

Toward Reionization: Experimental Techniques for Space-based Observation of the Cosmic Infrared Background

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The light shines in the darkness, and the darkness has not overcome it.

–John 1:5

ABSTRACT

The extragalactic Cosmic Infrared Background (CIB) represents a window into the study of the Epoch of Reionization, an era in the early history of the universe at the end of the Cosmic Dark Ages during which the first stars and galaxies formed. In particular, CIB anisotropy measurements of angular fluctuations as opposed to direct intensity measurements promise to mitigate local foregrounds and reveal insights into the process and timeline of Reionization. Reionization is expected to leave an imprint at characteristic $\theta \gtrsim 1'$ angular scales on the sky within the near-infrared CIB which has not yet been detected. However, several independent experiments including CIBER and Spitzer have detected a statistically significant angular power excess at these scales, with an amplitude suggesting Reionization is not the sole contributor. While the most popular explanation at present is that this excess is produced by stars tidally stripped from their parent galaxies at relatively low redshift (intrahalo light), the exact source of the excess and its properties remain hidden. New experiments developed to study the near-infrared CIB from space where airglow contamination becomes minimal, most prominently SPHEREx, have the potential to reveal the source of this mystery and to identify the contribution from Reionization itself.

This dissertation discusses various experimental and observational techniques related to the study of the CIB and a future measurement of its Reionization component as applied to the SPHEREx all-sky survey and the CIBER-2 sounding rocket experiment. In Chapter 2 (originally published separately), I present novel noise-reduction techniques targeted at improving specifically the large-angular-scale sensitivity of the SPHEREx detectors to optimize study of the CIB at large arcminute-to-degree scales and reduce the impact of $1/f$ noise. In Chapter 3 I discuss the CIBER-2 sounding rocket experiment, a purpose-built instrument for studying the CIB, with a particular focus on upgrades and characterization for the 2nd and 3rd flights; a new design of the cryogenic focal plane array used to support the long-wavelength H2RG detector and a description of its assembly is presented. We apply large-scale noise reduction techniques pioneered on SPHEREx to significantly improve CIBER-2 sensitivity to CIB fluctuations, and developed new applications of these methods for reducing excess $1/f$ or crosstalk noise post-flight. In Chapter 4, I discuss analysis techniques for simulating and removing systematic error produced by depth variations on galaxy surveys applied to the emerging field of CIB redshift tomography.

Finally, in Chapter 5, I present preliminary spectra of the far-infrared-correlated Diffuse Galactic Light, a relevant local foreground for extragalactic CIB observations, at near-infrared wavelengths using recent SPHEREx observations, which hint at variation across widely separated regions of the sky.

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Chapter 1

INTRODUCTION

1.1 The Λ -CDM Model and the Expansion of the Universe

Over a century ago, our current understanding of cosmology was initiated by the description of gravity encompassed by the theory of General Relativity (Einstein, 1916) and, in the decade that followed, the subsequent observational discovery of the expansion of the universe across large scales (Lemaitre, 1927, Hubble, 1929). The latter discovery was followed by the hypothesis that the initial state of the universe consisted of a small "primeval atom" (Lemaitre, 1931) which expanded to eventually form the universe we observe today in what we now broadly refer to as the "Big Bang". Theory, observation, and the experiments that make observation possible have worked hand-in-hand to greatly develop our understanding of the history of the universe in the decades that have followed.

Our present understanding of the evolution of the universe at the largest scales is broadly described by the Λ -CDM model, otherwise known as the Standard Model of Cosmology. Beginning with the theory of General Relativity described by Einstein's Field Equations, we can relate the distribution of energy to spacetime geometry using the Einstein tensor $G_{\mu\nu}$ as:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} - \Lambda g_{\mu\nu}, \quad (1.1)$$

where $R_{\mu\nu}$ is the Ricci tensor, R is the corresponding Ricci scalar, $T_{\mu\nu}$ is the stress-energy tensor, Λ is the cosmological constant representing vacuum energy, and $g_{\mu\nu}$ is the metric tensor encoding the geometry of spacetime. For flat spacetime (i.e. the simple case of Special Relativity), the metric tensor can be written as:

$$g_{\mu\nu} = \begin{pmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1.2)$$

Equivalently, using the notation $ds^2 = g_{\mu\nu}dx^\mu dx^\nu$, the same flat metric is given by:

$$ds^2 = -c^2 dt^2 + dx^2 + dy^2 + dz^2 \quad (1.3)$$

While special relativity is convenient for describing localized regions of empty space, spacetime in our universe as a whole is, of course, more complicated. Under the assumption that our expanding universe is homogeneous and isotropic at the largest scales, we can instead write the metric tensor in r, θ, ϕ spherical coordinates as (Barnes, 2022):

$$ds^2 = dt^2 - a^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right). \quad (1.4)$$

Here, k is a constant defining spatial curvature and $a = a(t) = \frac{R(t)}{R(t_0)}$ is a dimensionless scale factor for time-dependent scale factor $R(t)$. The present time t_0 is defined such that $a(t_0) = 1$, with $a(t < t_0) < 1$ for an expanding universe. Equation 1.4 is the Friedmann–Lemaître–Robertson–Walker metric (Friedman, 1922, Lemaître, 1927, Robertson, 1929, Walker, 1935) forming the foundation of the Λ -CDM model. Solving the field equations (Equation 1.1) with this metric and defining the cosmological fluid pressure p and density ρ respectively, we obtain the Friedmann Equations (Friedman, 1922):

$$\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = \frac{8\pi G\rho}{3} \quad (1.5)$$

$$2\frac{\ddot{a}}{a} = -8\pi Gp - \frac{\dot{a}^2}{a^2} - \frac{k}{a^2} = -8\pi G\left(p + \frac{\rho}{3}\right) \quad (1.6)$$

The composition of the universe, then, determines its expansion rate. Note that the cosmological redshift parameter z can be related to a simply as:

$$a = \frac{1}{z + 1}, \quad (1.7)$$

where $z = 0$ corresponds to the present time. Cosmological redshift is typically used as a proxy for distance in both space and time, but it of course also reduces the energy of photons with emitted energy ϵ to observed energy ϵ' traveling across redshift z as:

$$z + 1 = \frac{\epsilon}{\epsilon'} \quad (1.8)$$

We can now define a critical density ρ_c corresponding to a flat ($k = 0$) universe and the corresponding density parameter Ω as:

$$\rho_c = \frac{3}{8\pi G} \frac{\dot{a}^2}{a^2}, \quad (1.9)$$

$$\Omega = \frac{\rho}{\rho_c}. \quad (1.10)$$

We can then write the overall density at present time Ω_0 as the sum of the constituent sources of energy in the universe:

$$\Omega_0 = \sum \Omega_i = \Omega_b + \Omega_{CDM} + \Omega_r + \Omega_\Lambda, \quad (1.11)$$

where Ω_b , Ω_r correspond to directly observable non-relativistic baryonic mass and radiation respectively, Ω_{CDM} to indirectly observable cold dark matter, and Ω_Λ to dark energy. The Friedmann Equations then imply the following relationships:

$$\Omega_b, \Omega_{CDM} \propto a^{-3}, \quad (1.12)$$

$$\Omega_r \propto a^{-4}. \quad (1.13)$$

The radiation term therefore trends to zero as the universe expands and a increases; it is extremely low at present time ($\Omega_r \sim 10^{-4}$). Gravitationally, the dark matter term acts as ordinary matter and the two density parameter terms are often presented combined. The standard Λ -CDM model assumes constant dark energy per unit volume, resulting in Ω_Λ increasing over time (although recent measurements from the Dark Energy Spectroscopic Instrument (DESI) hint at the possibility of variation from this assumption, albeit with low statistical significance; Adame et al., 2025). Measurements of the cosmic microwave background (CMB) with the Planck spacecraft are consistent with the universe being flat (i.e. $\Omega_0 = 1$, $k = 0$) or extremely close to flat, with $(\Omega_K)_{\text{Planck}} = 1 - \Omega_0 = 0.001 \pm 0.002$ and $(\Omega_m)_{\text{Planck}} = \Omega_b + \Omega_{CDM} = 0.315 \pm 0.007$ (Aghanim et al., 2020).

The present universe is then overwhelmingly dominated by dark energy and matter, with baryonic directly-observable "ordinary" matter making up only a small fraction of this total. At time of writing, the precise physical nature of dark matter and dark

energy beyond their large-scale effects remains unknown despite their combined sum making up the vast majority of the energy within the universe today.

1.2 The Epoch of Reionization

Recombination and the Cosmic Dark Ages

As we travel back in time to the early history of the universe, Λ -CDM implies that Ω_Λ trends to zero while Ω_r eventually dominates, corresponding to a much higher universal background temperature. Beginning in this radiation-dominated, much younger universe a relatively short time after the Big Bang and going forward in time, we reach a threshold where $\Omega_r = \Omega_m$. Planck measurements indicate that this equality occurred at a redshift $z \approx 3400$ (Aghanim et al., 2020). As the universe continued to expand and Ω_m subsequently became dominant, the background temperature became low enough that protons and electrons were able to enter bound states and form neutral atoms. The universe thus transitioned from its opaque state in the radiation-dominated epoch to a state transparent to photons at $z \approx 1100$; the subsequent decoupling of photons, no longer able to interact with ordinary matter via Thompson scattering, gave rise to what we currently observe as the cosmic microwave background.

With photons now unable to reach the energy threshold to ionize neutral atoms, photons and ordinary matter fell out of thermal equilibrium with each other, giving rise to a long period of the early universe known as the Cosmic Dark Ages. This era is so called because, other than decoupled CMB photons, essentially no photons were produced; a notable exception are $\lambda = 21$ cm photons emitted by the neutral hydrogen spin-flip transition, which presents essentially the only way to directly observe the Dark Ages (Mondal and Barkana, 2023).

Reionization

As hundreds of millions of years passed, matter within this dark, transparent universe began to coalesce via gravity into massive objects – the first stars and galaxies. These objects at "cosmic dawn" produced their own radiation that began to ionize the neutral medium and began a new phase transition of the universe referred to as the Epoch of Reionization (EOR). Reionization led directly to the local universe we observe today, where the overwhelming majority of ordinary matter is ionized (Figure 1.1).

While the exact history of reionization is not currently well understood, there exist many pathways to accessing this part of cosmic history. A useful phenomena for

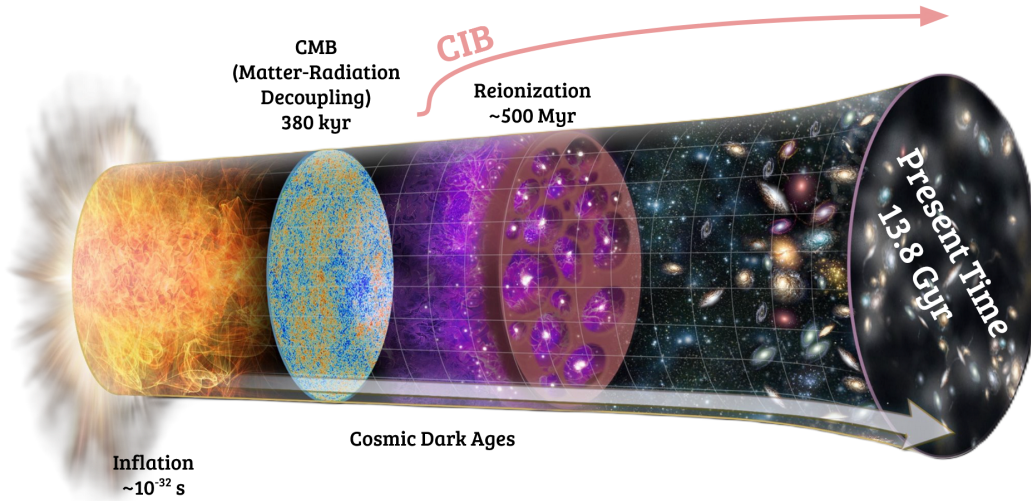


Figure 1.1: The history of the universe as described by the Λ -CDM Model. The Cosmic Infrared Background contains light reaching back to Cosmic Dawn and the Epoch of Reionization, with ultraviolet light from the first stars being redshifted down to near-infrared wavelengths at present time. Original unannotated image: SPHEREx collaboration

probing the later period of reionization is the Gunn-Peterson trough (Gunn and Peterson, 1965, Scheuer, 1965), a spectral feature consisting of a sharp cutoff corresponding to a redshifted Lyman- α absorption energy in high- z EOR objects. As neutral hydrogen strongly absorbs Lyman- α photons, such a trough indicates that the source possessing it occupied a universe with at least some neutral hydrogen in the intergalactic medium. Gunn-Peterson troughs were first detected in quasar spectra (Becker et al., 2001) with the Sloan Digital Sky Survey (SDSS). Similar spectral features have since been detected in the afterglow spectra of gamma ray bursts (Totani et al., 2006, Chornock et al., 2013) and recently in high- z galaxies themselves with the James Webb Space Telescope (JWST; Umeda et al., 2026). Quasar G-P trough measurements generally indicate that reionization was complete (i.e. no significant neutral regions remained in the universe) by $z \approx 5 - 6$ (Bouwens et al., 2015, Bosman et al., 2022).

Observations of the CMB can also place constraints on the timeline of reionization. CMB photons generally did not interact with ordinary matter during the Dark Ages due to the subsequent matter-radiation decoupling resulting from Recombination; however, in our present ionized universe, free electrons provide a small opportunity for interaction with CMB photons via Thomson scattering. As such, the CMB has a nonzero optical depth τ between the surface of last scattering and a present

time observer, reducing the fraction of CMB photons coming directly from the recombination decoupling event by a factor of $e^{-\tau}$. This optical depth leaves a detectable imprint on the polarization of the CMB (Figure 1.2), particularly at large $\theta \gtrsim 5^\circ$ angular scales (Zaldarriaga, 1997). Planck measurements of the Thomson scattering optical depth of the CMB suggest approximately half of the universe was reionized at redshift of $z \approx 7.7$, a value consist with the independent quasar G-P constraints on the end of reionization (Aghanim et al., 2020).

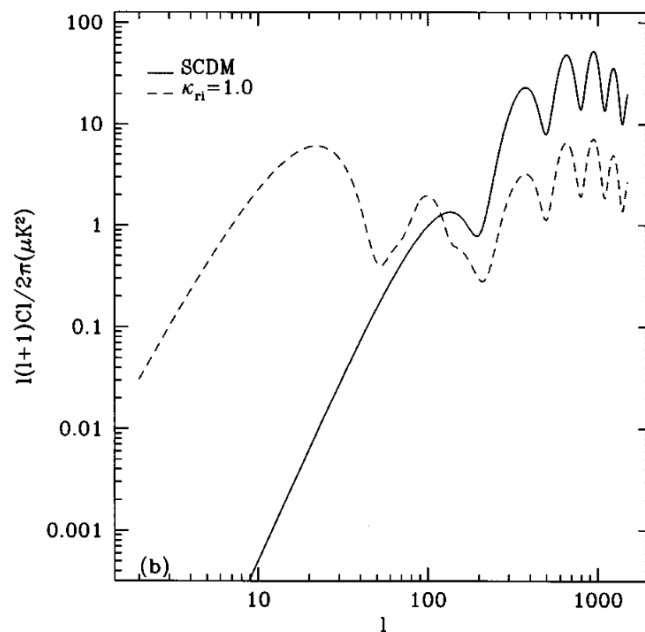


Figure 1.2: Subset of Figure 1 from Zaldarriaga, 1997: theoretical imprint of Thomson scattering optical depth on the CMB polarization power spectrum for a high $\tau = 1$ model. The ionized universe produces a detectable peak at very large $\theta \gtrsim 5^\circ$ scales (see Appendix A) in the polarization power spectrum. Planck measurements indicate an optical depth $\tau \ll 1$, with implications for the timeline of reionization.

CMB measurements also serve as a useful tool for measuring the overall duration of reionization. Since reionization was driven by compact sources, it would have proceeded in a variable "patchy" manner with ionized bubbles growing to eventually encompass the entire intergalactic medium. The kinetic Sunyaev-Zel'dovich (kSZ) effect, where CMB photons are scattered off of electrons with bulk motion relative to the overall expansion of the universe, further modulates the microwave background we view at present time, and this patchy reionization is predicted to leave imprints on the large-scale CMB power spectrum (Sunyaev and Zeldovich, 1980, McQuinn

et al., 2005). Observations of this effect have yielded measurement constraints on the 5%-95% reionization window of $\Delta z < 5.1$ (Chen et al., 2023) and on the 25%-75% window of $\Delta z < 4.5$ (Raghunathan et al., 2024).

The populations of objects that drove reionization are also of interest. Since its launch in late 2021, JWST has enabled unprecedented direct detection of extremely high redshift objects, with the current record at time of writing being an early EOR galaxy at $z = 14.44$ (Naidu et al., 2025). Candidates for Population-III stars – massive, short lived, early stars made up exclusively of hydrogen and helium that would have formed at the very beginning of Cosmic Dawn – have also been recently reported from JWST observations (Visbal et al., 2025). Direct-collapse black holes (DCBHs), hypothetical objects that would have formed at the end of the Dark Ages directly from accreting gas, would also contribute to reionization; although evidence for DCBHs has been reported (e.g. Natarajan et al., 2024), their existence has not yet been definitively confirmed.

Inherently, JWST direct detections of EOR objects will be biased towards the brightest such objects. An independent avenue for studying the EOR and obtaining insights into the formation of the first galaxies, one which makes use of statistical measurements over large angular scales similar to the previously mentioned CMB techniques, is to study the Cosmic Infrared Background.

1.3 Probing the EOR with the Cosmic Infrared Background

Broadly speaking, the entire extragalactic background light (EBL) constitutes all of the electromagnetic radiation in the universe excluding astronomical objects we can directly resolve (Figure 1.3). Different portions of its spectrum (e.g. the CMB) as we observe it today can originate from vastly different sources. In the near-infrared (NIR) section of the EBL, the Cosmic Infrared Background (CIB) is expected to contain an ancient imprint of light from the first stars and galaxies that drove reionization (Santos et al., 2002, Salvaterra and Ferrara, 2003, Cooray and Yoshida, 2004), with UV emission in the rest frame of an EOR object at $z > 6$ redshifted down into the NIR. Intensity mapping – measuring the entire combined unresolved sky brightness in a particular band over a relatively large region – offers to access this imprint.

Beyond simply contributing a constant average background intensity, the first EOR sources are also predicted to leave spectrally distinct signals at particular angular scales: these primordial galaxies, forming in rare high matter density regions within

dark matter halos at high redshift, should be detectable at large $\theta \gtrsim 10'$ scales (Kashlinsky et al., 2004, Cooray et al., 2004, Sun et al., 2021). Measurements across $\lambda \approx 1 - 5 \mu\text{m}$ have the potential to isolate the EOR signal from contributions from unresolved galaxies via such anisotropy measurements (Cooray et al., 2004). Additionally, cross-correlations between NIR intensity maps and the Cosmic X-ray Background have been suggested to contain a CIB component from reionization-era, and potentially direct-collapse, black holes (Cappelluti et al., 2013, Yue et al., 2013).

Local Foregrounds

We now turn to the practicalities of measuring the CIB. Simply measuring the extragalactic component of the NIR sky as a direct intensity (i.e. the monopole) is challenging due to abundant foregrounds within this band, and direct intensity measurements of the CIB require extremely precise estimates of said foregrounds. Beginning at Earth and moving outward, we immediately encounter the first and brightest NIR foreground: atmospheric airglow, at least two orders of magnitude brighter than the next largest contributor to the diffuse NIR sky (Leinert et al., 1998). The most effective way to manage airglow contamination is to simply go above it – airglow essentially on its own makes space-based instruments a necessity for precise study of the CIB. While sounding rocket and even orbital instruments are not necessarily completely free of airglow emission (e.g. Feder et al., 2025a, Hui et al., 2026a, Hui et al., 2026b), observation from space allows us to face the next foreground: the Zodiacal Light (ZL).

The Zodiacal Light consists of sunlight scattered by dust within our own solar system; it is orders of magnitude brighter than extragalactic and high-latitude galactic contributions, and is even visible to the naked eye in low light pollution. While it is technically possible to send instruments beyond the ZL via interstellar spacecraft (e.g. New Horizons; Zemcov et al., 2017), the enormous time and resource cost of doing so means that any realistic CIB instrument will need to account for this foreground. Thankfully, measuring diffuse backgrounds behind the bright curtain of the ZL is a solvable problem – the ZL is known to be essentially spatially smooth at the angular scales relevant to EOR CIB signals in the near-infrared (Arendt et al., 2016). As such, anisotropy (spatial fluctuation) measurements essentially bypass it. The ZL remains, however, an unavoidable source of small-scale photon (Poisson) noise; with ideally mitigated airglow and instrument read noise, the ZL sets the Poisson noise level for a CIB experiment.

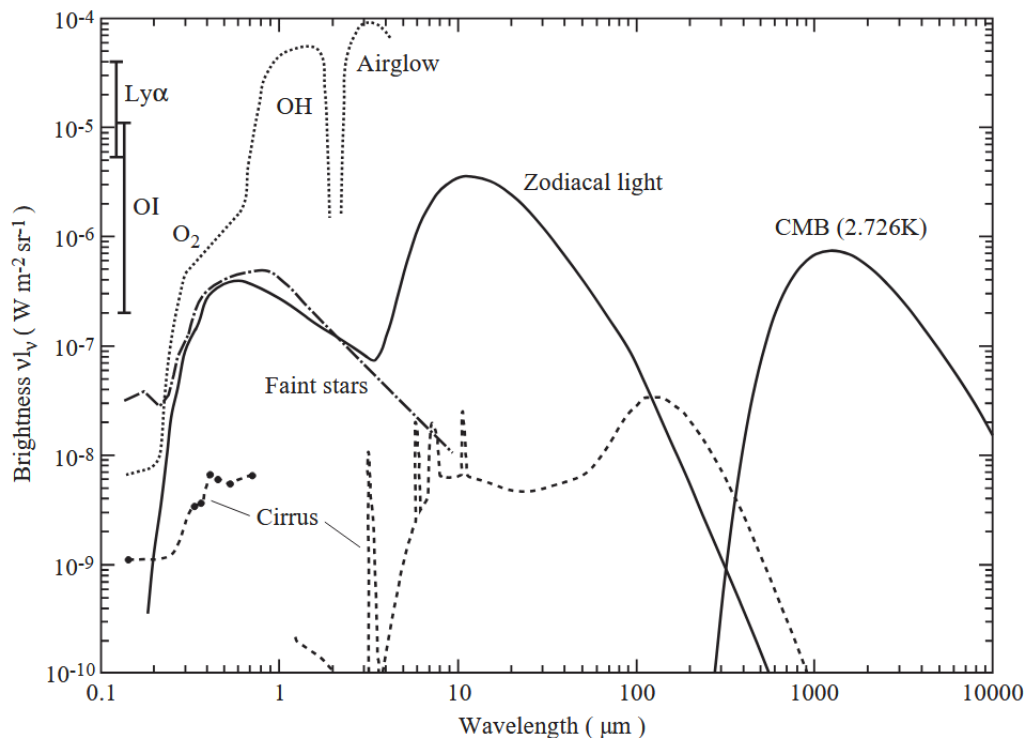


Figure 1.3: Figure 1 from Leinert et al., 1998: brightest components of the diffuse sky at various wavelengths. At near-infrared wavelengths, airglow generally dominates for ground-based measurements.

Light from interstellar dust, known as the Diffuse Galactic Light (DGL), provides the next barrier to observing extragalactic contributions to the NIR background. DGL traces dust scattering and thermal emission from heated dust grains, with energy for both mechanisms provided by the interstellar radiation field. It is extremely bright near the galactic plane but greatly decreases at high galactic latitudes. At NIR wavelengths and within optically-thin dust regions, DGL is often modeled via scaling far-infrared thermal-dominated $\lambda = 100 \mu\text{m}$ maps from the IRAS spacecraft (Zemcov et al., 2014, Arai et al., 2015; see Chapter 5 for new measurements of this correlation).

Individual stars within our galaxy also contribute to the measured background, referred to as Integrated Stellar Light (ISL). Fortunately for detecting the CIB, at the angular scales relevant to CIB anisotropy measurements, ISL essentially contributes only small-scale Poisson noise and is not as significant a contaminant.

Instrument noise is, of course, another concern. Pixel read noise contributes small-scale noise, translating to low angular scales when mapped to a detector field of view

and therefore lower relevance to CIB anisotropy (particularly when considering the low read noise of modern CMOS-based detectors). However, structure produced by noise at large spatial scales on a detector – often caused by the low-frequency components of $1/f$ noise – can frustrate attempts to extract faint extragalactic components via anisotropy measurements if not properly mitigated. Significant portions of this thesis address methods for reducing such large-scale noise on instruments targeting the CIB.

Once we have accounted for all local (i.e. contained within the Milky Way galaxy) foregrounds, instrument noise, and assorted systematics (e.g. imperfect resolved source masking), what remains is the extragalactic CIB itself.

Extragalactic Foregrounds

The expected EOR contribution is not the only constituent component of the extragalactic CIB. Extragalactic but generally low redshift contributions are combined into what is referred to as the Integrated Galactic Light (IGL). IGL contains primarily faint unresolved low- z galaxies and peaks at $z \approx 1.5 - 2$ (Zemcov et al., 2014); as these galaxies would be less biased compared to the first galaxies formed during the EOR, IGL contributes less signal at large angular scales relative to its Poisson level. It should be noted that the absolute spatial power at these scales is still larger for IGL than for predicted EOR contributions.

An important additional extragalactic component of the CIB, treated separately from IGL, is Intrahalo Light (IHL), a proposed contribution from low- z tidally stripped stars far from their parent galaxies. IHL is treated in the following section.

1.4 Past CIB Anisotropy Measurements and Excess CIB Fluctuations

The first attempt to measure NIR CIB anisotropy used the Diffuse Infrared Background Experiment (DIRBE) at a large beam size of 0.7° (Kashlinsky et al., 1996a, Kashlinsky et al., 1996b), while subsequent smaller arcminute-scale measurements used Two-Micron All Sky Survey (2MASS) fields (Kashlinsky et al., 2002). It was not until the Spitzer Space Telescope and its Infrared Array Camera (IRAC) became operational that the first CIB spatial fluctuations in excess of expected "local" IGL were detected (Kashlinsky et al., 2005, Kashlinsky et al., 2007, Kashlinsky et al., 2012). The Spitzer $\lambda = 3.6, 4.5 \mu\text{m}$ results and the detected excess power were at the time attributed to EOR, Population-III sources associated with the first stars and galaxies. Observations from the AKARI space telescope at $\lambda = 2.4, 3.2, 4.1 \mu\text{m}$ also found excess fluctuations at large scales which were again interpreted as arising

from EOR origins (Matsumoto et al., 2011).

Other measurements and analyses have challenged the interpretation that the large excess fluctuation power originate predominantly from the EOR. Madau and Silk, 2005 argued that attributing the observed Spitzer CIB excess to entirely EOR sources would imply an unrealistically large ionizing photon budget in the early universe; Helgason et al., 2016 comes to a similar conclusion, arguing that an EOR-only origin for the excess is unrealistic. An analysis at lower $\lambda = 1.1, 1.65 \mu\text{m}$ wavelengths with the Hubble Space Telescope (HST) Ultra Deep Field did not detect any excess fluctuations at all and attributed the CIB in these bands to be due to low redshift galaxies (Thompson et al., 2007), although due to the low field of view of the Ultra Deep Field this measurement was unable to probe scales beyond $\theta \approx 100''$. Additional measurements using Spitzer data confirmed the previously detected large-scale excess above known galaxy populations, but instead interpreted the majority of the signal as originating from IHL (Cooray et al., 2007, Cooray et al., 2012). The Cosmic Infrared Background Experiment (CIBER), a sounding rocket platform, detected the excess at $\lambda = 1.1, 1.6 \mu\text{m}$ and also attributed it to IHL (Zemcov et al., 2014). That work also reported the excess in cross-correlations between CIBER and the previously examined Spitzer data, indicating that whatever the cause of the excess is, it is shared across a range of NIR wavelengths.

Intrahalo Light

IHL is defined as light coming from stars at low ($z \lesssim 3$) redshift which have been tidally stripped from their parent galaxies, residing far out in their respective dark matter halos. Various models of IHL could explain the observed CIB excess, but the phenomenon's exact properties are not currently well understood. Cooray et al., 2012 find that IHL need make up only $< 0.2\%$ of the overall luminosity in faint galaxies to explain the observed excess. A later analysis of HST data from $\lambda = 0.6 - 1.6 \mu\text{m}$ detected the excess, again finding IHL models fit the observations and arguing that excess fluctuations at $\lambda = 0.6 \mu\text{m}$ rule out EOR sources as the sole cause of the NIR excess (Mitchell-Wynne et al., 2015). The ongoing SPHEREx all-sky survey will be able to distinguish between different models of IHL as the mechanism responsible for the observed CIB excess (Cheng and Bock, 2022), and as such new insights are expected over the next several years.

The Cosmic Infrared Background Experiment

As the instruments described in the rest of this thesis are essentially direct successors to CIBER, it is appropriate to treat that experiment in more detail here. Over the course of four flights (with the 4th flight launching the experiment to a much higher altitude than previous flights, simultaneously providing the highest quality data of the campaign and also intentionally sending the telescope into the Atlantic Ocean), CIBER obtained intensity maps of selected fields for the primary purpose of studying NIR CIB fluctuations. For intensity mapping, it utilized H1RG 1024×1024 pixel detectors with a field of view of $2^\circ \times 2^\circ$ at $\lambda = 1.1, 1.6 \mu\text{m}$ and a relatively wide $\Delta\lambda/\lambda \approx 0.5$ (Bock et al., 2013). Beyond the initial detection of the CIB excess in its auto- and cross-spectra (with Spitzer) in Zemcov et al., 2014, a recent analysis of re-processed data from the 4th flight again reported the excess, finding it exceeds fluctuations produced by IGL and known foregrounds by an order of magnitude (Feder et al., 2025a; Figure 1.4). CIBER data has also been used to carry out a stacking analysis with the SDSS photometric galaxy catalog, suggesting that non-linear one-halo effects may be necessary for properly modeling IHL contributions (Cheng et al., 2021). A redshift tomography analysis (c.f. Cheng and Chang, 2022) cross-correlating CIBER maps with external galaxy surveys is also currently in preparation (Feder et al., 2026; see Chapter 4).

The CIB Excess – A Brief Discussion

Regardless of its precise cause and composition, the observed CIB excess has been widely reported across different independent experiments over the past two decades. In addition to those already mentioned, it has been reported in subsequent analyses of new and re-processed observations from AKARI (Seo et al., 2015), Spitzer (Kashlinsky et al., 2025), and HST (Matsumoto and Tsumura, 2019). Kim et al., 2019 also detected the excess at very large scales using the Infrared Telescope in Space (IRTS) NIRS instrument. While it is not impossible that the excess corresponds to some as of yet unknown source of systematic error, its existence is well documented by numerous independent experiments and an astrophysical explanation appears likely.

It should be noted that at time of writing, the exact source of the observed CIB excess above known galaxy populations remains, strictly speaking, a mystery. While intrahalo light is currently a popular explanation, it is not the only proposed mechanism; it is also not unlikely that the excess represents a combination of sources even if it is dominated by one in particular, as the expected EOR component should

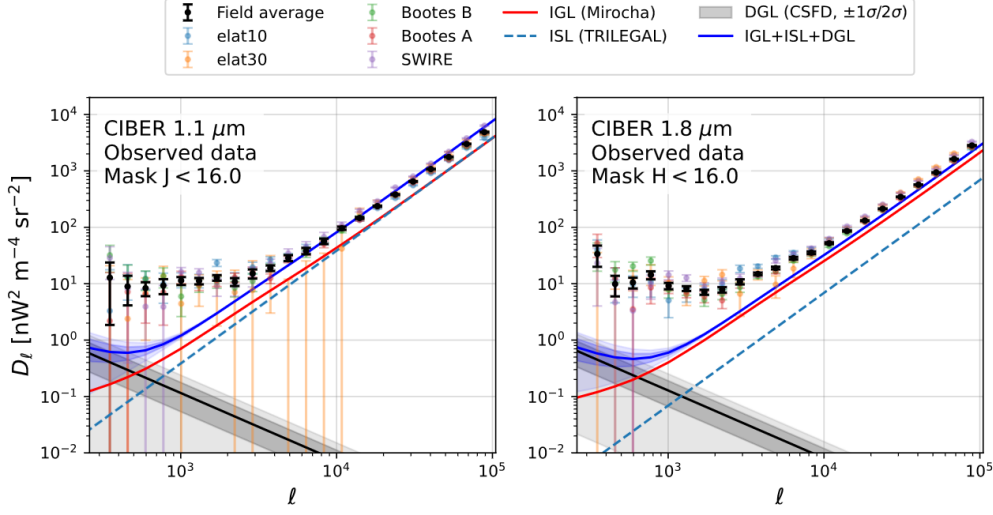


Figure 1.4: Figure 9 from Feder et al., 2025a: a recent measurement of excess large-scale CIB fluctuations using intensity map autospectra from the 4th flight of CIBER in two NIR bands. Note that the multipole ℓ is related to θ as $\ell \approx \frac{\pi}{\theta}$ (see Appendix A). The mean CIB fluctuation power at large $\ell < 2000$ scales is significantly above the power predicted by the combined sum of low- z Integrated Galactic Light (IGL) and local Integrated Stellar Light (ISL) / Diffuse Galactic Light (DGL).

be contained within a subset of it (even if EOR contributions cannot explain the entire excess). This observed excess, and to what extent IHL or the echos of the first galaxies contribute to it, represents an outstanding mystery in the field of near-infrared cosmology. With the advent of the SPHEREx space telescope launched just over a year prior to time of writing, our understanding of the Cosmic Infrared Background, the excess, and by extension the Epoch of Reionization are all likely to greatly improve in the near future.

1.5 Thesis Organization

This dissertation will discuss work on two space-based near-infrared experiments to study the Cosmic Infrared Background: the Cosmic Infrared Background Experiment 2 (CIBER-2) and the Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx). The former, CIBER-2, is a direct successor project to the original CIBER. CIBER-2 is launched on a suborbital trajectory via sounding rocket, with three flights conducted. Optimized specifically to study the CIB and through it the EOR, CIBER-2 covers a wider range of wavelengths than its predecessor including a band extending into optical wavelengths at $\lambda \approx 0.6 \mu\text{m}$ with newer H2RG detectors and a targeted $5\times$ increase in surface bright-

ness sensitivity. SPHEREx, a NASA Medium-class Explorer mission launched in 2025 after the three CIBER-2 flights had concluded, is an orbital all-sky survey with study of the CIB as one of its three primary science objectives; SPHEREx has already at time of writing completed an entire map of the sky from $\lambda = 0.75 - 5.0$ μm and will enable unprecedented insights into the CIB and its currently mysterious components.

Chapter 2 discusses development of the SPHEREx H2RG detector readout electronics, in particular focusing on simulation and new techniques for reduction of large-scale $1/f$ electronics noise which can contaminate CIB anisotropy measurements at large angular scales.

Chapter 3 discusses instrumentation work for enabling the 2nd and 3rd flights of CIBER-2, with a particular focus on a mechanical re-design of a cryogenic H2RG focal plane array, H2RG detector characterization, and new techniques for reducing $1/f$ and anomalous crosstalk noise to optimize CIBER-2 CIB anisotropy sensitivity.

Chapter 4 discusses methods for modeling and removing variable depth systematics associated with galaxy redshift surveys for the purposes of redshift tomography via cross-correlations with intensity maps (in this case, applied to CIBER maps).

Finally, Chapter 5 discusses a preliminary new measurement of the near-infrared spectrum of the Diffuse Galactic Light using spectral mosaics from SPHEREx cross-correlated with re-processed far-infrared IRAS maps, including a preliminary detection of variation in the correlated DGL across the sky.

This dissertation ends with several reference appendices. Appendix A details the C_ℓ, ℓ spatial power spectrum convention common in CMB/CIB anisotropy measurements and used throughout this work. Appendix B contains as-manufactured machine drawings for the re-designed CIBER-2 long-wavelength detector cryogenic focal plane array detailed in Chapter 3, flown on the experiment's 2nd and 3rd flights. Appendix C contains as-manufactured board layouts for the focal plane readout board used in the same focal plane array design.



Figure 1.5: A 60s stacked exposure taken by the author in the Eureka Valley of far eastern California in December 2025, six months before this thesis was completed. Zodiacal Light (left, pointing towards the sun hidden below the horizon) and the Milky Way galaxy containing both Integrated Stellar Light (unresolved stars) and the Diffuse Galactic Light, all important foregrounds discussed in this dissertation, are clearly visible to the naked eye in such dark skies.

Chapter 2

NOISE REDUCTION FOR LARGE-SCALE INTENSITY MAPPING WITH SPHEREX

Heaton, Grigory, Walter Cook, James Bock, Jill Burnham, Sam Condon, Viktor Hristov, Howard Hui, Branislav Kecman, Phillip Korngut, Hiromasa Miyasaka, et al. (2023). “Noise Reduction Methods for Large-scale Intensity-mapping Measurements with Infrared Detector Arrays”. In: *The Astrophysical Journal Supplement Series* 268.2, p. 44. URL: <https://doi.org/10.3847/1538-4365/acebc1>.

2.1 Abstract

Intensity mapping observations measure galaxy clustering fluctuations from spectral-spatial maps, requiring stable noise properties on large angular scales. We have developed specialized readouts and analysis methods for achieving large-scale noise stability with Teledyne 2048×2048 H2RG infrared detector arrays. We designed and fabricated a room-temperature low-noise ASIC Video8 amplifier to sample each of the 32 detector outputs continuously in sample-up-the-ramp mode with interleaved measurements of a stable reference voltage that remove current offsets and $1/f$ noise from the amplifier. The amplifier addresses rows in an order different from their physical arrangement on the array, modulating temporal $1/f$ noise in the H2RG to high spatial frequencies. Finally, we remove constant signal offsets in each of the 32 channels using reference pixels. These methods will be employed in the upcoming SPHEREx orbital mission that will carry out intensity mapping observations in near-infrared spectral maps in deep fields located near the ecliptic poles. We also developed a noise model for the H2RG and Video8 to optimize the choice of parameters. Our analysis indicates that these methods hold residual $1/f$ noise near the level of SPHEREx photon noise on angular scales smaller than ~ 30 arcminutes.

2.2 Introduction

The history of galaxy formation can be studied using intensity mapping measurements of the near-infrared extragalactic background light. Galaxy clustering produces large-scale structure on the order of tens of arcminutes (Cooray et al. (2004), Kashlinsky et al. (2004)). The sources that comprise the background can be accessed using fluctuation measurements rather than galaxy-by-galaxy photometry (e.g. Zemcov et al., 2014). Such intensity-mapping measurements promise to trace

total light production, including diffuse and faint sources of emission, over the history of galaxy formation back to the Epoch of Reionization (Kovetz et al., 2017). In order to optimize measurements of these large-scale background fluctuations, it is critical to minimize readout noise on tens of arcminute scales in astrophysical images.

The Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx) mission is an all-sky infrared (0.75-5.0 μm) survey satellite (Doré et al., 2014, Crill et al., 2020) selected under NASA’s Medium Explorer (MIDEX) program. Alongside other mission objectives, in deep maps, SPHEREx will study large-scale infrared extragalactic background structure. SPHEREx uses 6 Teledyne HAWAII-2RG (H2RG) HgCdTe sensors (Blank et al., 2012), each with a 2048 $\times$ 2048 array of pixels. Included in this count is a frame of reference pixels which are not sensitive to light, consisting of the outermost 4 pixels surrounding the sensor. These reference pixels are designed to emulate the electrical response of a typical optical pixel, allowing them to be used to correct for dark current and electrical noise in an image. The array is divided into 32 2048 $\times$ 64 pixel channels, each of which is read out simultaneously row by row. Noise from the readout electronics can manifest itself as spatial $1/f$ noise when the H2RG array is read.

In order to minimize spatial noise on angular scale $\theta \approx 30'$ in intensity mapping observations, we present several new methods for reducing the effects of electronics $1/f$ noise. “Row-chopping” reduces the effect of temporal $1/f$ noise by reading rows non-sequentially. Combined with multiple H2RG reference pixel samplings, we obtain significant noise reduction on the spatial scales of interest, optimizing large-scale background fluctuation measurements. We use a phantom pixel correction scheme based on measuring a stable reference voltage to remove dark current offsets produced by our custom ASIC amplifier. We validated these noise reduction methods first in a noise simulator and later in laboratory tests with a physical H2RG array.

In this paper, spatial noise power is expressed in terms of the spatial power spectrum $P(k)$, which represents the azimuthally-averaged spatial power as a function of angular wave number. For SPHEREx detectors, each array pixel corresponds to 6.2 arcseconds of sky angle, resulting in a wave number $k = 2\pi(6.2''/\theta)$ in pix^{-1} units for an angular period θ . This paper is structured as follows: In Section 2.3 we describe the SPHEREx readout electronics and Video8 amplifier, and outline various noise reduction techniques. In Section 2.4 we describe a full noise simulator to model the electronics noise, followed by optimization of noise reduction techniques

in Section 2.5. Section 2.6 compares the simulation outputs and modeled noise reduction with measured laboratory images. Finally, Section 2.7 summarizes our conclusions.

2.3 SPHEREx Readout Electronics

Readout Boards

The SPHEREx readout electronics consist of 6 identical readout boards (see Figure 2.1), a central electronics board (CEB), and a low voltage power supply. The boards are housed in a card cage and communicate with each other and the spacecraft via a backplane. Each readout board services a single H2RG array, providing bias, control signals, and readout via low-noise Video8 amplifiers (see Section 2.3) operated in 32-channel 100kHz mode. The channel blocks are 64 pixels wide (see Figure 2.3). The readout board logic and processor are embedded in an RTG4 FPGA, with a 3 Gbit SDRAM device providing on-board sample-up-the-ramp processing for all ~ 4 million H2RG pixels. The processor, aided by dedicated logic, compresses and formats the sample up the ramp data before sending it to the spacecraft via the CEB. Each readout board also has a housekeeping system to monitor various voltages and temperatures.

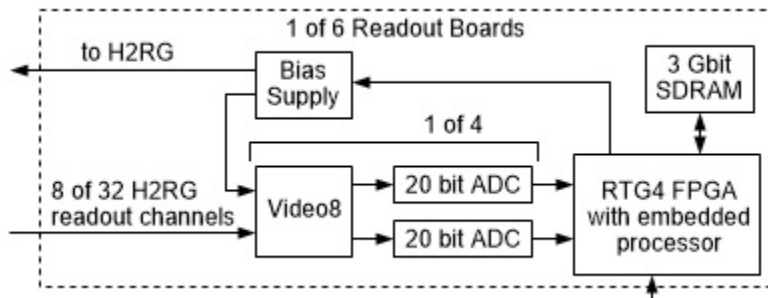


Figure 2.1: Overview of the SPHEREx readout electronics.

The CEB interfaces with the spacecraft, communicates with the 6 readout boards, monitors 25 Cernox temperature sensors mounted on the telescope, and controls the temperature of the focal plane arrays via precision readout of 8 Cernox sensors and 16 bit control of 8 heaters. An RTG4 FPGA with an embedded processor orchestrates the CEB activity, which includes the generation of low-speed (38.4 kbaud) housekeeping telemetry and the booting of all the embedded processors using code stored in MRAM.

