A Survey of Cost Estimating Methodologies for Distributed Spacecraft Missions

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Outline

- Distributed Spacecraft Missions
- Existing Cost Practices and Challenges
- Motivation
- Methodology
- Results and Recommendations
- Illustrative Example
- Conclusion

Distributed Spacecraft Missions

- Mission architecture deploying ***two or more satellites in support of a common goal, or goals***
- Emerging as essential tools for the future of earth science, given their multiplatform sensing capabilities, increased re-visit frequency
  - SmallSats in particular often lend themselves to DSM applications
- NASA's LandSat program has offered tremendous scientific value given it's contribution to a multi-decadal record

Types of DSMs

- **Constellations**: Missions designed as DSMs from their inception (GPS, MMS, CYGNSS)
- **Formation Flying Missions**: DSMs with specific spatial configuration requirements, such as relative distance or three dimensional arrangement (GRACE)
- **Fractionated Spacecraft Missions**: Missions that distribute the functional capabilities of a traditional, monolithic spacecraft across multiple platforms (DARPA System F6)

Types of DSMs (continued)

- **Ad Hoc Constellations**: Individual missions that are combined to support common goals
  - **Purely Ad Hoc**: Separate missions that combined either during development or after launch to create one mission (TOPEX/Poseidon, A-Train)
  - **Temporally Distributed Spacecraft Missions**: A series of missions (that may or may not have overlapping operational lifetimes) designed to support a common, long duration mission objective or objectives (Jason-2/3, LandSat, A-Train)

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Example: Afternoon Train

- The Afternoon Train (A-Train) represents both of these sub classifications
- The first four (Aqua, Aura, CloudSat, and CALIPSO) launched into highly similar orbits in the early 2000s
  - The Earth science community leveraged these satellites as a distributed system
  - These 4 spacecraft constitute a purely ad hoc constellation

Example: Afternoon Train

- Follow on missions (PARASOL, GCOM-W1, OCO-2, and Glory) were designed to support the existing satellites
  - These represent temporally distributed spacecraft missions that were used to further the previous observation objectives

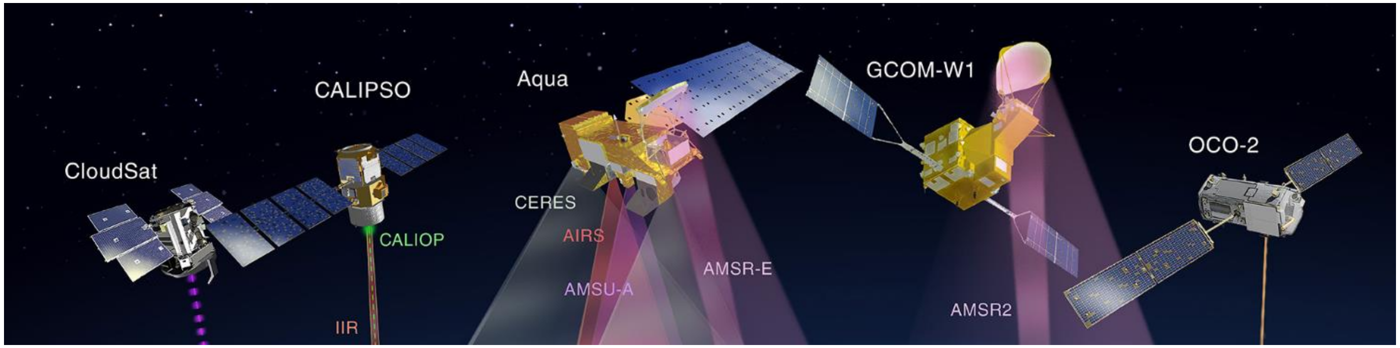


Image Credit: http://atrain.nasa.gov/

DSM Cost Estimating

- Parametric cost estimating
  - Relies on historical datasets and regression tactics to build Cost Estimating Relationships (CERs) predict cost according to key mission drivers
  - Wide range of existing tools for a range of satellite sizes, mission classifications, science objectives, and mission phases

