References

1. J. Schlager, "Systems engineering: key to modern development," IRE Transactions, EM-3 (3) 64–66 (July 1956) [doi: 10.11009/IRET-EM.1956.5007383].
2. https://en.wikipedia.org/wiki/International_Council_on_Systems_Engineering
3. M. Bay et al., "The Art and Science of Systems Engineering," NASA white paper, https://www.nasa.gov/pdf/311199main_Art_and_Sci_of_SE_SHORT_1_20_09.pdf
4. G. Lee, "So you want to be a Systems Engineer? - Personal Behaviors of a Systems Engineer," The Systems Engineering Advancement Project, https://www.youtube.com/watch?v=E6U_Ap2bDaE
5. R. Giacconi, *Secrets of the Hoary Deep: A Personal History of Modern Astronomy*, Baltimore: The Johns Hopkins University Press, 2008. Project MUSE. Web. 9 Aug. 2016. <https://muse.jhu.edu/>.
6. Systems Engineering Handbook, NASA/SP-2007-6105 Rev1, page 20.
7. R. Wessen et al., "Space Mission Concept Development using Concept Maturity Levels," AIAA SPACE 2013 Conference and Exposition. September.
8. Systems Engineering Handbook, NASA/SP-2007-6105 Rev1, page 51.
9. Systems Engineering Handbook, NASA/SP-2007-6105 Rev1, page 56.
10. G. Lee, "Systems Engineering When the Canvas is Blank," Frontline Lecture Series, November 18, 2007, https://www.youtube.com/watch?v=mLM-PiAO1nk; https://www.nasa.gov/pdf/311199main_Art_and_Sci_of_SE_SHORT_1_20_09.pdf
11. INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, Edition: 4, Publisher: John Wiley and Sons, Inc., Editor: David D. Walden, ESEP; Garry J. Roedler, ESEP; Kevin J. Forsberg, ESEP; R. Douglas Hamelin; Thomas M. Shortell, CSEP, ISBN: 9781118999400.
12. A. Kossiakoff and W. Sweet, "Systems Engineering: Principles and Practice," 2nd ed., p. 172, Wiley (2011) [doi: 10.1002/0471723630].

13. P. A. Lightsey, "Requirements management lessons learned: fuzzy 'most likely' versus clean shaven 'not to exceed'," *Proc. SPIE* **9583**, An Optical Believe It or Not: Key Lessons Learned IV, 95830B. (September 09, 2015) [doi: 10.1117/12.2196564].
14. P. A. Lightsey, B. B. Gallagher, N. Nickles, and T. Copp, "Optical transmission for the James Webb Space Telescope," *Proc. SPIE* **8442**, Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave 84423A (September 21, 2012) [doi: 10.1117/12.924841].
15. K. O'Keefe, "Dynamic Modeling Uncertainty," International Conference on Space Optical Systems and Applications, IEEE (2011).
16. W. Podgorski et al., "A novel systems engineering approach to the design of a precision radial velocity spectrograph: the GMT-Consortium Large Earth Finder (G-CLEF)," *Proc. SPIE* **9147**, 91478W (2014) [doi: 10.1117/12.2056329].
17. Ibid reference 16.
18. B. N. Taylor and C. E. Kuyat, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," NIST Technical Note 1297, 1994 Edition, URL http://www.nist.gov/pml/pubs/tn1297/, last accessed 10 August 2016.
19. W. T. Estler, "A Distribution-Independent Bound on the Level of Confidence in the Result of a Measurement," *J. Res. National Institute Standards Technol.* **102**, 587 (1997).
20. R. Savage, "Probability Inequalities of the Tchebycheff Type," Journal of Research of the National Bureau of Standards- B. Mathematics and Mathematical Physics, Vol. **65**B, No. 3, July–September 1961.
21. Ibid reference 19.
22. Ibid reference 20.
23. Ibid reference 20.
24. D. F. Vysochanskij and Y. I. Petunin, "Justification of the 3σ rule for unimodal distributions," *Theory of Probability and Mathematical Statistics* **21**, 25–36 (1980).
25. Ibid reference 20.
26. P. G. Hoel, S. C. Port, and C. S. Stone, *Introduction to Probability Theory*, Houghton Mifflin Company, Boston (1971).
27. R. Giacconi, *Secrets of the Hoary Deep: A Personal History of Modern Astronomy*, Project MUSE, https://muse.jhu.edu/, last accessed 9 Aug. 2016, Johns Hopkins University Press, Baltimore (2008).
28. https://en.wikipedia.org/wiki/Extremely_large_telescope
29. E. Elliot et al., "Space Telescopes in the Ultraviolet, Optical, and Infrared (UV/O/IR)," *Planets, Stars, and Stellar Systems, Volume 1: Telescopes and Instrumentation*, T. Oswalt and I. McLean, Eds., Springer, New York (2013).