The H2RG bias supply is designed for stability and is housed in an oven-controlled

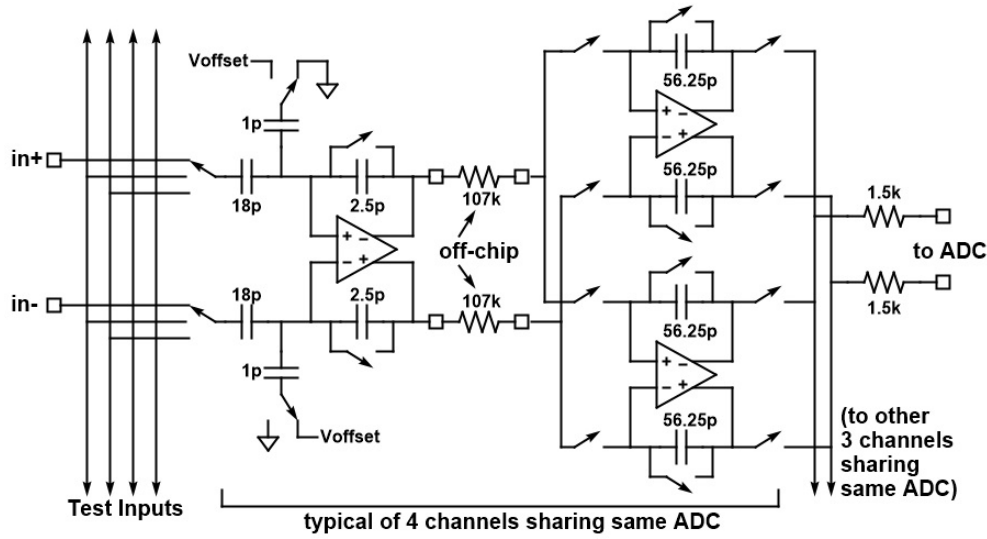


Figure 2.2: Internal schematic of a single Video8 preamplifier channel, one of eight on the chip. Differential input lines are capacitively coupled to a low-noise integrator, and the output is read with one of two sample and hold circuits. The Video8 input can be switched to a reference voltage intermittently to track amplifier drift.

region of the readout board to minimize thermal drifts. Each of the 32 H2RG channels sees a common bias voltage from this supply, resulting in any bias noise fluctuations or temperature offsets being repeated across all channels.

Video8 Amplifier

The Video8 amplifier is an Application-Specific Integrated Circuit (ASIC) designed at Caltech for SPHEREx. It interfaces preamplifiers and integrators between SPHEREx H2RG arrays and external RT2378-20 20 bit ADCs. The Video8 amplifiers are designed for stable operation over a wide temperature range from -50°C to $+50^{\circ}\text{C}$. For SPHEREx, the Video8 devices are located within the instrument electronics box and do not require special cooling. A cryo-harness connects the H2RG detectors, operating at 50-80K, to the Video8 inputs. In order to minimize spatially correlated noise, the Video8 was designed for low $1/f$ noise and low channel-to-channel crosstalk. Table 2.1 summarizes the performance characteristics of the Video8 architecture.

The Video8 incorporates 8 fully differential readout channels, each composed of a preamplifier and a pair of integrators (Figure 2.2). The 8 channels are grouped into

two banks of 4, with each bank being serviced by a single off-chip 20 bit ADC. The integrators box-car filter the signal for optimum noise performance, then perform a sample and hold. The two integrators associated with a given preamplifier operate in ping-pong fashion, with one performing an integration while the other holds a prior integration result for multiplexed output to one of the two off-chip ADCs. Multiplexing four channels to each ADC results in ADC operation at 400 kHz. The amplifiers and other internal circuitry of Video8 operate with a 5V supply voltage, while a separate 3.5V supply voltage determines the digital input signal voltage range.

Analog switches at the inputs to the preamplifiers provide flexibility for the input of reference and test levels. The inputs to the preamplifier are capacitively coupled and the feedback is purely capacitive, with a reset switch in parallel. Closing the reset switch nominally brings the preamplifier outputs to 2.5V. Additional capacitor/switch networks at the preamplifier inputs allow the preamplifier output levels to be adjusted, post-reset, in preparation for operation. The outputs of each preamplifier are connected through off-chip resistors to the inputs of a pair of integrators (see Figure 2.2). The feedback for the integrators is again purely capacitive with an associated reset switch in parallel. Switches at the integrator outputs multiplex the integrator signals for off-chip analog-to-digital conversion. The Video8 switches may be sequenced by external logic for optimal performance. Using off-chip resistors allows for some adjustment of the overall channel gain. With the use of low temperature coefficient (TC) resistors, the feedback capacitors (~ 20 ppm / $^{\circ}$ C) dominate the temperature susceptibility.

The Video8 devices are manufactured using the C5N 0.5 μ m CMOS process at Onsemi (ON Semiconductor), the same process used for manufacturing several ASICs designed at Caltech for prior space missions. Guard rings around groups of NMOS and PMOS FETs provide a “rad-hard by design” feature that boosts the latch-up threshold to >80 MeV/(mg-cm²), verified in test with heavy ions. The total dose tolerance has been verified up to 20 krad, well beyond the 7.5 krad SPHEREx lifetime requirement. The Video8 die size is 3.3x3.3 mm, and each device is packaged in a standard 84 pin ceramic quad flat pack. Caltech and the NASA Jet Propulsion Laboratory worked closely on the Video8 space qualification, following the process for prior Caltech-designed space ASICs.

Parameter	Value
Amplifier bandwidth	20 MHz
Read noise	1-2 e
Gain stability	20 ppm
Offset stability	3 $\mu\text{V}/\text{C}$
Integral non-linearity	<0.07%
Channel-to-channel cross-talk	<2e-4
Room temperature preamp output drift rate	<1 mV/s

Table 2.1: Video8 Performance Characteristics

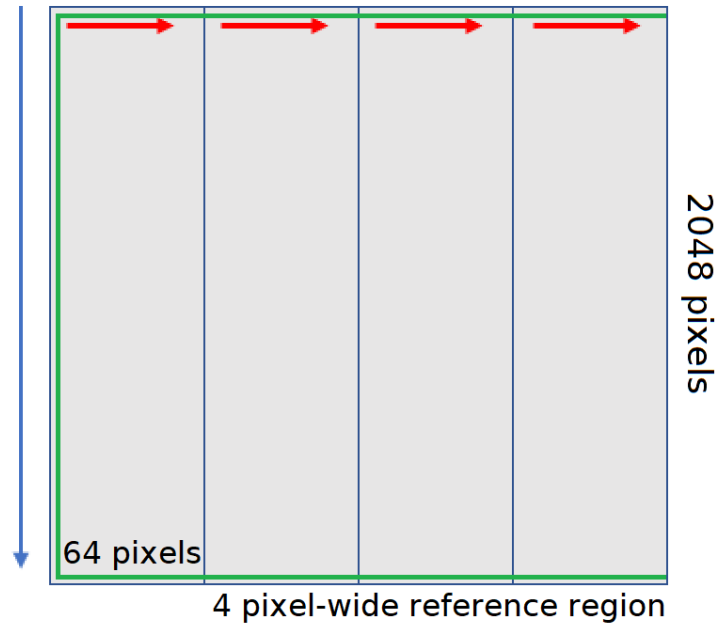


Figure 2.3: Illustration of the H2RG readout operated in 32-channel mode, truncated to 4 channels. Each channel is read simultaneously, row-by-row, progressing downward. The array has a surrounding border of reference pixels 4 pixels wide. We vary the sequence of row order for improved noise stability.

Row-chopping

Intensity mapping measurements of the extragalactic background require stable noise performance on tens of arcminute spatial scales where linear clustering peaks. However, noise stability is less important on small scales due to prominent Poissonian fluctuations from undetected galaxies. A new method for reading out channel rows, “row-chopping”, transfers correlated spatial noise from low to high spatial frequencies. Because noise at small spatial scales is largely subdominant to photon noise, row-chopping improves stability on large spatial scales.

Row-chopping reads out the rows of an image in a pre-defined non-sequential order. Rows can then be re-ordered after an exposure has been taken to recover the sky image. The result transfers $1/f$ noise power produced by the readout electronics to smaller spatial scales. The row-chopping algorithm we employ incorporates an integer skip parameter S which controls the scale of the noise reduction provided (Figure 2.4):

1. Read the first row in the image.
2. Skip over $S - 1$ rows without reading them. If this results in skipping over rows that are beyond the last physical row in the image, wrap around to the beginning of the image and continue counting, counting one additional time each time you wrap back to the first row.
3. Read the current row.
4. Repeat steps 1-3 with the same S until every physical row on the array has been read once.

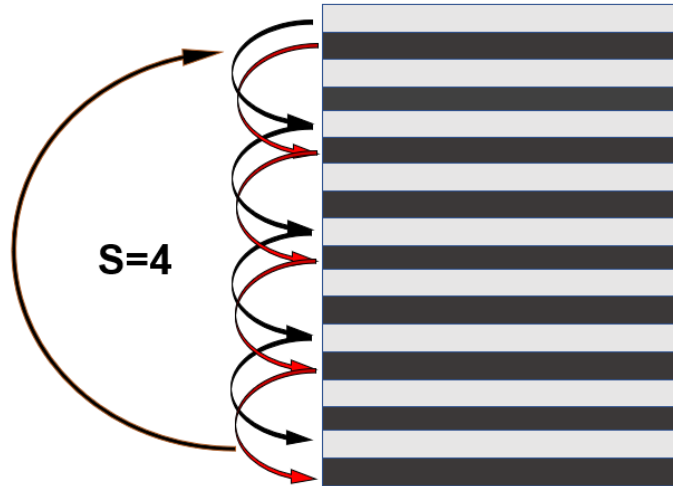


Figure 2.4: Illustration of row-chopping on an example grid for $S = 4$, with black arrows representing the first pass through the array and red arrows representing the second. A pre-defined number of rows (here, 4) are skipped over after reading each row, with a return to the first unread row every time the bottom of the array is reached.

The SPHEREx readout electronics execute row-chopping on each of the 32 channels simultaneously during readout. The parameter S controls the spatial scale to which noise is transferred, allowing for the selection of an S that minimizes noise power at low spatial frequencies (see Section 2.5). Row-chopping effectively reduces spatial $1/f$ noise along the vertical direction of the array, perpendicular to the rows. $1/f$ noise along each row, unaffected by row-chopping, is already small due to the short time required to read each row.

Reference Pixels

The largest remaining large-scale effect after row-chopping is an overall offset present within each channel due to common $1/f$ noise in the channel readout. We can use reference pixels to remove these per-channel offsets. Each H2RG array contains a 4 pixel-wide frame of the outermost pixels in the overall 2048×2048 grid which are not sensitive to light. These reference pixels are meant to reproduce the electrical behavior of an optical pixel without any photoresponse or photon noise. We use these pixels to correct for channel-level offsets from residual $1/f$ noise common to a channel readout.

These reference pixels are most easily read out in physical order, leaving 8 rows of reference pixels for each channel. There are an additional 4 columns of reference pixels on the right and left sides of the frame (only in channels 1 and 32). To optimize offset correction, the SPHEREx readout system can sample reference rows additional times per image, interspersing them evenly through an exposure (see Section 2.5). These additional reads are intended to increase the accuracy of the reference pixels through statistical averaging.

In some cases we also note a separate offset between even and odd columns within a channel (see Section 2.4). While this even/odd offset only enters at high spatial frequencies and is therefore not relevant to measurements at large spatial frequencies, it can be corrected by using even/odd reference pixels.

Phantom Pixel Correction

Each Video8 periodically samples a DC reference from the bias supply, injected into the data stream as a “phantom pixel”. The phantom pixel data are processed by the same sample-up-the-ramp algorithm as the H2RG pixels, correcting preamplifier $1/f$ noise, leakage current, and temperature drift. The Video8 leakage current is temperature-dependent and significant, typically a few electrons per second. Phantom pixel samples accurately remove these effects because only the low amplifier

noise is present when sampling the reference.

During readout, we collect c phantom measurements at the output of the Video8 with the input connected to a stable low-noise reference voltage. These phantom measurements are then averaged together into a single phantom pixel per row. Following this, we read the whole row of 64 pixels. We correct rows of the output image by subtracting the subsequent phantom pixel from each pixel in a row, resulting in 32×2048 corrections, as each H2RG channel has its own set of independent phantom pixels.

2.4 Noise Simulation

Simulation Inputs

In order to assess various correction parameters and to provide simulated noise images for the SPHEREx sky simulator package, we developed a Python simulation to generate unique noise images from predefined noise sources. We first characterize separately the noise power spectra produced by the various components of the readout electronics. Once power spectra are defined, we can generate an arbitrary quantity of simulated noise timestreams for a simulated image array. We generate an array of frames in this way for a simulated exposure and fit slopes for each pixel to produce a sample-up-the-ramp image.

We found that the SPHEREx readout noise timestream can be modeled by a noise power spectrum function p of the form:

$$p = \alpha + \beta/f + \gamma/f^{1.3}. \quad (2.1)$$

The factors α and β correspond to the white and $1/f$ noise coefficients of the system, respectively. Here, γ is only used to model a component of excess noise in the readout integrated circuit (ROIC) amplifier, with the additional power of 1.3 being found to best match the measured noise data.

Generating Simulated Images

We determined the noise coefficients for each of the readout components by fitting α , β , and γ to a measured noise power spectrum (Table 2.2). Power spectra corresponding to the different noise components are shown in Figure 2.5. We measured the ROIC amplifier white noise by correlated double sampling due to this noise component overwhelming other sources of noise at high sampling rates. For the

Video8 and ROIC noise sources, we generate independent unique noise timestreams for each of the 32 H2RG channels.

Since the noise components of the bias supply act simultaneously across all channels, we generate a single bias timestream for the entire 32-channel image at the start of each simulation. We further split bias contributions into three components to model how they affect phantom pixel measurements (see Section 2.3). These consist of a “phantom uncorrelated” bias term which is only visible to the phantom pixel reads, a “phantom uncorrelated” bias term which is only visible to the array and not to the phantom pixels, and a “phantom correlated” bias term that is visible to both. These terms account for the fact that the phantom reference and the detector bias are partially correlated, with independent and common-mode noise. The magnitude of the independent components largely determines how effectively the phantom pixel correction method in Section 2.3 corrects for bias fluctuations in addition to its primary function of removing Video8 amplifier leakage current.

Noise Source	α e^2/Hz	β e^2	γ $\text{e}^2 * \text{Hz}^{0.3}$
Video8	3.71e-5	8.40e-3	0
ROIC amplifiers	1.97e-3	0	1e-1
Phantom correlated bias	0	8.80e-5	0
Phantom uncorrelated bias, visible to phantom pixels	0	3.64e-6	0
Phantom uncorrelated bias, invisible to phantom pixels	2.91e-6	3.07e-7	0

Table 2.2: Measured best-fit noise components for SPHEREx readout electronics. Coefficients are calculated assuming a one-sided power spectrum convention.

With noise coefficients for all sources defined, we produce unique timestream realizations. Let R represent a random number with a uniform distribution on $(0, 1)$ and let f_s be the sampling frequency of the system (100 kHz). Given an arbitrary $n \times 1$ two-sided power spectrum array $\vec{p}$, n odd, we produce a timestream realization $\vec{x}$ corresponding to $\vec{p}$ by applying random phases to the non-DC components of the two-sided power spectrum components and taking an inverse Fourier transform as follows:

$$\vec{A} = [p_0^{1/2}, p_1^{1/2}, \dots, p_n^{1/2}], \quad (2.2)$$

$$\vec{\phi} = [e^{2\pi i R_0}, e^{2\pi i R_1}, \dots, e^{2\pi i R_{\text{floor}(n/2)}}], \quad (2.3)$$

$$\vec{a} = \vec{A} \cdot [1, \vec{\phi}, \vec{\phi}^*], \text{ and} \quad (2.4)$$

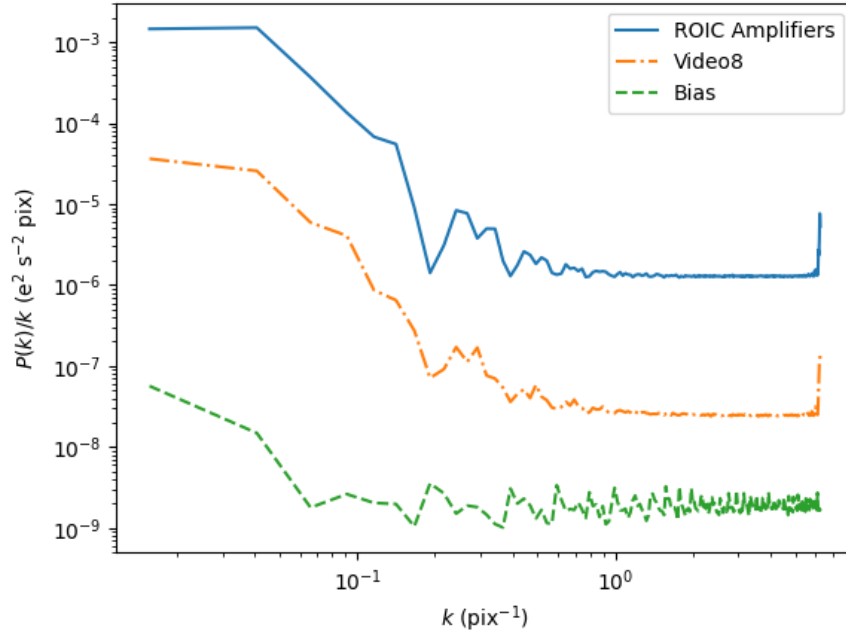


Figure 2.5: Simulated spatial power spectra realizations corresponding to each noise component power spectrum applied to a 2048×2048 image obtained in readout order, with no dark current. The ROIC amplifier noise dominates at all spatial frequencies. The prominent peak at high k for the Video8 and ROIC spectra is caused by alternating column noise, and is not relevant for large-scale measurements.

$$\vec{x} = \Re(\mathcal{F}^{-1}[\sqrt{n}f_s * \vec{a}]). \quad (2.5)$$

Since this calculation depends on $\text{floor}(n/2)$ random numbers, we can generate a large number of relevant timestreams given enough computation time. Once we generate a unique timestream for each channel and combine it with the bias timestream component, we can produce a unique frame corresponding to the noise power present on a perfectly dark exposure with no fixed dark current. For a sequence of N frames, we fit a slope to each pixel to produce a full noise image realization.

An additional source of H2RG noise is present in the form of an offset between the even- and odd-numbered columns of each channel, referred to by Rauscher, 2015 as alternating column noise (ACN). ACN effectively results in two common offsets for each channel. ACN primarily produces spatial noise at scales significantly smaller than those relevant to large-scale background measurements, but we include it for

completeness. We model ACN by splitting all noise components (except for the common bias components) into two realizations and applying one to each column parity, producing two independent offsets per channel.

Unmodeled Noise

Our measurements (see Section 2.6) also indicate the presence of a low level of low-frequency per-pixel telegraph noise. Such a noise component increases the effective white noise level in long integrations. This same noise also reduces the efficiency of multiple reference sampling once the readout noise falls below the per-pixel noise. We have chosen not to model this per-pixel noise, but point out its effects in long integrations, where it causes an offset in noise levels between simulated and measured images.

2.5 Noise Reduction and Optimization

After producing simulated noise images as detailed in Section 2.4, we apply the following noise reduction techniques on simulated images, calculate their spatial power spectra, and compare the post-processed power spectra with the spectra of the original images.

Phantom Pixel Correction Performance

For the particular noise sources monitored by the phantom pixel reads, phantom pixel corrections are very effective at reducing spatial $1/f$ noise due to the low Video8 noise. For simulated images generated using only noise sources visible to the phantom pixels and using $c = 4$ co-adds, the spatial noise is significantly reduced at low spatial frequencies (see Figure 2.6). For a full SPHEREx readout simulation with all noise sources active, the noise power contributed by the Video8 and bias is subdominant to the ROIC noise. However, this correction remains critical to remove the large leakage current from the Video8 amplifiers.

Row-chopping Optimization

The spatial scale for noise reduction in the row-chopping operation is determined by the parameter S , the number of rows skipped during each row read. This value is selected during system development and is not changed during flight. For S much less than the total number of rows in the image (in this case, 2048), increasing S generally pushes noise to smaller and smaller spatial scales.

As S increases, some noise wraps around to larger spatial scales rather than contin-

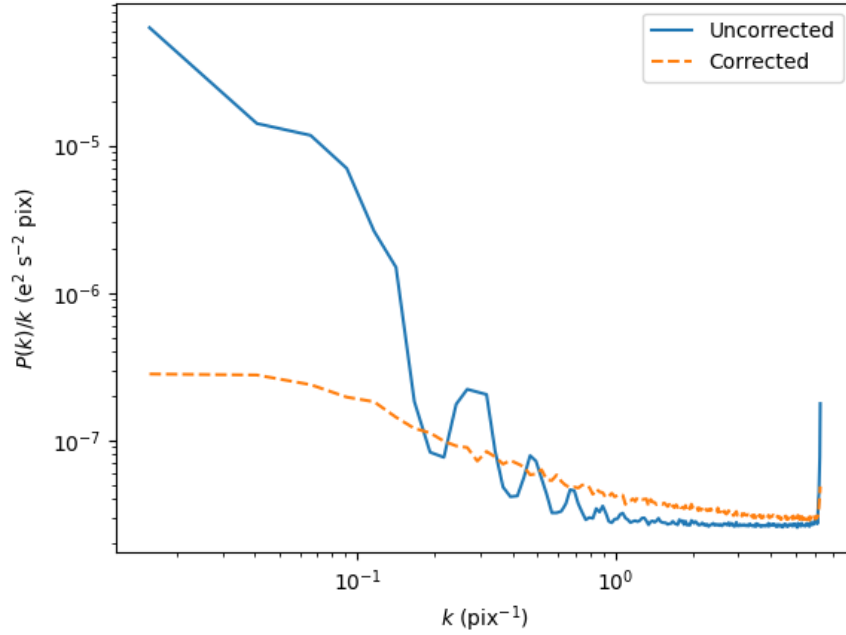


Figure 2.6: Power spectra for a 32-channel simulated image with all noise sources active except the ROIC amplifier terms, before and after $c = 4$ phantom pixel correction. The $1/f$ component here is from Video8 and bias noise. While subdominant to the ROIC noise, these sources of $1/f$ noise are mitigated by phantom pixel corrections.

uing the initial downward trend. Thus there is an optimal S that depends on project requirements. In this paper, we selected a skip parameter of $S = 24$ to minimize noise at tens of arcminutes scales (see Figure 2.7 and Figure 2.8). We selected this value by applying row-chopping to a full simulated image with the parameters described in Table 2.2. Increasing S beyond a few dozen rows results in a slight increase in noise at large spatial scales due to noise wrapping.

Reference Correction

Row-chopping mitigates $1/f$ noise in the vertical direction across the array but not across channels due to current offsets in individual H2RG channels, which are created by independent $1/f$ noise in each channel over an integration. Additional current offsets between even/odd columns at smaller spatial scales are produced by ACN. Both of these offsets can be eliminated by filtering the horizontal axis of the image centered in Fourier space, but at the cost of losing some astrophysical information. We can use reference pixels to approximate these corrections without

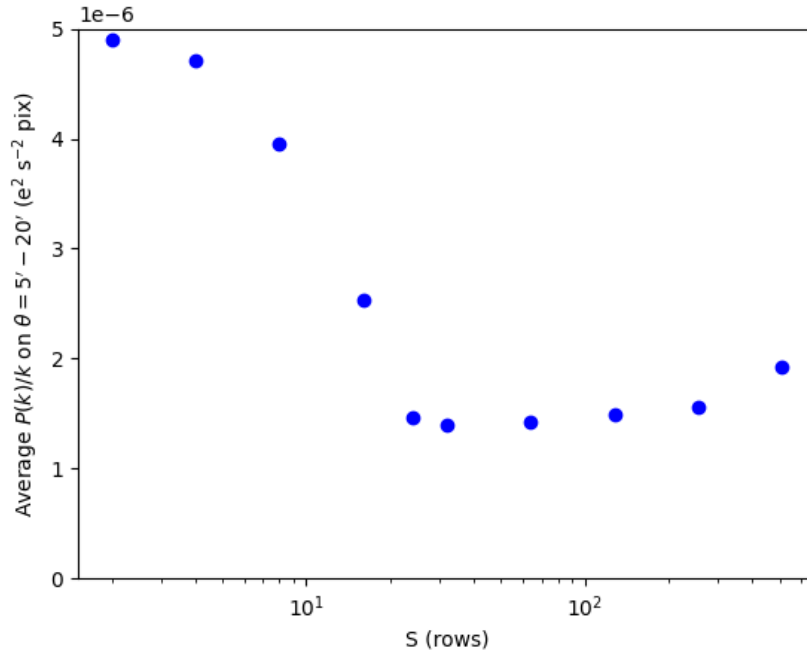


Figure 2.7: Average noise power on $\theta = 5 - 20$ arcminute scales ($0.03 < k < 0.13 \text{ pix}^{-1}$) with varying skip parameter S for a 32-channel $N = 74$ simulated reference-corrected image with all noise sources active. Here, we calculate noise after excluding the horizontal axis in Fourier space (see Figure 2.8) to isolate the effect of row-chopping from reference correction limitations.

this downside.

The most basic method for reference correction is to subtract a single average of all of the reference pixels in each channel. Because the H2RG array uses a 4-pixel-wide frame of reference pixels, this results in $8 \times 64 = 512$ reference pixels available for each channel, with an additional 8176 reference pixels for the first and last channels distributed along the side of the channel. More complex methods for reference correction have also been developed (see Rauscher et al., 2017 and Kubik et al., 2014).

We improved on the default reference correction method with two strategies: (1) reading the top and bottom rows repeatedly in place, and (2) spreading the multiple reads throughout the image. As shown in Figure 2.9, distributing the reference reads improves the performance of the correction. This improvement is due to low-frequency components in the noise timestreams, which are mitigated by reducing the average time interval between reference samples.

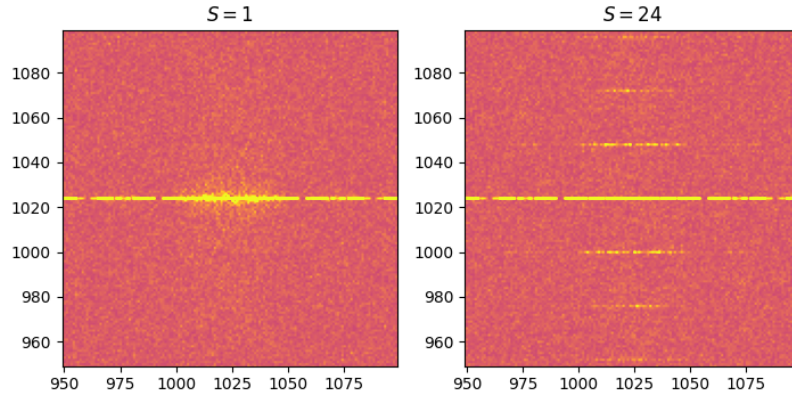


Figure 2.8: 2D FFT magnitudes in arbitrary units of a 32-channel simulated image before and after $S = 24$ row-chopping, cropped to show the region near the origin. Noise power is transferred from the horizontal axis to discrete packets above and below. Significant power remains on the horizontal axis, demonstrating the need for reference correction. We excluded the horizontal axis in Figure 2.7 to optimize the choice of skip parameter.

The overall reference correction algorithm operates as follows, utilizing only the reference rows physically at the top and bottom of each channel:

1. Define a desired number of reference row reads per channel r .
2. Define positions for the reference rows such that they are evenly distributed throughout the channel and insert these rows into the readout order by re-reading a physical reference row at each position. Physical reference rows are read cyclically, resulting in each being read an average of $r/8$ times per frame.
3. After producing a full image, average together all reference pixels for each channel, in even and odd columns (resulting in two corrections per channel) if desired, and subtract those values from the respective channel. A σ -clip operation should be performed prior to averaging reference pixels to eliminate any outlier hot pixels.

By default, we subtract a single average from each channel and do not correct for ACN in order to increase the statistical weight of the large spatial scale correction. Since the lowest frequency variations in the channel timestreams are effectively

eliminated by $S = 24$ row-chopping, subtracting a single average from each channel is essentially identical to subtracting a best-fit average to the reference pixels.

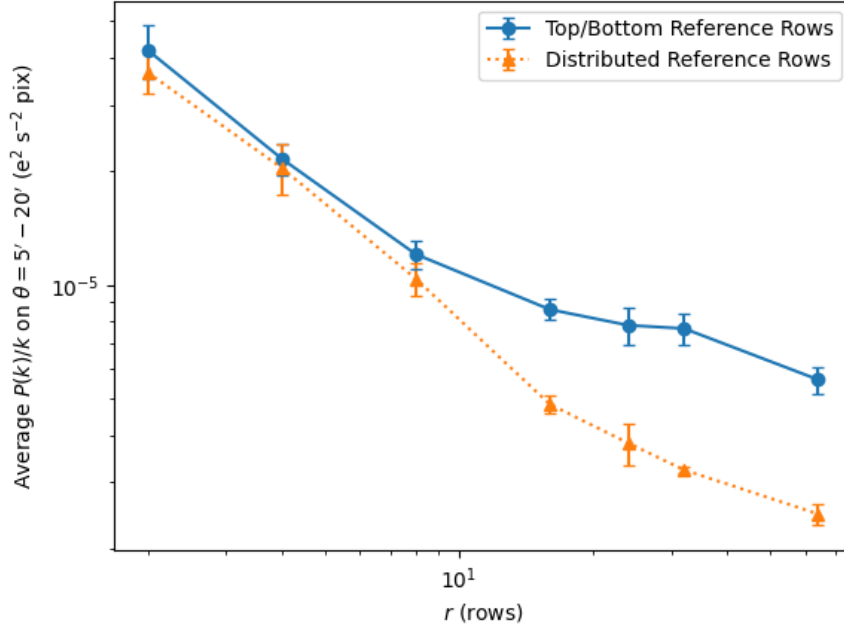


Figure 2.9: Average noise power on $\theta = 5 - 20$ arcminute scales as a function of the number of row samples r for both reference correction methods with $S = 24$ row-chopping, averaged over 5 simulated 32-channel images. The distributed method provides an improvement over repeated sampling of the default reference rows, at little cost to readout time from row shifts.

2.6 Model Predictions compared with Measurement

Simulation Output with Optimized Parameters

The described simulation generates noise image realizations that approximate the noise components present in dark images. Table 2.3 shows the simulation inputs for a standard SPHEREx exposure. Figure 2.10 and Figure 2.11 show an example of an image produced by the simulation and its corresponding spatial power spectrum.

Row-chopping and Reference Correction Model Predictions

While phantom pixel correction is largely negligible on simulated images that include all noise sources due to the already extremely low Video8 noise components, row-chopping and reference correction applied together have a very significant effect on correlated spatial noise. Using the selected $r = 32$ reference correction alongside $S = 24$ row-chopping, the average spatial noise on $\theta = 5 - 20$ arcminute scales is

Parameter	Value
Number of Frames N	74
Time Per Frame T_{int} (s)	1.51
S (rows)	24
r (rows)	32
c (pixels)	4

Table 2.3: Simulation Input

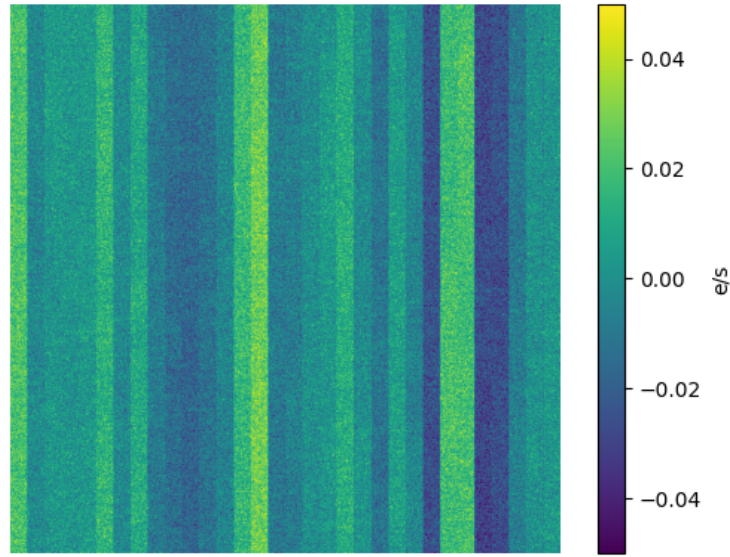


Figure 2.10: Example output 32-channel $N = 74$ noise realization generated by the described simulation. Large channel offsets due to low-frequency $1/f$ noise are visible prior to reference correction.

brought well below the original level on simulated image realizations (see Figure 2.12).

End-to-end Measurements

We compared simulated images with dark images produced by a representative H2RG array and readout electronics. Measured dark images were collected at an array temperature of 40K. Row-chopping was implemented at $S = 24$ rows during readout. The detector has a small level of optical response during these tests due to a combination of multiplexer glow and residual light leaks. We used phantom correction at $c = 4$ to remove Video8 leakage and amplifier $1/f$ noise.

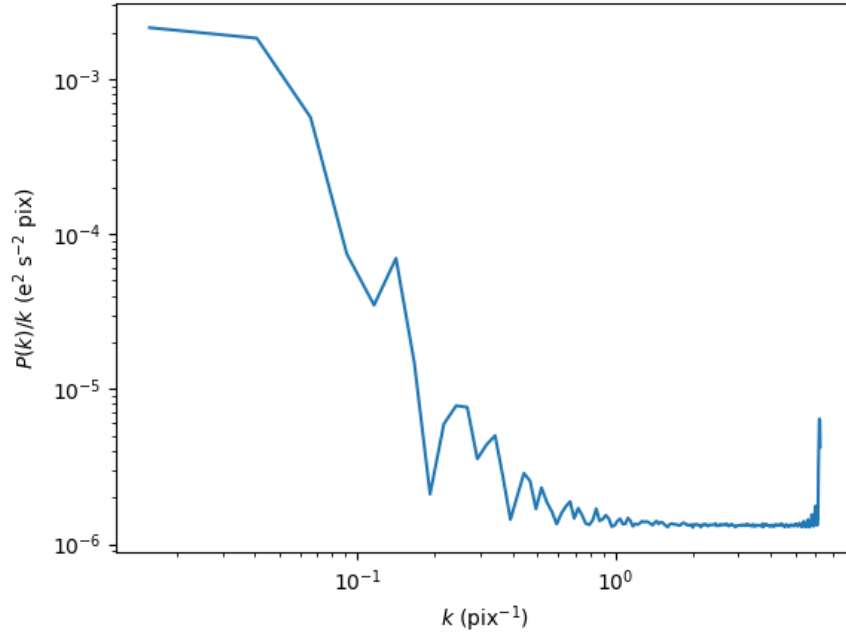


Figure 2.11: Spatial power spectrum corresponding to Figure 2.10, with phantom pixel correction but without reference pixel correction.

We compare images at $N = 74$ frames, the frame count planned for flight. Measured images were processed prior to reference correction by subtracting a second $N = 74$ exposure to remove small constant dark current offsets in the testbed, followed by iterative σ -clipping to 5 standard deviations to eliminate hot pixels and an additional factor of $1/\sqrt{2}$ to account for the image difference. A side-by-side comparison of a measured and simulated image is shown in Figure 2.13. The simulated images model the measured images well at low N before deviating as N increases. At $N = 74$, the apparent white noise level of the measured images is approximately 30% higher than in the simulated image after dark current is added (see Figure 2.15). We attribute this departure to per-pixel $1/f$ telegraph noise (see Section 2.4). The behavior at low k is otherwise well modeled by the simulation before applying reference correction.

System Performance at Large Spatial Scales

Implementing $S = 24$ on-board row-chopping and $r = 32$ reference correction with distributed reference row reads on the physical array and readout electronics results in a significant reduction of noise power on large spatial scales. For the specific application to SPHEREx, a relevant comparison can be made with the photon noise

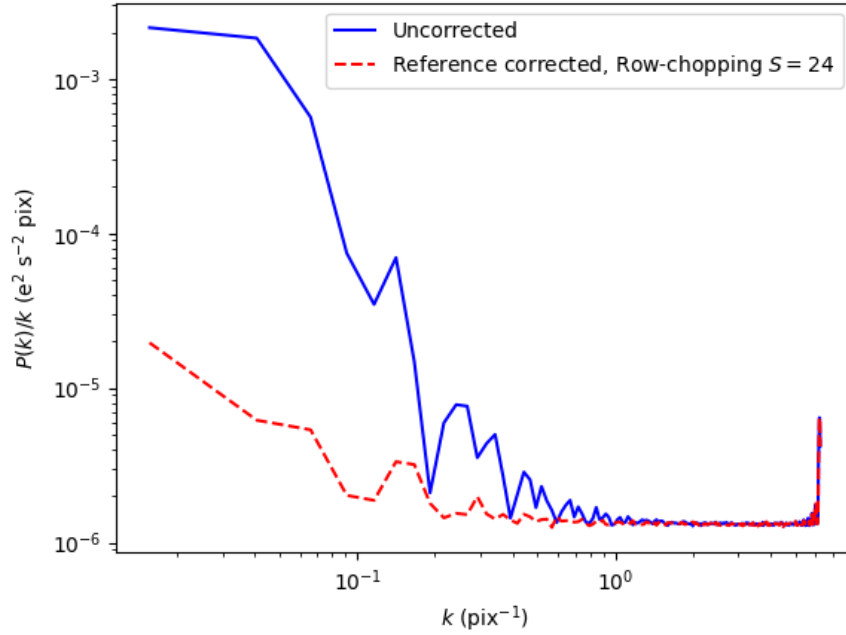


Figure 2.12: Spatial power spectrum from a 32-channel $N = 74$ simulated image realization with $S = 24$ row-chopping and $r = 32$ reference correction. We obtain a significant improvement at low k compared with the uncorrected image.

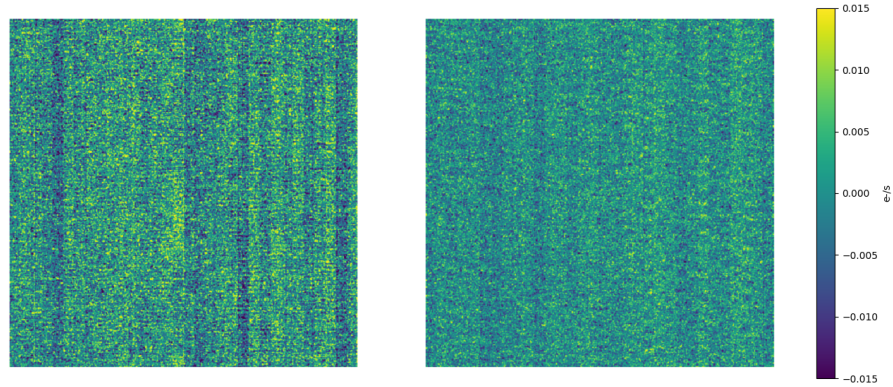


Figure 2.13: Side-by-side comparison of a measured (left) and simulated (right) $N = 74$ 32-channel image pair difference. Each image has $S = 24$ row-chopping and $r = 32$ distributed reference correction.

level caused by the bright Zodiacal light foreground, which contributes a Poissonian noise spectrum. While the SPHEREx instrument noise power requirement is not based on photon noise, the level of the ZL photon noise spectrum acts as a lower

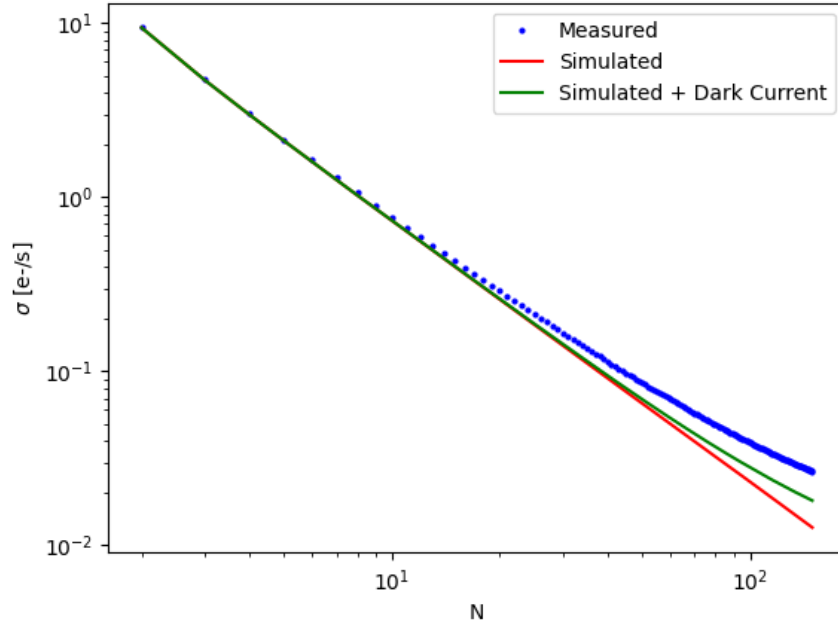


Figure 2.14: Pixel standard deviation σ as a function of frame count N , after σ -clipping, for measured and simulated images produced using a single Video8 (8 channels) with $r = 32$ ACN reference correction. Measured channels are processed by subtracting a low-noise $N = 386$ ACN reference-corrected long exposure. Unmodeled per-pixel noise increases the deviation between measured and simulated channels at large N , even after accounting for dark current variation (see Section 2.4).

limit on possible instrument observed noise power.

Figure 2.16 demonstrates the reduction in spatial power on $\theta = 5 - 20$ arcminute scales resulting from the described noise reduction methods. The noise reduction on measured images is significantly less than the reduction seen in simulated images (see Figures 2.12 and 2.16). Our testbed dark image measurements at various row-chopping S values also confirm the optimal S of a few dozen rows indicated by the simulation (see Figure 2.17). Measured images also show that increasing the number of reference row visits does not completely eliminate the excess channel offsets, with less noise reduction for higher r than simulated images would suggest. We note that the reference pixels do not completely follow the behavior of the optical pixels, even in the absence of photon noise in testbed images. Figure 2.16 includes an example of an alternative post-processing method for reference correction subtracting the median of all pixels (optical and reference) in each channel instead of the average of

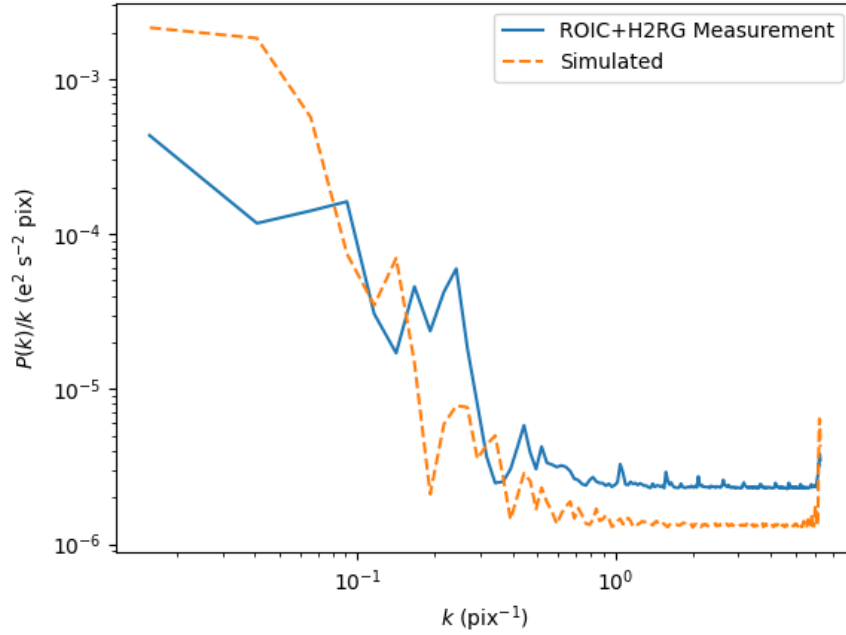


Figure 2.15: Spatial power spectra for uncorrected 32-channel image pairs at $N = 74$, showing an offset between output spectra, particularly at high k .

reference pixels, which we briefly mention here for the sake of comparison. Median correction in this way results in improved noise performance, with resulting spectra dropping below the SPHEREx band 1-4 photon noise levels at all presented spatial scales. However, this improved performance over the use of built-in reference pixel correction comes at the cost of loss of astrophysical information on real sky images, as each channel will necessarily include sky features. We further explore the use of median correction and the efficacy of SPHEREx reference pixel offset correction, as well as provide a more detailed overview of the testbed, in a future publication.