Work Breakdown Structure

- The Work Breakdown Structure (WBS) provides a hierarchical representation of project deliverables
- Work not included in the WBS is not accounted for within cost estimates

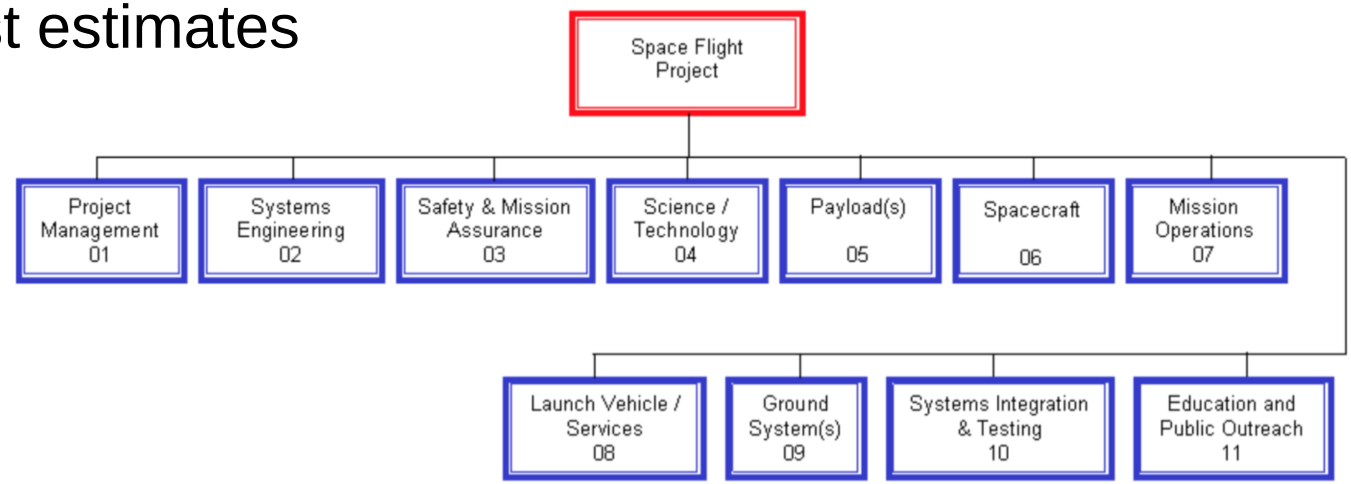


Image Credit: NASA Work Breakdown Structure Handbook

Existing DSM Costing Challenges

- The underlying assumptions regarding the design and manufacturing process are challenged by the emerging DSM paradigm
- Three obstacles to high fidelity constellation cost models:

    1. All CERs are developed based on historical datasets, and an underlying assumption is that historical trends will hold

        a. The application of existing CERs to DSM architectures, which often leverage advanced or specialized technology, may be inappropriate.

Existing DSM Costing Challenges

2. Tendency in early optimization efforts to estimate the total mission cost for a DSM containing n identical spacecraft by calculating the cost for one spacecraft and multiplying it n times.
   a. This method fails to account for benefits of developing multiple spacecraft simultaneously (e.g. economies of scale and learning curve advantages)
   b. Also fails to address the additional cost-risk associated with late design changes or manufacturing errors.

Existing DSM Costing Challenges

3. The design process for DSMs may account for system scalability and flexibility in a way not addressed by monolithic design efforts.
    a. This may result in different costs and value generated by the system must be taken into account through proper discounting and probabilistic cost estimating
    b. Cost and value depends not only on the initial architecture, but also on later decisions to exercise (or not exercise) system options.

