Reducing Space Mission Cost
Annotated Bibliography

***Jim Wertz*, Microcosm, March, 2011**

Note: This is intended as a very practical list of the best sources of information on reducing space mission cost. I have largely excluded discussions of approaches that may be physically possible, but are not yet technically feasible, such as the space elevator. I have also excluded discussions of particular pieces of hardware, such as a low-cost solar array or low-cost star sensor. While these may well be relevant, they do not typically drive the mission cost. Of course, most of the articles tend to be supportive of a particular technology or approach, but that is also true of the space technology literature in general. A number of the books and articles are relatively old. In this case, the methods and techniques may well still be applicable although the cost data will be out of date or incorrect**. If you are aware of other books, conferences, courses, professional papers, or study reports that we have not included and which meet the above criteria, please let me know at the E-mail address below.**

Finally, thanks to Nicola Sarzi-Amade and Donna Klungle of Microcosm for their assistance in collecting material for this bibliography.

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Books

Helvajian, H. and S. W. Janson (eds.), 2009, ***Small Satellites: Past, Present, and Future***, 859 pg., Los Angeles, CA: The Aerospace Press, October 30, 2009.

Provides an extensive history of smallsats and projections for future use. Provides a detailed overview of The Aerospace Corp's picosat program and their approach to testing technologies on picosats in order to mitigate risk on larger missions and advance the exploitation of space more quickly and at lower cost. [For the results of a Futron study funded by AFRL of the future of small satellites, see the professional paper by Foust, et al., 2008; see also the paper by Wertz, 2010.]

McCurdy, 2003. ***Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program***. Baltimore, MD: John Hopkins U. Press. 192 pg.

An historical overview of the “faster, better, cheaper” program introduced by NASA Administrator Dan Goldin. Discusses 16 specific NASA missions undertaken during the 1990’s and the successes and failures of the program.

Sandau, R., 2006. ***International Study on Cost Effective Earth Observation Missions,*** Leiden, The Netherlands: A. A. Balkema, 180 pg.

Contributions by multiple international authors on the general process of creating low-cost Earth observation missions. See also the IAA Symposium on Small Satellites for Earth Observation listed under conferences.

London, J.R. 1994. ***LEO on the Cheap — Methods for Achieving Drastic Reductions in Space Launch Costs****,* Maxwell AFB, AL: Air University Press. 213 pg.

An older study, but still the most definitive study available of launch system cost and methods of reducing them. Summarizes existing and proposed launch systems with particular emphasis on the reasons for high cost and the methods required to drive down cost. Available at no cost at http://www.dunnspace.com/leo_on_the_cheap.htm

Sarsfield, L., 1998. ***The Cosmos on a Shoestring — Small Spacecraft for Space and Earth Science***, Santa Monica, CA: RAND Corp., 221 pg.

This is the final report of a RAND Corp. study on using small spacecraft for space and Earth science missions. Includes an extensive bibliography. Available at no cost at: http://www.rand.org/publications/MR/MR864

Davidoff, M., 1998. ***The Radio Amateur's Satellite Handbook, 2nd edition***. Newington, CT: ARRL. 370 pg.

This AMSAT book provides a detailed recipe for the design and operation of very low-cost communications satellites; practical, relevant data and methods applicable to many missions; lots of references. Out of print. Replaced by Ford, below. Still an excellent reference with more detail than the Ford book.

Ford, S., 2009. ***The ARRL Satellite Handbook***. Newington, CT: ARRL. 208 pg.

This is the replacement for the 1998 Davidoff volume. Primarily oriented toward ground stations and ground users. Provides a brief history of amateur radio satellites, satellite orbits and tracking, satellite communication systems, satellite ground stations, satellite operating, and amateur satellite projects. An excellent reference from one of the most successful, low-cost satellite organizations in the world.

Wertz, J.R. and W.J. Larson, 1996**. *Reducing Space Mission Cost****,*** Dordrecht, The Netherlands: Kluwer Academic and Hawthorne, CA: Microcosm Press, 629 pg.