2.7 Conclusions

We developed new algorithms for improving large-scale noise properties in H2RG detector arrays for intensity mapping applications. A combination of reference correction and row-chopping substantially reduces the noise power present at large spatial scales. Row-chopping provides excellent low-frequency noise stability along the vertical direction of the array without appreciably increasing readout time. The custom Video8 preamplifier developed for array readout produces extremely low $1/f$ noise power using a phantom pixel correction scheme. As these methods are implemented during array readout rather than post-processing of sky exposures, no

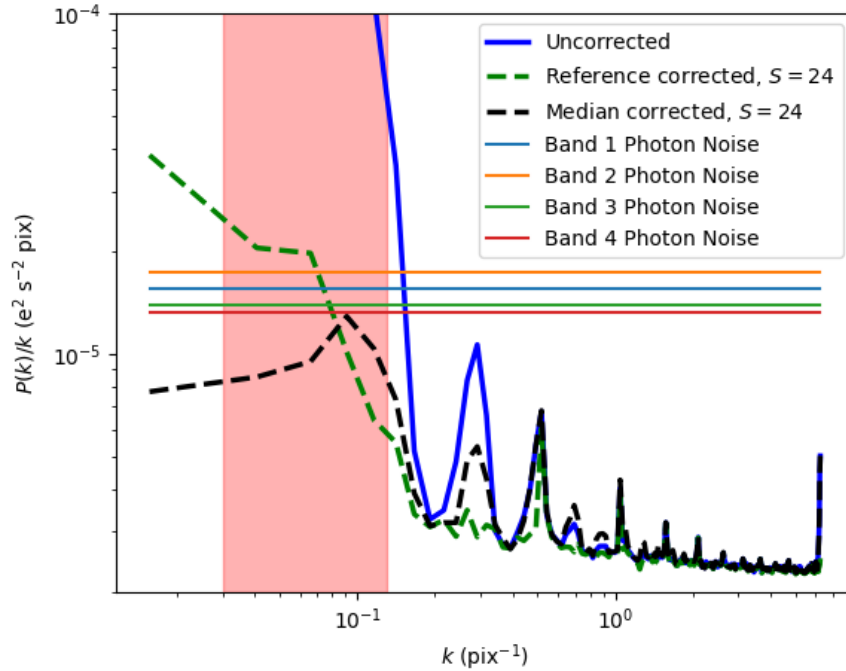


Figure 2.16: Spatial power spectrum of a 32-channel $N = 74$ image pair difference obtained with a physical H2RG array and the readout electronics, before and after $r = 32$ reference correction with distributed rows. $S = 24$ row-chopping is applied during readout. The range of $\theta = 5\text{--}20$ arcminutes is shown in red, corresponding to $0.03 < k < 0.13 \text{ pix}^{-1}$. An estimate of the photon noise spectra due to the expected Zodiacal light incident photocurrents in the first 4 SPHEREx bands (spanning $0.75\text{--}3.8\mu\text{m}$) for the SPHEREx deep fields at the ecliptic poles is also included. Reference correction and row-chopping provide a significant noise reduction at large spatial scales on measured images, with spatial noise brought near the level of the ZL photocurrent photon noise.

significant additional wavelength-dependence or effect on point sources is expected. While this work focuses specifically on applications for SPHEREx and H2RG arrays, the described row-chopping technique could be applied to any row-by-row infrared imaging system where reduced noise power at large spatial scales is desired.

The methods we developed reduce spatial readout noise to near the level of photon noise due to Zodiacal light photocurrent on large spatial scales for SPHEREx, with a $\sim 1 \text{ e/s}$ photocurrent and a 112s integration time. The combined large-scale statistical noise seen by the instrument resulting from the described noise-reduction methods is expected to be well below predicted EOR signals (Doré et al., 2014, especially Figure 24). Noise stability at large scales is limited by per-pixel

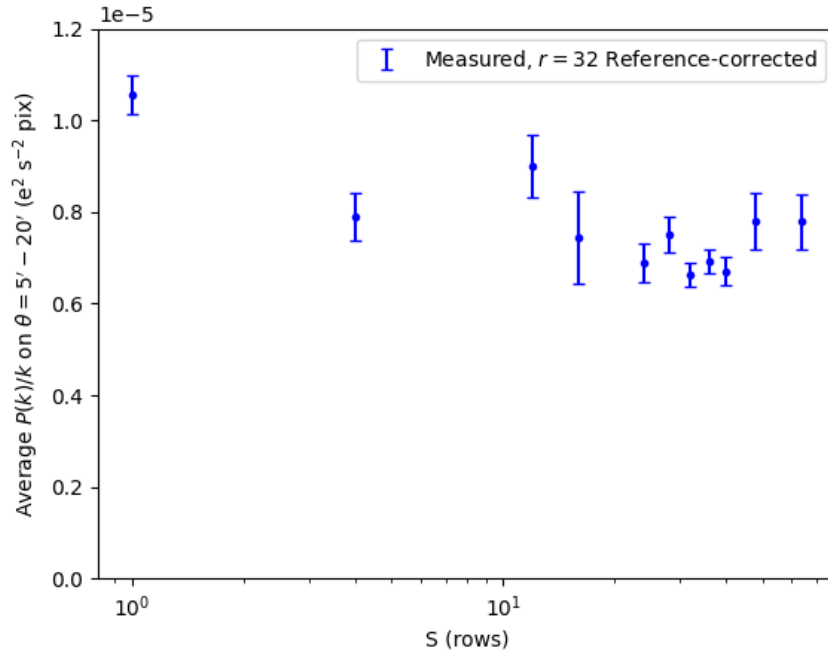


Figure 2.17: Average noise power on $\theta = 5 - 20$ arcminute scales ($0.03 < k < 0.13 \text{ pix}^{-1}$) with varying skip parameter S for 5 measured 32-channel $N = 74$ image pair differences with $r = 32$ reference correction. The measured optimal S of a few dozen rows is consistent with that provided by the simulated noise realizations, though with significantly more variation and a higher overall noise level. A substantial decrease in large-scale noise power is observed even at small values of S .

telegraph noise in the H2RG built-in reference pixels, which limits the effectiveness of repeatedly sampling reference pixels. Our simulated noise realizations generated from constituent noise components closely approximate measured images for low frame count N , but deviate at high N (particularly at small spatial scales). We plan to optimize the readout parameters in a future work using measured array data.

2.8 Acknowledgements

A portion of the research described here was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology. This article and analysis made use of the Astropy (Astropy Collaboration et al., 2022), Numpy (Harris et al., 2020), and Matplotlib (Hunter, 2007) Python packages. We acknowledge support from the SPHEREx project under a contract from the NASA/GODDARD Space Flight Center to the California Institute of Technology.

Chapter 3

EXPERIMENTAL METHODS FOR THE 2ND AND 3RD FLIGHTS OF THE CIBER-2 SOUNDING ROCKET PAYLOAD

3.1 The Cosmic Infrared Background Experiment-2

Optimized to study the cosmic infrared background from above the atmosphere, the Cosmic Infrared Background Experiment-2 (CIBER-2) is a sounding rocket payload utilizing three $2.5\mu\text{m}$ -cutoff HAWAII-2RG (H2RG) detectors to observe selected fields over wavelengths spanning $0.5\text{--}2.0\mu\text{m}$. CIBER-2 launched three times from White Sands Missile Range, New Mexico aboard Black Brant IX sounding rockets, with approximately ten minutes of nominal flight time above the 100km Kármán Line per flight (Burth et al., 2023).

CIBER-2 Systems Overview

An overview of instrument architecture for CIBER-2 is described in Zemcov et al., 2025, some of which is summarized here (Figure 3.1). CIBER-2 is a successor mission to the original Cosmic Infrared Background Experiment (CIBER, Bock et al., 2013, hereafter referred to as CIBER-1 for clarity). Compared to CIBER-1, CIBER-2 was designed for five times greater surface brightness sensitivity and includes shorter wavelength bands extending into optical wavelengths, allowing CIBER-2 to access the wavelengths of the redshifted Lyman break for the first galaxies. Photons emitted during the Epoch of Reionization with high enough rest frame energies to reach optical wavelengths at present time would have been energetic enough to be easily absorbed by neutral hydrogen; as a result, the CIBER-2 short wavelength band can access a background that should *not* contain significant EOR contribution. This optical regime measurement is unique to CIBER-2: it was not probed by CIBER-1, and is not fully accessible even to the much higher sensitivity SPHEREx survey.

Infrared Detectors and Readout Electronics

CIBER-2 utilizes three $2.5\mu\text{m}$ cutoff HAWAII-2RG (H2RG) HgCdTe detector arrays manufactured by Teledyne, each with 2048×2048 pixels. Each array consists of a 4-pixel-wide frame of reference pixels not sensitive to light surrounding the primary 2040×2040 photosensitive pixels.

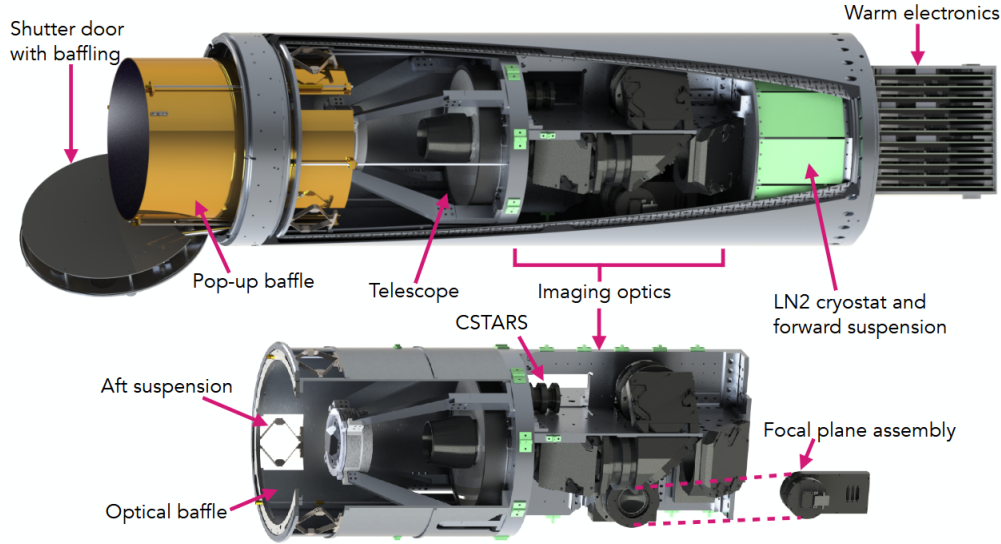


Figure 3.1: Figure 2 from Zemcov et al., 2025: CIBER-2 Overview.

We use a 32-channel readout mode to read each H2RG, dividing the array into 32 64×2048 pixel channel strips. Pixels within a given channel strip are read at a frequency of approximately 100 kHz. 32 rows (one from each channel strip), defined as the "fast-scan" 64-pixel dimension, are read simultaneously by the readout electronics, resulting in the entire horizontal dimension of the array being read in <1 ms. By contrast, the vertical "slow-scan" direction takes the full length of the exposure (approximately 1.33 s) to entirely read row-by-row. As a result, long timescale $1/f$ noise generally manifests as large scale spatial structure along the vertical dimension of the array. This 32-channel readout mode is identical to the mode used on SPHEREx (albeit using a different readout system), with a simplified illustration available in Figure 2.3 (Heaton et al., 2023).

Detector readout is accomplished using a custom "warm" electronics suite kept near ambient temperatures, with the only electronics in the cryogenic section of the experiment being simple focal plane readout boards to breakout I/O lines to and from the H2RG arrays, housekeeping sensors (e.g. thermometers), and the arrays themselves (Figure 3.2). Each array is serviced by a warm three-board cluster consisting of one "APHK" (Array Processing and Housekeeping) controller and two "DAS" (Data Acquisition System) boards. Each DAS board retrieves data from 16 of the 32 channel strips on a given array. Two additional boards, separate from the three clusters, contain solid state storage devices that store all exposures collected during flight until they can be recovered (nominally the day after a given flight). Each

board is structurally supported by an aluminum exoskeleton. Together, the eleven boards are stowed together at ambient temperatures in a custom rugged aluminum housing that protects the system from mechanical damage during launch (Figure 3.3). We use aluminum shielding plates between each APHK-DAS-DAS cluster to reduce electrical crosstalk noise when multiple arrays are active simultaneously (as they are in flight). The electronics suite is capable of either recording exposures on-demand during ground testing (in which case they are transmitted to the ground support electronics via fiber optic cables) or of recording and storing exposures automatically using the on-board storage during flight.

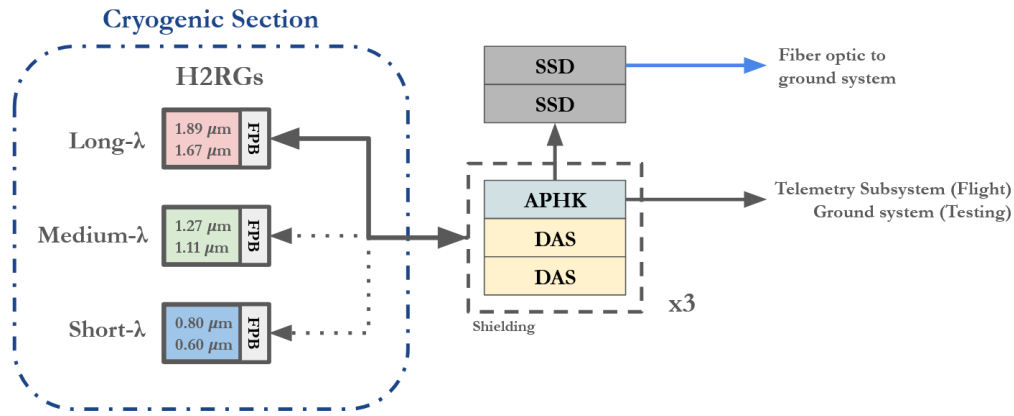


Figure 3.2: Simplified diagram of the CIBER-2 readout system. Each H2RG is operated by a cluster of one APHK and two DAS boards at ambient temperatures. The H2RG arrays themselves, along with each array's associated focal plane readout board, operate at cryogenic temperatures. Ground systems interact with the storage boards to retrieve frames from all three detectors via fiber optic cables either in real-time (for ground testing) or in bulk (for flight data retrieval). Dual-band filter pivot wavelengths are displayed for each detector.

Unlike SPHEREx (which preserves only the final sample-up-the-ramp slopes due to downlink bandwidth limitations), CIBER-2 stores individual frames from a given exposure, with the charge on each pixel non-destructively sampled for each frame. Pixel charge is reset using one of two methods: a standard reset that quickly clears an array's stored charge but does not synchronize the array clocks and a flight-initiation reset referred to as a "T1" signal that both resets and synchronizes the arrays. Standard resets are very fast (taking less than the time it takes to readout a frame to accomplish) and are tied to a variety of signals received during testing or flight (e.g. calibration lamp on/off triggers, opening or closing either the cold shutter

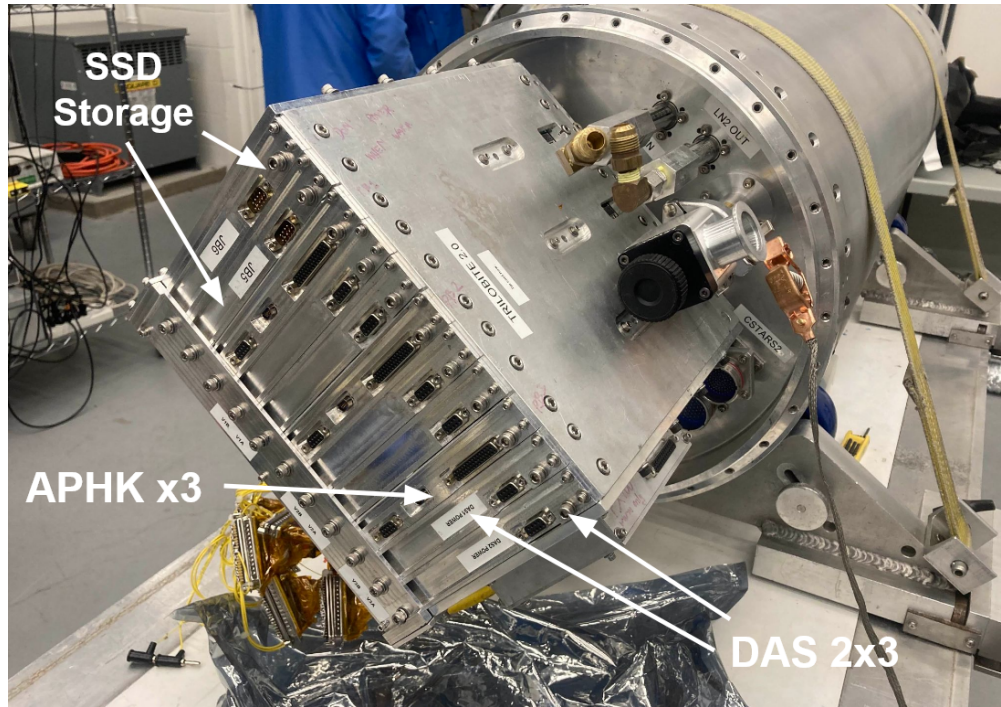


Figure 3.3: CIBER-2 warm electronics suite, as attached to the instrument during ground testing at NASA Wallops Flight Facility. APHK and DAS boards from one of three detector readout clusters are labeled alongside the two solid state storage boards. Thin aluminum shielding plates (inside stack and not visible) separate the three APHK-DAS clusters from each other.

or the vacuum door, beginning a flight field exposure, or major attitude control adjustments). Frequent resets during flight initiated by these various triggers, even for portions of the flight where the arrays are not actually imaging a patch of sky during the ascent, minimize any residual charge left over between resets. T1 resets are significantly slower, requiring multiple frame readouts to accomplish. In flight, these resets are used only at the very beginning of a launch as the 1st stage ignites. On the ground, we use T1 resets prior to any data collection to synchronize the three arrays and prevent any desynchronization-related crosstalk (see Section 3.4).

The reference pixels contained in each array approximate the electrical response of a photosensitive pixel, and as such can be used to correct long-timescale noise common to a 1-pixel-wide column (or, alternatively, a 64-pixel-wide channel strip). We generally do not use reference pixels to correct for horizontal noise patterns due to the chosen readout mode (which limits large-scale $1/f$ noise to the vertical slow-scan direction), instead using the increased statistical weight of the larger reference pixel sample size within the 1st and 32nd channel strips to improve correction within

those particular strips. However, as reference pixels are read out no differently than photosensitive pixels, they are available in general for any desired post-processing after recording an exposure.

Optical Systems and Instrument Configurations

CIBER-2 uses a Ritchey–Chrétien type telescope with a 285 mm diameter primary mirror and 105 mm diameter secondary mirror. The overall system has a field of view of $2.3^\circ \times 2.3^\circ$ with a pixel angular scale of $\phi \approx 4''$, an f-stop of f/3.26, and a focal length of 930 mm, with the focus fixed before flight targeting sources at infinity. The incoming beam is split by a pair of dichroic beam splitters to pass light to the three detectors, allowing all instrument bands to image portions of the same field simultaneously. A detailed description of the CIBER-2 optical chain is described in Shirahata et al., 2016.

Each detector array utilizes two filters: a single linear-variable filter (LVF) covering a field of view approximately $1.5^\circ \times 0.3^\circ$ ($\sim 200 \times 1500$ pixels) in what we define as the top of each array (with small adjacent dark regions where the fixed filter holder blocks light from reaching the detector), and a wider dual-band filter defining the primary detector wavelengths with a field of view of $2.2^\circ \times 1.1^\circ$ ($\approx 1900 \times 950$ pixels) each. Band definitions are shown in Tables 3.1 and 3.2.

Filter	λ (μm)	$\Delta\lambda$ (μm)
C1	0.60	0.20
C2	0.80	0.20
C3	1.11	0.15
C4	1.27	0.15
C5	1.67	0.25
C6	1.89	0.25

Table 3.1: CIBER-2 dual-band pivot wavelengths λ with bandwidths $\Delta\lambda$ associated with the three detectors.

Filter	λ (μm)
LVF-Short	0.50–0.87
LVF-Medium	0.81–1.39
LVF-Long	1.35–2.00

Table 3.2: CIBER-2 LVF wavelength ranges λ associated with the three detectors.

To enable dark data collection, both on the ground and for a small number of $N \approx 10$ in-flight characterization frames, we use an actuating optical shutter within

the cryogenic section of the instrument to block light from the focal plane arrays. The inner surface of the shutter is coated in dark Fineshut KIWAMI foam to reduce stray light. The shutter is operated by powering one of two latch electromagnets which pulls on permanent magnets embedded in the shutter to either open or close the shutter. Under normal conditions the shutter remains in its new position after power to the electromagnets is removed, preventing them from overheating from continuous current draw. Due to the relatively violent launch environment, the optical shutter open latch is kept powered on until approximately 8 seconds after the 2nd stage rocket motor has burned out to absolutely ensure that the shutter remains open during field observations.

CIBER-2 has two possible physical configurations: "optical test mode" where the aperture is sealed by staged fused-silicate quartz windows and "flight mode" where the aperture is sealed by a motor-operated shutter door. In optical test mode, the staged window filters out ~ 300 K thermal emission to allow for optical calibration. An aluminum bulkhead plate can be placed in front of the window to enable dark testing in optical test mode, although a dark room is necessary to eliminate stray light in this configuration. Vacuum level and detector settling temperatures vary somewhat between these two configurations, making it necessary for non-optical flight characterization tests (e.g. dark data collection, final focal plane temperature measurements, etc.) to be conducted in flight mode.

In-flight Deployable Systems

In flight, the telescope aperture is sealed by a motor-operated vacuum shutter door. Under normal operation, the door opens in flight after the ambient pressure reaches near-vacuum and re-seals the cryostat prior to atmospheric re-entry. Actuation of the shutter door is via timers and is not directly controllable remotely. The door includes thermal shields constructed from aluminum plates anodized on one side (facing the telescope). A rubber ring gasket between the door and outer ring, with vacuum grease applied during final integration, assists sealing of the cryostat section.

Driven by lessons learned from CIBER-1, CIBER-2 uses a deployable pop-up baffle to protect against image contamination by thermal emission from the metal rocket skin (which is close to ambient temperature during launch). A motor mounted to the inside of the vacuum door pulls a steel wire that guides the baffle outward along a set of steel rods. During flight, the baffle signal is sent by the NASA telemetry unit to the baffle control electronics, which mount to the side of the main warm

electronics suite; for ground testing we instead connect a small circuit to manually extend and retract the baffle.

Cryogenic Cooling

CIBER-2 is cooled by liquid nitrogen (LN2) with a 7-liter onboard cryostat. LN2 enters the system via an intake located near the warm electronics suite, opposite the telescope aperture. To prevent radiation from the rocket skin at ambient temperature from warming the optical chain and detectors, we use a radiation shield consisting of a 1 mm thick semi-rigid aluminum-1100 sheet wrapping around the entire instrument and forming a hollow cylinder. The shield is then isolated from the rocket skin by a five-layer mylar blanket. The shield and mylar blanket are installed around the cold vacuum section of the instrument before the entire instrument is inserted into the rocket skin via crane. Starting at ambient pressure and temperature, cooling the instrument to the point where the detectors are operating nominally typically takes a minimum of 48 hours; cooling is controlled automatically via computer to restrict cooling to $\frac{dT}{dt} < 1$ K/min to reduce stress on the optics due to components contracting/expanding at different rates. Warming is again completed slowly, requiring approximately 48 hours to reach ambient starting from operational temperatures.

3.2 CIBER-2 Launch Campaigns

Integrated testing (including vibration testing) of CIBER-2 took place at NASA Wallops Flight Facility (WFF) on the eastern shore of Virginia operated by the Goddard Space Flight Center, with final integration and launch taking place at White Sands Missile Range in New Mexico. While customization is made for each mission, the parachute and deployment mechanism, attitude control system, and telemetry system are generally standard subsystems developed by the NASA Sounding Rocket Operations Contract (NSROC) sounding rocket program at WFF.

Nominal Launch Sequence

CIBER-2 is delivered to its target suborbital trajectory by a two-stage Black Brant IX solid propellant launch vehicle, including a Terrier first stage (Figure 3.4). During a nominal flight, the CIBER-2 payload reaches an altitude of ~315 km and travels a horizontal distance of ~80 km, returning to the surface via parachute.

We send the command to initiate flight mode on the warm electronics suite 10 minutes before liftoff, causing the system to begin continuously recording frames

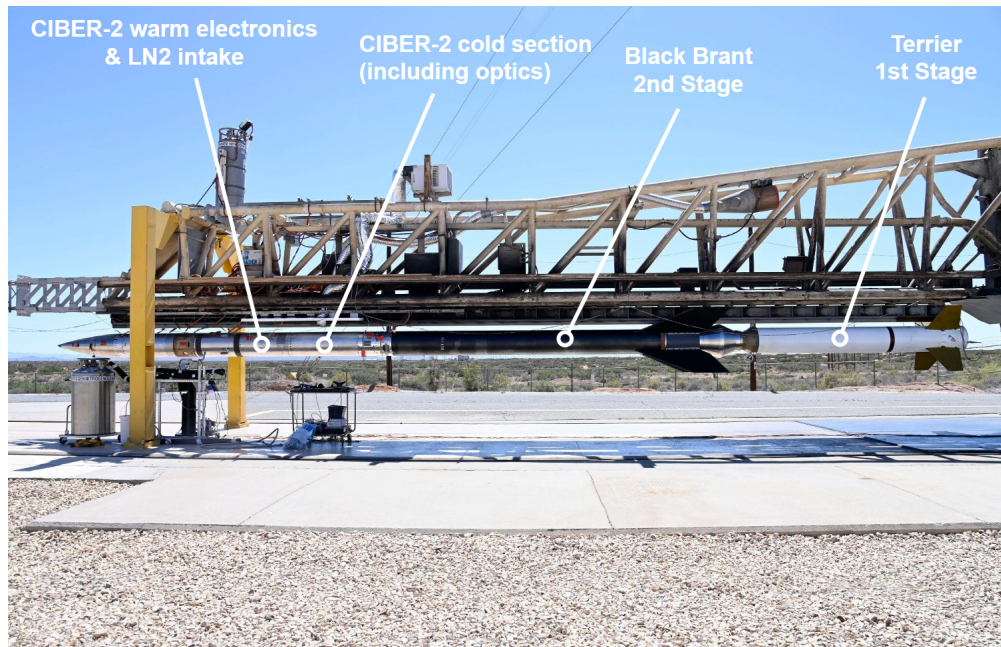


Figure 3.4: Annotated view of the assembled launch vehicle prior to the 3rd and final flight of CIBER-2 at White Sands Missile Range, New Mexico. Only systems to the left of and including the CIBER-2 cold section are recovered. During flight and after each rocket stage burns out, the ejected nosecone and both rocket stages fall unassisted to impact the surface. Original unannotated photo: NSROC

and writing them to the on-board storage. Flight mode remains active until a command is sent to deactivate it, typically sent after recovering the instrument the day after launch; however, the instrument does not remain powered on and recording frames for more than a few minutes after the flight is complete. At the moment of 1st state ignition, the three H2RG arrays are reset and synchronized with a long T1 signal (Section 3.4) and the optical shutter open latch electromagnet is powered on. As opposed to ground testing where this latch typically only operates for a few seconds, we do not release this latch until approximately 47 seconds into flight, well after the 2nd stage has burned out to guarantee that the shutter is open after rocket-induced vibrations have ceased. Fiber optic cables, connected on the launcher rail to interface with the storage boards, are physically torn away and destroyed at takeoff by the departing rocket. Calibration lamps are activated for 13 seconds shortly after power is removed from the shutter latch, followed by actuation of the vacuum door which exposes the telescope to open space.

In flight, we receive via telemetry downlink a live view of one 64×2048 channel strip per array, resulting in approximately 3% of the flight data being viewable in

real-time from the launcher blockhouse. While this is not a large enough portion of the array to be scientifically useful, this allows for array operation and bright sources to be seen during the flight. The overwhelming majority of the flight data must be physically recovered from the storage boards after the flight.

Total time for field imaging above the atmosphere is approximately 6 minutes distributed across the 6 target fields, after which the optical shutter is closed. Pointing is managed by a NSROC subsystem, utilizing a star tracker for attitude determination and cold gas thrusters for control. We obtain ~13 seconds of full array in-flight dark frames following the final field while the shutter is closed and before the baffle and vacuum door are retracted. After the cryostat has been nominally sealed by retraction of the door, the entire payload falls back to the surface protected by a deployable heatshield followed by subsequent parachute deployment. Exact timelines vary based on weather conditions and the precise trajectory, but an entire successful mission from 1st stage ignition to the payload coming to a rest on the desert floor is typically completed in less than 15 minutes. The instrument is recovered after each flight the following morning via Black Hawk helicopter; as such, the instrument must tolerate exposure to the high desert environment for up to 12 hours after launch and landing.

1st Flight – Mission 36.281, 2021

The inaugural flight of CIBER-2 took place at 00:25 MDT on June 7, 2021, with all launch vehicle systems performing nominally and the instrument reaching an altitude of ~311 km. The flight was an engineering success, with all deployable mechanical systems functioning successfully, all target fields observed, and a successful recovery of both the overall instrument and the onboard flight data. Issues with focus and the long-wavelength detector's H2RG array (Section 3.3) stemming from unexpected time in storage due to COVID-19-related delays limited the scientific usefulness of data from the 1st flight. The flight informed numerous upgrades to be made in the following two years to improve data quality for subsequent flights. These upgrades were implemented alongside the extensive refurbishment and re-testing that is required after any sounding rocket flight; several such upgrades are described here in detail in subsequent sections.

2nd Flight – Mission 36.383, 2023

The second flight of CIBER-2 took place at 23:03 MDT on April 16, 2023 – nearly two years after the first flight. Unfortunately, approximately 32 seconds into the flight and partway through the 2nd stage burn, White Sands range safety opted to manually activate the vehicle's flight termination system following what was later found to be a fault in a range radar ground station that had been tracking the flight. As such, the vehicle was lost before the planned trajectory could be achieved and the instrument reached an altitude of only ~50 km before falling back to the surface less than 10 km from the launch pad, far too low to image any flight fields. Fortunately, however, this altitude was high enough for the parachute (automatically triggered by increasing external pressure) to successfully deploy and eventually slow the descent of CIBER-2 following destruction of the launch vehicle, resulting in an impact velocity that was not particularly unusual even for a nominal mission.

With the exception of the parachute, most instrument systems activate on pre-determined timers (detector power and readout, deployable actuation, etc.) and as such the instrument did not receive a signal to close the external shutter door or to remove power from the detectors before it impacted the ground. The shutter door typically seals the instrument cryostat and maintains vacuum within the cryogenic section during descent, and as a result CIBER-2 continued to provide power to the three H2RG arrays for several minutes while exposed to ambient desert air and while undergoing a subsequent rapid warm-up. This also resulted in a large amount of water condensation being found inside the cryostat and near the detectors during recovery. Despite these conditions, extensive testing conducted at the Rochester Institute of Technology in the months immediately following the 2nd flight found no damage to any of the three arrays. With the instrument recovered intact and all upgrades made after the 1st flight still in place, we were able to refurbish CIBER-2 over the following year leading up to a final 3rd flight.

3rd Flight – Mission 36.396, 2024

CIBER-2's 3rd and final flight took place 21:32 MDT on May 5, 2024, with the instrument reaching a nominal altitude of ~316 km. The flight was a success, with CIBER-2 successfully imaging all fields and all flight data successfully recovered from the onboard electronics the following day (May 6, 2024). Numerous instrument upgrades implemented since and informed by the 1st flight – including significantly improved large-scale noise sensitivity – made the data collected during this flight

the most scientifically valuable of the campaign.

For the 3rd flight, we selected fields to optimize intensity mapping targeting extra-galactic measurements. The 6 flight fields are divided into two groups – COSMOS A/B/C/D and Lockman A/B, Figures 3.5, 3.6, 3.7, 3.8 – with each field being completely covered twice during the launch. This allows for different bands, each of which only occupies about half of the detector area, to be cross-correlated for the same regions of the sky. This strategy has the added benefit of reducing attitude adjustment time between fields during a brief sounding rocket flight where every second matters. On the 3rd flight, we did not dedicate observing time to additional fields for characterizing foregrounds (e.g. Zodiacal Light and Diffuse Galactic Light); this strategy was, however, employed on the 1st flight (Zemcov et al., 2025). Examples of flight images for the short- and long-wavelength detectors respectively are shown in Figures 3.9 and 3.10.

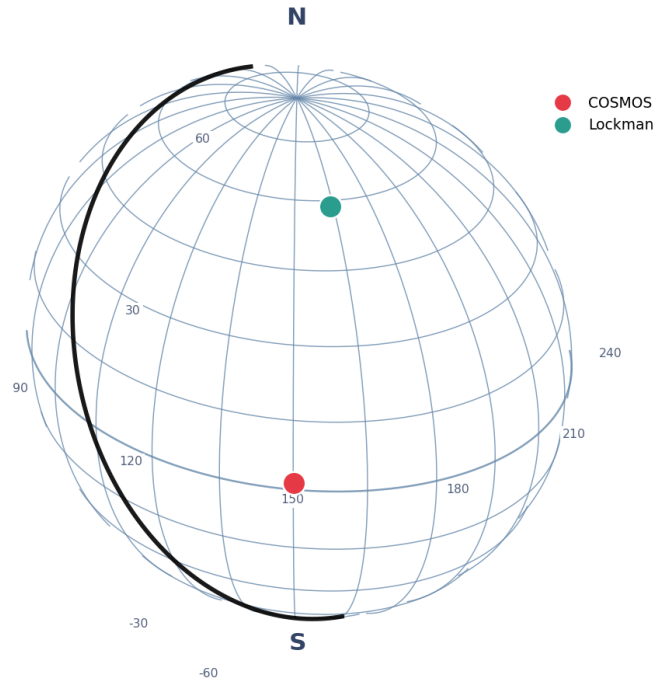


Figure 3.5: The target fields of the 3rd flight of CIBER-2, COSMOS and Lockman. The galactic plane is shown in black.

While essentially all sounding rocket flights come with some form of instrument damage and necessary refurbishment, CIBER-2 sustained somewhat more damage on its final flight than would be expected – curiously, even more than was sustained

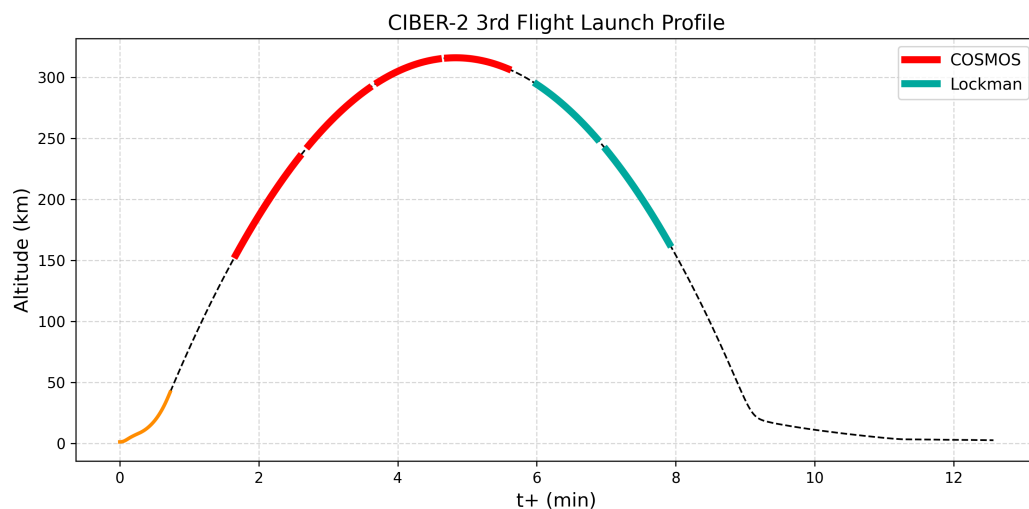


Figure 3.6: Measured launch profile for the 3rd flight of CIBER-2. The time between 1st stage ignition and 2nd stage cutoff is labeled in orange. Note the gap between COSMOS and Lockman observations due to instrument attitude slew between the fields.

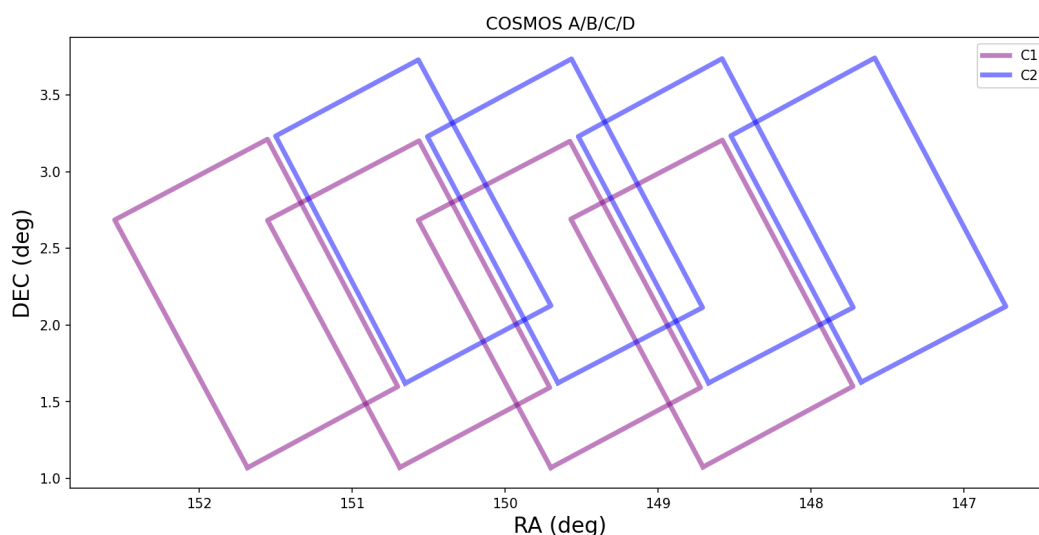


Figure 3.7: The COSMOS A/B/C/D fields for the 3rd flight of CIBER-2, shown for the short-wavelength detector bands only.

during the terminated 2nd flight during which the launch vehicle was lost mid-flight. During descent, the vacuum door sealing the aperture failed to fully close and was subsequently torn off either during atmospheric re-entry or more likely upon impact; the door itself was never recovered for this flight and its components presumably remain scattered in the Tularosa Basin. This incident resulted in the instrument being

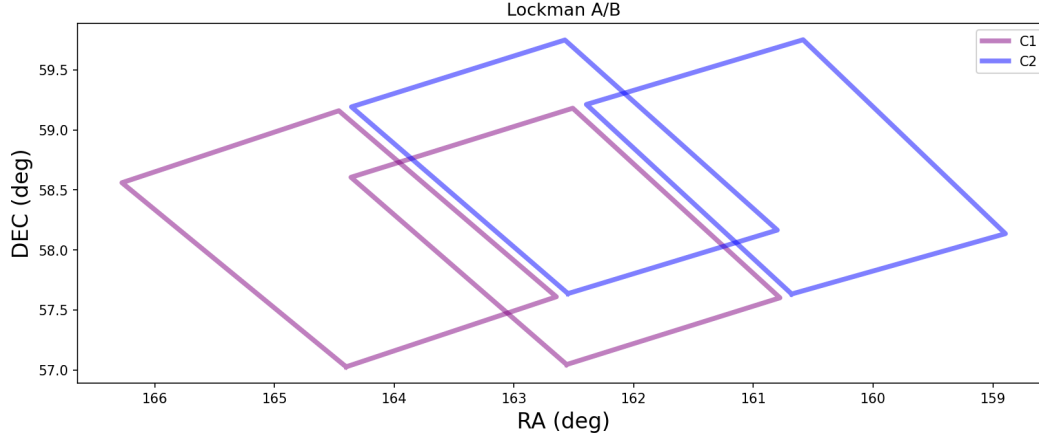


Figure 3.8: The Lockman A/B fields for the 3rd flight of CIBER-2, shown for the short-wavelength detector bands only.

