Characterization of Solar X-ray Response Data from the REXIS Instrument

by

Andrew T. Cummings

Submitted to the Department of Earth, Atmospheric, and Planetary
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Abstract

The REgolith X-ray Imaging Spectrometer (REXIS) is a student-built instrument that was flown on NASA's Origins, Spectral Interpretation, Resource Identification, Safety, Regolith Explorer (OSIRIS-REx) mission. During the primary science observation phase, the REXIS Solar X-ray Monitor (SXM) experienced a lower than anticipated solar x-ray count rate. Solar x-ray count decreased most prominently in the low energy region of instrument detection, and made calibrating the REXIS main spectrometer difficult. This thesis documents a root cause investigation into the cause of the low x-ray count anomaly in the SXM. Vulnerable electronic components are identified, and recommendations for hardware improvements are made to better facilitate future low-cost, high-risk instrumentation.

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I conducted my work as a research assistant with the REXIS program in the Space Systems Laboratory as a student in the MIT Department of Earth, Atmospheric, and Planetary Sciences and the MIT Department of Aeronautics and Astronautics. I owe this thesis to the dedication of countless friends, loved ones, faculty, and staff. Though there are too many to list, I wish to acknowledge a few:

First and foremost, I would like to express my gratitude to Dr. Rebecca Masterson for her guidance and encouragement in the past year. Thank you for always challenging me to grow and improve as an engineer, and for always believing in me.

I would like to thank my other advisor, Professor Richard Binzel, who first invited me to join the REXIS project, and whose passion for science motivated me to dream big and start down this road. Thank you for recognizing something in me, and for agreeing to advise just one last time. Additionally like to recognize the Harvard-Smithsonian Center for Astrophysics team of Dr. Branden Allen, Dr. Daniel Hoak, Dr. Jaesub Hong, and Professor Jonathan Grindlay for mentoring me. Many thanks to the REXIS cohort of Maddy Lambert, Carolyn Thayer, and David Guevel; I would do it all again for the laughs and camaraderie. Special thanks to Megan Jordan for tolerating endless paperwork and logistics, and at times, wrangling me in.

I would also like to thank my family for sending their love and support from so very far away. And to my friends: Lucy, Dan, Brandon, Ruth, Brendan, and Lara; Thank you for being the people who lifted me up when I was down, and for being with me all the way.

Lastly, I wish to thank the Halperin family, for welcoming me into their home during an unprecedented global crisis.

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Chapter 1

Introduction

This thesis is intended to provide an overview of operations involving the REXIS Solar X-ray Monitor (SXM), and an investigation into the cause of unanticipated low solar signal seen during data collection. The SXM is a subunit of the REgolith X-ray Imaging Spectrometer (REXIS), which is mounted aboard NASA's OSIRIS-REx mission.

REXIS an instrument intended to use to produce elemental abundance maps of the surface of the asteroid 101955 Bennu, a C-type near-Earth asteroid using spectrometry. Bennu is of particular interest because it has a 1-in-2700 chance of impacting Earth between 2175 and 2199 [9].

The SXM is a low-cost, high-risk payload. Isolating the root cause of the malfunction and identifying critical components that resulted in failure will provide future projects with additional knowledge for instrument design. The SXM works in conjunction with the REXIS spectrometer to characterize high-energy solar x-ray flux. The SXM is used to detect variable input from the Sun, which is used by the REXIS spectrometer to calibrate x-ray input to Bennu. This thesis will provide an explanation of how solar x-rays are captured by the SXM and how signal data are interpreted. Solar spectra analysis and solar temperature fitting techniques are discussed, as well as the limitations of SXM modeling. SXM hardware is explained, with a focus on the analog signal amplification chain.

An operational timeline of the SXM will be presented. The focus of the latter por-

tion of the thesis will be on a root cause analysis of the low x-ray count-rate anomaly that occurred late in the SXM's operational lifetime. This thesis will conclude with a roadmap for future work, including a more complete root cause investigation into thermal sensitivity, and a CAST analysis to highlight organizational and programmatic controls that may have contributed to the drop off in x-ray counts.

1.1 REXIS Mission

REXIS is a student experiment developed initially as part of the 2011 undergraduate capstone class in the Department of Aeronautics and Astronuatics at MIT. Construction and management of the instrument was conducted in the MIT Space Systems Laboratory (SSL) as part of a larger collaboration with Harvard College Observatory (HCO), the MIT Department of Earth, Atmospheric, and Planetary Science, the MIT Kavli Institute (MKI), MIT Lincoln Laboratories, and Aurora Flight Sciences. Day-to-day operations and engineering are conducted primarily by students with guidance from senior faculty and staff including Professor Richard Binzel, the REXIS Instrument Scientist, Professor Jonathan Grindlay, the REXIS Deputy Instrument scientist from HCO, and Dr. Rebecca Masterson, the REXIS Project Manager, from the MIT Department of Aeronautics and Astronautics. To date, over 80 students have worked on REXIS at all levels and stages of the project.

The REXIS main spectrometer relies on coded aperture mask spectroscopy to capture incident x-rays from Bennu's surface in the soft x-ray band (0.5-7.5 keV). A total x-ray spectrum is derived from the soft x-ray data and REXIS was designed to detect, if measurable, signals from Si, S, Mg, and O. REXIS has two operating modes: Imaging and Spectral. In imaging mode, REXIS maps specific abundances to locations on Bennu's surface with necessary spatial resolution at an observation distance of 700m. In spectral mode, REXIS records x-ray energies and produces the global average of the x-ray spectrum passing through the coded aperture mask. REXIS performs its science objective in concert with the other OSIRIS-REx instruments.

The flight schematic of REXIS is shown in Figure 1-1. The primary components

of REXIS are housed in the main instrument. These consist of a 2x2 array of CCD's housed within a coded aperture mask. Housed separately is the Solar X-Ray Monitor (SXM), which will be the focus of this study.
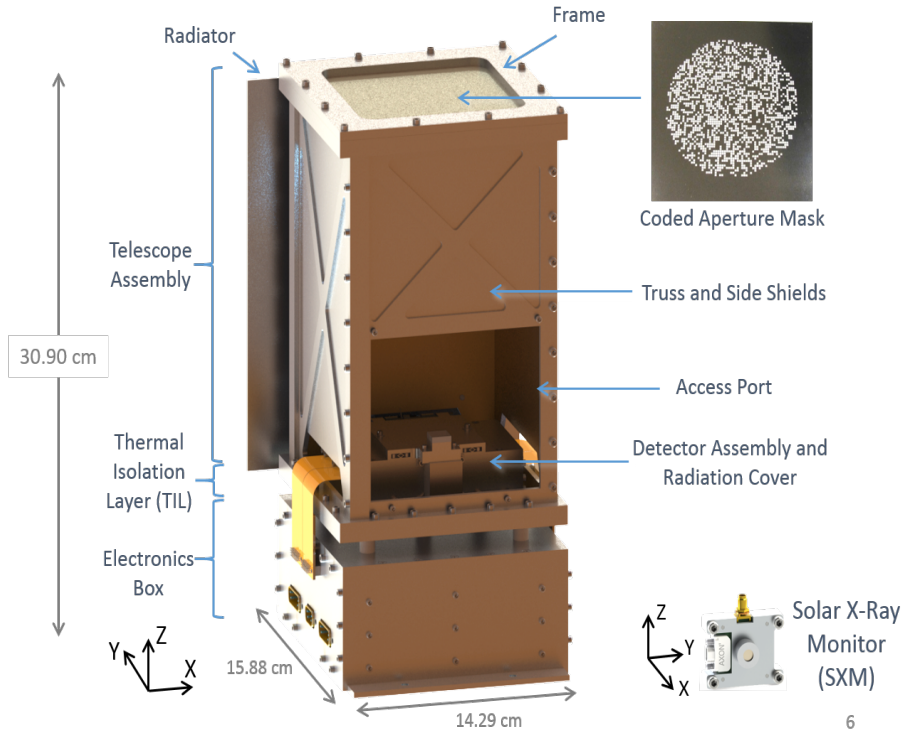
Figure 1-1: Schematic of the REXIS Instrument and SXM (shown to scale).

