Design of the Next Generation Optical System for the SuperBIT Balloon-borne Telescope

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Balloon-borne telescopes are a burgeoning technology in the astrophysical sciences, offering distinct advantages compared to traditional approaches such as ground-based observatories and satellite telescopes. Despite having time-limited deployments, balloon-borne telescopes are ideal for a wide range of astrophysical projects [1, 2, 3, 4]. Unlike ground based telescopes, balloon-borne telescopes capture images above 98% of the atmosphere by density and offer up to 80% transmission down to 300 nm (NUV) [5]. Compared to space telescopes, balloon-borne telescopes are significantly less expensive alternatives that also circumvent the safety and logistical demands of a space mission. However, balloon-borne telescopes suffer from three engineering limitations:

1. weight limitations which constrain the size of the mirrors and lenses that can be used,
2. control limitations caused by instabilities in the upper atmosphere, and
3. observation limitations caused by the dynamics of the ballooning platform.

The Super-pressure Balloon-borne Imaging Telescope (SuperBIT) and its successors aim to challenge the boundaries of these three engineering limitations inherent in balloon-borne telescopes. During its upcoming summer 2018 test flight, SuperBIT will perform < 0.25" imaging stability over a $0.5°$ field of view with a frequency coverage of 300 to 1000 nm with a $>$ 300-s integration time. Ultimately, SuperBIT will carry a facility-class instrument for a 100-day science mission. SuperBIT will measure 180 galaxy clusters through weak and strong gravitational lensing in order to put constraints on cluster mass-observable relations. These results will enable the resolution of discrepancies in constraints on cosmological parameters derived from the cosmic microwave background radiation and cluster number counts [6]. Through the next iteration of SuperBIT, we will provide a best-in-class calibration on galaxy cluster masses, at the 2-3% level [5].

In order to achieve these ambitious scientific goals, the engineering challenges that are still facing SuperBIT and its successors must be addressed. These challenges are two-fold – the design and construction of a gondola with sufficiently stabilizable gimbals that is lightweight and meets the strength and safety requirements [7], and the design and implementation of a diffraction limited optical system that is correctable under mechanical stresses and thermal deformations. While I have resolved the first of these problems for the current 0.5-m telescope gondola system, the solution is not yet scalable to the significantly larger future 1.3-m facility-class telescope. For the engineering portion of my thesis, I would like to undertake both of these challenges for the next iteration of SuperBIT.

My recent research and design activities have centered on the latter of these two challenges. I designed an upgraded optics box with actively controllable elements that will allow SuperBIT to achieve diffraction limited optics. We will build and install this new optics box in 2019. I am in the process of designing an optimal actuation system for the auto-alignment of the optical elements. This work employs techniques used in low order wavefront-sensing [8], linear control systems [9], machine learning for regression [10], and optical system optimization [11].

SuperBIT and its successors will fill an important niche in the astrophysical community, reaching beyond the stated scientific goals of the experiment. In particular, its high sensitivity UV measurements will provide valuable data for experiments such as WFIRST and EUCLID [5, 12]. Since SuperBIT will provide a springboard into the next generation of astronomical observatories, the design and development work discussed here will have a lasting impact on many future and ongoing experiments in subsequent years. I look forward to continuing to tackle SuperBIT's engineering challenges in order to maximize the scientific reach of the experiment.

References

[1] P. de Bernardis, P. A. R. Ade, J. J. Bock, J. R. Bond, J. Borrill, A. Boscaleri, K. Coble, B. P. Crill, G. De Gasperis, P. C. Farese, P. G. Ferreira, K. Ganga, M. Giacometti, E. Hivon, V. V. Hristov, A. Iacoangeli, A. H. Jaffe, A. E. Lange, L. Martinis, S. Masi, P. V. Mason, P. D. Mauskopf, A. Melchiorri, L. Miglio, T. Montroy, C. B. Netterfield, E. Pascale, F. Piacentini, D. Pogosyan, S. Prunet, S. Rao, G. Romeo, J. E. Ruhl, F. Scaramuzzi, D. Sforna, and N. Vittorio, "A flat universe from high-resolution maps of the cosmic microwave background radiation," *Nature*, vol. 404, pp. 955 EP –, Apr 2000, article. [Online]. Available: http://dx.doi.org/10.1038/35010035

[2] M. M. Kasliwal, R. Massey, R. S. Ellis, S. Miyazaki, and J. Rhodes, "A Comparison of Weak-Lensing Measurements from Ground- and Space-Based Facilities," vol. 684, pp. 34–45, Sep. 2008.

