potential to reduce spacecraft costs because it is directed at reducing the spacecraft power consumption. Also, a counter-intuitive mass argument is the following: Using heavier, mature, off-the-shelf technology may be more cost-effective than using lightweight advanced technology.

5. Power Subsystem Costs

Because power is a dominant factor in spacecraft costs for this class of missions, in this section we examine where the power is consumed with an eye toward reducing the power consumption and thus towards reducing the need to generate power.

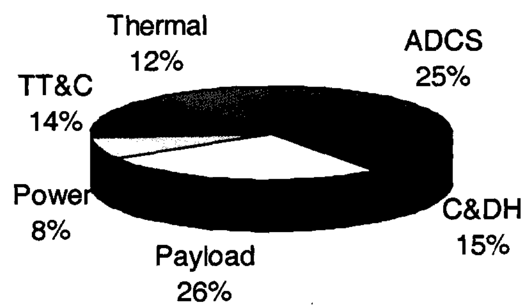

Figure 8. Clementine power load distribution.

The power distribution for the Clementine spacecraft [6] is illustrated in Fig. 8. It shows that, within spacecraft subsystems, the power is consumed mainly by the ADCS and C&DH (including avionics) subsystems and to a lesser extent by the TT&C and the thermal subsystems. The scientific payload consumes approximately 25% of the total power, which is typical for satellites of this size.

A similar power distribution for the EO-1 subsystems is shown in Fig. 9. As in the Clementine case, the ADCS (GN&C) and C&DH subsystems consume the largest fraction of the power, but not quite as much as the scientific payload.

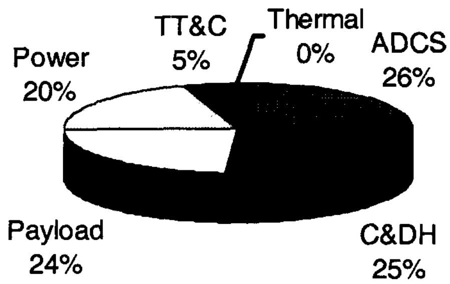

Figure 9. EO-1 as-designed power load distribution

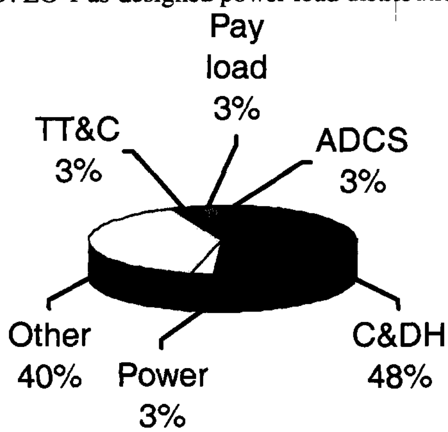

Figure 10. ST-5 as-designed power load distribution

Both Clementine and EO-1 are three-axis stabilized spacecraft. The power distribution for a spinning spacecraft was determined for the yet to be flown ST-5 spacecraft and the results are shown in Fig. 10. A comparison of power distributions for Clementine, EO-1, and ST-5 is listed in Table 2. The results reveal that the power consumption is application specific. For the three-axis stabilized spacecraft (Clementine and EO-1), the largest percentage of the power is consumed by the ADCS and CD&H subsystems ignoring the payload. For the spinner (ST-5), the power consumed by ADCS is small, whereas, the CD&H subsystem consumes a large fraction of the power budget. Thus, each spacecraft must be reviewed and the highest power consuming subsystems designed for minimum power consumption.

Table 2. Power distribution (in %)

SUBSYSTEM	Clementine	EO-1	ST-5
ADCS	25	26	3
C&DH	15	25	48
TT&C	14	5	3
Thermal	12	0	0
Power	8	20	3
Payload	26	24	3

6. Case Study

At Goddard Space Flight Center [7] a study was undertaken to determine the impact of introducing ultra-low power (ULP) electronics on the power system load. The starting point for the study was the as-designed power distribution for the EO-1 spacecraft seen in Fig. 9. Each subsystem found in the EO-1 spacecraft was examined and the power reduction results are shown in Fig. 11.