The SXM is an x-ray detector located on the outside of the spacecraft bus, so that it would be sun facing during observations of Bennu. The SXM is connected to REXIS by a coax cable, and SXM data processing occurs in the main REXIS instrument.

REXIS is the second student experiment to accompany a New Frontiers mission as part of NASA's education and public outreach initiative. The first student instrument, the Venetia Burney Student Dust Counter (VBSDC, formerly SDC) built by University of Colorado Boulder, flew on the New Horizons spacecraft and recorded interplanetary dust from between 2.6 and 15.5 AU [13]. REXIS is a significant leap in complexity from the VBSDC, and at its inception was required to "directly engage students at the undergraduate and graduate levels in the conception, design, implementation, and operation of space flight instrumentation. (2011 internal program

level doc.)"

1.2   REXIS Operational Timeline

This section will discuss the operational lifetime of REXIS and the SXM, from its launch on 8 September 2016 until the instrument's planned shutdown following the OSIRIS-REx Orbital R mission phase in November 2019. A more detailed explanation of SXM operations can be found in Chapter 3. Henceforth, some operational times will be referred to as "L+", which stands for months after launch, unless otherwise specified. For example, events in the L+30 phase of the mission occurred 30 months after launch. The REXIS timeline is inherently linked to the OSIRIS-REx timeline.

REXIS was powered on during L+14 Days for a payload inspection and functions check. The SXM took 3935 seconds of x-ray data, and the instrument function was nominal. The SXM was turned on for an additional function check at L+6, where the instrument threshold was set. A third functions check was conducted during L+18. The SXM remained nominal, and there were no anomalies in x-ray detection.

The next big milestone was the L+22 Checkout in July 2018, where REXIS and the SXM were again checked for behavioral anomalies. Data collected by the SXM demonstrated full functionality. During L+22, REXIS was internally calibrated to identify background noise and hot pixels. As a diode detector, the SXM cannot have hot pixels in the same way as a charge-coupled device (CCD) detector.

REXIS performed its cover opening operation in September 2018. The radiation cover was released using a frangibolt, after which REXIS detectors were first exposed to the space environment. REXIS underwent a series of cosmic x-ray calibrations (CXB), and the REXIS spectrometer was shown to be sensitive to stray light.

The L+30 Calibration was the first time Bennu was observable in the REXIS field of view. During this calibration, a hot pixel mask was tested on REXIS. SXM count rates were lower than previous observations, but returned to previously seen levels in later flight.

During flight, REXIS underwent a series of calibrations using the Crab Nebula and

Scorpius X-1 (Sco-X-1), two known cosmic x-ray sources. Using a known, stable x-ray emitter provided a source that allowed the gain and offset of the REXIS detector nodes to be set. Crab Calibration took place in November 2018 and March 2019, while Sco X-1 occurred later, during Mask Calibration.

Orbital B, the first REXIS observation phase, occurred from 1 July to 6 August, 2019. This was initially the only observation window for REXIS. The OSIRIS-REx spacecraft was placed in a stable orbit one kilometer above the surface of Bennu. The SXM count rate saturation anomaly was found during Orbital B, where the instrument reported abnormally high counts on the detector. On 5 July, SXM data was saturated with an additional value of 34880. It was believed that a "bit flip" occurred, where radiation moved the reset value on the SXM. This was corrected with a reset command from the ground.

Additionally, throughout Orbital B the SXM began showing a two order of magnitude decrease in x-ray signal disproportional to the spacecraft's solar distance. The results from results from the SXM's Internal Calibration are depicted in Figure 4-2. More on this anomaly can be found in Chapter 4. In all, two anomalies were detected in the SXM, and three were detected in REXIS. For more information on REXIS anomalies, consult Maddy Lambert's thesis [7].

Orbital R was the final observation window for REXIS, which occurred during November 2019. The REXIS team petitioned for, and was awarded, this additional observation to supplement limited data taken during Orbital B.

1.3 Anomaly Resolution during the OSIRIS-REx mission

Anomaly detection for instruments on OSIRIS-REx was primarily the job of the engineers and scientists behind the individual instrument. Generally, a few weeks were allotted after reporting the anomaly to conduct an investigation, and isolate the root cause.

After an assessment had been made, the instrument team would present a recommendation for how to proceed with using the instrument to the OSIRIS-REx PI. This recommendation included an identification of the incident, current results of the investigation, and conclusions about future instrument performance and how it might affect the spacecraft. The investigation could be closed without reaching a defined root cause, so long as the incident was isolated and did not impact other instruments on the spacecraft.

1.4 Motivation

Low-cost, high-risk spaceflight missions granting better accessibility to space than ever before. The REXIS project was developed with the philosophy of being a student instrument. From its inception as the final deliverable for 16.83, the MIT Aerospace Engineering senior design capstone class, where undergraduate students worked side-by-side with experienced research scientists and engineers. Students directly applied s learned in their undergraduate curricula, and produced an instrument of complexity, scale, and mission worthy of being included on a New Frontiers spacecraft. Like all projects, there were challenges faced along the way. A rotating ensemble of students created a challenging environment for informational and experiential entropy.

The REXIS instrument is categorized as a NASA Risk Class D mission, which is characterized by lower cost and the use of legacy hardware [11]. Indeed, a portion of the electronics design process for REXIS consisted of utilizing existing schematics from NICER, an x-ray instrument developed by the MIT Kavli Institute (MKI). These schematics were simplified for the design of the SXM as a matter of reducing cost. Identifying the source of the SXM spaceflight anomaly not only provides guidance on potential hardware vulnerabilities which exist in current spaceflight missions; it also yields a roadmap for future missions.

1.5 Thesis Roadmap

This thesis is organized into six chapters, which document the SXM background, instrument anomaly, and subsequent investigation. The current chapter has introduced the larger REXIS mission, operations over its lifetime, and how anomalies were identified, catalogued, and solved. Chapter 2 presents a background on the SXM, including an explanation of the SXM data pipeline and associated solar x-ray modeling. A broad overview of the electronic components that comprise the SXM will be provided, as well as how they operate in the space environment. In Chapter 3, the structure and design process of the SXM will be explained in greater detail. This is followed by a summary of instrument testing that occurred, both on the ground and after launch. Then, SXM flight operations leading up to and after the anomaly are discussed. Chapter 4 explores the SXM root cause analysis. The identification of the low count-rate anomaly is explained in depth. The investigation into the SXM pre-amplification chain electronics is next. The chapter ends with a plan for future research into the identification of the vulnerability that caused the anomaly and how such a finding may be interpreted.

