

Development and Integration of Readout Systems for the Simons Observatory and

Measuring the Extragalactic Background Light from

Optical Stacking of Quiescent Galaxies at Cosmic Noon

by

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A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

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December 2023

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ABSTRACT

Building on the legacies of *Planck* and the Atacama Cosmology Telescope, among others, future cosmic microwave background (CMB) observatories are poised to revolutionize our understanding of the cosmos by implementing proven detector systems at scales previously incomprehensible. Leading the charge is Simons Observatory (SO), a suite of four telescopes located at 5,200 meters elevation in the Atacama Desert of Chile. With more than 60,000 transition-edge sensor (TES) detectors deployed in six frequency bands across three half-meter telescopes and one 6-meter telescope, SO will observe CMB temperature and polarization at small and large scales with greater sensitivity and control over systematics than has yet been achieved.

In deploying more detectors than all other previous CMB experiments combined, SO must also chart new territory in the realm of TES readout. Breakthroughs in microwave multiplexing (μ -mux) readout technology now allow the simultaneous readout of approximately 1,000 detectors on a single set of cables, far surpassing the capabilities of previous systems. For the Large Aperture Telescope's $> 30,000$ detectors, this translates to a total of just 45 input/output lines.

A crucial piece of the SO readout architecture is the Universal Readout Harness (URH), a “plug-and-play” assembly that contains the 300K-4K elements. Configurable to support the readout requirements of each receiver, each URH can support up to 24 readout lines. In addition to the radiofrequency (RF) components, the URH can also support up to 12x50-wire DC cable looms, which provide detector and amplifier power. This dissertation describes the construction and testing of the 6 URHs required for nominal SO operations, as well as the on-site integration of the first Small Aperture Telescope.

Separately, an optical stacking analysis of quiescent galaxies at $z \sim 1$ using images from the Dark Energy Survey is presented. Motivated by a desire to better understand the evolution of massive elliptical galaxies, high signal-to-noise images generated from averaging $\sim 100,000$ individual galaxy cutouts are used to calculate surface brightness profiles in the *grizY* bands. Additionally, the extra-galactic background light is derived from these stacks and is found to be in good agreement with previous measurements.

"I just want to go home," said the astronaut.

"So come home," said ground control.

"s o c o m e h o m e," said the voice from the stars.

-jonny sun

ACKNOWLEDGMENTS

Sources of Funding and Support

Chapters 3 and 4 of this dissertation present work completed for the Simons Observatory, which is supported by the Simons Foundation, the Heising-Simons Foundation, and other research institutions within the collaboration. Research Computing at Arizona State University provided high-performance computing resources that have contributed to the work presented in Chapter 5.

Personal Acknowledgments

This dissertation has only my name on the cover, but I could never have made it this far on my own. I dedicate this moment to so, so, many people, but in particular:

To all of the wonderful teachers I've had over the years, especially at Park Road Montessori. To the late Sherry Herbert, to Anna Hurdle, Curt Frueh, Ann Palin, and Susan Richards: I have been a student for nearly twenty five years now, and the most important lessons are still the ones I learned in (and outside of) your classrooms. Thank you for laying the foundation.

To my Queens University of Charlotte family. To Prof. Andy Tucker for teaching me how to solder and for refusing to accept "I don't know" as a valid answer to "what are you doing after graduation?" To Prof. Fred DeAngelis for taking me to see my first telescope, for an infectious love of physics, and for unwavering support during my first few semesters of graduate school. To Prof. Greg Pillar for being such a supportive mentor (and for the legendary antics). To Prof. Jen Daniel, for *everything*.

To my Fisk-Vanderbilt Bridge family, for taking a chance on a girl with a chemistry degree from a tiny liberal arts college who said she wanted to do physics. To Constantine Coca, Dr. Arnold Burger and the Fisk University Materials Science Group, especially Dr. LaNell Williams and Dr. Liviu Matei. To Prof. Michael Watson and Dr. Akira Ueda for fearlessly leading me through the trenches of Arfken and Jackson. To Dr. Joy Garnett for coaching me across the bridge, for random acts of Crumbl, and above all, for being a cherished friend. To my cohort and the extended Bridge family — I will cherish those two years in Nashville with you all for the rest of my life.

To all my fellow ISTB4 dungeon-dwellers, past and present. To Justin Mathewson for being my right-hand man. To Dr. Caleb Wheeler for trusting me to see his insane designs through to reality. To Dr. Hamdi Mani for never being too busy to teach me how to use a piece of equipment. To Dr. Emily

Lunde for doing all of the scary things with me, like cryostat maintenance and dissertation writing. Hey, look at us. Who would have thought?

To my esteemed Simons Observatory collaborators, particularly my fellow junior members. Those telescopes were built with our blood, sweat, and tears, and it has been incredible to see it all come together over the past few months. To my adoptive lab family at UCSD: Max, Michael, Tran, Joe, JB, Bryce, Nick, Kevin, Alyssa, Matt, Remy and Jack — thanks for taking me in as one of your own and giving me the chance to be more than just the girl from ASU that builds those crazy readout harnesses. To Marius Lungu, king of spreadsheets, for helping me keep my life together during peak harness mania. To the people of San Pedro de Atacama and our Chilean colleagues for their hospitality.

To my committee: Phil, you welcomed me in to your group even though I had approximately zero previous experience in astronomical instrumentation, and then you promptly threw me into the deep end of the astronomical instrumentation pool. Even when I thought for sure I was going to drown, you had faith that I'd learn how to swim. Thank you for always believing in me and for giving me the freedom to do my own thing, even if that meant never being in the lab because I was too busy working in somebody else's lab or on top of a volcano in Chile. I am endlessly grateful for the support and guidance you've given me over the years as well as the many spirited discussions we've had (I still don't want your job, go Heels). Chris, thank you for being the steadfast voice of reason. Evan, thank you for keeping Phil's grand visions in check. Seth, thank you for teaching me astronomy and for graciously answering all of my stupid questions. Kam, thanks for bringing me into the fold and for letting me be a part of the SAT1 chaos. I've thoroughly enjoyed it.

To all of my friends and family around the world who have never been quite sure what it is I do but have hyped me up to everyone they know anyway. Your messages, FaceTimes, memes, and Mario Kart nights have kept me going even on the hardest days.

To Alec for keeping me humble like only an older brother can and to Lindsey for never being afraid to ask questions. To Barbara, Karen, and Papa, whose spirits I have felt with me every step of the way. To my beloved Nana.

To my dearest, darlingest Momsie and Popsicle.

We did it.

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Chapter 1

INTRODUCTION

1.1 The Cosmic Microwave Background

In the beginning there was soup. In the first fractions of a second following the Big Bang, this soup was a hot, dense plasma consisting of photons, electrons, and other elementary particles interacting with each other in thermal equilibrium at $\sim 10^{10}$ K. As the universe expanded and cooled, these elementary particles combined to form baryons (e.g., protons and neutrons). These subatomic particles remained in thermal equilibrium with neutrinos until approximately one second after the Big Bang, when the neutrinos were “frozen out,” or decoupled, from the primordial soup. Continued expansion and cooling of the universe led to the formation of hydrogen and helium nuclei within the first minutes.

Throughout this phase and for many years thereafter the primordial soup was too hot and dense for stable atoms to exist, and collisions with subatomic particles prevented photons from moving throughout space. Thus, the universe at this time was an opaque, ionized plasma. Over the course of the next several hundred thousand years (known as the epoch of “recombination”), the universe cooled to a temperature of $\sim 3,000$ K and conditions became favorable for the formation of neutral hydrogen. The number of free electrons in the soup subsequently dwindled, and by $\sim 380,000$ years post-Big Bang, photons, like the neutrinos, were decoupled from matter and could at last begin to move freely through space. This radiation, known today as the Cosmic Microwave Background, is the oldest light in the universe.

The point at which matter and radiation decoupled and began to evolve independently is known as the last scattering surface. Following this epoch, the universe as we know it today began to take shape. As depicted in Figure 1, the tiny density fluctuations created in the first moments after the Big Bang lead to the development of large-scale structure over the course of billions of years. Throughout

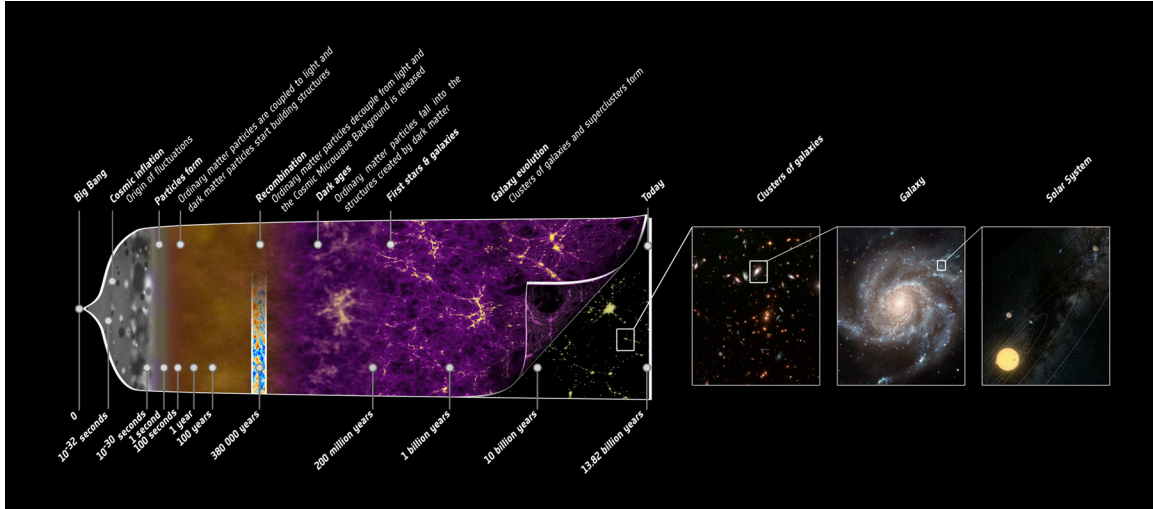


Figure 1. The evolution of the Universe. Image credit: ESA

this time, photons from the last scattering surface traveled throughout the universe unimpeded, their energy decreasing as the continued expansion of the universe redshifted them to longer wavelengths.

This depiction of the evolution of the universe is of course the well-known “Big-Bang” theory, widely accepted today thanks to decades of astrophysical observations that have confirmed theoretical predictions. In the mid-1900s, however, the jury was still out on the origins of the universe. Observations by Hubble had proven the universe was expanding, as was predicted by Lemaître and Friedmann, but the origins of this expansion and of the universe were still not understood. The two leading theories at the time were:

1. The steady-state model: The universe is eternal, without beginning or end. The universe expands, but continuous creation of matter ensures the density remains constant (Bondi and Gold 1948).
2. The Big-Bang model: The universe began as a single, infinitely dense point that underwent an initial period of violent inflation, followed by continuous expansion over the course of 13.8 billion years (Lemaître 1931a).

Alpher, Herman and Gamow, proponents of the Big-Bang theory, were the first to suggest that the

expansion of the universe following the Big Bang must leave behind an observable imprint in the form of background radiation from the surface of last scattering (Alpher and R. Herman 1948; Alpher and R. C. Herman 1949). In the late 60s, Dicke and colleagues independently came to the same conclusion (Dicke et al. 1965). Around the same time Penzias and Wilson infamously stumbled upon a constant, inexplicable background microwave signal at $\sim 3.5\text{K}$ while observing with the Holmdel Horn Antenna at Bell Labs (Penzias and Wilson 1965). This noise was constant, regardless of direction, time of day, or season, and could not be attributed to any known sources or instrument systematics. After some correspondence with the theorists, Penzias and Wilson realized they had accidentally discovered the Cosmic Microwave Background. This observation provided the first experimental evidence in support of the Big-Bang theory.

Following Penzias and Wilson’s discovery, theorists began earnestly working to describe the potential observable characteristics of the CMB. While the signal picked up by the Holmdel antenna was markedly uniform (“isotropic”), many believed the CMB would exhibit slight variations (“anisotropies”) in temperature (see Hu and Dodelson 2002 for a comprehensive review). The largest anisotropies were suggested to originate from acoustic oscillations in the primordial soup, while Sachs and Wolfe theorized that density fluctuations in the early universe would also lead to temperature anisotropies due to variations in gravitational redshift of CMB photons (the Sachs-Wolfe effect; Sachs and Wolfe 1967). Silk predicted these CMB anisotropies would be smoothed out on small angular scales due to local thermalization of photons during the recombination epoch (Silk 1968). In addition to these primary temperature anisotropies, several phenomena are posited to induce secondary perturbations, such as inverse scattering of CMB photons as they pass through galaxy clusters (the Sunyaev-Zel’dovich or SZ effect; citesunyaevSmallScaleFluctuationsRelic1970), and gravitational lensing. These anisotropies are characterized by plotting their amplitude as a function of angular size in what is known as the CMB power spectrum.

The aforementioned scalar perturbations in the early universe are also expected to have imprinted a polarization pattern a small portion of CMB photons during the time of last scattering (Rees 1968; see also Hu and White 1997). In addition to this E-mode polarization, B-mode polarization is also predicted at small angular scales as a result of gravitational lensing of the CMB as well as at large

angular scales due to tensor perturbations from primordial gravitational waves, a key component of inflationary models (Starobinskiĭ 1979; Guth 1981; K. N. Abazajian et al. 2015). Observational evidence of large-scale B-mode polarization of the CMB could be the “smoking gun” for inflation, much like the discovery of the CMB was for the Big-Bang theory.

Today, the most widely accepted model of the universe is the Λ CDM (lambda-cold dark matter) model, also referred to as the Standard Model. This model, informed by CMB observations, builds off of Big Bang cosmology and incorporates dark matter and dark energy, which are expected to dominate the matter and energy densities of the universe. In this model, the universe is homogeneous and isotropic as described by the Friedmann-Lemaître-Robertson-Walker metric (FLRW; Friedmann 1922; Lemaître 1931b; Robertson 1935; Walker 1937):

$$ds^2 = -c^2 dt^2 + a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right) \quad (1.1)$$

where $d\Omega = d\theta^2 + \sin^2 \theta d\phi^2$, c is the speed of light, $a(t)$ is the scale factor, and k is the curvature parameter, which may be equal to -1, 0, or +1. This metric can be used to generate solutions to Einstein’s field equations known as the Friedmann equations (Einstein 1915; Friedmann 1922). The expansion rate of the universe is described by the first Friedmann equation:

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3} \quad (1.2)$$

where H is the Hubble parameter, G is the gravitational constant, ρ is the density, and Λ is the cosmological constant. The value of the Hubble parameter at the present time t_0 is known as the Hubble constant, H_0 (Hubble 1929). For a flat universe at the present time we define a critical density:

$$\rho_c = \frac{3H_0^2}{8\pi G} \quad (1.3)$$

The densities $\Omega_x = \rho_x / \rho_c$ of the various components of the universe (enumerated below) are normalized with respect to this critical density.

The Λ CDM paradigm is nominally described by the following parameters:

1. $\Omega_c, \Omega_b, \Omega_\Lambda$, the dark matter, baryon, and dark energy (vacuum) densities. From these values we also derive $\Omega_k = 1 - \Omega_c - \Omega_b - \Omega_\Lambda$, the curvature parameter. $\Omega_k > 1$ indicates positive curvature, $\Omega_k < 1$ indicates negative curvature, and $\Omega_k = 1$ indicates a flat universe.

2. A_S, A_T , the amplitude of scalar and tensor perturbations, and the tensor-to-scalar ratio r
3. n_S, n_T , the spectral index of scalar and tensor perturbations
4. τ , the optical depth since reionization

Markov Chain Monte Carlo methods are used to estimate the values of these parameters from CMB observations (Kosowsky, Milosavljevic, and Jimenez 2002; Staggs, Dunkley, and Page 2018). Estimations of these and other derived parameters, along with maps of the CMB temperature and polarization and the angular power spectra, are the key data products of any CMB experiment.

1.2 Observing the Cosmic Microwave Background

1.2.1 A Brief History of Experimental Cosmology

After decades of observation, we know the cosmic microwave background (CMB) fills all of space and behaves as a black-body with an intensity spectrum described by Planck's Law:

$$B(\nu, T) = \frac{2h\nu^2}{c^2} \frac{1}{\exp(\frac{h\nu}{k_B T}) - 1} \quad (1.4)$$

where h is Planck's constant, c is the speed of light, and k_B is Boltzmann's constant. Some thirty years following Penzias and Wilson's discovery, the landmark observations of the COsmic Background Explorer (*COBE*) satellite provided the first measurements of the CMB spectrum (Figure 2), which showed a peak CMB intensity near 1.9 mm (~ 160 GHz) and an absolute temperature of 2.728 ± 0.004 K. *COBE* also generated the first CMB temperature maps with $\sim 7^\circ$ angular resolution, which showed anisotropies on the order of $\sim 10^{-5}$ K (Fixsen et al. 1996).

Since the success of *COBE*, many ground-based, balloon-borne, and space-based experiments have further refined our view of the universe and its history. In 2000, the balloon-borne BOOMERanG telescope observed the CMB on angular scales of ~ 10 arcminutes ($\sim 0.2^\circ$), generating much more detailed images of the temperature fluctuations. From the angular power spectrum, BOOMERanG made the first measurement of the dominant peak from acoustic oscillations, providing observational

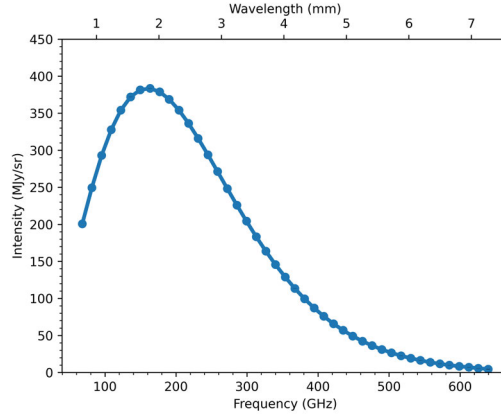


Figure 2. CMB intensity spectrum measured by *COBE*. Errorbars are smaller than plot markers. Data taken from Fixsen et al. 1996

evidence suggesting the geometry of the universe is flat (Mauskopf et al. 2000; Netterfield et al. 2002; Jones et al. 2006). Around the same time, the Degree Angular Scale Interferometer (DASI) made the first detection of CMB polarization (Halverson et al. 1998; Kovac et al. 2002). In 2001, the Wilkinson Microwave Anisotropy Probe (*WMAP*; Bennett et al. 2003) launched and by 2003 had produced its first all-sky maps with nearly 50 times better sensitivity than the *COBE* maps. Over the course of its nine year lifetime, *WMAP*'s observations, carried out over a much wider range of angular scales, helped to refine the cosmological model by putting tighter constraints on the various cosmological parameters.

Throughout the late 2000s and into the early 2010s, continued technical advances in CMB instrumentation enabled even more precise CMB observations at a wide range of angular scales. Perhaps the most well-known experiment of this era is the *Planck* satellite (Planck Collaboration, P. A. R. Ade, Aghanim, Arnaud, et al. 2011), which launched in 2009 and observed for four years. With even greater sensitivity than *WMAP* before it, *Planck* observed the CMB on angular scales ranging from 5 arcminutes to half a degree, producing the most detailed all-sky CMB temperature (Figure 3) and polarization maps to date. From the ground, observatories in Antarctica as well as Chile (see next section) also made significant strides. The Atacama Cosmology Telescope (ACT; Swetz et al. 2011), a high-resolution experiment in Chile, has made the first detections of CMB lensing, the kinetic SZ

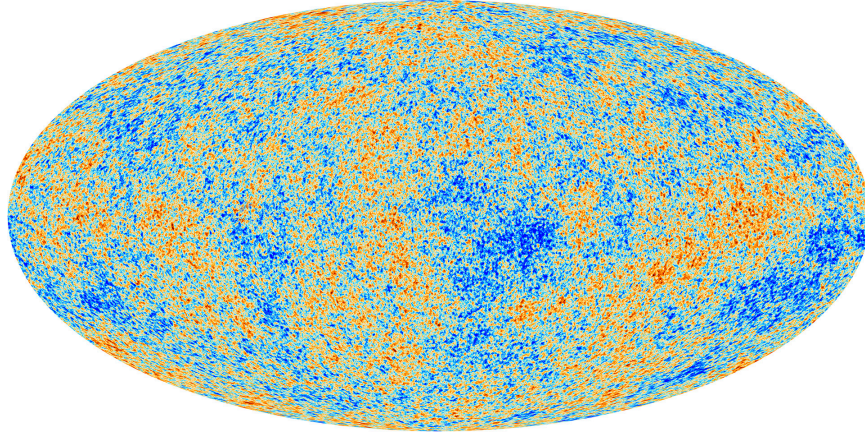


Figure 3. The cosmic microwave background as seen by *Planck*. Image credit: Planck Collaboration, P. A. R. Ade, Aghanim, Alves, et al. 2014

(kSZ) effect, (Das et al. 2011). The South Pole Telescope (SPT; Carlstrom et al. 2011) has discovered countless galaxy clusters through the thermal SZ (tSZ) effect and in 2013 made the first detection of B-mode polarization due to gravitational lensing of the CMB (Hanson et al. 2013; Bleem et al. 2015).

Figure 4 illustrates just how sharply the CMB has come into focus over the last three decades. Advances in instrument capabilities (e.g. detector and optical performance), as well as better control over instrument systematics and contaminants (e.g. dust, galactic emission) have ushered in an era of precision cosmology. Next generation experiments from the ground (e.g., CMB-S4; K. Abazajian et al. 2019) will employ orders of magnitude more detectors to further increase sensitivity and improve our ability to separate the faintest signals from foregrounds and other noise. Precise maps of the sky over a wide range of frequencies and angular scales combined with overlapping observations from non-CMB observatories will probe the development of large-scale structure. Detection (or non-detection) of primordial gravitational waves is within reach. This next generation of observations will enable us to look even further back in time and deepen our understanding of the primordial soup.

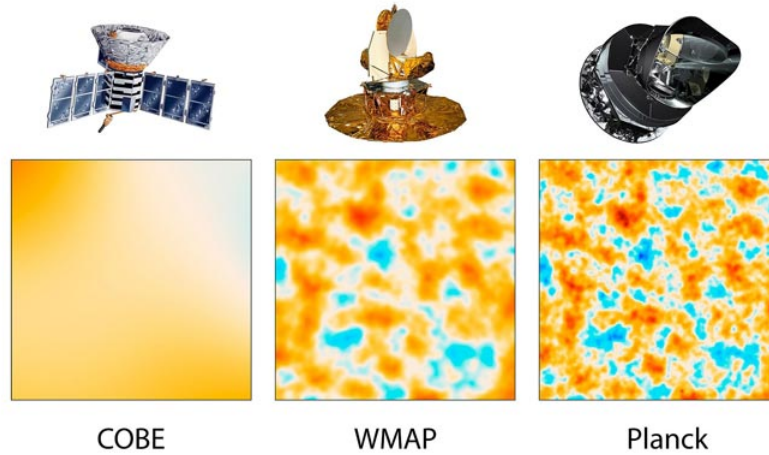


Figure 4. CMB temperature as seen by *COBE*, *WMAP*, and *Planck*. Figure credit: NASA.

1.2.2 Surveying the Cosmos from the Atacama Desert

Absorption and scattering of electromagnetic radiation by Earth’s atmosphere poses significant challenges to ground-based observatories. Figure 5 shows that while the atmosphere is moderately transparent to many radio and visible wavelengths of the electromagnetic spectrum, few such transmission windows exist at microwave frequencies (millimeter wavelengths). Thus, the superior location to observe these wavelengths is generally space, however space-based telescopes are extremely expensive and must be limited in size. In order to mitigate the detrimental effects of the atmosphere and make precision observations from the ground, CMB observatories must be sited at extremely high altitude locations to reduce the height of the atmospheric column that must be observed through, and in extremely arid locations where the amount of precipitable water vapor (PWV) in the atmosphere is low. The Atacama Desert in Chile is one of the few locations in the world that fits both criteria.

Extending from the coast of northern Chile to the western Andes mountains, the Atacama Desert is one of the most arid regions of the world (second only to portions of Antarctica), with annual median PWV of 1.1mm (Bustos et al. 2014). Sitting at over 5,000 meters above sea level (masl), the Chajnantor region (Figure 6) of this area is one of the world’s pre-eminent locations for observing the microwave

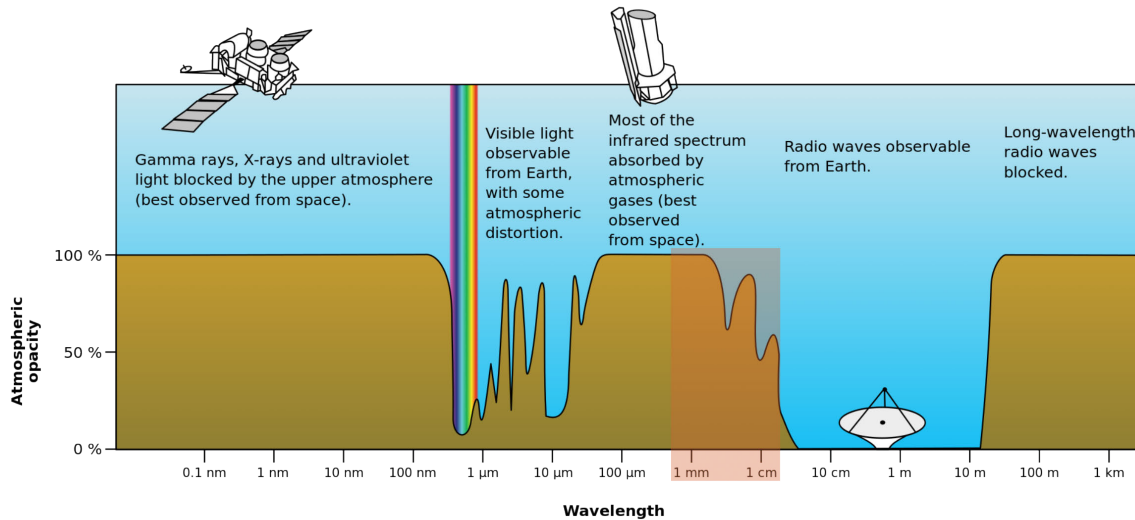


Figure 5. Atmospheric opacity as a function of wavelength. The Simons Observatory frequency range is highlighted in orange. Figure modified, original image credit: NASA.

sky. In addition to excellent atmospheric conditions and high altitude, this remote region of Chile is significantly easier to access than other preferred observing sites, such as the South Pole. As a result, this region of Chile is home to many of the world's most advanced observatories.

The many antennae of the Atacama Large Millimeter/submillimeter Array (ALMA; Wootten and Thompson 2009) sit at 5,000 masl along the Chajnantor Plateau (Figure 7). They can be spotted from nearby Cerro Toco (Figure 8), which sits at 5,200 masl and is the site of numerous observatories including The Simons Observatory, CLASS: the Cosmology Large Angular Scale Surveyor (Essinger-Hileman et al. 2014), Simons Array/POLARBEAR (Suzuki, P. Ade, et al. 2016), and, until mid-2023, ACT. The Tokyo Atacama Observatory (TAO; Yoshii et al. 2010), which currently holds the record for highest observatory on Earth, is situated at 5,640 masl on Cerro Chajnantor. Just below TAO at 5,612 masl on Cerro Chajnantor will soon be the Fred Young Submillimeter Telescope (formerly known as CCAT-prime), which aims to see first light in late 2024 (Stacey et al. 2018).

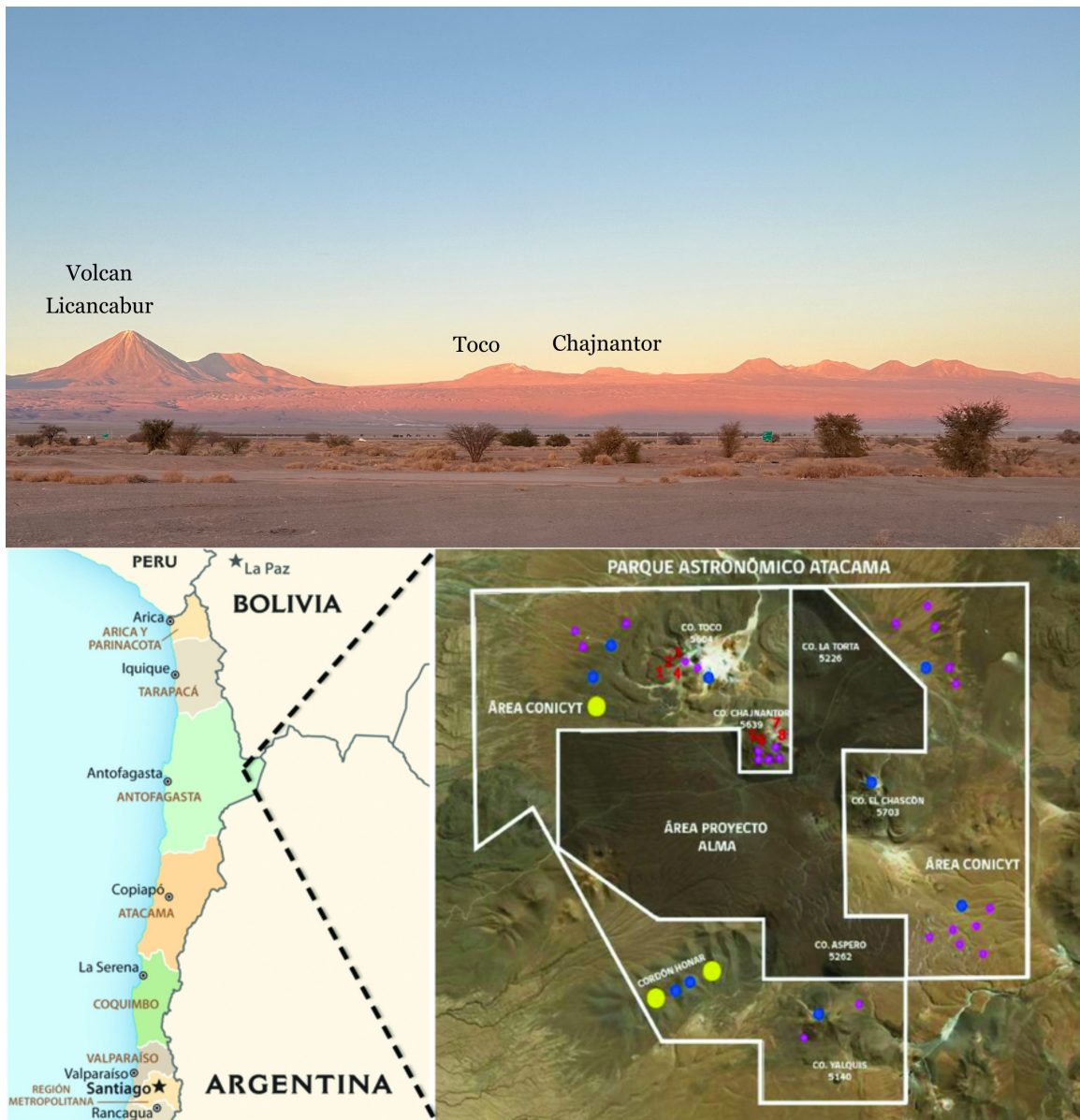


Figure 6. Sites for astronomical observation in the Atacama Desert of Chile. Top image taken from San Pedro de Atacama, facing east. Bottom image credit: Bustos et al. 2014.



Figure 7. ALMA as seen from Cerro Toco.



Figure 8. The telescopes of Cerro Toco. Image credit: Anna Kofman



Figure 9. Panoramic view of the Simons Observatory site atop Cerro Toco.

1.3 The Simons Observatory

The Simons Observatory (SO) is a new CMB observatory located atop Cerro Toco in the Parque Astronómico Atacama (Bustos et al. 2014) in the Atacama Desert of northern Chile (Figure 9). At an elevation of 5,200 masl it is one of the highest observatories in the world, situated less than 500 meters below TAO on neighboring Cerro Chajnantor. In its initial phase of operations, SO will consist of three 0.5-meter small-aperture telescopes (SATs) and one 6-meter large aperture telescope (LAT) observing in six frequency bands from 27 to 285 GHz with a collective 60,000 transition-edge sensor (TES) detectors split amongst the four receivers. With more detectors on the sky than all other previous CMB experiments combined, the Simons Observatory will usher in a new era of CMB experiment, marked by significant increases in measurement sensitivity and resolution and driven by substantial technological advancements in detectors and instrumentation (The Simons Observatory Collaboration et al. 2019; Galitzki et al. 2018). A summary of instrument parameters and expected (or realized) performance for SO and several previous and existing CMB observatories is provided in Table 1.

1.3.1 Science Goals

The unique combination of small and large-aperture telescopes will enable SO to make measurements of CMB temperature and polarization at both large and small angular scales with greater preci-

Table 1. Instrument Parameters for The Simons Observatory and Other CMB Experiments.

Experiment	AdvACT ^a	Planck ^b	SPT-3G ^c	POLARBEAR- 2 ^d	Simons Observatory ^e
Frequencies (GHz)	27-220	30-857	95-220	95-270	27-280
Number of bands	5	9	3	4	6
Angular Resolution (arcmin)	1.4 (150 GHz)	10 (100 GHz)	1.57 (95 GHz)	3.5 (150 GHz)	LAT: 2.2 SAT: 30 (93 GHz)
Number of Detectors	5,612	74	15,234	22,764	60,000
Multiplexing Factor	64	n/a	68	40	1,000
Noise (μ K-arcmin)	7 (150 GHz)	0.0215 (100 GHz)	5 (95 GHz)	6.3 (150 GHz)	LAT: 6 SAT: 2 (93/145 GHz)
Survey Size	1,800deg ²	all-sky	1,500deg ²	30deg ²	LAT: 40% SAT: 10% Chile
Location	Chile	Space	South Pole	Chile	

^a Henderson, Allison, et al. 2016

^b Planck Collaboration, Aghanim, et al. 2020

^c Sobrin et al. 2022

^d Howe et al. 2018

^e The Simons Observatory Collaboration et al. 2019

sion and greater control over systematics than previous CMB experiments. This precision is motivated by five core science goals (The Simons Observatory Collaboration et al. 2019):

1. Characterize the primordial perturbations of the CMB and look for evidence of inflation through measurement of the tensor-to-scalar ratio, as well as the scalar amplitude and non-Gaussianity of primordial perturbations.
2. Measure the number of relativistic species through measurements of the CMB temperature and polarization power spectra.
3. Constrain the sum of neutrino masses by combining SO CMB lensing and SZ measurements with measurements of baryon acoustic oscillations and weak lensing from overlapping surveys such as DESI and Rubin.

4. Reduce uncertainty in the Hubble constant and search for physics beyond the Standard Model through measurements of the CMB temperature and polarization power spectra and measurement of the amplitude of matter perturbations.
5. Further expand our knowledge of galaxy evolution through measurements of the thermal and kinetic SZ effects.
6. Further constrain the duration of the period of reionization through measurements of the CMB temperature and polarization power spectra.

Figure 10 shows the survey footprint of both the LAT and the SATs, along with the forecast CMB power spectra. The SATs will conduct deep, degree-scale surveys over a smaller region of the sky to search for signs of primordial gravitational waves by measuring the B-mode polarization of the CMB and constraining the tensor-to-scalar ratio (goal 1). These measurements will test and constrain inflationary models of the universe. The LAT will make arcminute-scale observations of CMB temperature and polarization over a larger patch of the sky that overlaps with several other surveys including the forthcoming Rubin Observatory (formerly known as the Large Scale Synoptic Telescope; Ivezić et al. 2019), as well as the Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration et al. 2016), allowing for the cross-correlated measurements necessary to achieve goals 3, 4, and 5. In addition to the aforementioned cosmological science goals, SO observations in the low and ultra-high-frequency bands will also be able to help answer outstanding questions pertaining to galactic science (Hensley et al. 2022). Finally, numerous catalogs of SZ-detected galaxy clusters, active galactic nuclei (AGN), and other point sources are expected to be generated.