Previous Work

- Existing optimization efforts have leveraged existing CERs but generally have not tailored cost modules specifically for DSMs
  - Multiply by *n* approach
- Nag et al. (2014) addressed the challenges of using traditional costing methods for DSM
  - Low reliability of existing learning curve factors
  - Lack of parametric tools for satellites with mass < 20kg
  - Insufficient experience with small sat operations

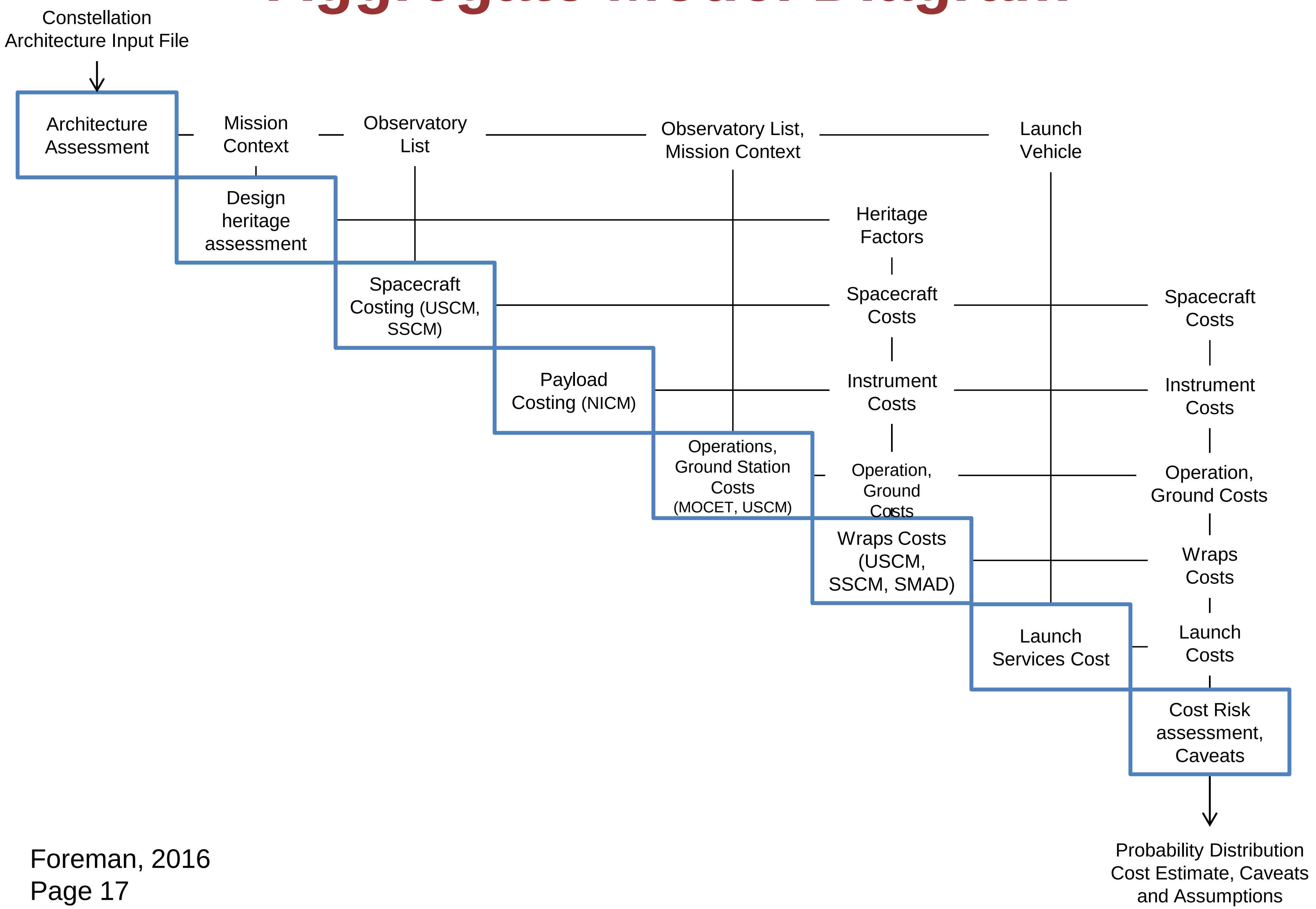
Motivation

- Reliable cost estimating is essential to the mission proposal process
- As DSMs offer new advantages to the realm of Earth science and observation, they also offer new challenges to cost estimators
- New cost estimating practices are required to more accurately represent the new technological landscape