30. M. A. van Dam et al., "Angular anisoplanatism in laser guide star adaptive optics," *Proc. SPIE* **6272**, 627231 (2006) [doi: 10.1117/12.669737].
31. Ibid reference 29.
32. D. Ebbets et al., "The Ball Aerospace Concept for the Next Generation Space Telescope," P. A. Lightsey and D. Ebbets, "TRW/ Ball Aerospace Concept for NGST," *ASP Conference Series*, E. P. Smith and K. S. Long, Eds., Vol. **2007** (2000).
33. T. Kelsall et al., "The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. II. Model of the Interplanetary Dust Cloud," *The Astrophysical Journal* **508**(1) (1998).
34. E. L. Wright, "Angular Power Spectra of the *COBE* DIRBE Maps," *The Astrophysical Journal* **496**(1–8) (1998).
35. P. A. Lightsey, "Stray Light field dependence for the James Webb Space Telescope," *Proc. SPIE* **9904**, Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave 9904-9 (2016).
36. L. Petro, M. L. Lallo, and S. Stallcup, "JWST Mission Simulator Model of the Sky Spectral Radiance," STScI-JWST-TM-2003-0020 A, Space Telescope Science Institute, 3 November 2003.
37. https://en.wikipedia.org/wiki/Analytic_hierarchy_process
38. http://www.keckobservatory.org/
39. http://www.eso.org/public/usa/teles-instr/paranal/
40. J. W. Arenberg, A. S. Lo, T. M. Glassman, and C. L. Lillie, "New Worlds Observer: System and Mission Architecture," Proceedings of the Society of Photo-optical Instrumentation Engineers, volume **6693** (2007).
41. J. W. Arenberg, T. E. Schuman, and H. A. Knutson, "Optimization of Revisit Times for Direct Detection Expolanet Searches: A Shot in the Dark," Northrop Grumman Technology Review Journal, Fall/Winter 2005.
42. Ibid reference 41.
43. M. C. Turnbull, "The search for habitable worlds: From the Terrestrial Planet Finder to SETI," Ph.D. Thesis, University of Arizona, 2004.
44. J. A. Dooley, "Technology Plan for the Terrestrial Planet Finder Coronagraph," found at https://exoplanets.nasa.gov/files/exep/TPF-CTechPlan.pdf, last accessed 13 August 2016.
45. L. Feinberg et al., "End-to-end assessment of a large aperture segmented ultraviolet optical infrared (UVOIR) telescope architecture," *Proc. SPIE* **9904**, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, 99040H (July 29, 2016) [doi: 10.1117/12.2231487].
46. R. Toland, "Alien Planets to Pose for Giant Pinhole Camera in Space" at URL www.nasa.gov/vision/universe/newworlds/new_worlds_imager.html, last accessed 10 Aug 2016.
47. Ibid reference 46.
48. L. Spitzer, 1962, American Scientist, **50**, 473.

49. F. H. Cocks et al., *Proc. SPIE* **2807**, 74 (1996).
50. C. J. Copi and G. Starkman, *The Astrophysical Journal* **532**, 581 (2000).
51. I. Jordan et al., *Proc. SPIE* **5487**, 1391 (2004).
52. C. Marchal, *Acta Astronautica* **12**, 195 (1985).
53. W. Cash, *Nature* **442**, 51 (2006).
54. J. W. Arenberg and W. C. Cash, "New Worlds Observer: A Novel Mission For The Detection Of Exoplanets," *Direct Imaging of Exoplanets: Science and Techniques*, C. Aime and F. Vakili, Eds., Cambridge University Press (2006).
55. J. W. Arenberg, T. M. Glassman, and A. S. Lo, "Light Scattering from the New Worlds Starshade," *Proc. SPIE* **6693**, (2007).
56. A. Shipley et al., "New Worlds Observer: Tolerance Overview," *Proc. SPIE* **6687**, (2007).
57. Ibid reference 56.
58. J. W. Arenberg, A. S. Lo, T. M. Glassman, and C. L. Lillie, "New Worlds Observer: System and Mission Architecture," *Proc. SPIE* **6693**, (2007).
59. B. Dickey, "Safety assessments released on four NASA projects" at http://www.govexec.com/management/2004/05/safety-assessments-released-on-four-nasa-projects/16673/, last accessed 10 Aug 2016.
60. "Potter Stewart" at https://en.wikipedia.org/wiki/I_know_it_when_I_see_it#cite_note-4, last accessed 10 August 2016.
61. C. N. Parkinson, (November 19, 1955), Parkinson's Law, The Economist. Can be found at http://www.economist.com/node/14116121, last accessed 10 Aug 2016.
62. H. M. Robert, *Robert's Rules of Order-Revised*, 1915 Edition (public domain), found at http://www.robertsrules.org/rror--00.htm, last accessed 10 Aug 2016.
63. J. Arenberg et al., "Lessons we learned designing and building the Chandra telescope," *Proc. SPIE* **9144**, 91440Q (2014) [doi: 10.1117/12.2055515].
64. C. Atkinson et al., "Architecting a revised optical test approach for JWST," *Proc. SPIE* **7010**, 70100Q (2007) [doi: 10.1117/12.777021].
65. J. Arenberg et al., "Lessons we learned designing and building the Chandra telescope," *Proc. SPIE* **9144**, 91440Q (2014) [doi: 10.1117/12.2055515].