1.3.2 Instrument Overview

1.3.2.1 Large Aperture Telescope

The Simons Observatory Large Aperture Telescope (Figure 11) is a 6-meter crossed-Dragone telescope that, at its maximal configuration, will utilize over 60,000 TES detectors to make arcminute-

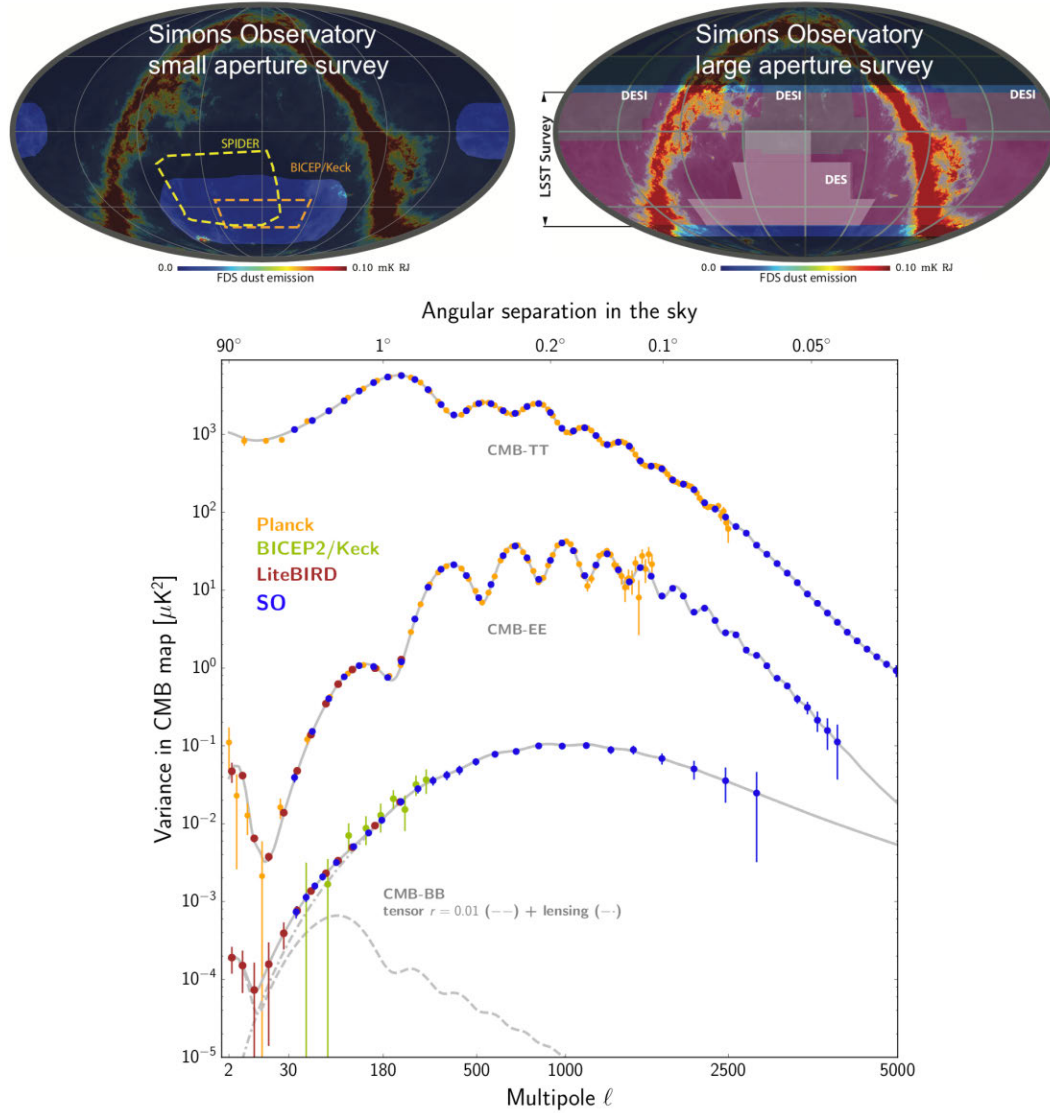


Figure 10. Top panel: Planned survey fields for the Small Aperture Telescopes and the Large Aperture Telescope. Bottom panel: forecast CMB angular power spectra for the Simons Observatory. Figure from The Simons Observatory Collaboration et al. 2019.



Figure 11. The Simons Observatory Large Aperture Telescope. Not pictured are the primary and secondary mirrors, which are due to be installed in early 2024.

scale observations of the CMB. Up to 13 optics tubes (OTs) containing $\sim 5,000$ detectors each can be installed in the 2.4-meter Large Aperture Telescope Receiver (LATR) situated across from the secondary mirror at the LAT focal point. Over the course of its five year observing campaign, The LAT will observe $\sim 40\%$ of the sky in all six SO frequency bands with a field of view of 7.8° (Parshley et al. 2018; Xu et al. 2021; Zhu et al. 2021).

During the initial phase of SO operations, the LATR (Figure 12) will be populated with 7 OTs containing a total of $\sim 30,000$ detectors distributed approximately as 66/34/1% MF/UHF/LF detectors, respectively. Each OT has its own set of cold optics to reimage light from the secondary mirror onto the detectors, along with various filters and a Lyot stop to reduce thermal and optical loading Dicker

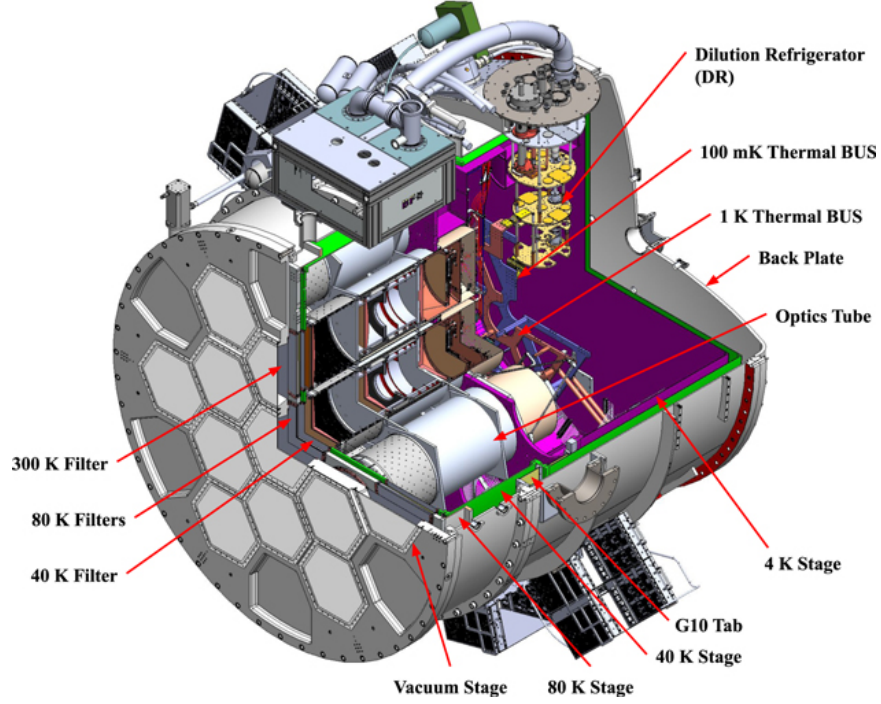


Figure 12. The Simons Observatory Large Aperture Telescope Receiver. Figure from Zhu et al. 2021.

et al. 2018. Each OT has a field of view of 1.3° . In the mid-frequency bands, the LAT is expected to achieve sensitivity levels of $\sim 6\mu\text{K-arcmin}$ (The Simons Observatory Collaboration et al. 2019).

1.3.2.2 Small Aperture Telescopes

During the initial phase of operations, the Simons Observatory will concurrently observe $\sim 10\%$ of the sky on degree-scales with three 0.42-meter refracting Small Aperture Telescopes (Figure 13), each with a field of view of 35° . Each SAT contains one optics tube with $\sim 10,000$ detectors sensitive to one of the three frequency pairs (LF/MF/UHF). Two MF SATs will observe the peak CMB signal at 93 and 145 GHz while LF and UHF SATs will enable precise characterization and removal of bright foregrounds from synchrotron radiation and dust, respectively. In the 93/145 GHz MF bands, the SAT is expected to achieve a sensitivity of $2\mu\text{K-arcmin}$.

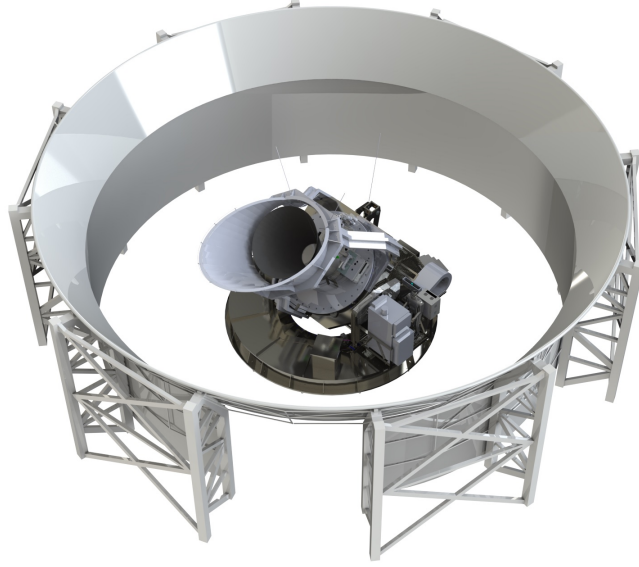


Figure 13. The Simons Observatory Small Aperture Telescope

The SO site currently has three SAT platforms (SATPs) constructed for the initial 5-year phase of operations (Figure 14). In this phase, known as *SO:Nominal*, observations are to be conducted primarily with the MF and UHF SATs. In the original plan, one of the MF SATs was to be swapped out for a short period during which the LF SAT would observe. However, recently announced expansions (described further in Chapter 6) will add an additional three SAT platforms to the site. As the primordial B-mode signal is extremely faint, significant steps must be taken to minimize the impact of instrument systematics and noise. To this end, each platform features a large comoving shield and is enclosed by a large ground screen (Figure 15) to reduce pickup and contamination from stray light. Additionally, a cryogenic half-wave plate (CHWP) is employed to modulate the incoming CMB polarization signal and to suppress $1/f$ noise introduced by atmospheric fluctuations (Yamada et al. 2023).

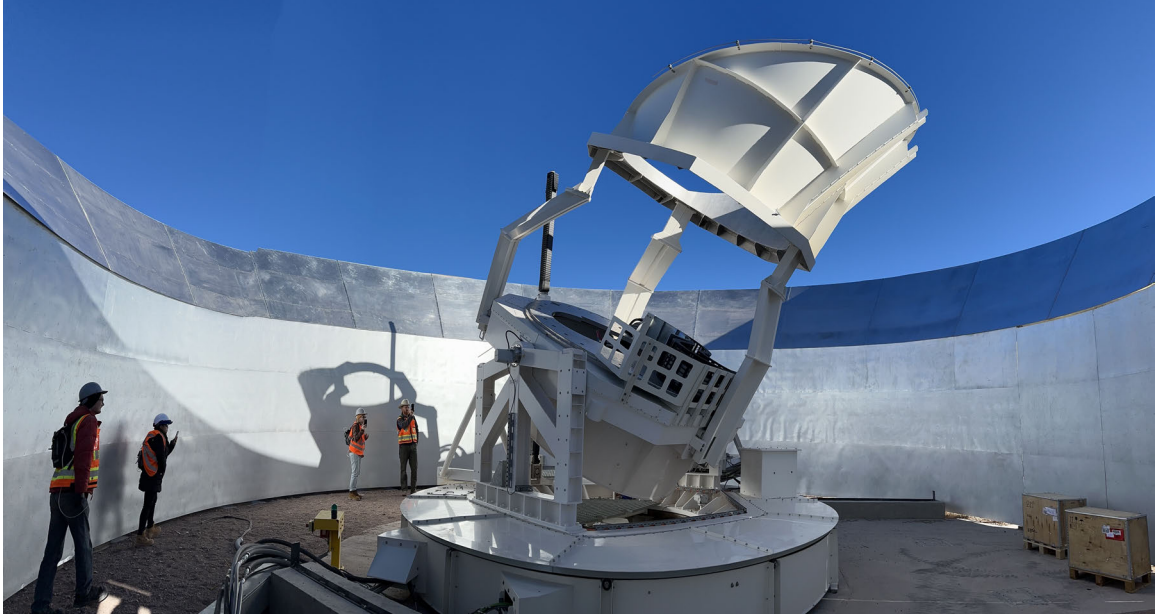


Figure 14. The SAT-MF1 platform



Figure 15. The SAT-MF1 platform ground screen

1.3.2.3 Detectors and Readout

Modern superconducting detectors for CMB instruments are photon-noise limited, meaning their performance is limited not by noise inherent to the detectors or associated readout circuits but by the noise associated with the random nature of photons they detect. As a Poisson phenomenon, this noise is reduced as the number of photons detected increases. Thus, to achieve the improved measurement sensitivity required to meet the core science goals, SO will field orders of magnitude more detectors than previous CMB observatories.

As the complexity and volume of associated readout systems increases with the number of detectors, this massive leap in detector count is only possible with similar advances in readout technology. Because superconducting TESes must be cooled to ~ 100 mK to operate, careful consideration must be taken to reduce the amount of thermal loading introduced by the electronic components and cables that are required to read them out. Like previous experiments, SO does this by utilizing a multiplexing readout scheme in which many TESes are read out on a single channel. While current TES-based systems have achieved multiplexing factors as good as 68 detectors per channel (e.g., Sobrin et al. 2022), the SO telescopes will read out $\mathcal{O}(1,000)$ detectors per readout channel. With approximately 1,700 detectors per MF/UHF array (and less than 1,000 per LF array), this correlates to just 14 pairs of readout input/output cables per receiver to read out the $\sim 10,000$ detectors in each MF/UHF SAT and 45 such pairs to read out the $\sim 30,000$ LAT detectors.

1.4 Dissertation Outline

I came to ASU to build instruments, not to be an astrophysicist. I succeeded at the first of those missions and failed at the second (though I still firmly reject the “astrophysicist” label). After wrapping up URH construction in 2021, I began a science-based project to satisfy the requirements of the Exploration Systems Design degree with the intent on ditching it after passing my qualifying exam. What started as a short little data analysis project to check off the science requirement turned into an interesting project that very quickly consumed my whole academic life. As luck (and the program

requirements) would have it this project, which easily could have its own standalone dissertation, is entirely unrelated to my “main” dissertation work. What this means for you, the reader, is that you get two dissertations for the price of one. The main content of this document is broken down as follows:

1. Chapter 1 (you are here) provides a general introduction to cosmology, the history of CMB instrumentation, and the Simons Observatory.
2. Chapter 2 provides a more in-depth introduction to transition edge sensors and their readout systems for CMB observatories, with a specific focus on how these systems are implemented in the Simons Observatory.
3. Chapter 3 was originally published as a conference proceedings for the 2022 SPIE Astronomical Instrumentation meeting. It covers the design and testing of the Universal Readout Harnesses for the Simons Observatory.
4. Chapter 4 details the on-site integration of the first SO small-aperture telescope (SAT-MF1) that occurred in July and August of 2023.
5. Chapter 5 pivots to my work on quiescent galaxy stacking and measurements of the extragalactic background light using images from the Dark Energy Survey (the bonus dissertation).
6. Finally, in Chapter 6 I attempt to tie both projects up with separate bows and discuss future directions.

OBSERVING THE COSMIC MICROWAVE BACKGROUND WITH TRANSITION EDGE SENSORS

2.1 Transition Edge Sensors

Transition Edge Sensors (TESes) are superconducting devices that exploit the superconducting transition to detect extremely faint sources of light. Superconductors are a class of materials whose electrical resistance sharply drops to zero below some critical temperature (Figure 16). The steepness of this superconducting transition can be described by the unitless parameter

$$\alpha = \frac{T}{R} \frac{dR}{dT} \quad (2.1)$$

TES bolometers (Figure 17) couple superconducting films to thermally isolated absorbers which are together coupled to a thermal bath via a weak thermal conductance G . When driven with a bias voltage at the critical temperature T_c (typically on the order of 100 milliKelvin), any minute change in temperature (e.g., from power deposited by an absorbed photon) will lead to a sharp increase in

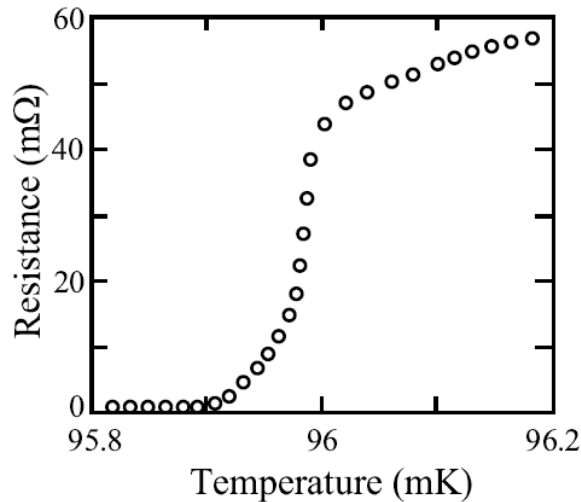


Figure 16. An example superconducting transition curve. Figure from Irwin and Hilton 2005.

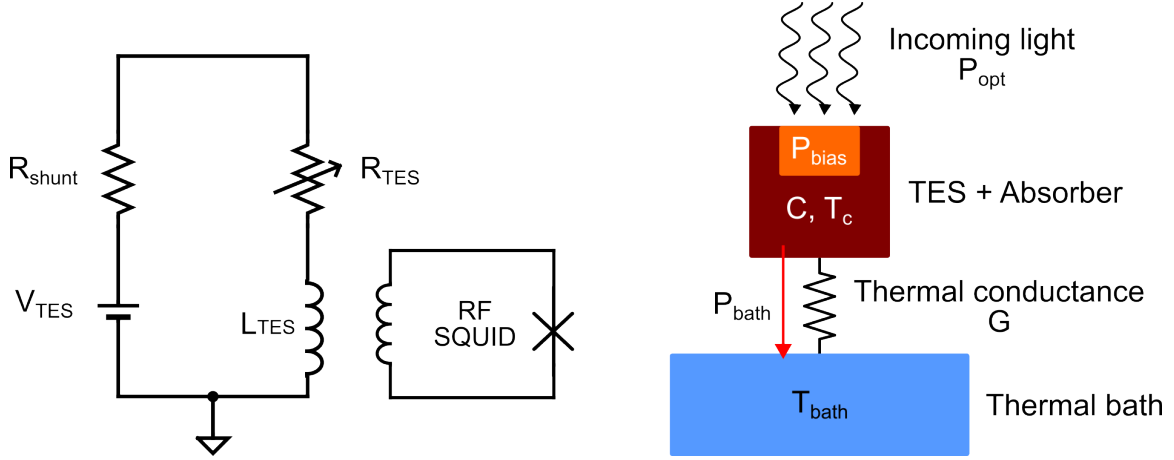


Figure 17. Left: A typical readout circuit for a TES consists of a constant voltage bias and a superconducting quantum interference device current sensor. Right: Schematic thermal circuit showing the absorbed optical power heating the absorber with lumped heat capacity C . Heat flows to the temperature bath through a weak thermal conductance G .

resistance. This increase in temperature and resistance is mitigated by a decrease in current if the applied bias voltage is held constant. This electro-thermal feedback keeps the TES operating within the transition. The following discussion of TES performance summarizes the derivations presented in Irwin and Hilton 2005 and Mauskopf 2018 and is included here for reference.

Electro-thermal feedback is quantified by the loop gain

$$\mathcal{L} = \frac{\alpha P_{bias}}{GT} \quad (2.2)$$

where

$$G \equiv \frac{dP_{bath}}{dT} \quad (2.3)$$

is the thermal conductance between the TES and the bath and α is the steepness of the resistance-temperature curve defined in Equation 2.1. The loop gain describes the change in detector response speed due to electrothermal feedback. The time constant

$$\tau = \frac{C}{G} \quad (2.4)$$

where C is the heat capacity of the suspended absorber, describes how quickly the detector recovers.

The thermal response of an ideal TES with heat capacity C is given by

$$C \frac{dT}{dt} = P_{opt} + P_{bias} - P_{bath} \quad (2.5)$$

where P_{opt} is the power deposited by a photon in the TES and $P_{bias} = V_{bias}^2/R(T, I)$ is the power from the bias circuit. Taking the small-signal approximation and rearranging Equation 2.5, we have

$$i\omega C \delta T = \delta P_{opt} + \frac{\partial P_{elec}}{\partial T} \delta T - G \delta T \quad (2.6)$$

Solving for δP_{opt} , we have

$$\delta P_{opt} = G \delta T + i\omega C \delta T + \frac{\alpha}{T} \frac{V_{bias}^2}{R} \delta T \quad (2.7)$$

The responsivity S_I quantifies the change in TES current as a result of deposited optical power.

$$S_I = \frac{dI}{dP_{opt}} = \frac{dI}{dR} \frac{dR}{dT} \frac{dT}{dP_{opt}} \quad (2.8)$$

Using Equations 2.1, 2.2, and 2.7, we have

$$\begin{aligned} S_I &= \frac{d}{dR} \left(\frac{V_{bias}}{R} \right) \frac{dR}{dT} \left(G + i\omega C + \frac{\alpha}{T} \frac{V_{bias}^2}{R} \right)^{-1} \\ &= -\frac{V_{bias}}{R^2} \frac{dR}{dT} \left(G + i\omega C + \frac{\alpha}{T} \frac{V_{bias}^2}{R} \right)^{-1} \\ &= -\frac{P_{bias}}{V_{bias}} \frac{\alpha}{T} \left(G + i\omega C + \frac{\alpha}{T} P_{bias} \right)^{-1} \\ &= -\frac{P_{bias}}{V_{bias}} \frac{\alpha}{GT} \left(1 + \frac{i\omega C}{G} + \frac{\alpha P_{bias}}{GT} \right)^{-1} \\ &= -\frac{1}{V_{bias}} \frac{\alpha P_{bias}}{GT} (1 + i\omega\tau + \mathcal{L})^{-1} \\ &= -\frac{1}{V_{bias}} \mathcal{L} \left[(\mathcal{L} + 1) \left(1 + \frac{i\omega\tau}{1 + \mathcal{L}} \right) \right]^{-1} \\ &= -\frac{1}{V_{bias}} \frac{\mathcal{L}}{\mathcal{L} + 1} \frac{1}{1 + \frac{i\omega\tau}{\mathcal{L} + 1}} \end{aligned}$$

Defining $\tau_{eff} = \frac{\tau}{\mathcal{L} + 1}$ as the effective time constant, we have

$$S_I(A/W) = -\frac{1}{V_{bias}} \frac{\mathcal{L}}{\mathcal{L} + 1} \frac{1}{1 + i\omega\tau_{eff}} \quad (2.9)$$

An important design parameter of TESes is the saturation power P_{sat} , which is the amount of power required to drive the detector into the normal regime

$$P_{sat} = k(T_c^n - T_{bath}^n) \quad (2.10)$$

where

$$k = \frac{G}{nT_c^{n-1}} \quad (2.11)$$

and n is a thermal constant typically in the range of 3-5. Detector P_{sat} must be higher than the expected incident optical power P_{opt} in order for the TES to stay on the superconducting transition. Saturation power is tuned by adjusting the geometry of the link between the TES and the thermal bath in order to change G . Changing G also changes the detector time constant τ , which can be countered by changing the heat capacity C . In practice, achieving a target P_{sat} and time constant at a desired T_c requires quite a bit of iterative fine tuning (see Niemack et al. 2012; Dutcher et al. 2018; Stevens et al. 2020). A similar calculus exists for the determination of the TES normal resistance R_n . Measurements of TES current as a function of bias voltage (“I-V curves”) are typically carried out at multiple bath temperatures to derive the values of many of the aforementioned parameters and establish relationships between them. Additionally, measurements of the complex impedance

$$Z_{TES}(\omega) = R_0(1 + \beta) + \frac{R_0 \mathcal{L}_I}{1 - \mathcal{L}_I} \frac{(2 + \beta)}{1 + i\omega\tau_I} \quad (2.12)$$

where

$$\tau_I = \frac{\tau}{1 - \mathcal{L}_I} \quad (2.13)$$

and

$$\mathcal{L}_I \equiv \frac{P_0 \alpha}{GT_0} \quad (2.14)$$

as a function of frequency ω and bias power P_0 (e.g., Cothard et al. 2020) can yield measurements of C , α , and β , where

$$\beta \equiv \frac{I}{R} \frac{dR}{dI} \quad (2.15)$$

is the current responsivity of the TES (Irwin and Hilton 2005). Careful tuning of the aforementioned parameters allows for optimization of the various sources of noise, which are discussed in the following section.

2.1.1 Sources of Noise

The primary sources of noise in a TES device (not including the associated readout architecture) are Johnson-Nyquist noise and thermal fluctuation noise (TFN). These are both forms of shot (Poisson) noise, and are due to the quantized nature of charge carriers and phonons, respectively. The Johnson-Nyquist noise in a TES is due to current fluctuations in the TES circuit. This noise is secondary to the thermal fluctuation or phonon noise, which is due to fluctuations in heat flow between the bath and the absorber (Zmuidzinas 2003; Irwin and Hilton 2005; Mauskopf 2018).

Following the derivation presented in Mauskopf 2018, these sources of noise can be expressed in terms of noise equivalent power (NEP_J and NEP_{th}) as

$$NEP_J^2 \simeq 4k_B T^2 G \frac{GT}{P_{bias}} \frac{1 + \omega^2 \tau_{eff}^2}{\alpha^2} \quad (2.16)$$

and

$$NEP_{th}^2 = F_{link} 4k_B T_c^2 G \approx F_{link} 4k_B T_c n(1 + \gamma) \frac{P_{opt}}{T_c} \quad (2.17)$$

where

$$F_{link} = \frac{n+1}{2n+3} \frac{1 - (T_{bath}/T_c)^{2n+3}}{1 - (T_{bath}/T_c)^{n-1}} \quad (2.18)$$

and $\gamma = P_{bias}/P_{opt}$. The impact of this noise can be lowered by choosing a lower critical temperature, typically around 1.5-2 times the bath temperature, which is ultimately determined by the capabilities of the cryogenic system. Noise also arises from the associated readout circuit, but this can be kept below the detector noise level by increasing the current responsivity (achieved in practice by decreasing TES normal resistance R_n).

Current state-of-the-art systems are limited by the noise of the incoming photons. This noise is comprised of shot noise due to the random statistical fluctuations in arrival times at the detector as well as wave noise (photon bunching noise), which becomes important at radio wavelengths and in densely packed detector arrays where adjacent detectors may sample the same mode (Brown and Twiss 1956; Lamarre 1986; Hill and Kusaka 2023). For a photon frequency ν , the photon noise can be approximated as (Mauskopf 2018)

$$NEP_{photon}^2 \approx 2P_{opt} h\nu + \frac{2P_{opt}^2}{\Delta\nu} = 2P_{opt} h\nu (1 + \eta n_{occ}) \quad (2.19)$$

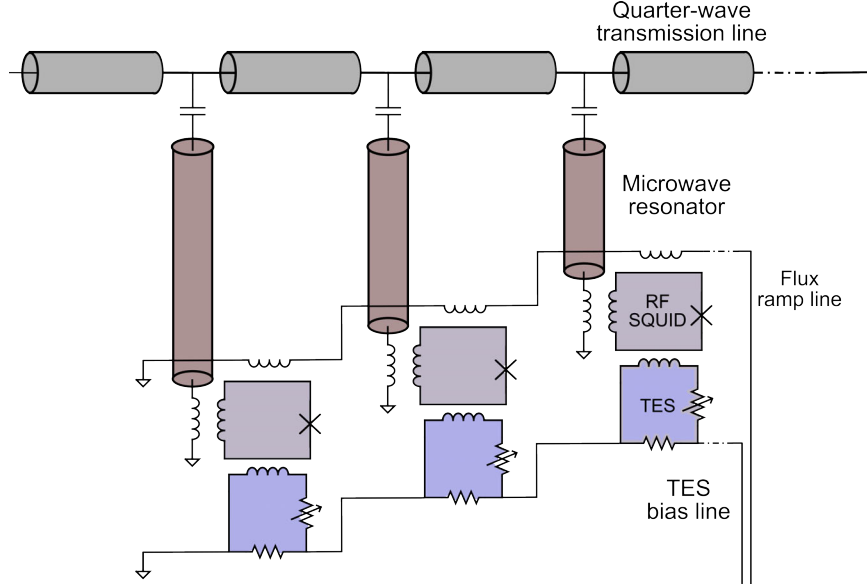


Figure 18. The Microwave Multiplexing (μ -mux) circuit.

where η is the optical efficiency of the system and n_{occ} is the photon occupation number. The first term in this equation represents the shot noise and the second term represents the wave noise. To ensure photon-noise limited performance, T_c must be selected such that the ratio of the photon noise equivalent power to the thermal noise equivalent power is greater than 1. In photon-noise limited systems, the most straightforward way to reduce noise is to add more detectors. This has led to a push for the development of much larger arrays of detectors à la Simons Observatory and CMB-S4.

2.2 Multiplexed Readout of TES Detector Arrays

Microwave multiplexing (μ -mux) is a readout architecture that enables the simultaneous readout of $\mathcal{O}$ 1,000 TES detectors on a single readout channel (Mates 2011). The fundamental μ -mux circuit, shown in Figure 18, features radio frequency superconducting quantum interference devices (RF SQUIDs) that are inductively coupled to TES detectors and microwave resonators. The microwave resonators are in turn coupled to a single microwave transmission line. Each resonator is fabricated to a unique electrical length and thus has a distinct resonance frequency.

In this system, the RF SQUID fluxes are modulated by a periodic sawtooth signal fed through a common flux ramp line, which constantly shifts the resonator frequencies of the coupled resonators. The change in TES current induced by the absorption of photons induces an additional change in the SQUID flux, which imposes a shift in phase of the SQUID response to the flux ramp signal (Mates et al. 2012). Warm readout electronics generate probe tones that are sent through the common transmission line to monitor these changes and recover the detector signals. Cryogenic low-noise amplifiers are commonly employed to amplify the output signals which are then demodulated by the warm readout (Henderson, Ahmed, et al. 2018).

The noise equivalent power associated with the described readout architecture is

$$NEP_{readout} = \frac{NEI}{S_I} \quad (2.20)$$

or, in the limit where $\mathcal{L} \gg 1$,

$$NEP_{readout} = V_{bias} \times NEI \quad (2.21)$$

where NEI is the noise equivalent current. The noise equivalent current primarily consists of contributions from excess frequency or two-level system (TLS) noise, noise from tone generation (DAC noise), and amplifier noise. TLS noise arises from fluctuations between ground and excited energy states on the surface of the dielectric material of the microwave resonators (Gao, Zmuidzinas, et al. 2007; Gao, Daal, Vayonakis, et al. 2008; Gao, Daal, Martinis, et al. 2008). DAC noise refers to the $1/f$ or low-frequency noise that arises from the tone generation process (Dobbs et al. 2012; Yu et al. 2023). Intermodulation distortion in low-noise amplifiers (described in further detail in subsequent paragraphs) generates a noise floor that scales with drive power. Additional contributions to the readout noise come from the cables, attenuators, and other components in the RF chain. A comprehensive model of readout noise for the Simons Observatory is presented in Silva-Feaver 2023.

Readout noise is lowered by minimizing the various sources of NEI , or by operating at a lower V_{bias} . Experimental requirements typically place stringent limits on the contribution to the overall noise from the readout. Modern systems are typically able to achieve readout noise levels that degrade the overall noise performance by less than 10% (Yu et al. 2023).

Table 2. Intermodulation products created from a two-tone input signal.

Order	Frequency	Amplitude
Second	$2\omega_1, 2\omega_2$	$\frac{1}{2}a_2V_0^2$
Second	$\omega_1 \pm \omega_2$	$a_2V_0^2$
Third	$3\omega_1, 3\omega_2$	$\frac{1}{4}a_3V_0^3$
Third	$2\omega_1 \pm \omega_2, 2\omega_2 \pm \omega_1$	$\frac{3}{4}a_3V_0^3$

One significant challenge in highly multiplexed systems is amplifier linearity. When a device is given an input signal consisting of two or more closely spaced frequencies, third order intermodulation products can arise and degrade the output signal (Pozar 2012). In the case of an input signal comprised of two closely spaced tones at frequencies ω_1 and ω_2 , the input voltage can be expressed as:

$$v_i = V_0(\cos \omega_1 t + \cos \omega_2 t) \quad (2.22)$$

The resulting output can be expanded in a Taylor series

$$\begin{aligned} v_o = & a_0 + a_1 V_0(\cos \omega_1 t + \cos \omega_2 t) \\ & + a_2 V_0^2(\cos \omega_1 t + \cos \omega_2 t) \\ & + a_3 V_0^3(\cos \omega_1 t + \cos \omega_2 t) + \dots \end{aligned} \quad (2.23)$$

which, when further expanded, results in additional spurious tones at multiples, sums, and differences of the input frequencies. In the case of the two-tone input signal, a total of ten such spurious tones are generated (Table 2).

While most of these spurious tones will fall out of band, the third-order difference tones will appear in band, very close to the input frequencies. For example, a device driven with input tones $\omega_1 = 6.00$ GHz and $\omega_2 = 6.01$ GHz will theoretically have third-order intermodulation products appear at $2\omega_1 - \omega_2 = 5.99$ GHz and $2\omega_2 - \omega_1 = 6.02$ GHz. The number of third-order tones scales with the number of input tones as $2N(N - 1)$, thus for a multiplexing factor on order 1,000, approximately two million spurious tones will fall in band. In order to avoid this distortion, the device must be driven with an input power level below that of the third-order intercept point (IP₃), where the third

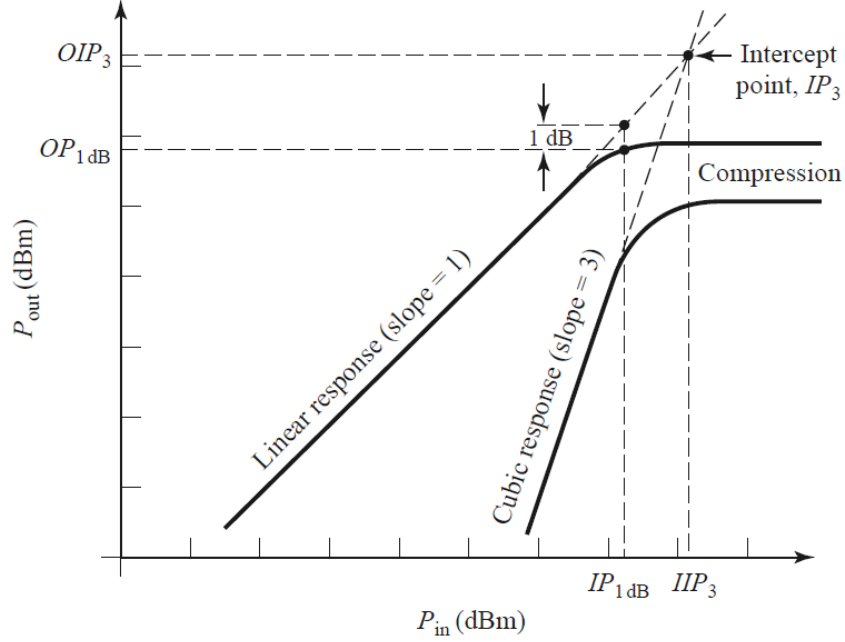


Figure 19. Theoretical linear and cubic (third-order) responses of a nonlinear amplifier. The extrapolated intersection of the two curves defines the third-order intercept point (IP_3) of the amplifier. Figure from Pozar 2012.

order intermodulation products and the desired response would theoretically have the same response (Figure 19).

The overall noise equivalent power, accounting for photon, for the combined detector and readout system in terms of CMB temperature (NET) for a single detector is given by

$$NET_{det} = \frac{\sqrt{NEP_{photon}^2 + NEP_{th}^2 + NEP_J^2 + NEP_{readout}^2}}{\sqrt{2}(dP/dT_{CMB})} \quad (2.24)$$

where dP/dT_{CMB} is the efficiency of the conversion from incident optical power to CMB temperature.

For a full detector array we have

$$NET_{array} = \frac{NET_{det}}{\sqrt{Y N_{det}}} \Gamma \quad (2.25)$$

where Γ is a factor that quantifies the degree of noise correlation between pixels (≥ 1), Y is detector yield, and N_{det} is the total number of detectors (Hill, Bruno, et al. 2018).

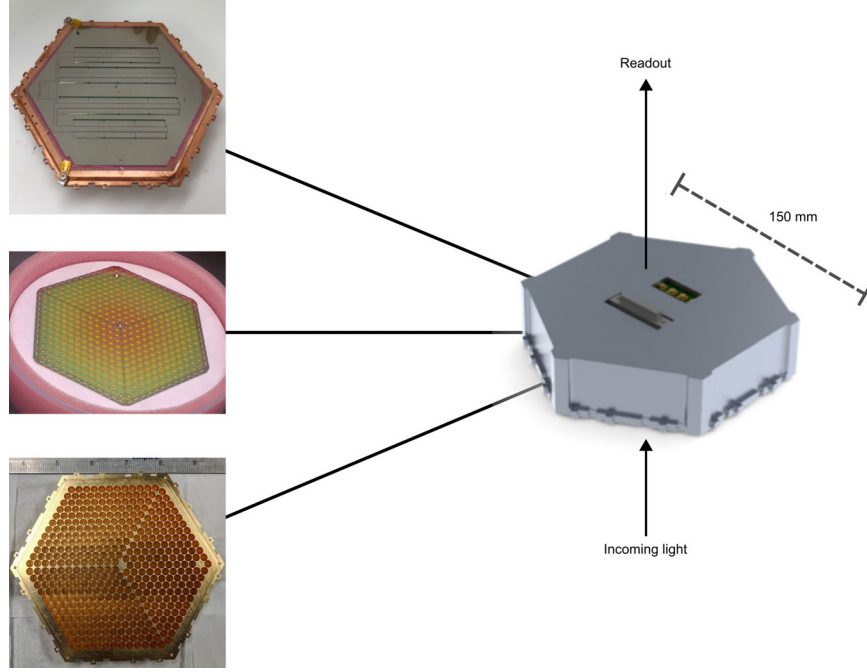


Figure 20. Simons Observatory Universal Focal Plane Module (right) is comprised of optical coupling (bottom left), detector stack (middle left), and cold readout (top left) arrays. Components shown here are for mid-frequency (93/145 GHz) operation.

2.3 Detectors and Readout for The Simons Observatory

At the heart of the detectors and readout system for Simons Observatory is the Universal Focal Plane Module (UFM; Figure 20) that is implemented identically in both the LAT and the SATs. Each UFM is comprised of an array of optical coupling elements, an array of TES bolometers, and a Universal Multiplexing Module (UMM), which contains all of the multiplexing readout circuit elements. In the Small-Aperture Telescopes, seven UFM's are tiled in a honeycomb pattern while each LAT optics tube contains three UFM's arranged in a clover-like shape (Figure 21). These UFM's are read out through a series of RF components staged at 1, 4, 40, and 300 K using SLAC Microresonator Radiofrequency (SMuRF) electronics (Henderson, Ahmed, et al. 2018; Yu et al. 2023). A schematic of the full SO detector and readout system is presented in Figure 22.