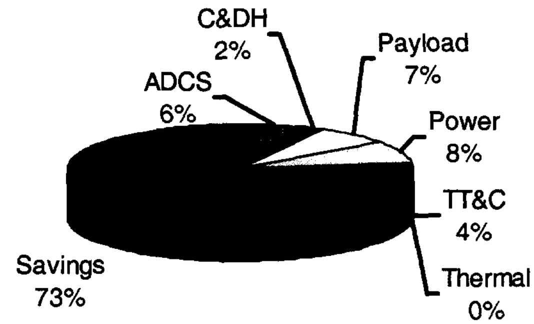

Figure 11. EO-1 power load distribution after including ultra-low power electronics.

The reduction in power consumption was achieved by reducing the power supply voltage to the digital logic. The reduction in power consumption was assumed to follow a V^2 law. Only the digital logic was examined and it was assumed that all the digital circuits in EO-1 used 5 V logic. The power reduction was achieved by lowering the logic supply voltage from 5 V to 0.5 V, which according to the V^2 law produces an order of magnitude reduction in power demand for these circuits. The results, shown in Fig. 11, indicate that the spacecraft power consumption can be reduced by 73%.

The cost saving results seen in Fig. 11 can be translated into cost reduction by looking at historical cost-power relationship shown in Fig. 12. The data in this figure were bounded by a linear relationship with a slope between 0.02 and 0.5 M$/W. According to this analysis, the 73% power reduction implies a 73% cost savings.

Clearly the use of ULP electronics will not actually result in a 73% cost savings because the cost of the new ULP technology is not likely to be the same in k$/kg of the old technology. But, it is important to keep in mind the trickle down subsystem mass savings that are obtainable with the use of ULP electronics when designing a new satellite. Unfortunately, cost models such as SSCM will always lag technology because the model is based on historical cost data. The example merely illustrates the potential effect of introducing new technology, ULP logic circuits in this case, on spacecraft cost.

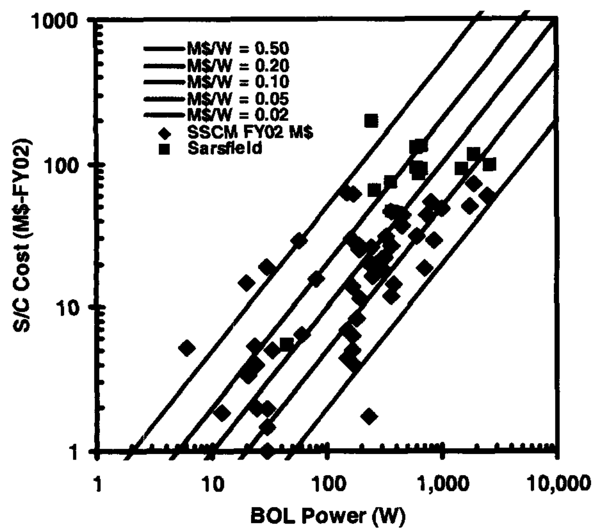

Figure 12. Historical cost-power data derived from Sarsfield [5, p. 100] and the SSCM data.

7. Power-Mass Relationship

In order to evaluate the estimation procedures without involving cost estimates, the spacecraft mass and power were compared. This is shown in Fig. 13 using the SEC parameters listed in Table A1 as well as data from the SSDB and Sarsfeld [5]. As seen in the figure, the data are approximately bounded between 0.1 and 5 W/kg with and average of 0.29 W/kg. The SEC mission set is offset to the right of the main distribution, perhaps reflecting the incorporation of more efficient subsystems.

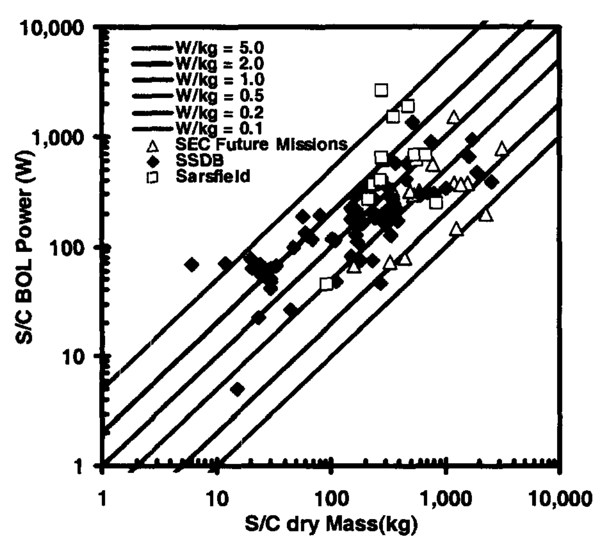

Figure 13. Spacecraft power-mass dependence for the SEC mission set, EO-1 and Clementine.