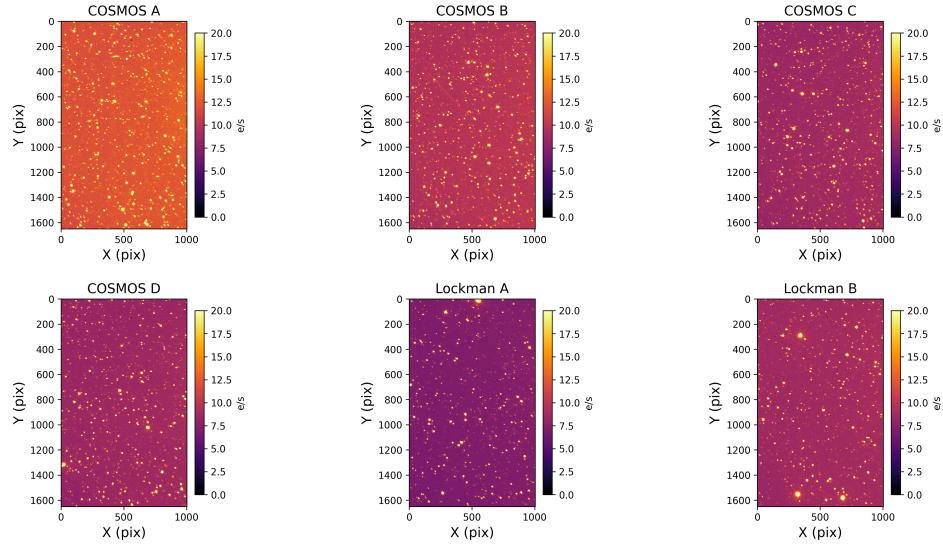


Figure 3.9: 3rd flight unprocessed CIBER-2 images for each of the 6 target fields on the short-wavelength detector in band C1, the shortest wavelength filter ($\lambda = 0.60 \mu\text{m}$, Table 3.1). Note the gradually decreasing background level due to excess airglow as the flight proceeds even at this shortest wavelength, with COSMOS A observed first and Lockman B observed last (see Section 3.6). A satellite streak, increasingly common, is visible in COSMOS B.

powered on while directly viewing bright re-entry plasma. Parachute deployment was nominal, with CIBER-2 touching down at typical speeds in the northern Tularosa Basin within the expected landing area. Since the door was either already gone or wide open upon touchdown, the landing forced the pop-up baffle back into the

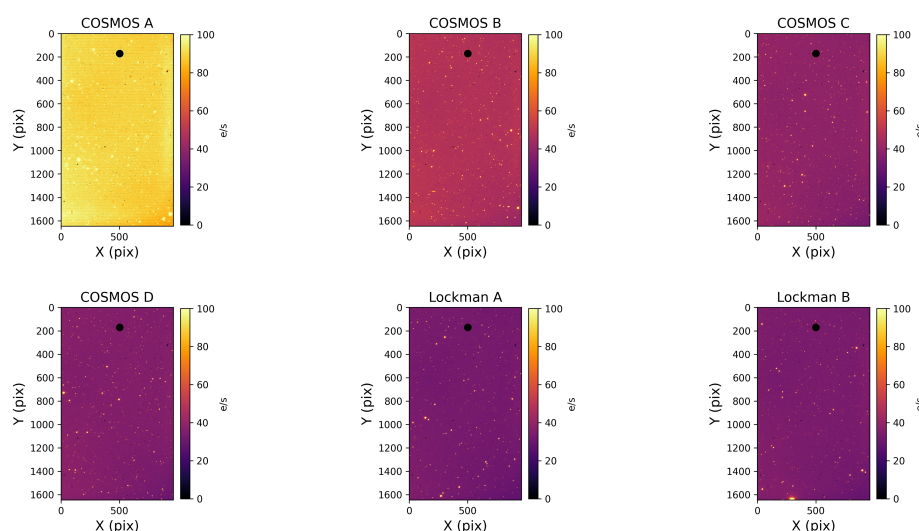


Figure 3.10: 3rd flight unprocessed CIBER-2 images for each of the 6 target fields on the long-wavelength detector in band C6, the longest wavelength filter ($\lambda = 1.89 \mu\text{m}$, Table 3.1). Note the high airglow in the earlier fields compared to the short-wavelength case in Figure 3.9. The "hole" near the top of each field is a known array defect.

instrument, damaging the baffle. High surface winds, not an obstacle to launch, then proceeded to drag the entire instrument stack by its parachute over a kilometer through the desert, filling much of the open cryogenic section with sand; CIBER-2 only came to a stop when the parachute was caught on a soaptree yucca. Despite this sequence of events, which involved the entire cryogenic section rapidly warming up to ambient temperatures similar to what occurred during the terminated 2nd flight, all three detectors were unharmed as confirmed by extensive post-launch testing at the Rochester Institute of Technology. CIBER-2's onboard solid-state storage and overall electronics suite, protected by the warm electronics enclosure hardened against physical shock and vibration, was completely unharmed by the flight.



Figure 3.11: CIBER-2 as recovered after the 3rd flight on May 6, 2024, far from its original touchdown site. Note damage to the pop-up baffle. The detectors and warm electronics suite were unharmed, and all flight data was successfully recovered later that day. Photos: NSROC

3.3 Design of a Cryogenic Focal Plane Array for the CIBER-2 Long Wavelength Detector

A significant upgrade between the 1st and 2nd/3rd flights was the design and installation of a new focal plane array to accommodate an upgraded long-wavelength H2RG detector. Physically interfacing the three CIBER-2 detectors to the optical chain is accomplished with three cryogenic focal plane arrays (FPAs). Each FPA holds the H2RG array itself, the associated dual-band and linear variable filters, and support electronics for reading out the array. The original three FPAs utilized a nearly identical mechanical design to each other and flew successfully on the 1st flight of CIBER-2.

Following an unexpected 1-year delay of the 1st flight of CIBER-2 due to closures associated with the COVID-19 pandemic during which the instrument was inaccessible, we observed a fault in the H2RG array associated with the long-wavelength detector causing loss of a significant fraction of pixels, increasing from roughly 5% of pixels to 15% over the final few weeks prior to the flight. This had a significant impact on long-wavelength data quality, and the array was removed following the 1st flight. Teledyne provided us with a replacement H2RG; however, the newer model replacement array used a significantly different mechanical package and connector interface that required a re-design of the long-wavelength FPA, described in this section.

Starting with the original design as a baseline, we designed a new focal plane array to accommodate the modified mechanical package and connector of the replacement long-wavelength H2RG array, including a re-designed cryogenic focal plane readout board. Design took place during the first half of 2022, with final assembly and integration into the CIBER-2 instrument occurring in January 2023. In order to avoid modification of the rest of the CIBER-2 cold section including the optical chain, the new FPA was designed with the optical interface and overall stack height unchanged from the original design.

Baseline FPA Design and Overview of Design Considerations

The original preliminary design of the CIBER-2 focal plane arrays is described in Lanz, 2018. Each H2RG array is secured to a molybdenum "mushroom" serving to hold the array in place and, critically, match the array's thermal expansion coefficient to minimize mechanical stress during repeated cooling and warming cycles. An aluminum top cap is attached to the mushroom, surrounding the array, holding the

dual-band filter, and providing a place to secure the LVF holder above the top edge of the H2RG. The dual-band filter is held in place by spring-loaded clamps at a minimum manufacturer-specified safety clearance of 100 μm above the surface of the array, while the LVF (via the aluminum LVF holder) are secured in place with screws and lockwashers. This original design continued to be used on the medium- and short-wavelength detectors throughout all three flights of CIBER-2.

As CIBER-2 is both a cryogenic instrument and a rocket-borne payload, any system within the CIBER-2 cold section must withstand both the harsh vibration environment associated with a rocket launch and the repeated cooling/warming cycles between room temperature and the $>77\text{ K}$ temperatures associated with liquid nitrogen cooling. In addition to components being able to tolerate repeated thermal stress, mechanical design for the former requirement must accommodate both physical assembly at room temperature and required spacing at cryogenic temperatures. Tight mechanical tolerances are required to ensure that the H2RG remains undamaged at any point during assembly, testing, or launch, and to enable precise placement of filters to minimize optical ghosting (which increases with an increasing filter-array gap) while maintaining the minimum safety clearance.

Molybdenum H2RG Mount

The original molybdenum "mushroom", designed to accommodate specific H2RG mounting points and a flat-flex cable extending outward along the plane of the array, was replaced by a more complex two-part asymmetrical design. Splitting the original mushroom into two components was driven by the self-imposed requirement to keep the external dimensions of the fully-assembled FPA as similar to the original design as possible as well as mitigate the difficulty and cost of machining molybdenum. As before, the use of molybdenum allows the entire assembly between the two pieces and the H2RG to experience minimal thermal stress during warming and cooling cycles by matching thermal expansion coefficients.

The modified molybdenum mount (Figure 3.12), as well as space for the new H2RG connector and wire harness (as opposed to the flat-flex harness of the old design), served as the main driving change to the original design. The major changes to this portion of the assembly from the original mushroom design resulted in downstream changes to nearly every component in the original FPA design.

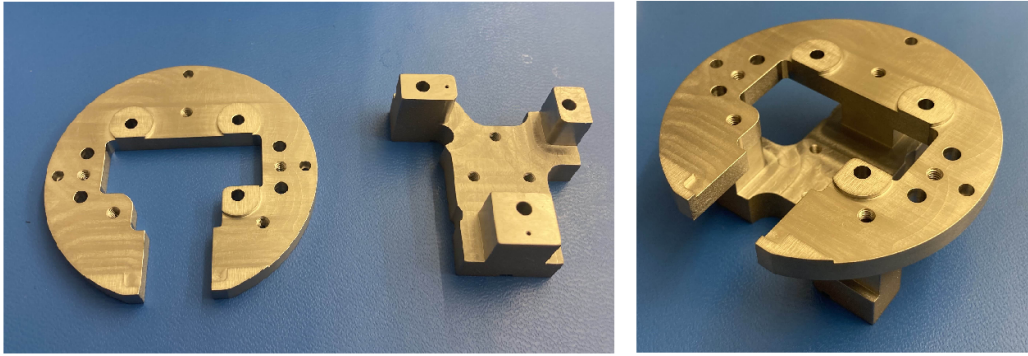


Figure 3.12: The flight molybdenum H2RG mount, disassembled (left) and assembled (right), prior to integration into the FPA. The H2RG is attached via the three visible raised platforms with #4-40 fasteners and lock-washers. The hollow space underneath the array provides space for the new Nano-D connector and custom wire harness. The harness itself emerges to meet the focal plane readout board through the large gap at the bottom of the flat platform. The fastener associated with the lower right raised platform shown in the figure extends through both molybdenum components, leading to the decision to retain both components as molybdenum.

Design Overview

An overview of the design of the overall FPA stack can be found in Figure 3.13, with a side-by-side comparison with the original design in Figure 3.14. Beyond the two-part mount described in the previous section and an overall titanium housing for thermal regulation providing coupling to the optical chain, the rest of the mechanical components of the FPA were machined from Aluminum-6061. A new aluminum top cap for supporting the filters (modified to accommodate the new array and molybdenum mount) surrounds the array. Besides the H2RG itself, the electronics within the cold FPA consist solely of a focal plane readout board, heavily modified from the original design to accommodate new Micro-D connectors which break-out the wire harness emerging from the array. This board essentially passes the array's signal lines to the main warm electronics suite, and is housed in a large flat anodized aluminum enclosure attached to the main FPA stack (Figure 3.15).

From a thermal perspective, the H2RG array is thermally coupled to the rest of the system only via the molybdenum mount (with radiative heat transfer inside the cryostat treated as negligible). The top cap and associated filters never actually touch the array; as a result, heat conduction into the H2RG from the rest of the instrument can only occur through the titanium housing, then the aluminum base plate at the base of the stack, and finally the molybdenum mount. Since the CIBER-2 cryostat is

allowed days to cool prior to flight or data collection, this thermal insulation isolates the arrays from temperature instabilities induced during launch.

Mechanical drawings for new focal plane array components are included in Appendix B.

Focal Plane Readout Board

The custom cryogenic focal plane readout board for the long-wavelength detector FPA essentially serves as a break-out board for the H2RG, routing I/O lines from the array to robust external connectors that can be safely attached to the rest of the CIBER-2 readout system. The original design interfaced with the H2RG via a flat-flex cable, providing the same break-out functionality; the new design replaced this with a custom breakout harness converting the H2RG-side Nano-D connector into three Micro-D connectors which attach to the new readout board. The board then passes these to a different set of three fixed connectors which protrude from the FPA housing, placed identically to the previous FPA design. The final as-flown board is shown in Figures 3.21 and 3.22.

The focal plane readout board itself is a 6-layer design, with ground (layer 2) and power (layer 5) planes. Layouts for each layer are included in Appendix C.

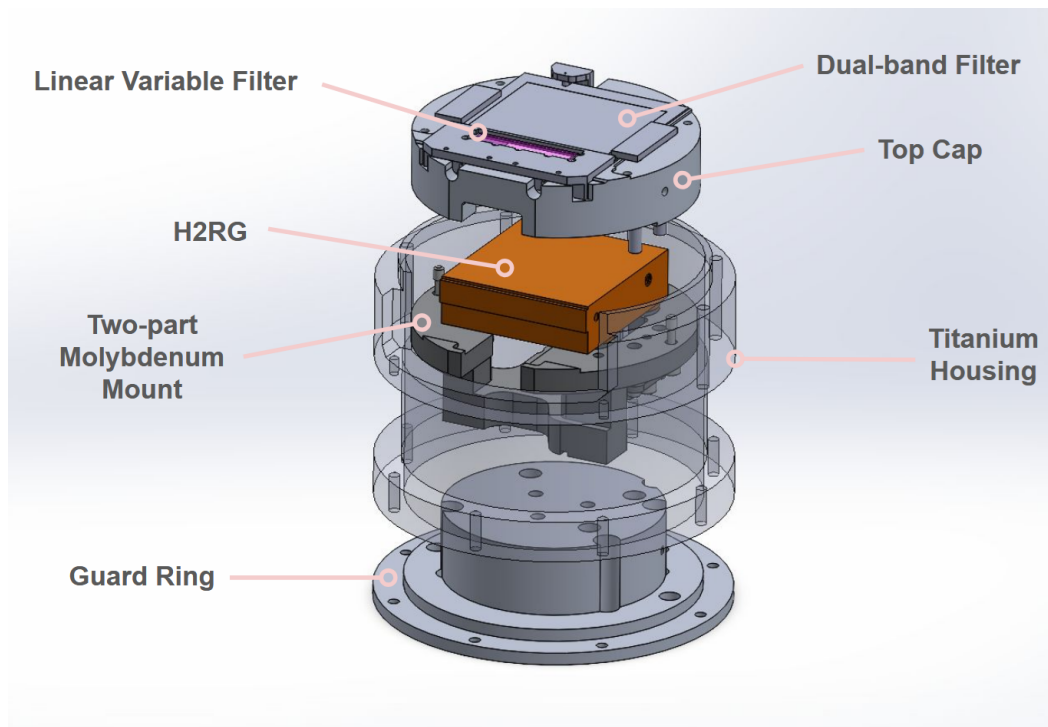


Figure 3.13: CAD model exploded view of the final design of the new long-wavelength array stack, not including the H2RG readout harness or focal plane readout board housing. The majority of the array is covered by a dual-band filter, flanked by two spring-loaded clamps which hold the filter in place during the violent vibration environment of launch. The LVF, in pink, covers a small portion of the array; it is held in its anodized aluminum mount with adhesive which is in turn held in place with screws.

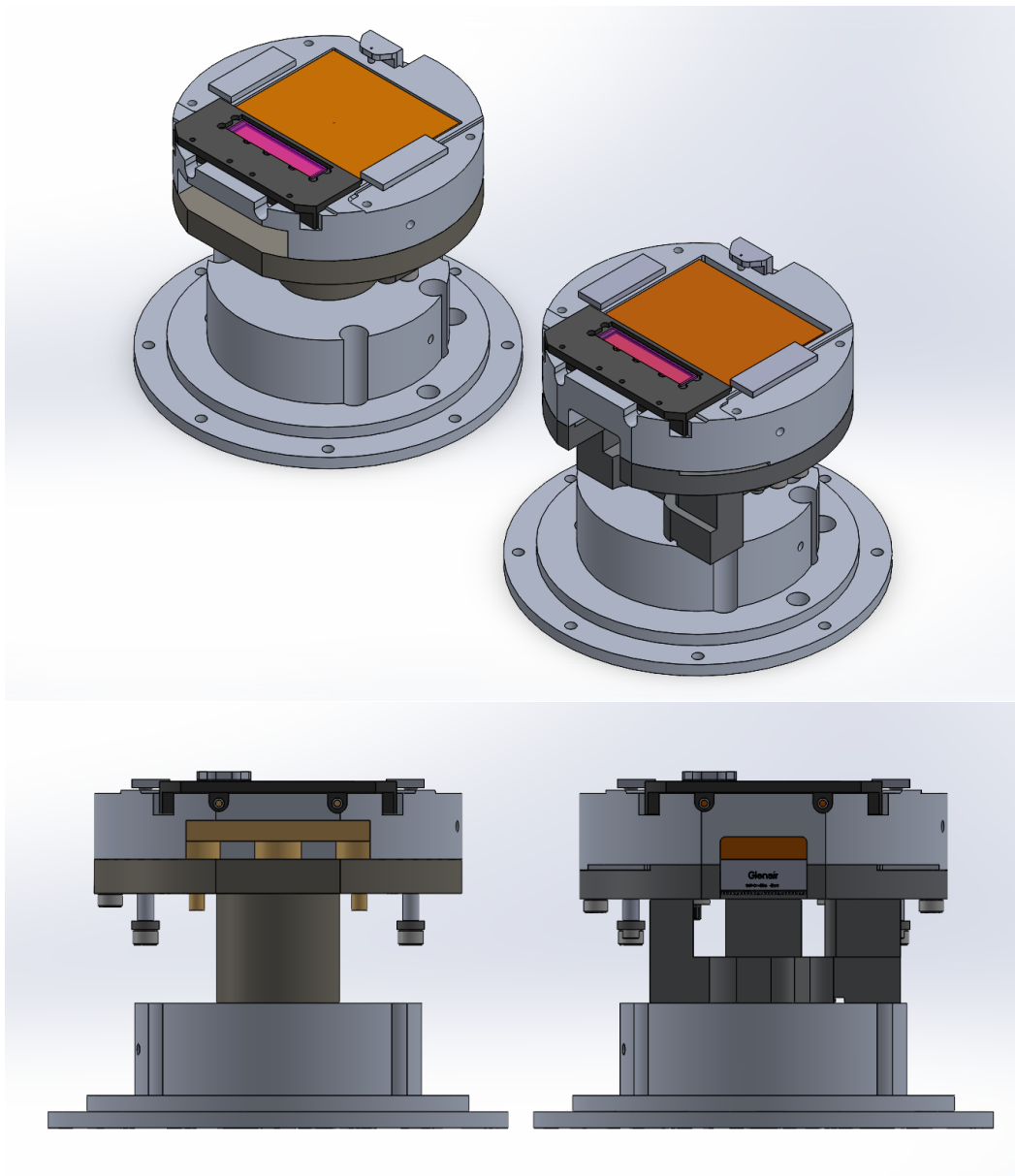


Figure 3.14: Side-by-side view CAD models of the original (left) and new (right) long-wavelength detector focal plane arrays. The new molybdenum mount has significantly more space to accommodate the new connector and discrete wire harness as opposed to the old flat-flex cable. Thermal isolation of the array from temperature transients during launch is maintained in the new design.

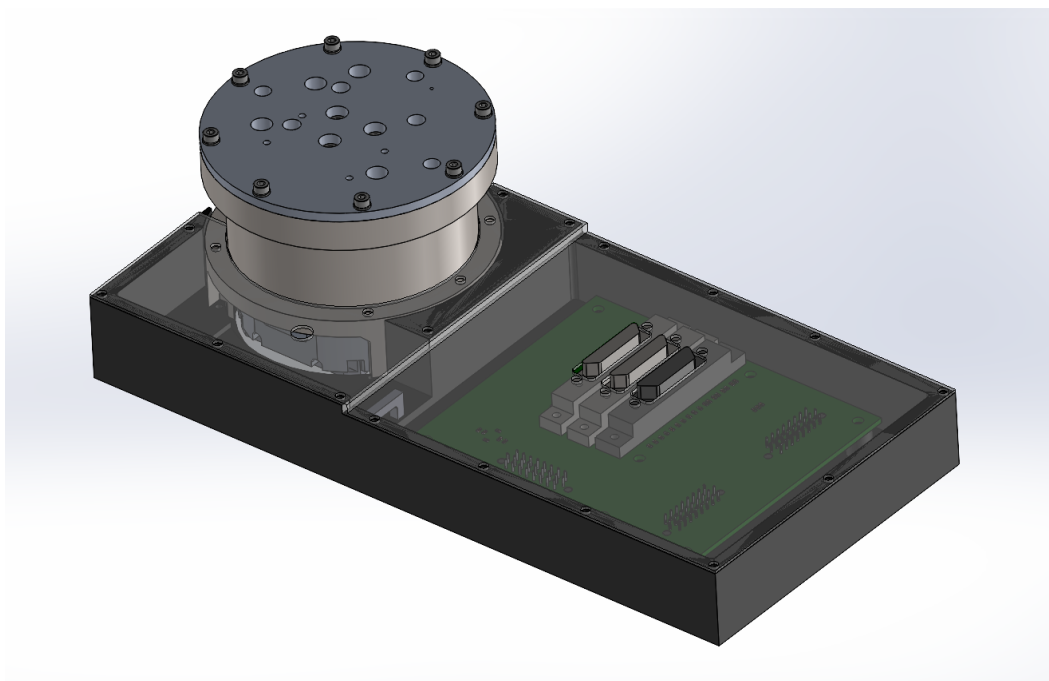


Figure 3.15: CAD model of the final design of the entire long-wavelength FPA, including the focal plane readout board housing and associated connectors. Here, the anodized aluminum plate that encloses the top of the focal plane readout board is shown as transparent, and the H2RG itself is pointing down and out of view. Mylar tape was used to seal any holes used to access fasteners or gaps in the structure to eliminate light leaks.

FPA Assembly

All assembly of the re-designed long-wavelength FPA took place in a cleanroom at the Rochester Institute of Technology. Special care was taken to protect the sensitive H2RG array from electrostatic discharge and dust during assembly. An array mounting rig provided by Teledyne allowed for the nano-miniature connector (and associated wire harness) to be attached to the array prior to assembly. As with CIBER-2 in general, FPA fasteners were secured against launch vibrations with lock-washers rather than epoxy in order to simplify any potential future disassembly.

It is absolutely essential that the H2RG itself not be touched at any point during the assembly, except on the underside where fasteners attach it to the FPA. The Nano-D connector, attached to a custom-made harness that routes I/O lines to the focal plane readout board, is connected before removing the H2RG from the secure housing provided by Teledyne with the array (Figure 3.16). Once the new molybdenum mount was assembled and prior to attaching the array, the assembly was connected to a modified aluminum base plate and then in turn to a temporary standoff rig which allows the person assembling the device to reach fasteners underneath the stack before the H2RG was secured (Figure 3.17). Once the H2RG itself was fully secured, a specialized clamshell jig (unmodified from the original design) allowed for the modified aluminum top cap to be safely inserted on top of the array without risk of physically damaging it. We used an aluminum safety cap secured to the top cap (removed prior to integration inside the CIBER-2 cryostat) to both protect the H2RG surface when exposing it is not necessary and to pre-load the spring clamps used to secure the dual-band filter. Figures 3.16, 3.17, 3.18, 3.19, 3.20, 3.21, and 3.22 detail the assembly process.

Prior to placing and securing the two filters, we measured the gap between the delicate array surface and the surface of the top cap (where both filters rest) using a microscope. Array wirebonds, which cannot be touched by the assembly under any circumstances, were measured to be 40-60 μm above the top cap surface – well within the clearance slot built into the LVF holder, which was unmodified on the new long-wavelength FPA. The gap Δ between the array surface and the dual-band filter should be as low as possible to reduce the size of optic ghosts produced by internal reflection while still maintaining the manufacturer-specified 100 μm minimum surface safety clearance; the original long-wavelength FPA used on the 1st flight was measured at $\Delta \approx 300 \mu\text{m}$. During assembly of the modified FPA, we measured Δ at 6 points to range from $\Delta \approx 170 - 240 \mu\text{m}$, lower than the older

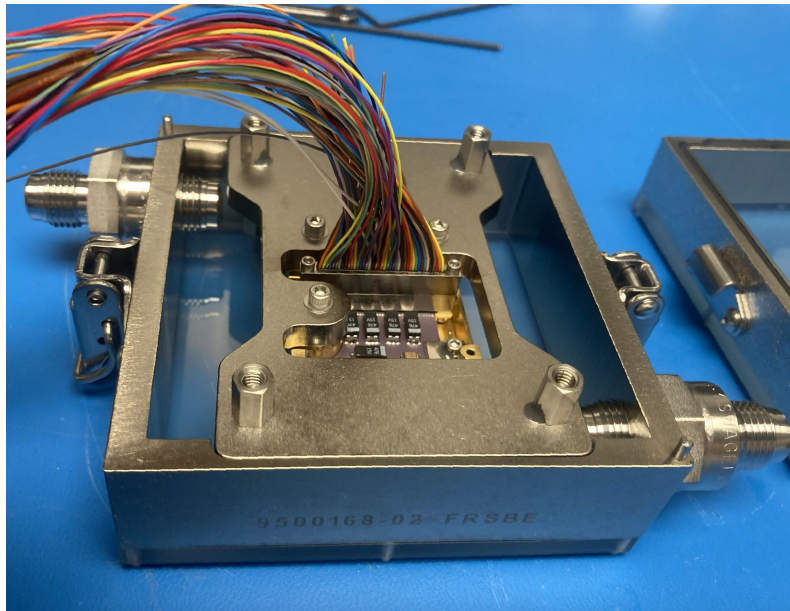


Figure 3.16: The new long-wavelength H2RG, still in its secure housing as received from Teledyne, after attaching the Nano-D connector and associated custom harness. This connector is never removed once the H2RG is removed from the housing.

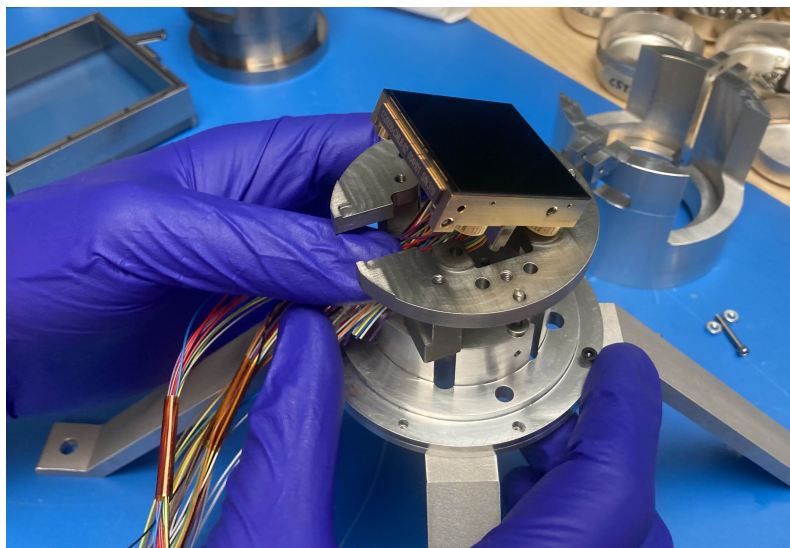


Figure 3.17: The H2RG array being integrated into the in-progress FPA stack, with the temporary standoff rig in place. The standoff is removed after the H2RG is secured in place, and was essential to reliably assembling the stack without ever touching any part of the H2RG itself.

assembly while being above the safety limit (Table 3.3).

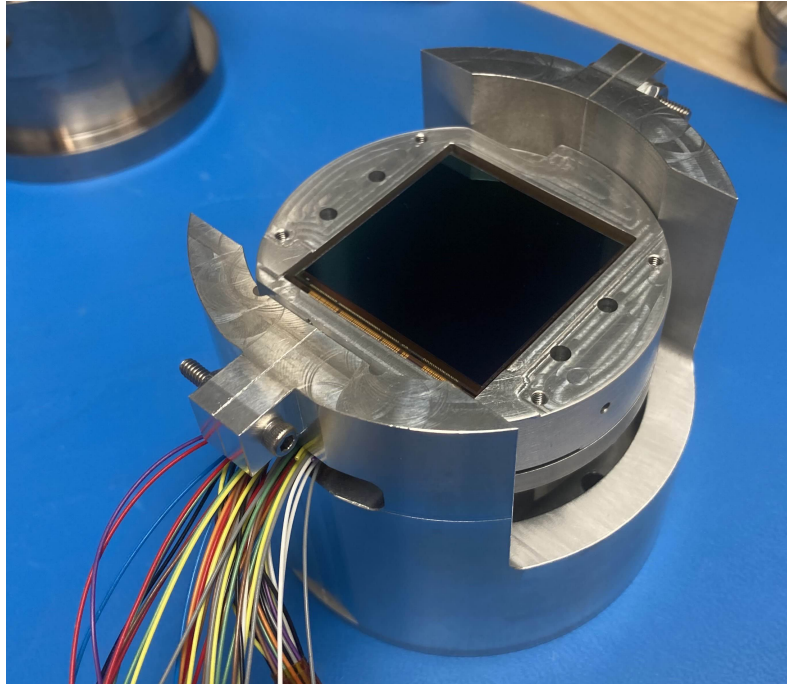


Figure 3.18: The in-progress FPA stack with the H2RG secured, just after attaching the top cap using a custom clamshell jig. This clamshell jig was unmodified from the original FPAs still used on the short- and medium-wavelength detectors. The jig allows for the top cap to be set in place without ever touching any part of the array itself. Here, no filters have yet been integrated into the stack.

Integration

After assembling the FPA and conducting a thorough manual pin-check of all FPA harnessing, we integrated the new long-wavelength FPA into the overall CIBER-2 assembly and began a cooldown cycle of the cryostat. Due to time constraints for readiness for the 2nd flight, we did not perform a separate test with the FPA alone inside a smaller cryostat. As the detector cannot be operated at room temperature, we successfully powered on the detector for the first time after the FPA fell below 100 K. Aside from a minor wire modification required on the new focal plane readout board during the next warming cycle to resolve an observed issue reading one of the array's $32\,64 \times 2048$ pixel channel strips, we found the new long-wavelength detector assembly and readout board to be fully functional. This new FPA flew successfully on the 2nd and 3rd flights of CIBER-2 within design specifications with no observed mechanical or electrical issues. An example dark exposure from the new detector after being installed in the re-designed FPA is shown in Figure 3.23.

Position	Δ (μm)
Lower Left	195.3
Middle Left	243.5
Upper Left	167.9
Upper Right	214.0
Middle Right	198.4
Lower Right	218.8

Table 3.3: Microscope-measured displacements between long-wavelength H2RG surface and the surface of the top cap where the dual-band filter rests. Positions are listed going counter-clockwise around the array, with "lower" defined as the surface containing the wirebonds. Measured displacement should be as low as possible without falling below the $100\mu\text{m}$ safety threshold; all displacements were found to be above this threshold and below the measured gap of $\approx 350\mu\text{m}$ for the original FPA used for the 1st flight.

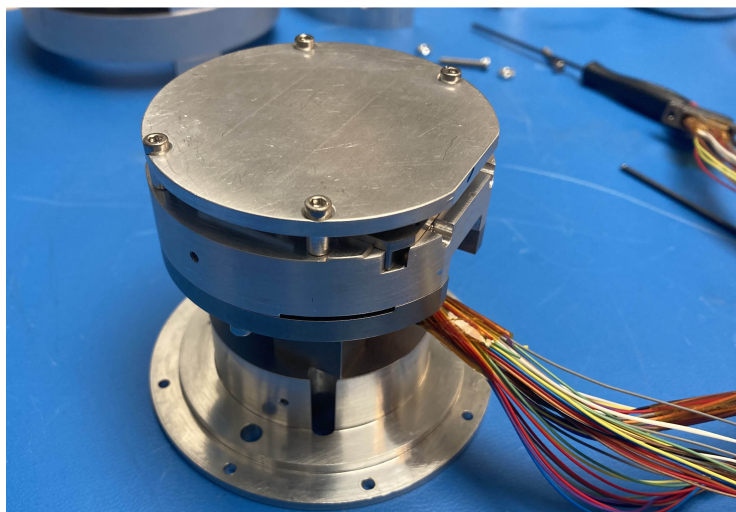


Figure 3.19: The in-progress FPA stack after integrating the LVF and dual-band filter, with the safety cap installed. In addition to protecting the array and filters during the rest of the assembly process, the safety cap serves to pre-load the dual-band filter spring clamps during filter integration, allowing the clamps to be gently lowered into place.



Figure 3.20: The fully assembled FPA stack after integration into the titanium housing, with both filters covering the H2RG surface visible. Dust on the filters, an inevitability even in a cleanroom environment, was removed with a squeeze blower prior to integration into the overall instrument. Note the gap between the aluminum top cap and the titanium housing, providing thermal stability for the H2RG by forcing all heat transfer to occur only through the housing, aluminum base plate (not visible), and molybdenum mount (not visible).

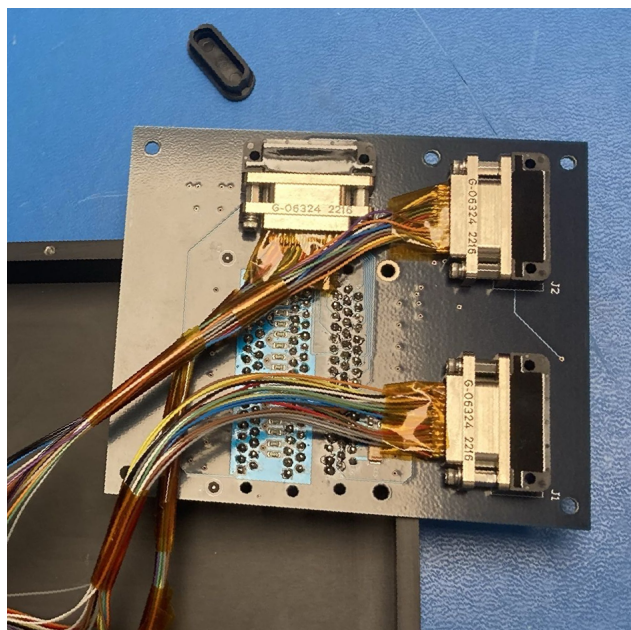


Figure 3.21: The new custom focal plane readout board, attached to the custom H2RG harness by three Micro-D connectors. The other end of this harness is connected to a single Nano-D connector (Figure 3.16). Harness bundles are secured with kapton tape prior to integration into the FPA enclosure.



Figure 3.22: The final fully assembled long-wavelength focal plane array, lacking only the anodized aluminum cover that normally conceals the focal plane readout board. All openings in the aluminum base plate (top left) as well as seams on the anodized housing were covered in mylar tape prior to integration into the overall instrument to prevent light leaks. The custom focal plane readout board (right) breaks the H2RG signal output into three standard connectors that can be accessed without opening the FPA, routing to the main CIBER-2 warm electronics suite.

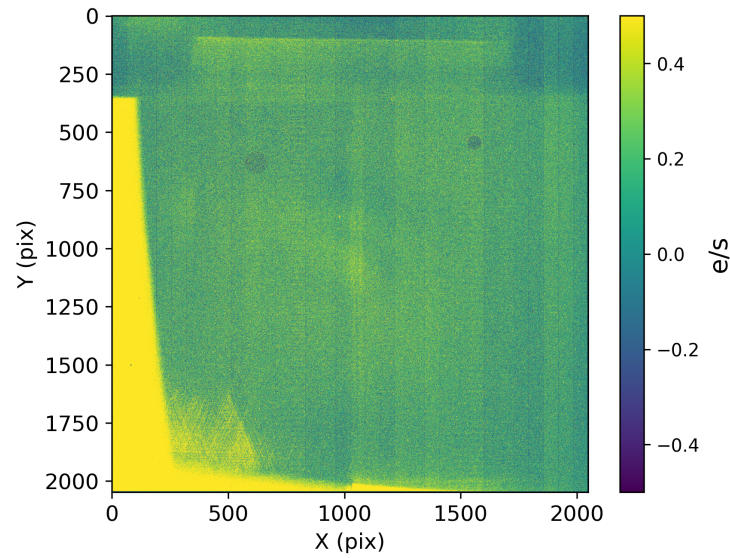


Figure 3.23: $N = 44$ frame (~ 1 minute) dark current exposure from the new long-wavelength detector taken shortly before the 3rd flight of CIBER-2. A small misalignment of the cold shutter which appeared after the 1st flight is responsible for the thermal glow around the lower left corner, which was excluded from dark noise characterization for this detector (see Zemcov et al., 2025). This glow is caused by thermal emission from the bulkhead sealing the aperture of the telescope during dark testing, and as such is not seen in images of flight fields.

3.4 Large Spatial Scale Noise Reduction for CIBER-2

CIBER-2 Row-chopping Implementation

The row-chopping noise reduction technique described in Heaton et al., 2023 (see Section 2.3) was implemented on CIBER-2 for the 2nd and 3rd flights. As CIBER-2 uses the same 32-channel H2RG readout mode as SPHEREx (Zemcov et al., 2025, Nguyen et al., 2025), optimizing spatial noise performance at $\theta > 5'$ scales using this technique corresponds to the same $S \approx 20 - 30$ skip parameter. While we did not implement additional reference row reads beyond the default 8 on CIBER-2, applying row-chopping to the entire array has the added benefit of mimicking the distributed reference row reads demonstrated to improve noise performance on SPHEREx. The latter instrument interleaves reference row reads evenly in time throughout each frame readout independent of row-chopping skips (Nguyen et al., 2025). On CIBER-2, reference rows are treated identically to optically-sensitive rows and are therefore distributed somewhat by row-chopping, resulting in row-chopped exposures having even lower large-scale noise compared to standard exposures when channel-level reference correction is applied to each. Using $S = 25$ row-chopping, we observe a 30% reduction in $\theta = 5' - 20'$ ($\ell = 500 - 2000$) spatial noise without reference correction and a 50% reduction with reference correction.

Following validation testing in November 2022 and January 2023 (Figure 3.24), the 2nd and 3rd flights were conducted with $S = 25$ row-chopping implemented on all three detectors. Frames are unscrambled back to their physical order before being written to the on-board storage, resulting in no manual unscrambling being necessary during post-flight data processing to recover images.

Large-scale Crosstalk Correction

Significant reductions in large-scale noise sensitivity on the CIBER-2 detectors were implemented between the instrument's 1st and 2nd/3rd flights. With dark current already reduced to significantly below the photon noise level produced by the dominant Zodiacal Light emission seen in flight, reducing large-spatial-scale crosstalk noise observed during the 1st flight was a high priority.

With all three arrays active simultaneously as they would be in flight, ground testing prior to the 1st flight revealed significant crosstalk at amplitudes (>0.2 e/s) meeting or exceeding observed array dark current on all three detectors (Figure 3.25). This crosstalk manifested itself on each array into two main categories: "block" crosstalk consisting of very long timescale (>1 s) step-function-like signals affecting all 32

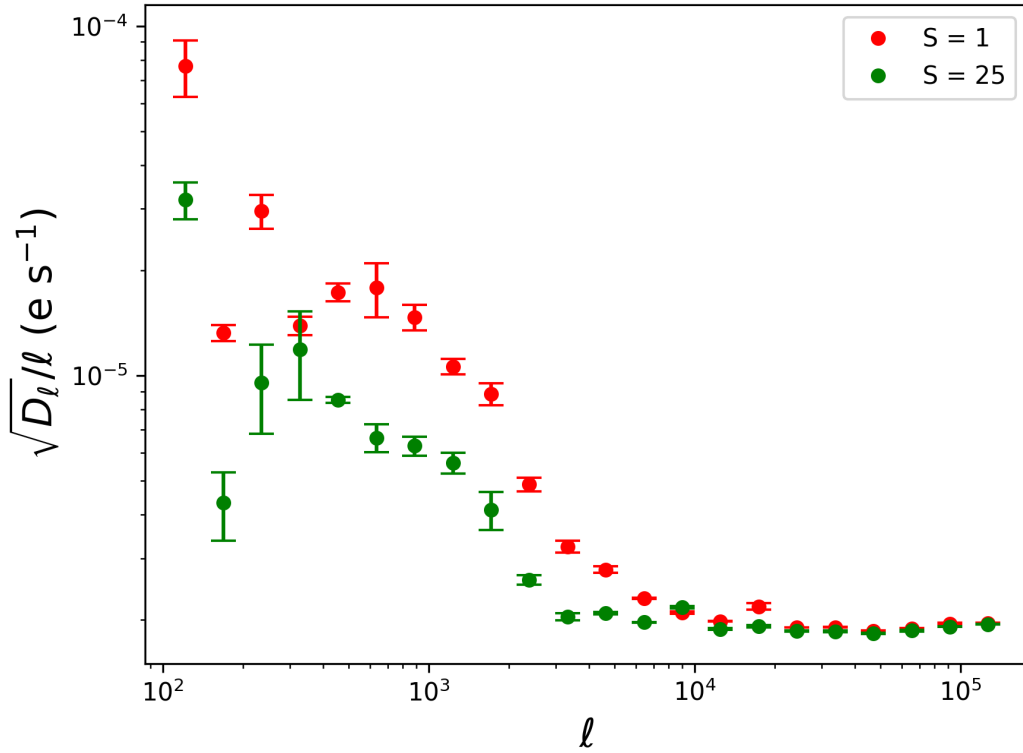


Figure 3.24: Spatial power spectra comparing row-chopped data to un-row-chopped data for 30s dark exposures taken with the CIBER-2 short-wavelength detector in January 2023, several months before the instrument’s 2nd flight. Here, S is defined in the same way as in Heaton et al., 2023, with $S = 1$ corresponding to reading the H2RG in the usual unmodified manner. For each S , 6 exposures with no reference correction were used to create 3 pair differences and the resulting spectra were averaged. Row-chopping in the $S \sim 20 - 30$ range provides optimal noise reduction at large scales while leaving overall average noise power largely unchanged.

64×2048 array channel strips simultaneously and "channel" crosstalk producing stripes and offsets within individual channel strips. The implementation of row-chopping for the latter two flights modulates power from block-type crosstalk into somewhat smaller spatial scales but leaves channel-type crosstalk unaffected.

Some reduction in observed crosstalk was obtained by improving shielding on the instrument’s cold and warm harnessing. To validate that no significant crosstalk was being contributed by radiative signals between harnessing/boards after improving the warm harnessing, we enveloped the entire warm electronics suite in a crude Faraday cage constructed of aluminum foil and observed no increase in crosstalk noise. We instead found that much of the crosstalk of both types was caused by a lack of synchronization between arrays. The relevant crosstalk was finally eliminated

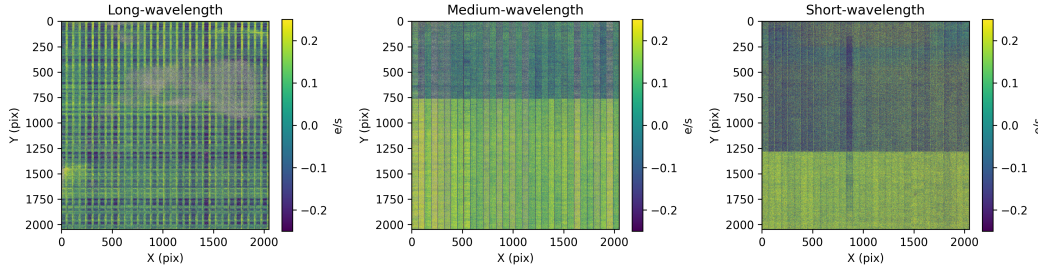


Figure 3.25: $N = 37$ frame (~ 49 s) dark exposure pair differences for all three detectors two weeks prior to the 1st flight, showing significant large-scale de-synchronization crosstalk patterns. These exposures were taken before implementing row-chopping, resulting in block-type signals being clearly visible. Here, reference correction at the channel strip level has been applied using all 8 reference rows. The horizontal block-type structure represents a long-timescale signal that varies between exposures and as such is not a fixed pattern. Note the large "cloud" of dead pixels present on the long-wavelength array; this data was taken with the original long-wavelength array and focal plane array, prior to their replacement for the 2nd and 3rd flights.

by tying the initial in-flight array long reset (or "T1" signal) sent from the flight telemetry module provided by WFF to the CIBER-2 warm electronics suite to a single relay (Figure 3.26). The T1 signal is interpreted by the CIBER-2 electronics software to both reset the accumulated charge on a given array and to reset the onboard frame counter to indicate that the instrument is in flight; this form of charge reset is relatively slow, taking several readout frames to accomplish. By using a single relay to send this signal rather than the initial three used on the NSROC telemetry module (which sent the long T1 reset individually to the three detectors), all three arrays are synchronized at the moment of takeoff and remain synchronized for the purposes of crosstalk for an observed >10 minutes (Figure 3.27), at which time the instrument has completed observing all target fields.