An older book, but still the only volume available that directly addresses all aspects of space mission cost reduction. Includes 10 case study missions from various areas with both extended discussions and detailed costs for each. Intended as a

practical guide to reducing mission cost and to what works and what doesn't work in reducing cost. Extensive references.

Fleeter, R., 2000. ***The Logic of Microspace****,* Dordrecht, The Netherlands: Kluwer Academic and Hawthorne: Microcosm Press, 447 pg.

An excellent volume by the former president of Aero-Astro. Well-written — likely the most entertaining book available on small satellites. Discusses both the technology and management of low-cost space missions. Well worth reading for practical advice on truly changing the rules of the game for space business and creating reliable, low-cost spacecraft.

Harland, D.M. and R.D. Lorenz, 2005. ***Space System Failures — Disasters and Rescues of Satellites, Rockets, and Space Probes****,* Chichester, UK: Praxis Publishing, 368 pg.

This book is not directly associated with reducing space mission cost, but I have included it in the list because it is the most authoritative book available on space system failures. And the process of trying to avoid failures has been a major driver of cost increases in the space program.

Johnson, S.B., 2002. ***The Secret of Apollo: Systems Management in American and European Space Programs****,* Baltimore, MD: Johns Hopkins University Press, 290 pg.

The Apollo Moon program was the single most expensive space program in history. However, it was also remarkably successful in many respects — landing a man on the Moon only 8 years from the start of the program, including the development of the Saturn V, the largest, most reliable, and lowest cost per pound launch vehicle ever built. Johnson tells the story of the development of the Systems Management process that allowed Apollo to happen.

Committee on Cost Growth in NASA Earth and Space Science Missions, and National Research Council, 2010, ***Controlling Cost Growth of NASA Earth and Space Science Missions***, 76 pg., Washington, DC: National Academies Press, September 21, 2010.

This report is the result of a study of recent NASA science missions. It finds 4 primary causes of cost and schedule growth and makes 11 recommendations to control this problem and reduce cost and schedule.

Conferences

There are six principal conferences that are strongly associated with low-cost or reduced-cost, more responsive space programs — two in the US and four at various international locations.

AIAA/USU Small Satellite Conference, held annually in August at Utah State University in Logan, UT. The 25th SmallSat Conference will be Aug. 8–11, 2011. An excellent conference which nearly all of the small satellite community attends. Past proceedings on CD are for sale on conference website, www.smallsat.org. List of paper titles and authors available on line. If you attend, be sure to make hotel reservations early. Logan is a small town and is usually filled up by the conference, such that late comers may have to stay a long ways away.

Responsive Space® Conference/Reinventing Space Conference sponsored by the AIAA LA and Orange County Sections and the Space Systems Technical Committee. Held annually in LA in the general vicinity of LAX. Starting in 2011, the name of the conference will change to ***Reinventing Space*** to emphasize the initial purpose of the conference -- much lower cost, more responsive space missions. RS8 was held Mar. 8–11, 2010 at the LAX Westin Hotel. RS2011 will be held the first week of May 2011, also at the LAX Westin. Past papers are searchable and downloadable from the conference website, www.responsivespace.com, which also has contact information, call-for-papers, and a responsive space dictionary and acronym list. Most people and organizations associated with low-cost, responsive space (including the AF Operationally Responsive Space office) will be there.

Small Satellites Systems and Services (4S) Symposium, a biennial event sponsored by ESA with large international participation. All aspects of small satellite programs are considered including flight experiences, mission definition, technologies, launches, ground segment, and data exploitation. The 4S Symposium 2010 was held May 31-June 4, 2010, in Funchal, Portugal. Information is available at http://www.congrex.nl/10a03/.

IAA Symposium on Small Satellites for Earth Observation, sponsored by the International Academy of Astronautics. The 8th symposium will be held April 4-8, 2011 in Berlin, Germany. The conference website (in English) is www.dlr.de/iaa.symp/en/desktopdefault.aspx/tabid-4802/. Papers from previous conferences are available on the website. As the name implies, this is an international symposium on the use of small satellites with a strong orientation toward low cost.