The relationship shown in Fig. 13 is important for it validates the trend in spacecraft cost modeling. As mentioned previously, the newer cost models are based more on spacecraft power than on mass. In addition this figure provides an independent check on the spacecraft estimation procedures for the relation ship between power and mass is based more on engineering data and is less influenced by cost estimation.

8. Spacecraft Cost Triage Rule

Results from this study lead to the following observations:

1. Power subsystems have the highest impact on reducing spacecraft cost for this class of missions; see Figs. 4 and 5.
2. ADCS and C&DH subsystems are the highest power consuming subsystems; see Table 2.
3. Reducing spacecraft mass leads to a reduction in spacecraft cost; see Figs. 4 and 5.

From these observations, we formulated the *Spacecraft Cost Triage Rule*: To reduce spacecraft costs, use technologies that reduce power. For maximum cost reduction, design the ADCS and C&DH subsystems for minimum power consumption. Low power systems are less massive requiring less massive systems to support them. Less massive systems are cheaper and reduce total spacecraft cost.

9. Application of the Triage Rule

Suggestions for technologies that have a high impact on reducing spacecraft costs are listed in Table 3 [3, p. 277]. The table is arranged with the highest subsystem cost impact listed first.

The top four technologies were chosen for inclusion in the ST8 NRA call, as shown in Table 4. Key phrases are shown in bold type. Notice that three out of the top four technologies have a chance of reducing spacecraft cost based in the triage rule. The fourth item, COTS, will also potentially reduce spacecraft costs but is not a direct technology investment per se. COTS investments lie more in the domains of architecture and manufacturing (Fig. 3.).

To identify high-cost impact technologies, look for phrases like: "low-cost," "light-weight," "energy saving," "low-density," "miniature" and "integrated". These phrases are shown in bold type in the table and indicate the highest cost impact technologies. While somewhat of an oversimplification, these technologies provide a good starting point for the design process of low cost satellites.

Table 3. Key technologies for reducing spacecraft costs [3, p. 277].

SUBSYSTEM	COMPONENTS/TECHNOLOGIES
1. Power	High-Performance, **Light-weight** Solar Arrays with Solar Concentrators **Small High-Energy-Density** Batteries **Low-Cost** NiCd Batteries
2. ADCS: Attitude Determination and Control Subsystem	**Low-Cost**, High Performance Gyros **Low-Cost** Star Tracker **Low-Cost** Sun Sensor **Miniature** Optical IMU **Low-Cost Integrated** GN&C Precision Reaction Wheels **Low-cost** ADCS
3. Structures and Mechanisms	Inflatable Antennas
4. C&DH: Command and Data Handling	Centralized Motherboard Electronics **Miniature** Microprocessors Large-Capacity Solid-State Data Storage Digital Voice and Video Data Compression
5. TT&C: Telemetry, Tracking and Control	**Miniature Low-Cost** EHF Adaptive Uplink Antennas High-Speed, **Low-Power** Digital Signal Processing **Lightweight** Freq.-Hopping Synthesizers **Efficient** Solid-State Transmitters
6. Thermal	Thermal Radiators
7. Propulsion	Propulsion Tanks

It is interesting to note that the authors [3] of Table 3 did not list ULP electronics as a key technology. Thus, Table 3 is not exhaustive and other technologies need to be examined for their cost-effectiveness.

Another use of the Spacecraft Cost Triage Rule is in identifying technologies that can reduce spacecraft costs. Considered the technologies proposed for the New Millennium Program (NMP) ST8 validation flight. These technologies are listed in Table 4. Note that almost half of the technologies propose for ST8 may lead to future cost savings, the remaining technologies are targeted towards increased capabilities.

Given the current interest in payload specific technologies that NMP promotes under ST-8, it is important to look at the effect of the payload on the cost of the spacecraft. Earlier we identified the payload as being a significant power consumer, and power consumption has been demonstrated to be a significant driver in spacecraft cost. ULP electronics can certainly alleviate the payload's power demand on the spacecraft; however mass is still a significant driver in spacecraft cost. Item number 11 in Table 4 refers to low-density optics, which would reduce mass of the payload and therefore the mass and cost of the spacecraft.