Post-flight Crosstalk Reduction and Characterization using Row-chopping

Row-chopping on the 3rd flight, in addition to its original purpose of reducing overall $1/f$ noise at large spatial scales, also provided a novel method for characterizing and reducing residual noise at large scales relative to a given array. An anomalous T1 array reset affecting only the medium-wavelength array was observed ~ 77 s into the 3rd flight, resulting in the arrays being de-synchronized for the remainder of the flight; during a nominal flight sequence, the T1 reset signal would not be sent after the initial takeoff reset at 1st stage ignition. This injected a fraction of the

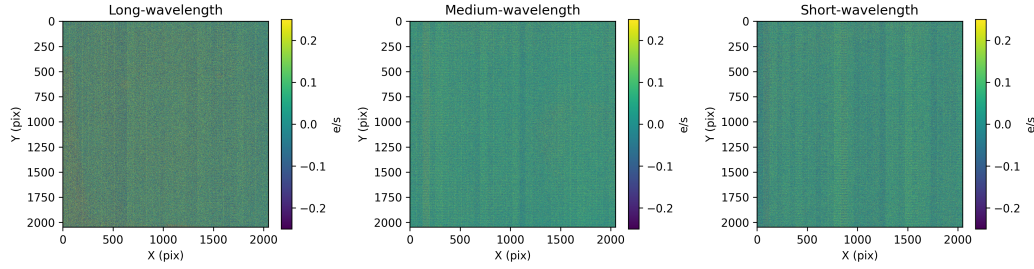


Figure 3.26: $N = 44$ frame (~ 1 minute) dark exposure pair differences for all three detectors one day prior to the 3rd flight while the instrument was integrated into the launch vehicle and on the launcher rail, using the same reference pixel correction and colorscale as Figure 3.25. Here, $S = 25$ row-chopping and a synchronized T1 reset have been implemented. Note that the new long-wavelength array used on the 2nd and 3rd flights is in use. Inter-channel crosstalk has been essentially eliminated, with large scale noise structure reduced to the level of single-array exposures. Minor residual block-type noise, faintly visible and present even on single channel exposures, has been modulated to smaller spatial scales by row-chopping.

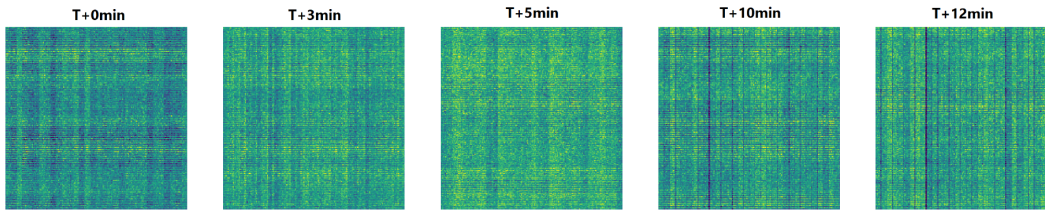


Figure 3.27: Dark pair-difference images from a 3-channel crosstalk drift test conducted at NASA WFF with the medium-wavelength detector prior to the 2nd flight to verify that crosstalk remains negligible throughout the timeline of a typical flight. At T+0, all three detectors are synchronized using a long T1 reset; the detectors are then allowed to drift apart with standard non-synchronizing resets used to collect each subsequent exposure. To construct pair differences, each exposure is subtracted from a separate exposure taken on the same detector for the same exposure time without other detectors active (i.e. an exposure with no crosstalk) to highlight crosstalk noise structure. No detectable crosstalk due to de-synchronization is present until approximately 10 minutes have passed, long enough to cover an entire CIBER-2 flight.

large-scale crosstalk previously eliminated in ground exposures into flight exposures for the long- and medium-wavelength detectors; the short-wavelength detector was largely unaffected. Since both block- and channel-type crosstalk vary in amplitude and phase across exposures, the small number of dark frames collected with the cryogenic shutter closed as CIBER-2 falls back to the surface are inadequate on their own for correcting the injected noise.

During typical row-by-row array readout without row-chopping, block-type crosstalk injects a signal that varies over the entire vertical length of the array in the slow-scan direction. Under these circumstances, there is no way to robustly separate long-timescale crosstalk noise from sky signal. Since row-chopping essentially decouples the sky signal from the noise, any structure in the vertical slow-scan direction of 3rd flight images with a period greater than the skip parameter S (in this, case $S = 25$ rows) must be from the sky and vice-versa on images where row-chopped data has been unscrambled to put the array into time-ordering. This allows us to decouple the electrical signal from the sky signal within the array and address each separately (Figure 3.28).

To remove the block-type crosstalk injected by the anomalous reset, we use the following general method:

1. Beginning with a 64×2048 channel strip of a flight exposure, apply column-wise reference pixel correction (resulting in 8 reference pixels per each of the 64 columns)
2. Mask all known sources, reference pixels, and the linear variable filter region
3. From the photosensitive dual-band filter region, subtract the median photocurrent
4. Apply the row-chopping algorithm described in Heaton et al., 2023 in reverse, putting the channel strip into time-ordering
5. Fit a step function to the channel strip after applying a σ -clip operation
6. Subtract the best-fit step function and unscramble the strip back into physical ordering, repeating all previous steps on each of the 32 channel strips

This decoupling of the electrical signal and sky signal is also useful for validating the level of crosstalk reduction after this (or any other) removal technique is applied. With row-chopping readout, a sample of the entire timestream is imprinted into a relatively small portion of the array, allowing for a very small dark region to be used for characterizing the entire array. In this case, a coarse sample of the entire frame timestream all the way down the array is imprinted into just the first 25 rows. Here, we use the small dark region created by the linear variable filter holder ($2 \times \sim 256 \times 256$ pixel corners and a small ~ 100 pixel wide strip connecting them) on each

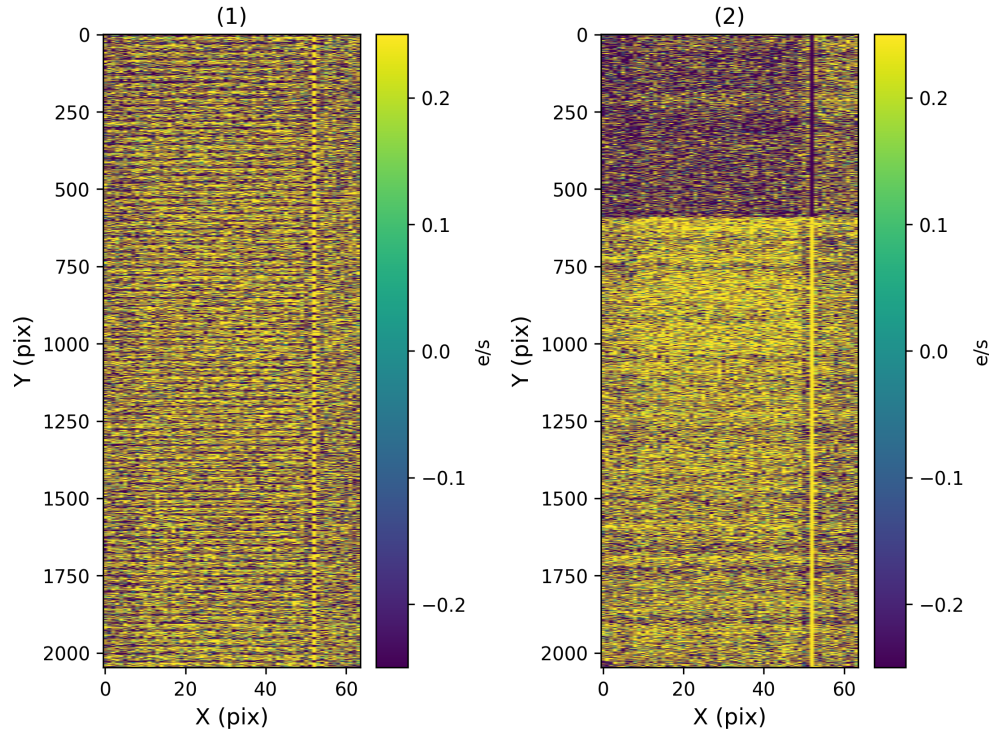


Figure 3.28: An individual dark-corrected 64×2048 pixel channel strip from the $N = 10$ frame dark exposure taken after the 6th field (Lockman B) was observed during the 3rd flight on the medium-wavelength detector, with the cold shutter closed. (1): The channel strip in physical row order as read in flight, with $S = 25$ row-chopping. (2): The channel strip with row-chopping manually undone post-flight to re-arrange the rows into time-ordering, with the original low-frequency block-type crosstalk signal clearly visible. Row-chopping decouples the electrical signal from the sky signal; undoing the row-chopping operation post-flight has the effect of essentially applying row-chopping to the sky signal while unscrambling the noise.

array to characterize this crosstalk on exposures from the 3rd flight (Figure 3.29). Spatial power spectra of the relevant dark regions, which contain a sampled imprint of the entire timestream along the channel strips involved, show the corrected images have large-scale noise performance comparable to the pre-anomaly dark data taken on the launcher rail prior to the flight (Figure 3.30). Work continues to refine this technique into a complete noise model for the CIBER-2 3rd flight data.

Overall, row-chopping is effective both at its original intended purpose of significantly reducing the large-spatial-scale impact of $1/f$ detector noise and at characterizing excess large-scale noise on images post-collection, all while keeping sky

signals intact. The techniques described here based on row-chopping are useful beyond the study of CIB anisotropy for any application where noise at large scales relative to field of view of a detector is relevant.

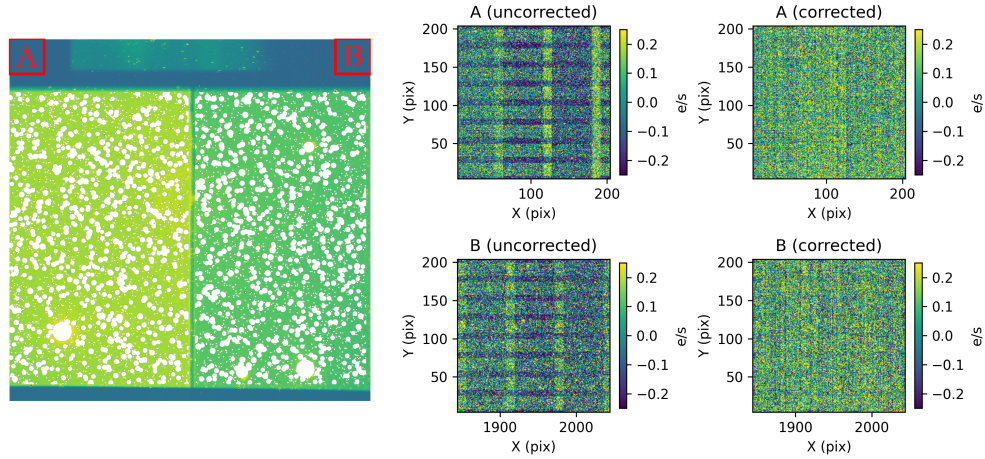


Figure 3.29: Application of the row-chopping-assisted step-function fit noise reduction technique, as seen in dark 200×200 pixel regions shielded from light by the linear variable filter holder on the full medium-wavelength Lockman B $N = 37$ frame dark-corrected flight exposure. This technique is effective at removing large-scale crosstalk injected due to the anomalous medium-wavelength detector reset encountered during the 3rd flight of CIBER-2. Note the periodic grid structure formed by the $S = 25$ row row-chopping readout. Each of these 25-pixel-wide blocks contains a sampling of the entire vertical direction of the array – as a result, if the noise reduction technique is validated in a dark region near the top of the array, any such findings apply all the way down to the bottom of the array within the relevant 64-pixel-wide channel strips.

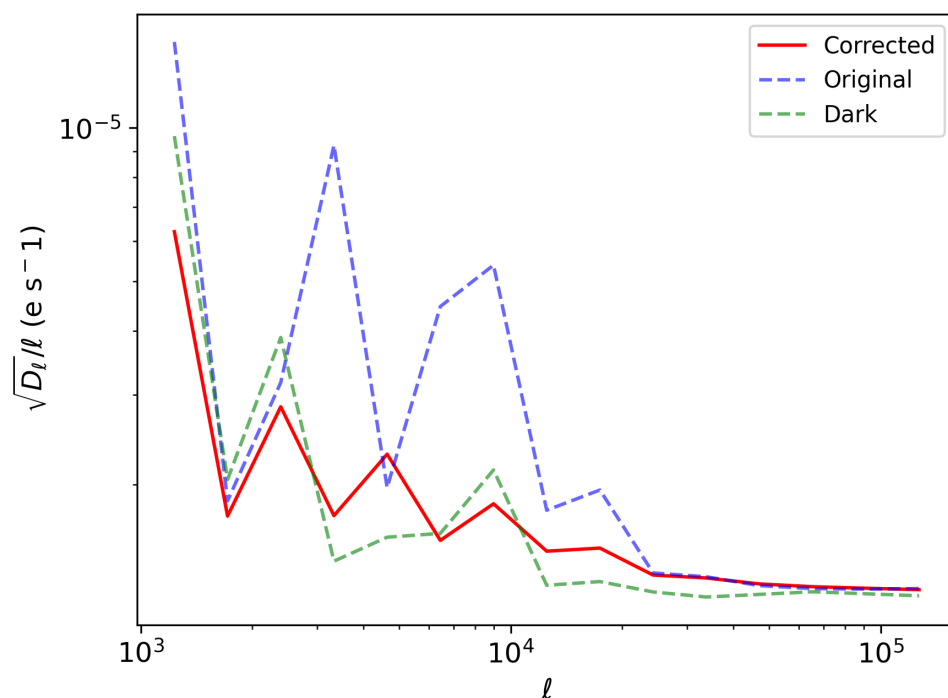


Figure 3.30: Average spatial power spectra for the $2 \times 200 \times 200$ pixel dark regions shielded from light by the linear variable filter holder on the full medium-wavelength Lockman B $N = 37$ frame dark-corrected flight exposure, labeled *A* and *B* on Figure 3.29. The dark reference spectra here is calculated from a pair difference for dark exposures taken while CIBER-2 was on the launcher rail the day before the 3rd flight. The described row-chopping-assisted step-function fit noise reduction technique is effective at bringing large-scale spatial noise power down to the level of the dark exposures taken before the anomalous medium-wavelength detector reset injected additional crosstalk into the large scale modes.

3.5 H2RG Gain Calibration

We utilize the discrete nature of photon noise on an array to calibrate the CIBER-2 detectors with precisely measured gains converting recorded pixel voltage to electrons per second, implementing the methods described in Nguyen, 2021 and Nguyen et al., 2025. Following the formalism described in Garnett and Forrest, 1993, the photon noise σ on a photocurrent I_e (both in e/s) resulting from a best-fit slope to an H2RG exposure is given by:

$$\sigma^2 = \frac{6}{5} \frac{1}{T} \frac{N^2 + 1}{N^2 - 1} * I_e \quad (3.1)$$

Here, T is the exposure time and N is the number of samples (frames) in the exposure. Suppose we begin with a guess of the conversion between recorded microvolts (μV) and electrons g_0 to measure an observed photocurrent I_g . Defining α as a correction factor with $\alpha = 1$ when our guess is correct (i.e. $\alpha I_g = I_e$), we can write:

$$\sigma_g^2 = \frac{6}{5} \frac{1}{T} \frac{N^2 + 1}{N^2 - 1} * I_g * \frac{1}{\alpha}, \quad (3.2)$$

where σ_g is the measured standard deviation resulting from the incident photocurrent observed with our initial guess for the gain. All values in Equation 3.2 except for α are now either known or directly measurable. By binning the pixels in an exposure by photocurrent and using a linear regression to obtain $\frac{1}{\alpha}$, we can obtain a robust estimate of the true array gain $g = \alpha g_0$.

For gain calibration, we calculate a single average gain for each of the three H2RG arrays. Datasets used in this calculation include exposures taken during routine health checks with the calibration lamps active, exposures with the cold shutter open such that the long-wavelength detector observes thermal emission from the bulkhead, and exposures generated during flat-field calibration – all of which provide a range of photocurrents on which to construct bins. Exposures with very high photocurrents are unsuitable for this measurement due to charge accumulation non-linearity caused by pixel saturation. Dark exposures dominated by dark current are also not optimal due to the narrow range of photocurrents to bin upon. We use the following procedure based on methods described in Nguyen et al., 2025 to calculate a gain correction factor for a pair of exposures taken at identical photocurrents (Figure 3.31):

1. Difference the two exposures to obtain a noise image, multiplying by the necessary $\frac{1}{\sqrt{2}}$ prefactor and applying a sigma-clip operation to remove bad pixels
2. Calculate the mean of the two exposures and construct bins of equal photocurrent width, using the average photocurrent in the bin as I_g
3. For pixel positions within a given bin, calculate σ_g as the standard deviation of these binned pixels on the noise image
4. Estimate $\frac{1}{\alpha}$ as the slope given by the linear regression described in Equation 3.2 across all bins

Using this procedure, we obtain the average array gains as $g_L = 4.24 \mu\text{V}/e$, $g_M = 4.53 \mu\text{V}/e$, and $g_S = 3.56 \mu\text{V}/e$ for the long-, medium-, and short-wavelength H2RG arrays respectively.

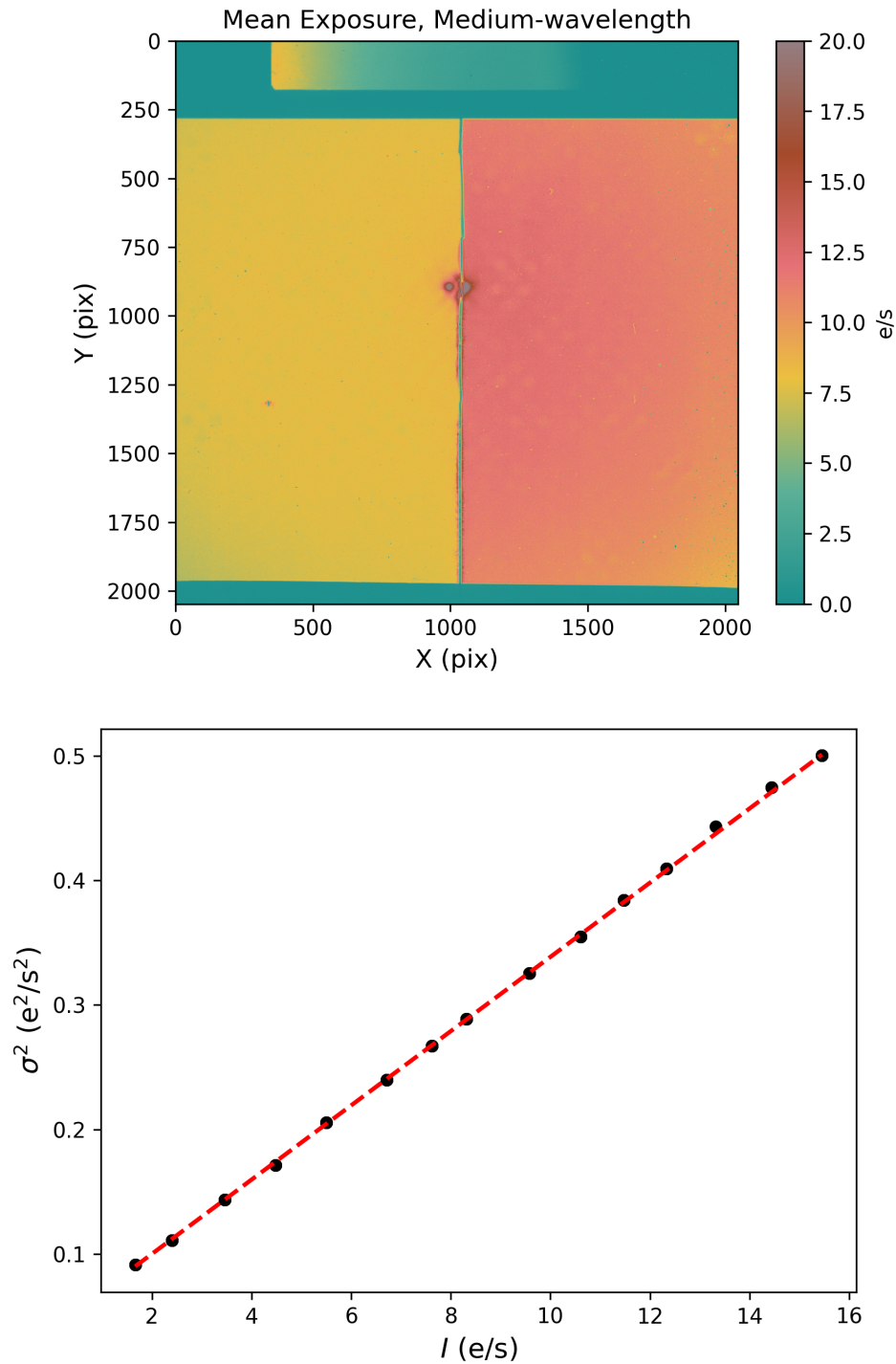


Figure 3.31: Example of H2RG photon noise gain calibration on the medium-wavelength H2RG array. Above: $N = 30$ frame health check exposure taken with the cold shutter open and calibration lamps on, providing a range of non-saturating photocurrents. Below: corresponding plot of measured σ^2 vs. I with corresponding linear fit in red. Here, the average calculated gain for the medium-wavelength array was already applied to the image, resulting in a recovered $\alpha \approx 1$.

3.6 3rd Flight Detector Dark Characterization

Dark data collection on CIBER-2 is enabled by the cold optical shutter (Section 3.1), which is actuated either manually during ground testing or automatically in flight and blocks bright thermal emission from the shutter door. While we routinely collect dark exposures throughout the course of the deployment campaign leading up to a launch, we collect the main characterization dataset the day prior to launch: a large number of $T = 75$ s dark exposures while the instrument is on the launcher rail. This dataset, taken with the instrument in flight mode and attached to the rocket, is intended to closely mimic the noise performance the detectors will have in flight and is used to create a post-flight noise model. A subset of the launcher rail dark dataset is also taken with the instrument powered by internal battery power to provide the most flight-like data possible. Finite battery capacity and long charge times while the vehicle is on the launcher rail limit the number of internal power exposures that can be obtained.

We also take a small $N = 10$ frame in-flight dark dataset ($T \approx 13$ s) in the short period between the end of the final observation field and the vacuum shutter door closing for re-entry into the atmosphere (Figure 3.32). This exposure is not sufficient for dark characterization, but provides a small sample of dark data closely matching conditions with those of the flight fields. For the 3rd flight, this dataset shows the excess crosstalk associated with the anomalous medium-wavelength detector T1 reset that occurred early in the mission (Section 3.4). Dark current measurements from this set are also noisy due to the short integration time and detector persistence from bright sources observed during the final Lockman B field observation immediately before.

Following the 1st flight, we observed a light leak on the long-wavelength detector caused by a small misalignment of the cold optical shutter. This leak affects $< 10\%$ of the pixels of the long-wavelength array and, in flight mode, represents thermal emission from the closed vacuum shutter door sealing the cryogenic section. Although this somewhat complicates dark characterization, the leak is not present in flight field images; the leak is present in the small in-flight dark dataset with the cold optical shutter closed, but in that case it is instead caused by atmospheric airglow as the instrument descends to lower altitudes. For dark current, CDS, and spatial noise measurements presented here, the light leak region (confined to one edge of the array) is masked out on this detector.

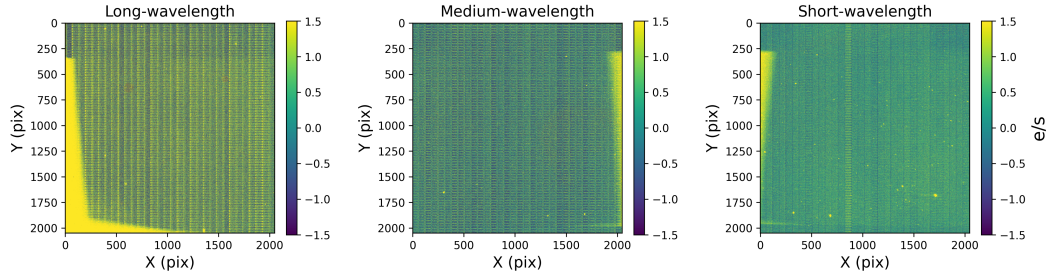


Figure 3.32: $N = 10$ frame ($T \approx 13$ s) uncorrected in-flight dark exposures from the 3rd flight, taken with the cold optical shutter closed just after observation of the Lockman B field. Stripes due to excess de-synchronization crosstalk are clearly visible, with the long-wavelength detector most affected. Note the light leak visible on all three arrays due to the slight cold shutter misalignment; this glow is due to airglow emission entering the telescope as CIBER-2 dropped back into the atmosphere. Ghost "stars" visible in all three detectors are due to detector persistence from Lockman B observations immediately prior.

Dark Current

Dark current is the observed current on a detector that is not caused by an incident signal. On CIBER-2, we measure dark current on the ground using $T \approx 75$ s dark exposures with the cold optical shutter closed. A T1 synchronizing reset is manually sent at the start of each exposure – we skip the first 5 frames of each exposure to remove residual effects from this slow reset, resulting in a final usable exposure time of $T = 60$ s per image. This exposure time was chosen such that the dark exposures can be used to model any flight observation field exposure and to limit the effect of read noise on dark current measurements, which decreases with increasing exposure time.

Individual image frames, which are stored and recoverable on CIBER-2, capture integrated charge throughout the entire exposure. To calculate the average dark current for each detector, we first fit a slope to each pixel of a given exposure, returning an average current over the entire array. We average many such exposures to obtain a dark current template (Figure 3.33) as well as a single mean value of I_{dark} for each detector. We do not observe a significant exponentially decaying dark current component on the CIBER-2 detectors such as the effect described in Biesiadzinski et al., 2011 and as a result record only a constant dark current (Nguyen et al., 2025). Measured mean dark currents for the three main characterization datasets are presented in Table 3.4, with all three arrays showing very low dark current consistent with each other. All three measured mean dark currents are far

	Internal Flight-like	External Flight-like	Flight
I_{dark} (e/s)	0.07, 0.03, 0.08	0.08, 0.05, 0.07	0.02, -0.09, 0.00
$\sigma[I_{dark}]$ (e/s)	0.01, 0.03, 0.08	0.01, 0.05, 0.06	–
CDS (e)	16.0, 16.0, 23.3	16.0, 15.9, 23.3	16.0, 15.7, 23.6
$\sigma[\text{CDS}]$ (e)	0.02, 0.14, 0.09	0.04, 0.14, 0.10	–
N_{exp}	8	22	1
T (s)	60	60	13

Table 3.4: Dark current I_{dark} , CDS noise, measured I_{dark} & CDS standard deviation across exposures, number of exposures used, and per-exposure times for the three primary dark characterization datasets. Values are listed for the short- (blue), medium- (teal), and long- (red) wavelength detectors respectively – for the long-wavelength ground data and all in-flight data, the images are cropped prior to calculation to avoid light-leak regions which do not represent true dark current. The independent sample size for CDS noise is $N/2$ due to pair differencing. A large flight-like dataset on external power and a smaller flight-like dataset on internal battery power were taken the day prior to launch while the assembled launch vehicle was horizontal on the launcher rail. A very small in-flight dark dataset is taken in the brief time between the end of observation and the instrument beginning re-entry into the atmosphere. Here, ground datasets are $N_{frame} = 44$, 1-minute exposures with a T1 reset manually sent 5 frames prior to all used frames, while the flight datasets uses a standard non-synchronizing reset and consists of only a single $N_{frame} = 10$, 13-second exposure. The negative dark current associated with the in-flight medium-wavelength exposure represents an artifact of the very small sample size ($N_{exp} = 1$) for this dataset.

below the expected $\sim 4 - 8$ e/s minimum field photocurrent from the Zodiacal Light, and are generally consistent with the ~ 0.05 e/s expected dark current for a $2.5\mu\text{m}$ cutoff H2RG (Teledyne Imaging Sensors, 2022).

Correlated Double Sampling Noise

We measure correlated double sampling (CDS) read noise using the individual frames themselves, which non-destructively record total integrated charge in each pixel. For a given dark exposure, we difference adjacent frames (resulting in $N/2$ independent frame differences for an exposure with N total frames) and measure the standard deviation of all pixels in the frame difference as the CDS noise. Extreme outliers (e.g. dead pixels) are removed by a $5\text{-}\sigma$ -clip operation on each frame difference. The total mean CDS for a given exposure is then obtained as the average CDS across all frame differences. The long-wavelength detector, which was replaced after the 1st flight and is therefore a different H2RG variant compared to the short- and medium-wavelength detectors, shows the highest CDS noise – somewhat higher

than the expected $\sim \leq 18$ e for a $2.5\mu\text{m}$ cutoff H2RG (Teledyne Imaging Sensors, 2022).

Large-scale Spatial Noise Performance

CIBER-2 was designed to be photon noise limited at large spatial scales $\ell > 1000$. We validate this by comparing the spectra of pair-differenced dark exposures to the spectra of photon noise caused by the bright Zodiacal light. The latter, consisting of purely Poisson noise, is flat in terms of $\sqrt{D_\ell}/\ell$. For dark spatial spectra characterization, we pair-difference dark exposures to produce $N_{exp}/2$ independent dark noise images and apply a $5\text{-}\sigma$ -clip operation followed by reference correction. Alternating column noise, a result of the column bus implementation in H2RG arrays (Rauscher, 2015), is present on CIBER-2 and contributes noise at relatively small scales; here, as with SPHEREx (Heaton et al., 2023), it is ignored in favor of improving the statistical power of the larger spatial scale correction by averaging all reference pixels within each given 64×2048 channel strip and subtracting a single value from the entire strip. For the long-wavelength detector, we crop out the light leak caused by the cold shutter misalignment as photon noise contributed by this leak is not present in flight field images. Zodiacal Light intensities in each observed field are estimated using the SPHEREx sky simulator (Crill et al., 2025, which in turn uses a Zodiacal Light model based on a modified variant of the Kelsall model (Kelsall et al., 1998); these intensities are then converted to e/s photocurrents using the CIBER-2 calibration factors.

Average dark spectra from combining the Internal and External Flight-like datasets taken while CIBER-2 was horizontal on the launcher rail prior to launch show that the detectors were photon noise limited for $\ell \gtrsim 1500$ when compared to the highest predicted Zodiacal Light photocurrent in any of the six observation fields for each of the six filter bands (Figure 3.34).

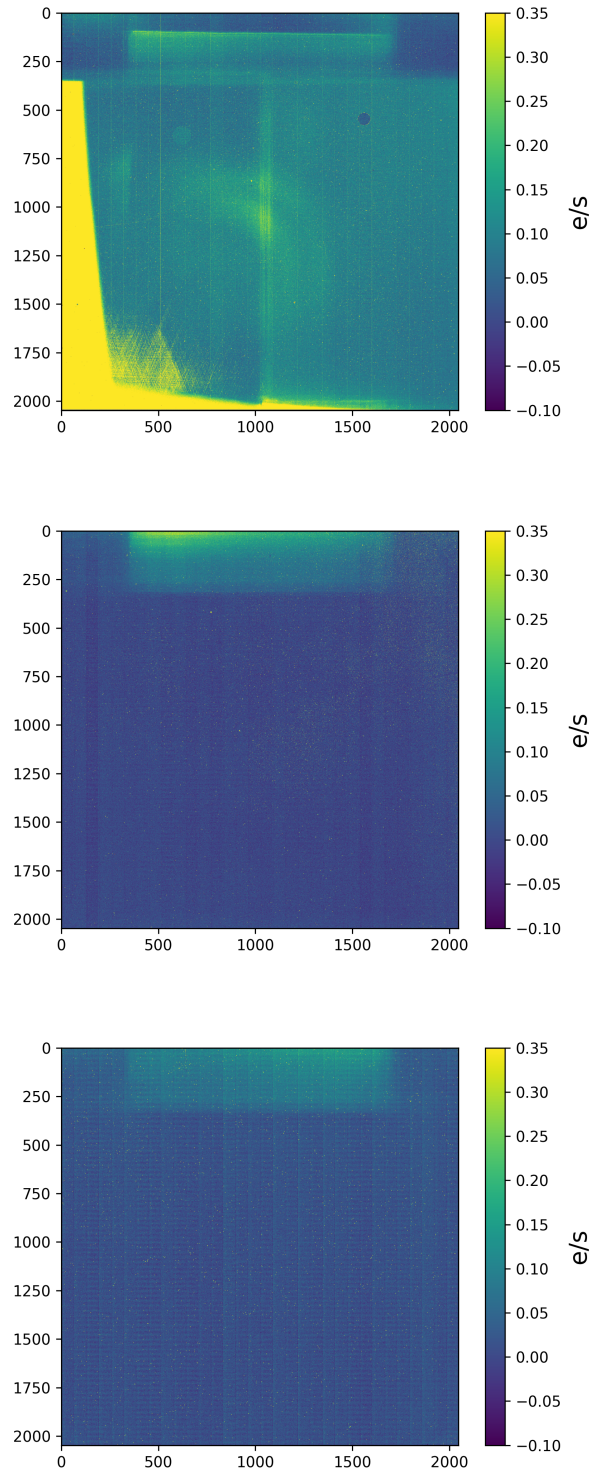


Figure 3.33: Average of $N_{exp} = 22$, $N = 44$ frame ($T = 60$ s) dark exposures from the External Flight-like dataset taken while the experiment was horizontal on the launcher rail for the long-wavelength (top), medium-wavelength (middle), and short-wavelength (bottom) detectors. Note the large shutter misalignment light leak on the long-wavelength detector, and a small light leak associated with the LVF on all three detectors.

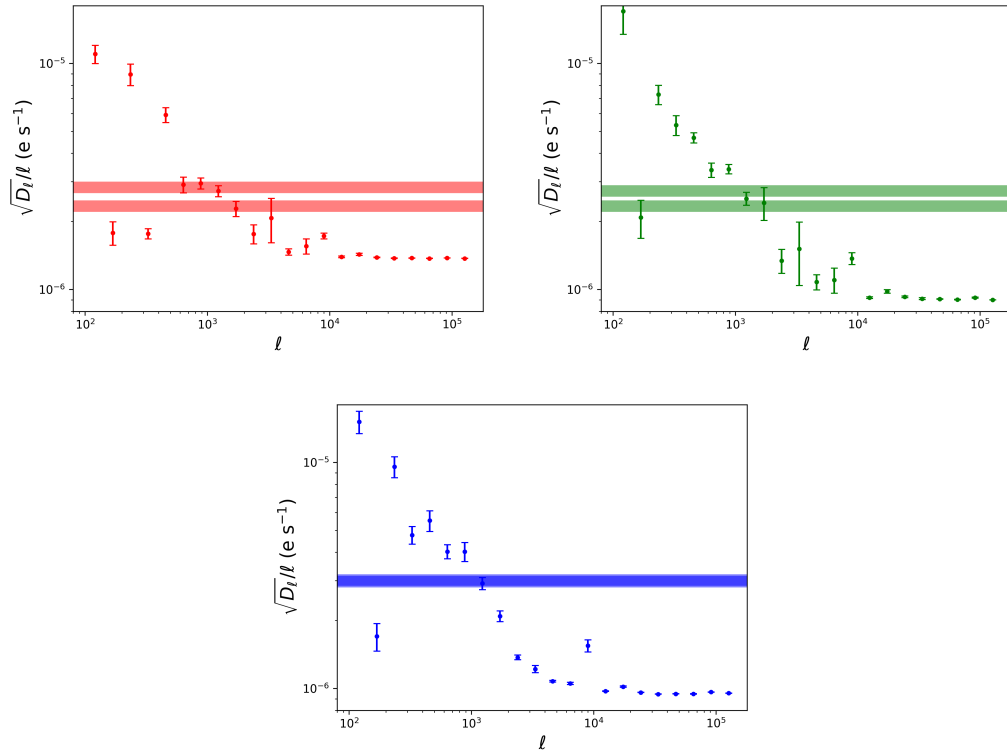


Figure 3.34: Average mean angular power spectra for the long-wavelength (red), medium-wavelength (green), and short-wavelength (blue) detectors from the combined Internal (on-board battery) and External Flight-like dark datasets taken while CIBER-2 was horizontal on the launcher rail attached to the launch vehicle. Channel strip reference correction is applied to each of $N_{exp}/2 = 15$ independent pair differences. Photon noise levels are defined as those resulting from the highest estimated Zodiacal Light photocurrent from any of the six observation fields; this level is calculated for each of the six CIBER-2 bands C1-6, resulting in two displayed levels for each detector. Neglecting contributions from airglow, CIBER-2 is photon noise limited for $l \gtrsim 1500$ ($\theta \approx 0.12^\circ$) spatial scales.

3rd Flight Airglow

Airglow can remain an issue for diffuse background observations even on suborbital sounding rocket payloads. The definition of "space" is somewhat arbitrary, with atmospheric emission remaining potentially non-negligible even at altitudes exceeding hundreds of kilometers above Earth's surface. For example, the SPHEREx instrument in orbit at an altitude of ~ 700 km still observes a prominent atmospheric He-I triplet line at $\lambda \approx 1.08 \mu\text{m}$ (Hui et al., 2026a, Hui et al., 2026b). Sounding rockets such as CIBER-2 and its predecessor CIBER-1, which reach significantly lower altitudes than many orbital missions despite still traveling above the overwhelming majority of Earth's atmosphere, can still be affected by excess airglow on images. This occurs particularly at longer wavelengths (Feder et al., 2025a) where thermal black body emission from atmospheric gas close to ambient temperature becomes significant.

During the 3rd flight, CIBER-2 observed significant time- and altitude-dependent airglow emission which significantly increased the actual photon noise on flight field images (Figures 3.35, 3.36). The total background emission varied widely across fields and wavelengths: ranging from very close to the predicted photocurrent due to Zodiacal Light for some fields on the shortest wavelength band to over an order of magnitude greater photocurrent above the predicted value for the longest wavelength band at the start of field observations (Zemcov et al., 2025). This large excess intensity at longer wavelengths, orders of magnitude higher than expected contributions from fainter diffuse backgrounds such as the Diffuse Galactic Light or EBL, is likely due to airglow from material carried up with the instrument which is then lost over time.

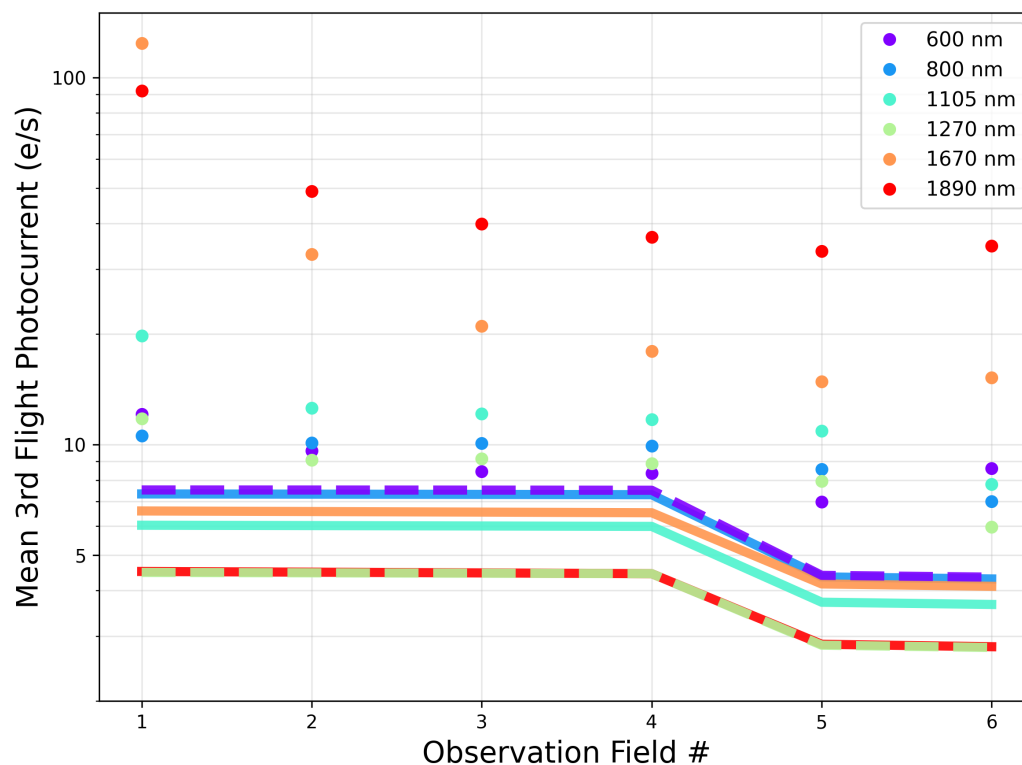


Figure 3.35: Measured mean photocurrents for each of the six observation fields during the 3rd flight of CIBER-2, with the model-based predictions of Zodiacal Light photocurrent shown as solid/dashed bars. Fields were observed in order during the flight; excess observed intensity, due almost entirely to airglow, decreases as a function of flight time. Airglow contamination is most severe in the two longest wavelength bands (corresponding to the long-wavelength detector).

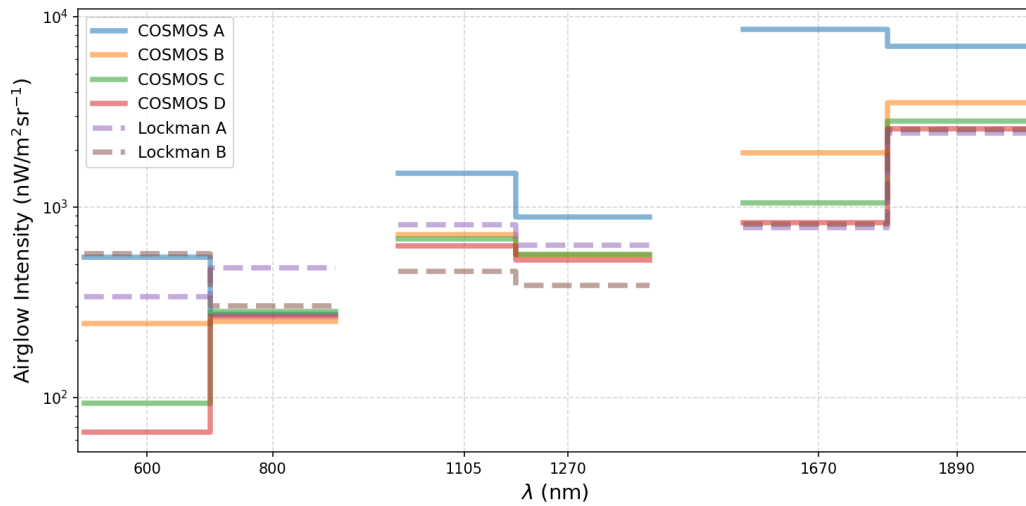


Figure 3.36: Measured coarse airglow spectrum with the six CIBER-2 primary dual-band filters C1-6 during the 3rd flight. Here, airglow intensity is estimated as the total mean background intensity within a given band and field minus expected contributions from Zodiacal Light and Diffuse Galactic Light, with fainter contributions (e.g. EBL) assumed to be negligible. Airglow is generally highest during the first field observed (COSMOS A) before decreasing, likely due primarily to material carried up with the launch vehicle. There is some evidence for an altitude-dependent component, particularly at short wavelengths, with the COSMOS A and Lockman B fields occurring at the lowest altitudes.