IAA International Conference on Low-Cost Planetary Missions, sponsored by the International Academy of Astronautics. The 9th conference will be held June 21-24, 2011 in Goa, India. Information is available on the IAA website, http://lcpm9.jhuapl.edu/. Information on the 8th conference, held in Goa, India Aug.

31-Sept. 4, 2009, is available at http://lcpm8.isro.gov.in. Papers from most previous conferences are available. This conference is approximately bi-annual and focuses on low-cost interplanetary missions.

Reducing the Costs of Spacecraft Ground Systems and Operations (RCSGSO), sponsored by the major space agencies. An extensive conference with parallel sessions on topics such as Mission Planning, Autonomous Operations, Software Development, Standardization, Flight Dynamics and Navigation, Global Networks, and Low-Cost Mission Operations Concepts. The 8th RCSGSO conference was held in May, 2009, at JAXA Tsukuba Space Center, Japan.

Courses

There are two courses directly associated with the problem of reducing space mission cost

J. Wertz, ***Reinventing Space: The Design of Low-Cost Space Missions***, taught every other year in the Spring semester as a televised graduate course at USC. (Next course begins January, 2013.) Requires graduate student standing. Best done if the participants have either had a previous SMAD course or, preferably, worked in the space industry. Approximately half the course is lecture on cost reduction approaches and half is discussion based on either current events or questions/issues raised by the participants. Can be taken as a televised course anywhere in the country. However, this is a graded course with homework, mid-term and a final.

This course is also offered from time-to-time as a 5-day short course. This is occasionally done at Microcosm and occasionally at or near an interested organization, most recently for the Canadian Space Agency. For more information, contact Julie Jackson at jjackson@smad.com.

J. Wertz, ***Responsive Space Mission Analysis and Design, R-SMAD***, 5-day short course taught from time-to-time at Microcosm or at sponsoring organizations. The course covers all of the topics in the *Space Mission Analysis and Design* course, but from the point of view of wanting to create truly responsive, very low cost ($20M – $40M) missions.

Professional Papers

Note: Most of the professional papers are discussions of a particular program or technology. Those that discuss cost reduction in more general terms and, therefore, are more broadly applicable are marked with an *.

***** Andrews, D. and E. Soerensen, 2003. ***Standardized Mission Operational Methodologies*****,** 5th International Symposium on Reducing the Cost of Spacecraft Ground Systems and Operations, July 8–11 2003, Pasadena, CA.

Barabash, S., et al., 2004. ***Towards Low-Cost Swedish Planetary Missions***, 24th International Symposium on Space Technology and Science, Miyazaki, Japan, May 30–June 6, 2004.

Barnhart, D.J., T. Vladimirova, and A. M. Baker, 2006. ***A Low-Cost Femtosatellite to Enable Distributed Space Missions***, Report No. A039264, 16 pg., Surrey University (Guildford, United Kingdom), Surrey Space Centre, Sept. 20, 2006.

Bauer, T.P., R. C. Conger, J. R. Wertz, and N. Sarzi-Amade, 2010, ***Design, Performance, and Responsiveness of a Low-Cost Micro-Satellite Launch Vehicle***, RS8-2010-5003, 8th Responsive Space Conference, March 8-11, 2010, Los Angeles, CA.

Bermyn, J., 2010, ***Proba Spacecraft Family — Affordable Small Mission Solutions for Earth Orbit***. RS8-2010-7005, 8th Responsive Space Conference, March 8-11, 2010, Los Angeles, CA.

***** Branco, M.S.A., G. Loureiro, and L.G. Trabasso, 2007. ***Space Mission Architecture Trade-off Based on Stakeholder Value***, (book chapter), *Complex Systems Concurrent Engineering*, Part 2, pg. 91–98, London: Springer.

***** Brewer, A.M., 2007. ***Using COTS to Reduce Cost and Mitigate Risk in Support of the Vision for Space Exploration***, AIAA Houston Section, Annual Technical Symposium, ATS 2007.

Burt, R., 2010, ***Cost Advantages of Modular Scalable Avionics***, RS8-2010-4001, 8th Responsive Space Conference, March 8-11, 2010, Los Angeles, CA.