Methodology

- To survey the existing cost estimating toolkit as it pertains to DSMs, we have developed an aggregate cost model for constellation cost estimating.
  - Leveraging widely accepted CERs
  - Pre-Phase A comparative, not exact value, estimate
  - Not addressing schedule or scope creep
    - Assuming project is executed at the optimal pace
- In support of a NASA Goddard effort to develop a Tradespace Analysis Tool for Constellations (TAT-C)

Aggregate Model Diagram



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Results and Recommendations

- Building the aggregate cost model required examination of each step of the DSM development process
- We found four areas were existing cost estimating methodologies do not account for the innovative nature of DSM development:
  1. Design iteration
  2. System Integration and Testing
  3. Mission Operations
  4. Technology Development

Design Iteration

- DSM optimization often results in a set of possible solutions, so design iteration and rework are essential to the early development process
- Constellation rework may pertain to a single spacecraft, multiple instances of one component, or the entire system
- The NASA WBS Handbook specifically excludes “rework, retesting, and refurbishing” from the standard WBS
  - Existing margins may not account for the change propagation associated with DSM systems
  - Late stage design changes can have significant impact on cost growth

Design Iteration Example: MMS

- The Magnetospheric Multiscale Mission (MMS) consisted of four identical spacecraft
- Failed component within the Fast Plasma Instrument (FPI) was discovered during the integration phase, requiring significant rework
  - Before the end of the integration and test phase, MMS had used almost all of its available budget
  - The component failure also contributed to significant schedule delays

Design Iteration: Recommendation

- We recommend that design iteration, which has the potential to result in design rework, retesting, and refurbishment, be specifically included within WBS Element 6 (Spacecraft) for constellation missions as an essential spacecraft deliverable required to achieve project objectives.
- We intend to examine the applicability of existing design heritage factors to Earth science constellations and ad-hoc DSMs in a future work, as a method of accounting for the cost savings associated with using iterations of previous work.

Systems Integration and Testing

- For DSMs, system integration includes both the integration of each individual satellite and the fleet as a whole
  - Previous CERs may not account appropriately for this two-tier integration and testing requirement
- Scientific program managers have begun implementing process assembly lines, in which spacecraft are built in parallel, with teams and services move from product to product

Systems Integration and Testing

- Wider use of concurrent engineering practices suggests that costs for planning manufacturing, integration, and testing may be incurred as part of the design phase
- Design phase can also choose to accept lower fault tolerance for individual spacecraft if the constellation can tolerate the loss of one or more spacecraft
  - Introduces a tradeoff between spacecraft reliability and constellation redundancy

Systems Integration and Testing: Recommendations

- We recommend manufacturing be considered as an element of systems integration and testing (WBS10) for constellation missions and encourage cost estimating model developers to develop CERs that address the unique nature of satellite constellation manufacturing and integration.
- We further recommend that program managers and cost estimators consider the nuances of constellation fault tolerance and system testing when allocating project funding and considering the tradeoffs between individual satellite and DSM risk.

Mission Operations

- DSMs are relying on increased levels of automation for normal system operations
- Automated operations introduce new tradeoffs between cost and risk:
  - Reduce the need for some ground station equipment and personnel
    - Increased need for off-nominal operating teams
  - Increase development costs earlier in the project lifecycle and software specific risks

Mission Operations Example: ST5

- Space Technology 5 mission, consisted of three 25 kg satellites
- Despite initial challenges, ST5 was able to achieve its mission objectives, largely due to the Anomaly Team
- Toward the end of its 100 day mission, ST5 completed a weeklong ‘lights out’ operating period

Mission Operations: Recommendation

- We recommend that the current approach to DSM operations cost estimating be reconsidered, including the development of a new CER that addresses the degree of autonomy built into a given constellation operation plan.
- Given that approximately 10% of the NASA Earth science budget is spent maintaining and processing data from spacecraft that have exceeded their operational lifetimes, this should also be considered as part of the Phase E planning process.