Chapter 2

Background

This chapter will describe the circuitry used in the SXM. The SXM relies on an intricate array of amplifiers and filters, which are capable of x-ray detection when combined. The chapter will begin with an introduction of standard electrical components and how they operate. An example circuit of each component is provided and includes a visual representation of ideal operation. This will create a foundation of understanding that will translate to more complex electrical engineering systems seen in the SXM. The first advanced concept explained is signal amplification. Signal amplification is the primary means through which a signal is passed from the SXM detector and recorded by the instrument. Typical amplification techniques will be compared against amplification used in the SXM. To understand signal processing in the SXM, an explanation of analog-to-digital conversion is provided. A more thorough model of SXM signal processing is covered later in the chapter. The thermal sensitivity of electrical systems is explained, and typical response sensitivities are modeled. An overview of the SXM will explain the functions of the instrument in broad terms. The SXM Data Pipeline will be explained from end-to-end. A theoretical solar x-ray response will be followed from detection, through the pipeline, and finally to transmission to the ground. Finally, the chapter concludes with theoretical instrument response using the Chianti Atomic Database and an explanation of how it was implemented in the Data Pipeline. SXM instrument simulation code can be found in Appendix B.

2.1 Basic Circuitry

This section introduces the common electrical components used in the SXM, how they operate individually, and how they are used together to create more complex circuitry.

2.1.1 Common Components

Resistor
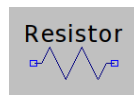
Figure 2-1: The symbol used to represent a resistor in circuit diagrams.

A resistor is an electrical element with a positive and negative terminal that utilizes the property of electrical resistance. Its primary functions include voltage division, current flow reduction, and signal reduction. Ideal resistors function based on Ohm's law,

$$V = IR \tag{2.1}$$

where the voltage differential across the resistor is proportional to the product of current and resistivity. Resistors are commonly used in two constructions: parallel and series. Resistors in parallel are be treated as the multiplicative inverse of the sum of the reciprocals of individual resistors,

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}. \tag{2.2}$$

Series resistors are treated as the sum of individual resistances,

$$R_{eq} = R_1 + R_2 + \ldots + R_n. \tag{2.3}$$

.

In practical application, resistors are susceptible to series induction and parallel

capacitance in alternating current (AC) systems. These vulnerabilities are expressed primarily in the high frequency regime, which can impact signal amplification. Resistors are thermally emissive as a property of power dissipation. Power dissipation in an ideal resistor is modeled as

$$P = \frac{V^2}{R} = I^2 R = IV. \tag{2.4}$$

This power is converted to heat and emitted by the component.

Capacitor
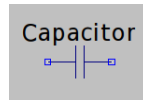
Figure 2-2: The symbol used to represent a capacitor in circuit diagrams.

A capacitor is a passive, two terminal component that stores electrical charge. When a voltage potential is passed along a capacitor, an electrical charge is produced. A capacitor consists of two charged conducting nodes separated by a non-conductive medium. This medium consists of either a vacuum or a dielectric material, which can increase the capacitance of the component. Capacitors are characterized by their capacitance. In an ideal capacitor, its capacitance is measured as the ratio of charge held to the voltage across the component. This is represented in the formula

$$C = \frac{Q}{V} \tag{2.5}$$

in a DC system. In AC systems, a capacitor's impedance influences the capacitance of the system. Impedance can be considered as a vector quantity described as the sum of the resistance and reactance, which is the component's opposition to current. Impedance is inversely related to capacitance and signal frequency.

The characteristics of capacitors in parallel and series are exactly opposite of a resistor. The capacitance of multiple capacitors in parallel are be calculated as the

sum of the capacitance of the individual components. This is represented by the equation

$$C_{eq} = C_1 + C_2 + \ldots + C_n. \tag{2.6}$$

For capacitors in series, the total capacitance can be calculated as the multiplicative inverse of the sum of the reciprocals of individual resistors and represented by the formula

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}. \tag{2.7}$$

Diode
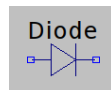
Figure 2-3: The symbol used to represent a diode in circuit diagrams. The positive terminal is to the left, and the negative terminal is on the right.

A diode is a unidirectional conductor that passes current from a positive to negative terminal, and restricts current flow in the reverse direction. A typical diode utilizes a p-n junction material to generate a forward direction with zero resistance, and a backward direction of infinite resistance. A diode has two response modes known as reverse-bias and forward-bias. A diode that is reverse-biased will act as an insulator and will ideally prohibit current from being passed, so long as its voltage limit is not exceeded. Conversely, a diode that is operating with a forward-bias will become a conductor, and current can pass backwards through the diode. Diodes also possess a property known as breakdown voltage, which flips a diode's bias when reached. When a diode is exposed to its breakdown voltage in the direction opposite the flow of current, the formerly infinite resistance drops to low resistance, and current backflows. This property is exploited to direct current in anomalous situations such as overvoltage. When an overvoltage situation occurs, a diode will switch from being negative-biased to being positively-biased, and will direct current away from sensitive components. Additionally, diodes have a characteristic voltage drop in the

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direction of current flow, which is described in its commercial datasheet. This can be used to help shape a voltage in signal processing.

Gain

In analog amplification systems like the SXM, gain refers to the ratio of output to input signal. Voltage gain will be primarily discussed henceforth, as this is what occurs in the SXM amplification chain, although power, amplitude, and current are all other methods of measuring gain.

2.1.2 Operational Amplifiers

An Operational Amplifier, or op-amp is a high-gain voltage amplifier that takes a differential input and produces a single output. It is directly coupled, meaning that it relies on direct current transmission, rather than through inductive or capacitive coupling [2]. In a circuit diagram, an op-amp has five terminals, which are labeled in Figure 2-4.
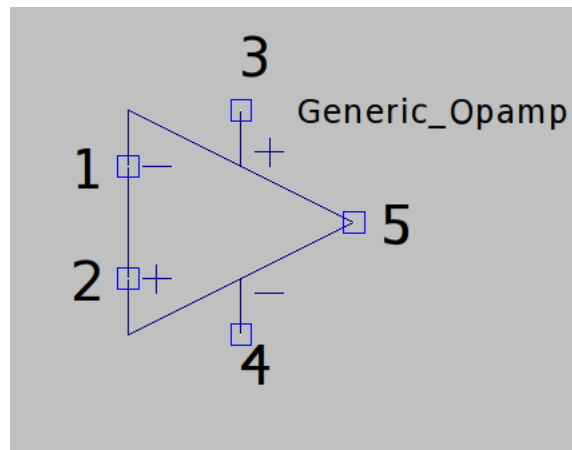
Figure 2-4: A generic op-amp. (1) Inverting input, (2) Non-inverting input, (3) Positive power supply, (4) Negative power supply, (5) Output.