Deininger W.D., L. Andreozzi, K.W. Epstein, E.L. Norman-Gravseth, W. Purcell, 2001. ***Micromission Spacecraft-a Low-Cost, High-Capability Platform for Space Science Missions*****,** Aerospace Conference 2001, Big Sky, MT, IEEE Proceedings, vol. 1, pg. 1/33–1/40.

***** Deloitte Consulting LLP, 2008**. *Can We Afford Our Own Future? Why A&D Programs are Over-Budget and What Can Be Done to Fix the Problem***. Corporate report available at http://www.deloitte.com/dtt/article/0,1002,sid%253D2223%2526cid%253D233750,00.html.

* Foust, J., D. Vaccaro, C. Frappier, and D. Kaiser, 2008. ***If You Build It, Who Will Come? Identifying Markets for Low-Cost Small Satellites***. Paper No. SSC08-I-1, presented at the 22nd AIAA/US Conference on Small Satellites, Logan, UT, August 11–14, 2008.

Giaretta, D. et al., 1998. ***Cost Savings vs. Cost Effectiveness of Space Missions***

and the Use of CCSDS Panel 2 Standards, SpaceOps '98, Tokyo, Japan, 1998.

Girolamo, G. D, 1998. ***The Integral Mission Control System (IMCS): Low-Cost Design for a Complex Ground Segment***, Paper ID: 2b013, SpaceOps '98, Tokyo, Japan.

Hamann, R.J. et al., 2008. ***Nano-Satellites for Micro-Technology Pre-Qualification: The Delfi Program of Delft University of Technology***, in *Small Satellites for Earth Observation*, Section 8, pg. 319–330, The Netherlands: Springer.

* Herrell, L. 2009. **A Systems Approach to Lower Cost Missions: Following the Rideshare Paradigm**, AIAA Space 2009 Conference & Exposition, AIAA 2009-6503, September 14-17, 2009, Pasadena, CA.

***** Hogie, K., E. Criscuolo, and R. Parise, 2005. ***Using Standard Internet Protocols and Applications in Space***, *Computer Networks*, ISSN 1389-1286, 2005, vol. 47, no. 5, pg. 603–650.

* Hurley, M. and B. Purdy, 2010. ***Designing and Managing for a Reliability of Zero*****,** European Space Agency 4S Symposium, Funchal, Portugal, May 31 – June 4, 2010, Paper No. 1885505.

***** Kitts, C.A. and R.J. Twiggs, 1998. ***Low Cost Space Missions for Education and Technology Research***, 21st International Symposium on Space Technology and Science, Omiya, Japan, May 24–31, 1998.

Kitts, C., et al., 1999a. ***Emerald: An Experimental Mission in Robust Distributed Space Systems*****,** 13th Annual AIAA/USU Conference on Small Satellites, Logan, UT, Aug. 23–26, 1999.

Kitts, C., et al., 1999b. ***Experiments in Distributed Microsatellite Space Systems***, Proceedings of the AIAA Space Technology Conference and Exhibit, Albuquerque, NM, September 28–30, 1999.

Kitts, C., et al., 2000. ***Emerald: A Low-Cost Spacecraft Mission for Validating Formation Flying Technologies*****,** Proceedings IEEE Aerospace Conference, 2000.

* Koller, M. and C. Schurig, 2009, ***Cost Reduction - Buzzwords and Their Real Use: Mission Families, Mission Planning, Mission Automation and Standardization***, 3rd IEEE International Conference on Space Mission Challenges for Information Technology, pg. 305 – 312, July 19-23, 2009, Pasadena, CA.

Kulpa, J., et al., 2003. ***Responsive Launch With the Scorpius Family of Low-Cost Expendable Launch Vehicles***, 1st Responsive Space Conference, April 1–3, 2003, Redondo Beach, CA.

Manzella., D. 2007. ***Low Cost Electric Propulsion Thruster for Deep Space Robotic Missions***, 2007 NASA Science and Technology Conference (NSTC–07) College Park, MD, June 19–21, 2007.