A Note on Technology Development

- Raising TRL on small satellite missions, while simultaneously attempting aggressive science goals, can generate significant cost growth
  - ST5 experienced 62.5% cost growth
  - Cubesatellite missions have been difficult to cost, in part due to the cost associated with miniaturizing complex instruments
    - We plan to examine this impact in a future work

Illustrative Example

- Consider a costing reference mission:
  - 12 identical spacecraft
  - each with a dry mass of 100 kg
  - Earth observation payload
- To demonstrate the impact of our first recommendation, we will cost the constellation first using the multiply-by-*n* approach

Traditional costing of a single spacecraft

- We can cost one of the spacecraft using CERs available from the 1996 Small Satellite Cost Model:

$$C_{spacecraft} = 781 + 26.1\ m_{dry}1.261$$

$$C_{payload} = 0.4\ C_{spacecraft}$$

$$C_{satellite} = C_{spacecraft} + C_{payload}$$

- We assume the nonrecurring and recurring costs constitute 60% and 40% of the the satellite total respectively

Traditional Costing Results

- To calculate the cost of the constellation, we multiply $C_{satellite}$ *by 12*

	Single Satellite	Single Satellite Nonrecurring	Single Satellite Recurring	Constellation	Constellation Nonrecurring	Constellation Recurring
Spacecraft Bus Cost (FY00$)	$9,463,414.34	$5,678,048.60	$3,785,365.74	$51,102,437.44	$5,678,048.60	$45,424,388.84
Payload Cost (FY00$)	$3,785,365.74	$2,271,219.44	$1,514,146.29	$20,440,974.98	$2,271,219.44	$18,169,755.53
Total Cost (FY00$)	$13,248,780.08	$7,949,268.05	$5,299,512.03	$71,543,412.42	$7,949,268.05	$63,594,144.37

Implementing the first recommendation set

- To account for design iteration and the cost of designing the DSM as a system, we leverage a heritage factor of 0.2 to scale the development costs for copy satellites
  - The first satellite will incur normal recurring costs, and each of the following *n-1* satellites will 20% of the nonrecurring costs
- This will account for some systems level costs and design iteration considerations that pertain to the constellation system

Implementing the first recommendation set (cont.)

- We then apply the learning curve factor proposed by Nag et al. for small satellites to scale the recurring costs.
- The recurring costs, using a learning curve, are calculated:

$$RC_{constellation} = RC_{individual}\, n^{\log_2 b}$$

where $RC_{constellation}$ is the constellation recurring cost

$RC_{individual}$ is recurring cost of a single (original) satellite

b is the learning curve factor for small satellites, 0.67

Refined Costing Results

	Single Satellite	Single Satellite Nonrecurring	Single Satellite Recurring	Constellation	Constellation Nonrecurring	Constellation Recurring
Spacecraft Bus Cost (FY00$)	$9,463,414.34	$5,678,048.60	$3,785,365.74	$28,978,463.49	$18,169,755.53	$10,808,707.95
Payload Cost (FY00$)	$3,785,365.74	$2,271,219.44	$1,514,146.29	$11,591,385.40	$7,267,902.21	$4,323,483.18
Total Revised Cost (FY00$)	$13,248,780.08	$7,949,268.05	$5,299,512.03	$40,569,848.88	$25,437,657.75	$15,132,191.13
Total Difference (FY00$)	$0.00	$0.00	$0.00	$30,973,563.53	($17,488,389.70)	$48,461,953.24

Illustrative Example Conclusions

- Demonstration of high-level trends in cost due to learning curve effect and design iteration:
  - Design iteration results in an increase in nonrecurring costs
  - Learning curve effects reduce recurring costs
- By further refining the estimate, and accounting for other DSM specific cost trends earlier, program managers could produce more reliable, tailored cost estimates

Conclusion

- We have developed an aggregate cost model for constellations and identified four shortcomings of the existing cost estimating toolkit, as it pertains to DSMs:

  1. Design iteration
  2. System Integration and Testing
  3. Mission Operations
  4. Technology Development

- We have offered preliminary recommendations to address these shortcomings and demonstrated their impact through an illustrative example.