Table 4. Candidate technologies for ST8.

No.	TECHNOLOGY
1	**Ultra Lightweight** Deployable Boom
2	**Lightweight** Solar Array Deployment
3	**Miniature Energy-Saving** Thermal Control Subsystem
4	COTS Based High performance Computing
5	Solar Sail Deployment
6	Large Deployable Antennas
7	Space-to-Space Optical Communications
8	Navigation above the GPS Constellation
9	Attitude Control of Large Non-Rigid Structures
10	Tethered Spacecraft Formation Flying
11	**Ultra Low Density** Optics
12	Continuously Operating Cyro-Cooler
13	**Miniaturized** Low-Energy Particle Detector

10. DISCUSSION

Affordable spacecraft is an important factor to the success of the SEC missions. This study examined the impact of technology choices on spacecraft cost. It found that the technology's *mass and power* consumption are primary drivers in reducing cost.

This principle was captured using the *Spacecraft Cost Triage Rule* as a way of sorting the myriad of possibilities and identifying high priority technologies. Key phrases were presented to aid in identifying likely cost reducing technologies.

A potential use for the results of this study could be in identifying technologies that require NMP flight validation. The main NMP flight validation factor is that a candidate technology can only be flight validated in space. An example is technologies that are influenced by microgravity such as the deployment of large space structures. It is suggested that NMP might consider modifying its flight validation requirements to include *technologies that, in addition to needing validation in space, also contribute significantly to lowering spacecraft costs.*

The amount of the cost reduction estimate depends, of course, on the cost of the new technology and on the fidelity of the cost estimation models. The cost models are backward looking for they are based on historical data from flown spacecraft. The use of historically based-cost estimation models must be used with great care when it comes to the estimating the impact of new technology on spacecraft costs.

11. CONCLUSION

Technology can be used to reduce spacecraft cost. A number of technologies were identified, in Table 3, as being important in lowering spacecraft costs. In the ULP electronics case study, this technology implied a directly lower spacecraft cost by as much as 73%.

The insight gained in this analysis can help program managers make technology choices that favor technologies that have potential of reducing spacecraft cost. As indicated above, the key words to look for are *mass and power*.

The results of this study can be applied to the NMP by giving "extra credit" to those technologies that have the potential of lowering spacecraft costs.

12. ACKNOWLEDGMENTS

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14. APPENDIX

Table A1 contains the data used in developing Figs. 1a and 1b.

Table A1. SEC mission set parameters.

No.	Mission	No. S/C	Launch YYMM	Mission Life years	Wet Mass (each) kg	Power W
1	Auroral Multi-Scale (AMS)	4	Long-term	1.5	150[A2]	72
2	Bepi-Colombo	3	1001	3.0		
3	Dayside Boundary Layer Constellation (DBC)	30	Long-term		20[A4]	
4	Geospace Electrodynamics Connections (GEC)	4	1103	2.7		
5	Ionosphere Thermosphere Storm Probes	2	808	2.4	260[A1]	
6	Radiation Belt Storm Probes	2	1009	2.3	213[A1]	
7	Geospace System Response Imager (GSRI)	4	Long-term	2.0	131[A2]	328
8	Heliospheric Imager and Galactic Observer (HIGO)	1	1806E	4.8	532[A7]	290
9	Inner Heliosphere Sentinels (IHS)	4	1201	5.6	300[A9]	375
10	Inner Magnetospheric Constellation (IMC)	6	1401	2.0	109	66
11	Interstellar Probe	1	Long-term	15.0	313[A7]	318
12	Io Electrodynamics		Long-term			
13	Ionosphere Thermosphere Mesosphere Waves Coupler	2	1700E	2.5	350	557
14	Jupiter Polar Orbiter (JPO)	1	NET 09xx	5.6	1565[A7]	380
15	L1-Diamond	4	Long-term	3.0	555	195
16	Magnetic TRAnsition region Probe (MTRAP)	1	1800	3.3	3160	771
17	Magnetospheric Constellation (MC)	30	1208	3.0	23[A3]	
18	Magnetosphere-Ionosphere Observatory MIO Large s/c	1	Long-term	2.0	352	80
19	MIO Small s/c	3	Long-term		153	
20	Magnetospheric Multiscale (MMS)	4	1001	3.0	380[A5]	
21	Mars Aeronomy Probe		Long-term			
22	Neptune Orbiter		Long-term			
23	Particle Acceleration Solar Orbiter (PASO)		Long-term			
24	Reconnection and Microscale (RAM)	1	1506	2.0	2683	1493
25	Solar-B		0609			
26	Solar Connection Observatory for Planetary Environments (SCOPE)		Long-term			
27	Solar Dynamics Observatory (SDO)	1	0804	2.8		
28	Solar Imaging Radio Array (SIRA)	10	Long-term		100	
29	Solar Orbiter		NET 09xx			
30	Solar Polar Imager	1	Long-term	3.0	590[A7]	
31	Solar Probe	1	NET 10xx	6.5	686[A6]	320
32	Solar-TERrestrial RElations Observatory (STEREO)	2	0511	3.0	628[A8]	
33	Stellar Imager	2	Long-term	3.0		
34	Sun-Earth Energy Connector (SEEC)	30	Long-term	3.0		
35	Sun-Heliosphere-Earth Constellation	10	Long-term			
36	Telemachus	1	1301	11.4	1371[A7]	360
37	Tropical ITM Coupler	3	1600	2.0	300	144
38	Venus Aeronomy Probe		Long-term			