3.7 3rd Flight Temperatures and Thermal Controller Modules

Lakeshore DT-670 diode thermometers placed around the cryogenic section of the instrument are used to record relevant temperatures during both testing and in flight. During ground testing, we read these temperatures values in real-time; in flight, they are stored in the on-board solid state memory. For the latter case, each APHK-DAS-DAS cluster handles a set of up to 6 thermometers; note that thermometers recording temperatures near each detector FPA are not necessarily read by the detector's associated cluster.

FPA Thermal Control

We utilize thermal controllers to stabilize H2RG array temperatures during launch, implemented on the 3rd flight. Each controller (one per focal plane array) uses a PID control algorithm to smooth out temperature fluctuations caused by the violent shaking of the cryostat prior to 2nd stage engine cutoff. As it is not possible to safely directly attach a controller to an H2RG itself, we instead use controllers attached to the aluminum base plate at the base of each focal plane array. Treating radiative heat transfer under vacuum conditions as insignificant, heat can only transfer between a given H2RG (and its associated molybdenum mount) and the rest of the system conductively via this base plate (see Section 3.3). As a result, stabilizing temperature fluctuations on the base plate will also stabilize fluctuations on the H2RG by preventing in-flight temperature transients from actually reaching the array.

The controller measurement circuit consists of a simple Wheatstone bridge with a platinum resistance temperature detector (RTD) as one bridge leg (Figure 3.37). A simple resistive heater provides control, with a second auxiliary heater present to allow raising the the detector baseline temperature if desired. As detector temperatures on the relevant 3rd flight were somewhat higher than anticipated due to a poorer than expected vacuum, this auxiliary heater was not used. The controller circuit was housed in an anodized aluminum enclosure and potted with Stycast 2850 prior to integration into the instrument.

Each controller is operated via the relevant detector's associated APHK board with a refresh rate of $T = 0.5$ s using a standard PID algorithm with control function:

$$u(t) = K_p V(t) + K_i \int_0^t V(\tau) d\tau + K_d \frac{dV(t)}{dt}, \quad (3.3)$$

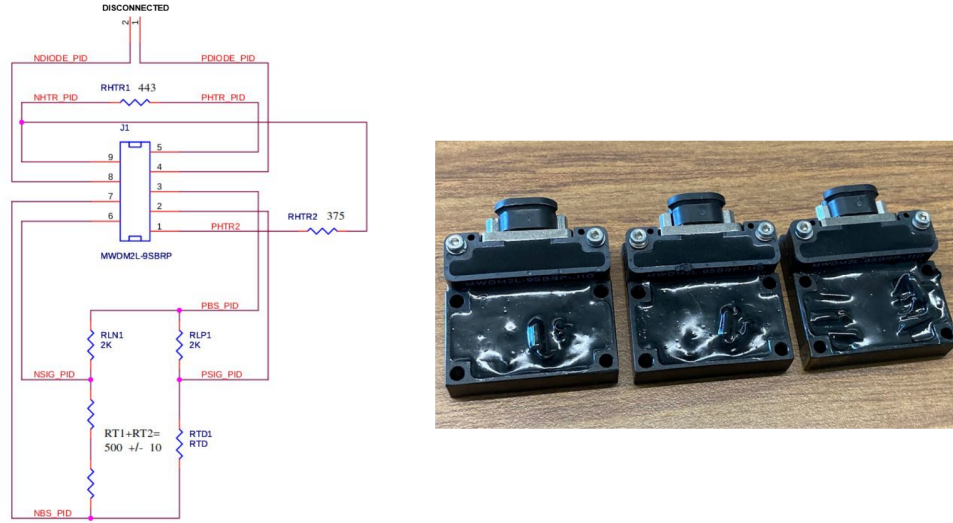


Figure 3.37: Schematic of a CIBER-2 thermal module (left) and assembled flight modules after being encased in Stycast 2850 (right). Temperature is read using a Wheatstone bridge with one leg consisting of a RTD thermometer. The flat surface of each controller (opposite, not visible) is secured to the aluminum base plate of each focal plane array.

where K_p , K_i , and K_d are the proportional, integral, and derivative gains respectively and $V(t)$ is the measured input signal. The baseline control temperature was set manually to ~ 1 K above the normal settling temperature of each detector. We optimized the control gains for each detector separately starting with the open-loop Ziegler-Nichols method (Ziegler and Nichols, 1942) and fine-tuning. Due to a mechanical interface issue between the warm electronics suite and a LN2 intake line while the instrument is in flight mode, we were only able to use the controllers for the medium- and long-wavelength detectors on the 3rd flight, with targeted control temperatures of $T_M = 85.7$ K and $T_L = 90.8$ K, respectively.

3rd Flight Temperatures

Due to the premature termination of the 2nd flight of CIBER-2, the 3rd flight was the first opportunity to record in-flight temperatures with the new long-wavelength detector FPA and to operate the thermal controller modules (which were not implemented on the 1st flight). Vacuum pressure in flight mode leading up to the 3rd flight was higher than expected, resulting in the instrument heating up more quickly when removed from its vacuum pump. The pump is removed several hours prior to launch; as a result, all three detectors were warmer during the 3rd flight by $\sim 3 - 17$ K

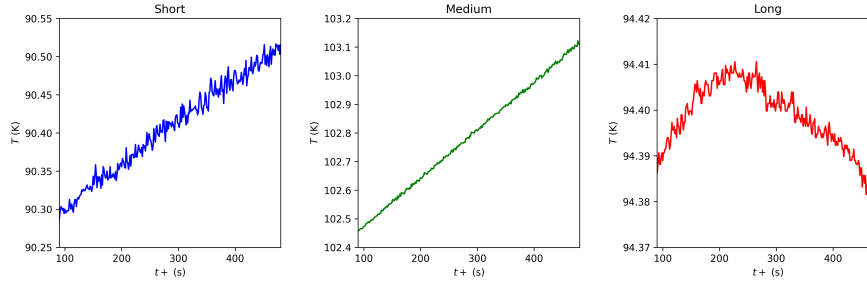


Figure 3.38: Focal plane array temperatures for the 3rd flight during field observation, with time measured as time since 1st stage ignition. Note the significantly different temperature scales for each detector. The medium-wavelength detector shows by far the most variation, a roughly linear temperature increase over the course of the flight caused by an unexpectedly poor vacuum prior to launch.

compared to during ground testing, with the medium-wavelength detector being by far the most affected (Figure 3.38, Table 3.5). This unexpected temperature increase was not substantial enough to significantly affect data quality, but did render the two active thermal controller modules ineffective by raising the baseline settling temperature of the focal plane arrays above the targeted control temperatures.

	Short	Medium	Long
T (K)	90.3	102.5	94.4
ΔT (K)	0.2	0.6	0.03

Table 3.5: Recorded in-flight temperatures for the 3rd flight of CIBER-2 at the start of observation. ΔT represents the maximum temperature drift recorded through to the end of observing the final field ~ 375 s later. A poorer than expected vacuum level resulted in decreased insulation and warmer temperatures during flight than during ground testing. The long-wavelength detector was extremely stable, while the medium-wavelength detector showed both the warmest temperature (up to 17 K above ground levels) and highest variation. Note that the DT-670 thermometers monitoring the focal plane arrays are located outside of the FPA stacks, implying that the redesign of the long-wavelength detector should not have had a significant effect on its associated thermometer output. The observed increased stability is instead likely due to the position of the long-wavelength FPA within the cryostat.

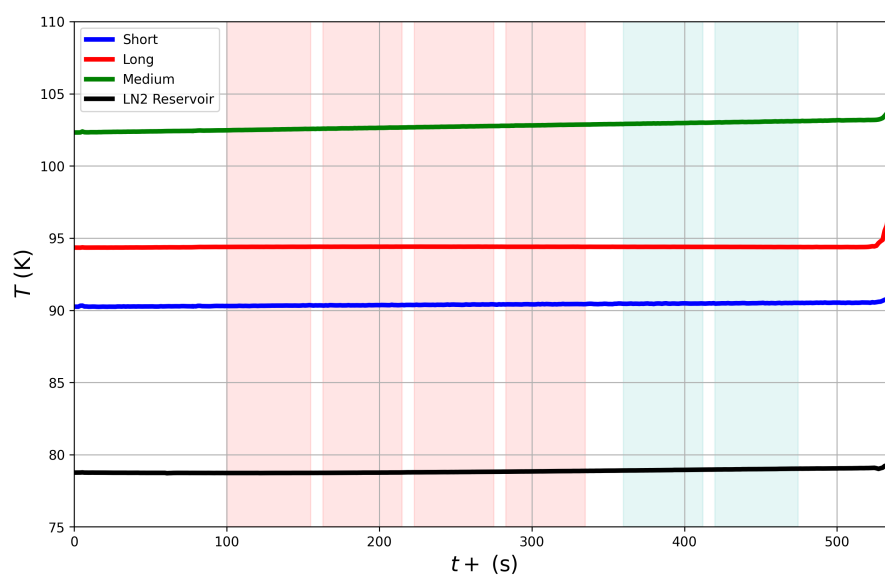


Figure 3.39: Temperatures for the three detector focal plane arrays and the liquid nitrogen reservoir for the 3rd flight, with time measured from 1st stage ignition at $t \approx 0$. Field observation times are shown as shaded regions with COSMOS A-D in red and Lockman A-B in teal. A rapid spike in all temperatures is observed when CIBER-2 begins to contact the atmosphere due to the shutter door failing to close.

Chapter 4

DEPTH CORRECTION FOR INTENSITY MAP CROSS-CORRELATIONS WITH GALAXY REDSHIFT SURVEYS

The extragalactic component of the cosmic infrared background (CIB) contains primarily redshifted stellar emission, and at high redshifts can be used to probe the Epoch of Reionization. Accessing this component, however, is complicated by various foregrounds even when fluctuation power-based measurements are used to partially bypass local foregrounds such as the Zodiacal Light. Additionally, auto-spectra measurements of the CIB mix power from all redshifts even when local and galactic foregrounds are accounted for.

Cross-correlations between large-area near-infrared intensity maps (such as those produced by CIBER-1, CIBER-2, and SPHEREx) and redshift tracers provided by external galaxy catalogs provide a solution to both of these issues, simultaneously reducing systematic foreground contamination and enabling redshift tomography of the CIB, isolating CIB power into distinct "slices" of known redshift to trace the history of the universe (Cheng and Chang, 2022). A particular future application of this technique will be to probe the history of intrahalo light (IHL) production. IHL is a theorized contribution to the CIB from $z < 3$ stars tidally stripped from their parent galaxies and residing in the galaxies' dark matter halos (Cooray et al., 2012), and has been proposed as the mechanism behind an observed excess spatial power in near-infrared CIB power spectra at large $\theta > 5'$ scales (Zemcov et al., 2014). Redshift tomography via galaxy-intensity cross-correlations will allow for particular redshift slices to be examined independently; a detection of the currently observed power excess confined to low redshifts would provide evidence for the IHL hypothesis.

Near-infrared intensity maps produced during the 4th flight of the original sounding rocket Cosmic Infrared Background Experiment (CIBER-1, Zemcov et al., 2013) are of particular interest for applying this cross-correlation technique, both as a pathfinder for the much larger SPHEREx dataset in progress and because the aforementioned excess power at $\theta > 5'$, $\ell < 2000$ scales was detected in auto-spectra of CIBER-1 1.1 μm , 1.8 μm intensity maps (Zemcov et al., 2014, Feder et al., 2025b).

The fields observed by CIBER-1 overlap with photometric galaxy catalogs produced by the Wide-field Infrared Survey Explorer (WISE, Wright et al., 2010), the Hyper Suprime-Cam (HSC, Miyazaki et al., 2018), and the Dark Energy Spectroscopic Instrument (DESI) Legacy Survey (Dey et al., 2019), allowing for cross-correlation tomography between CIBER-1 and each survey.

While cross-correlations in this manner mitigate systematic error on the original intensity maps used, they also introduce systematic errors associated with the galaxy survey catalogs themselves. A well-known source of error in galaxy catalogs if left uncorrected is depth variation (e.g. Leistedt et al., 2016), resulting in the density of detected sources fluctuating across a given field. In the context of CIB redshift tomography, uncorrected depth variations can contaminate anisotropy measurements of cross-power at spatial scales determined by the variations themselves; often, this scale overlaps with the large $\ell < 2000$ scales targeted by such measurements. In the absence of pre-existing random catalogs (catalogs of randomly distributed points encoding the geometry and depth variations of a survey, typically much denser than the survey itself) of sufficient density to correct the relevant galaxy catalog, the easiest method for removing this systematic is to simply remove all sources fainter than a pre-determined cutoff magnitude; this cutoff can be chosen such that sources faint enough to be likely to be affected by finite instrument depth are excluded. However, this necessarily decreases the number of sources available for cross-correlations and also disproportionately impacts high redshift sources (which are more likely to be faint). To maximize the available source density, it is instead necessary to correct for variable instrument depth.

This chapter will focus on methods used to correct this depth variation within the HSC Deep/Ultra-Deep (D/UD) field, with specific application to cross-correlations with CIBER-1. Similar corrections will also be necessary for future galaxy survey cross-correlations with the much larger dataset produced by SPHEREx.

4.1 HSC Depth Modeling

The HSC D/UD field dataset, which overlaps with a single $2^\circ \times 2^\circ$ CIBER-1 field (SWIRE ELAIS-N1; Bock et al., 2013), provides measured depth values in $\sim 10' \times 10'$ survey "patches" for each of the five *grizy* survey bands. Discrete source density variations on patches of this size will directly translate into large spatial scale contamination when cross-correlated with CIBER-1 intensity maps, and as such need to be corrected for if one wishes to not exclude faint sources. While HSC

random catalogs that encode the survey area are publicly available for the D/UD field, they lack the necessary source density or depth imprint required to directly use for our purposes, making it necessary to produce custom random catalogs for correcting the relevant depth variation.

All five HSC-*grizy* bands are used in the HSC source detection algorithm, but the HSC-i band (centered on $\lambda \approx 0.77 \mu\text{m}$; Kawanomoto et al., 2018) is first in the algorithm's priority order and most directly impacts the measurement; we therefore use the HSC-i band for subsequent analysis. To begin, we can define the completeness fraction for a part of the field simply as a function of magnitude m as:

$$C(m) = \frac{N(m)}{N_{\text{model}}(m)}, \quad (4.1)$$

where $N_{\text{model}}(m)$ is the expected count at infinite sensitivity and $N(m)$ is the count actually observed. To formulate $N_{\text{model}}(m)$, we use a two-part power law with a transition pivot at $m_{AB} = 24.7$. For the bright-end regime, we use the observed HSC-i slope between $22.0 < m_{AB} < 23.5$, assumed to be complete ($C(m) = 1$); for the faint-end regime, we use the slope provided by Helgason et al., 2012. With this model in place, we can observe $N(m)$ directly from the HSC-i dataset to estimate $C(m)$ within the CIBER-relevant portion of the HSC D/UD field. Defining free parameters σ and m_{eff} , we model the completeness function $C_{\text{fit}}(m)$ as:

$$C_{\text{fit}}(m) = \frac{1}{2} \left[1 - \text{erf} \left(\frac{m - m_{\text{eff}}}{\sigma} \right) \right]. \quad (4.2)$$

Here, as before, $C_{\text{fit}}(m)$ varies as a function of two-dimensional position on the field (or in the specific case of HSC, as a function of survey patch). By fitting $C_{\text{fit}}(m)$ to the observed $C(m)$ HSC-i data, we can determine the "true" effective 50% completeness depth m_{eff} defined as $C_{\text{fit}}(m_{\text{eff}}) = 0.5$. Prior to fitting, we bin reported HSC-i depths into 8 even-width bins. We find that Equation 4.2 is a good fit to the observed $C(m)$ (Figure 4.1), and that the mean derived effective HSC-i depth $m_{\text{eff}} \approx 25.8$ is over a magnitude shallower than the original reported median depth (Figure 4.2). Repeating this analysis with variations of $\pm 50\%$ in the faint-end slope results in a small change in the derived effective depth $\Delta m_{\text{eff}} = \pm 0.1$, indicating that the model is robust to moderate error in the assumed portion of the distribution model. As a result, the deviation between reported and derived 50% completeness depth for HSC-i is not likely to be the result of an error in the source distribution model.

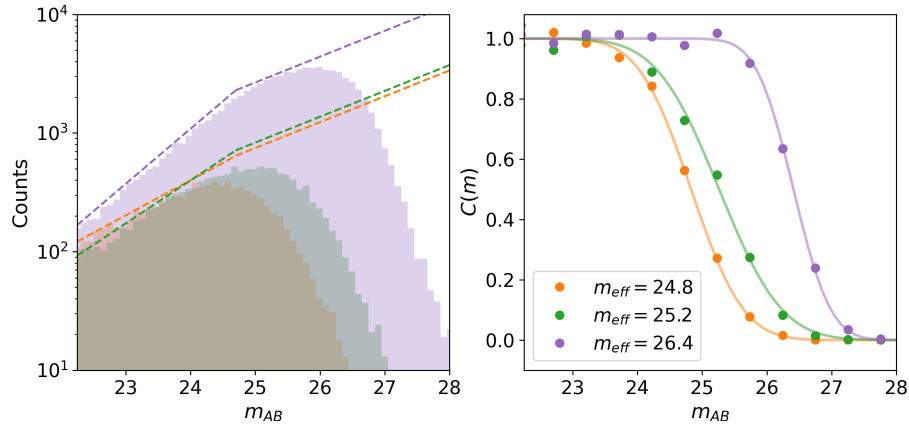


Figure 4.1: Left: observed HSC-i source counts as a function of AB magnitude, with the double power law source distribution model in use as dashed lines, for selected bins of reported HSC-i depth. Right: estimated HSC-i source completeness $C(m) = \frac{N(m)}{N_{model}(m)}$ as points with best-fit $C_{fit}(m)$ as solid lines for the same selected bins. Reported HSC-i depths are binned into 8 even-width bins prior to fitting, with the derived effective 50% completeness for each of the 3 displayed bins shown as m_{eff} . Displayed $C(m)$ points are co-added to a factor of 5 for visibility from the original binned dataset used for fitting to Equation 4.2. $C_{fit}(m)$ is found to fit the observed data well with the chosen source distribution model.

4.2 HSC Random Catalog Synthesis

A random catalog provides randomly distributed points covering the survey area of a given astronomical survey, encoding the survey geometry (i.e. coverage, field of view, masking) as well as systematics such as depth variations. Defining the number of galaxies falling within the field in a particular image pixel (i.e. a pixel of a CIBER-1 H1RG detector) as $n(x, y)$ and the un-normalized number of random catalog samples in the same pixel as $n_r(x, y)$, we can write the random-corrected overdensity field $D(x, y)$ as:

$$D(x, y) = \frac{n(x, y) - \frac{N}{N_r} n_r(x, y)}{\bar{n}(x, y)}, \quad (4.3)$$

where N , N_r are the total number of sources/points in the galaxy and random catalogs, respectively; their ratio normalizes a random sampling of arbitrary sample size. With properly constructed random catalogs, $D(x, y)$ is corrected for biases encoded therein.

In order to generate custom HSC random catalogs that contain both the observed depth variation and adequate density for use with 1024×1024 pixel CIBER intensity

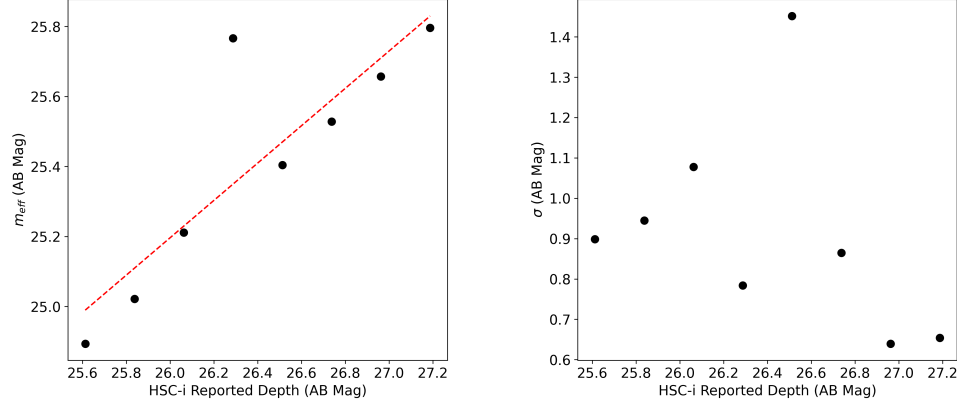


Figure 4.2: Best-fit parameters for Equation 4.2 on HSC-i D/UD sources and the described double power law source distribution model: derived effective 50% HSC-i completeness depth m_{eff} (left) and σ (right), both as a function of reported HSC-i depth. m_{eff} follows a generally linear trend; the best-fit line (red) is used to calculate m_{eff} for modeling completeness on mock sources. m_{eff} falls below the reported depth by $\Delta m_{AB} \approx 0.7 - 1.4$.

maps at $\approx 7''$ pixel scale, we utilize realistic mock galaxy catalogs from Mirocha, J. et al., 2026. Beginning with the patch-level depth variation reported for the HSC-i band, we begin by assigning a single value of reported depth to each CIBER pixel; in narrow regions where patches overlap, the mean of the reported depths is assigned. In order to calculate the completeness for a source of magnitude m in a given pixel $C_{fit}(m, x, y)$, we assign a value of σ and effective depth m_{eff} to each pixel. Since σ shows no clear trend as a function of reported depth, each pixel is assigned the fixed value of σ corresponding to the bin within which that pixel's reported HSC-i depth falls (resulting in 8 possible values of σ ; see Figure 4.2). For m_{eff} , which shows a linear trend as a function of reported depth, each pixel is assigned an effective depth according to the fit function $m_{eff} \approx 0.515m_d + 11.8$, where m_d is the reported HSC-i depth in AB magnitude. A comparison of reported m_d and derived m_{eff} depth maps mapped to a CIBER-1 detector are shown in Figure 4.3.

A given mock source falling within an arbitrary CIBER pixel (x, y) can now be assigned a unique completeness $C_{fit}(m, x, y)$, representing the probability that the source would be detected by HSC. Starting with a catalog of mock galaxies corresponding to the field of view of CIBER and a grid of zeros corresponding to CIBER pixels, we randomize all source positions. For each mock source with magnitude m_s , a random value $\alpha = [0, 1)$ is drawn to determine if the source is detected; if $\alpha < C_{fit}(m_s, x, y)$ the source is detected and the value for the pixel it falls on is

increased by one, otherwise the source is skipped over. This process is repeated for all sources in the mock catalog, followed by re-randomizing all sources and repeating the entire process for $N_{real} = 20$ realizations to create a random catalog $n_r(x, y)$ with $N_r = \sum_{x,y} n_r(x, y)$ corresponding to the portion of the HSC D/UD field that falls on the relevant CIBER observation field. This new random catalog is much denser than the HSC source catalog itself. By mapping this new catalog to a CIBER detector and applying Equation 4.3, we can remove the density imprint created by nonuniform depth from an observed galaxy overdensity map and eliminate the associated systematic error at large angular scales.

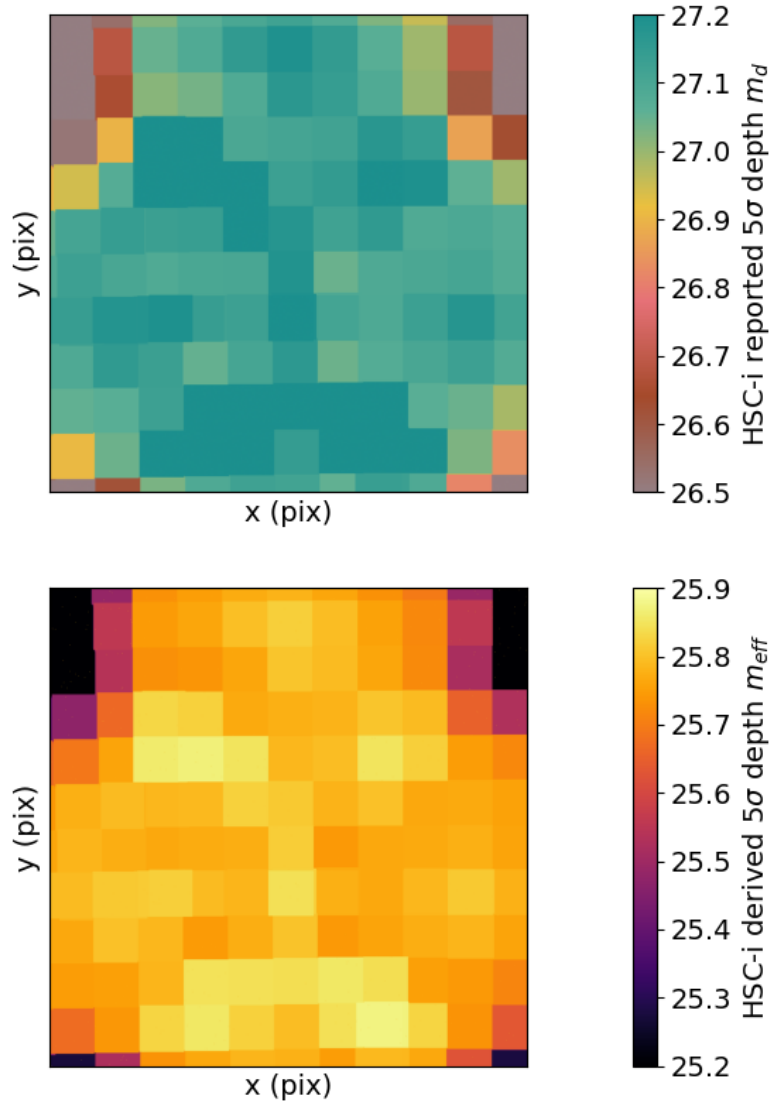


Figure 4.3: Reported (top) and derived effective (bottom) depth maps for the HSC-i band D/UD field mapped onto the CIBER $1.8\mu\text{m}$ 1024×1024 pixel imager for the SWIRE ELAIS-N1 field. Note differing color maps and scale. All magnitudes are reported in AB magnitude.

Chapter 5

A MEASUREMENT OF THE NEAR-INFRARED DIFFUSE GALACTIC LIGHT SPECTRUM WITH SPHEREX

5.1 Introduction

The diffuse galactic light (DGL) represents the imprint of dust within the Milky Way across the sky, consisting of starlight scattered by and thermal emission from this dust. It appears as broad-spectrum diffuse emission at all points on the sky, with peak brightness near the galactic plane. In addition to allowing for study of dust within our galaxy (Mathis, 1973, Schiminovich et al., 2001, Sujatha et al., 2005, Brandt and Draine, 2012, Arai et al., 2015), the DGL also encodes information about the interstellar radiation field (ISRF) (Witt et al., 1997) and is a foreground for extragalactic background light observations.

Evidence of starlight scattered by interstellar dust was first suggested by studies of dark nebulae (Struve and Elvey, 1936), followed shortly after by the first measurement of the optical DGL near the galactic plane (Elvey and Roach, 1937) and subsequent measurements at higher latitudes (Henyey and Greenstein, 1941, Elsässer and Haug, 1960). Observation of the DGL, however, is complicated by the local Zodiacal Light (ZL) produced by sunlight scattered off interplanetary dust within the solar system and (in the case of ground-based telescopes) bright airglow from Earth’s atmosphere. To mitigate effects of the latter, the first space-based measurement of the DGL was carried out via sounding rocket (Wolstencroft and Rose, 1966). Later, the space telescope IRAS (Infrared Astronomical Satellite) enabled mapping the thermal DGL emission of Milky Way dust at far-infrared wavelengths (Low et al., 1984).

At near-infrared and optical wavelengths, there has been success disentangling the DGL from the ZL and other sources via linear correlations between near-infrared intensity maps and dust-dominated far-infrared maps derived from IRAS observations. Despite this, the properties of the DGL far-infrared-correlated component at shorter wavelengths are not yet fully understood. Empirical ratios between optical and IRAS 100 μ m measurements were first reported by Laureijs et al., 1987 and later Guhathakurta and Tyson, 1989. More recently, Brandt and Draine, 2012 used this technique to measure the optical $\lambda = 0.39 - 0.92\mu$ m DGL spectrum using

correlations with the Sloan Digital Sky Survey (SDSS) over three large regions of the sky, mostly at high galactic latitudes. Tsumura et al., 2013 used the far-infrared correlation method to probe the near-infrared $\lambda = 1.8 - 5.3\mu\text{m}$ spectrum using the AKARI InfraRed camera, detecting a galactic polycyclic aromatic hydrocarbon (PAH) emission line at $\lambda = 3.3\mu\text{m}$ at low galactic latitudes. Arai et al., 2015 builds on this result at shorter, scattering-regime near-infrared wavelengths from $\lambda = 0.95 - 1.65\mu\text{m}$ using the Cosmic Infrared Background Experiment (CIBER) low-resolution spectrometer, reporting an average spectra across several small regions of the sky consistent with scattering by small dust grains. Precise follow-up far-infrared correlated measurements of the DGL spectrum have also been reported for the a high-latitude molecular dust cloud (MBM32, at galactic latitude $b \approx 41^\circ$) with two different experiments: at optical $\lambda = 0.45 - 0.65\mu\text{m}$ wavelengths with the Diffuse Infrared Background Experiment (DIRBE) by Ienaka et al., 2013 and at near-infrared $\lambda = 1.1, 1.6\mu\text{m}$ wavelengths with the Multi-purpose InfraRed Imaging System (MIRIS) on STSAT-3 by Onishi et al., 2018.

Previous measurements have found evidence that the DGL spectrum may vary across different parts of the sky. Brandt and Draine, 2012 detected some variation between their selected regions, but did not rule out contamination by extragalactic background light at higher latitudes. Spectra obtained by Sano et al., 2016 using DIRBE and more recently by Chellew et al., 2022 with the Baryon Oscillation Spectroscopic Survey (BOSS, part of the third phase of SDSS) also suggest that the scaling relation between $100\mu\text{m}$ emission and near-infrared/optical DGL, respectively, may vary across the sky.

This chapter presents new preliminary measurements of the far-infrared-correlated DGL spectrum from $\lambda = 0.75 - 5.0\mu\text{m}$ for localized fields across various regions of the sky using SPHEREx in 69 bands. Preliminary results suggest significant variation of the correlated DGL spectrum across all wavelengths, with the greatest variation in the emission-dominated regime at $\lambda \gtrsim 2.0\mu\text{m}$. We discuss the methodology for measurement of a far-infrared correlated spectrum between IRAS-derived maps and SPHEREx spectral mosaics in Section 5.2, including diffuse target field selection. In Section 5.3, we discuss the resulting spectra and consistency checks. Finally, conclusions are presented in Section 5.4.

5.2 Methodology

SPHEREx Map-making

The SPHEREx detectors consist of 6 HAWAII-2RG (H2RG) HgCdTe arrays, each covering a portion of the overall instrument spectrum between $\lambda = 0.75 - 5.00\mu\text{m}$. To obtain a complete spectrum at every point on the entire sky, SPHEREx uses novel linear-variable filter spectrometers which map a broad spectrum onto a given detector (Korngut et al., 2026, Bock et al., 2026). As a result, all 2040×2040 photosensitive pixels in any given SPHEREx H2RG exposure are mapped to a different wavelength.

To create images of the sky in fixed bands across the overall SPHEREx spectrum, the SPHEREx collaboration has developed a process to combine many multi-wavelength exposures into a single monochromatic mosaic, implemented into the SPHEREx data pipeline (Cukierman et al., 2026). The pipeline also handles various data processing tasks such as rejection of aurora-contaminated exposures, applying bright source and anomaly (e.g. satellite track) masks, generating simulated foreground (e.g. Zodiacal Light) exposures, and applying dark current and reference pixel corrections. Each mosaic then covers an arbitrary region of the sky at a single wavelength with pre-defined bandwidth; by default, the overall SPHEREx spectrum is divided into 102 such bands, resulting in 102 mosaics for any given region. Groups of pixels on a given mosaic are then separated in time from each other by much more than the exposure time to read a single H2RG, resulting in the modulation of time-dependent signals on the sky. Most notably, this includes the Zodiacal Light (ZL) produced by sunlight scattering off of interplanetary dust grains, which varies in intensity as a specific region of the sky is observed multiple times at different points along Earth's orbit. The ZL is very bright at near-infrared wavelengths, resulting in any given mosaic containing many bright "stripes" caused by the time-variation of the ZL across the numerous exposures used to construct each mosaic.

Zodiacal Light Filtering

To correct for ZL contamination (and any other time-varying but spatially smooth signal, such as airglow), a contour filter is used. By default, this filter removes a mean value from all pixels within a given exposure along a 1-pixel-wide constant wavelength span. This technique is effective at removing bulk offsets produced by the ZL, but comes at the cost of also modulating underlying bright diffuse backgrounds such as the DGL itself. The default filter, relying on a single offset subtraction,

removes the vast majority of ZL signal but is unable to completely remove higher order ZL variations; these residuals remain as a source of systematic error within any given mosaic. The effect of this residual is generally less important for target fields with either bright DGL intensity or situated far from the ecliptic plane. However, for faint fields targeting the diffuse interstellar medium, the residual from higher order ZL variations can significantly bias DGL correlation measurements via spurious correlation even at high ecliptic latitudes. To account for this, we instead use a 1st order correction by subtracting a linear regression between intensity and contour pixel position from each exposure contour, reducing the ZL residual by an additional order of magnitude to negligible levels.

The 100 μm Correlation Technique

For an arbitrary region of the sky and wavelength λ with bright sources masked, the total background intensity $I(\lambda)$ can be written as:

$$I(\lambda) = I_{AG}(\lambda) + I_{ZL}(\lambda) + I_{DGL}(\lambda) + I_b(\lambda), \quad (5.1)$$

where $I_{AG}(\lambda)$ represents the intensity contributed by atmospheric airglow, $I_{ZL}(\lambda)$ is that contributed by the local Zodiacal Light (ZL), $I_{DGL}(\lambda)$ is that contributed by interstellar dust within the galaxy, and $I_b(\lambda)$ represents generally faint extragalactic contributions. For SPHEREx in an essentially circular orbit at an altitude of $\approx 660\text{km}$, $I_{AG}(\lambda)$ is generally lower than $I_{ZL}(\lambda)$; a notable exception exists at $\lambda = 1.083\mu\text{m}$, where a bright He-I triplet line from atmospheric helium causes airglow to exceed contributions from the ZL by more than an order of magnitude (Hui et al., 2026a, Hui et al., 2026b). $I_{AG}(\lambda)$, $I_{ZL}(\lambda)$, and the faint $I_b(\lambda)$ are similar in that their structure can be assumed not to depend on the distribution of interstellar dust within the Milky Way. With $I_{ZL}(\lambda)$ and residual $I_{AG}(\lambda)$ being relatively spatially smooth and largely filtered out as part of the SPHEREx map-making process described in the previous section, we can lump these three non-correlating terms together as $I_{nc}(\lambda)$.

By contrast, $I_{DGL}(\lambda)$ is directly produced by emission or scattering from the dust and should strongly correlate with the dust's distribution across the sky. In the far-infrared regime, thermal emission by this dust dominates the total intensity observed from a space-based platform; at shorter NIR wavelengths $\lambda \lesssim 2\mu\text{m}$, DGL is dominated by scattered light driven by the ISRF. Following Arai et al., 2015 and Tsumura et al., 2013, we can write the near-infrared DGL intensity for both

scattering- and emission-regime DGL respectively in diffuse optically-thin regions as:

$$I_{DGL}(\lambda) \approx b(\lambda)I_{100\mu\text{m}}^*, \quad (5.2)$$

where $I_{100\mu\text{m}}^*$ is the temperature-corrected sky intensity at $\lambda = 100\mu\text{m}$ (a far-infrared regime where dust thermal emission dominates the sky) obtained from the dust reddening $E(B - V)$. The overall diffuse intensity of the selected region of the sky is then:

$$I(\lambda) = b(\lambda)I_{100\mu\text{m}}^* + I_{nc}(\lambda). \quad (5.3)$$

By measuring the slope of the linear correlation between a map of $I_{100\mu\text{m}}^*$ and a SPHEREx mosaic at near-infrared wavelength λ , we can then extract the DGL spectrum as the scale factor $b(\lambda)$ depending only on wavelength.

To obtain $I_{100\mu\text{m}}^*$, we use the corrected Schlegel-Finkbeiner-Davis (CSFD) dust reddening all-sky map of Chiang, 2023. The CSFD map builds on the original SFD map (Schlegel et al., 1998) based on observations combining data from IRAS and the COBE Diffuse Infrared Background Experiment (DIRBE) by removing imprints of extragalactic large-scale structure. For our purposes in measuring a DGL spectrum, in addition to removing dependence on dust temperature, use of the CSFD is intended to reduce the $I_b(\lambda)$ non-correlating offset term; while this term is expected to be small compared to other sources of systematic error, its reduction would improve measurement of $b(\lambda)$.

At risk of stating the obvious, it should be noted that this technique is only able to access the component of the DGL that is *correlated* with far-infrared emission; any non-correlated DGL component will be invisible to this methodology, and as a result any spectrum derived using this technique should be assumed to be at least somewhat incomplete.

Field Selection

While SPHEREx has observed the entire sky, not every region is ideal for measurement of the DGL spectrum. Although it is theoretically possible to measure a linear correlation for any value of $b(\lambda)$ and $I_{100\mu\text{m}}^*$, attempting the far-infrared correlation method on regions of the sky with very faint $I_{DGL}(\lambda)$ will result in extremely high

measurement error. Optical depth constraints for assuming a linear correlation also eliminate much of the low galactic latitude region near the galactic plane where dust is extremely bright. Additionally, we avoid regions with very low ecliptic latitude of less than $\approx 10^\circ$ (that is, near the ecliptic plane) to avoid high variation in the ZL, which can contribute image artifacts that escape contour filtering and bias spectral measurements.

Under these constraints, we select five large $5.2^\circ \times 5.2^\circ$ widely separated regions of the sky for our analysis (Table 5.1, Figure 5.1). Each field is selected to target diffuse regions on the sky, with $\bar{I}_{100\mu\text{m}}^* = 2 - 3 \text{ MJy sr}^{-1}$. To maximize the range of pixel intensities upon which to fit $b(\lambda)$, we specifically target high-contrast regions with relatively large variation in $I_{100\mu\text{m}}^*$. Using the CCM89 model for dust extinction (Cardelli et al., 1989), we find that the maximum optical depth across $\lambda = 1.0 - 5.0\mu\text{m}$ for any part of the selected fields is $\tau \approx 0.25$ at $\lambda = 1.0\mu\text{m}$ with the overwhelming majority of pixels and spectral channels corresponding to much lower τ , validating our assumption of optically-thin dust.

Table 5.1: Target Field Definitions

Field	$\bar{I}_{100\mu\text{m}}^*$ (MJy sr $^{-1}$)	$I_{100\mu\text{m}}^*$ (MJy sr $^{-1}$)	ℓ (deg)	b (deg)
1	3.0	1.4-6.0	28.4	53.2
2	2.2	0.8-12.4	141.3	34.5
3	2.6	1.4-6.7	280.0	40.2
4	2.3	0.8-5.8	340.2	-42.9
5	2.5	0.8-6.3	217.2	-46.9

Linear Correlation Methodology and Data Processing

For each field, we generate contour-filtered 2080×2080 pixel SPHEREx mosaics at $9''$ pixel scale and associated CSFD mappings (Figure 5.2). Since the contour filter will affect DGL structure when applied to a SPHEREx mosaic, we also apply the same contour filter and masking parameters to CSFD maps prior to our analysis. We then smooth the SPHEREx mosaics to the much lower $6'$ resolution of the CSFD map using a Gaussian filter. Bright resolved stars and galaxies are masked primarily using the built-in SPHEREx sky simulator masking algorithm using a multi-survey reference catalog. Simulated sources, generated with a pre-flight model of the SPHEREx PSF, allow for masking down to arbitrary flux. We use a union mask to ensure that each spectral mosaic for a given field spans essentially the same region of the sky – a pixel masked at any given wavelength due to falling within a source mask, containing an anomaly flag (e.g. satellite trail, hot pixels), or missing data

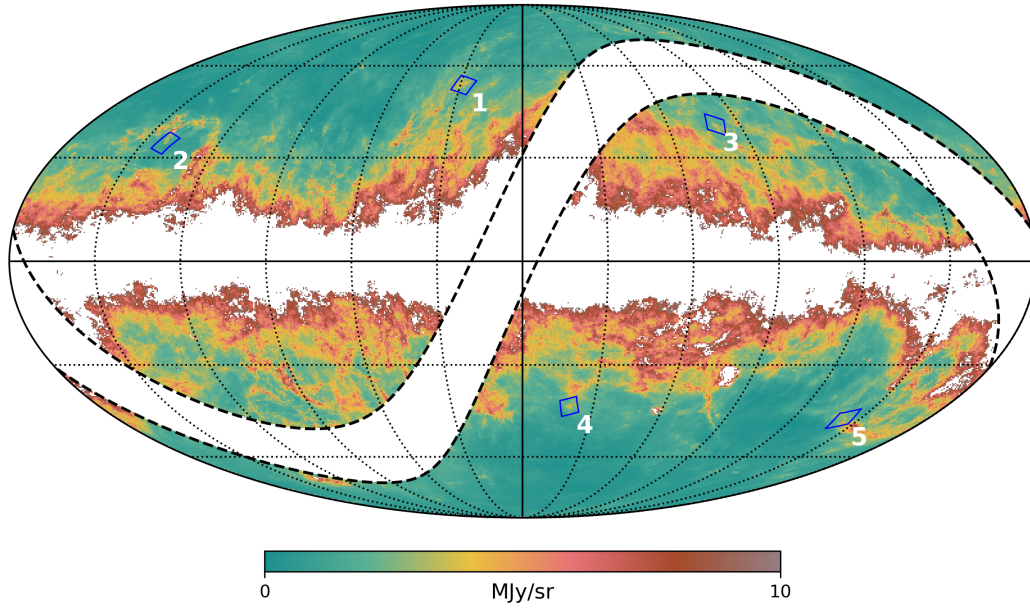


Figure 5.1: All-sky CSFD map with target $5.2^\circ \times 5.2^\circ$ fields, defined such that one central axis of each square field is aligned with declination. The ecliptic plane $\pm 10^\circ$ is marked with dashed lines. Fields were selected to target diffuse regions away from the galactic plane while avoiding the high ZL residuals associated with areas near the ecliptic.

will be masked at all wavelengths. This ensures consistency across all channels, albeit at the cost of significantly reducing overall usable pixel count.

Prior to fitting, each smoothed mosaic and its associated CSFD map are sub-divided into a 5×5 grid, resulting in $N = 25$ $1.04^\circ \times 1.04^\circ$ pairs of "blocks" per band (Figure 5.3). Each block is then down-scaled by averaging all pixels within a 26×26 sub-grid, resulting in a processed individual block resolution of 16×16 down-scaled pixels. Each down-scaled pixel is assigned a weight proportional to the number of masked real pixels contained within it. Down-scaled pixels with $> 95\%$ masked real pixels are masked entirely; likewise, blocks containing $> 75\%$ masked down-scaled pixels are excluded from analysis. By dividing fields as described, we are able to obtain a more robust estimate of the measurement error across a given field.