Matsuda, S., K. Yagi, J. Yokote, A.C. Charania, T. Fuji, and H. Kanayam, 2010, ***Development of an Affordable and Dedicated Nano-Launcher***, RS8-2010-5006, 8th Responsive Space Conference, March 8-11, 2010, Los Angeles, CA.

* Matthews, G., K. Havey, Jr., and R. Egerman, 2010, ***A Paradigm Shift to Enable More Cost-Effective Space Science Telescope Missions in the Upcoming Decades***. Modeling, Systems Engineering, and Project Management for Astronomy IV Conference, Proc. SPIE, Vol. 7738, 773824 (2010), San Diego, California, June 27, 2010.

McDermott, S.A. and D.J. Goldstein, 2000. ***The Bitsy™ Spacecraft Kernel: Reducing Mission Cost with Modular Architecture and Miniature Technology***, Aerospace Conference Proceedings, 2000 IEEE, vol. 4, pg.1–6.

Meissinger, H.F. and S. Dawson, 1997. ***Reducing Planetary Mission Cost by a Modified Launch Mode***, AAS/AIAA Astrodynamics Specialist Conference in Sun Valley, ID, Aug. 4, 1997.

Neri J. A., et al., 1996. ***SACI-1 - A Cost-Effective Microsatellite Bus for Multiple Mission Payloads***, International Conference on Small Satellites: Missions and Technology, Sept. 9–13, 1996, Madrid, Spain.

***** Nowinski, E.H. and R.J. Kohler, 2008. ***The Lost Art of Program Management in the Intelligence Community***, CIA publication available at: https://www.cia.gov/library/center-for-the-study-of-intelligence/csi-publications/csi-studies/studies/vol50no2/html_files/Program_Management_4.htm.

Phipps, A., A. da Silva Curiel, M. Meerman, D. Gibbon, M. Sweeting, and L. Gomes. 2003. ***Low Cost Lunar Orbiter System Design***, in Proceedings of the Aerospace Conference. Big Sky, MT: IEEE.

Quigley, D. and A. Monham, 2003. ***Reducing Mission Costs Through Effective Lifecycle Management of Operations Knowledge***, 5th International Symposium on Reducing the Cost of Spacecraft Ground Systems and Operations, July 8–11 2003, Pasadena, CA.

***** Ridenoure, R. and K. Polk, 1998. **Private, Commercial and Student-oriented Low-Cost Deep-Space Missions: A Global Survey of Activity**, 3rd IAA International Conference on Low-Cost Planetary Missions, April 27–May 1, 1998, Pasadena, CA.

Silny, J., S. Schiller, and E. Gussin, 2010, ***Design Decisions that Enabled the Responsive Space ARTEMIS Sensor on TacSat-3***, RS8-2010-3001, 8th Responsive Space Conference, March 8-11, 2010, Los Angeles, CA.

Stephens, J. P. 2003. ***Developing National Space Capability with Small Low Cost Satellites***, in Proceedings of the International Conference on Recent Advances in Space Technologies. Istanbul, Turkey: IEEE.

Stuart, J. C. et al., 2006. ***CryoSat Mission Preparation: A Cost Savings and Quality Improvement Case Study***, American Institute of Aeronautics and Astronautics, SpaceOps 2006, Paper No. AIAA 2006-5922.

Susan C. Murphy, S.C. and J.J. Louie. 1997. ***Reducing the Cost of Mission-Unique Data Systems for Deep Space Missions***, JPL Multimission Ground Systems Office Telemetry, Command & Data Management Program Element, July 22, 1997.

Swartwout M.A. and C.A. Kitts, 1997. ***Automated Health Operations for the Sapphire Spacecraft***, ITC/USA '96: 33rd Annual International Telemetering Conference, Las Vegas, NV, Oct. 30–Nov. 1, 1997.

Trajkovic, S., G. Tyc, K. James, D. Schulten, P. Allan, E. Ahad, R. Allen, and S. Ladouceur, 2009, ***A Modular, Multi-Use Payload Electronics Architecture for Affordable, Responsive Missions***, RS7-2009-3006, 7th Responsive Space Conference, April 27-30, 2009, Los Angeles, CA.