[3] J. Rhodes, B. Dobke, J. Booth, R. Massey, K. Liewer, R. Smith, A. Amara, J. Aldrich, J. Berge, N. Bezawada, P. Brugarolas, P. Clark, C. M. Dubbeldam, R. Ellis, C. Frenk,

A. Gallie, A. Heavens, D. Henry, E. Jullo, T. Kitching, J. Lanzi, S. Lilly, D. Lunney, S. Miyazaki, D. Morris, C. Paine, J. Peacock, S. Pellegrino, R. Pittock, P. Pool, A. Refregier, M. Seiffert, R. Sharples, A. Smith, D. Stuchlik, A. Taylor, H. Teplitz, R. Ali Vanderveld, and J. Wu, "Space-quality data from balloon-borne telescopes: The High Altitude Lensing Observatory (HALO)," *Astroparticle Physics*, vol. 38, pp. 31–40, Oct. 2012.

[4] E. Young, *HST-Like Performance from Balloon-borne Telescopes*, Next Generation Subortbital Reseachers Conference, 2012, http://www.boulder.swri.edu/~efy/efy_talks/EFY_BalloonObs_v01.pdf.

[5] W. C. Jones, "Superbit: Wide-field, sub-arcsecond imaging from the super-pressure balloon platform," *NASA APRA Proposal*, 2014.

[6] D. N. Spergel, R. Flauger, and R. Hložek, "Planck data reconsidered," *Phys. Rev. D*, vol. 91, p. 023518, Jan 2015. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevD.91.023518

[7] *Structural Requirements and Recommendations for Balloon Gondola Design*, Om-220-10-h, rev. a ed., Columbia Scientific Ballooning Facility, Palestine, TX, April 2013, https://www.csbf.nasa.gov/documents/gondola/OM-220-10-H-A%20Structural%20Rqrmnts%20Gondola%20Design.pdf.

[8] F. Shi, K. Balasubramanian, R. Bartos, R. Hein, M. M. Raymond Lam, D. Moore, J. Moore, I. P. Keith Patterson, E. S. Joel Shields, T. T. Hong Tang, J. K. Wallace, X. Wang, and D. W. Wilson, "Low order wavefront sensing and control for wfirst coronagraph," *Proc.SPIE*, vol. 9904, pp. 9904 – 9904 – 17, 2016. [Online]. Available: https://doi.org/10.1117/12.2234226

[9] C. W. Rowley, *Introduction to Feedback Control*, Princeton, NJ 08540, 2017.

[10] M. Bremer, *Multiple Linear Regression – Math 261A*, Cornell University, 2012, http://mezeylab.cb.bscb.cornell.edu/labmembers/documents/supplement%205%20-%20multiple%20regression.pdf.

[11] G. R. Lemaitre, "Optical design and active optics methods in astronomy," *Optical Review*, vol. 20, no. 2, pp. 103–117, Mar 2013. [Online]. Available: https://doi.org/10.1007/s10043-013-0015-4

[12] D. Spergel, N. Gehrels, J. Breckinridge, M. Donahue, A. Dressler, B. S. Gaudi, T. Greene, O. Guyon, C. Hirata, J. Kalirai, N. J. Kasdin, W. Moos, S. Perlmutter, M. Postman, B. Rauscher, J. Rhodes, Y. Wang, D. Weinberg, J. Centrella, W. Traub, C. Baltay, J. Colbert, D. Bennett, A. Kiessling, B. Macintosh, J. Merten, M. Mortonson, M. Penny, E. Rozo, D. Savransky, K. Stapelfeldt, Y. Zu, C. Baker, E. Cheng, D. Content, J. Dooley, M. Foote, R. Goullioud, K. Grady, C. Jackson, J. Kruk, M. Levine, M. Melton, C. Peddie, J. Ruffa, and S. Shaklan, "Wide-Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA Final Report," *ArXiv e-prints*, May 2013.