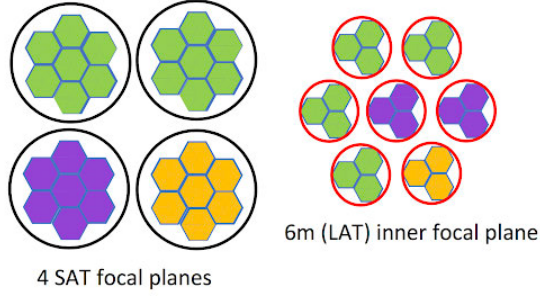


Figure 21. UFM arrangement in the SATs and LAT optics tubes. Green, purple, and yellow hexagons represent MF, UHF, and LF arrays, respectively.

SO utilizes dual-frequency, dual-polarization pixels which are each sensitive to the orthogonal polarizations of a pair of frequencies: 27/39 GHz (LF), 93/145 GHz (MF), or 225/285 GHz (UHF). Each pixel contains four aluminum manganese (AlMn) TES detectors which are designed to have a critical temperature of 160 mK and a normal resistance of 8 m Ω for operation in a 100 milliKelvin bath, with P_{sat} ranging from 4-24 pW for MF and UHF detectors, respectively (Stevens et al. 2020). These detectors are arranged into hexagonal arrays on top of silicon wafers with $\sim 1,700$ TESes per MF/UHF array and ~ 450 per LF array. An array of feedhorns (MF/UHF) or lenslets (LF) situated directly in front of the detector arrays couples the incoming beam to the detector modules. Orthomode transducers (MF/UHF) or sinuous antennas (LF) split the light according to polarization before it is filtered according to frequency (Suzuki, Arnold, et al. 2014; Simon et al. 2018).

Underneath the detector array, the cold readout components are situated on the Universal Multiplexing Module (UMM). The fundamental unit of the Universal Multiplexing Module is the multiplexing (mux) chip, of which there are 28 per UMM (Healy, Ali, et al. 2020; McCarrick, Healy, et al. 2021; Dober et al. 2021). Each chip contains 64 multiplexing channels, which each contain the inductively coupled RF SQUID/resonator circuit needed to read out one detector. Each multiplexing channel in a mux chip shares a common transmission line that is capacitively coupled to the resonators and a common flux ramp that is inductively coupled to the RF SQUIDs. The microwave resonators are each fabricated to unique electrical lengths that correspond to resonance frequencies within the 4-6 GHz band. Within the footprint of the UFM, wirebonds connect the UMM to the detector module and

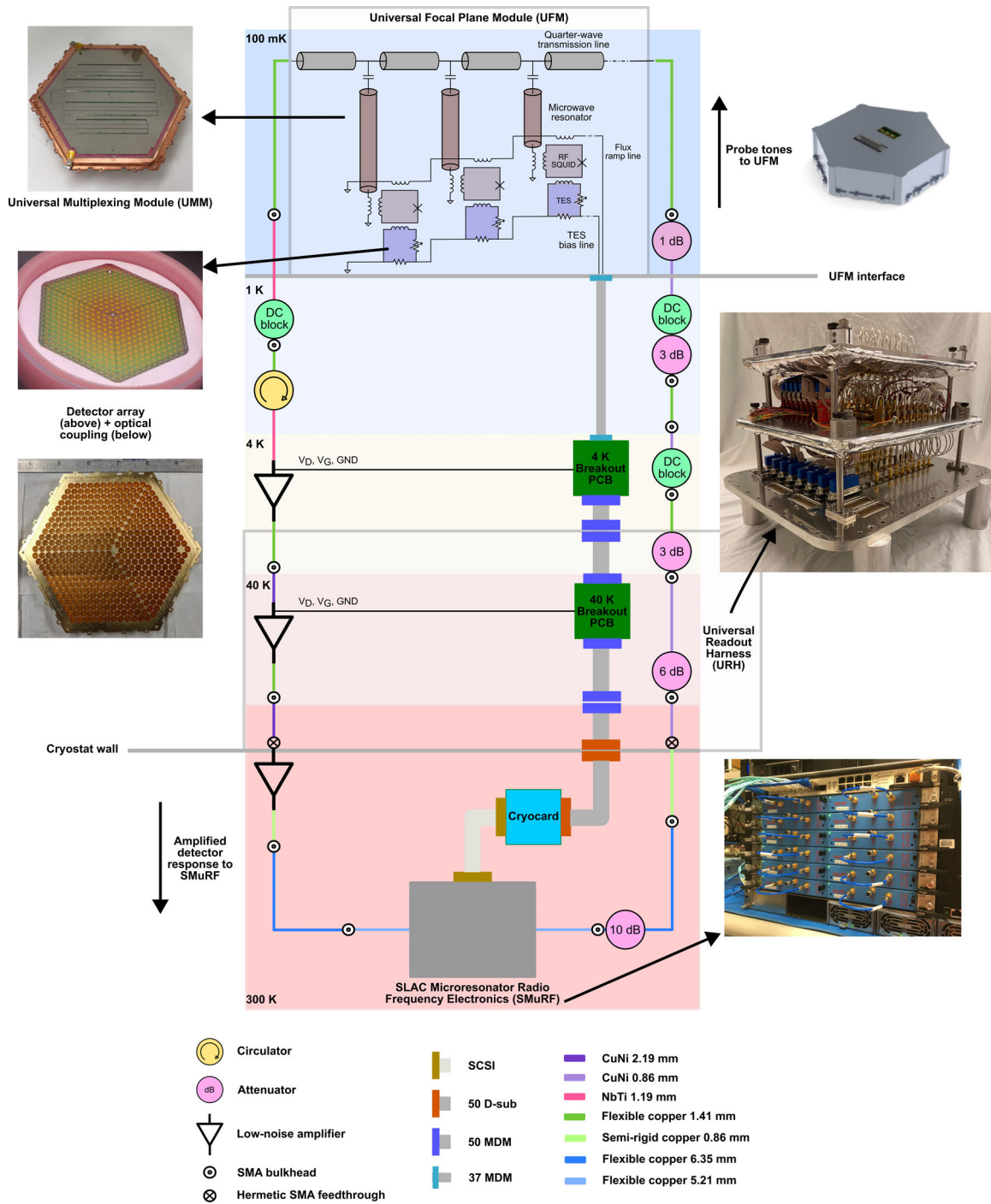


Figure 22. Simons Observatory readout schematic for one half of one UFM. For a full UFM, an additional set of RF components is required. Cables not drawn to scale.

silicon wafer which contains the TES bias circuitry. This stacked configuration of the optical coupling, detector, and multiplexing elements allows for maximum optimization of focal plane area. Outside of the UFM package, just two sets of coaxial cables and one DC ribbon cable are needed to connect the UFM to the broader readout system and read out all 28 mux chips.

On the warm side, the SMuRF system generates and tracks probe tones to facilitate resonator read out. Inside the cryostat, attenuators are placed on multiple temperature stages on the input RF lines to reduce the noise temperature and attenuate input tone power to the optimal level of $\sim -70\text{dBm}$. On the output side, the SO readout chain employs a two-stage cryogenic amplification system designed to amplify the output signal from the resonators while minimizing signal degradation due to nonlinear effects, which can be substantial when reading out $\sim 1,000$ tones at one time (Henderson, Ahmed, et al. 2018).

The cryogenic amplifier chain consists of a commercially available 4 K low-noise amplifier manufactured by Low-Noise Factory followed by a second low-noise amplifier at 40 K, designed and constructed in-house at ASU specifically to meet the requirements of the SO readout system. The cryogenic amplifiers are followed by an additional warm amplifier at the output of the cryostat. The characteristics of these amplifiers are summarized in Table 3. The 4 K LNA was selected such that its input-referred IP3 would limit the linearity of the entire system, with each subsequent amplifier having an input-referred IP3 less than the previous amplifier’s output-referred IP3 (Sathyanarayana Rao et al. 2020).

Cryogenic RF components are connected by various flavors of coaxial cables depending on the varying priorities at different locations in the line. On the input side, thin pieces of cupronickel (CuNi) coax are used between temperature stages to minimize thermal conduction. On the output side, superconducting niobium titanium (NbTi) coaxial cables are used to minimize signal loss prior to hitting the first amplifier, beyond which slightly larger diameter CuNi cables are used. For connections between components at the same temperature, flexible copper coax is used. TES bias power, flux ramp lines, and amplifier power is generated by SMuRF, facilitated by PCBs mounted on the cryostat exterior known as cryocards, and transported through the cryostat by a series of manganin (PhBr) DC

Table 3. Summary of characteristics for low-noise amplifiers employed in the Simons Observatory readout system. Table adapted from Sathyanarayana Rao et al. 2020.

Temperature Stage (K)	Manufacturer	Expected P_{in} (dBm)	T_{noise}	IIP3 (dBm)	Gain (dB)	OIP3 (dBm)
4	Low-Noise Factory (LNC4_8LG)	-50	2	-30	24	-6
40	Arizona State University	-26	35	7	14	21
300	Minicircuits (ZX60- 83LN12+)	-14	100	13	20	33

cable looms. PCBs connected inline with the DC ribbon cables at 40 K and 4 K break out sets of bias triplets for the cryogenic amplifiers.

Between the focal plane and the 4 K stage, the readout circuit remains the same for both the SATs and the LATR, however the implementation differs due to the layout and size differences between the receivers. In the SATs, the 100 mK-4 K readout circuitry is split into two concentric cold readout assemblies (CRAs) that surround the focal plane (see Chapter 4 for more details). In the LATR, the 100 mK-4 K readout components are situated in the optics tubes directly behind the focal plane (Figure 23). In both cases, long isothermal copper coaxial cable and DC ribbon loom “highways” connect the cold readout to the Universal Readout Harness, which is the subject of Chapter 3.

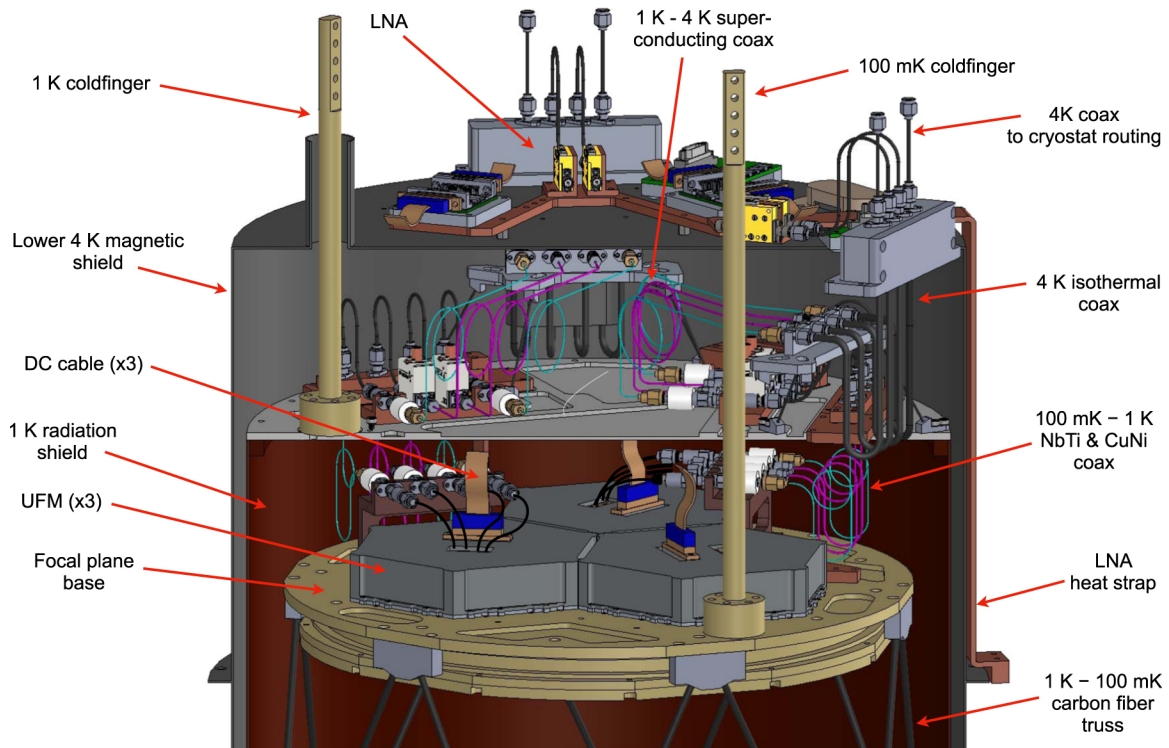


Figure 23. Schematic of detector and readout components in the Large Aperture Telescope Receiver optics tube. Figure from Zhu et al. 2021.

Chapter 3

DEVELOPMENT AND PERFORMANCE OF UNIVERSAL READOUT HARNESES FOR THE SIMONS OBSERVATORY

3.1 Abstract

The Simons Observatory (SO) is a ground-based cosmic microwave background (CMB) survey experiment that consists of three 0.5 m small-aperture telescopes and one 6 m large-aperture telescope, sited at an elevation of 5200 m in the Atacama Desert in Chile. SO will utilize more than 60,000 transition edge sensors (TES) to observe CMB temperature and polarization in six frequency bands from 27-280 GHz. Common to both the small and large aperture telescope receivers (LATR) is the 300K-4K Universal Readout Harness (URH), which supports up to 600 DC bias lines and 24 radio frequency (RF) channels consisting of input and output coaxial cables, input attenuators and custom high dynamic range 40K low-noise amplifiers (LNAs) on the output readout coaxial cable. Each RF channel can read out up to 1000 TES detectors. In this paper, we will present the design and characterization of the six URHs constructed for the initial phase of SO deployment.

3.2 Introduction

The Simons Observatory (SO) is a new ground-based cosmic microwave background (CMB) survey experiment sited at an elevation of 5200 meters in the Atacama Desert in Chile (The Simons Observatory Collaboration et al. 2019). SO will utilize three 0.5-meter small aperture telescopes (SATs) and one 6-meter large aperture telescope (LAT) to observe CMB temperature and polarization at both small (degree) and large (arcminute) angular scales. More than 60,000 transition edge sensors (TES) distributed across the four receivers will be used observe the CMB in six frequency bands from 27-280 GHz. These detectors will be read out using microwave SQUID multiplexing (μ -mux; Mates 2011) technology with a targeted multiplexing factor of order 1,000 detectors per radio frequency (RF) in-

put/output pair. Both the total number of detectors and the target multiplexing factor are greater than any previous CMB experiment.

The Universal Readout Harness (URH) (Fig. 24) is a three-stage assembly that houses all of the 300K-40K and 40K-4K readout wiring and electronics for all Simons Observatory (SO) receivers. A fully populated URH can support up to 24 RF input/output coaxial cable pairs (“RF channels”) and a maximum of 600 DC bias lines grouped together in looms of 50 wires (“DC channels”). With the current SO multiplexing scheme, each RF channel can support the readout of ~ 1000 transition-edge sensors (TES). The URH directly interfaces with the SLAC Microresonator Radio Frequency electronics system (SMuRF; Henderson, Ahmed, et al. 2018) on the 300K side and with the cold (4K-0.1K) readout on the 4K side. The readout architecture within the URH is standardized across all SO receivers, with the number of populated channels tailored to suit the readout requirements of each receiver. For initial deployment, the small-aperture telescopes (SATs; Ali et al. 2020) each require a single harness with 14 RF channels and 8x50 DC bias lines (Fig. 25) and the large-aperture telescope receiver (LATR; Zhu et al. 2021) requires two harnesses with a collective 46 RF channels. One additional harness is also used in the LATR optics tube testbed (LATRt; Harrington et al. 2021), which will ultimately be converted into an additional SAT. Housing all of these coaxial cables and components within a standalone wiring harness greatly simplifies the readout assembly and disassembly processes.

3.3 Harness Design

3.3.1 Mechanical Design

Structurally, the URH is comprised of three aluminum plates held in place by support rods. The aluminum support rods are required only for assembly and installation, and are removed once the harness plates have been securely bolted to the 300K, 40K, and 4K receiver shells. The 300K vacuum

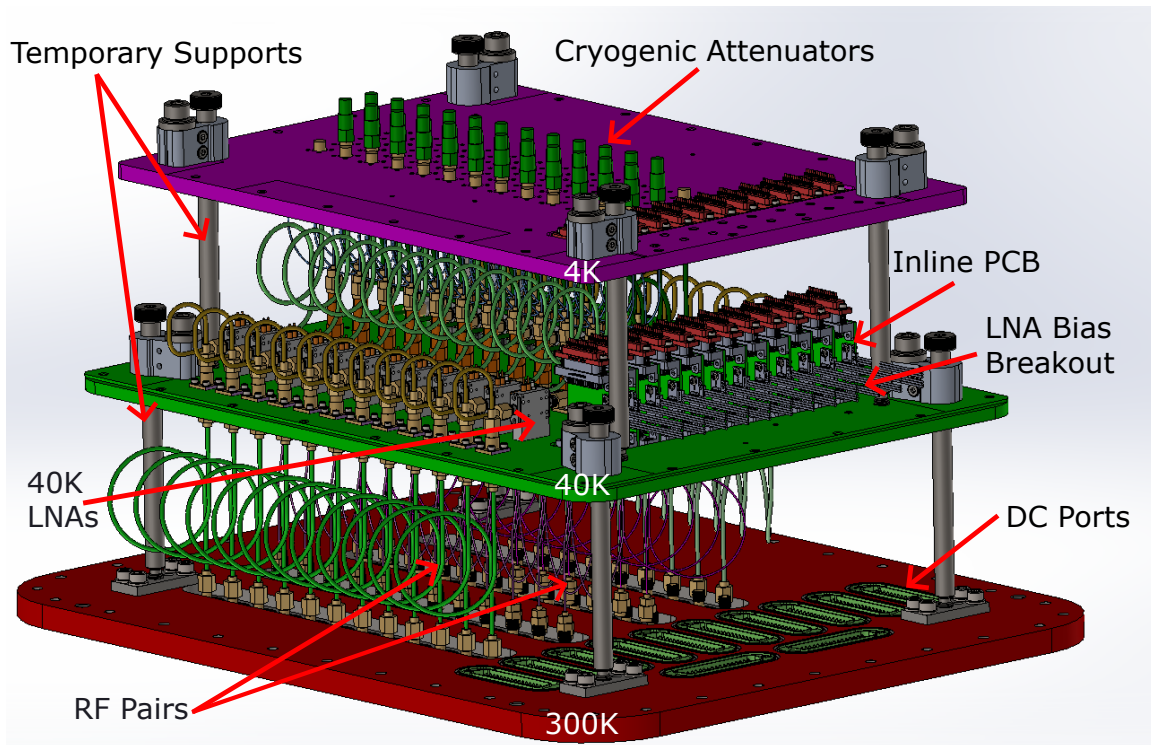


Figure 24. CAD rendering of the Universal Readout Harness. DC ribbon cables are not shown.

plate features hermetically sealed laser-welded SMA¹ and 50-position subminiature-D (D-sub)² connectors, while standard bulkhead connectors are used on the 40K and 4K stages. Each URH stands approximately 35x50x270 cm, weighs approximately 25 kg and can be fitted with either forklift tubes or handles to simplify handling and installing into the receiver.

Careful consideration must be taken to minimize thermal loading from the large number of components packed into the small footprint of the URH. Low thermal conductivity material is used in cables that connect temperature stages, and attenuators are used to help manage heat loads on the input RF lines. Fixed components such as low-noise amplifiers (LNAs) and PCBs are attached to the harness plates with conical spring washers to ensure good thermal contact is maintained. Multi-layer mylar

¹Ceramtec, Laurens, SC 29360 USA

²AccuGlass Products, Inc., Valencia, CA 91355 USA

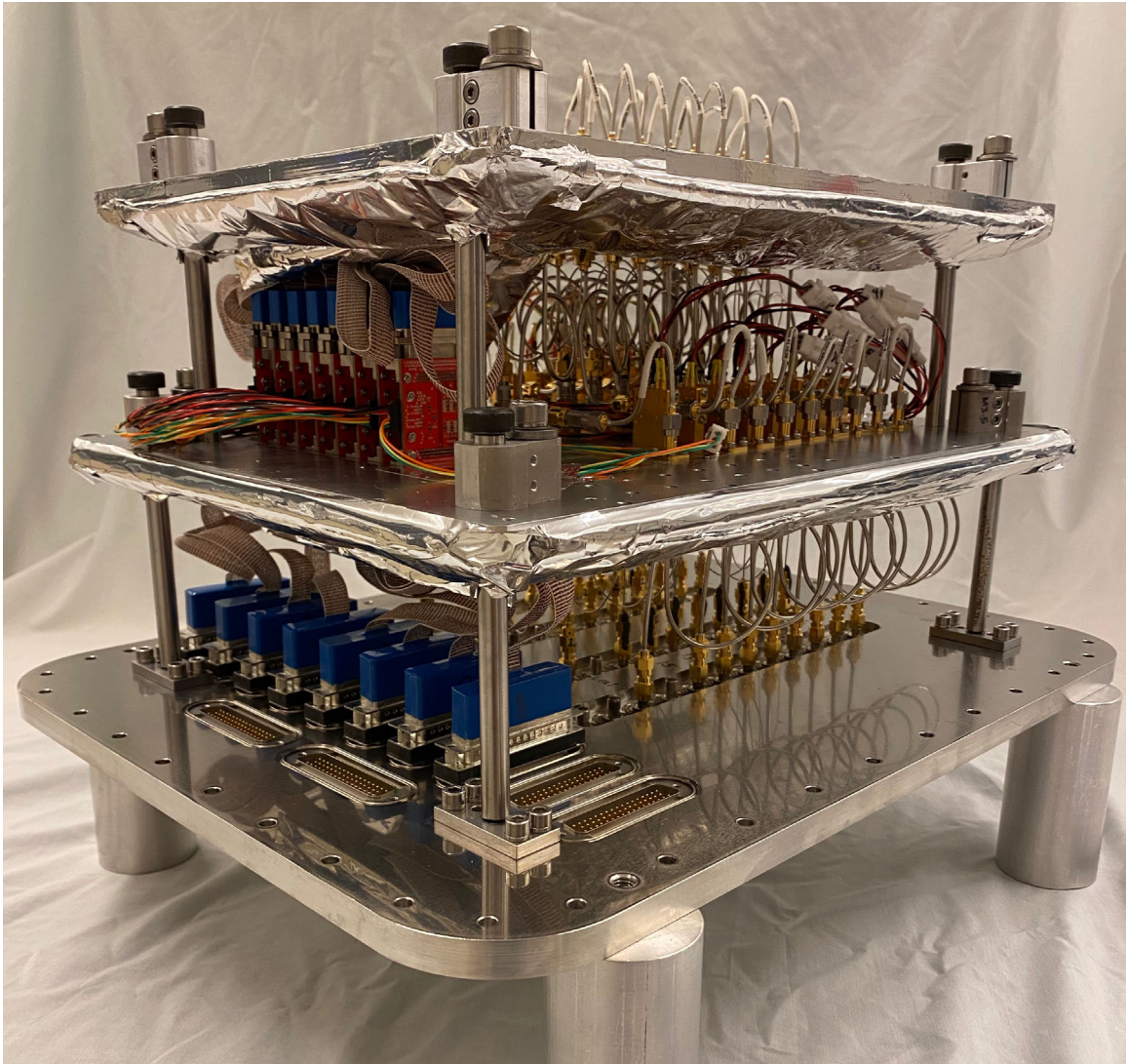


Figure 25. A Universal Readout Harness configured for a SAT featuring 15 RF channels and 400 DC bias lines.

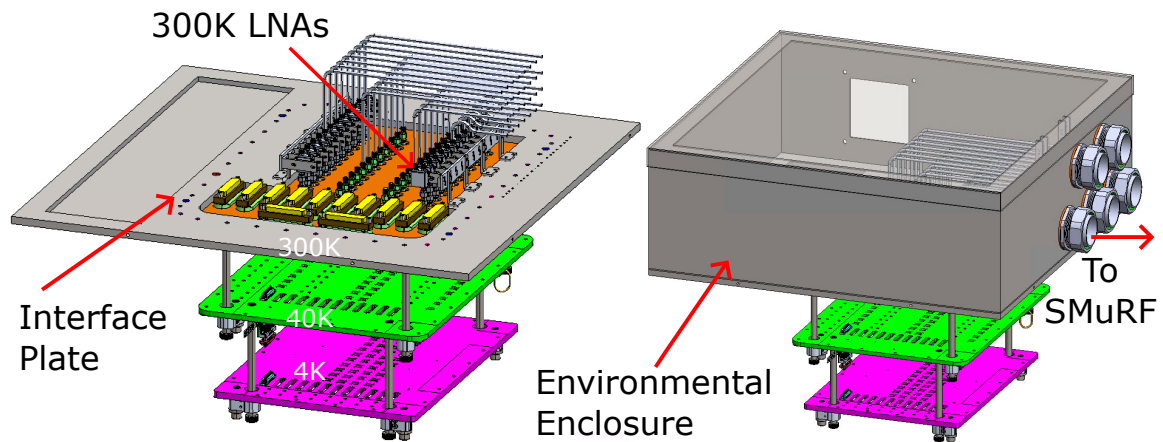


Figure 26. After the URH is integrated into the receiver, warm readout electronics are mounted directly to the air-facing side of the 300K URH plate. An environmental enclosure protects the URH and warm electronics from the elements. Design shown is for the SATs.

insulation (MLI)³ blankets are used on the warm-facing sides of the 40K and 4K harness plates and around the DC ribbon cables. Receiver heatstraps are connected directly to the 40K and 4K harness plates.

While the URH design and implementation is identical for all SO receivers, the interfaces and integration procedures differ between the SATs and the LATR. In the more densely populated LATR, the 4K stage of the URHs are connected to the optics tubes (OTs) via isothermal coaxial cable “highways” that run along the inside of the receiver shell to the OTs. In the SATs, the URH interfaces with the cold readout assembly (CRA) via isothermal coaxial cables distributed radially around the CRA. The endpoint of the cold readout for all SO receivers is the Universal Focal Plane Module (UFM; Healy, Dutcher, et al. 2022), which contains the multiplexing module, detector stack, and optical coupling. On the warm side, the URH interfaces with SMuRF through a series of warm electronics that are connected directly to the air side of the 300K URH vacuum plate. An environmental enclosure mounted to the cryostat shell protects the air-facing side of the URH and warm readout electronics from the elements (Fig. 26). More details regarding the URH interfaces in the different receivers may be found in Zhu et al. 2021 and in forthcoming publications.

³RUAG Space GmbH, 1120 Vienna, Austria

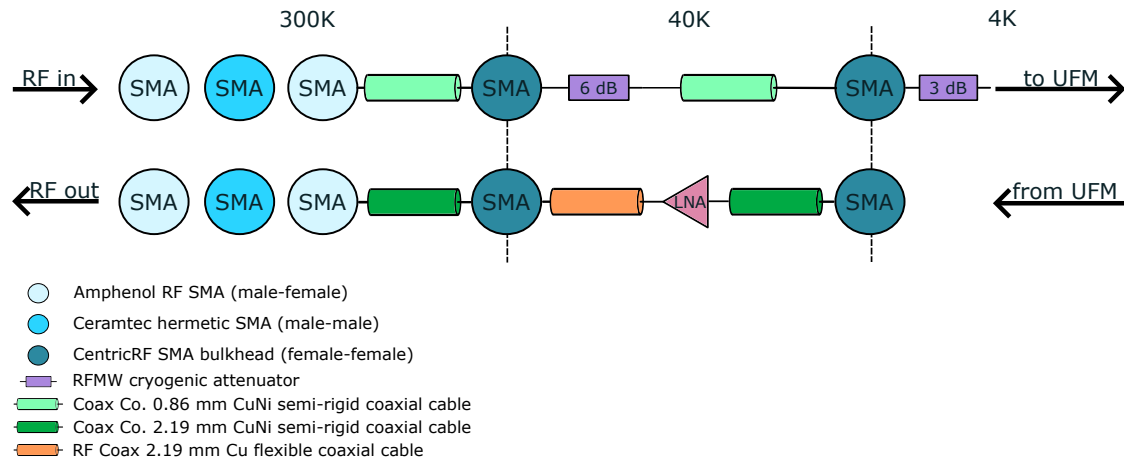


Figure 27. URH RF channel layout. During harness testing, additional pieces of copper coax (not shown) are installed between the 4K attenuators and the 4K SMA bulkheads to bridge RF input to RF output.

3.3.2 RF and DC Design

A block diagram of the full URH RF chain is illustrated in Figure 27. Due to its relatively low attenuation and thermal conductivity, semirigid coaxial cables⁴ fabricated out of cupronickel (CuNi) are used for connections between temperature stages. Selected cable geometries feature lengths and diameters that strike a balance between high signal-to-noise (SNR) and low thermal conductivity while helical shapes enable dense packing and provide strain relief. For isothermal connections, flexible copper coaxial cables⁵ are used. To help moderate input signal levels and reduce thermal noise, 6 dB and 3 dB cryogenic attenuators⁶ are used on the RF input lines at 40K and 4K, respectively. All components are selected to have a characteristic impedance of 50 ohms to minimize reflections due to impedance mismatch.

A primary feature of the Universal Readout Harness are the custom high dynamic range low-noise

⁴COAX JAPAN CO., LTD., Kanagawa 225-0012 Japan

⁵RF COAX INC., Hollister, CA 95023 USA

⁶RFMW Ltd., San Jose, CA 95119 USA

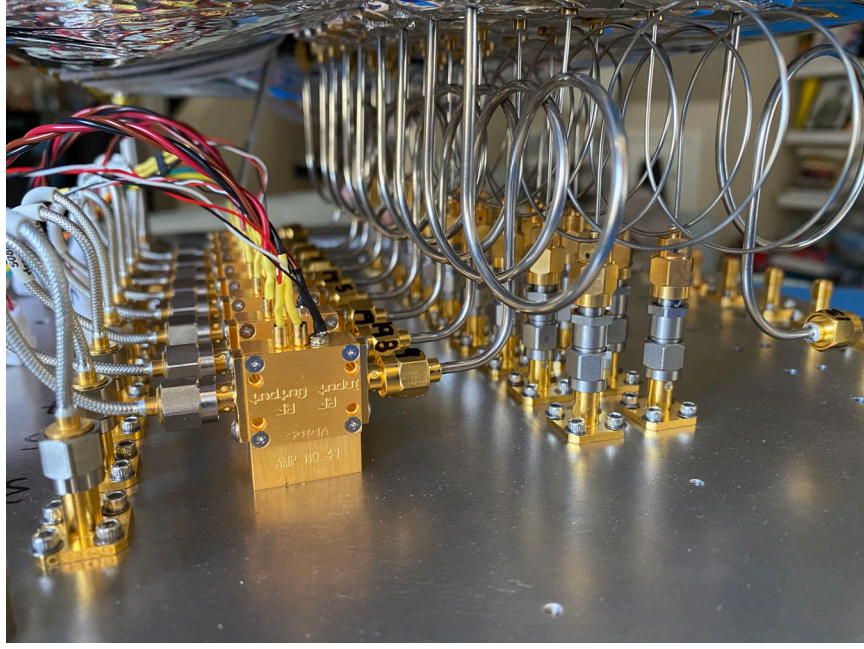


Figure 28. Low-noise amplifiers on the 40K stage of the Universal Readout Harness

Table 4. 40K LNA parameters.

LNA parameter	Gain (dB)	IIP3 (dBm)	IP1dB dBm	T_{noise} (K)	P_{diss} (mW)
Value at 4V/15mA/40K	14	7	-2	~ 30	60

amplifiers (LNAs)⁷ used on each RF output line on the 40K stage (Fig. 28). Designed and manufactured in-house specifically to meet the readout noise and linearity requirements for SO (Sathyanarayana Rao et al. 2020), they provide flat 14 dB gain across the 4-8 GHz band. A full description of LNA parameters is given in Table 4 and a plot of amplifier gain and noise temperature is shown in Figure 29. The amplifiers feature a three-wire (gate voltage V_G , drain voltage V_D , and ground) biasing design and receive power from the 40K inline PCBs via breakout wire triplets.

Each URH can support up to 600 DC wires for detector biasing, amplifier biasing, and flux ramp-

⁷Gropi Labs, Arizona State University, Tempe, AZ 85287 USA, www.thz.asu.edu

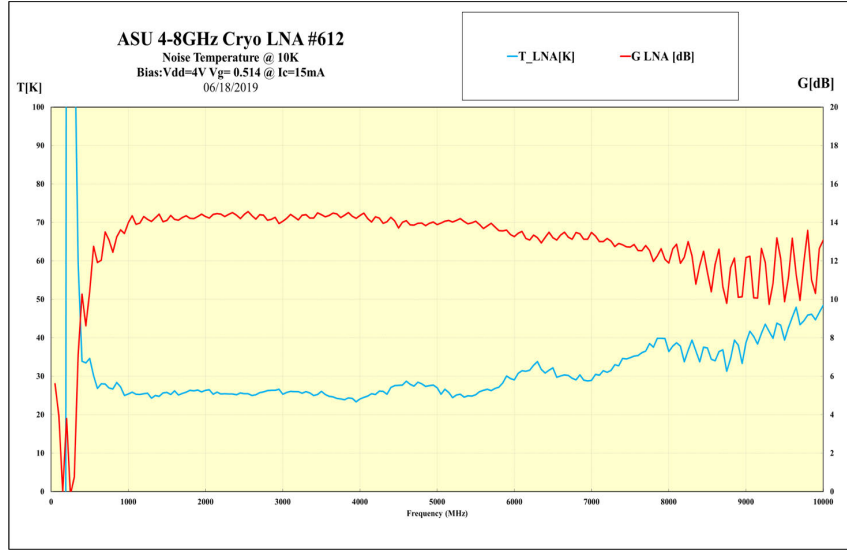


Figure 29. Noise temperature and gain of the 40K low-noise amplifiers measured at 10K.

ing. These wires are grouped together in custom ribbon cable looms⁸. Each cable loom consists of 36 AWG manganin (PhBr) wires in twisted pairs and triplets woven together with DuPont Nomex fiber. On the 4K and 40K stages these cables are terminated in 51-position micro-D (MDM) connectors⁹ while 50-position subminiature-D (D-sub) connectors are used for the 300K terminations. All connectors are encapsulated with stycast to provide strain relief. On the 40K stage, custom inline PCBs provide power to the 40K LNAs via a 6-pin breakout connector, with each PCB powering two LNAs. This breakout power is carried to the LNAs via 24 AWG twisted triplet pigtailed with Molex Ditto genderless connectors.

One particular challenge with the URH RF design is the high density of SMA connections. Each RF input/output pair requires a total of 17 SMA connections, each of which could introduce problems if not properly connected. Improper SMA mating due to operator error or faulty connector geometry (Fig. 30) can not only cause physical damage to the components themselves, but may also result in undesirable features in the microwave signal such as discontinuities in transmission (Fig. 31) or

⁸Tekdata Interconnections Limited, ST1 5SQ Staffordshire UK

⁹Omnetics Connector Corporation, Minneapolis, MN, 55432 USA



Figure 30. A faulty SMA connector. Excess dielectric material protrudes beyond the metal contact ring and prevents proper mating.

excessive reflections due to poor contact between the two connector interfaces. If the mismatch is slight, these effects may not be seen until after one or more thermal cycles. Since the densely packed nature of the instrument prevents simple debugging of connections post-assembly, it is imperative that SMA connections are verified at multiple points in the harness assembly process. This is done by verifying the geometry of each SMA connector prior to installation using an SMA gauge kit and using a vector network analyzer (VNA) to examine the s-parameters of components after they are installed in the harness whenever possible. If the s-parameters appear nominal in static and slightly stressed (e.g. applying gentle pressure to semirigid coax loops, wiggling SMA connectors) conditions, the connections are then fixed in place with a thin stripe of ScotchWeld epoxy according to the procedure outlined in (Kerr 2006). To maintain the integrity of the welded SMA connectors on the 300K plate, epoxy is not applied directly to those connectors. Instead, the semirigid cables are connected to male to female SMA “connector savers.”

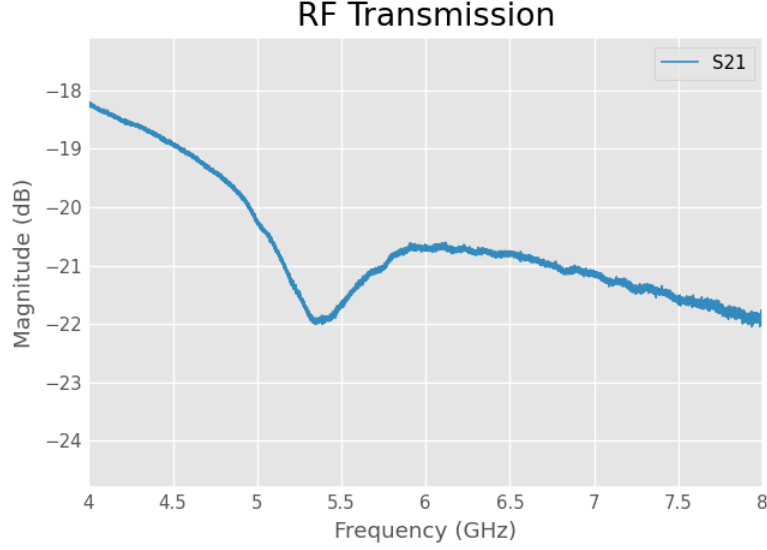


Figure 31. An example plot of RF transmission (S21) through a URH RF channel with a faulty SMA connection. The dip in S21 near 5.5 GHz is a result of the poor connection.