Additionally, an ideal op-amp has the following characteristics [2]:

- No output impedance

- No noise contribution to the output signal

- No DC offset in the output signal

- Infinite bandwidth

- Infinite input impedance

- Infinite open-loop voltage gain

Open-loop gain is entirely dependent on the input. Consider Figure 2-5 in which an op-amp is placed in the open-loop configuration. For any non-zero voltage input, the open-loop gain drives the op-amp output into saturation. When the op-amp is saturated, the output voltage no longer increases. When the voltage input to the op-amp is zero, the output from the op-amp is also zero. An op-amp in the open-loop configuration is liable to latch-up, where the op-amp experiences a short circuit and ceases to work. Op-amp saturation is not always reversible, and can permanently disrupt current flow through the circuit.
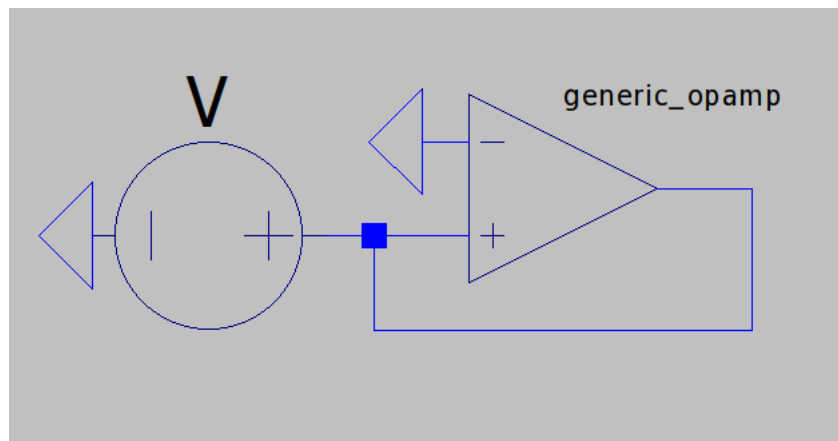
Figure 2-5: A generic op-amp with open-loop gain.

In order to guard against voltage output saturation, an op-amp can be configured for closed-loop gain, as shown in Figure 2-6. Closed-loop gain relies on the output signal feeding back into the input in order to shape desired input. Op-amps that amplify through the use of closed-loop gain are less susceptible to voltage saturation through amplification. However, it should be noted that saturation can still occur through overvoltage from the input.

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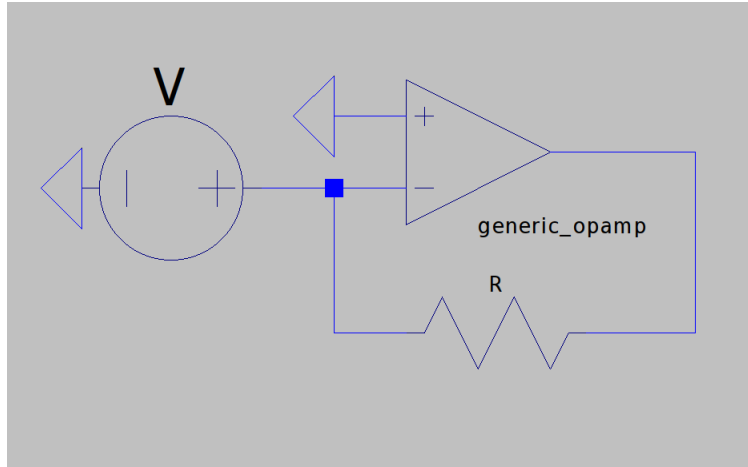
Figure 2-6:   A generic op-amp with closed-loop gain.

2.1.3   Signal Amplification

The SXM uses a signal amplification chain to shape and condition x-ray flux signal
for analog-to-digital conversion. Two different input configurations will be discussed
in this section, and select common amplification circuits will be explained.

Inverting amplifiers take a positive DC voltage at the input and produce a larger
negative voltage at the output. In AC amplification, the output is exactly 180 °)
out of phase with the input. Non-inverting amplifiers take an AC input and preserve
its phase in the amplified output. A positive voltage DC input will yield a positive
voltage output.

The first common amplification circuit is a differentiator, shown in Figure 2-7. A
differentiator is created using an inverting amplifier with a capacitor in the input line,
and a resistor in the negative feedback loop, which can be considered a rudimentary
high-pass filter. This causes the output from the op-amp to be proportional to the
time derivative of the input, which is where the circuit owes its name. The differentia-
tor has a few characteristic limitations. For instance, a differentiator is susceptible to
circuit noise which may be amplified in the output. A differentiator is also susceptible
to high-frequency noise, which can cause instability [2].

Similar to the differentiator, an integrator is used to integrate and invert an input
signal. The output voltage is the time-dependent integral of the input voltage [2]. In
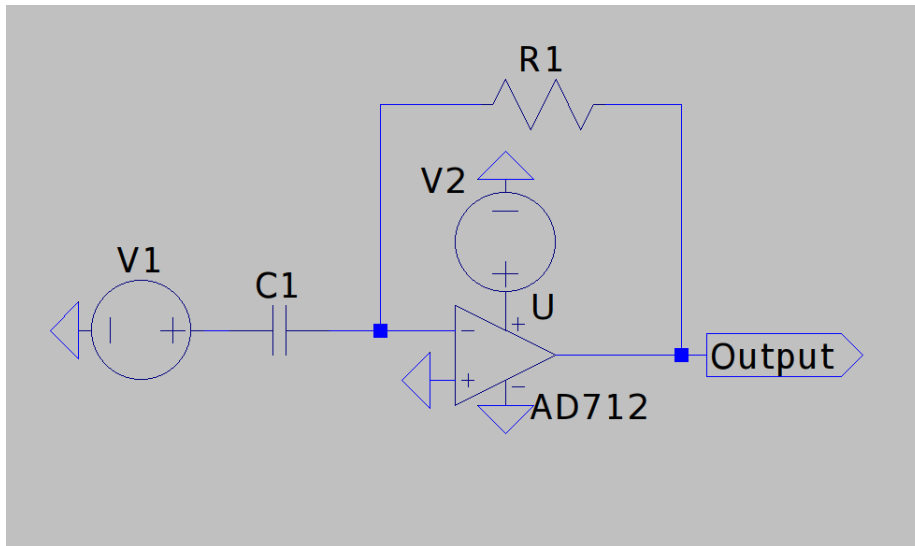
Figure 2-7: An example differentiator circuit.

this configuration, a resistor is included on the input line, and a capacitor is placed in the negative feedback loop, which creates a low-pass filter, as shown in Figure 2-8.
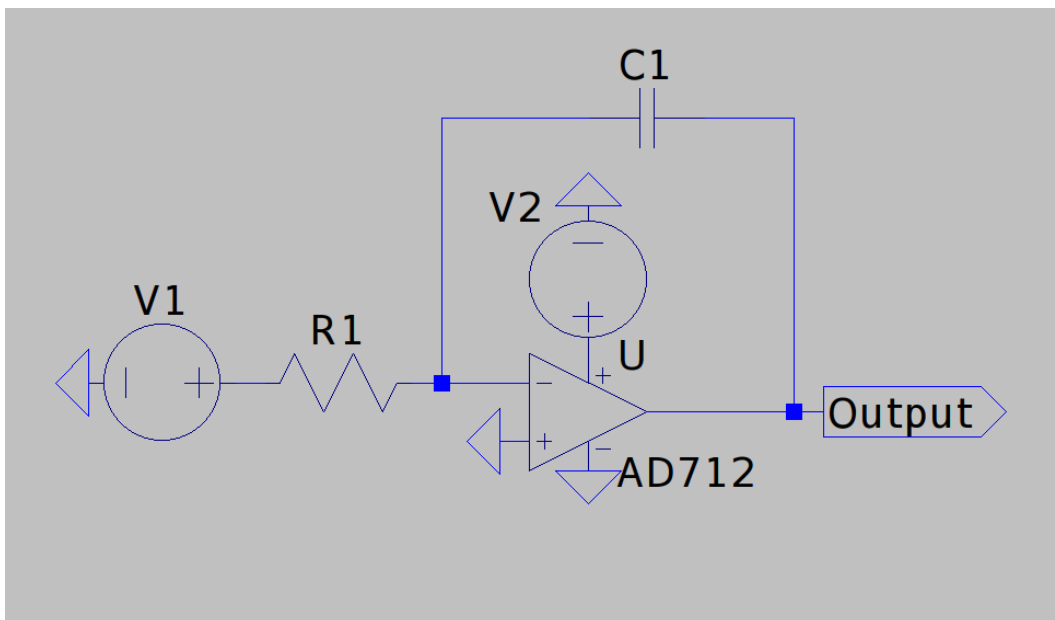
Figure 2-8: An example integrator circuit.