Thank you for your attention

QUESTIONS?

References

- S. Nag, J.J. LeMoigne, D.W. Miller, O.L. de Weck, "A Framework for Orbital Performance Evaluation in Distributed Space Missions for Earth Observation", IEEE Aerospace Xplore 10.1109/AERO.2015.7119227, ISBN: 978-1-4799-5379-0, March 2015.
- "GRACE - Gravity Recovery and Climate Experiment." GRACE - Gravity Recovery and Climate Experiment. University of Texas, 20 Aug. 2010. Web. 21 June 2016.
- United States. Government Accountability Office. *Additional Knowledge Would Better Support Decisions about Disaggregating Large Satellites (GAO-15-7)*. N.p.: Government Accountability Office, 2014. Print.
- NASAESTO. "NASA Earth Science at 2030: A Vision of the Future." YouTube. NASA Earth Science Technology Office, 01 Aug. 2012. Web. 19 July 2016.
- National Aeronautics and Space Administration. NASA Newsroom. NASA Selects Low Cost, High Science Earth Venture Space System (12-203). NASA, 18 June 2012. Web. 25 June 2016.
- Sanchez Net, Marc, Daniel Selva, and Alessandro Golkar. "Exploring classification algorithms for early mission formulation cost estimation." Aerospace Conference, 2014 IEEE. IEEE, 2014.
- S. Nag, J.J. LeMoigne, O.L. de Weck "Cost and Risk Analysis of Small Satellite Constellations for Earth Observation", IEEE Aerospace Xplore 10.1109/AERO.2014.6836396, ISBN: 978-1-4799-5582-4, March 2014.
- Sega R., de Weck O.L, et al., “Controlling Cost Growth of NASA Earth and Space Science Missions” By Committee on Cost Growth in NASA Earth and Space Science Missions, National Research Council (NRC) of the National Academy of Sciences, ISBN-13: 978-0-309-15737, Washington. D.C., July 2010.
- De Selding, Peter B. "First Batch of Iridium Next Satellites Good to Go for July SpaceX Launch - SpaceNews.com." *SpaceNews.com*. N.p., 29 Apr. 2016. Web. 22 July 2016.
- De Selding, Peter B. "OneWeb Satellites to Open Factory in Florida with Eyes on Business beyond OneWeb - SpaceNews.com." *SpaceNews.com*. N.p., 18 Apr. 2016. Web. 22 July 2016.
- “MMS Mission Overview.” *NASA*. Ed. Rob Garner. NASA, 22 Oct. 2015. Web. 30 June 2016.
- “TROPICS: Mission Overview.” *Mission Overview*. MIT Lincoln Laboratory, 2015. Web. 1 June 2016.
- Bearden, David A. "Small-satellite costs." *Crosslink* 2.1 (2001): 32-44.
- Rasmussen, Amy L. "Cost models for large versus small spacecraft." *SPIE's International Symposium on Optical Science, Engineering, and Instrumentation*. International Society for Optics and Photonics, 1998.