3.4 Testing

Each URH undergoes extensive testing in a dedicated test cryostat (Fig. 32) at ASU prior to integration in SO receivers. The primary goal of this pre-integration testing is to verify that the RF chains are performing nominally and to provide baseline 40K LNA bias voltage requirements and performance data. Establishing these baseline performance measures for the URH portion of the SO readout scheme enables tracking of channel/amplifier performance over time and allows for easier debugging in the event that issues arise after integration. This verification is done by performing a series of “loopback” measurements, where each RF input chain is connected to its corresponding RF output chain at the 4K stage by a small piece of flexible copper coax. An external power supply connected to the DC ports on the air-facing side of the 300K plate provides power to the 40K LNAs.

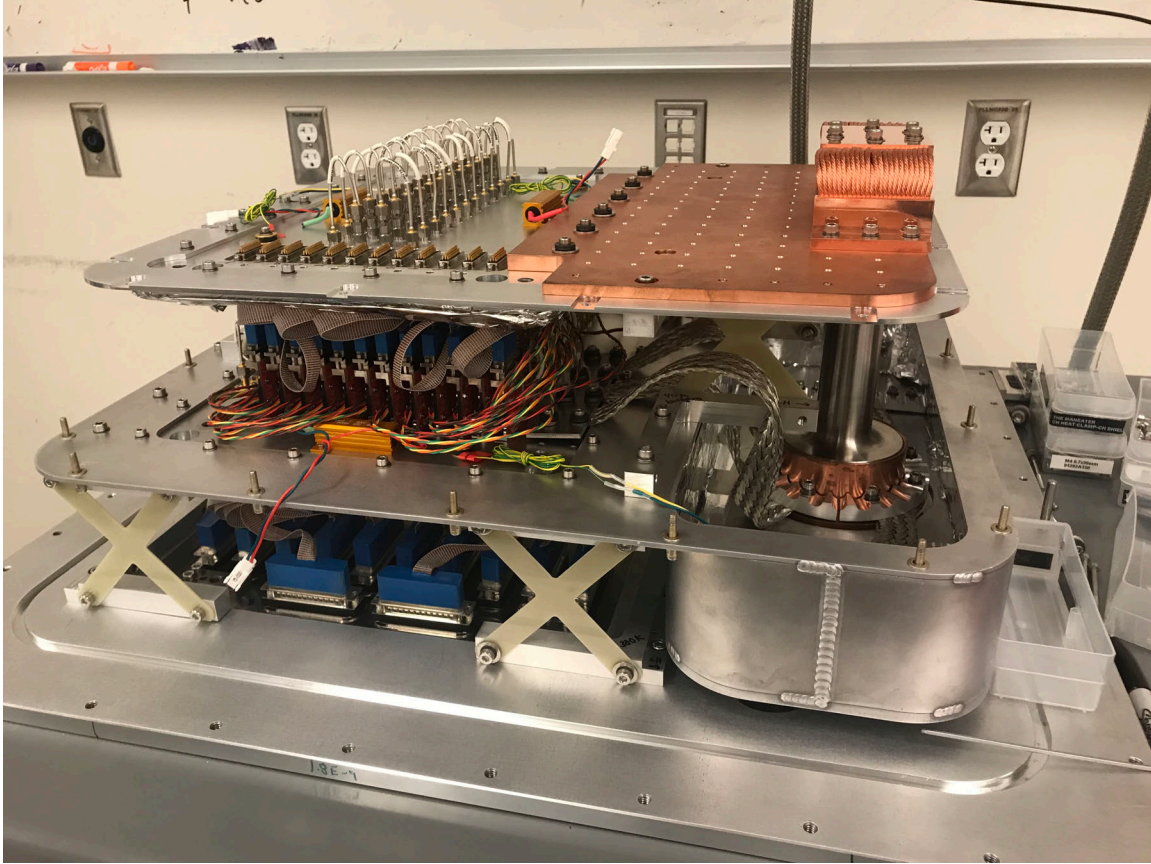


Figure 32. Universal Readout Harness installed in the dedicated harness test cryostat

3.4.1 RF Validation

Prior to cryogenic testing of each harness, loopback s-parameter measurements are taken at room temperature for each complete RF channel. This serves as a final check of all connections and establishes the baseline shape of the signal through each chain. The harness is then installed in the test cryostat and cooled with a two-stage Gifford-McMahon (GM) cryocooler to approximately 6K (4K stage) and 60K (40K stage). It is suspected that excessive radiative thermal loading from the large radiation shields (Fig. 33) covering the 40K and 4K stages of the test cryostat are the limiting factor in cooling power in this test setup, as thermal analyses conducted with the URH installed in the receivers have indicated the total heat load from the URH to be approximately 7 W at 40K and 0.15 W at 4K, which is within the design requirements (Zhu et al. 2021).



Figure 33. Radiation shields cover the 40K and 4K stages of the harness test cryostat

Once the harness reaches base temperatures, S-parameter measurements are repeated for each RF channel. These measurements are compared against the 300K measurements to detect any changes in transmission profile shape (e.g. introduction of “dip” features). These measurements are saved and provided together with individual amplifier bias parameters to receiver institutions as a reference for how each RF channel should perform in cryogenic conditions. To recover de-embedded amplifier gain measurements, s-parameter measurements of calibration RF chains with a 0 dB SMA thru in place of the LNA are taken. The de-embedded amplifier gain is taken as the difference between the full chain and calibration chain transmission (S_{21}). Due to the scale of the project ($N_{LNA} \sim 100$), de-embedding is preferable to individually cooling and testing each amplifier in a separate testbed prior to installation in the URH. An example of full-chain and de-embedded measurements is shown in Figures 34 and 35.

Following cryogenic testing, one last set of s-parameter measurements is taken at room temperature after the harness has been removed from the test cryostat. This last set of measurements is used

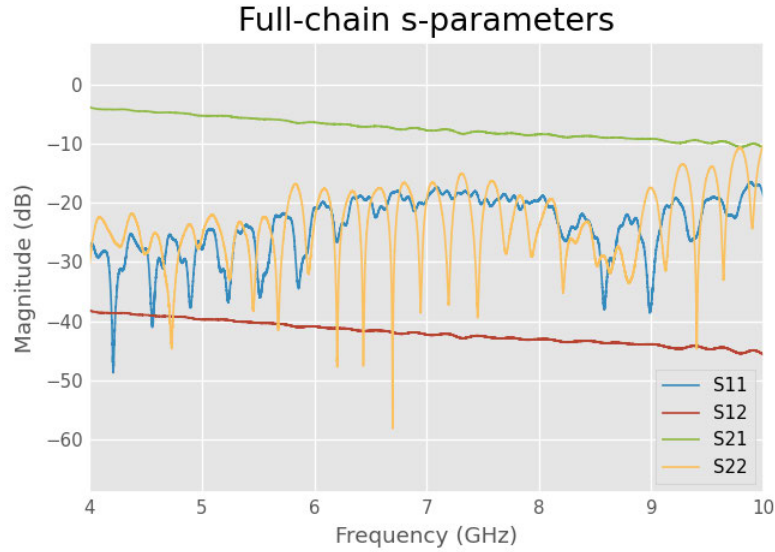


Figure 34. Example s-parameter measurement for a full URH RF chain in loopback mode. Green line shows forward transmission (S21) through the RF chain, which has a downward slope due to frequency-dependent loss of the cupronickel coaxial cables.

to detect any changes that may have occurred during the thermal cycle and serves as a pre-shipping baseline. These measurements are repeated immediately after unpacking the harness at the receiver institution to ascertain if any damage occurred in transit.

3.4.2 Linearity Measurements

In addition to s-parameter measurements, cryogenic measurements of amplifier 1-dB compression point (P1dB) and third-order intercept point (IP3) are also conducted to ensure that each 40K LNA meets the linearity requirements of the SO readout scheme. These tests are also done in-situ, with the attenuation of all non-LNA RF components carefully accounted for and subtracted out in post. While some VNAs have features that allow for simple P1dB and IP3 calculations, the high linear range of the LNAs coupled with the large amount of attenuation in the RF chains (~ 18 dB prior to LNA input) means that the input power must be swept up to ~ 20 dB to reach the nonlinear regime

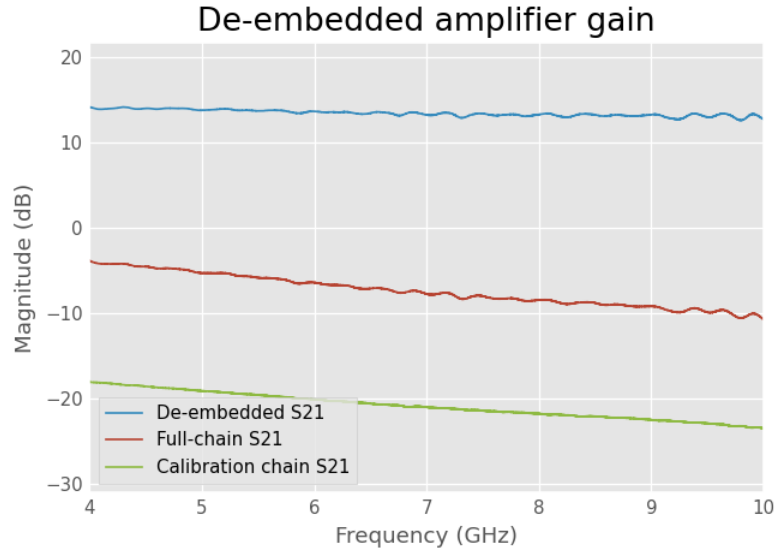


Figure 35. Example de-embedded 40K LNA gain measurement (blue line) obtained by subtracting out the loss of additional RF chain components and cables (green line) from the full-chain S21 measurement (red line). The recovered gain is approximately 14 dB flat across the 4-10 GHz band

of the LNAs, which is beyond the capabilities of available VNAs. Instead, P1dB measurements are done by conducting a single 6GHz tone power sweep with a signal generator connected to the 300K air-facing RF input port. The output power is measured by a power meter connected to the 300K air-facing RF output port, and a Python script is used to fit the response and determine the P1dB. For IP3 measurements, a power combiner is used to combine signals from two signal generators and feed them in to the 300K RF input port. A power sweep of 6 GHz and 6.01 GHz tones is conducted and the response is measured by a spectrum analyzer connected to the 300K RF output port. A Python script fits the response at the fundamental and intermodulation product frequencies and extrapolates to find the intercept point. Example linearity measurements are shown in Figures 36 and 37. While these in-situ methods are not as precise as individually cooling and testing each LNA in an isolated environment, the values obtained are good enough to determine whether a given LNA meets the linearity requirement.

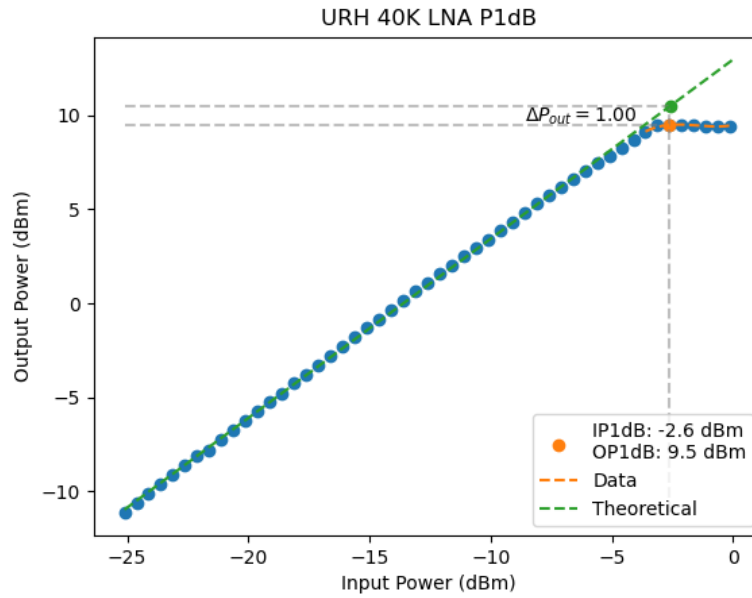


Figure 36. Example 40K LNA 1-dB compression point (P1dB) measurement

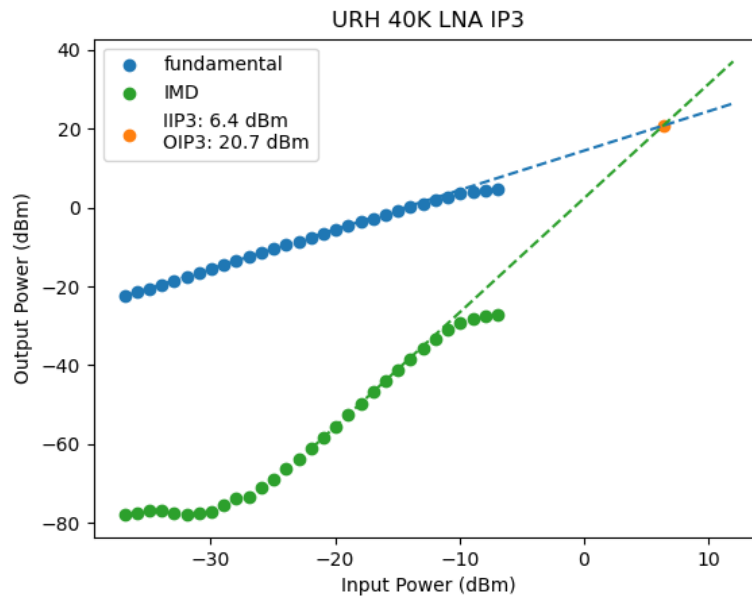


Figure 37. Example 40K LNA third order intercept point (IP3) measurement

3.5 Conclusions and Future Work

We have presented the design, construction, and testing of 300K-4K Universal Readout Harnesses for the Simons Observatory. To date, six Universal Readout Harnesses have been assembled, tested, and delivered to collaborating institutions in preparation for the initial phase of SO operation. In addition the six required for operation, a seventh harness is also in development. This “spare” harness will be used to further characterize the electrical and thermal performance of the URH and serve as an emergency back up in the event of a major failure. Additionally, this harness will be used to test the in-situ performance of a new proprietary 4K low-noise amplifier recently developed at ASU. While current SO readout systems utilize commercially available 4K LNAs, future iterations and expansions to SO hope to utilize this new design.

Integration of harnesses into SO receivers is well underway. Thus far, two harnesses have been successfully integrated into the mid-frequency small aperture telescopes, SAT-MF1 at the University of California San Diego (Fig. 38) and SAT-MF2 at Princeton (Fig. 39), and a further two harnesses have been installed into the LATR at the University of Pennsylvania (Fig. 40). A more sparsely populated (7 RF channel) harness has also been successfully integrated into the LATR “tester” (LATRt) at the University of Chicago, which has been used to validate the LATR optics tubes and will ultimately be converted into an additional SAT (Fig. 41). Harness integration efforts for the ultra high-frequency SAT (SAT-UHF) at the University of California Berkeley remain ongoing. Both the LATR and SAT-1 are expected to deploy in the near future, and further details about post-integration readout performance for those receivers are presented in Refs. Zhu et al. 2021; Harrington et al. 2021; Kofman et al. 2022; Bhandarkar et al. 2022 and in future publications.

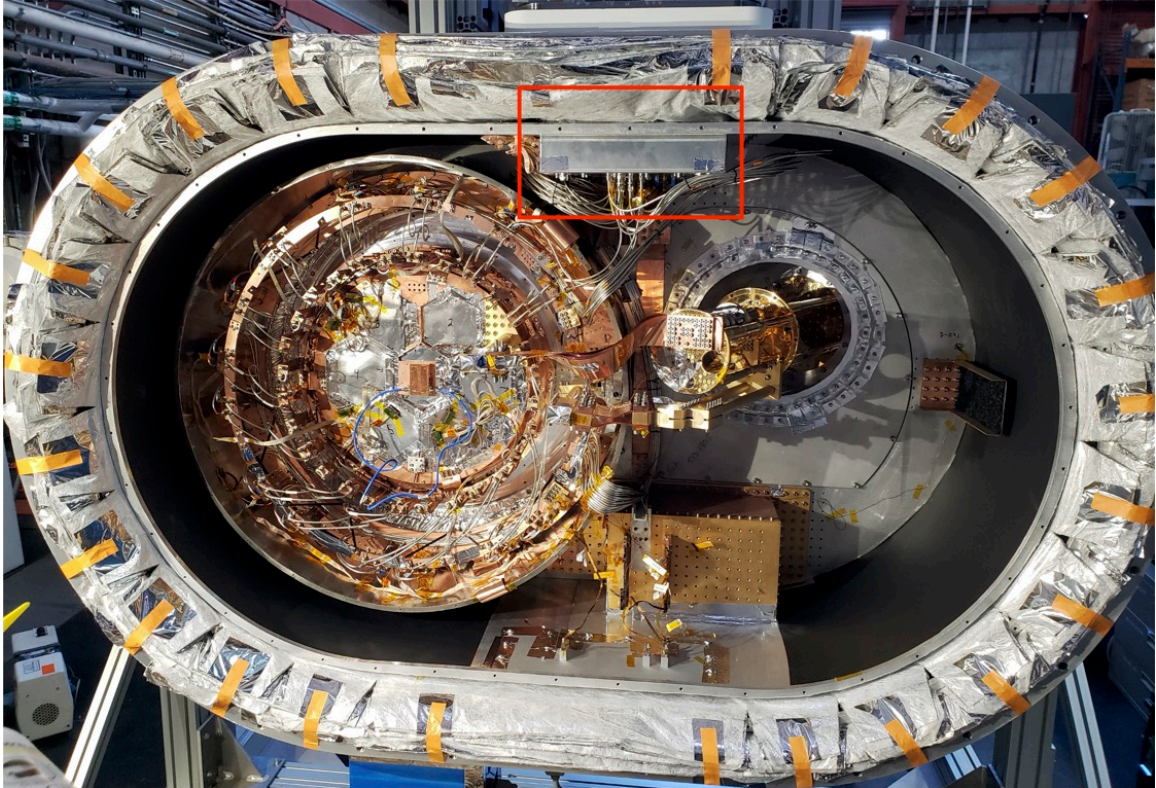


Figure 38. The SAT-MF1 receiver. The integrated URH is outlined in red. Photo courtesy of the Arnold Lab at UCSD.

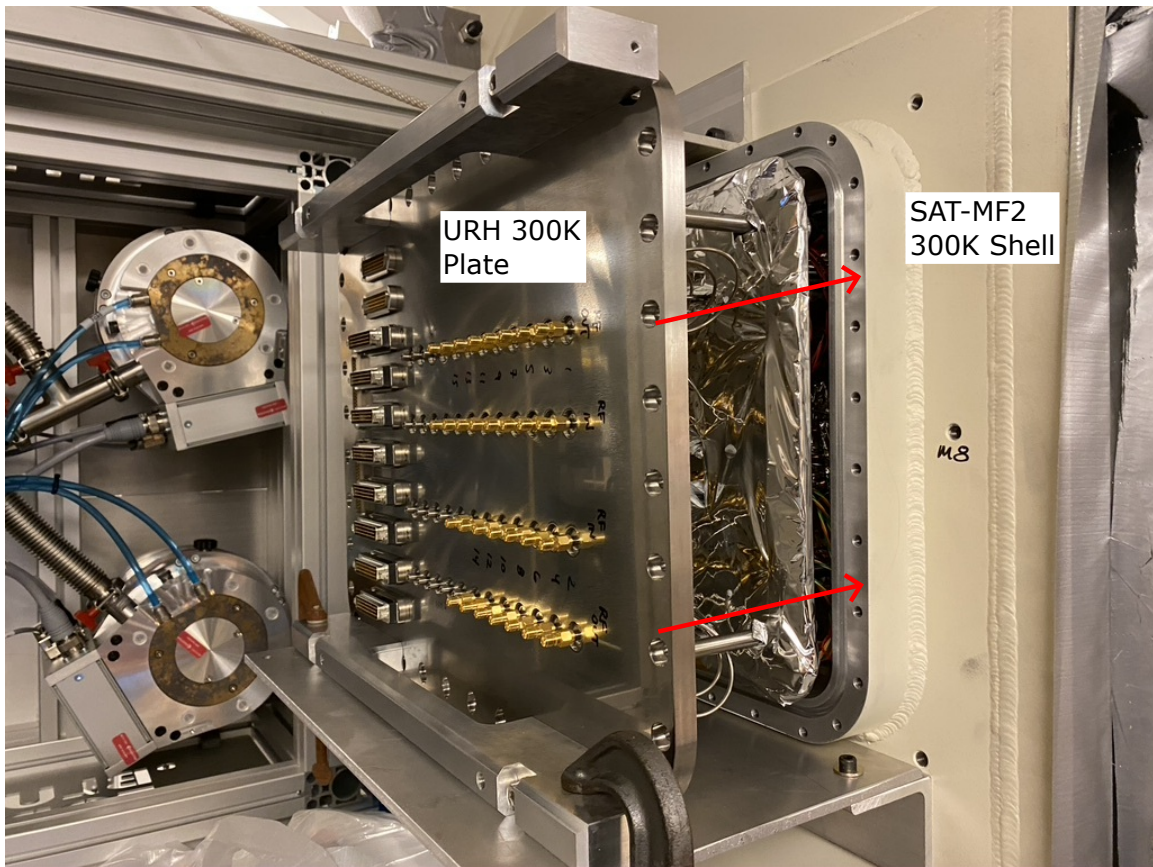


Figure 39. The URH during installation into the SAT-MF2 receiver. Arrows illustrate direction of installation into the cryostat.

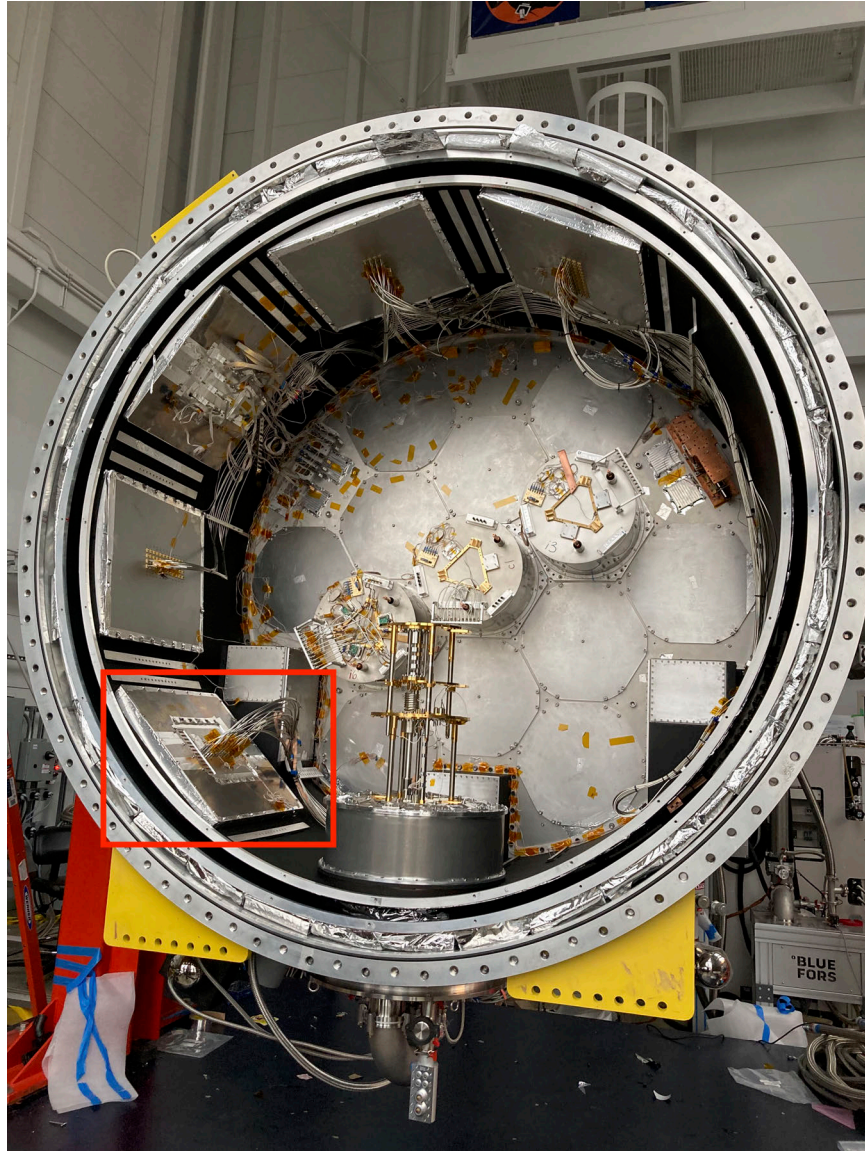


Figure 40. The Large Aperture Telescope Receiver. One of two integrated URHs is outlined in red. Photo courtesy of the Devlin Lab at UPenn.

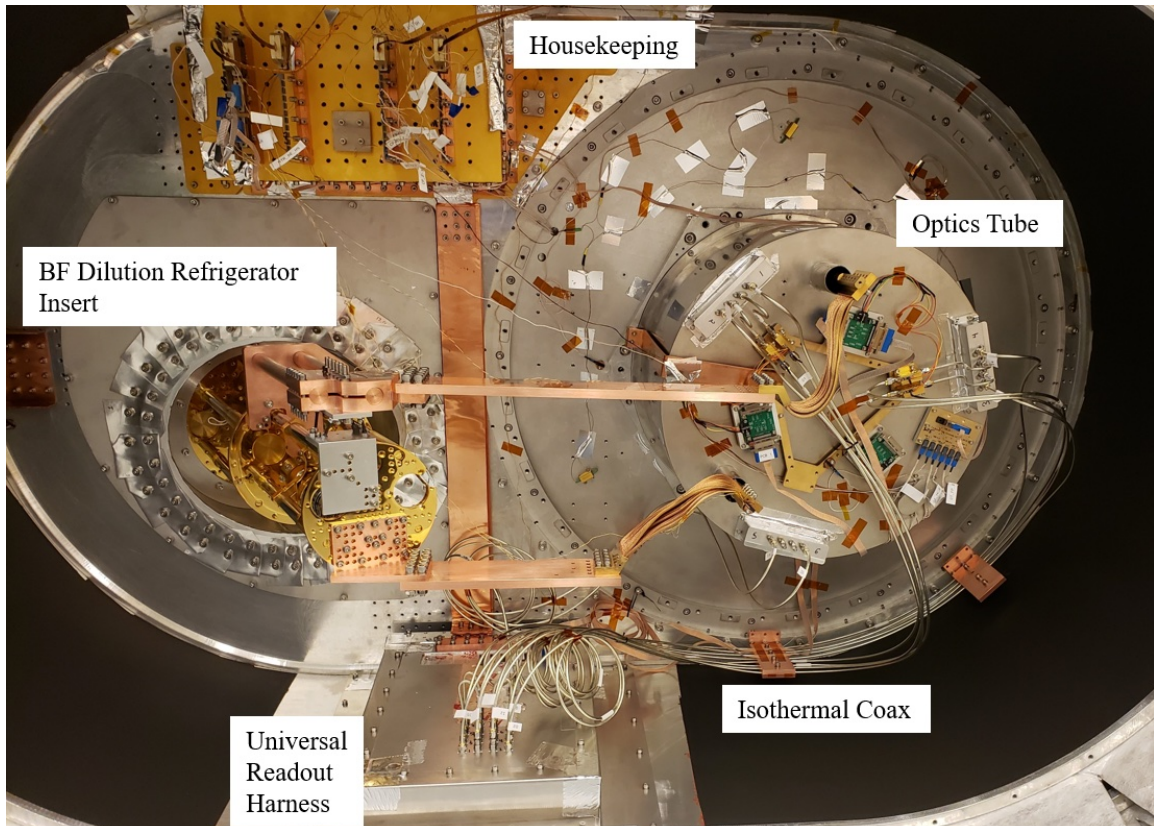


Figure 41. The LATR optics tube testbed with an integrated URH. Figure courtesy of Katie Harrington.

Chapter 4

INTEGRATION AND TESTING OF THE FIRST SIMONS OBSERVATORY SMALL APERTURE TELESCOPE

In the southern Winter of 2023, teams of Simons Observatory collaborators from all over the world deployed to San Pedro de Atacama, Chile to facilitate the on-site integration and commissioning of both the Large Aperture Telescope Receiver and SAT-MF1. The following section describes the integration testing of the SAT-MF1 readout system in the highbay at the Simons Observatory site.

4.1 The SAT-MF1 Readout System

In the small aperture telescopes, the URH interfaces on the 4 K side with the cold readout assembly (CRA) (Sathyanarayana Rao et al. 2020). This assembly consists of all of the readout components and cables for the 4 K, 1 K, and 100 mK stages, mounted radially around the focal plane. On the input side, 3 dB and 1 dB attenuators are situated on the 1 K and 100 mK stages, respectively. On the output side, circulators and low-noise amplifiers are installed at 4 K. DC blocks are situated between temperature stages on the input and output lines. Superconducting, low-loss niobium titanium (NbTi) semi-rigid coaxial cables are used below 4 K. Long isothermal copper coaxial cable “highways” route from the 4 K stage of the CRA to the 4 K URH plate. DC ribbon cables carry the 4 K amplifier bias as well as detector bias and flux ramp lines from the URH to the CRA and focal plane. 4 K breakout PCBs (similar to those in the URH at 40 K) provide power to the 4 K LNAs.

In its nominally configured state the SAT-MF1 focal plane contains seven hexagonal TES detector wafers, each containing approximately 1,720 aluminum-manganese (AlMn) detectors. Each detector array is packaged together with a microwave multiplexing module (UMM) and a feedhorn array for optical coupling. The full stack is referred to as a Universal Focal Plane Module (UFM). Each UFM is split into “north” and “south” halves, with each half read out on one RF line for a total of two RF

lines per UFM. All detector arrays across the collaboration are dichroic, and in the case of SAT-MF1 the detectors are sensitive to 90 and 150 GHz (McCarrick, Arnold, et al. 2021).

On the 300 K side, the URH interfaces with the SMuRF readout system. With seven UFM's installed, SAT-MF1 requires seven SMuRF “carriers” (also referred to as “slots”) which are distributed amongst two crates. The front side of each SMuRF slot contains two advanced mezzanine cards (AMCs) used for RF signals, with each connecting to one half of one UFM (north or south). The rear side of each SMuRF slot contains a rear transition module (RTM), which provides DC bias as well as timing signals. In between each RTM and the cryostat is a cryostat card, which provides additional filtering and conversion of RTM signals for the cryogenic amplifiers and detector bias and flux ramps (Yu et al. 2023). The cryostat cards are packaged together in an enclosure that is mounted directly to the URH-cryostat interface plate. SCSI cables are used to connect the output of each RTM to its corresponding cryocard input, and short 50 pin D-sub cables are used to connect the output of the cryostat cards to the hermetic connectors on the URH 300 K plate. Each SMuRF crate connects via single-mode LC fiber to its own dedicated server that contains all of the scripts needed for controlling the system and taking data.

The cable connections between the outside-facing plane of the URH and the SMuRF crates require special care, as they are external to the cryostat and thus exposed to the elements out on the platform (Figure 14). To protect the integrity of the hermetic connectors on the URH 300 K plate from exposure to dust or moisture on the platform, low-profile warm readout components and cables are mounted directly to the URH plate and covered with an environmental enclosure. Longer, more robust cables are then used to connect to the SMuRF system through sealed cable ducts and environmentally-rated panel-mount connectors installed on the side of the enclosure (Figure 42).

Inside the enclosure, an interface plate bolted to the 300 K URH plate provides a mounting location for additional brackets and assemblies required for warm readout components. Warm amplifiers mounted to the URH RF output connectors are fixed in place with a series of brackets to strain relieve and protect the rigid connection to the hermetic SMAs from damage from sudden impacts. These amplifiers are powered by a series of voltage regulator boards mounted directly above the SMA con-

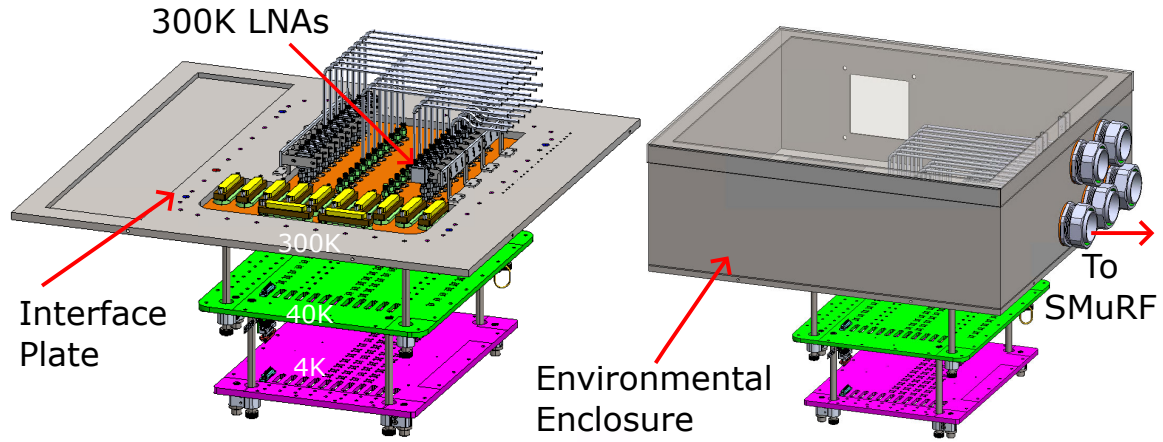


Figure 42. CAD model of environmental enclosure for SAT URH

nectors. Each of the three voltage regulator boards take in 15 V DC input and provide 12 V DC output. The external power supply is housed in one of two “housekeeping” enclosures situated directly across the telescope from the URH. Two twisted pairs of 20 AWG stranded wire are routed in parallel from the power supply to rail-mounted terminal blocks installed adjacent to the regulator boards, where it is broken out to the input V_{in} and ground pins on each of the three boards. The output voltage and ground wires are similarly installed in additional terminal blocks. Jumper pins are used to connect the upper and lower layers of the terminal blocks, thereby enabling each regulator board to supply power to up to 6 amplifiers, with a maximum of two wires per terminal. Short lengths of hand-formed semi-rigid copper coaxial cable connect the URH input SMAs and the 300 K LNA outputs to a SMA feedthrough bracket mounted below the URH SMAs. The completed assembly is pictured in Figure 43.

Both SMuRF crates have similar SMA feedthrough brackets mounted to the sides of the crate frames. These feedthrough brackets allow for more robust cables to be used in between the cryostat and SMuRF without inducing stresses on the SMA connectors on the URH or SMuRF crates. Short lengths of flexible MiniCircuits copper coaxial cables are used between the SMA connectors on each SMuRF slot and the SMuRF SMA feedthrough brackets. 10 dB attenuators are installed on the SMuRF output (URH input) lines. In between the URH SMA feedthrough bracket and the SMuRF feedthrough brackets are long lengths of FlexCo low-loss, flexible copper coaxial cables with robust outer jackets.

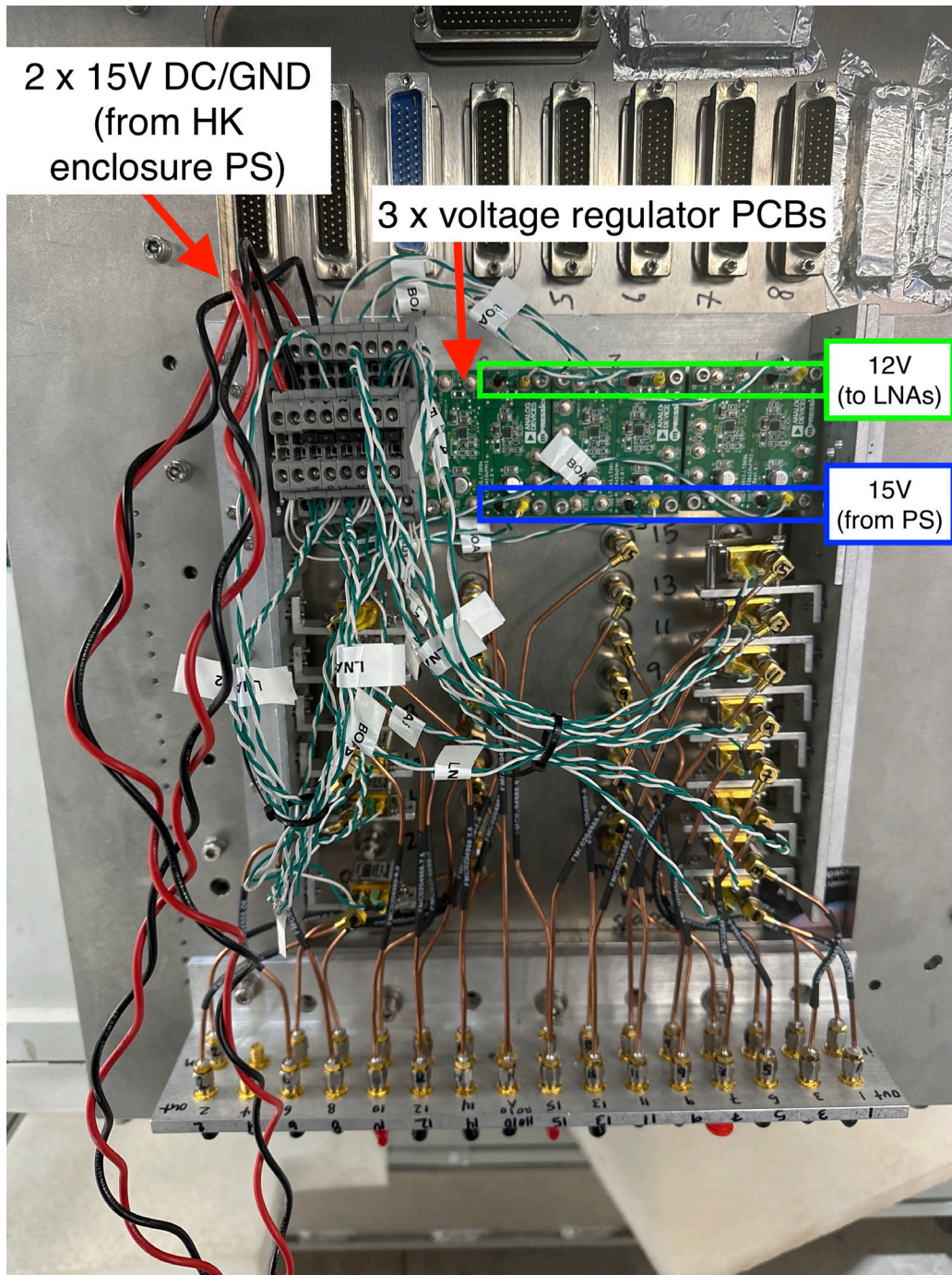


Figure 43. Warm readout electronics mounted to the SAT-MF1 URH. Red and black wires connect an external power supply to the voltage regulator PCBs, which convert the power to the appropriate bias voltage. Green and white wires provide +V and GND to the low-noise amplifiers. Copper coaxial cables connect the low-noise amplifiers to an SMA mounting bracket. Additional coaxial cables (not shown) from the SMuRF system are connected on the opposite face of the SMA bracket.