In its simplest configuration, an integrator circuit requires periodic discharge of the capacitor, which can become saturated with charge. When this occurs, the output voltage can drift beyond the optimal range of the op-amp. One way to mitigate this

challenge is to include a resistor in the feedback loop that functions as a discharge path for the loop capacitor (Figure 2-9).
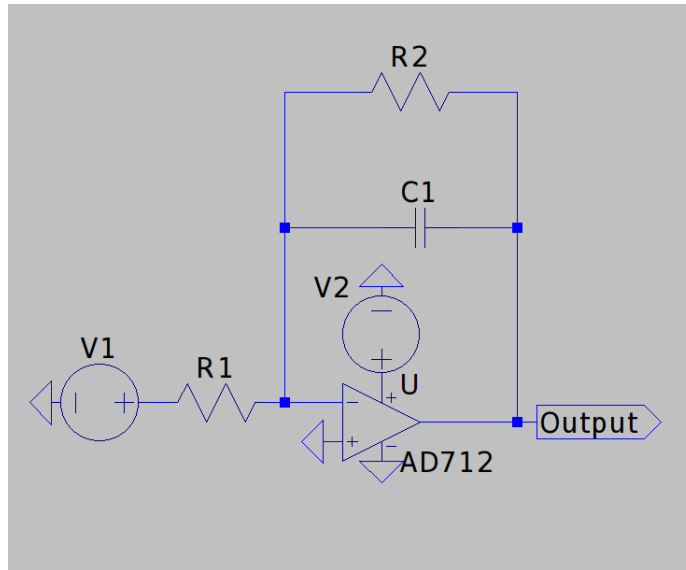
Figure 2-9: An integrator circuit with an additional resistor added to the feedback loop provides a discharge path for the capacitor.

The last configuration worth mentioning is the Schmitt Trigger, which shapes an input signal into a square wave. An example Schmitt Trigger is provided in Figure 2-10. This configuration can be used to shape a signal at a set voltage, so that it can achieve a more lossless input into an analog-to-digital converter. A Schmitt Trigger is a modified integrator with positive feedback. A voltage divider is used to set the positive feedback, and looped back to the non-inverting input. When a prescribed threshold voltage is exceeded, the input voltage triggers and changes the state of the output voltage. This configuration is vulnerable to hysteresis effects, where the input voltage is above the threshold voltage.

2.1.4 Analog-to-Digital Signal Conversion

Analog-to-digital conversion is the process through which an analog signal is translated into a series of digital values using an analog-to-digital converter (ADC). In the SXM, an input x-ray signal is amplified and shaped before being converted and digitized for data processing. The digital output from the ADC is proportional to the
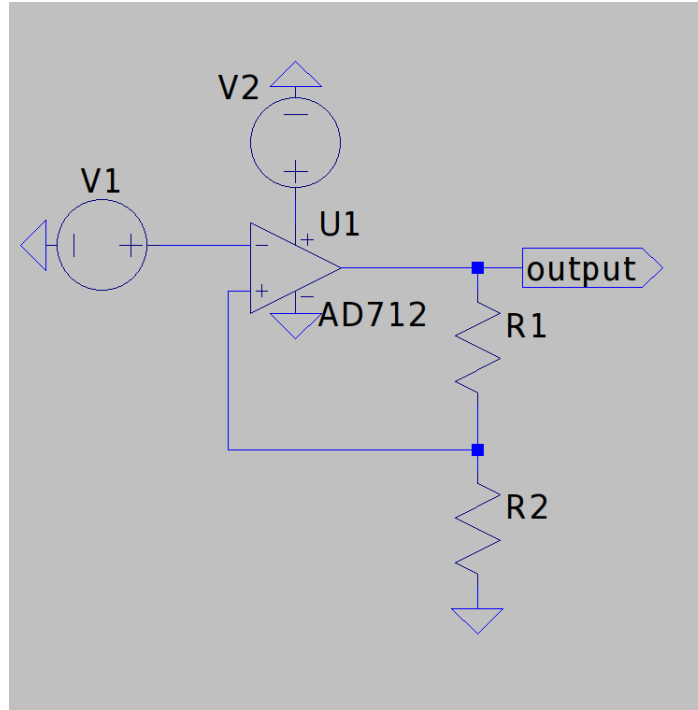
Figure 2-10: An example Schmitt Trigger.

analog input signal, and is limited by quantization speed and accuracy concerns.

2.1.5   Thermal Impact on Circuitry

Temperature concerns must be accounted for when creating and operating complex electrical systems. Amplification circuits often have a small window of acceptable input voltages, and signals must remain within specified bounds in order to be amplified and ultimately converted by an ADC. Furthermore, unwanted over- or under-voltage can cause temporary or even irreversible damage to sensitive electrical systems.

While voltage itself is not thermally dependent, individual circuit elements are dependent. For instance, an increase in temperature can affect power dissipation in resistors. This can cause permanent damage to resistors by burning or melting the resistor. In capacitors, temperature can alter how charge moves within a dielectric material, increasing or decreasing the amount of charge required to saturate the component. Additionally, resistivity in the wiring connecting circuit elements scales positively with temperature, which can cause unintended voltages within the circuit.

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Temperature concerns are considered in the design process of space hardware. For Class D missions, NASA recommends that only Level 1, Qualified Manufacturer List Class V (QMLV) legacy hardware is used in instrumentation. Circuitry tested to this level is rated for interplanetary spaceflight, where extreme radiation and thermal conditions are experienced [10].

2.2 SXM Overview

The SXM component of the REXIS instrument suite is a subassembly located on the OSIRIS-REx bus such that it will face the sun during windows of operation that REXIS is pointed at Bennu. The electrical elements of the SXM are attached to the REXIS Main Electronics Board (MEB) by a coax tether. The SXM mechanically adheres to the spacecraft bus using an aluminum mounting bracket. The external elements of the SXM consist of an Amptek XR-100SSD silicon drift diode (SSD) detector connected to a pre-amplification circuit (henceforth referred to as the preamp) located on a mounted printed circuit board (PCB).

When a solar x-ray hits the SSD detector, an analog signal is passed through the preamp, where it is conditioned and sent to the MEB. At the MEB, the analog signal passes through an ADC, which outputs a digital response. This digital response is processed further by the MEB into x-ray energy event histograms sorted by energy level. Event energy data is kept in Analog-to-Digital Units, which can be converted to units of Electronvolt (eV). A conversion from ADU to eV is calculated using the formula

$$keV = 0.0219 * ADU, \tag{2.8}$$

for the REXIS SXM.