- Budianto, Irene A., and John R. Olds. "Design and deployment of a satellite constellation using collaborative optimization." Journal of spacecraft and rockets 41.6 (2004): 956-963.
- Underwood J., de Weck O.L., Chan S., Samuels A., Shah N. “Optimization of Hybrid Satellite Constellations using Multiple Layers and Mixed Circular-Elliptical Orbits”, AIAA-2004-3205, 22nd AIAA International Communications Satellite Systems Conference and Exhibit, Monterey, California, May 9-12, 2004.
- Wertz, James Richard., and Wiley J. Larson. Space Mission Analysis and Design. 3rd ed. Torrance, CA: Microcosm, 1999. Print.
- Howard, Joseph, Dipak Oza, and Danford S. Smith. "Best Practices for Operations of Satellite Constellations." (2006).
- de Weck, O.L., de Neufville R. and Chaize M., “Staged Deployment of Communications Satellite Constellations in Low Earth Orbit”, *Journal of Aerospace Computing, Information, and Communication*, 1 (3), 119-136, March 2004.
- J. Le Moigne, J.C. Adams, P. Dabney, D. Leisawitz, F. Lemoine, S. Nag, W. Powell, D. Smith, K. Thome, and S. Tompkins, "An Overview of Distributed Spacecraft Missions (DSM)", IEEE *Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS)*, in preparation.
- "TDRS Home | Goddard Space Flight Center." *TDRS Home | Goddard Space Flight Center*. NASA, 2 Oct. 2014. Web. 01 Aug. 2016.
- Ferster, Warren. "DARPA Cancels Formation-flying Satellite Demo." *SpaceNews.com*. N.p., 17 May 2013. Web. 01 Aug. 2016.
- Marinan, Anne, Austin Nicholas, and Kerri Cahoy. "Ad hoc CubeSat constellations: Secondary launch coverage and distribution." *Aerospace Conference, 2013 IEEE*. IEEE, 2013.
- "Missions." *Ocean Surface Topography From Space*. Ed. Margaret Srinivasan. NASA Jet Propulsion Laboratory, n.d. Web. 01 Aug. 2016.
- "Landsat." *Landsat*. US Geological Survey, 23 May 2016. Web. 26 July 2016.
- NASA. N. *Introducing the A-Train*. *NASA News*. NASA, 26 Oct. 2010. Web. 26 July 2016.
- "The Afternoon Constellation." *National Aeronautics and Space Administration*. Ed. Steven Platnick. NASA, 5 June 2012. Web. 26 July 2016.
- NASA, NASA. "Cost Estimating Handbook: Version 4.0." *Washington, DC* (2015).
- Filippazzo, Giancarlo. "Complexity based cost estimating relationships for space systems." *Aerospace Conference, 2004. Proceedings. 2004 IEEE*. Vol. 6. IEEE, 2004.
- Nguyen, Phu, et al. "Unmanned Space Vehicle Cost Model." *US Air Force Space and Missile Systems Center (SMC/FMC)* 2430 (1994): 90245-4687.