With the data processed into blocks, we apply a weighted linear correlation to all SPHEREx down-scaled pixels with respect to their associated CSFD down-scaled pixels for each block to obtain the slope $b_{ij}(\lambda)$. The final measured correlation factor $b(\lambda)$ for a given band is then just the mean of $b_{ij}(\lambda)$ for all unmasked blocks, with associated $1-\sigma$ standard error μ measured directly from the variation on $b_{ij}(\lambda)$ as

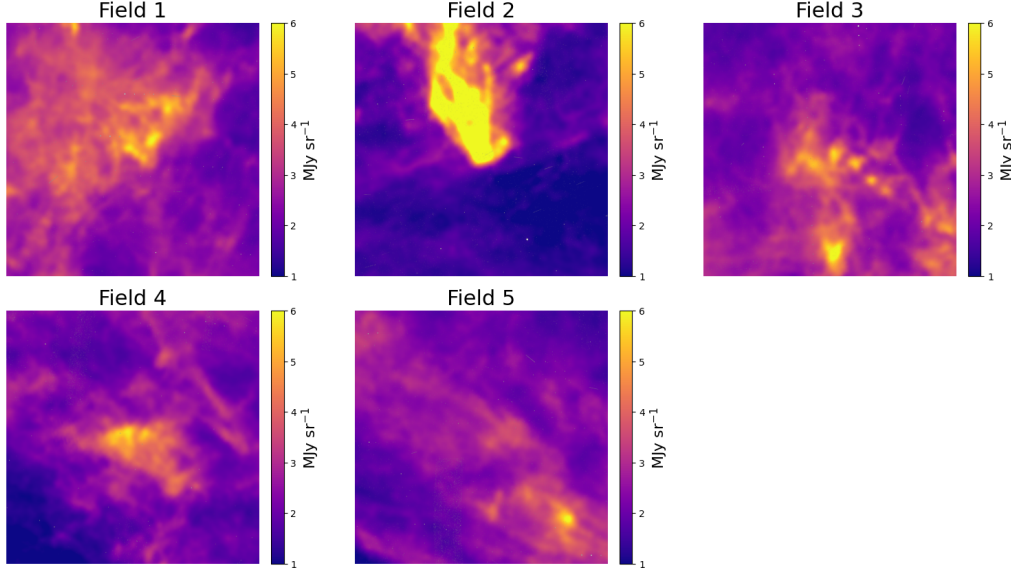


Figure 5.2: CSFD maps for all target $5.2^\circ \times 5.2^\circ$ fields. Fields were selected to target relatively high contrast regions within the relatively faint diffuse interstellar medium.

$\mu = \sigma / \sqrt{N(b_{ij}(\lambda))}$ for $N(b_{ij}(\lambda))$ unmasked blocks. We apply a $3\text{-}\sigma$ -clip operation to the entire mosaic prior to smoothing as well as to each individual block to remove outlier pixels (e.g. hot pixels missed by the pipeline; note that this σ -clip operation is done individually on each channel, and is the only portion of the image mask that varies between channels). We do not exclude blocks with low measured correlation coefficient in order to avoid biasing our overall measurement of mean $b(\lambda)$ for a given field; we do, however, exclude any major outlier $b_{ij}(\lambda)$ from a given mosaic's block ensemble, defined here as falling $> 3\sigma$ from the mean $b(\lambda)$.

The linear-variable filter architecture of SPHEREx allows for arbitrary spectral channel definitions within physical limits; by default, this amounts to 102 channels across the entire SPHEREx wavelength range, or 17 channels per H2RG array. To improve signal at the longest wavelengths where DGL is generally faint, we co-add to reduce the number of channels on the two longest wavelength arrays – corresponding to 8 spectral channels for $\lambda = 3.8 - 4.4\mu\text{m}$ and 4 channels for $\lambda = 4.4 - 5.0\mu\text{m}$. Due to the use of a union mask for all channels, we additionally remove the first channel from each of the 6 arrays and the last channel from the 4 arrays without additional co-adding (which tend to show incomplete data). Finally, we exclude an additional channel in the 1st array near $\lambda = 1.083\mu\text{m}$ to avoid contamination from the aforementioned He-I triplet airglow emission line. This reduction results in 69

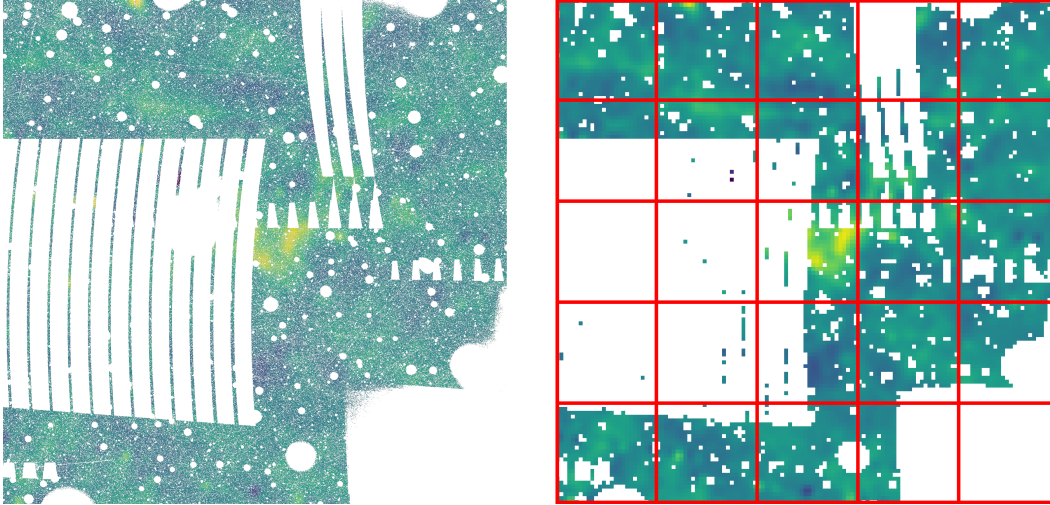


Figure 5.3: Illustration of SPHEREx image processing with union mask. Left: $5.2^\circ \times 5.2^\circ$ SPHEREx $\lambda = 3.3\mu\text{m}$ mosaic after applying Gaussian smoothing to match the CSFD beam; note the visible DGL structure in the center. Right: The same mosaic after down-scaling, with block subdivision boundaries shown in red. The union mask significantly decreases the number of usable pixels below that available to any given mosaic – the linear-variable filter architecture of SPHEREx results in even a small patch of missing data propagating into a much larger masked region within the union mask.

available spectral channels upon which to measure a DGL spectrum, with increased channel width at the longest wavelengths. An example of processed SPHEREx mosaics for all fields at $\lambda = 3.3\mu\text{m}$ is shown in Figure 5.4.

5.3 Results & Discussion

Systematic Error Management

For the faint regions of the sky at SPHEREx wavelengths, typically resulting either from using fields with very low $I_{100\mu\text{m}}^*$ or from observing at the longest wavelengths where DGL is minimal, the DGL signal becomes comparable in brightness to various sources of systematic error on the SPHEREx mosaics. These primarily consist of residual unmasked sources (or similar, e.g. mosaic artifacts or the edge pixels of satellite tracks), excess stripe offsets resulting from the contour filter process being biased by said unmasked sources, and residual signal from ZL caused by ZL spatial variation across a given stripe. The latter effect is resolved by our selection of fields away from the ecliptic plane and by using the previously described 1st-order contour filter.

For mitigating the effect of imperfect masking of resolved sources, a tradeoff must

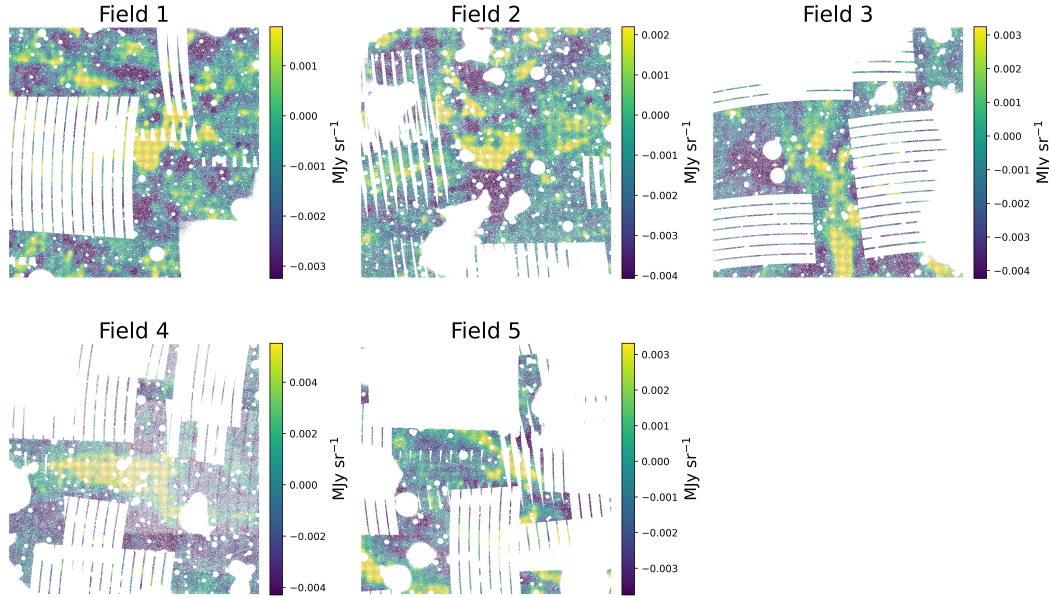


Figure 5.4: SPHEREx $\lambda = 3.3\mu\text{m}$ smoothed mosaics for all 5 target fields, with union masks applied and DGL structure clearly visible. The union mask maintains consistency across the region seen by all spectral channels, but greatly reduces the number of usable pixels. Note varying colorscales across fields.

be considered between aggressively masking source halos (which are only approximately described by external source catalogs and the simulated SPHEREx PSF) and maintaining adequate pixel counts for correlation; fully masking all source contribution would necessarily require masking every pixel. In faint regions of the diffuse interstellar medium, sources (and their residual unmasked halos) are expected to be uncorrelated with respect to diffuse DGL structure. To validate this assumption, we apply various masking thresholds in the SPHEREx pipeline to Field 2. We define different simulated source mask intensity thresholds (S_{dim} , S_{bright}) based on source brightness; here, S_{dim} is defined as sources fainter than, and S_{bright} as those brighter than, $m_{AB} = 10$. This division allows for masking brighter sources to more aggressive thresholds than faint sources to mitigate PSF errors. Applying a range of mask thresholds to the diffuse target field and re-applying the contour filter algorithm at each threshold, we find the resulting extracted DGL spectrum is highly resistant to changes to the masking threshold even with an extremely inadequate source mask (Figure 5.5). As a balance between source masking and maintaining adequate pixel count, we select $(S_{dim}, S_{bright}) = (1 \times 10^{-2}, 1.5 \times 10^{-3}) \text{ MJy sr}^{-1}$ as our default masking threshold for all target fields as a result of this analysis.

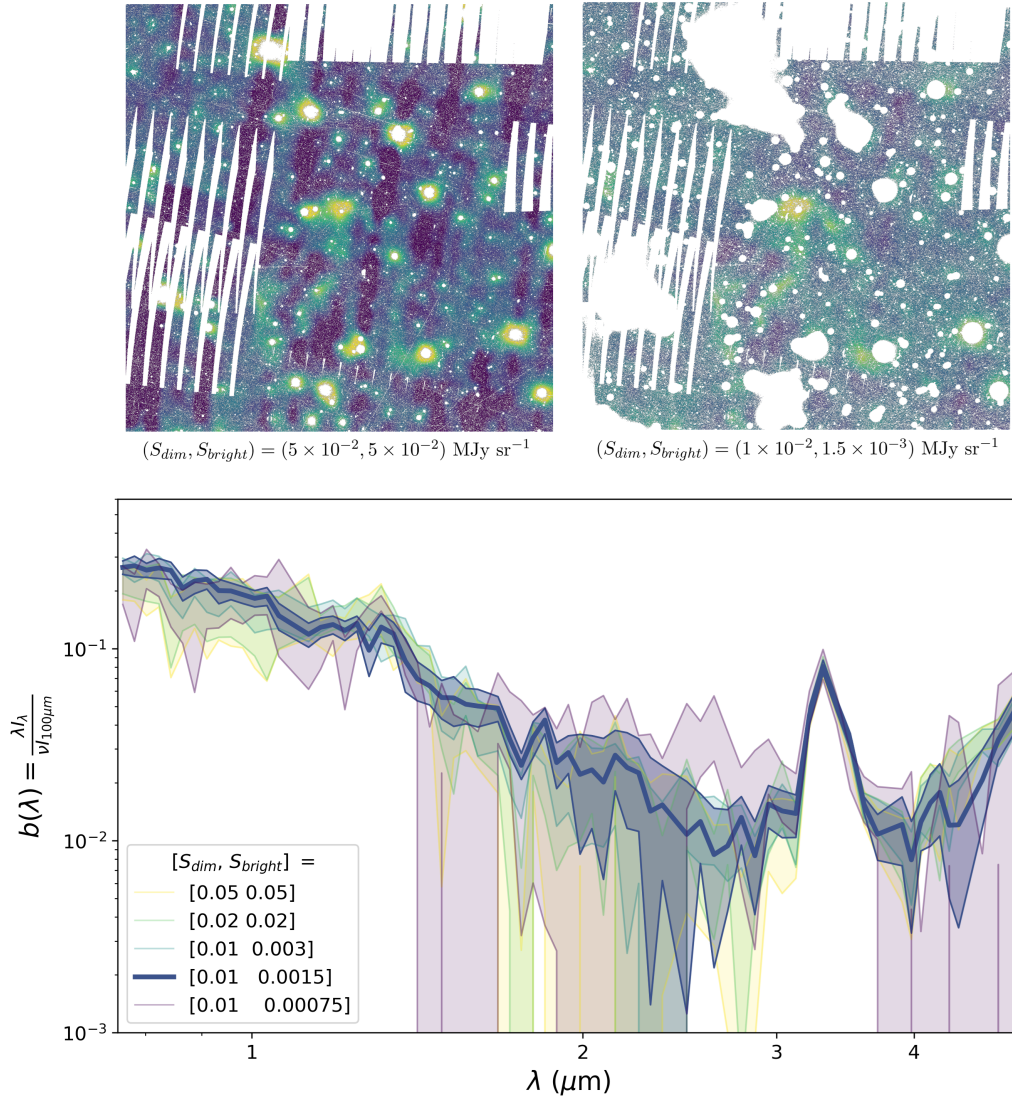


Figure 5.5: Impact of varying source masking thresholds on extracted DGL spectrum slope on Field 2. Top left: SPHEREx $\lambda = 0.96\mu\text{m}$ mosaic with extremely inadequate source mask threshold; source halos and associated contour filter errors are clearly visible. Top right: the same mosaic with the source mask threshold used in this work; bright sources are much more aggressively masked, at the cost of more masked pixels. Bottom: resulting SPHEREx-CSFD correlation slopes $b(\lambda)$ for five such selections of masking thresholds, with shaded regions representing ± 1 standard error μ from the mean. The DGL spectrum measurement for this diffuse field is extremely resistant to the choice of source mask, with deviations of $> 1\mu$ occurring only for the most lax and most restrictive masks (and then only within a limited number of channels). In the case of the most aggressive mask at $(S_{\text{dim}}, S_{\text{bright}}) = (1 \times 10^{-2}, 0.75 \times 10^{-3}) \text{ MJy sr}^{-1}$, only $< 7\%$ of pixels are retained. Note that this figure uses the default (mean-subtraction) contour filter rather than the 1st order filter used in the rest of this work.

Results

Figure 5.6 presents the resulting measured preliminary spectra across the five diffuse target fields. A broad emission line at $\lambda = 3.3\mu\text{m}$ associated with galactic polycyclic aromatic hydrocarbons (PAH) is clearly observed in all fields. The spectral channels associated with this peak provide the lowest error on measurements of $b(\lambda)$ across all utilized SPHEREx wavelengths.

These preliminary results indicate substantial variation within the PAH line, with $b(3.3\mu\text{m})$ varying by over a factor of 2 between the most disparate fields (Figure 5.7). The data also hints at less statistically significant variation at the shortest ($\lambda \lesssim 1\mu\text{m}$) and longest ($\lambda \lesssim 4.5\mu\text{m}$) wavelengths, the former largely driven by Field 4.

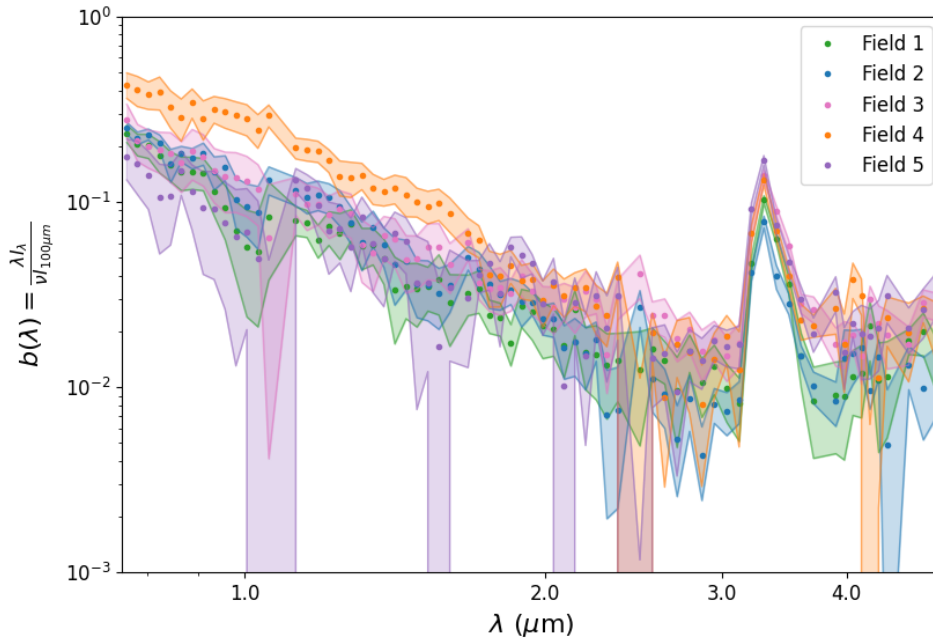


Figure 5.6: Preliminary correlated Diffuse Galactic Light spectra for diffuse target fields 1-5 across $\lambda = 0.75 - 5.0\mu\text{m}$. Shaded regions represent ± 1 standard error μ from the mean. Significant variation is observed in the PAH line centered on $\lambda = 3.3\mu\text{m}$; at shorter wavelengths where scattering dominates, the spectra hint at additional variation, albeit with lower statistical significance.

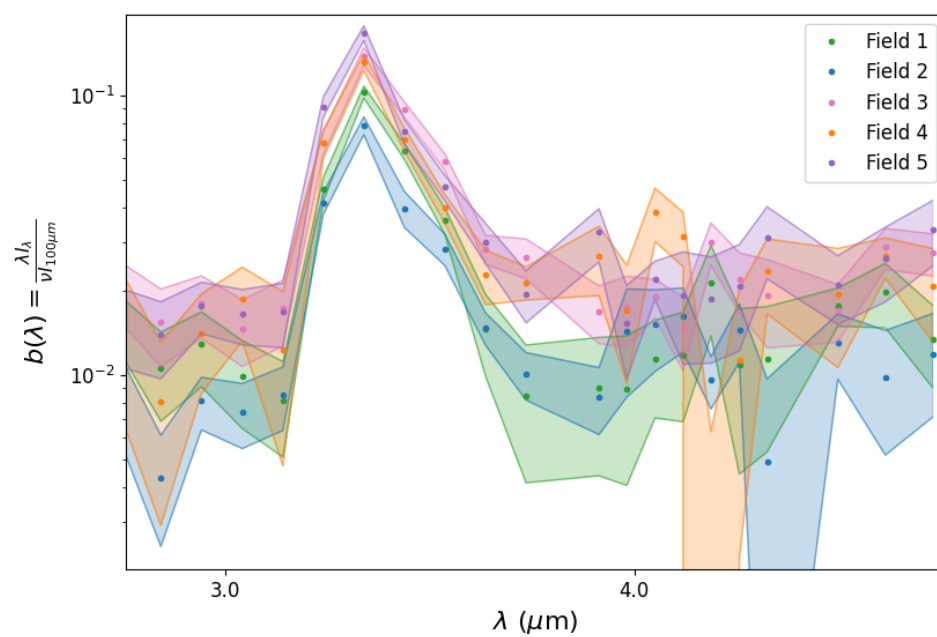


Figure 5.7: Preliminary correlated Diffuse Galactic Light spectra for diffuse target fields 1-5 as in Figure 5.6, truncated to show the thermal emission $\lambda \approx 2.8 - 5.0 \mu\text{m}$ regime. Significant variation is observed in the PAH line centered on $\lambda = 3.3 \mu\text{m}$

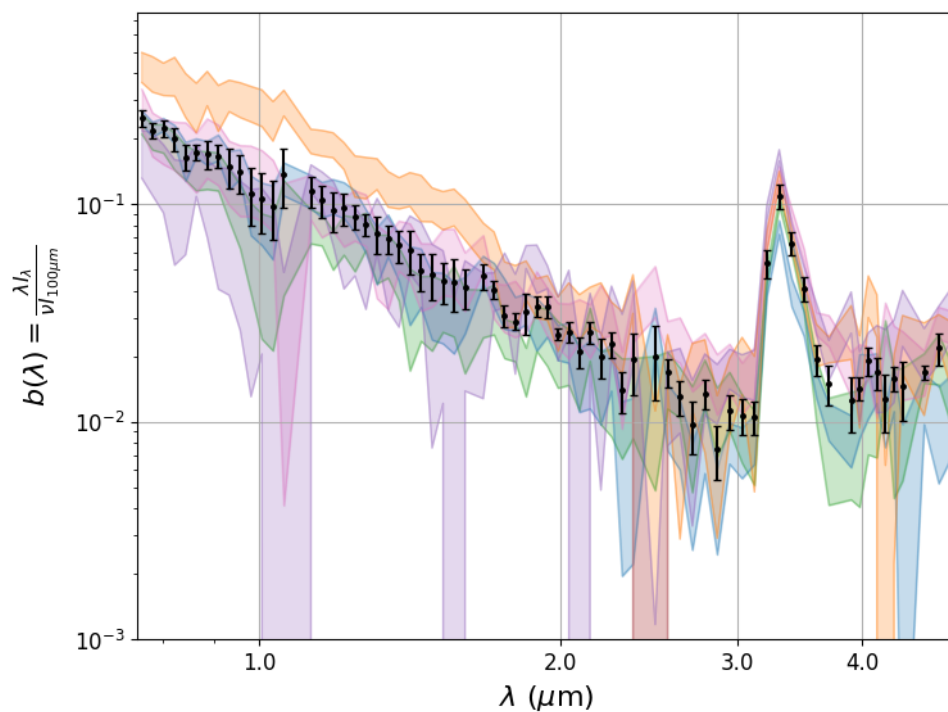


Figure 5.8: Preliminary variance-weighted mean of DGL spectra for diffuse target fields 1-5 across $\lambda = 0.75 - 5.0\mu\text{m}$. Shaded regions and fields are defined as in Figure 5.6. It is emphasized that as the target fields presented here were not selected at random, this mean spectra should not be taken as a true unbiased mean for the entire sky.

The data suggest a lack of correlation between the spectral scaling factors $b(\lambda)$ at shorter wavelengths where scattered light driven by the ISRF dominates versus those at longer $\lambda \gtrsim 2\mu\text{m}$ wavelengths. As light at longer NIR wavelengths is expected to be produced by thermal emission from heated small dust grains (and therefore has a different production mechanism compared to the shorter wavelengths), this lack of correlation is expected.

Figure 5.8 shows the variance-weighted mean correlated DGL spectrum for the target fields. It is critical to emphasize the inherent limitations of such a mean measurement in the context of variation across the individual fields. The diffuse target fields discussed in this work are broadly distributed across the sky, but they were also manually selected – as such, they are not a random unbiased sample, and the selection’s sample size is small. In addition, the per-field spectra strongly imply significant variation across large portions of the near-infrared DGL spectrum even within the narrow range of $I_{100\mu\text{m}}^*$ regions targeted and particularly in the PAH band where measurement precision is highest. This in turn suggests that use of this mean spectrum for modeling the DGL contribution for a particular local region of sky would likely be significantly biased for at least some wavelengths. For these reasons, the amplitude of the mean spectrum presented here should not be compared directly to all-sky measurements nor should it be used to model particular smaller patches of sky. What the mean spectrum can provide insight into is the overall average *structure* of the correlated DGL component rather than providing a useful amplitude. Beginning in the short wavelength scattering regime and descending to $\lambda \approx 3\mu\text{m}$ prior to the PAH peak, the mean spectrum contains no broad spectral lines or significant structure beyond the apparent power law. The spectral resolution of SPHEREx channels is inadequate to resolve narrow spectral lines, but this preliminary result implies an expected lack of broad spectral features for this regime.

5.4 Conclusions

We present preliminary correlated Diffuse Galactic Light spectra across widely distributed regions of the diffuse interstellar medium using SPHEREx data. The preliminary spectra suggest substantial variation within the broad $\lambda = 3.3\mu\text{m}$ galactic PAH emission line, with less statistically significant variation observed at other wavelengths across both the scattering and thermal emission regimes. Work continues to refine these spectral estimates and improve measurement precision for future publication.

Observations from SPHEREx enable unprecedented resolution for measurements of the far-infrared-correlated near-infrared DGL spectrum. In principle and limited essentially only by computation time, the techniques outlined in this chapter could be used to create a map of variations in the correlated DGL spectrum across the entire diffuse sky for near-infrared wavelengths. Such a large-scale map would significantly improve our understanding of the NIR DGL as well as allow for a targeted analysis of the galactic foreground for extragalactic observations.

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Appendix A

ANGULAR POWER SPECTRA FORMALISM

This work makes extensive use of angular (or spatial) power spectra to characterize noise or signal at particular angular scales on the sky. With the exception of Chapter 2, the convention commonly used in study of the cosmic microwave background is used, summarized here.

For a field $f(\hat{x})$, we can write the spherical harmonic expansion of the field as:

$$f(\hat{x}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{x}), \quad (\text{A.1})$$

where $Y_{\ell m}$ are the associated Legendre polynomials. With this decomposition, we can then write the angular power C_{ℓ} as the weighted sum of the coefficients:

$$C_{\ell} = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m} \quad (\text{A.2})$$

The frequently used associated quantity D_{ℓ} is defined as:

$$D_{\ell} = \frac{\ell(\ell + 1)}{2\pi} C_{\ell} \quad (\text{A.3})$$

Usefully, the quantity $\sqrt{D_{\ell}}/\ell$ is constant for Poisson noise. For calculating angular power spectra in a discrete numerical context, beginning with a two-dimensional $N \times M$ map A_{ij} with angular pixel scale ϕ , we can define the quantity K_{ij} associated with the auto-spectrum as:

$$K_{ij} = NM\phi^2 (F_2^{-1}(A_{ij}))^* F_2^{-1}(A_{ij}), \quad (\text{A.4})$$

where $F^{-1}(A_{ij})$ is the inverse discrete Fourier transform of A_{ij} . By averaging K_{ij} over bins centered on spherical multipoles ℓ with specified widths $\Delta\ell$, we can obtain the discrete angular power C_{ℓ} .

For $\ell \gg 1$, which is almost always the case in the context of the study of the cosmic infrared background, we can relate the spherical multipole to angular scale θ simply as:

$$\ell \approx \frac{\pi}{\theta}. \quad (\text{A.5})$$

*Appendix B***MECHANICAL DRAWINGS**

This appendix includes as-manufactured mechanical drawings for the re-designed CIBER-2 long-wavelength detector cryogenic focal plane array described in Chapter 3. Components which were unmodified from the original design (e.g. the titanium enclosure canister, filter pane retainers) are not included here; see Lanz, 2018 for the original design and drawings of earlier revisions of many of these components.

The modified "top cap" filter holder (Figures B.8, B.9) required slight shortening during assembly; as such drawings for this component differ slightly from the final component as flown on the 2nd and 3rd flights.

Figure B.1: Mechanical drawing for the lower molybdenum H2RG mount; Part 1/2

Figure B.2: Mechanical drawing for the lower molybdenum H2RG mount; Part 2/2

Figure B.3: Mechanical drawing for the upper molybdenum H2RG mount; Part 1/3

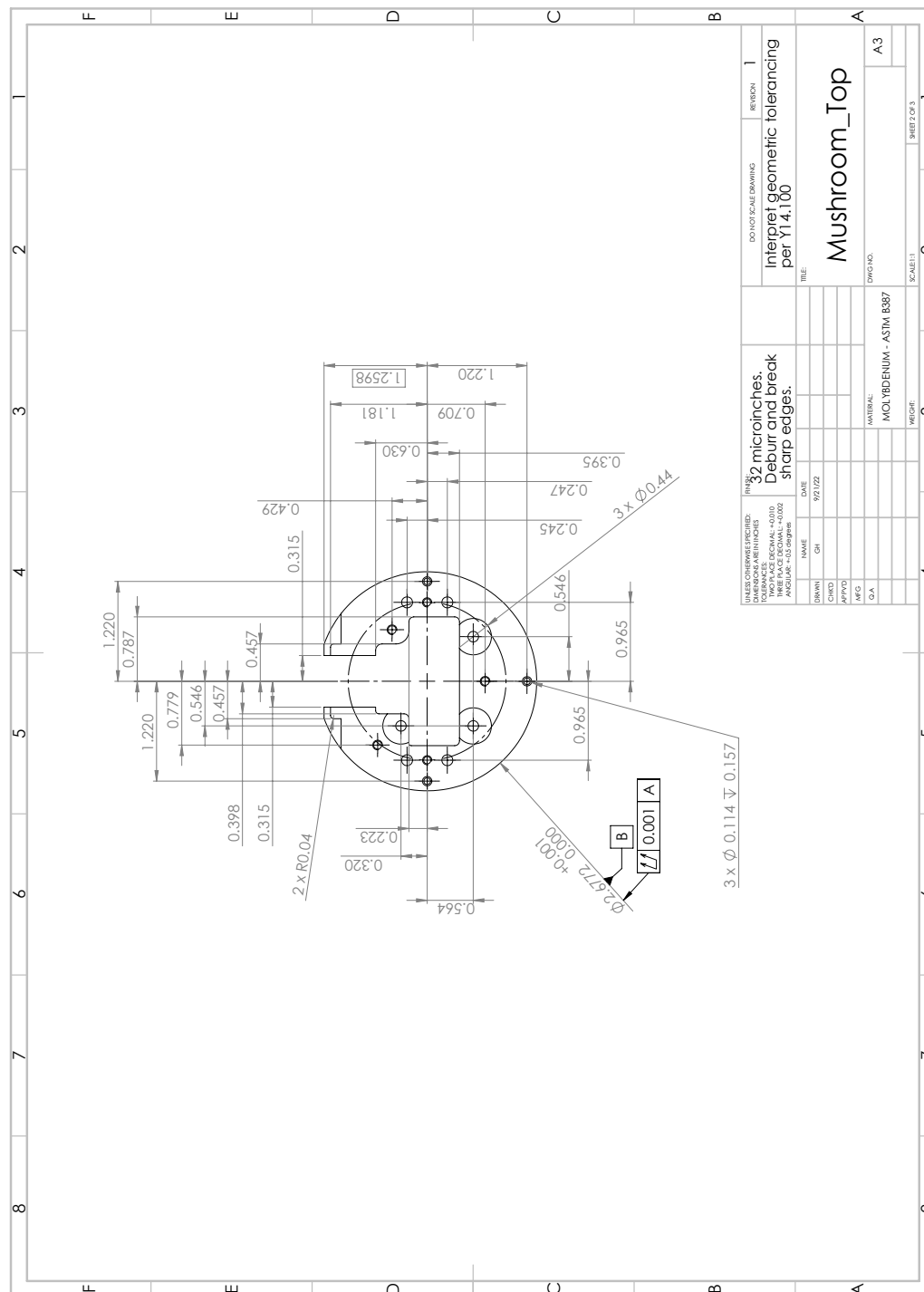


Figure B.4: Mechanical drawing for the upper molybdenum H2RG mount; Part 2/3

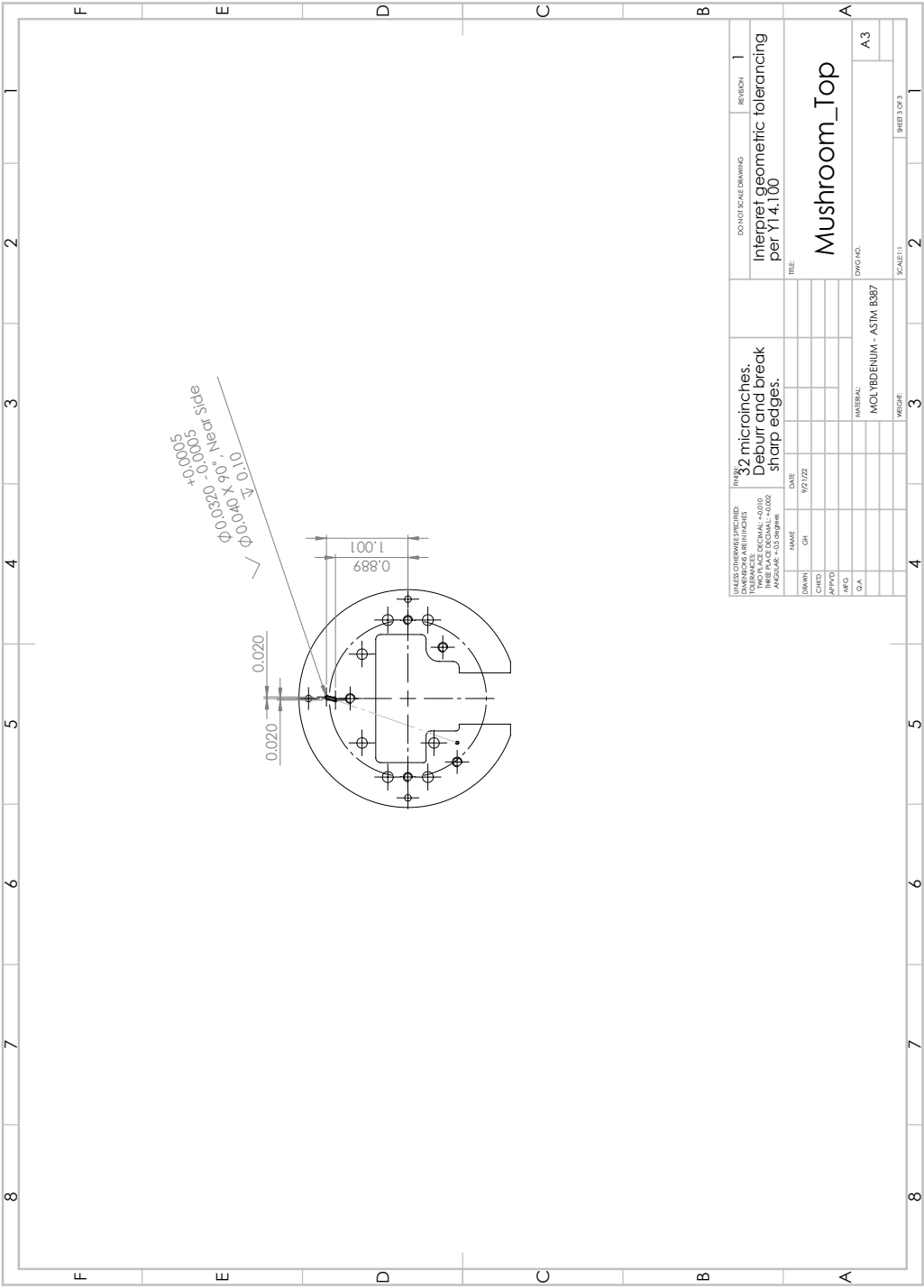


Figure B.5: Mechanical drawing for the upper molybdenum H2RG mount; Part 3/3

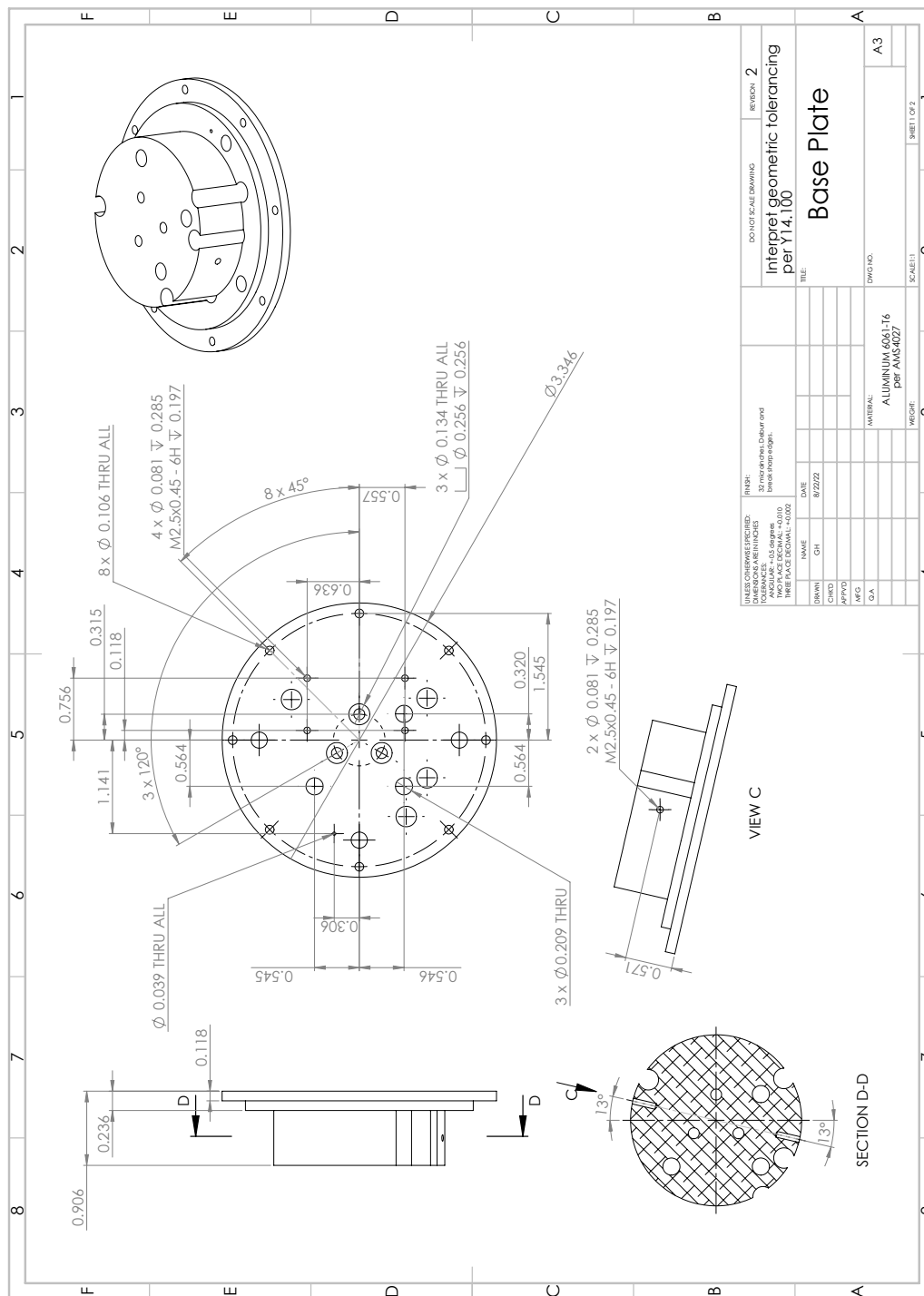


Figure B.6: Mechanical drawing for the modified aluminum base plate; Part 1/2

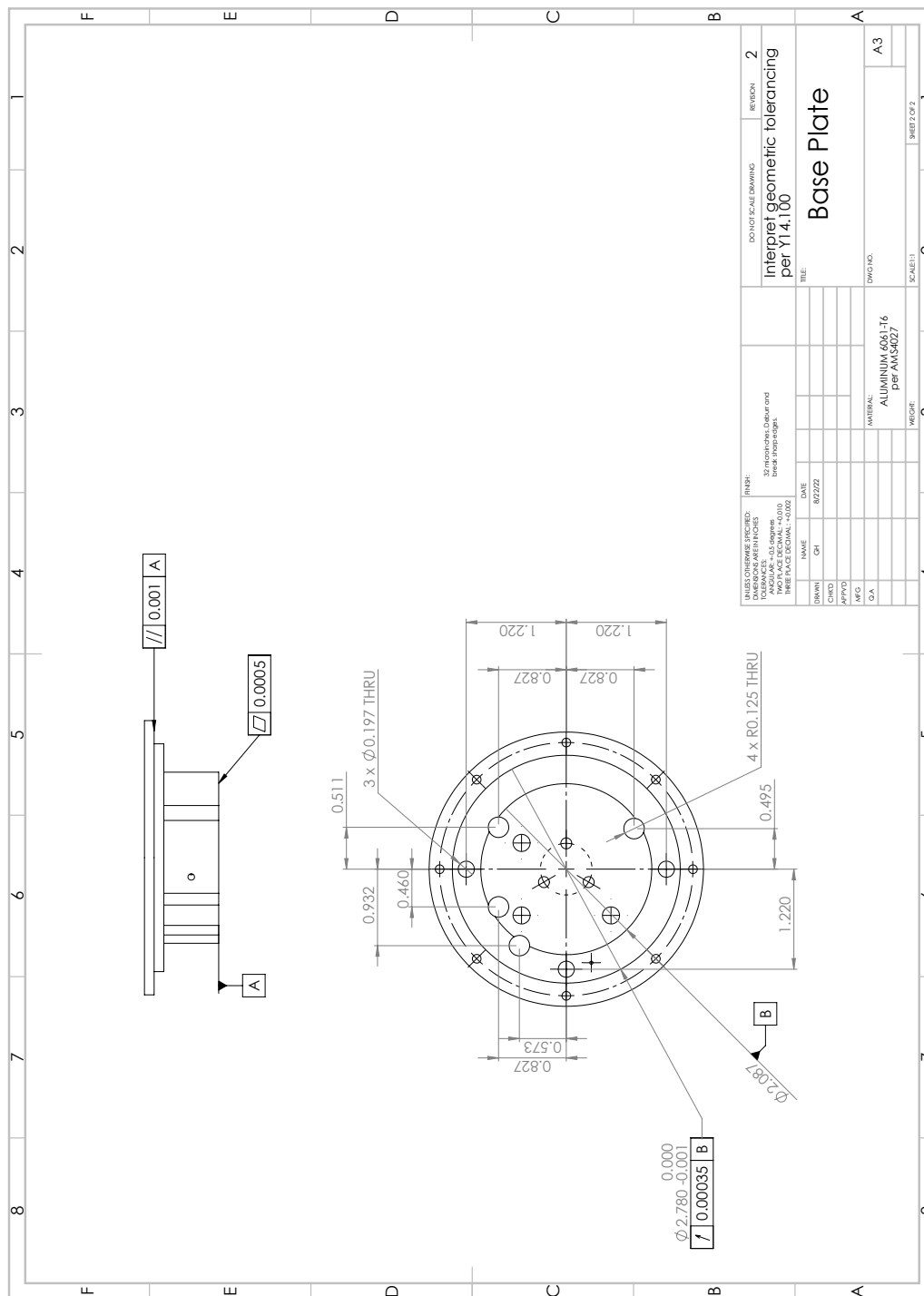


Figure B.7: Mechanical drawing for the modified aluminum base plate; Part 2/2

Figure B.8: Mechanical drawing for the modified aluminum "top cap" filter holder;
Part 1/2