Solar x-rays and their energies are then used to calculate the influx and energy of primary solar x-rays onto Bennu. A knowledge of primary x-ray energies is required to calibrate the secondary x-ray fluorescence capture by the REXIS detector.

2.3 SXM Data Pipeline

The SXM Data Pipeline takes a converted signal from the SXM ADC and processes it into data packets that are transmitted to the ground.

2.3.1 Instrument Response Modeling

The SXM underwent a series of ground and in-flight validations between 2013 and 2019. This section will focus on the instrument response modeling that was used to verify early in-flight observations. The SXM Data Pipeline included a model of ideal SXM response, which at its core took a sample time-series of x-ray detections and produced energy histograms. These energy histograms could then be fitted to a known solar abundance model, which would match an input signal to x-ray characteristics of elements in the Sun's photosphere, and subsequently constrain solar temperature at the time of x-ray emission. While this function fell beyond the original scope of the SXM's purpose, it provided yet another way to produce instrument science.

2.3.2 Chianti Atomic Database

The Chianti Atomic Database was used to create an instrument response model across all temperatures and energies observable by the SXM. The Chianti Database is an atomic spectra database built and maintained by a global consortium of atomic scientists [8]. Chianti and its associated python package, ChiantiPy, allow a user to generate model spectra of astrophysical bodies. For the purposes of the SXM, Chianti provided a known database against which sample SXM histograms could be matched. Both coronal and photospheric abundance models were generated at the temperatures and energies observable by the SXM, and ideal instrument response was cross-referenced against early in-flight calibration data that was taken prior to the REXIS instrument's primary observation window. The intention of this cross-reference was to build reasonable confidence in the instrument response model such that temperatures and spectra abundances could be derived from data collected during observation.

Chapter 3

SXM Design and Operation

This chapter describes the design process and flight operations of the REXIS Solar X-ray Monitor (SXM). The first section will focus on the design constraints of the instrument. REXIS is a Risk Class D mission, which means it is a low budget instrument, and is designed to use legacy, off-the-shelf components [11],[12]. This section also describes the science mission requirements for the SXM, as well as design requirements stipulated by the OSIRIS-REx team. The design section will primarily detail the development of the SXM signal amplification chain, which is at the center of the Root Cause investigation found in Chapter 4.

The next section of this chapter will describe the testing battery used to characterize the SXM on the ground and in flight. The SXM's pre-flight ground testing regimen will include testing data relevant to the SXM root cause analysis, and include rationale for why some tests were foregone. Results of SXM flight testing will be presented, and nominal x-ray count data will be shown.

The last section of this chapter summarizes SXM flight operations. A timeline of operations is included to understand where flight testing occurred relative to science observations. Flight operations are separated into three distinct phases, which correlate to OSIRIS-REx mission phases. Early flight operations are described, followed by operations during Orbital B and Orbital R, the SXM's two science operation phases.

3.1 SXM Design Background

The SXM was first designed as part of the 16.83 undergraduate capstone class in the MIT Department of Aeronautics and Astronautics in 2011. This first design became the foundation upon which the SXM flight model was developed. The REXIS instrument was designed to use heritage spaceflight technology to reduce the design timeline. The SXM detector is an Amptek XR-100SDD, which is an updated model of detectors flown on previous x-ray instruments. The XR-100SDD is an updated version of the XR-100CR, and the former uses a silicon drift diode, while the latter uses a PIN photodiode [1]. Both models a beryllium window above an evacuated chamber in which the detector is housed. Amptek XR-100CR detectors were used in the Solar X-ray Spectrometer aboard GSAT-2, a space-based Indian solar observatory [5]. A similar Russian space observatory used the XR-100CR in the Solar Photometer in X-rays (SphinX) instrument [15]. Both of these previous instruments demonstrated that the Amptek XR-100 class detector could be reasonably be used to for x-ray solar observation, despite the XR-100SDD never having flown prior to REXIS.

The XR-100SDD detector was also included in early designs of the Neutron star Interior Composition ExploreR (NICER) instrument. NICER was developed by the MIT Kavli Institute (MKI), and the engineering teams worked closely together in the development processes. Both Professor Richard Binzel and Dr. Rebecca Masterson, who represent two-thirds of REXIS leadership, are affiliated with the Kavli Institute. Additionally, the Kavli Institute is located in the same building as the REXIS team, meaning collaboration was as easy as going upstairs. Additionally, the Goddard Spaceflight Center serves as the managing center for both REXIS and NICER. This closeness of personnel was reflected in the design of the REXIS SXM.

The NICER instrument is mounted aboard the International Space Station, where its main spectrometer observes neutron stars in the 0.2 to 12 keV range [4]. The REXIS SXM shares both structural and electronic heritage with the NICER instrument. An early design of NICER implemented 56 XR-100SDD detectors, the same detector used by the REXIS SXM. The NICER team later changed their design to

use an Amptek CMOS detector, which benefits from higher temporal resolution.

While the NICER instrument and the REXIS SXM's designs diverged during the design phase, the SXM was heavily influenced by this early NICER design. The design of the SXM preamp circuit and SXM Electronics Board resemble the NICER preamplifier board and surrounding electronics housing respectively. These similarities are the legacy of John Doty, an engineer affiliated with MIT who created the SXM timing circuitry, signal pulse shaping, and threshold trigger. A complete documentation of SXM circuit diagrams can be found in Appendix A.

3.1.1 Mission Requirements

REXIS SXM requirements fall under the REXIS instrument's main requirements, which in turn are derived from OSIRIS-REx requirements for the instrument. The REXIS requirements documentation flow was described extensively in Mike Jones's Master's thesis [6]. The information flow diagram for REXIS is shown in Figure 3-1
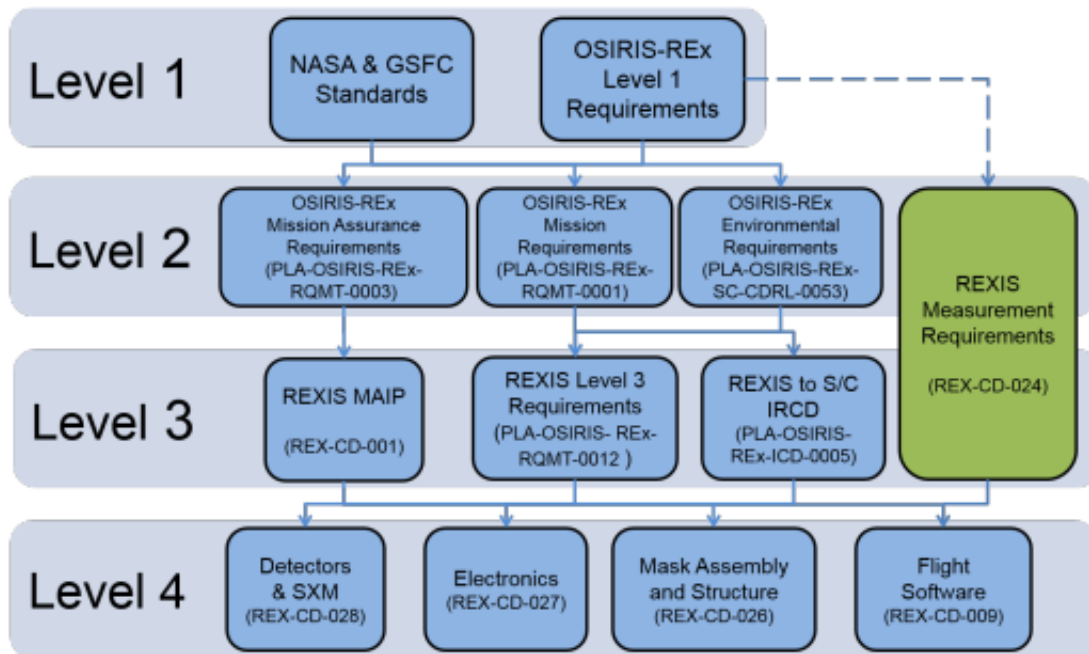
Figure 3-1: The REXIS Requirements documentation flow from Jones, 2015 [6].