Index

Paul A. Lightsey has more than 50 years' experience in Physics, Mathematics, and Engineering, much of which has been in the area of optical systems analysis and design. He is currently the Chief Engineer for the James Webb Space Telescope program at Ball and a member of the NASA Mission Systems Engineering Optical Leads for Webb. He has contributed to all phases of development, from new business through design, fabrication, alignment, test, calibration, and on-orbit operations while at Ball. He has extensive experience working on Hubble Space Telescope (HST) instruments. He was the Systems Engineer for the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS), which was installed with its sister instrument, the Space Telescope Imaging Spectrograph (STIS), in February 1997. He developed a system optical performance model for the design analysis of COSTAR, the corrective optics for the HST. COSTAR was installed aboard the HST in December 1993. This model includes modeling of structural dynamics and thermal effects on the imaging performance and was also used for the design of NICMOS and STIS.

Lightsey was involved in analyses and field experiments for the Retroreflector Assisted Imaging Laser Experiment (RAILE) and the Relay Mirror Experiment (RME). These activities included simulation and analysis of atmospheric propagation of laser beams, optical pointing and tracking systems, and imaging performance assessment. He has collaborated on the design and construction of an airborne coherent Doppler lidar for atmospheric remote sensing and on studies for a coherent differential Doppler technique for air motion sensing from aircraft. Other activities included spectrophotometric measurements of stratospheric ozone, quaternion formulation for spacecraft rotation, stability analysis of gymnastics rotations, and low-temperature measurements of electronic transport and magnetic resonance properties in materials exhibiting metal–insulator transitions. Before coming to Ball, Lightsey was a professor of Physics and Mathematics for 14 years. He has an eclectic publication record that includes articles in such diverse journals as *Physical Review, American Journal of Physics, Journal of the International Society of Sports Mechanics, American Meteorological Society, Optical Engineering, Astronomical Society of the Pacific Proceedings, SPIE Proceedings*, and *Runner's World*. He has taught in the Johns Hopkins University Masters of Science in Systems Engineering program; a systems engineering short course for SPIE; and systems engineering courses internal to Ball.

Lightsey received his B.S. in Physics with High Distinction from Colorado State University in 1966, and his Ph.D. in Physics from Cornell University in 1972. In 2003, he received the William H. Follett, Jr. Award for Excellence in System Engineering, and in 2007 he received the Distinguished Public Service Medal, the highest award given by NASA to individuals not employed by NASA. He is a Senior Member of OSA and an SPIE Fellow.

Jonathan W. Arenberg has over 35 years of experience in the application of physics, mathematics, and engineering, with most of this effort focused on astronomical and high-energy laser systems. He is currently the Chief Engineer for Space Science Missions at Northrop Grumman Aerospace Systems (NGAS). He held a long tenure on the James Webb Space Telescope program at NG, starting with technology development, systems engineering, design integration, and finally as Northrop's Chief Engineer for James Webb.

He began his career in 1982 at Hughes Aircraft Company, working on tactical lasers, night vision, and other sensor systems. It was at Hughes Aircraft where he was first introduced to the problem of laser damage and its measurement and quantification. In 1989, Arenberg left Hughes Aircraft for TRW (now NGAS) and was supposed to be assigned to a laser program. Upon his arrival at TRW, this laser program has not started, and he was assigned temporarily to the Advanced X-ray Astrophysics Facility (now the Chandra X-ray Observatory) for a few weeks as the other contract was put in place. During his almost nine-year tenure on Chandra, Arenberg worked on many aspects of the mission, x-ray calibration and test equipment, alignment requirements, stay light, baffles, magnetic broom and the aspect-determination system.

Following Chandra, Arenberg worked on a number of high-energy chemical and solid state laser programs, including the Space-Based Laser program, where he was the resonator and diagnostics lead, and the Airborne Laser, where he contributed to the development of the alignment units that allow for resonator alignment in a flying flexible aircraft. He returned to space science to work on business and concept development on TRW's concepts for TPF-C, Constellation-X, SAFIR, and the starshade, among other missions. His other work experience includes other optical and space systems, as well as a wide variety of technology development. He is a member of the US National and International (ISO) committees charged with writing standards for laser and electro-optical systems and components, and is the project leader for the revision of the standard for the measurement of laser-induced damage.

Arenberg has authored over 170 conference presentations, refereed papers, book chapters, and professional short courses, and he holds a dozen European and US patents in a wide range of technologies. He is on the planning committee for several conferences and is a journal referee. He teaches a systems engineering short course for SPIE, which is the basis of this book, and courses internal to NGAS. He received his B.S. in Physics from the University of California, Los Angeles in 1983, where he was a Regents Scholar and the Edward A. Dickson alumni scholar. He received his M.S. and Ph.D. in Engineering on a Howard Hughes fellowship from the same school in 1985 and 1987, respectively. In 1991, along with other colleagues he received the

TRW Chairman's Award for the development of optics for the AXAF (now Chandra) telescope. He is the recipient of seven group achievement awards from NASA for his work on Chandra and Webb. He is a member of the American Association for the Advancement of Science and Sigma Xi, and he is an SPIE Fellow.