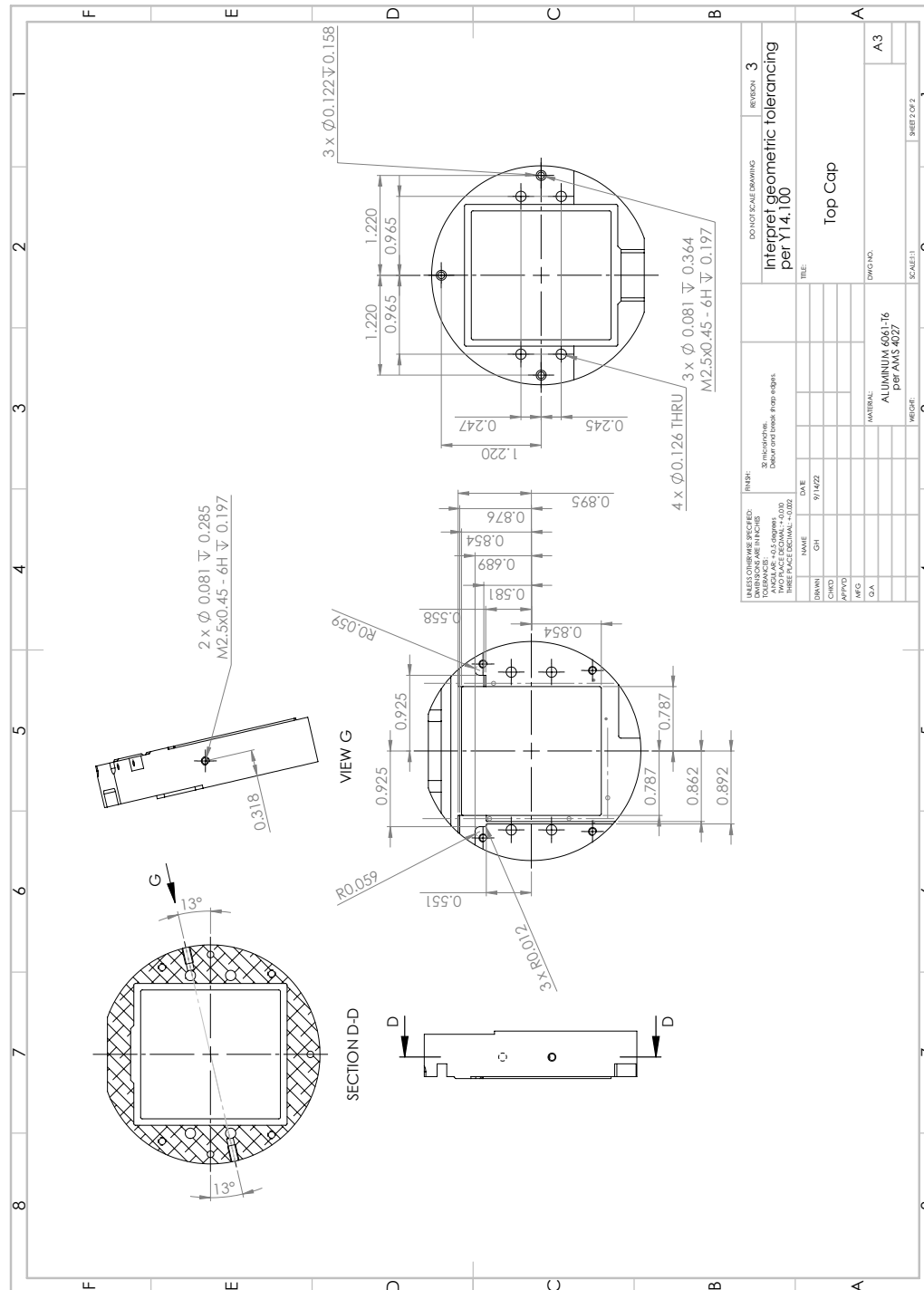


Figure B.9: Mechanical drawing for the modified aluminum "top cap" filter holder; Part 2/2

$1/2$

Figure B.11: Mechanical drawing for the focal plane readout board enclosure; Part 2/2

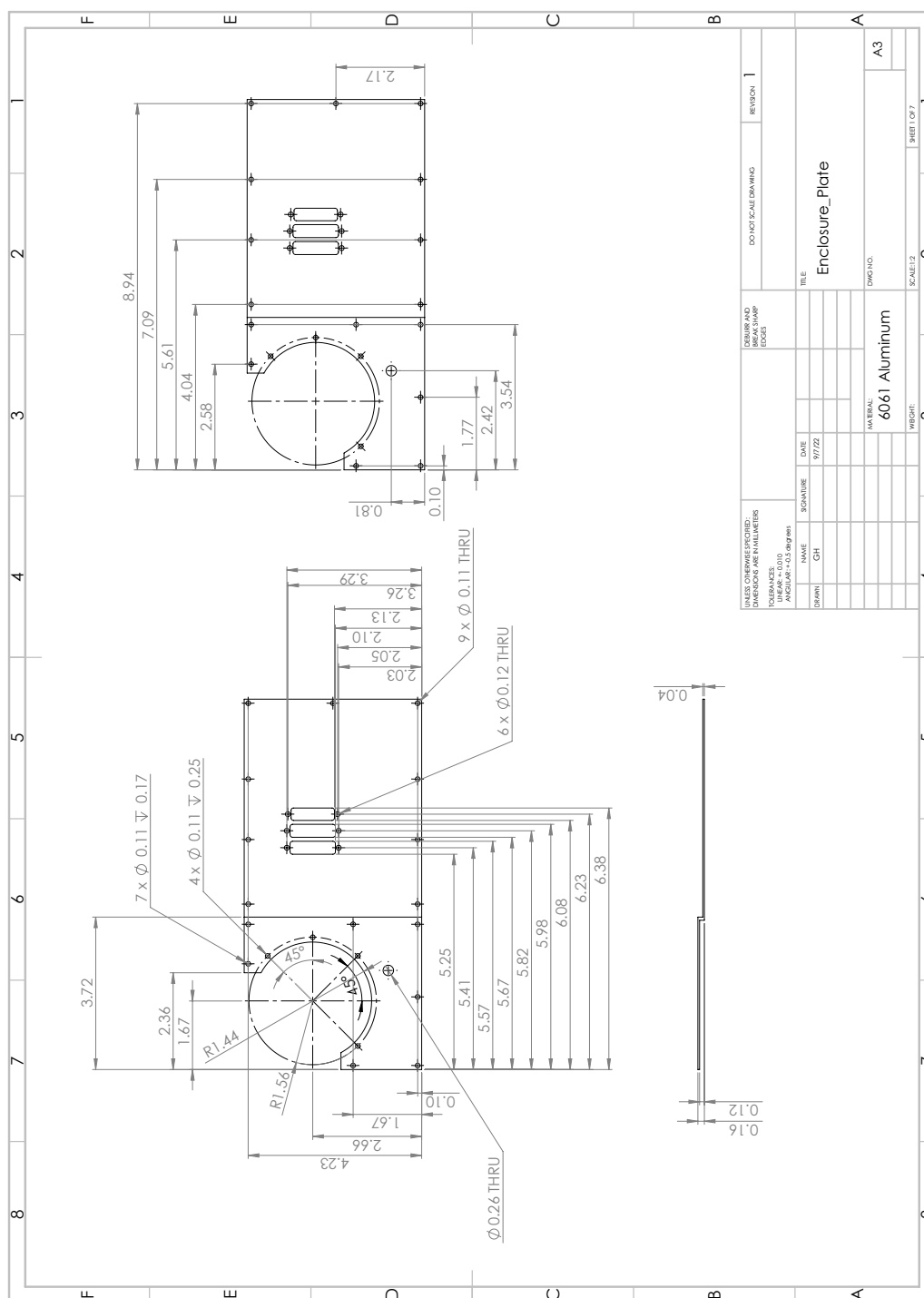


Figure B.12: Mechanical drawing for the focal plane readout board enclosure cover plate

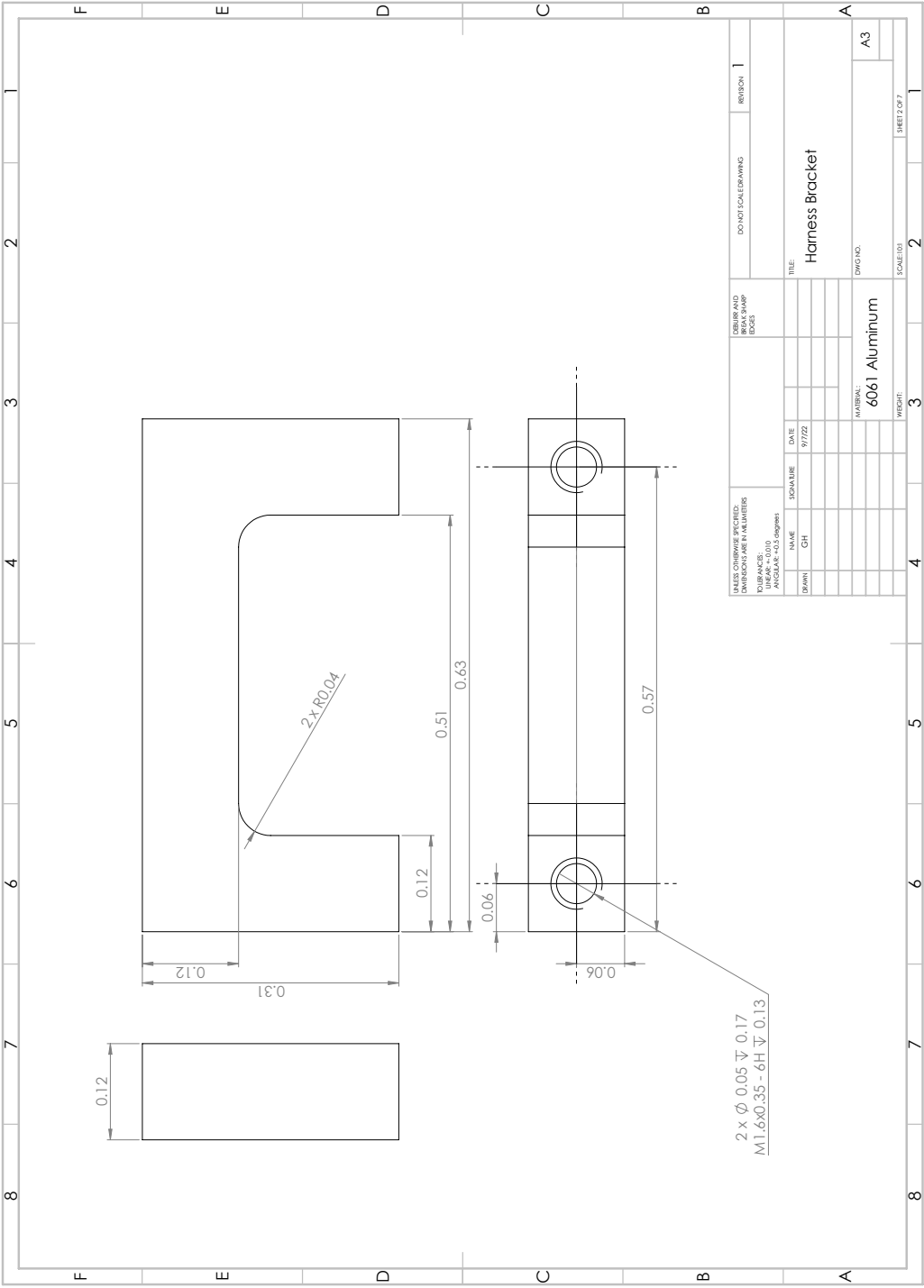


Figure B.13: Mechanical drawing for the simple harness bracket within the focal plane readout board enclosure. This component prevents strain on the cryogenic H2RG harness from putting stress on the H2RG Nano-D connector itself.

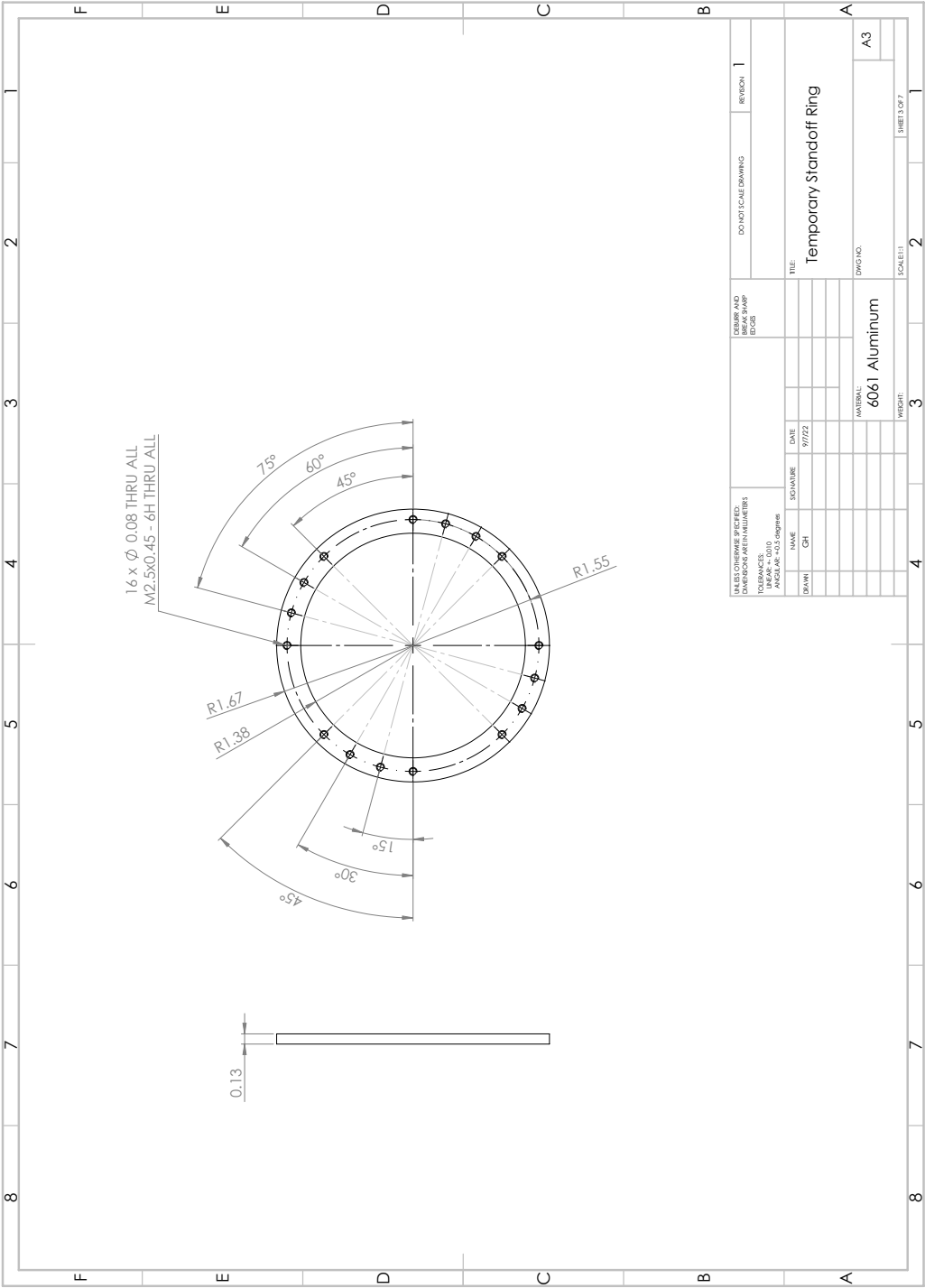


Figure B.14: Mechanical drawing for the temporary standoff ring. This non-flight component assists in raising the assembly safely off of the surface, allowing the H2RG to be secured to the molybdenum mount without touching the array surface or edges.

Figure B.15: Mechanical drawing for the temporary standoff leg (4× manufactured). This non-flight component assists in raising the assembly safely off of the surface, allowing the H2RG to be secured to the molybdenum mount without touching the array surface or edges.

*Appendix C***FOCAL PLANE READOUT BOARD LAYOUT**

This appendix contains as-manufactured board layouts for the 6-layer focal plane readout board designed for the upgraded CIBER-2 long-wavelength detector cryogenic focal plane array, as described in Chapter 3.3.

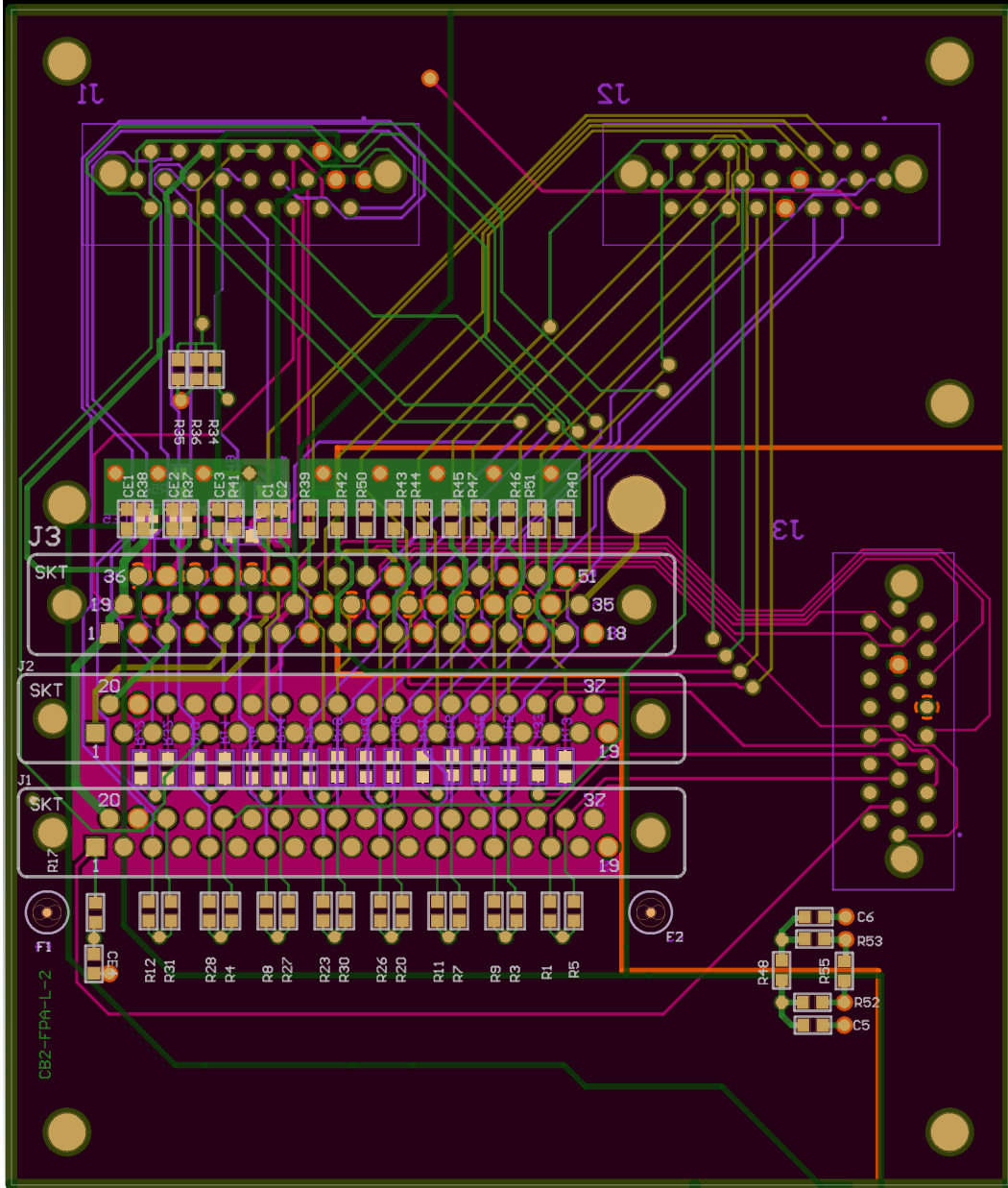


Figure C.1: Overall focal plane readout board layout.

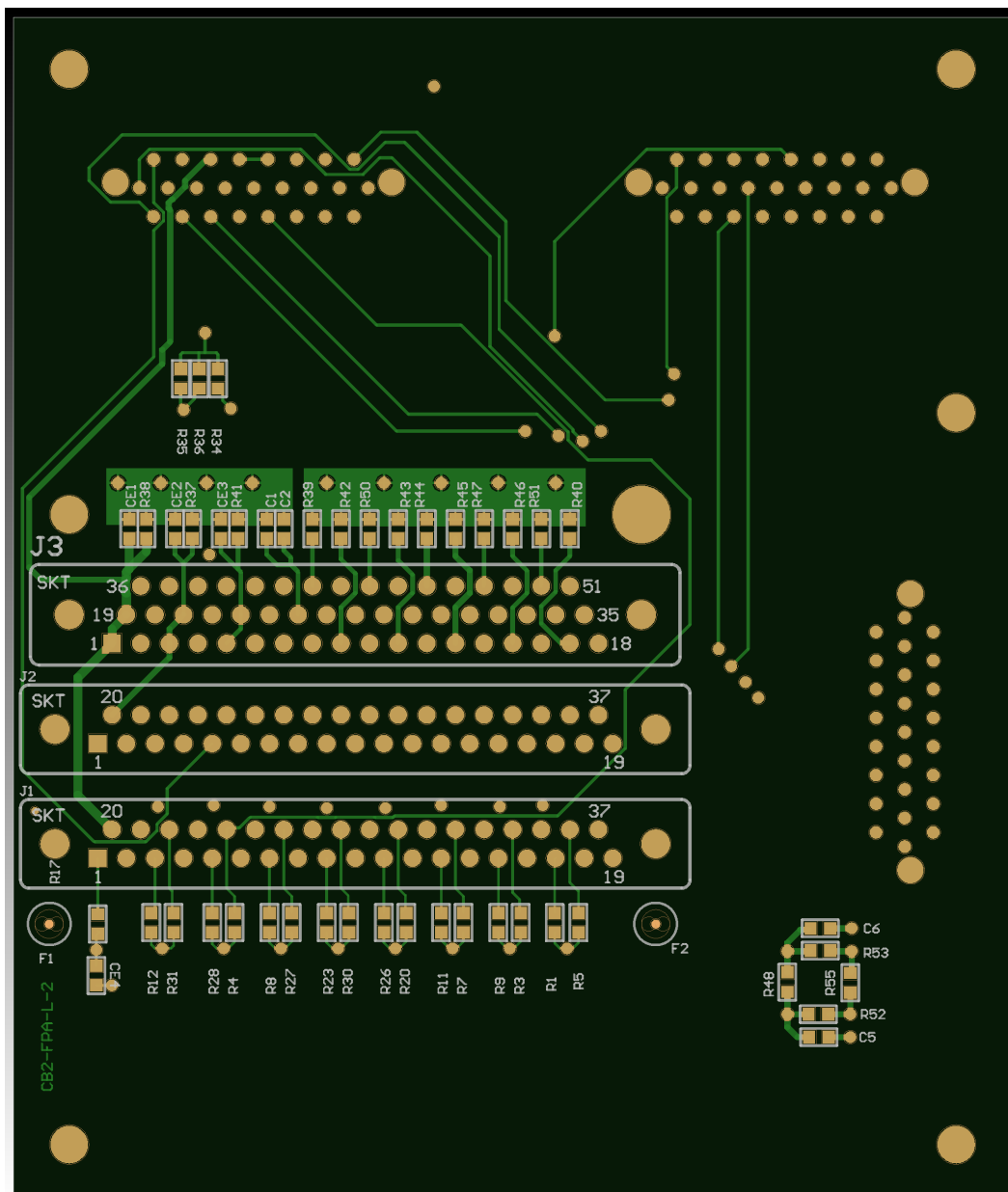


Figure C.2: Top layer (1) – focal plane readout board layout.

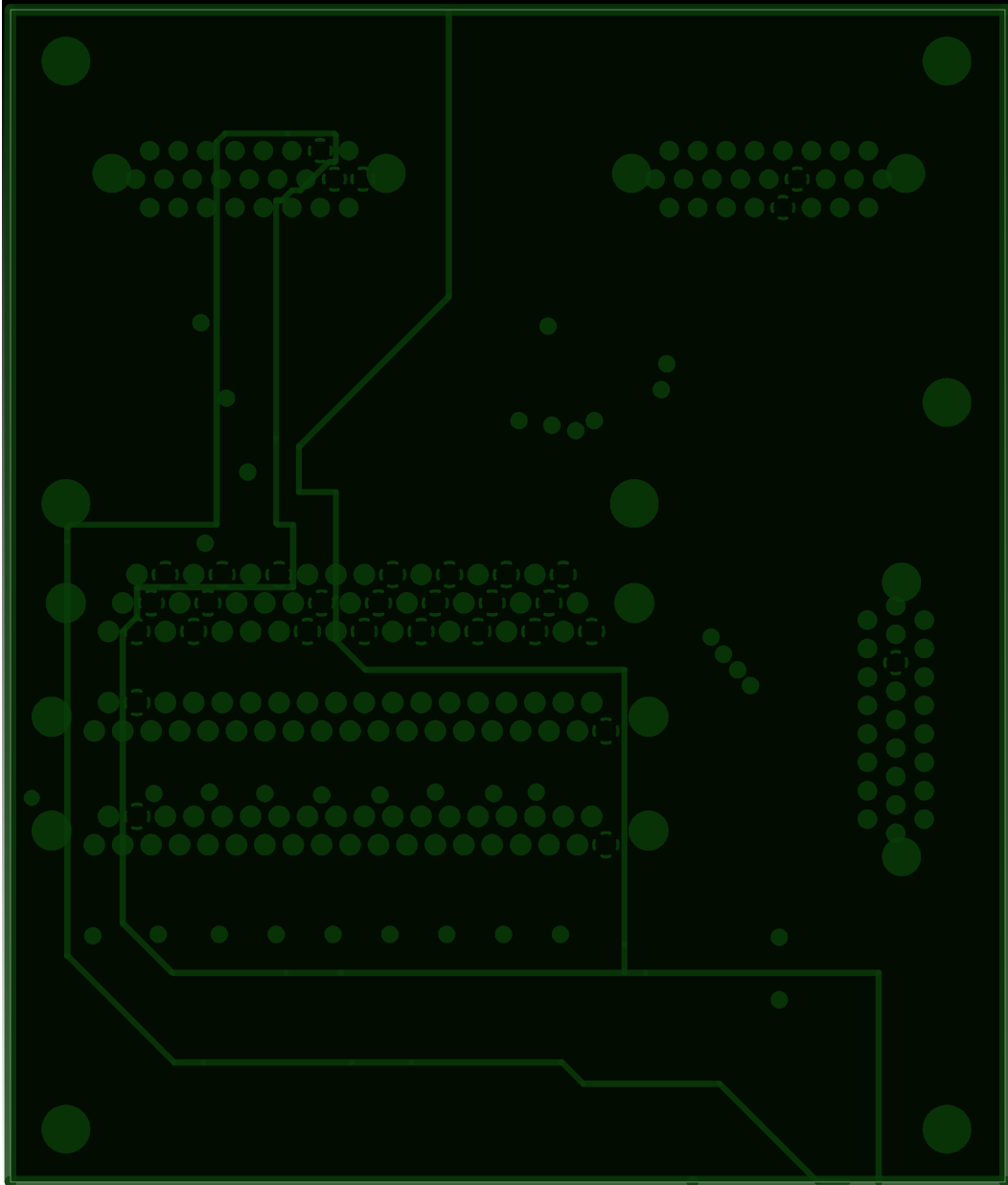


Figure C.3: GND layer (2) – focal plane readout board layout.

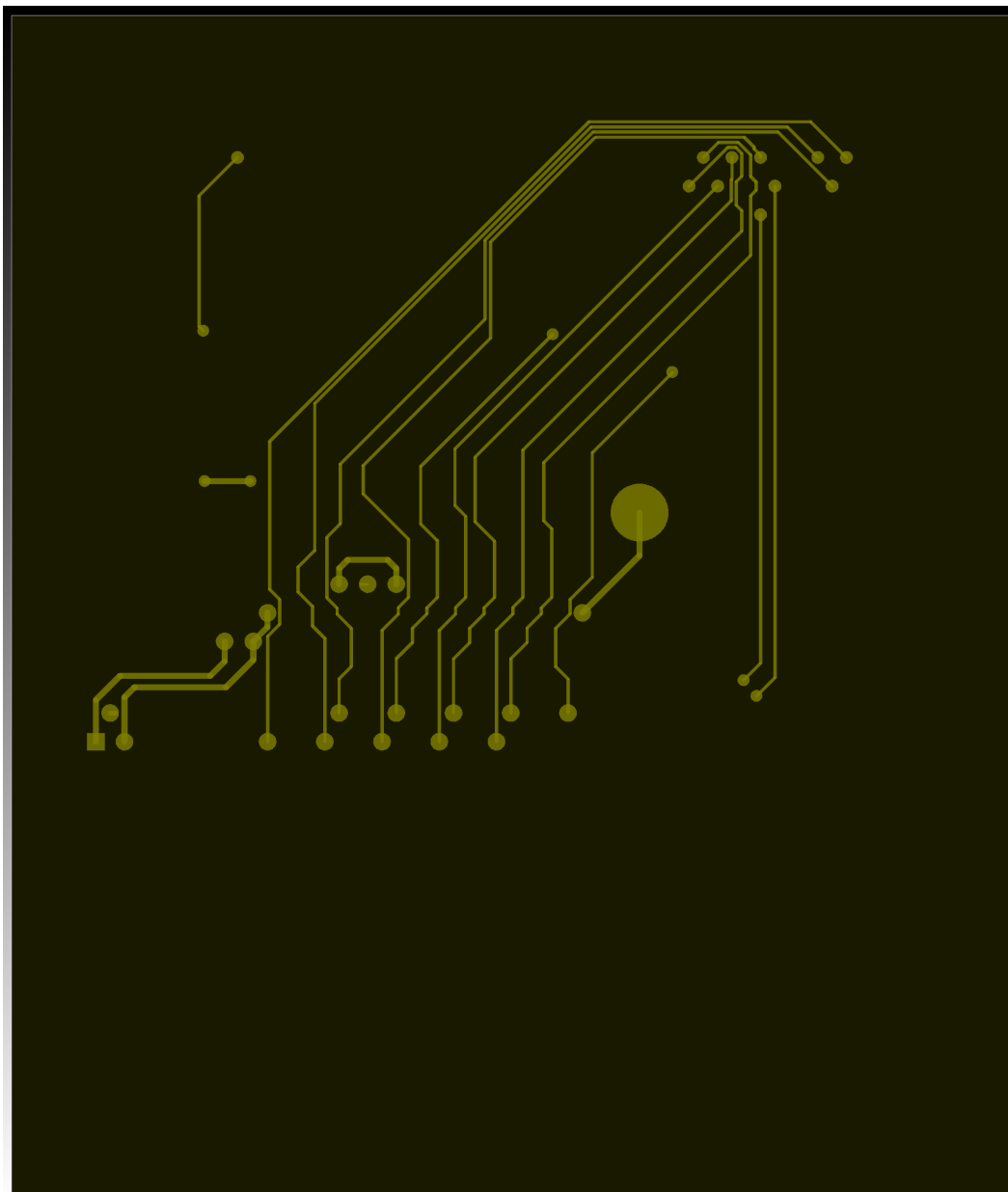


Figure C.4: Middle layer 1 (3) – focal plane readout board layout.

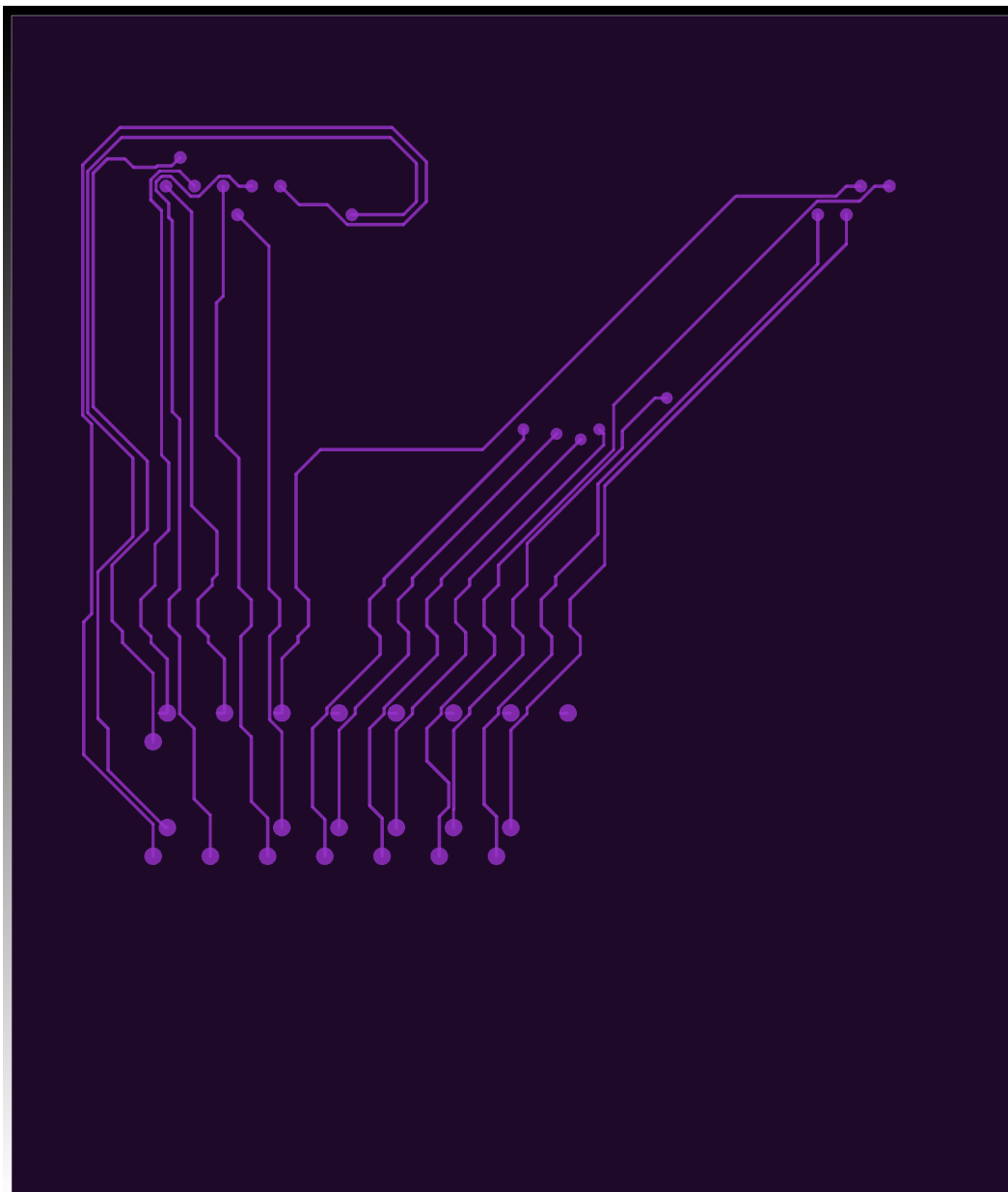


Figure C.5: Middle layer 2 (4) – focal plane readout board layout.

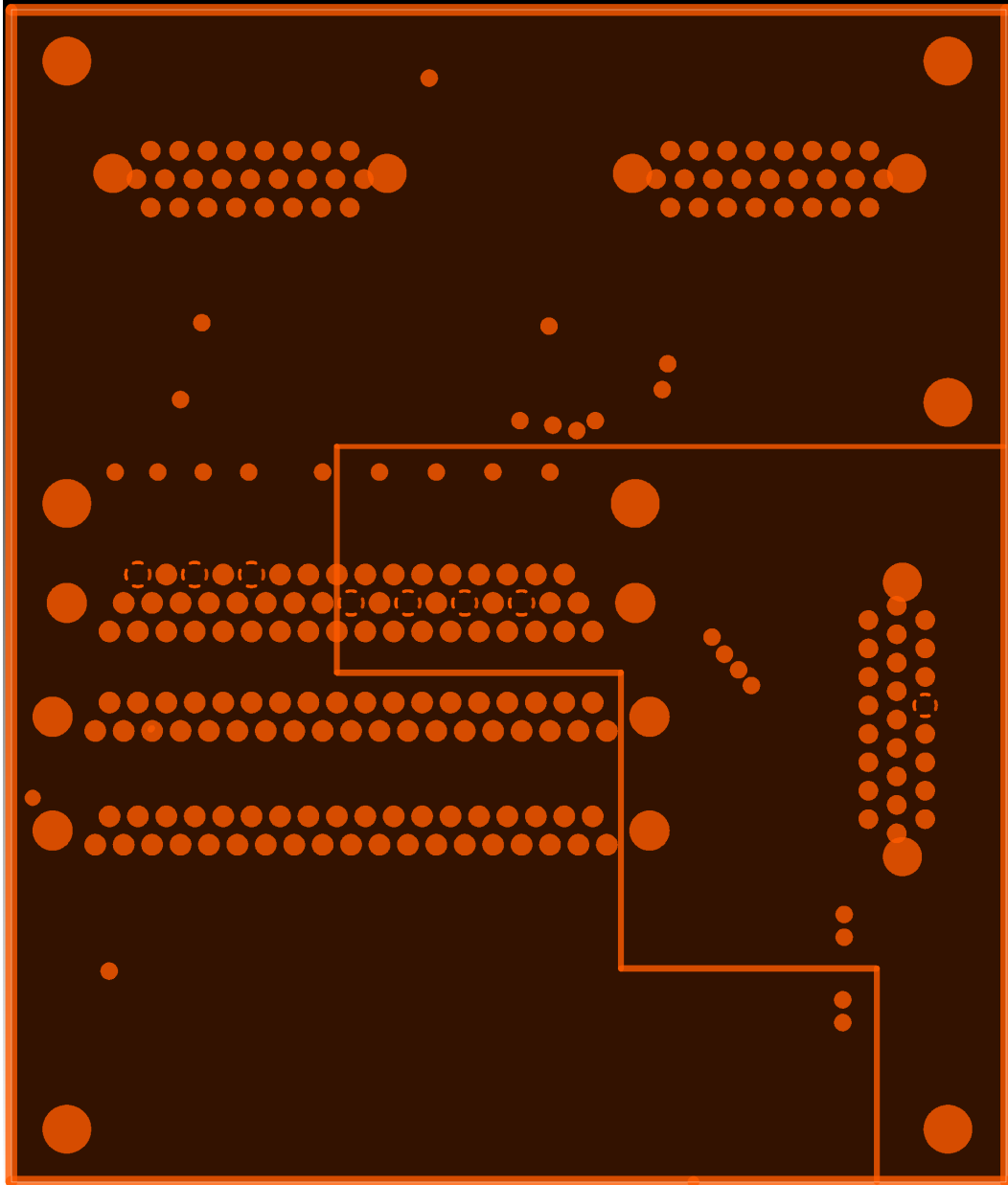


Figure C.6: PWR layer (5) – focal plane readout board layout.

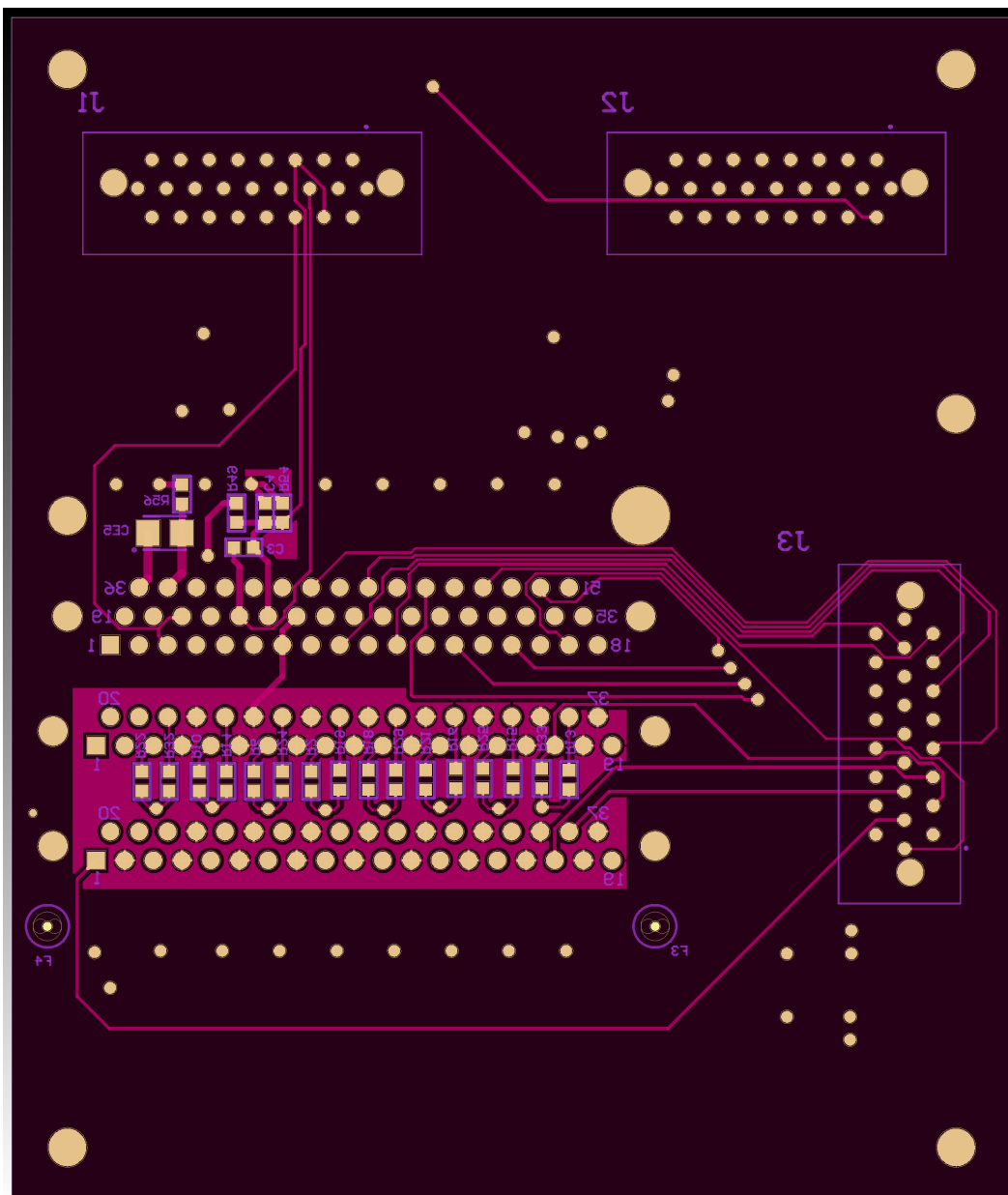


Figure C.7: Bottom layer (6) – focal plane readout board layout.