References

- Slain, N. Y., T. J. Mosher, and J. M. Neff. "Small Satellite Cost Model, Version 98 InTRO." (1999).
- Habib-Agahi, Hamid, Joe Mrozinski, and George Fox. "NASA instrument cost/schedule model Hamid Habib-Agahi." *Aerospace Conference, 2011 IEEE*. IEEE, 2011.
- Hayhurst, Marc, Shirin Eftekharzadeh, Brian Wood, Vishnu Jyothindran, Robert Kellogg, Cindy Daniels, Lissa Jordin, and Washito Sasamoto. "Mission Operations Cost Estimation Tool (MOCET)." 2015 NASA Cost Symposium. Ames Research Center, Moffett Field, CA. *NASA 2015 Cost Symposium Presentations*. NASA Cost Analysis Division, 2015. Web. 22 July 2016.
- "PCEC – Project Cost Estimating Capability." *NASA*. Ed. Bill Keeter. NASA, 18 Aug. 2014. Web. 02 Aug. 2016.
- Boghosian, Mary. "Cost Estimating Methodology for Very Small Satellites: A-PICOMO (Aerospace Picosatellite Cost Model)." 1st Interplanetary CubeSat Workshop. Cambridge, MA. ICubeSat, 2012. Web. 27 July 2016.
- "COSYSMO." *COSYSMO*. Massachusetts Institute of Technology, 2016. Web. 08 Aug. 2016.
- John, James K., Eric Plumer, Mike Blandford, and Julie McAfee. "One NASA Cost Engineering Database (ONCE)." NASA 2015 Cost Symposium. Ames Research Center, Moffett Field, CA. 29 Apr. 2016. Lecture.
- Shishko, Robert, and Robert Aster. "NASA systems engineering handbook." NASA Special Publication 6105 (1995).
- NASA Headquarters. Earned Value Management Office. *NASA Work Breakdown Structure Handbook*. NASA, 2010. Web. 25 June 2016.
- Foreman, Veronica, Jacqueline Le Moigne, and Olivier De Weck. "Satellite Constellation Cost Modeling: An Aggregate Model." *ESTF2016*. Proc. of Earth Science Technology Forum 2016, Annapolis, MD. NASA Earth Science Technology Office, 13 July 2016. Web. 15 July 2016.
- Le Moigne, Jacqueline. "A Trade-space Analysis Tool for Constellations." Earth Science Technology Forum 2016. Annapolis, MD. 14 June 2016. Lecture.
- Shao, Anthony, Elizabeth A. Koltz, and James R. Wertz. "Performance Based Cost Modeling: Quantifying the Cost Reduction Potential of Small Observation Satellites." AIAA Reinventing Space Conference, AIAA-RS-2013-1003, Los Angeles, CA, Oct. 2013.Bearden, David A. "Small Satellite Costs." Crosslink. Aerospace Corporation, 2000. Web. 6 Jun. 2016.
- Brumbaugh, Katharine Mary. *The Metrics of Spacecraft Design Reusability and Cost Analysis as Applied to CubeSats*. Thesis. The University of Texas at Austin, 2012. N.p.: n.p., n.d. Print.
- United States. Government Accountability Office,. *NASA Assessments of Selected Large-Scale Projects: Report to Congressional Committees*. Washington, D.C.: United States Government Accountability Office, 2014. 12+. Print.
- United States. National Research Council. Committee on Heliophysics Performance Assessment. *A Performance Assessment of NASA's Heliophysics Program*. Washington DC: National Academies, 2009. 30-31. Print.
- Leone, Dan. "After Dodging Bullets in Development, MMS Set for Launch." *SpaceNews.com*. N.p., 09 Mar. 2015. Web. 03 Aug. 2016.
- United States. Office of the Inspector General. Office of Audits. *AUDIT OF NASA'S JOINT COST AND SCHEDULE CONFIDENCE LEVEL PROCESS (Report No. IG-15-024)*. Washington DC: n.p., 2015. 2-5. Print.
- Wertz, James R., et al. "Autonomous constellation maintenance." *Mission Design & Implementation of Satellite Constellations*. Springer Netherlands, 1998. 263-273.
- Foreman, Veronica L., et al. "Software in military aviation and drone mishaps: Analysis and recommendations for the investigation process." *Reliability Engineering & System Safety* 137 (2015): 101-111.
- "Space Technology 5 (ST5)." *EoPortal Directory - Satellite Missions*. European Space Agency, n.d. Web. 03 Aug. 2016.
- O'Donnell, James R., et al. "Space Technology 5 launch and operations." (2007).
- Freilich, Michael. "Forum Welcome & Plenary Address." Earth Science Technology Forum 2016. Annapolis, MD. 14 June 2014. Speech.
- Carlisle, Candace C., and Eric J. Finnegan. "Space Technology 5: pathfinder for future micro-sat constellations." *Aerospace Conference, 2004. Proceedings. 2004 IEEE*. Vol. 1. IEEE, 2004.
- Amer, Tahani R. *Development of Risk Uncertainty Factors from Historical NASA Projects*. Diss. Old Dominion University, 2011.
- 6. IEEE, 2004.
- Nguyen, Phu, et al. "Unmanned Space Vehicle Cost Model." *US Air Force Space and Missile Systems Center (SMC/FMC)* 2430 (1994): 90245-4687.