The SXM's energy band of interest is from 0.6 keV to 6 keV. Quantum efficiency for the SXM is also outlined in the REX-74 requirement. Quantum efficiency is the

ratio of photon events that are successfully converted to electrons by the detector, and is a metric used to evaluate the performance of an instrument at different detection energies (shown in Table 3.1).

Quantum Efficiency	Energy Range (keV)
>0.01	0.62 - 0.7
>0.03	0.7 - 0.8
>0.09	0.8 - 1.2
>0.65	1.6 - 2.8
>0.85	2.8 - 4.1
>0.9	6.0 - 7.0

Table 3.1: Quantum Efficiency Requirements for the SXM Detector.

The REXIS SXM Requirements are derived from the different levels of REXIS requirements. SXM operational and environmental requirements are found in the Level 4 documentation. Level 3 documentation describes the requirements for detector functionality. The Level 2 requirement REX-7 is the highest-level requirement pertaining to the SXM. REX-7 requires that the SXM "shall measure solar coronal temperature to within 0.1 MK every 50 sec while observing Bennu in Phase 5B assuming a single temperature model." A complete overview of Level 3 and Level 4 requirements can be seen in Tables 3.2 and 3.3.

ID No.	Title	Description
REX-225	Integration Time	The SXM shall integrate counts for 32 seconds (nominally) to form a spectrum.
REX-73	Spectral Resolution	The SXM shall have a spectral resolution (FWHM) that is less than 200 eV from 0.6 to 6 keV.
REX-74	Quantum Efficiency	The SXM shall detect x-ray events from 0.6 to 6.0 keV with quantum efficiencies as given in Table 3.1.
REX-75	Field of View	The SXM shall have a full width zero intensity (FWZI) FOV of no greater than 60 deg full cone and a full width full intensity (FWFI) FOV of no less than 10 deg full cone.

Table 3.2: SXM Level 3 Requirements.

ID No.	Title	Description
REX-228	SDD Survival Temperature	The temperature of the SDD shall always be greater than -65°C and less than 150°C.
REX-229	SDD Operating Temperature	The temperature of the SDD shall be less than -30°Cand greater than -70°C.
REX-76	Preamp Survival Temperature	The temperature of the SXM Preamp shall be greater than -55°C and less than 85°C.
REX-77	Preamp Operating Temperature	The temperature of the SXM preamp shall be greater than -40°C and less than 85°C while operating.
REX-78	SXM Health	The SXM shall survive and remain operational through the end of Phase 8.
REX-79	SXM Operational Time	The SXM shall be capable of operating 24 hours per day

Table 3.3: SXM Level 4 Requirements.

3.1.2 Overview of SXM Signal Amplification Chain

The SXM amplification chain is responsible for priming a signal from the SDD detector before it is converted by the Analog-to-Digital Converter (ADC). The amplification chain is housed on the SXM Main Electronics Board (MEB), which is located within the REXIS instrument on the spacecraft. The SXM detector and preamp circuit are housed in the SXM backpack, which is bolted to the outside of the spacecraft, and is connected to the MEB by a coaxial cable. The SXM detector housing is shown in Figure 3-2.

The SXM ADC requires a positive voltage signal pulse to be passed to it in order to register a detection count. When an x-ray strikes the detector, an analog signal pulse is created. The raw signal biased at 3.3 V, sent through the preamp, and then sent across the coax cable to the MEB. When the signal reaches the MEB, it is passed through three opamps, which amplify the signal. Then the voltage signal is divided, where one signal passes through an integrator circuit and the other signal through a differentiator circuit. The output from the integrator circuit is labeled *outu*, and the output from the differentiator circuit is labeled *outb*. The amplification chain schematic diagram is shown in Figure 3-3. Additional SXM electronics schematics
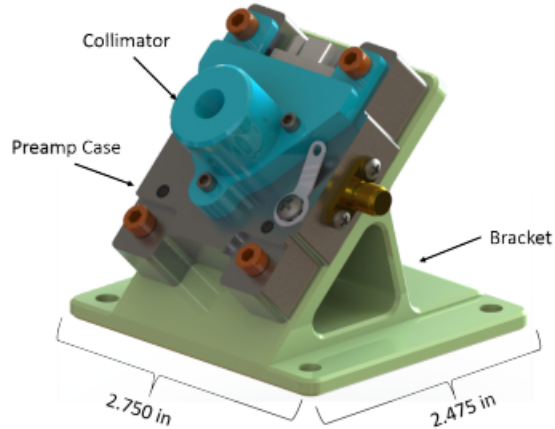
Figure 3-2: SXM detector and preamp housing. The SXM detector is located below the collimator.

can be found in Appendix A.

The signals are then sent through a low pass filter to eliminate high frequency noise artifacts added to the signal when it passed through the preamp circuit. The *outu* signal is then sent to the final section of the amplification circuit, where 3 V of bias are subtracted, leaving the signal with a residual 0.3 V bias. This bias is required to keep the *outu* signal positive because the ADC used in the SXM electronics chain is not rated for negative voltage inputs.

Next, Signal *outu* is sent to the ADC to be measured, while signal *outb* is sent to a zero cross monitor, which provides the timing for the ADC to sample new signal, now named *outu1*.

In order to trigger an ADC detection, the SXM relies on a trigger circuit that uses a series of comparators to compare *outb* to a reference voltage. The trigger circuit is shown in Figure 3-4.