During lab testing, these cables were connected directly and left exposed, as shown in Figure 44. In the field, the FlexCo coaxial cables and the SCSI cables that go from the SMuRF RTMs to the cryocard assembly are routed from the SMuRF enclosure to the URH enclosure through a sealed cable duct.

4.2 Integration of the Universal Readout Harness

Before SAT-MF1 was packed and shipped to Chile, the URH was removed from the cryostat and packaged in its own crate for extra protection. Upon arrival at site, a benchtop checkout of the URH revealed two of the fifteen RF chains were no longer functional. One chain exhibited normal LNA power draw but no gain, indicating a potentially damaged wirebond within the amplifier package. A spare LNA was swapped in and the chain returned to nominal performance. The other problematic chain exhibited a dip in transmission much like those discussed in Section 3.3.2. After prodding at all of the SMA connections in that channel, the issue was found to be with one of the interior (RF input) coaxial cables. Since accessing any of the interior URH cables requires substantial disassembly of neighboring cables, many of which are epoxied, that channel was abandoned and the spare RF channel was utilized in its place. With the SAT pointed at horizon, the URH was slowly lowered into the cryostat using a crane. Once bolted into place, the temporary supports between stages were removed and the URH was connected to the CRA. Prior to connecting the full URH+CRA integrated readout to the focal plane assembly (FPA), VNA sweeps were done on each chain in loopback mode to verify nominal performance. The full cryogenic readout system is pictured in Figure 45.

After the URH and CRA were successfully installed and verified, the UFM's were mounted onto the focal plane. Given the especially dry conditions at the site ($< 10\%$ humidity) and the extreme sensitivity of the modules to electrostatic discharge (ESD), significant precautions (ESD protective clothing, air ionizers, etc.) were taken to help minimize the likelihood of ESD events occurring. Once all UFM's were mounted, isothermal coaxial cables (two sets of input/output per UFM) and DC ribbon

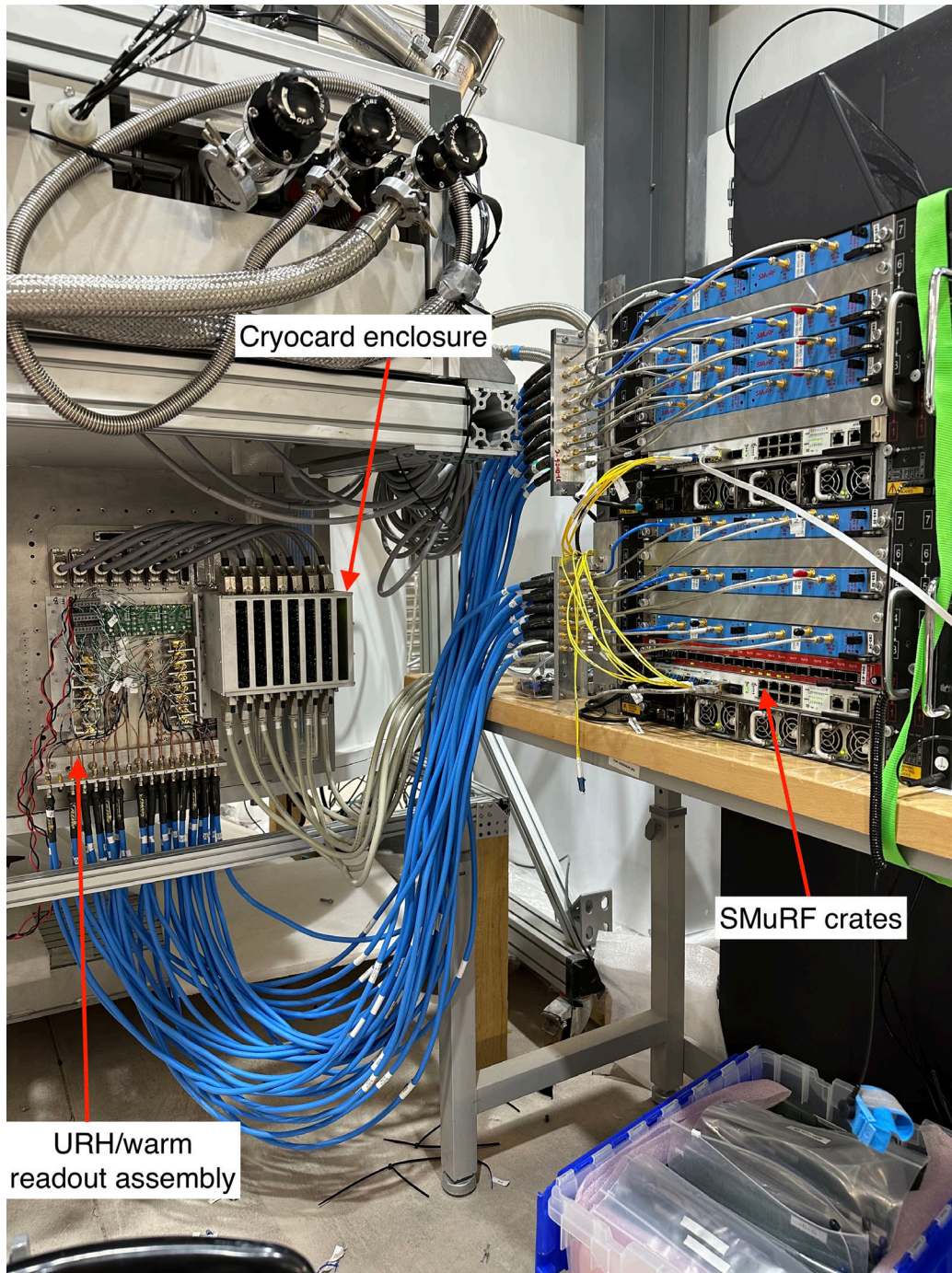


Figure 44. The complete warm readout setup for SAT-MF1. Two SMuRF crates, stacked on top of each other, are shown on the right. Many coaxial and SCSI cables route from the SMuRF crates to the warm readout assembly and cryocard enclosure, respectively. Short D-sub cables connect the cryocards to the URH DC ports.

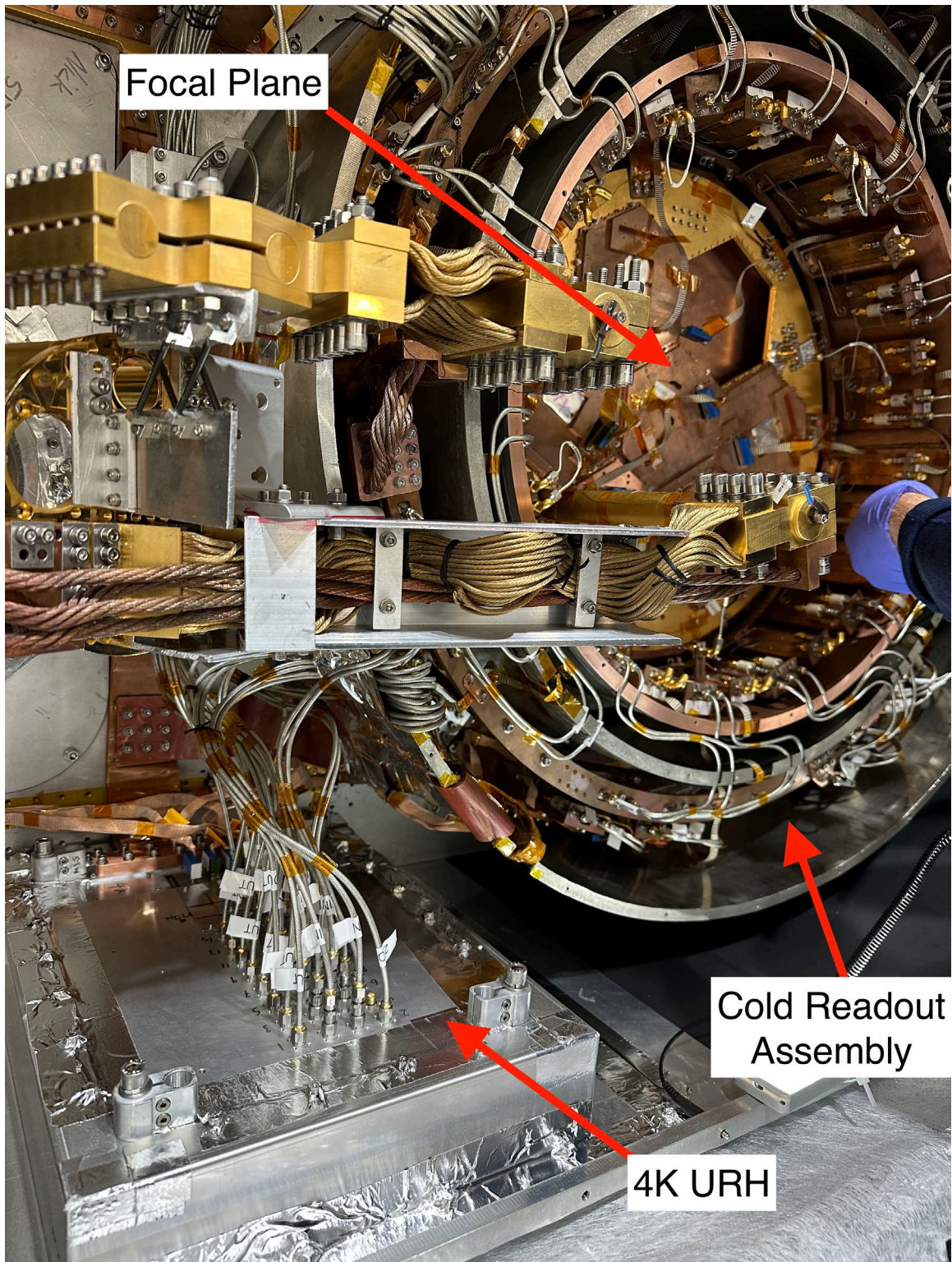


Figure 45. Interior view of SAT-MF1 with integrated URH, cold readout assembly, and focal plane

cables (one per UFM) were installed to connect each wafer to the CRA. The fully populated focal plane is pictured in Figure 46.

4.3 Integrated Testing of SAT-MF1

Prior to installing SAT-MF1 on the platform (Figure 15), one final highbay cooldown was done in the site highbay to verify cryogenic performance and to get an initial approximation of detector yield and noise for all seven wafers. After approximately nine days of cooling, the focal plane reached a base temperature of 95 mK. Initial setup and “tuning” of each UFM was carried out on the SMuRF servers using code from `sodetlib`¹⁰, the observatory’s software repository for detector and readout operations, and `pysmurf`¹¹, the lower-level SMuRF control software from SLAC. The following sections provide a rudimentary description of this tuning process and present initial detector performance estimates from the site highbay cooldown.

4.3.1 UFM tuning

All UFM setup, tuning, and debugging is carried out by running `sodetlib` functions in Jupyter notebooks (one UFM per notebook) on the two SMuRF servers. The SMuRF servers store all of the system-level (SMuRF crate) and device-level (UFM) configuration files that contain parameter information that is required to run the various `sodetlib` and `pysmurf` functions. The device configuration files are updated continuously throughout the tuning procedure. Prior to running any of the `sodetlib` scripts, the system-level files are updated with details about the current configuration of the system (e.g. SMuRF slot to UFM mapping, device configuration file paths). For each SMuRF slot (UFM), attenuation levels are optimized by physically installing attenuators on the SMuRF output

¹⁰<https://github.com/simonsobs/sodetlib>

¹¹<https://github.com/slaclab/pysmurf>

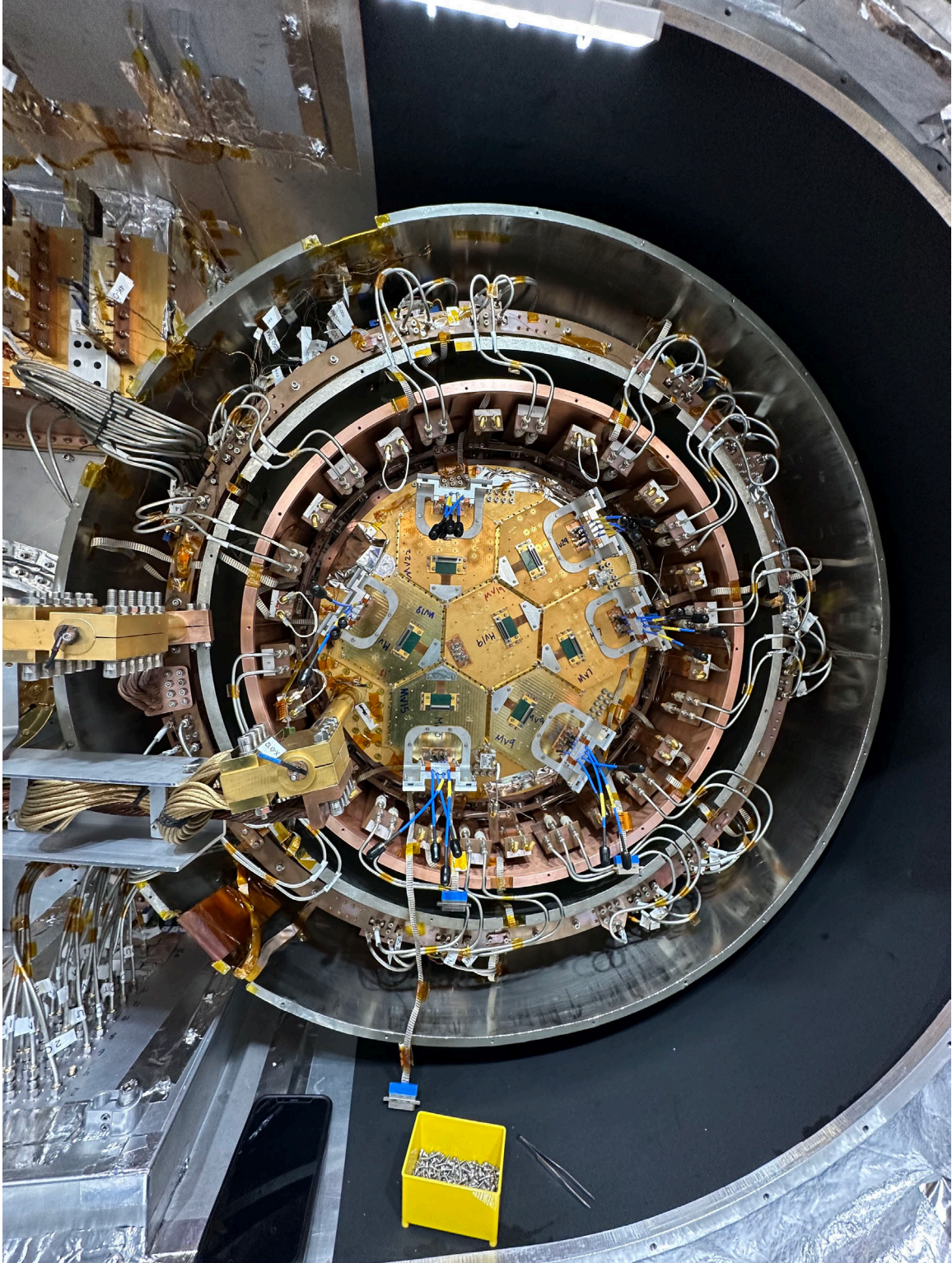


Figure 46. The SAT-MF1 focal plane with seven detector wafers installed.

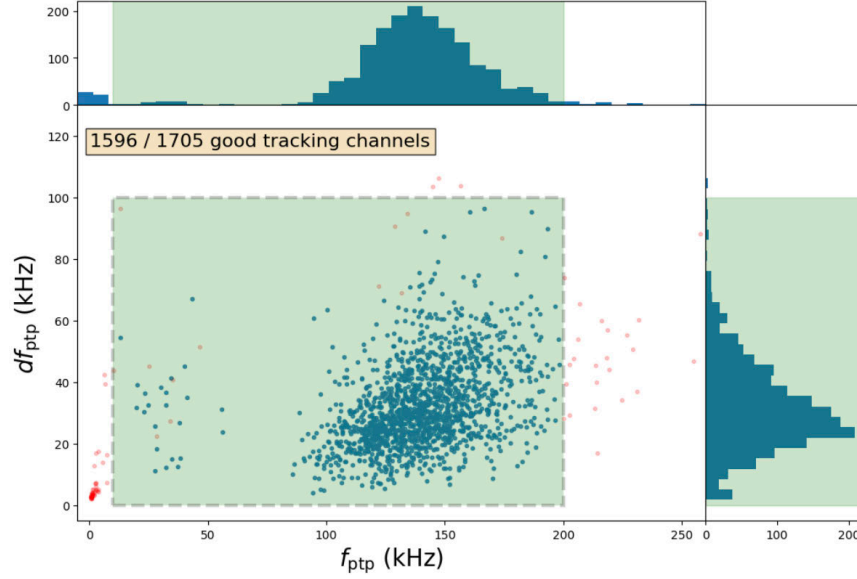


Figure 47. An example SMuRF tracking plot showing the tracked resonators for one UFM. The x-axis is the peak-to-peak amplitude of the tracked frequency f . The y-axis is the peak-to-peak amplitude of the tracked frequency error df . Red points lie outside of the desired parameter space and are discarded.

(URH input) lines, and by setting digital attenuator values in the device configuration files for each UFM. The cryogenic amplifiers are powered on and bias voltages are optimized using the `setup_amps` function. Once the attenuation and amplifier optimization is complete, the `setup_phase_delay` function is used to estimate the phase delay of the system and apply a correction. At this point, the UFM is ready for tuning.

Tuning begins with the `setup_tune` function, which runs through a series of lower-level functions to find the peak resonance frequencies for each detector (“channel”). After that, the `setup_tracking_params` function, which initializes the tone tracking parameters. This function sets up the flux ramp modulation signal and measures the shift in tracked resonator frequency for each channel over a period of time. The stability of a tracked frequency over time along with the estimated error, is used to determine whether a channel is good or bad, as shown in Figure 47. This is the most basic estimate of how many detectors in a UFM are operational.

A more informed calculation of detector yield incorporates detector noise and normal resistance.

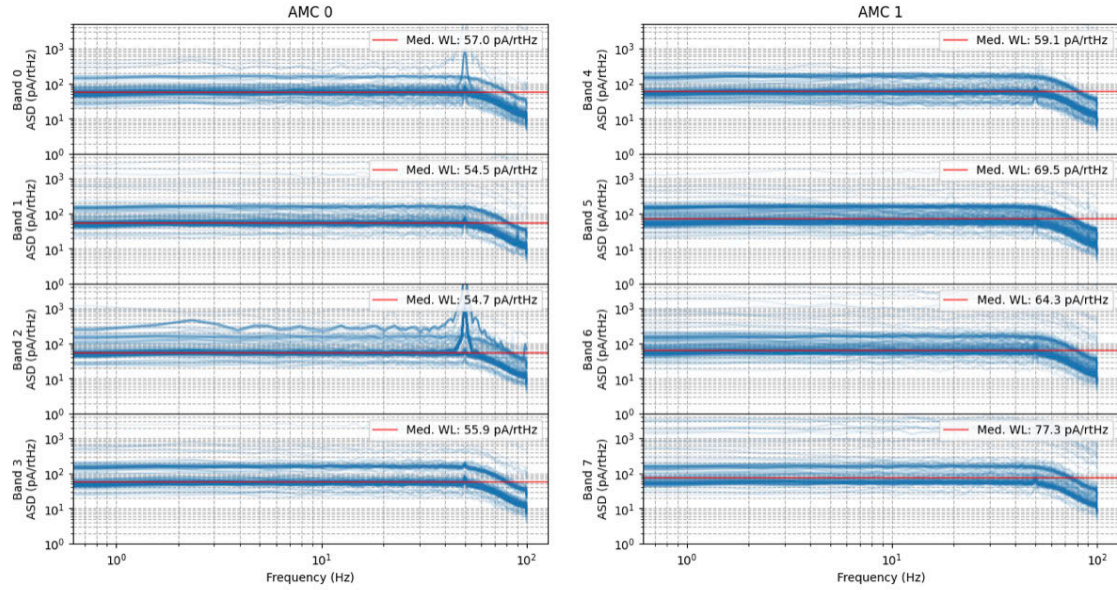


Figure 48. An example plot showing detector amplitude spectral densities grouped by SMuRF band. The ASDs are used to estimate the white noise level. Here the detectors are in the normal state, and the estimated white noise level contains contributions from the readout noise as well as the Johnson-Nyquist noise from the TES shunt resistors.

The `take_noise` function takes a short stream of data, then computes the amplitude spectral density (ASD). An example plot showing ASDs separated by SMuRF band is shown in Figure 48. The white noise level is taken to be the median value along the flat portion of the ASD. This can also be visualized by making a histogram of the white noise values for all the detectors in a UFM (Figure 49). For the yield calculation, noise is taken while the detectors are in the overbiased state.

On each UFM, there are twelve bias lines that are used to bias detectors. Detectors are mapped to their respective bias line (“bias group”) with the `take_bimap` function. This function puts the detectors in the superconducting (zero bias) state and then cycles through a bias stepping procedure where the bias voltage of each bias line is incremented by a small amount and the detectors are assigned to bias groups based on their response to the bias steps. IV curves are then taken using the `take_iv` function. This function initially applies a high voltage to the bias lines to drive the detectors into the overbiased (“normal”) state, then slowly ramps the voltage down to allow the detectors to pass

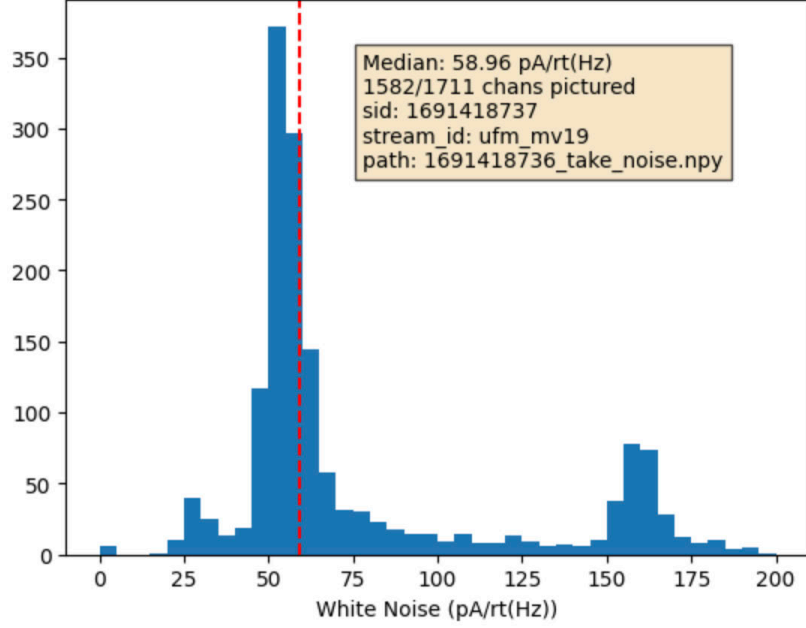


Figure 49. An example histogram showing median white noise levels for all detectors in a UFM.

through the transition and into the superconducting state. Detector resistance is calculated from the measured current response over the range of bias voltages (the IV curve), and the normal resistance R_n is calculated by fitting the normal regime of the IV curve. Since each bias line biases multiple detectors, each of which may experience varying loading conditions, when biasing into transition the system optimizes the bias line voltage such that the maximum number of detectors have resistances within a certain percentage range of their calculated normal resistance (R_{frac}) (Wang, Bhandarkar, et al. 2022; Wang, Zheng, et al. 2022). An example plot of this R_{frac} as a function of V_{bias} is shown in Figure 50. The `take_iv` function also produces a histogram of R_n values, as shown in Figure 51.

With tracking parameters, noise levels, bias group assignments, and normal resistance values in hand, an informed estimate of detector yield can be made for each UFM. While cryogenic performance was nominal during the site highbay cooldown, the detectors were saturated (normal) due to the loading from the 300K aluminum window cover. The window cover was briefly removed and makeshift hex cell “mirrors” were used to attempt to direct sky light onto the focal plane (Figure 52), but no dis-

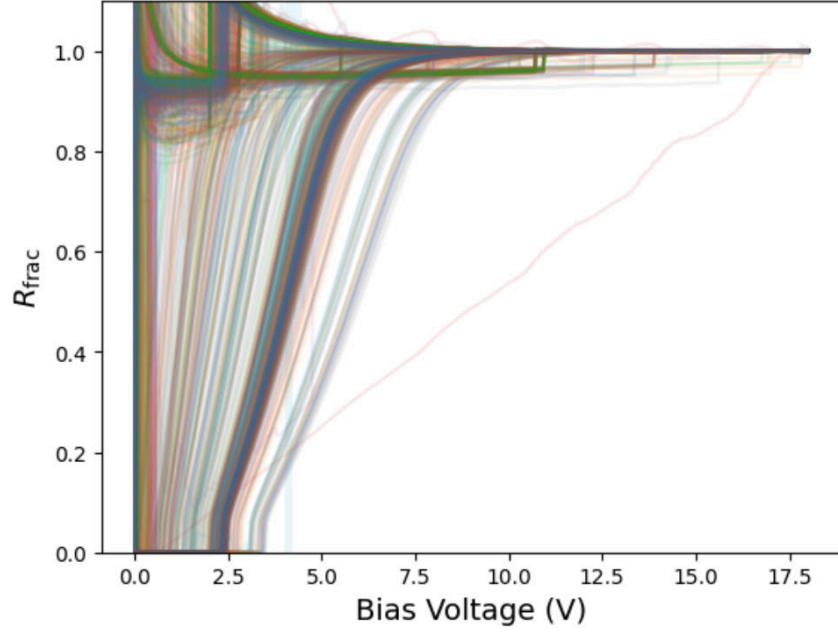


Figure 50. An example plot of TES R_{frac} versus V_{bias} obtained from IV measurements. R_{frac} is the ratio of TES resistance to the normal resistance R_n . These measurements are used to identify the nominal operating bias voltage for each bias line that drives the maximum number of detectors into a specified R_{frac} range.

cernible change in detector response was noted. Detector saturation made accurate estimates of R_n somewhat difficult. Additionally, two UFM exhibited behavior indicative of broken flux ramp lines, rendering half of each UFM unusable. These flux ramp issues may be the result of ESD events or intermittent shorts. There were also numerous issues with the SMuRF hardware that required extensive debugging, including a faulty RTM, a faulty carrier, and intermittently losing the ability to bias cryogenic amplifiers on any slots in one crate, amongst others. Despite these challenges, yield estimates were obtained for all seven UFM and are presented in Table 5. While the total yield is lower than the baseline goal of 70%, there is reason to believe that it will improve over time with further optimization of the system (e.g. attenuation, grounding). There were also several UFM with bias groups that seemed to not receive any signal, which could be due to a problem somewhere in the warm readout. If so, those detectors can likely be recovered.

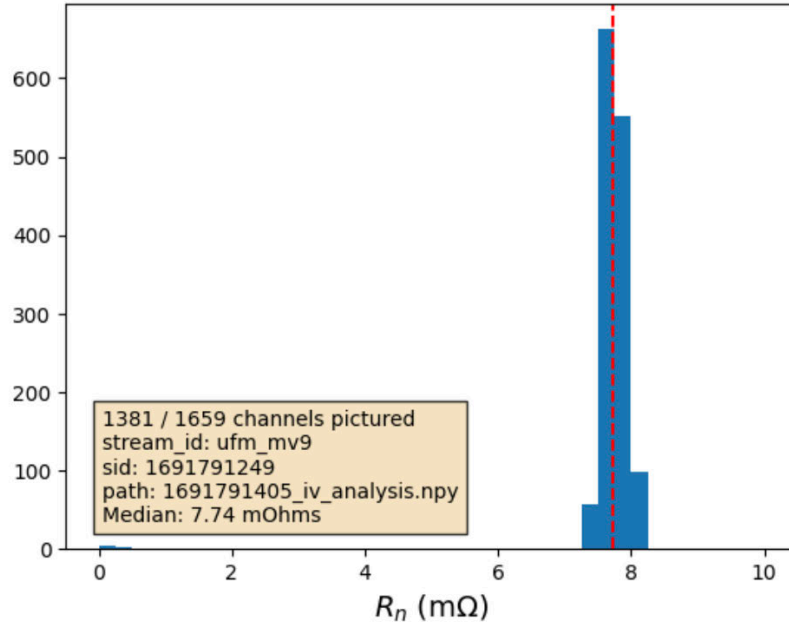


Figure 51. An example histogram of TES normal resistances (R_n) values calculated from IV curves.

Table 5. Detector yield estimates from SAT-MF1 site highbay cooldown. The acceptable white noise range is $40 - 80 pA/\sqrt{Hz}$ and the acceptable R_n range is $6 - 9 m\Omega$. Total yield percentages are calculated assuming 12,040 total detectors.

UFM ID	Tracked	Assigned to Bias Group	Acceptable Noise and R_n
Mv19	1711	1384	1031
Mv18	1644	1451	1326
Mv29	702	663	438
Mv22	1801	1606	1443
Mv15	1567	1088	970
Mv9	1661	1495	1242
Mv7	791	628	343
Total	9877	8315	6793
% Yield	82.03	69.06	56.42



Figure 52. Two mirrors are used to attempt to direct sky light onto the SAT-MF1 focal plane during the site highbay cooldown.

On-site integration and commissioning of SAT-MF1 remains ongoing, with the second site cooldown (first on-platform cooldown) currently underway as of Fall 2023. Further details are presented in Chapter 6.

ESTIMATING THE COSMIC OPTICAL AND INFRARED BACKGROUNDS BEYOND $z \sim 1.1$ VIA OPTICAL/NEAR-INFRARED STACKING OF MASSIVE ELLIPTICAL GALAXIES

Author’s note: The following chapter details a project that, at its conception, was supposed to be a short endeavor to supplement the SZ science group’s ongoing study of massive elliptical galaxies. What started as a one-semester side quest to examine the average surface brightness profiles of massive ellipticals turned into a three year main quest that spawned countless other side quests of its own and culminated in accidentally stumbling upon a method for estimating the extragalactic background light.

5.1 Background and Motivation

5.1.1 Massive Elliptical Galaxies

There is still much to be understood about the formation and evolution of massive elliptical galaxies. In the hierarchical model of structure formation in the Λ CDM model of the universe, galaxies accumulate mass over time, with increasingly massive galaxies forming at later times as the result of mergers of smaller galaxies. However, this model cannot alone account for the observed population of massive elliptical galaxies (see Somerville and Davé 2015 for a review). Of particular interest are quiescent galaxies, which are comprised mainly of old stars and exhibit little to no active star formation. How and why these galaxies ceased to form new stars remain important open questions in astrophysics. Some have argued that galaxy mergers could cause the cold gas necessary for star formation to be consumed or expelled (A. Toomre and J. Toomre 1972; Hernquist 1993). Another promising explanation is feedback from active galactic nuclei (AGN), which produce intense amounts of energy as a result of matter accreting on the supermassive black holes found at the centers of these galaxies. This energy can heat or expel the gas, thus quenching star formation (reviewed in Fabian 2012).

The present work builds on recent work (Meinke, Böckmann, et al. 2021; Meinke, Cohen, et al. 2023) which utilizes measurements of the thermal Sunyaev-Zel’dovich (tSZ) effect to study the circumgalactic medium (CGM) surrounding quiescent galaxies and the role of AGN feedback in their evolution. The tSZ effect was measured from stacked SPT cutouts at 95, 150, and 220 GHz. From the tSZ effect the overall thermal energy of the CGM was calculated and an energy-mass relation was derived. Such measurements can better inform theoretical models and provide constraints for simulations of AGN feedback. One major limitation in these analyses was the ability to separate the tSZ signal from the dust. Future millimeter experiments with improved resolution will enable better separation of these signals. Another major limitation was the uncertainty in the stellar mass and subsequent stellar mass-halo mass relation. Stellar mass estimates can be improved by fitting the spectral energy distribution (SED), which requires observations in the optical and infrared regimes.

5.1.2 Optical Stacking Analysis

A useful tool in decoding a galaxy’s history is its surface brightness profile, which describes how the intensity of light within the galaxy varies with distance from the galaxy’s center. By determining the manner in which the light in a galaxy is distributed, one may examine the distribution of stars within the galaxy, identify substructures (i.e. disks, bulges), and gain an understanding of the galaxy’s stellar mass distribution. The stellar mass distribution may then shed light on the evolutionary history of the galaxy. Traditionally, the light profiles of elliptical galaxies (e.g., Figure 53) have been well-fit with a $R^{1/4}$ law known as de Vaucouleurs Law (de Vaucouleurs 1948)

$$\ln I(R) = \ln I_0 - kR^{1/4} \quad (5.1)$$

where I_0 is the intensity at $R = 0$, and k is a constant. However, modern studies with better observational data led to the adaptation of the more general $R^{1/n}$ Sérsic function (Sérsic 1963; D’Onofrio, Capaccioli, and Caon 1994)

$$\ln I(R) = \ln I_0 - kR^{1/n} \quad (5.2)$$

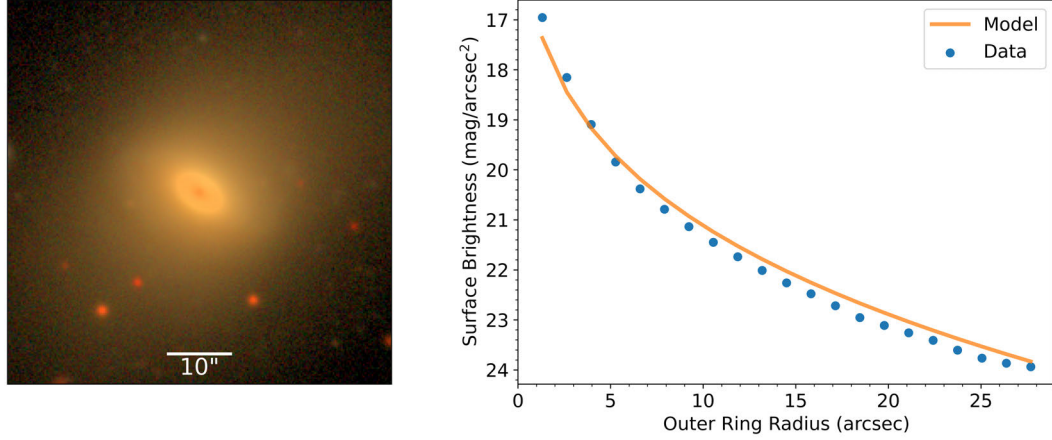


Figure 53. Left: RGB image of a nearby elliptical galaxy generated from z, i, and r-band image data. Right: The corresponding surface brightness profile measured from successive circular annuli (blue dots) and as modeled by a Sérsic function with $n = 4$ (orange line).

An alternative form of the Sérsic function is

$$I(R) = I_e \exp \left[-k \left[\left(\frac{R}{R_e} \right)^{1/n} - 1 \right] \right] \quad (5.3)$$

where R_e , the effective or half-light radius, is the radius containing half of the total light of the object, I_e is the intensity at R_e , and n is the Sérsic index, which controls the degree of curvature of the function. Special forms of the Sérsic function include the Gaussian ($n = 0.5$), exponential ($n = 1$) and the de Vaucouleurs Law ($n = 4$). In general, a larger value of n indicates a more centrally concentrated distribution. Recent studies indicate that massive elliptical galaxies are well-fit by Sérsic profiles with Sérsic indices in the range of ~ 2.5 to ~ 10 (G. Bertin, Ciotti, and Del Principe 2002).

In general, the lack of bright, young stars makes individual quiescent elliptical galaxies at $z \sim 1$ too faint to resolve or measure light profiles for. However, it is possible to generate a very high signal-to-noise ratio image by stacking many individual galaxy images on top of each other. From such an image, an accurate average light profile may be calculated.

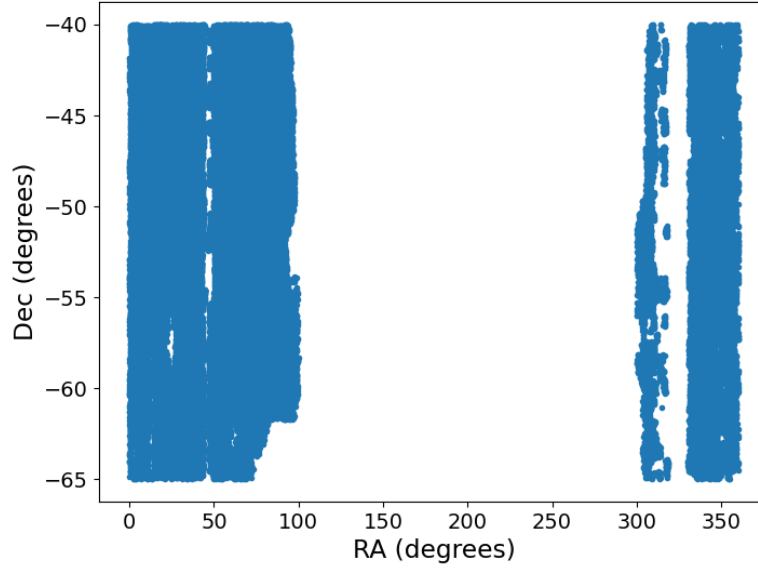


Figure 54. Sky coverage of the galaxy catalog used in this analysis. This region encompasses 2,500 square degrees of the southern sky where DES and SPT overlap.