References for Table A1:

[A1] Per Geospace Mission Definition Team report, 2002.

[A2] Per Oberright, GSFC Mission Studies for SEC Roadmap, Summer 2002.
[A3] Per GSFC Mission Study, Fall 2002.
[A4] Per Van Sant, based upon MagCon mass estimate and two-instrument suite.
[A5] Per Thurber, MMS System Engineer, September 2003.
[A6]
[A7] Per Ayon, JPL Roadmap Mission Studies, 2002.
[A8]
[A9] Per GSFC Mission Study, 2000.

Table A2 contains the findings of Neil Dennehy, GSFC, concerning the disciplines and technologies needed for the spacecraft "Factory of the Future". In this table, technology development is proposed to directly support a revolutionary high volume, commodity-like manufacturing, spacecraft "Factory of the Future" employing completely new paradigms. The idea is to develop an E2E small (25 - 50 kg) spacecraft design, fabrication, integration, test, launch and operation that will reduce bus costs by a factor of 2 – 5 over current costs.

Table A2: Disciplines and technologies for the spacecraft "factory of the future

· Engineering Complex System (ECS) like technology for executing a globally optimized spacecraft bus Total Cost/Integrated Performance design process (versus the current traditional design approach of integrating a set of multiple, locally optimized subsystems)
· Standard "catalog item", common, modular, long shelf life spacecraft bus components
· Storable battery modules, Storable propulsion modules, Storable reaction/momentum wheels
· Zero Integration Time (ZIT) Plug & Play component technology utilizing standard bus interfaces and employing comprehensive autonomous Built-In-Test (BIT) functions
· Internet-based "harnessless" command/telemetry interconnection technology
· Highly Reliable/Reusable Flight Software technology
· Advanced material and fabrication technology
· High volume injection molded spacecraft bus shell structures
· Lightweight laminated structures
· Multifunction bus subsystem technologies and Multifunction Structure technology
· Structural Battery technology
· Micro-Navigator/Multifunction GN&C Avionics technology
· Integrated Power and Attitude Control Subsystem (IPACS) technology
· Low power/Radiation Hard microsystem electronics packaging technology for highly integrated spacecraft C&DH, GN&C, Power and Communications subsystem architectures
· "SiliconSat" spacecraft architectures employing MEMS device/subassembly, Multi Chip Module (MCM), and High Density Interconnect technologies
· Zero defect production with technologies for highly automated Spacecraft-level Comprehensive Integrated Test and autonomous component–level Built-In-Test
· Advanced software/hardware test bed technology supporting new rapid "Requirements-to-Design" spacecraft systems engineering process incorporating maximum hardware/software re-use across multiple platforms
· Autonomous spacecraft-level Vehicle Health Monitoring (VHM) supporting not only on-orbit operations but also factory integration, pre-launch, and launch operations
· Autonomous ground system planning, scheduling, commanding and telemetry monitoring technology for "lights out" on-orbit operations