Tsou H., A. Mileant, R. Lee, and S. Hinedi, 1995. ***The Recovery of Buffered Telemetry Data for Future Low Cost Space Missions***, 1995 IEEE International Conference, vol. 2, pg. 919–923, Seattle, WA, June 18–22, 1995.

Tuli, T.S., N.G. Orr, and R.E. Zee, 2006. ***Low Cost Ground Station Design for Nanosatellite Missions***, 2006 AMSAT North American Space Symposium, San Francisco, CA, Oct. 5–10, 2006.

Van Gaasbeck, J., A. Posner, and A. J. Jeffries, 1997. ***Design and Development of the Satellite Control Center (SCC) for the Far Ultraviolet Spectroscopic Explorer (FUSE) Mission***, 2nd International Symposium on Reducing the Cost of Spacecraft Ground Systems and Operations, July 21–23, 1997.

* Ward, D. 2010. ***Faster, Better, Cheaper Revisited. Program Management Lessons from NASA.*** Defense AT&L, pg. 48-52, March-April 2010.

***** Wertz, J.R., 2000. ***Economic Model of Reusable vs. Expendable Launch Vehicles***, 51st International Astronautical Congress, Oct. 2–6, 2000, Rio de Janeiro, Brazil.

* Wertz, J.R., 2009, ***Dramatically Reducing Space Mission Cost***, Microcosm White Paper, April 25, 2009. Available for no cost at http://www.smad.com/course/Reducing%20Mission%20Cost%20R4.pdf

* Wertz, J.R., 2010, ***Assessment of SmallSat Utility and the Need for Dedicated, Low-Cost, Responsive Small Satellite Launch***, RS8-2010-5005, 8th Responsive Space Conference, March 8-11, 2010, Los Angeles, CA.

***** Wertz, J., and S. Dawson, 1996. ***What's the Price of Low Cost?***, 10th Annual AIAA/USU Conference on Small Satellites, Sept.1996, Logan, UT.

Wertz, J.R., and G. Gurevich, 2001. ***Autonomous Orbit Control: Flight Results and Cost Reduction***, JHU/APL Symposium on Autonomous Ground Systems for 2001 and Beyond, April 25–27, 2001, Laurel, MD.

Wertz, J.R., R.E. Van Allen, and T. Barcley, 2010, ***NanoEye — Military Relevant Surveillance for Less Than $5 Million Total Recurring Mission Cost***, RS8-2010-1008, 8th Responsive Space Conference, March 8-11, 2010, Los Angeles, CA.

Zee, R.E. and P. Stibrany. 2004. ***Canada's First Microsatellite — An Enabling Low-Cost Technology for Future Space Science and Technology Missions***, Canadian Aeronautics and Space, journal 48, no. 1, pg. 1–3, Mar. 2002.

* Zenick, R., 2009, ***The Benefits of Applying the Lessons from Microspace to Achieving the Goals of Responsive Space***, RS7-2009-3005, 7th Responsive Space Conference, April 27-30, 2009, Los Angeles, CA.

Zhenping, Li, and C. Savkli, 2006***. Autonomic Computing for Spacecraft Ground Systems***, Space Mission Challenges for Information Technology. SMC-IT 2006, 2nd IEEE International Conference, July 17–20, 2006, pg. 8.

The Journal or Reducing Space Mission Cost, J.RSMC

The *Journal of Reducing Space Mission Cost* was published in 1998 and 1999, but was not successful and ceased publication after the first volume. Nonetheless, it represents the largest single collection of refereed articles directly related to mission cost reduction, many or most of which are still relevant. If you would like a PDF copy of any of these articles, send an E-mail to Donna Klungle at bookproject@smad.com.

Note: Of particular interest here is the article by Randii Wessen and David Porter on the Cassini Resource Exchange. (The first paper in Vol. 1, No. 1.) This one presents a truly unique and apparently successful approach to constraining cost overruns in science missions with multiple payloads.

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