5.2 Catalog and Data

5.2.1 Target Catalog

The galaxy catalog used in this work consists of over 100,000 quiescent galaxies in the $\sim 2500\text{deg}^2$ overlapping region of DES, SPT, and AllWISE at $0.5 \leq z \leq 1.5$ with age > 1 GYr and specific star formation rate (SSFR) $< 0.01\text{GYr}^{-1}$. The catalog galaxy coordinates are plotted in Figure 54 and histograms of galaxy redshift, magnitudes, and stellar mass are shown in Figures 55, 56, and 57, respectively. These galaxies were selected by SED fits to a larger crossmatched catalog of the five DES bands as well as WISE W1 (3.4 microns). A full description of the selection methods used to generate this catalog is provided in Meinke, Böckmann, et al. 2021.

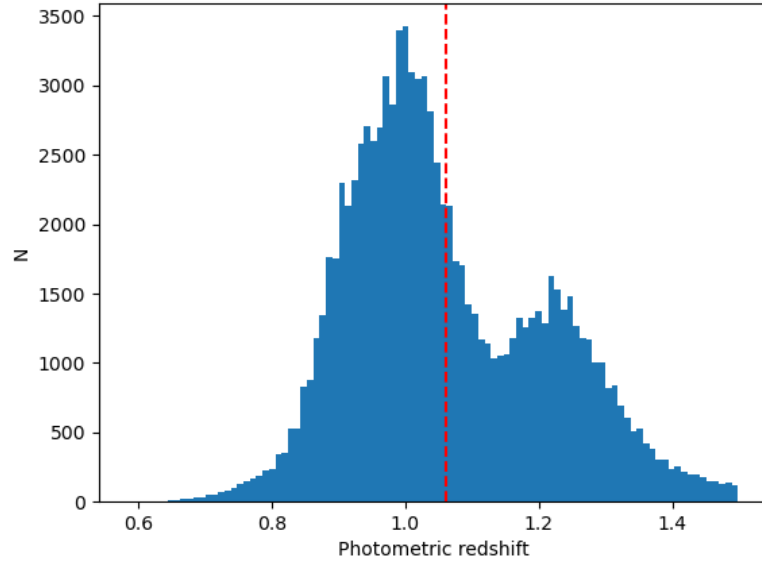


Figure 55. Photometric redshifts of the catalog galaxies. The mean redshift, indicated by the dashed red line, is ~ 1.1

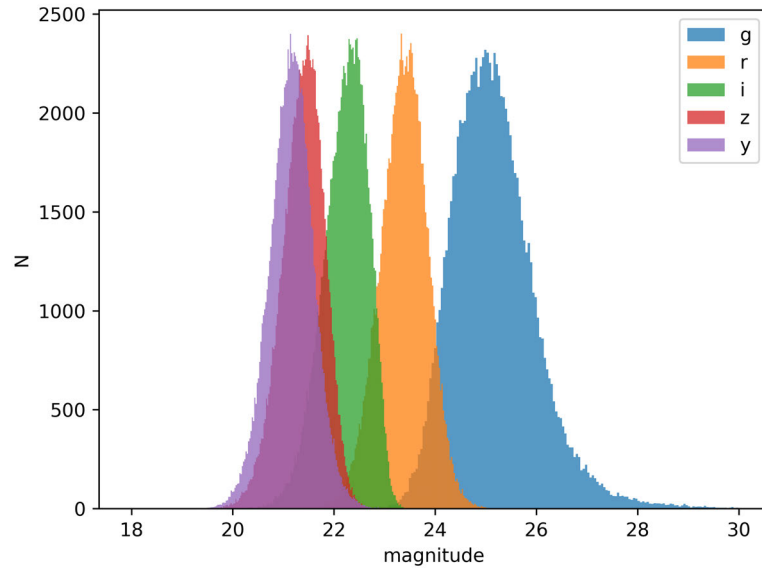


Figure 56. Magnitude distribution of target galaxies as computed from DES cutout images.

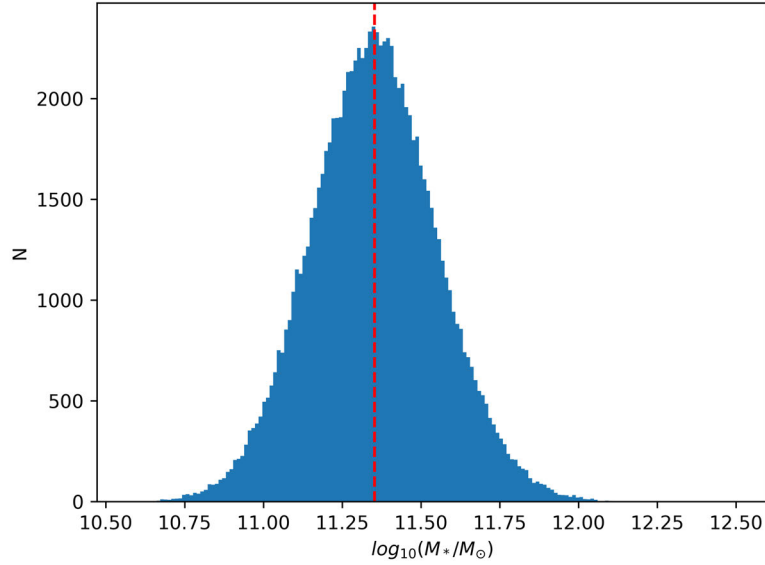


Figure 57. Log stellar mass distribution of target galaxies. The mean $\log_{10}(M_*/M_\odot)$, indicated by the dashed red line, is 11.35.

5.2.2 Data Description and Retrieval

The Dark Energy Survey (DES) is an optical/near-infrared observatory located in the Cerro Tololo Inter-American Observatory in Chile (Flaugher et al. 2015). The Dark Energy Camera (DECam) mounted on the 4 meter Blanco Telescope observes $\sim 5,000\text{deg}^2$ of the southern sky in five photometric bands from 400 – 1065nm (grizY). Data Release 2 (DR2) includes images and data from six years of observations from 2013-2019 (Abbott et al. 2021). A by-band summary of image quality for DES DR2 coadd images is presented in Table 6. Public access to DR2 images and catalog data is available on the DES Data Management (DESDM) website, facilitated by the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign.

For each galaxy in the Meinke, Böckmann, et al. 2021 catalog, 1×1 arcminute image cutouts centered at the galaxy coordinates were retrieved from the DES DR2 multi-epoch (coadd) tiles. The DR2 coadd images are constructed from at least three exposures of 90 seconds (griz bands) or 45 seconds (Y band) each, thus providing improved signal-to-noise over individual single exposures. The

Table 6. DES image quality summary for DR2 coadded images. Information from Abbott et al. 2021

Band	Wavelength (nm)	PSF FWHM (arcsec)	Limiting Magnitude
g	477.08	1.11	24.7
r	637.13	0.95	24.4
i	777.42	0.88	23.8
z	915.79	0.83	23.1
Y	988.63	0.90	21.7

image cutouts obtained for this work were constructed, on average, from 12 separate single exposures in each band. The pixel scale for DES coadd image tiles is 0.2637 arcseconds per pixel and the zero point magnitude is 30 mag (Morganson et al. 2018).

5.3 Optical Image Stacking Pipeline

5.3.1 Image Processing

An overview of the image processing and stacking pipeline developed for this project is presented in Figure 58. All of the image processing and stacking was conducted in Python on the Agave super-computer at Arizona State University. The coadded images retrieved from the DES cutout server are multi-extension FITS files with science, weight, and mask frames. For each catalog galaxy, all five science frames were coadded into a single detection image using SWarp (E. Bertin, Mellier, et al. 2002). Source catalogs were then generated for each band by running SourceExtractor (E. Bertin and Arnouts 1996) in dual image mode on each individual frame with the SWarp coadded image as the detection image. Configuration parameters used in source extraction were adapted from those used in Morganson et al. 2018 and are presented in Table 7.

For quality control purposes, each set of *grizY* images was subjected to a series of checks prior to stacking. To make image alignment and stacking straightforward, all images that were not 1×1

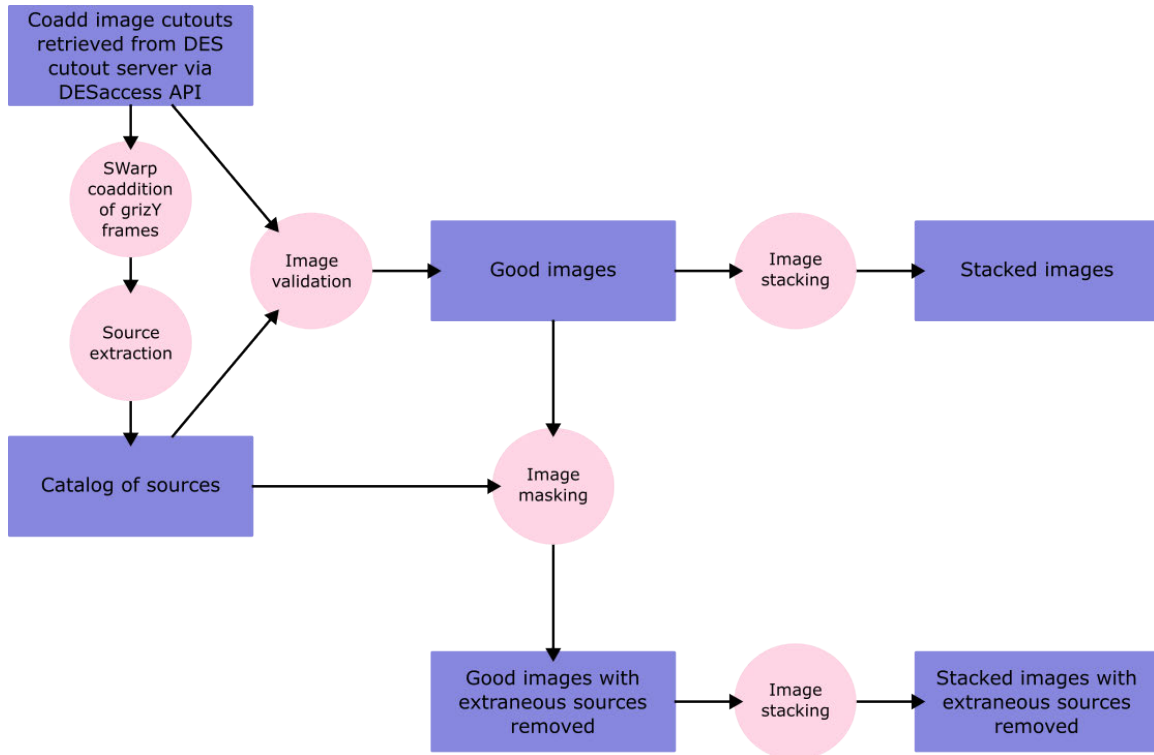


Figure 58. Overview of the image processing and stacking pipeline developed for this analysis. Purple rectangles indicate data or image products, while pink circles indicate Python processing steps.

arcmin (228×228 pixel) squares were automatically discarded. Similarly, any images that contained flags (as reported in the `SourceExtractor` output catalogs) were also discarded. Images contaminated by very large sources or spurious signals that were not already flagged in the previous step were culled by imposing maximum limits on source FWHM and ELLIPTICITY. To keep the total number of galaxies equal in each band, an “all or none” approach was taken: if any one of the five cutouts for a given target galaxy failed any of the aforementioned criteria, the entire set of images was removed from the stack. This validation process reduced the total number of galaxies to 98,713.

The filter on image size was applied to rule out any images that were near the edge of the DES tiles. Since the DES cutout server centers each requested cutout on the coordinates provided, as long as the image cutouts are all the same size, they may be easily stacked together as-is, without the need for resampling or centering. This was verified by calculating the average and standard deviation of

Table 7. SourceExtractor configuration parameters.

Configuration Parameter	Value
DETECT_MINAREA	4
THRESH_TYPE	RELATIVE
DETECT_THRESH	1.5
ANALYSIS_THRESH	1.1
DEBLEND_NTHRESH	32
DEBLEND_MINCONT	0.0001
CLEAN	Y
CLEAN_PARAM	1.0
WEIGHT_TYPE	MAP_WEIGHT
RESCALE_WEIGHTS	N
WEIGHT_GAIN	Y
BACK_TYPE	AUTO
BACK_SIZE	256
BACK_FILTERSIZE	3
BACKPHOTO_TYPE	GLOBAL

Table 8. Average and standard deviation of target galaxy coordinates.

	Average (pix)	σ (pix)
X_IMAGE	114.09	0.46
Y_IMAGE	114.44	0.49

the SourceExtractor-determined coordinates for all the target galaxies (Table 8). The sub-pixel standard deviation indicated the images were indeed well-centered at the image center (114, 114).

5.3.2 Image Stacking

From the image validation process, the pipeline split into two branches. In one branch, the galaxy images were stacked as-is, without any further processing or source masking (“unmasked” stack). In the other branch, the output source catalogs and segmentation images from SourceExtractor were used to generate source masks that removed all but the target galaxy from the image (“masked” stack). This process is illustrated for a single set of cutouts in Figure 59. To ensure there would be no influence

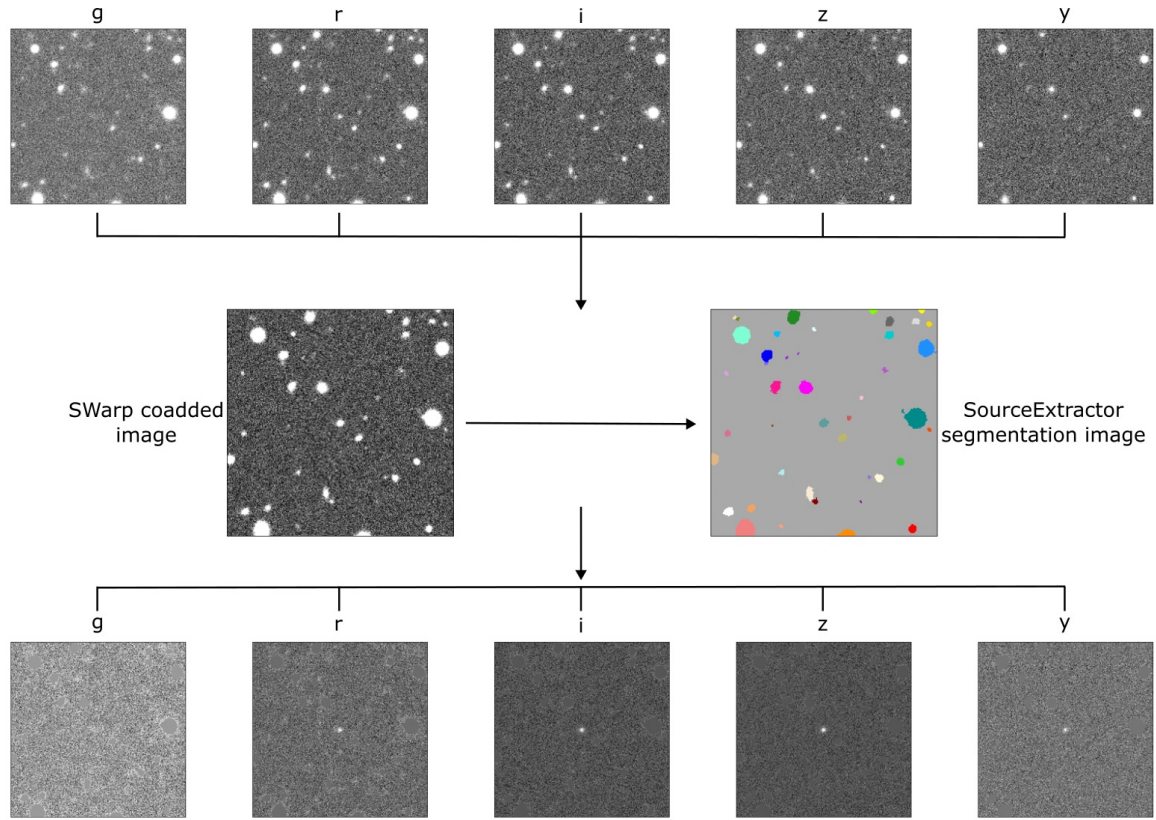


Figure 59. Demonstration of image masking on a single set of cutouts. Raw images (top row) are coadded in SWarp to make a detection image (middle left). SourceExtractor is used to generate a segmentation map (middle right), which is used to generate images with all sources but the target galaxy removed (bottom row).

on the stacking calculation, these extraneous sources were masked by setting their associated image pixel values to NaN rather than zero.

To create the unmasked stacked images, for each band the science and weight frames for each target galaxy were concatenated together into $228 \times 228 \times 98713$ NumPy arrays (Harris et al. 2020). The weighted average was then computed over all the images, with each pixel of each cutout weighted according to the inverse variance provided in the weight frame. The pixel units of the stacked images were then converted from their raw units (counts/second) to more physically meaningful units. The five resulting images are shown in column one of Figure 60.

The masked images were stacked in a similar manner, with the pixels associated with non-target

sources set to NaN and their weights set to zero. The DES coadd images are already background-subtracted, which led to an issue of mostly negative pixel values in the background pixels of the masked images. To mitigate this, source-removed stacks of an equal number of random positions covering the same area of the sky as the galaxy catalog were subtracted from the masked galaxy stacks. The masked stacked images are shown in column two of Figure 60.

As described in the previous paragraph, the same methods detailed above were used to generate unmasked and masked stacks of an equivalent number ($N=98,713$) of random positions on the sky (columns three and four of Figure 60). These images were used to model the background in the galaxy images. Additionally, the point spread function of each band was also modeled by stacking a smaller number ($N=14,111$) of stars. The unmasked stacks of stars are shown in Figure 61.

5.4 Analysis

5.4.1 Radial Surface Brightness Profiles

Radial profiles of the stacked images were constructed by calculating the average pixel values in successive circular annuli out to a radius of ~ 28 arcseconds (105 pixels). To ensure sufficient pixel sampling, the radius of the innermost circular aperture and the thickness of each surrounding circular annulus was set to ~ 1.3 arcseconds (5 pixels), which is larger than any of the DES PSF FWHMs. The `Photutils` Python package (Bradley et al. 2022) was used to generate the annuli and fit them to the stacked image data. The average pixel values were first calculated in raw image units of counts/second and subsequently converted to logarithmic surface brightness (SB) units ($\text{mag}/\text{arcsec}^2$) as follows:

$$\text{SB (mag arcsec}^{-2}\text{)} = 30.0 - 2.5 \log \frac{F}{0.2637^2} \quad (5.4)$$

where F is the image pixel values in counts/second, 30.0 mag is the DES zeropoint magnitude

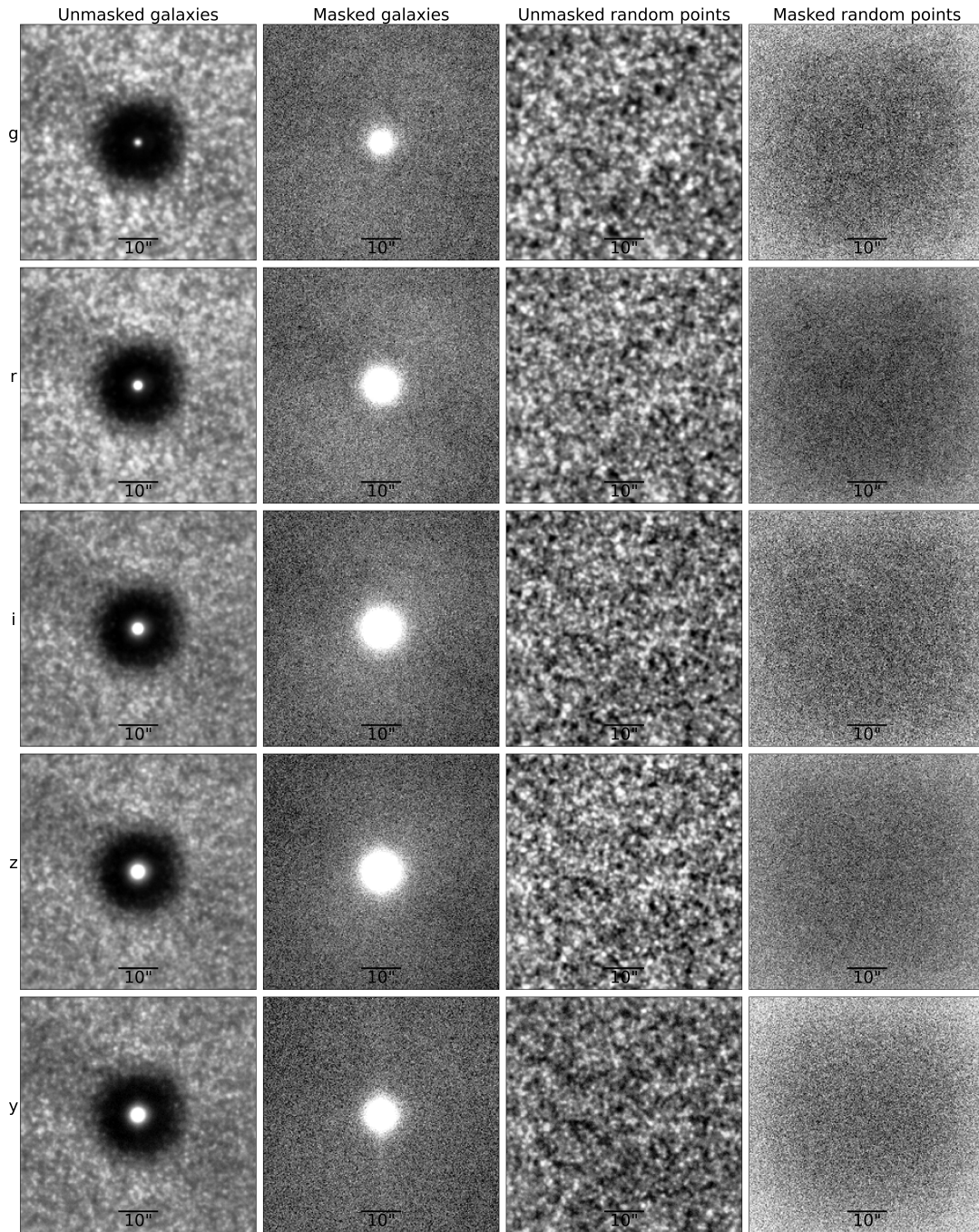


Figure 60. Weighted average stacked images of 98,713 individual DES DR2 coadd image cutouts. Unmasked images (columns 1 and 3) are stacked as-is, while masked images (columns 2 and 4) undergo a source removal procedure prior to averaging. Z-scaling has been applied to all images to enhance contrast.

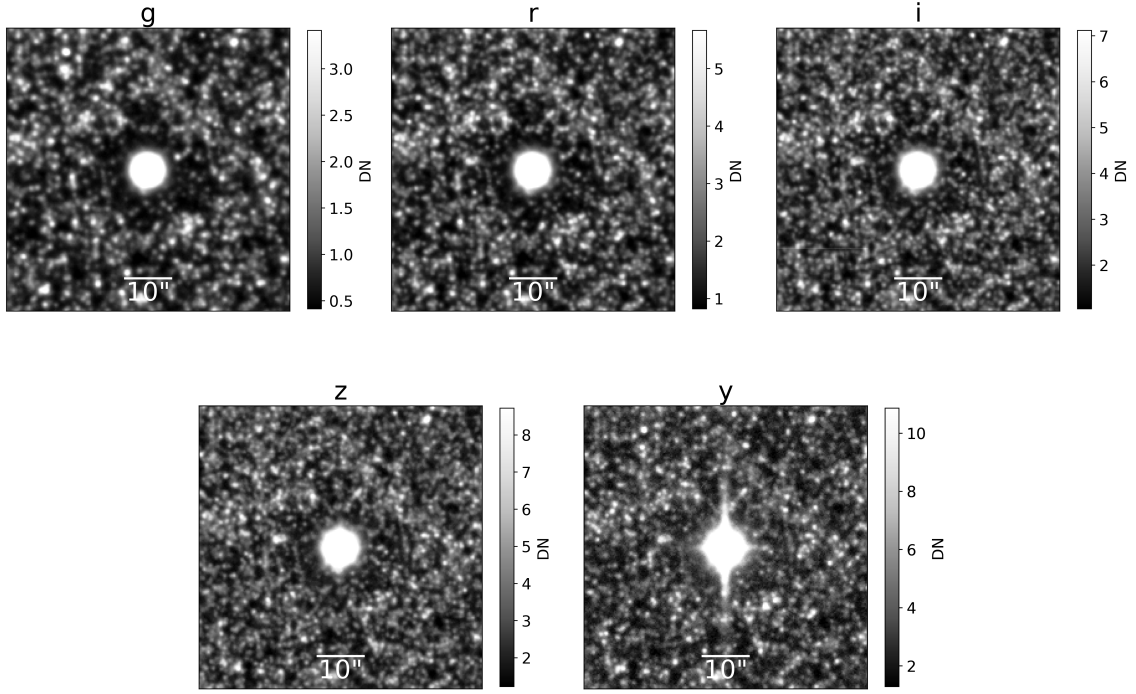


Figure 61. Weighted average stacks of 14,711 stars. Z-scaling has been applied to all images to enhance contrast.

and 0.2637 arcseconds/pixel is the DES pixel scale. The profiles are subsequently converted to linear units as follows:

$$SB(\text{MJy sr}^{-1}) = 10^{\frac{SB_{\text{mag}} - 8.9}{-2.5}} \times 206265^2 \times 10^{-6} \quad (5.5)$$

$$SB(\text{nW m}^{-2} \text{sr}^{-1}) = SB_{\text{MJy}} \times 10^{-11} \times \frac{c}{\lambda} \quad (5.6)$$

The surface brightness profiles for the unmasked and masked galaxy stacks are shown in Figures 62 and 63. The sky background, modeled by the dashed line on the profiles, was determined by calculating the radial profile of the unmasked random stack and taking the average of all the values. The dark ring feature seen in the unmasked galaxy stacked images manifests as a dip in the surface brightness profile from $\sim 3 - 15$ arcseconds. Beyond 15 arcseconds, the profile is well-aligned with the sky

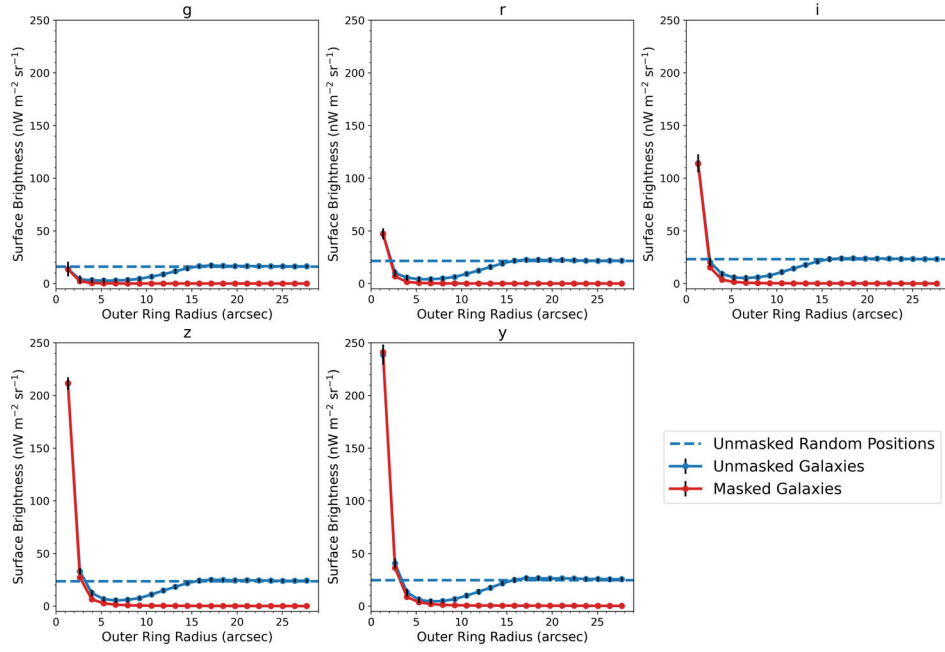


Figure 62. Surface brightness profiles of unmasked (blue) and masked (red) galaxy stacks in linear units. The average background level, determined from unmasked stacks of random positions, is represented by the dashed line.

background level derived from the stack of random positions. The masked galaxy profiles exhibit no such dip in surface brightness. All radial profile values and their errors for the unmasked and masked galaxy stacks in linear units are presented in Tables 9 and 10, respectively and in magnitude units in Tables 11 and 12.

Table 9. Radial profile data for the unmasked galaxy stacks. All values in $\text{nW m}^{-2} \text{sr}^{-1}$.

Radius ($''$)	g (error)	r (error)	i (error)	z (error)	Y (error)
1.3185	13.8 (6.97)	47.35 (5.24)	114.24 (8.59)	211.43 (6.01)	238.81 (9.63)
2.637	4.03 (3.68)	10.03 (3.48)	20.26 (4.04)	33.09 (3.12)	40.7 (4.9)
3.9555	3.15 (2.48)	5.65 (2.71)	9.17 (2.59)	12.41 (3.28)	13.22 (3.44)
5.274	2.74 (2.7)	4.13 (2.54)	5.77 (2.71)	6.71 (2.09)	6.17 (3.14)
6.5925	2.86 (1.79)	4.07 (2.27)	5.22 (2.84)	5.44 (2.18)	4.48 (2.87)
7.911	3.38 (2.1)	4.85 (1.93)	6.0 (1.75)	6.05 (2.05)	4.91 (1.56)
9.2295	4.52 (1.8)	6.31 (1.51)	7.61 (1.95)	7.65 (1.46)	6.63 (1.69)
10.548	6.6 (1.79)	9.25 (1.54)	10.91 (2.12)	11.14 (1.74)	10.06 (2.06)
11.8665	8.81 (2.01)	12.34 (1.64)	14.33 (1.72)	14.81 (1.94)	13.65 (2.43)
13.185	11.66 (1.98)	15.76 (2.2)	17.73 (1.68)	18.38 (2.01)	17.47 (2.2)
14.5035	14.51 (2.32)	19.15 (2.31)	21.0 (2.06)	21.89 (1.7)	21.74 (2.27)
15.822	16.48 (1.36)	21.65 (1.73)	23.26 (2.35)	24.24 (2.08)	24.95 (2.6)
17.1405	17.21 (2.06)	22.54 (1.88)	23.87 (2.22)	25.08 (1.69)	26.62 (2.29)
18.459	16.81 (1.41)	22.44 (2.19)	24.0 (1.85)	24.89 (1.36)	26.54 (2.08)
19.7775	16.61 (1.5)	22.3 (1.82)	23.66 (1.31)	24.5 (1.65)	26.28 (1.66)
21.096	16.61 (1.61)	22.25 (1.85)	23.72 (1.45)	24.6 (1.59)	26.38 (1.62)
22.4145	16.5 (1.25)	22.0 (1.68)	23.7 (1.43)	24.52 (1.48)	26.19 (1.38)
23.733	16.43 (1.33)	21.72 (1.53)	23.43 (1.48)	24.28 (1.39)	25.74 (1.86)
25.0515	16.37 (1.26)	21.64 (1.42)	23.35 (1.25)	24.06 (1.45)	25.8 (1.82)
26.37	16.31 (1.55)	21.74 (1.58)	23.26 (1.13)	24.16 (1.31)	25.54 (2.01)
27.6885	16.33 (1.35)	21.7 (1.61)	23.2 (1.38)	24.22 (1.35)	25.59 (1.91)

Table 10. Radial profile data for the masked galaxy stacks. All values in $\text{nW m}^{-2} \text{sr}^{-1}$.

Radius (")	g (error)	r (error)	i (error)	z (error)	Y (error)
1.3185	13.49 (0.1)	47.01 (0.2)	113.73 (0.49)	211.73 (1.21)	241.26 (1.23)
2.637	2.21 (0.04)	6.87 (0.07)	15.27 (0.11)	27.22 (0.19)	36.32 (0.31)
3.9555	0.48 (0.05)	1.53 (0.04)	3.58 (0.05)	6.47 (0.09)	8.82 (0.23)
5.274	0.22 (0.03)	0.61 (0.04)	1.53 (0.05)	2.73 (0.06)	3.75 (0.1)
6.5925	0.12 (0.02)	0.29 (0.04)	0.78 (0.04)	1.43 (0.06)	1.99 (0.15)
7.911	0.06 (0.03)	0.15 (0.02)	0.47 (0.04)	0.87 (0.05)	1.21 (0.11)
9.2295	0.05 (0.02)	0.09 (0.03)	0.33 (0.04)	0.61 (0.06)	0.89 (0.1)
10.548	0.04 (0.02)	0.06 (0.03)	0.24 (0.03)	0.48 (0.04)	0.68 (0.12)
11.8665	0.04 (0.02)	0.06 (0.02)	0.21 (0.02)	0.4 (0.04)	0.57 (0.1)
13.185	0.04 (0.01)	0.06 (0.02)	0.19 (0.03)	0.36 (0.03)	0.59 (0.08)
14.5035	0.03 (0.02)	0.05 (0.01)	0.16 (0.02)	0.31 (0.03)	0.5 (0.1)
15.822	0.03 (0.02)	0.05 (0.02)	0.15 (0.02)	0.27 (0.03)	0.47 (0.07)
17.1405	0.03 (0.01)	0.04 (0.02)	0.13 (0.02)	0.24 (0.03)	0.43 (0.1)
18.459	0.03 (0.01)	0.04 (0.02)	0.12 (0.02)	0.23 (0.03)	0.43 (0.08)
19.7775	0.03 (0.02)	0.05 (0.02)	0.12 (0.02)	0.21 (0.03)	0.41 (0.09)
21.096	0.03 (0.02)	0.04 (0.02)	0.11 (0.02)	0.2 (0.03)	0.43 (0.1)
22.4145	0.03 (0.01)	0.04 (0.01)	0.1 (0.02)	0.16 (0.02)	0.43 (0.07)
23.733	0.02 (0.01)	0.03 (0.01)	0.09 (0.01)	0.17 (0.03)	0.37 (0.07)
25.0515	0.01 (0.01)	0.03 (0.01)	0.06 (0.02)	0.14 (0.03)	0.32 (0.06)
26.37	0.01 (0.01)	0.02 (0.01)	0.05 (0.02)	0.12 (0.03)	0.32 (0.06)
27.6885	0.0 (0.01)	0.01 (0.01)	0.05 (0.02)	0.1 (0.03)	0.28 (0.06)

Table 11. Radial profile data for the unmasked galaxy stacks. All values in magnitudes per square arcsecond. Error values reported as (upper error, lower error).

Radius (")	g (error)	r (error)	i (error)	z (error)	Y (error)
1.3185	27.12 (0.44, 0.76)	25.47 (0.11, 0.13)	24.29 (0.08, 0.08)	23.45 (0.03, 0.03)	23.23 (0.04, 0.04)
2.637	28.45 (0.7, 2.65)	27.15 (0.32, 0.46)	26.17 (0.2, 0.24)	25.46 (0.1, 0.11)	25.15 (0.12, 0.14)
3.9555	28.72 (0.63, 1.68)	27.77 (0.43, 0.71)	27.03 (0.27, 0.36)	26.53 (0.25, 0.33)	26.37 (0.25, 0.33)
5.274	28.87 (0.74, 4.53)	28.11 (0.52, 1.04)	27.54 (0.42, 0.69)	27.19 (0.29, 0.4)	27.2 (0.45, 0.77)
6.5925	28.83 (0.53, 1.07)	28.13 (0.48, 0.89)	27.64 (0.47, 0.85)	27.42 (0.37, 0.56)	27.55 (0.54, 1.11)
7.911	28.64 (0.52, 1.06)	27.94 (0.36, 0.55)	27.49 (0.28, 0.38)	27.31 (0.32, 0.45)	27.45 (0.3, 0.41)
9.2295	28.33 (0.36, 0.55)	27.65 (0.23, 0.3)	27.23 (0.25, 0.32)	27.05 (0.19, 0.23)	27.12 (0.25, 0.32)
10.548	27.92 (0.26, 0.34)	27.24 (0.17, 0.2)	26.84 (0.19, 0.23)	26.64 (0.16, 0.18)	26.67 (0.2, 0.25)
11.8665	27.61 (0.22, 0.28)	26.93 (0.14, 0.15)	26.55 (0.12, 0.14)	26.33 (0.13, 0.15)	26.34 (0.18, 0.21)
13.185	27.3 (0.17, 0.2)	26.66 (0.14, 0.16)	26.32 (0.1, 0.11)	26.1 (0.11, 0.13)	26.07 (0.13, 0.15)
14.5035	27.06 (0.16, 0.19)	26.45 (0.12, 0.14)	26.13 (0.1, 0.11)	25.91 (0.08, 0.09)	25.83 (0.11, 0.12)
15.822	26.92 (0.09, 0.09)	26.32 (0.08, 0.09)	26.02 (0.1, 0.12)	25.8 (0.09, 0.1)	25.68 (0.11, 0.12)
17.1405	26.88 (0.12, 0.14)	26.27 (0.09, 0.09)	25.99 (0.1, 0.11)	25.76 (0.07, 0.08)	25.61 (0.09, 0.1)
18.459	26.9 (0.09, 0.09)	26.28 (0.1, 0.11)	25.99 (0.08, 0.09)	25.77 (0.06, 0.06)	25.62 (0.08, 0.09)
19.7775	26.92 (0.09, 0.1)	26.28 (0.09, 0.09)	26.0 (0.06, 0.06)	25.79 (0.07, 0.08)	25.63 (0.07, 0.07)
21.096	26.92 (0.1, 0.11)	26.29 (0.09, 0.09)	26.0 (0.06, 0.07)	25.78 (0.07, 0.07)	25.62 (0.06, 0.07)
22.4145	26.92 (0.08, 0.09)	26.3 (0.08, 0.09)	26.0 (0.06, 0.07)	25.79 (0.06, 0.07)	25.63 (0.06, 0.06)
23.733	26.93 (0.08, 0.09)	26.31 (0.07, 0.08)	26.01 (0.07, 0.07)	25.8 (0.06, 0.06)	25.65 (0.08, 0.08)
25.0515	26.93 (0.08, 0.09)	26.32 (0.07, 0.07)	26.02 (0.06, 0.06)	25.81 (0.06, 0.07)	25.65 (0.07, 0.08)
26.37	26.94 (0.1, 0.11)	26.31 (0.08, 0.08)	26.02 (0.05, 0.05)	25.8 (0.06, 0.06)	25.66 (0.08, 0.09)
27.6885	26.94 (0.09, 0.09)	26.31 (0.08, 0.08)	26.02 (0.06, 0.07)	25.8 (0.06, 0.06)	25.66 (0.08, 0.08)

Table 12. Radial profile data for the masked galaxy stacks. All values in magnitudes per square arcsecond. Error values reported as (upper error, lower error).

Radius (")	g (error)	r (error)	i (error)	z (error)	Y (error)
1.3185	27.14 (0.01, 0.01)	25.47 (0.0, 0.0)	24.3 (0.0, 0.0)	23.45 (0.01, 0.01)	23.22 (0.01, 0.01)
2.637	29.1 (0.02, 0.02)	27.56 (0.01, 0.01)	26.48 (0.01, 0.01)	25.67 (0.01, 0.01)	25.28 (0.01, 0.01)
3.9555	30.76 (0.1, 0.11)	29.19 (0.02, 0.03)	28.05 (0.02, 0.02)	27.23 (0.01, 0.01)	26.81 (0.03, 0.03)
5.274	31.59 (0.16, 0.18)	30.18 (0.06, 0.07)	28.97 (0.04, 0.04)	28.17 (0.02, 0.02)	27.74 (0.03, 0.03)
6.5925	32.27 (0.2, 0.25)	31.0 (0.13, 0.14)	29.7 (0.05, 0.06)	28.87 (0.05, 0.05)	28.43 (0.08, 0.09)
7.911	33.0 (0.39, 0.62)	31.74 (0.17, 0.2)	30.26 (0.08, 0.09)	29.42 (0.06, 0.06)	28.97 (0.09, 0.1)
9.2295	33.27 (0.42, 0.68)	32.24 (0.3, 0.42)	30.64 (0.11, 0.12)	29.8 (0.09, 0.1)	29.31 (0.12, 0.13)
10.548	33.48 (0.43, 0.73)	32.71 (0.41, 0.66)	31.0 (0.14, 0.16)	30.05 (0.09, 0.1)	29.59 (0.17, 0.21)
11.8665	33.5 (0.41, 0.68)	32.74 (0.32, 0.45)	31.15 (0.12, 0.14)	30.25 (0.1, 0.11)	29.79 (0.17, 0.21)
13.185	33.52 (0.35, 0.53)	32.74 (0.32, 0.46)	31.22 (0.14, 0.16)	30.37 (0.1, 0.11)	29.76 (0.14, 0.16)
14.5035	33.75 (0.44, 0.74)	32.82 (0.26, 0.34)	31.39 (0.13, 0.15)	30.52 (0.09, 0.1)	29.92 (0.19, 0.23)
15.822	33.68 (0.48, 0.89)	32.93 (0.3, 0.42)	31.5 (0.14, 0.15)	30.68 (0.13, 0.15)	30.0 (0.16, 0.18)
17.1405	33.75 (0.42, 0.68)	33.06 (0.35, 0.52)	31.69 (0.12, 0.14)	30.83 (0.12, 0.14)	30.09 (0.22, 0.28)
18.459	33.87 (0.45, 0.8)	33.06 (0.35, 0.52)	31.76 (0.15, 0.17)	30.86 (0.12, 0.14)	30.09 (0.18, 0.21)
19.7775	33.87 (0.49, 0.93)	33.01 (0.38, 0.58)	31.78 (0.17, 0.2)	30.98 (0.15, 0.17)	30.14 (0.21, 0.27)
21.096	33.95 (0.56, 1.2)	33.04 (0.35, 0.52)	31.84 (0.19, 0.22)	31.01 (0.15, 0.18)	30.09 (0.22, 0.28)
22.4145	33.77 (0.39, 0.62)	33.14 (0.3, 0.41)	31.95 (0.16, 0.19)	31.28 (0.16, 0.18)	30.09 (0.16, 0.19)
23.733	34.04 (0.51, 1.0)	33.3 (0.36, 0.54)	32.1 (0.17, 0.21)	31.21 (0.18, 0.21)	30.25 (0.19, 0.23)
25.0515	34.6 (0.73, 3.45)	33.57 (0.46, 0.83)	32.41 (0.28, 0.38)	31.43 (0.19, 0.23)	30.43 (0.19, 0.23)
26.37	35.19 (0.95, 5.0)	34.13 (0.68, 2.25)	32.62 (0.31, 0.43)	31.57 (0.23, 0.29)	30.41 (0.19, 0.23)
27.6885	36.27 (1.5, 5.0)	34.65 (0.82, 5.0)	32.75 (0.35, 0.51)	31.79 (0.29, 0.4)	30.56 (0.2, 0.25)

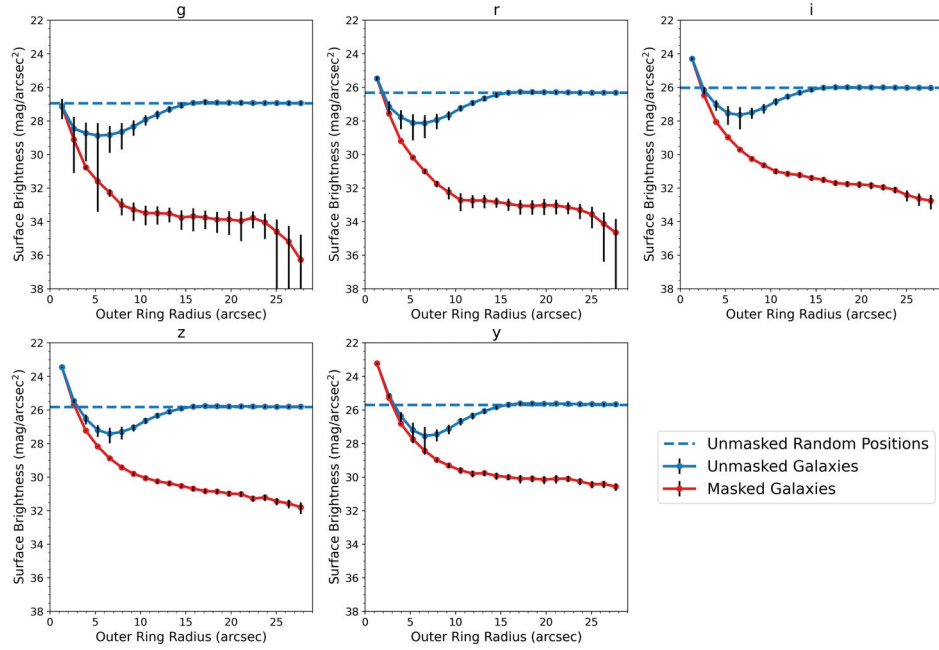


Figure 63. Surface brightness profiles of unmasked (blue) and masked (red) galaxy stacks in magnitude units. The average background level, determined from unmasked stacks of random positions, is represented by the dashed line.

5.4.2 Error Estimation

The error bars shown on the surface brightness profiles are the total error, which was calculated as the quadrature sum of the error in the background level and the error in the pixel values for each annulus. To estimate each of these errors, a series of jackknife tests was performed on the stacks of galaxies and the stacks of random positions. In each test, the image stacking algorithm described in Section 5.3.1 was applied to the full set of images, but with half of the images randomly selected to be multiplied by -1 prior to stacking. This effectively nullified the galaxy and background signals, leaving behind only the pixel variations, as shown in Figure 64.

Each jackknife image was normalized by subtracting out the mean pixel value of the image. Radial

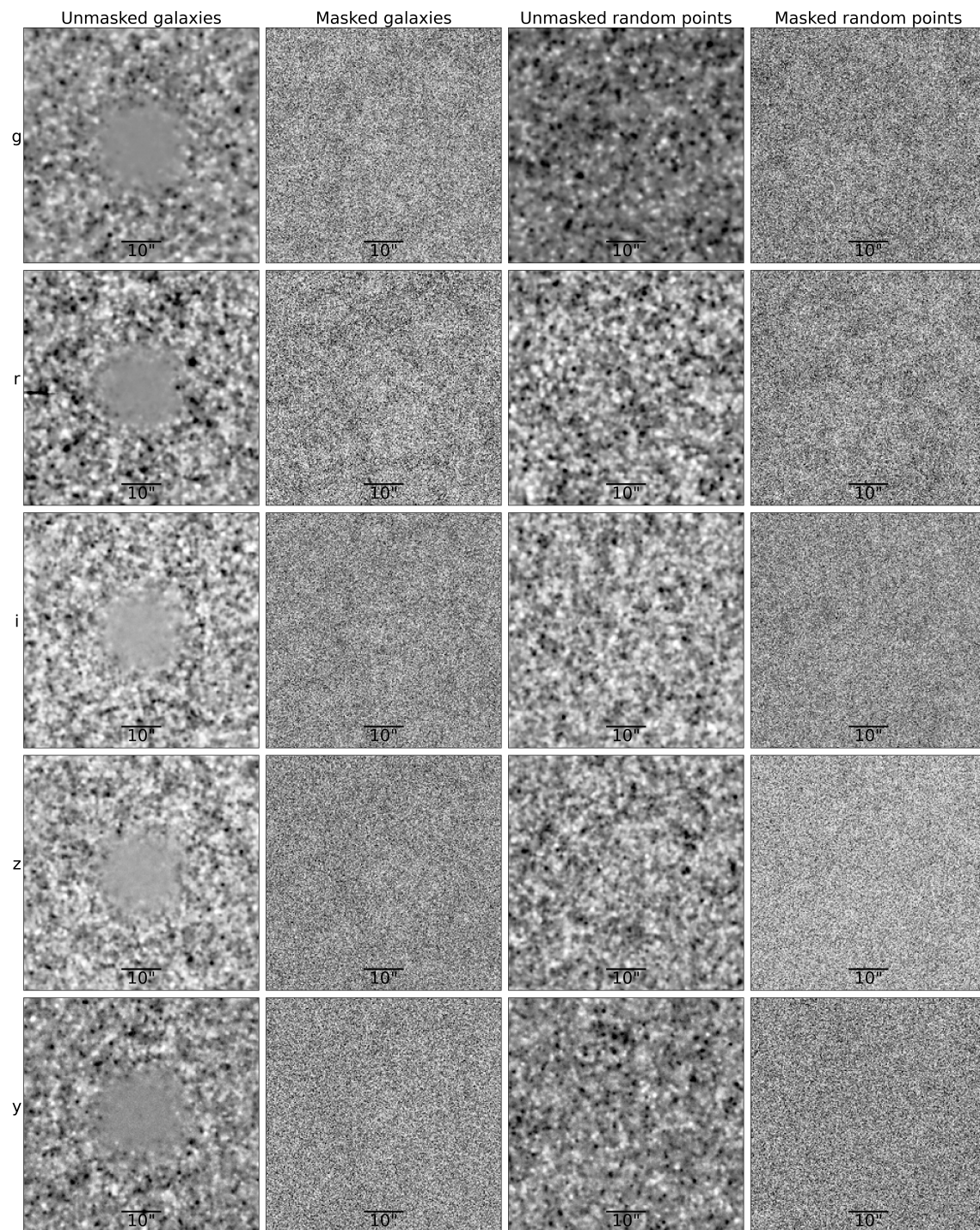


Figure 64. Average images from 16 sets of jackknife images, in which 50% of individual images have been multiplied by -1. From left to right: unmasked galaxies, masked galaxies, unmasked random positions, masked random positions. From top to bottom: g, r, i, z, y.

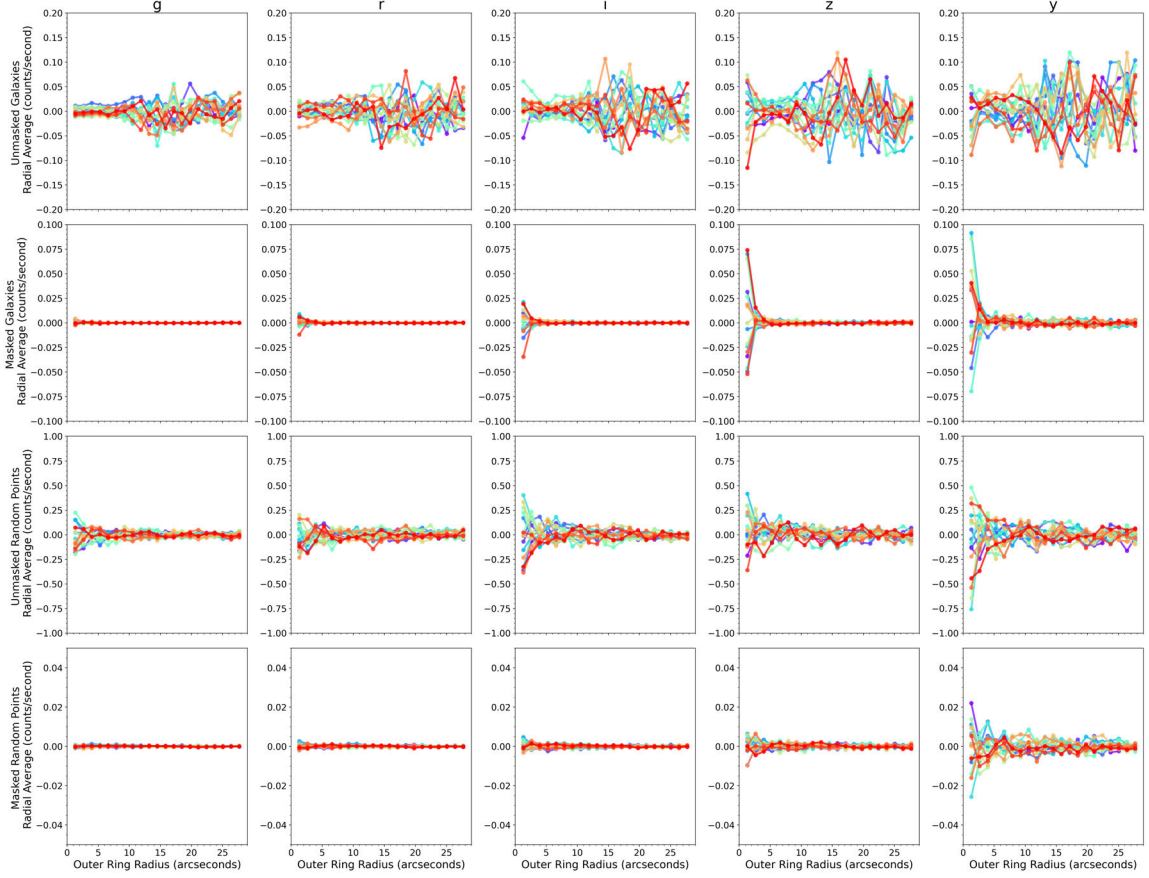


Figure 65. Radial profiles for 16 sets of jackknife stacks. Each color represents a different jackknife image. From left to right: g, r, i, z, and Y. From top to bottom: unmasked galaxies, masked galaxies, unmasked random positions, masked random positions.

profiles were then calculated for each jackknife stack following the procedure outlined in Section 5.4.1 and are shown in Figure 65. The error values for the full unmasked and masked galaxy stacks were then calculated as the quadrature sum of the root-mean-square of the galaxy and random jackknife profile values at each radial bin, with the pixel-to-pixel variation represented by the RMS of the galaxy jackknife stacks and the error in the background represented by the RMS of the random jackknife stacks. The calculated error values are shown in Figure 66.

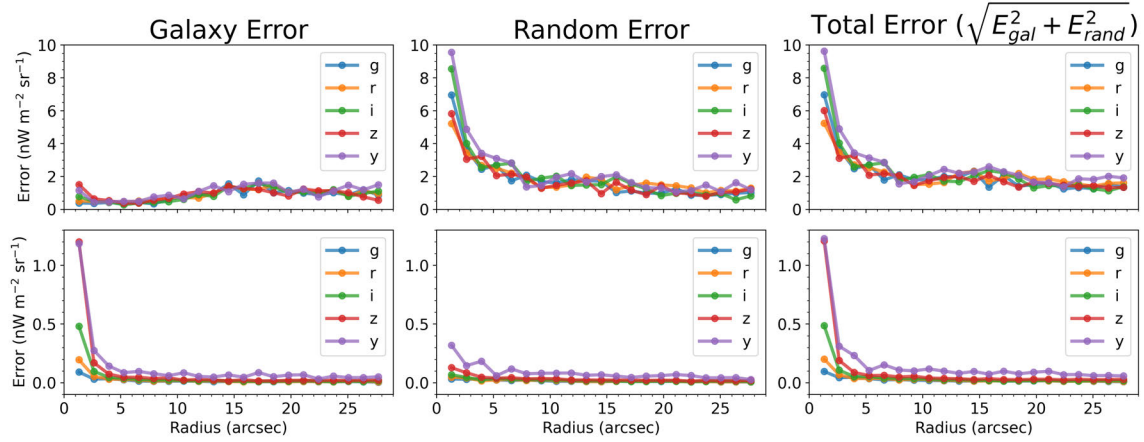


Figure 66. Calculated pixel-to-pixel errors (“Galaxy Error”), background error (“Random Error”), and total error values for the unmasked and masked stacks.

5.5 The Dark Ring

Of note in the unmasked galaxy stacks is the large dark ring surrounding the central galaxy, extending from $3'' \lesssim r \lesssim 15''$. This ring manifests in the radial profiles as a dip in surface brightness. This feature is not seen in any individual cutouts (e.g., Figure 59), nor is it seen in the masked galaxy stacks or in the stacks of random positions or stars. Smaller stacks of 100, 1,000, and 10,000 galaxies were generated to analyze the emergence of this dark signal. Surface brightness profiles for these stacks are shown in Figure 67. Rescaling each profile by the mean and background level of its corresponding image to directly compare stacks of different numbers of galaxies reveals what is also apparent in the raw images (Figure 68): the dark signal increases in intensity as the number of galaxies stacked together increases.

This signal could perhaps be explained as an instrumental effect, or an artifact from the stacking procedure. Or could it be that massive elliptical galaxies are surrounded by large dust clouds not visible on an individual image level? The subsequent paragraphs describe the extensive testing conducted to determine the origin of this mysterious feature.

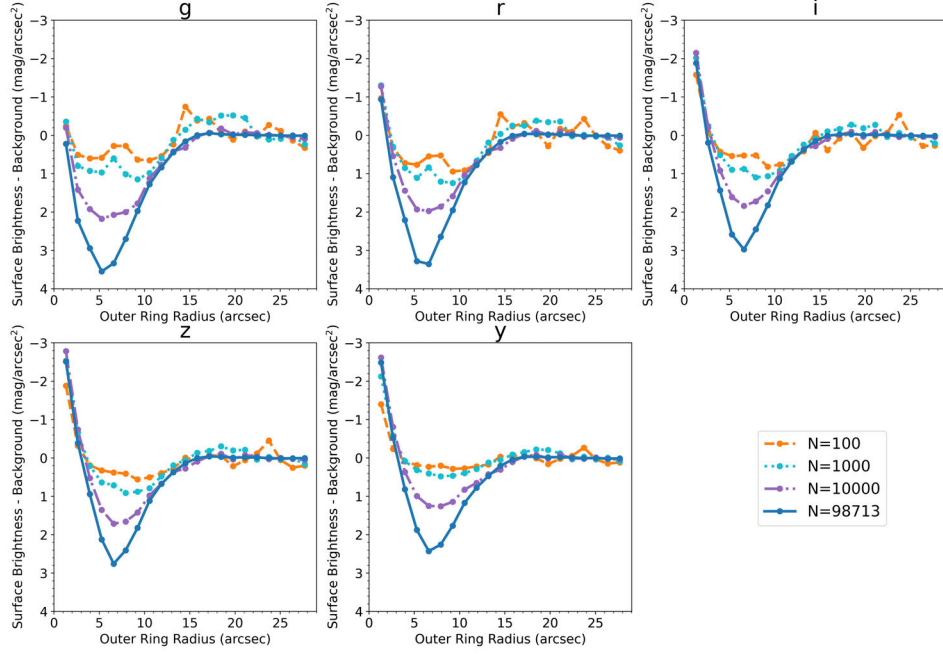


Figure 67. Surface brightness profiles of 100 (orange dashed line), 1,000 (dotted cyan line), 10,000 (dashed-dotted purple line), and 98,713 (blue solid line) show that the dip in surface brightness associated with the dark ring seen around the central galaxy grows larger as the number of galaxies stacked together increases.

5.5.1 Alternative Stacking Methods

To determine whether the dark ring was an artifact of the image processing and stacking algorithm, several alternative methods of stacking were employed. Stacking (averaging) the unmasked galaxy cutouts without weighting the pixels according to the inverse variance weight maps yields stacks that are nearly identical to the weighted average stacks. Median stacks calculated by computing the median pixel value for each pixel across all images yields stacks that more closely resemble the masked weighted average stacks. They have a smoother background, but a slight dark ring around the center galaxy remains. All three sets of radial profiles and stacked images are shown in Figures 69 and 70.

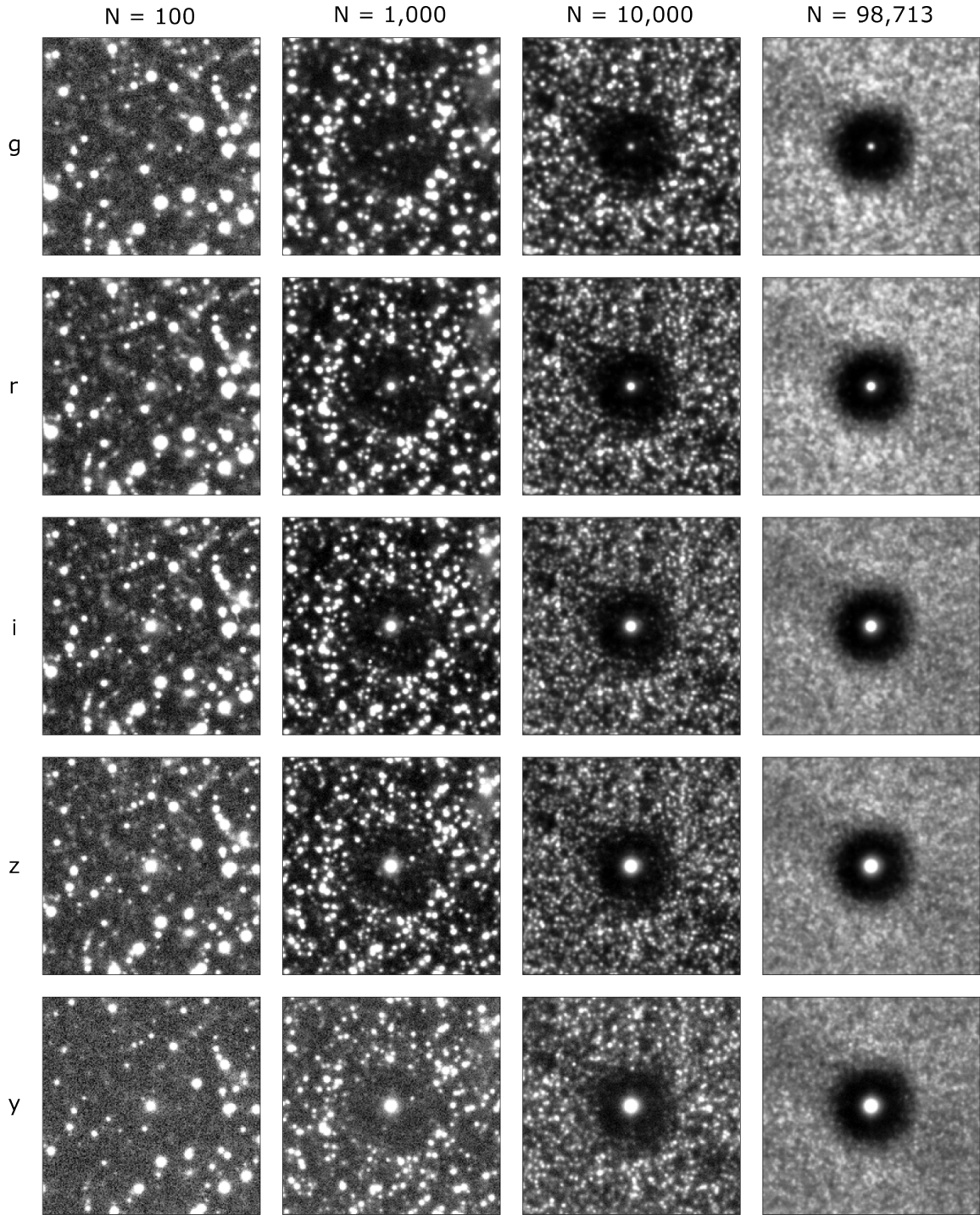


Figure 68. A dark ring emerges around the central galaxy as the number of cutouts stacked together increases. From left to right: 100, 1,000, 10,000, and 98,713 galaxies. From top to bottom: g, r, i, z, y.

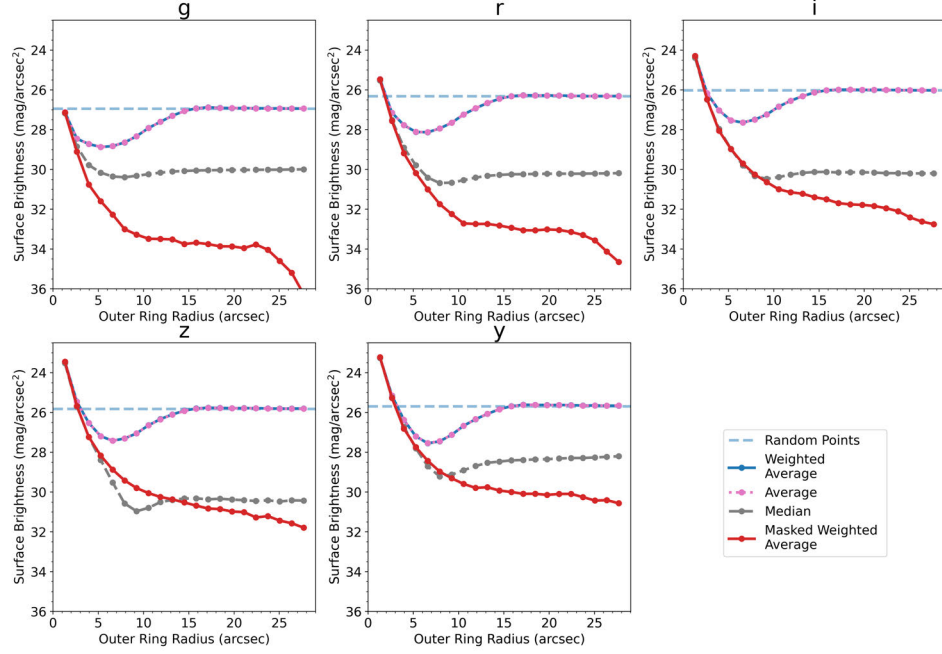


Figure 69. Surface brightness profiles of unmasked galaxy stacks generated by computing the weighted average (blue solid line), standard average (pink dotted line), and median (gray dashed line) of all 98,713 images. The red line is the masked weighted average profile. The faint blue dashed line is the sky background derived from unmasked stacks of random positions.

The persistent presence of the dark ring regardless of stack calculation method suggests the feature is not an artifact introduced during the stacking process.

5.5.2 Stacking Alternative Images

To rule out any potential DECam instrumental effects that could be responsible for the dark ring, optical images from other surveys were stacked and compared against the DES stacks. The main catalog used in this work covers a narrow range of the southern sky (Figure 54) that does not overlap with other optical surveys such as the Sloan Digital Sky Survey (SDSS). A small ($N \sim 1400$) subset

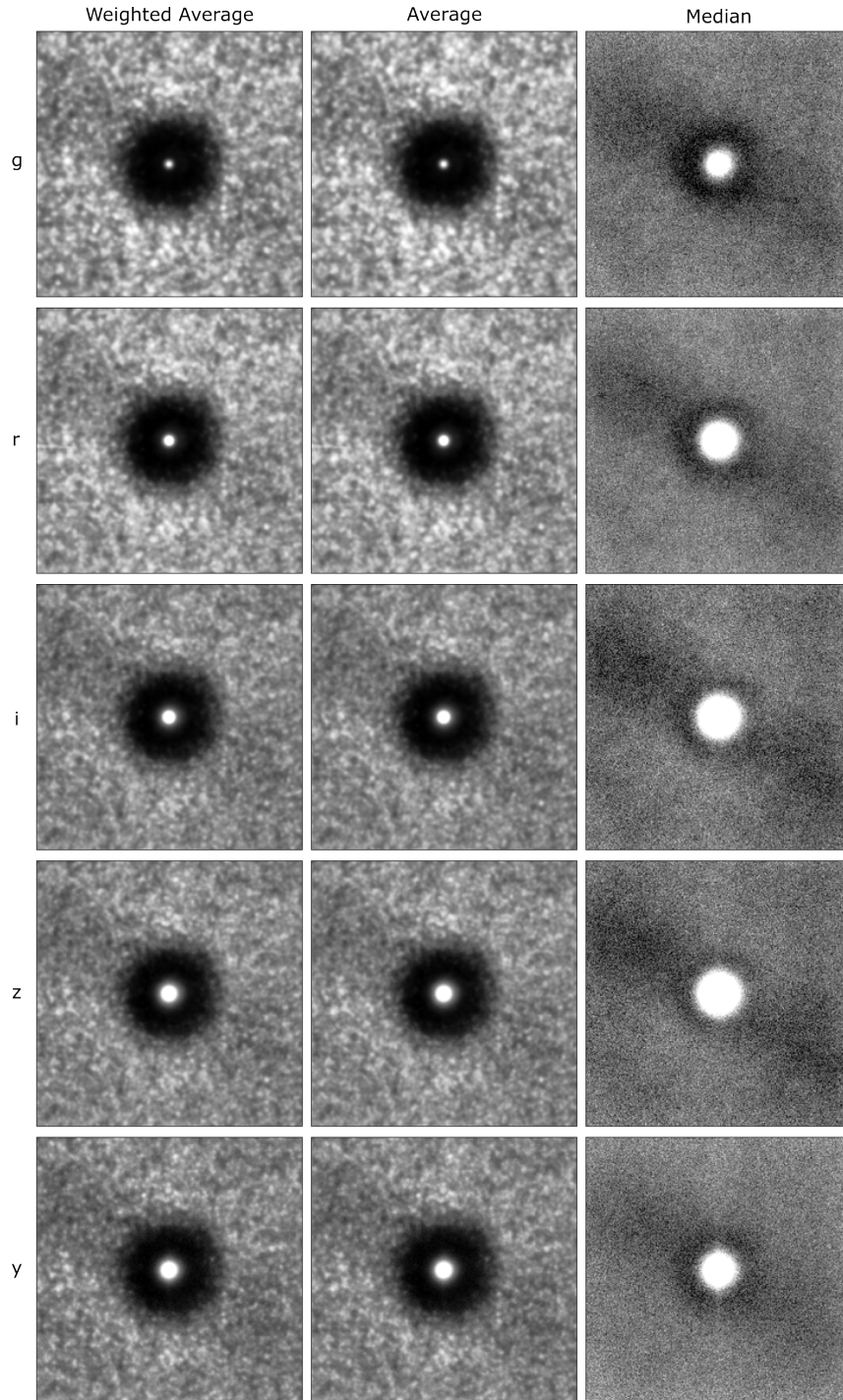


Figure 70. Unmasked galaxy stacks generated by computing the weighted average (left), standard average (middle), and median (right) of all 98,713 images.

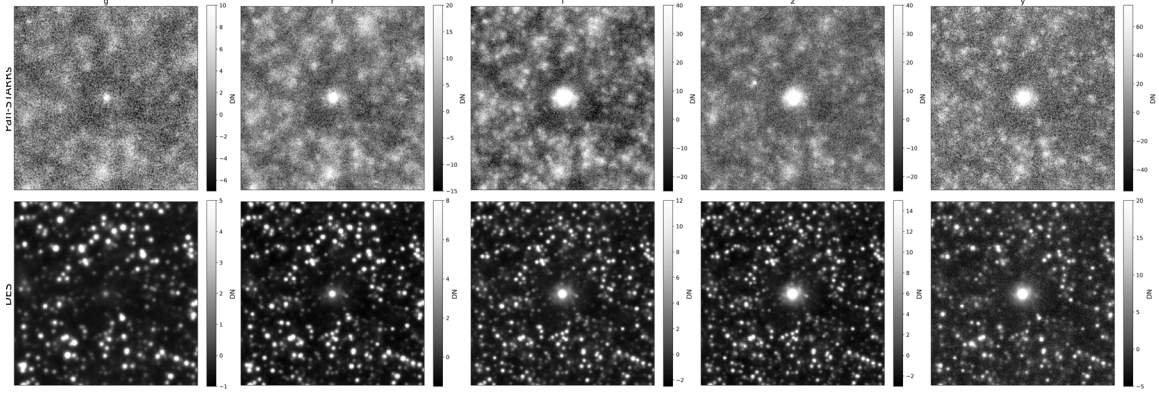


Figure 71. Unmasked (weighted average) stacked Pan-STARRS1 (top row) and DES (bottom row) images of 1,335 galaxies in the SDSS Stripe 82 region. Images are mean subtracted and shown in raw pixel units.

of galaxies was instead selected from the catalog described in Meinke, Cohen, et al. 2023, which is an expanded edition of the catalog used in this work and in Meinke, Böckmann, et al. 2021. This expanded catalog covers regions of the DES, SPT, and ACT footprints. The subset of galaxies selected from this catalog for optical stacking were selected from the SDSS Stripe 82 region (Jiang et al. 2014), which lies on the celestial equator and overlaps with the footprint of the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS).

The Pan-STARRS1 telescope (PS1) is a 1.8 meter Richey-Chretien telescope sited at Haleakala Observatories in Maui, Hawaii (Chambers et al. 2016). From 2010 to 2014, PS1 repeatedly surveyed the sky in grizY bands to generate stacked images with 5σ limiting magnitudes of $g = 23.3$, $r = 23.2$, $i = 23.1$, $z = 22.3$, and $Y = 21.4$. Stack (coadd) images for the catalog galaxies were obtained in the grizY bands from both Pan-STARRS1 and DES DR2. Images were processed according to the procedure outlined in Section 5.3.1 and stacked by taking the average across all frames, weighting each pixel in each frame by the inverse variance values provided in the associated weight maps. The stacked images (Figure 71) were mean subtracted and surface brightness profiles (Figure 72) were calculated and normalized to the average brightness level beyond a radius of $\sim 21''$. The surface brightness profiles of both the DES and the Pan-STARRS1 stacks exhibit the same dip observed in the previous stacks, which suggests that the feature does not have an instrumental origin.

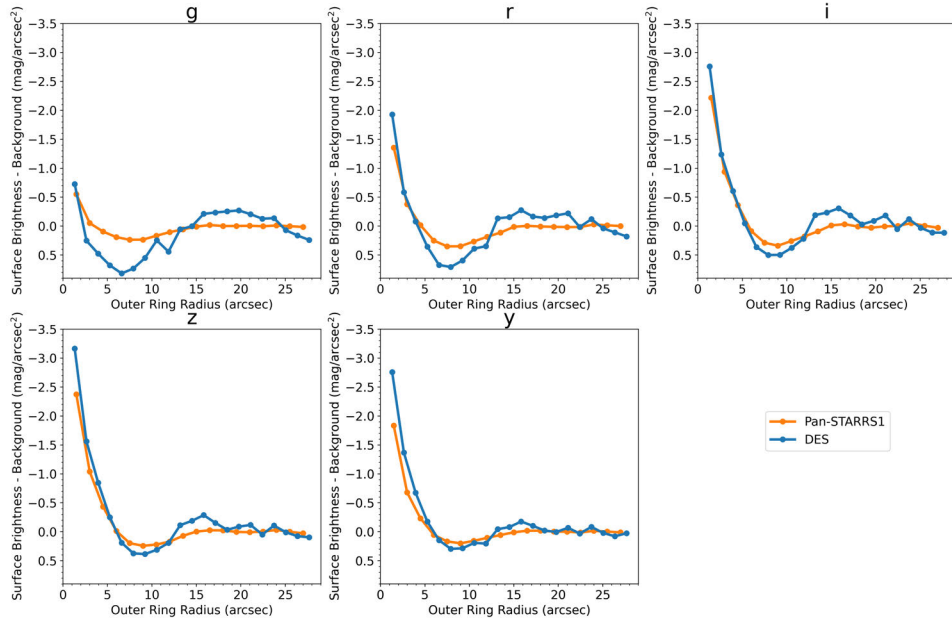


Figure 72. Background-normalized surface brightness profiles for PAN-STARRS1 (orange line) and DES (blue line) stacks of galaxies in the SDSS Stripe 82 region.

5.5.3 Infrared Stacking

With instrumental and image processing effects ruled out, attention turned to potential astrophysical explanations for the dark ring. Perhaps the most obvious potential explanation is that the target galaxies are surrounded by large dust clouds that attenuate the light from the galaxies. Indeed, Meinke, Böckmann, et al. 2021; Meinke, Cohen, et al. 2023 found evidence for dust in millimeter (SPT) stacks of the same galaxy catalog, with the dust signal increasing with stellar mass. In this case, the dip in surface brightness could be explained as dust absorption, growing stronger with radius until reaching peak absorption near 6", after which the sky background gradually becomes dominant. As dust is transparent to infrared light, if the origin of the dark signal seen in the optical stacks was due to the presence of a dust cloud, infrared stacks of the same galaxies should have no such feature.

The WISE all-sky survey completed in 2010 imaged the entire sky in four infrared bands (W1, W2,

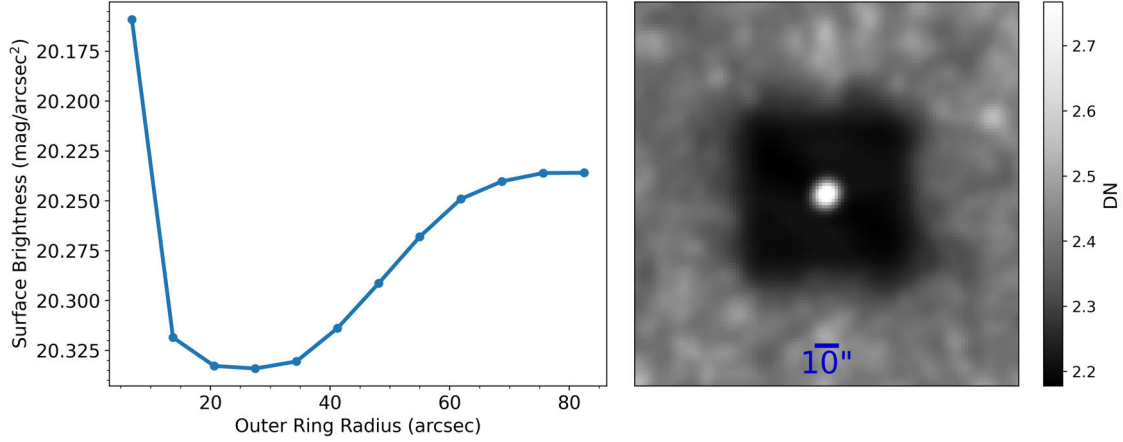


Figure 73. Unmasked (weighted average) stacked WISE W1 image and surface brightness profile of 95,163 galaxies from the original catalog. Image is shown in raw pixel units (DN).

W3, W4) (Wright et al. 2010). The W1 band ($3.4\mu\text{m}$) data has an angular resolution of $6.1''$ and 5σ sensitivity of 0.068mJy . W1 images for $\sim 95,000$ galaxies from the original catalog were obtained from the WISE Image Atlas and processed according to the procedure outlined in Section 5.3.1. The resulting stacked image and surface brightness profile are shown in Figure 73. Because of the large (5x) difference in resolution between WISE and DES images, it is difficult to directly compare the surface brightness profiles, but a slight dip in brightness is seen in the W1 profile, albeit on a larger radius scale. Additionally, a large dark square surrounds the center galaxy in the stacked image. The presence of the dark feature in the infrared stacks suggests that while a dust signal was detected in the millimeter stacks, and may contribute somewhat to the observed decrease in brightness, it is not the main source of the dark feature seen in the optical and infrared stacks.

5.5.4 Stacking by Parameters

To analyze the influence of target galaxy characteristics on the intensity of the dark ring feature, numerous sets of sub-stacks were generated by binning the target galaxies according to various parameters as described below.

5.5.4.1 By Stellar Mass

To further probe the relationship between stellar mass and dust, the catalog galaxies were binned by stellar mass and stacked according to the 0.1 dex mass bins specified in Meinke, Böckmann, et al. 2021. Prior to calculating the surface brightness profiles, the stacked images were mean subtracted and rescaled to a minimum pixel value of zero. Background-subtracted surface brightness profiles shown in Figure 74 show that the magnitude of the dip in brightness increases as stellar mass decreases. This trend seems to support the conclusion that the dark signal is not caused by dust, since higher mass galaxies (which have more dust) would be expected to have a larger dip. However, it is possible that the higher mass galaxies exhibit less of a dip in surface brightness because they are overall larger and contain more stars than the lower mass galaxies.

5.5.4.2 By Photometric Redshift

To discern if galaxy redshift has any influence on the dark signal, stacks of galaxies at redshift less than the mean catalog redshift of 1.1 were compared to stacks of galaxies at redshifts higher than 1.1. To account for potential differences in the distribution of target galaxy magnitudes in either subset, galaxies were selected from a narrow magnitude range around the mean g-band magnitude. The background-subtracted surface brightness profiles (Figure 75) show that while both stacks of galaxies see some degree of dip in surface brightness, the dip is of slightly greater magnitude and begins at a slightly larger radius in the higher redshift stack. A side-by-side comparison of the stacked images for the i-band is shown in Figure 76.

Additionally, $\sim 5,000$ galaxies were selected from a catalog of nearby (mean redshift ~ 0.17) quiescent galaxies and stacked. To account for the larger appearance of the lower redshift galaxies, the cutout size was doubled (2x2 arcmin). The i-band surface brightness profile and stacked image

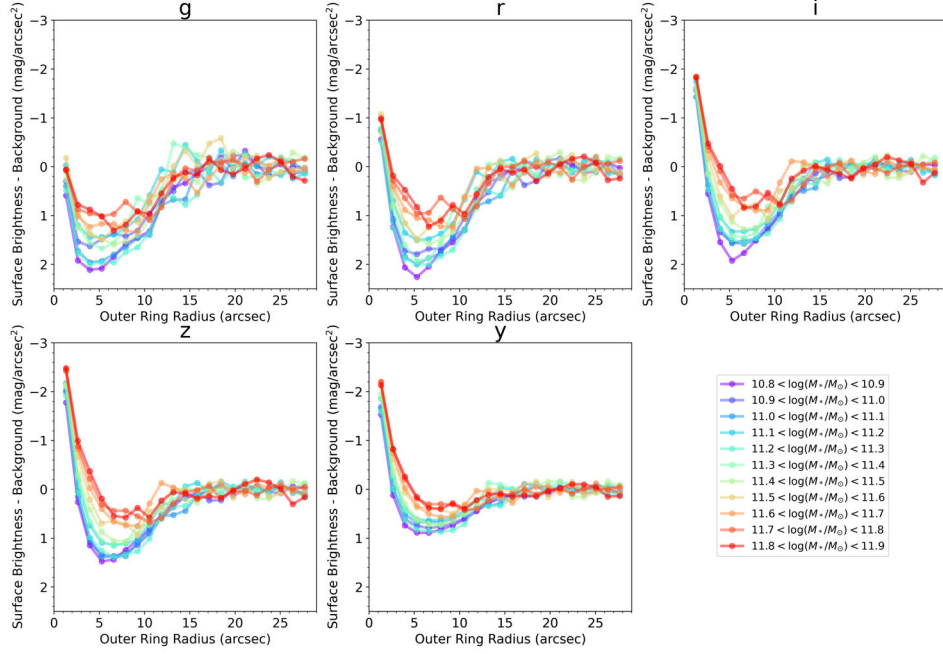


Figure 74. Background subtracted surface brightness profiles for stacks of galaxies binned according to stellar mass ($N=800$). Each color represents a different mass bin, with red representing the most massive galaxies in the catalog and purple representing the least massive galaxies in the catalog.

are shown in Figure 77. There is no evidence of a dark signal surrounding the central galaxy in any of the low-redshift stacks.

5.5.4.3 By Magnitude

Finally, the target galaxies were divided according to i-band magnitude into eleven 0.2-mag wide bins from 21 to 23.2 mag and stacked. Figures 78 and 79 show the sub-stacked images and surface brightness profiles. From both figures there is a clear relationship between target source magnitude and the existence and intensity of the dark ring feature surrounding the target galaxy. In the brighter stacks, the surface brightness profiles have a much less significant dip, and the central galaxy appears

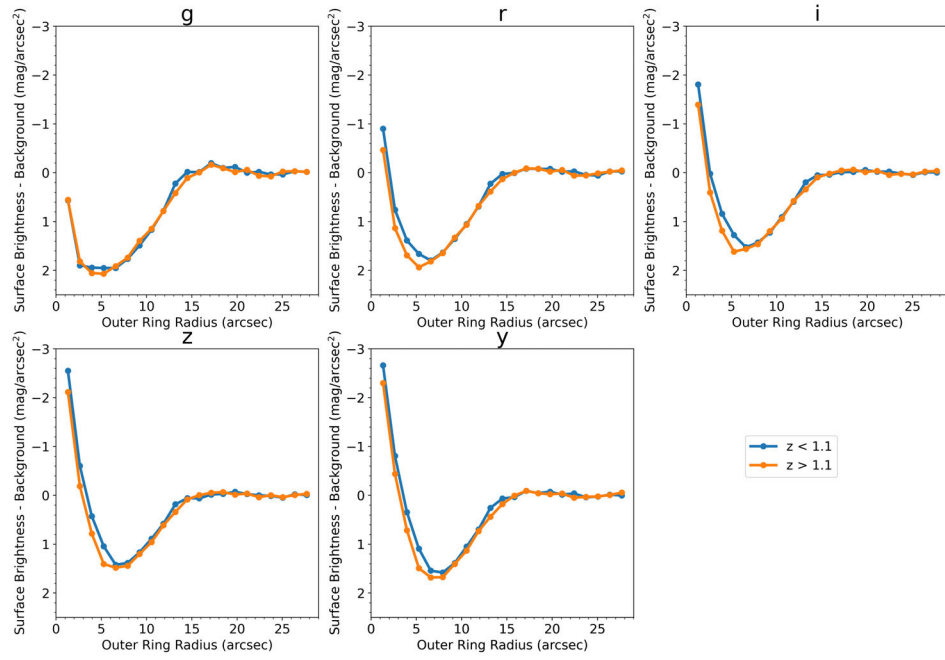


Figure 75. Background-subtracted surface brightness profiles for stacks of 7,000 galaxies at $z < 1.1$ (blue line) and $z > 1.1$ (orange line).

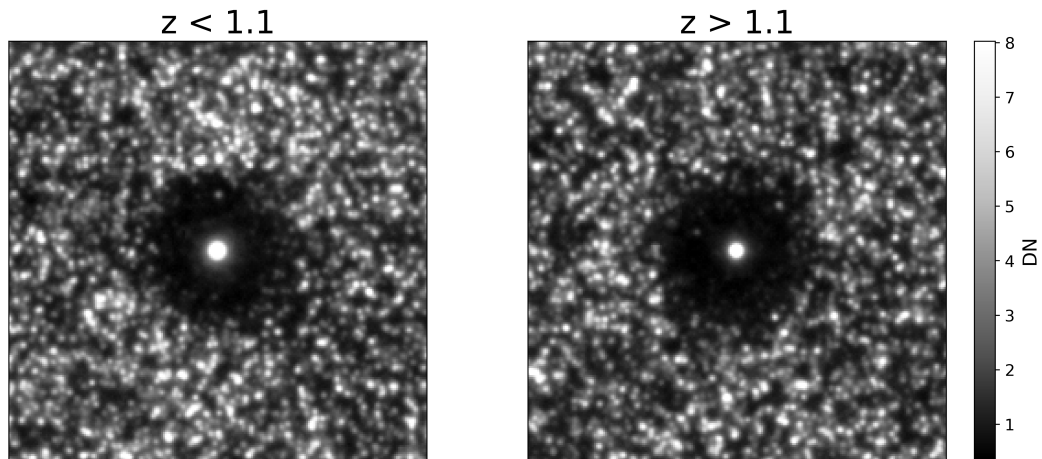


Figure 76. i-band stacked images of 7,000 galaxies at $z < 1.1$ (left) and $z > 1.1$ (right). Images are shown in raw pixel units (DN).

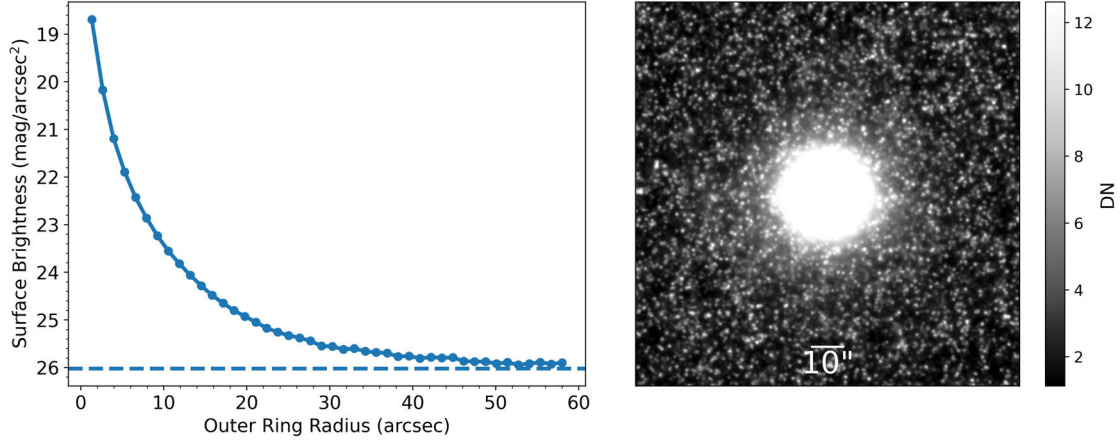


Figure 77. i-band stacked image and surface brightness profile for 5,263 low redshift galaxies. Image is shown in raw pixel units (DN).

much larger and brighter. This trend is seen in all DES bands and is also seen in stacks of other DES/WISE sources.

5.5.5 The Influence of Neighbors

The magnitude-binned stacks in Figure 79 show that as the target galaxy magnitude decreases, the dark ring surrounding it is filled in with neighboring sources. This suggests that the dark region around the target galaxy is not, in fact, due to a physical characteristic of the galaxies themselves but rather a consequence of their location. In other words, the fainter galaxies are surrounded by a dark ring because there are no other sources within that region to fill the area with light.

To examine the location and magnitude distribution of nearby sources for the catalog galaxies, a two-dimensional histogram H was generated for each band by binning all of the neighboring sources detected by `SourceExtractor` in all of the individual galaxy images according to their magnitude m and radial distance r from the center of the cutout. To account for the larger area associated with the larger radius bins, each histogram value was normalized by the center of its radius bin such that

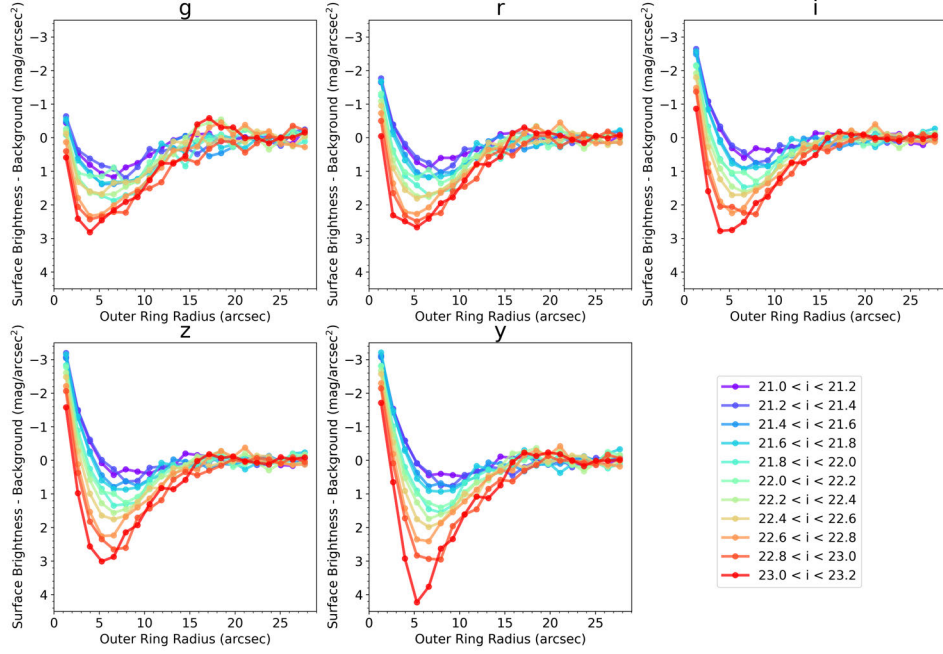


Figure 78. Background-subtracted surface brightness profiles of subsets ($N=1000$) of target galaxies binned by i -band magnitude. Each color represents a different magnitude bin, with red representing the faintest galaxies and purple representing the brightest galaxies.

$$H_{\text{r norm.}}[r, m] = \frac{H[r, m]}{r} \quad (5.7)$$

The histogram values were also subsequently normalized by the average number of sources in their respective magnitude bins such that

$$H_{\text{r, m norm.}}[r, m] = \frac{H_{\text{r norm.}}[r, m]}{\frac{1}{N} \sum_{i=1}^N H_{\text{r norm.}}[r_i, m]} \quad (5.8)$$

The normalized histograms are shown in Figure 80, alongside the radial profiles for the masked and unmasked galaxy stacks. As expected, no neighboring sources of any magnitude are detected within $\sim 2''$ of the target galaxy. Neighboring sources within this range would likely overlap with the target galaxies and make them difficult to detect or deblend. As the radial distance increases,

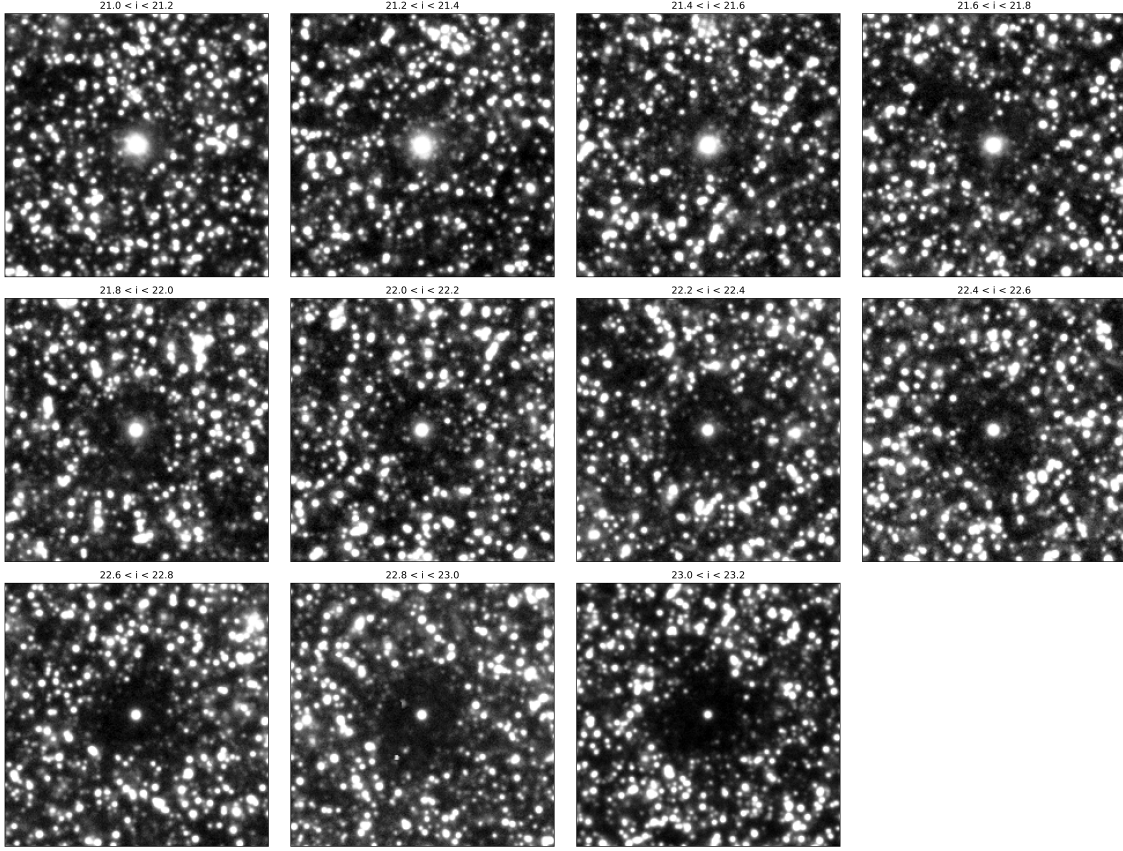


Figure 79. Stacked i-band images of 1,000 target galaxies binned by i-band magnitude. Target galaxy magnitude increases (gets fainter) going from the top left image to bottom right image.

more, gradually brighter sources are found. However, there is a distinct dearth of bright neighbors inwards of $\sim 13''$ from the target galaxy, which correlates with the width of the dip feature seen in the unmasked galaxy profiles.

The dark shadow seen surrounding the galaxy in the unmasked stacked images is most likely a result of this lack of neighboring sources. This is an unintentional selection effects introduced during the catalog generation process. The galaxy catalog was compiled from the DES/AllWISE crossmatch source catalog, thus, the catalog contains only galaxies that were detected by both DES and AllWISE. Because these galaxies are relatively faint, any nearby bright sources would likely overpower any signal from the galaxies, rendering them undetectable with WISE.

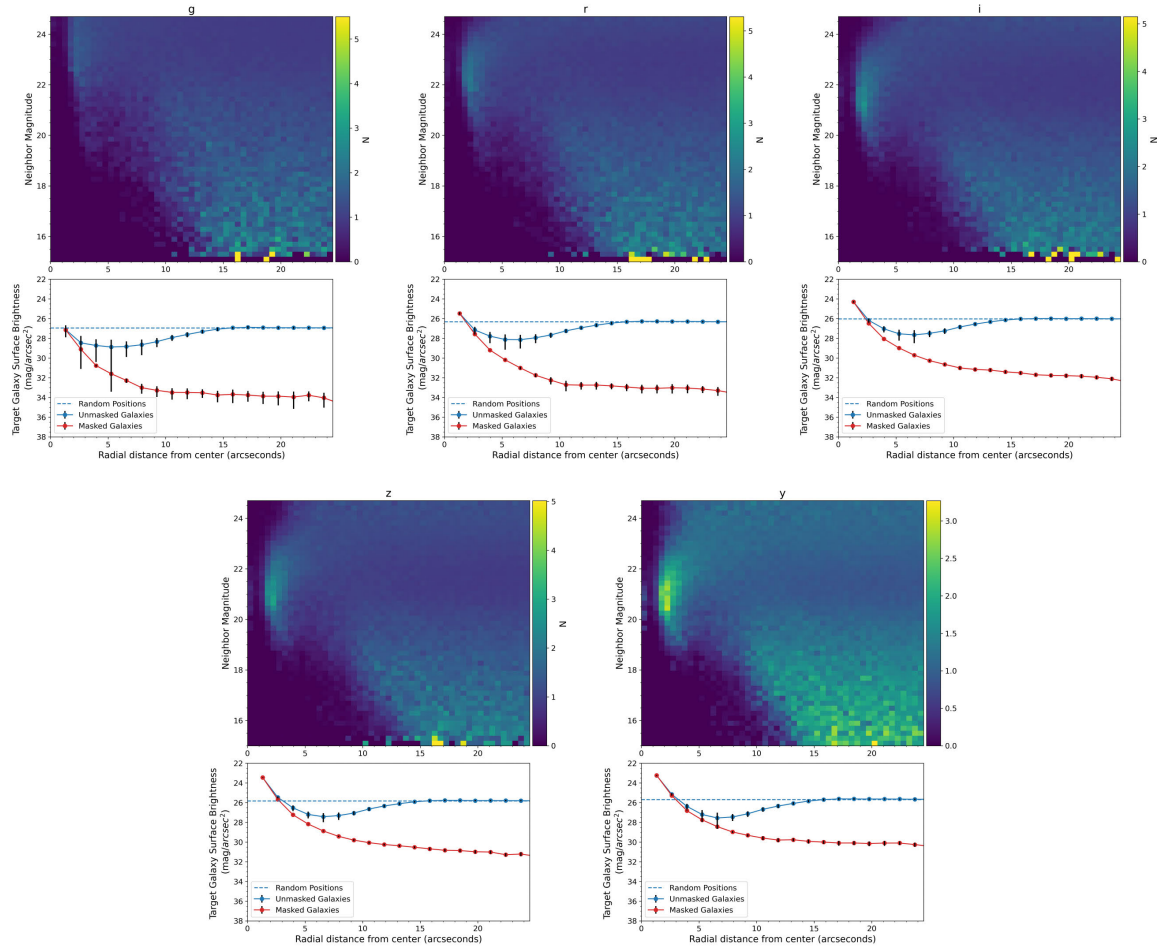


Figure 80. Magnitude and distance distribution of neighboring sources detected in the galaxy image cutouts plotted alongside the unmasked (blue) and masked (red) galaxy surface brightness profiles. Histogram counts have been normalized by radius and average source count per magnitude bin. The lack of neighboring sources within $\sim 12''$ is due to an unintentional selection effect.

5.6 Extragalactic Background Light

All of the light emitted outside of our Milky Way galaxy is collectively known as the extragalactic background light (EBL). In the optical and near-infrared regime, this cosmic optical background (COB) and cosmic infrared background (CIB) light is primarily made up of light from star formation within galaxies and thus is an important metric in constraining models of the formation and evolution of stars and galaxies (Cooray 2016). Historically, measurements of the COB and CIB have been challenging due to the presence of bright foregrounds from within our solar system (zodiacal light), our galaxy (scattered starlight), and for ground-based observations, Earth’s atmosphere. Careful estimation and subtraction of these local foregrounds is required to recover the EBL signal (Hauser and Dwek 2001).

Previous measurements have utilized data from space-based instruments, such as the Wide Field and Planetary Camera on the Hubble Space Telescope (WFPC2) (Bernstein 2007), Pioneer 10/11 (Matsuoka et al. 2011), the Cosmic Infrared Background Experiment (CIBER) (Matsuura et al. 2017), and most recently, the Long Range Reconnaissance Imager (LORRI) on the New Horizons spacecraft (Zemcov et al. 2017; Lauer et al. 2021; Symons et al. 2023). Observations of the dark cloud Lynds 1642 with the ground-based European Southern Observatory’s Very Large Telescope (VLT) have also been used to estimate the EBL (Mattila, Lehtinen, et al. 2017; Mattila, Väisänen, et al. 2017).

The calculated surface brightness profiles can be used to determine the extragalactic background light in each of the DES bands. At sufficiently large distances from the central galaxy ($r \gtrsim 17''$), the galaxy profiles flatten out to a smooth background level that approximately matches the brightness level measured from stacks of random positions. In the unmasked stacks, the average brightness at large radii is comprised of light from sources and the overall background. In the masked stacks, from which all neighboring sources have been removed, the signal at large radii contains just the background. While this can be done using masked and unmasked stacks of any set of target sources, it is preferable to use stacks of random positions as the average brightness can be calculated over the entire image.

To calculate the EBL in each of the DES bands, the average brightness level for each stack of

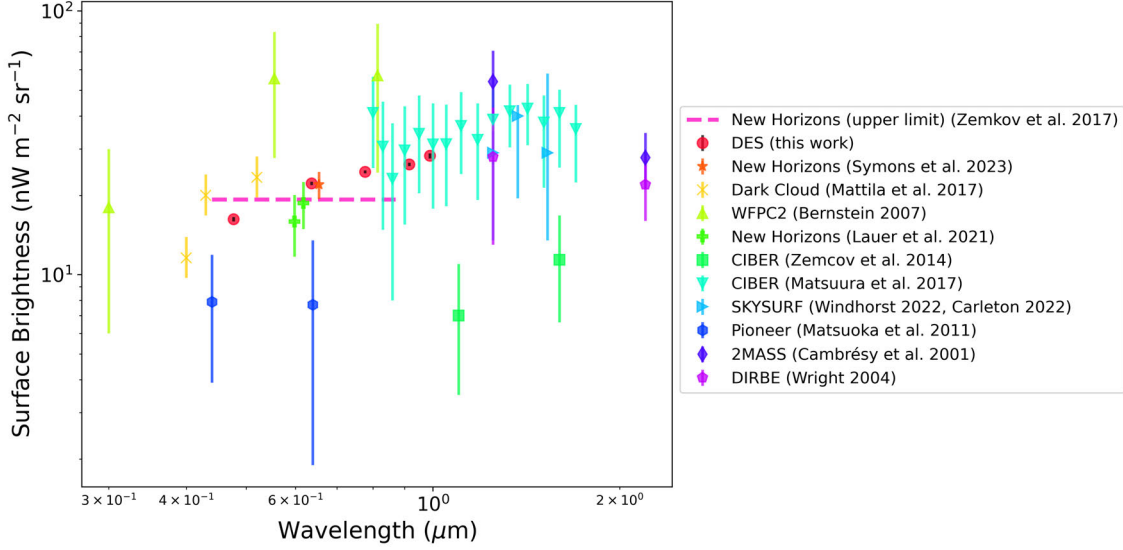


Figure 81. Measurements of the extragalactic background light from this work (red circles) and previously reported studies. Error bars for DES measurements are smaller than plot markers due to the large number of images stacked together.

Table 13. Extragalactic background light measurements and associated error as calculated from stacks of random positions. All values are in $\text{nW m}^{-2} \text{sr}^{-1}$

Band	EBL ($\text{nW m}^{-2} \text{sr}^{-1}$)	Error ($\text{nW m}^{-2} \text{sr}^{-1}$)
g	16.24	0.30
r	22.20	0.36
i	24.57	0.33
z	26.23	0.38
Y	28.26	0.62

random positions is calculated by computing the radial profile as described in Section 5.4.1 and calculating the average brightness over all the annuli. The extragalactic background light is then calculated by subtracting the average brightness level of the masked stack from the average brightness level of the unmasked stack. The error at each point is calculated as the quadrature sum of the standard deviation of the radial surface brightness values of the masked and unmasked stacks. The calculated EBL values are plotted in Figure 81 alongside previously reported values obtained through various other methods.

Historically, accurate measurements of the EBL at these wavelengths have been hampered by the presence of bright foregrounds from within our own galaxy and from Earth’s atmosphere (for ground-based observations). Because the EBL is calculated by taking the difference in brightness of masked and unmasked stacks that are generated from the same set of individual images, these foregrounds as well as any introduced by the telescope itself are cancelled out. The EBL values calculated in this work are in close agreement with previously reported values, notably those most recently obtained from the numerous New Horizons analyses carried out with data taken at the far reaches of our solar system (Zemcov et al. 2017; Lauer et al. 2021; Symons et al. 2023).

Chapter 6

CONCLUSIONS

While this dissertation is approaching its end, the work described herein continues.

On the galaxy stacking front, after a great deal of time spent on what we *weren't* seeing, efforts are now turning towards understanding what we *are* seeing. Analysis is still ongoing to extract information about our galaxy catalog from the surface brightness profiles. Preliminary fits of A_V magnitude as a function of radius suggest that these galaxies are indeed quite dusty. Further work, including model fitting, will hopefully lead to more definitive conclusions that will better inform the millimeter stacking analysis efforts.

Atop Cerro Toco and in all of the Simons Observatory labs across the world, an incredible amount of progress has been made over the last five years despite many challenges. In late summer 2023, both the Large Aperture Telescope Receiver and the first of the Small Aperture Telescopes (SAT-MF1) were installed on their respective platforms at the Simons Observatory site. As of October 2023, SAT-MF1 has seen first light and SAT-MF2 has begun on-site highbay integration, with SAT-UHF not far behind. The LATR is preparing for its first cooldown in the receiver cabin in anticipation of mirror installation in early 2024. With the first test scans happening eminently, members of the data processing working groups will be able to put their pipelines to the test with real data.

The initial phase of operations for SO, set to wrap up in 2028, is just the beginning. Additional contributions announced in the past year are set to greatly enhance the capabilities of SO and keep the project online through the next decade. Funding from Japan will enable the construction of an additional low-frequency Small Aperture Telescope while funding from the United Kingdom will add two additional SATs with microwave kinetic-inductance detectors (mKID) in place of transition-edge sensors. Substantial support from the NSF for “Advanced SO” will see the LATR fully populated with 60,000+ detectors across 13 optics tubes, doubling the mapping speed, and enable the construction of solar arrays atop Cerro Toco to reduce the carbon footprint of the observatory.

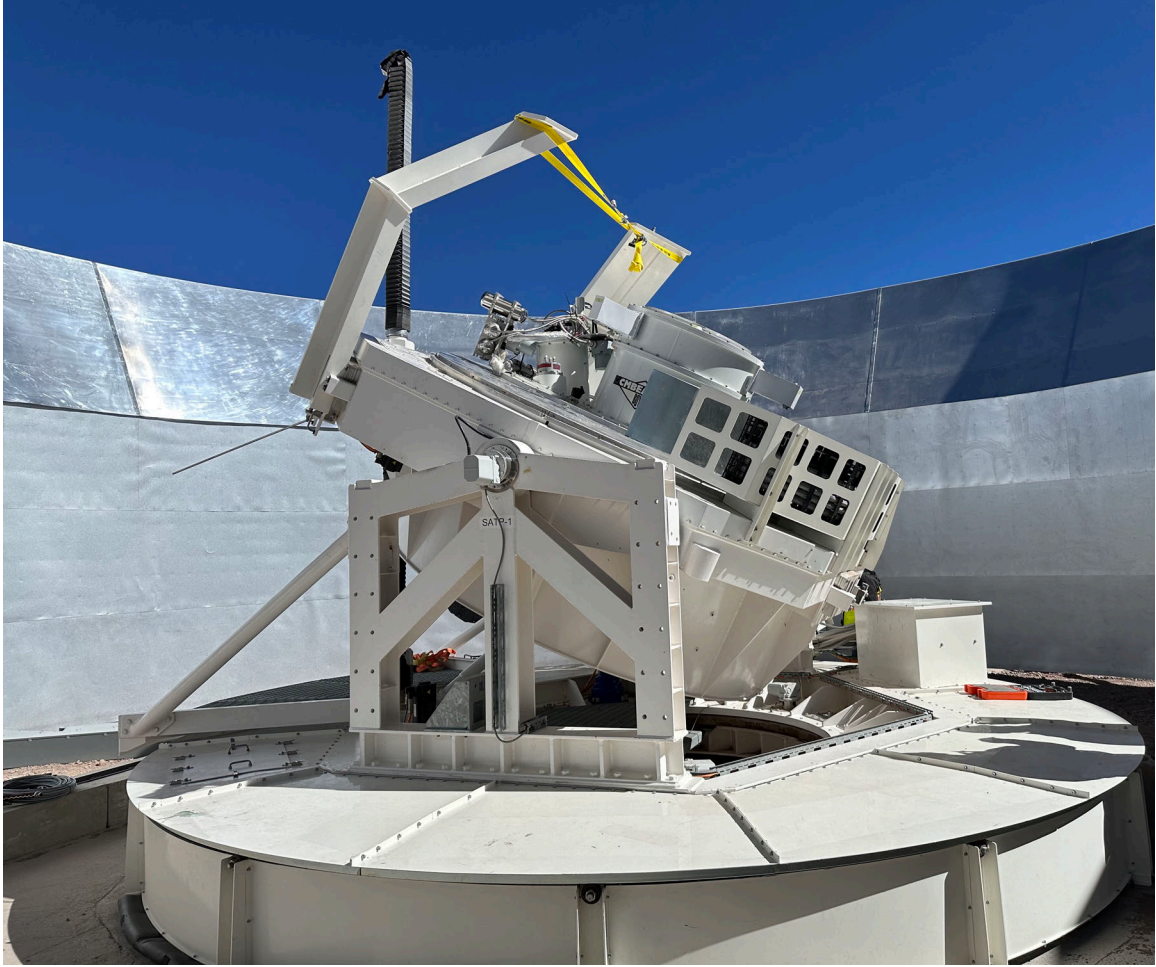


Figure 82. SAT-MF1 installed on the platform in October 2023. Image credit: Katie Harrington.

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APPENDIX A

PREVIOUSLY PUBLISHED WORK

A.1 Development and Performance of Universal Readout Harnesses for the Simons Observatory

The content of Chapter 3 was previously published in 2022 as part of the Proceedings of the SPIE, Volume 12190, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy XI (article ID 1219025). The content of the chapter is identical to that of the original publication. Minor formatting changes were made to comply with the ASU dissertation formatting guide. Co-authors have granted permission for the inclusion of this publication in this dissertation. The full citation, author list, and abstract are reproduced below.

J. Moore et al. (Aug. 31, 2022). “Development and Performance of Universal Readout Harnesses for the Simons Observatory”. In: *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy XI*. Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy XI. SPIE, p. 140

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A.1.1 Abstract

The Simons Observatory (SO) is a ground-based cosmic microwave background (CMB) survey experiment that consists of three 0.5 m small-aperture telescopes and one 6 m large-aperture telescope, sited at an elevation of 5200 m in the Atacama Desert in Chile. SO will utilize more than 60,000 transition edge sensors (TES) to observe CMB temperature and polarization in six frequency bands from 27-280 GHz. Common to both the small and large aperture telescope receivers (LATR) is the 300K-4K Universal Readout Harness (URH), which supports up to 600 DC bias lines and 24 radio frequency (RF) channels consisting of input and output coaxial cables, input attenuators and custom high dynamic range 40K low-noise amplifiers (LNAs) on the output readout coaxial cable. Each RF channel can read out up to 1000 TES detectors. In this paper, we will present the design and characterization of the six URHs constructed for the initial phase of SO deployment.