This trigger includes a command to manually set the threshold Voltage Lower Limit of Detection (VLLD). The VLLD is set above the *outb* bias voltage as well as the noise floor to prevent the SXM from accidentally triggering due to random noise in the electronics. The relationship of *outb* to VLLD is given as:

$$LLD = outb - VLLD, \tag{3.1}$$
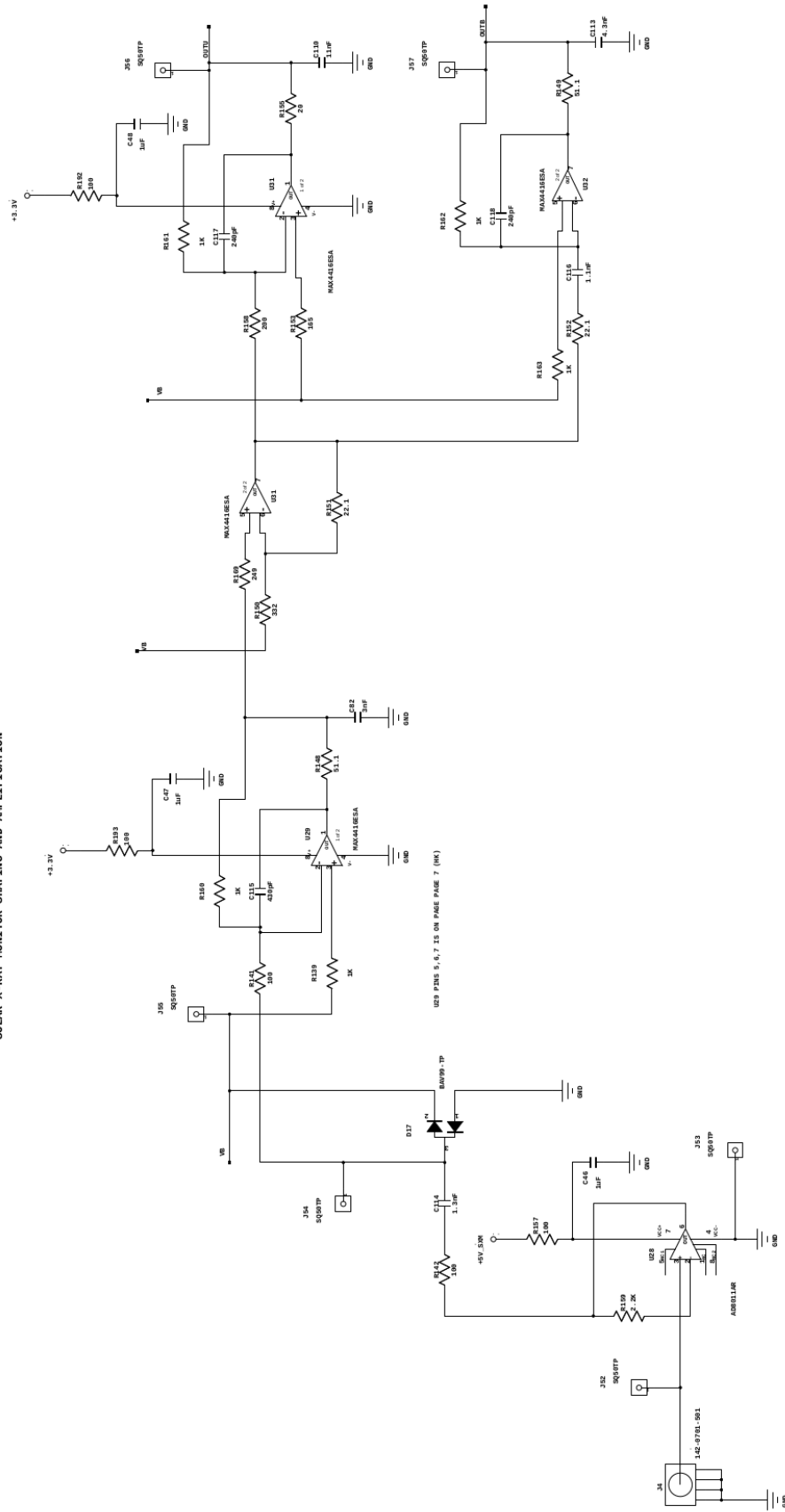
Figure 3-3: Schematic of SXM Amplification Chain. Outputs *outb* and *outu* are seen on the far right.
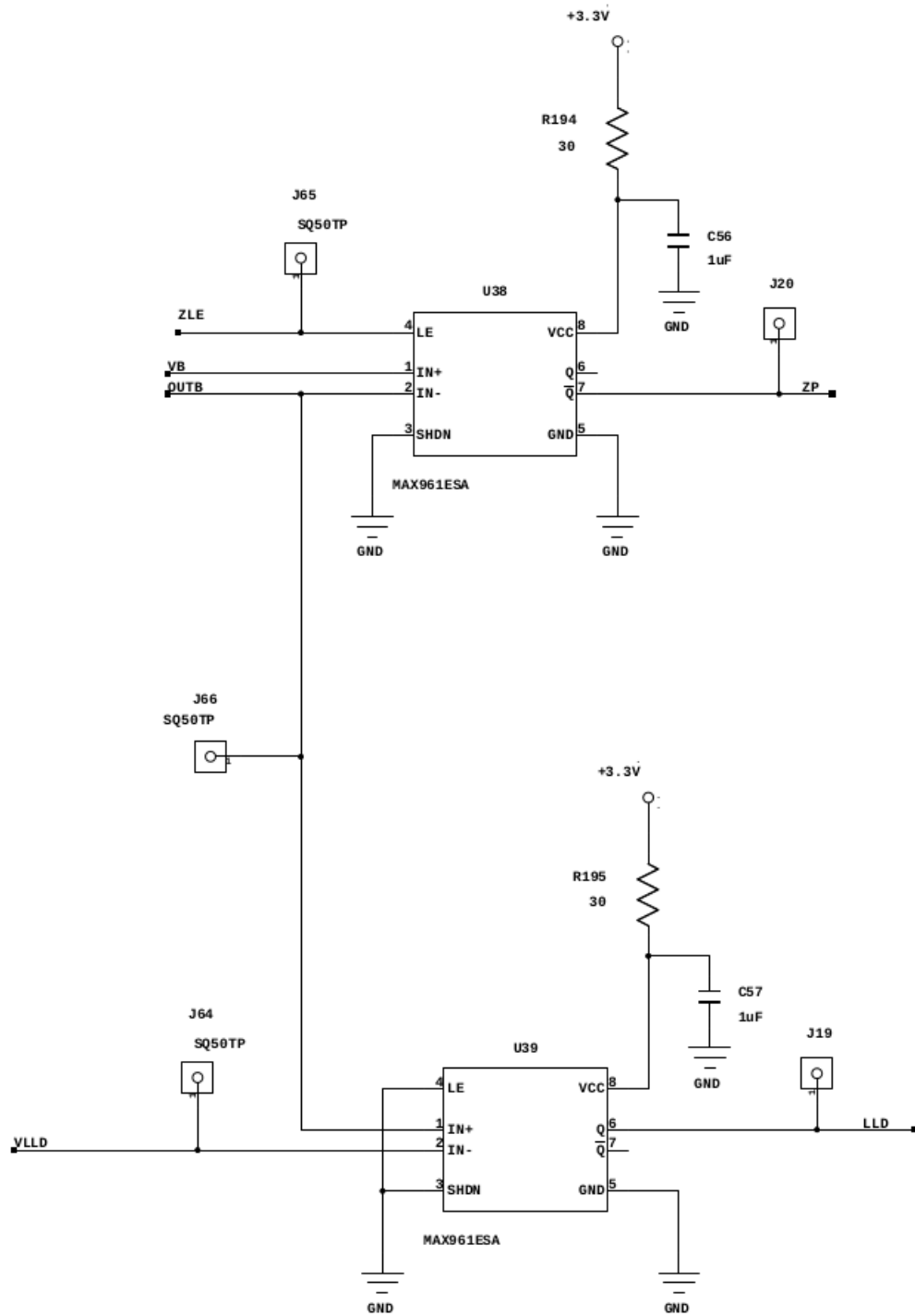
Figure 3-4: SXM Trigger Circuit Schematic.

where LLD is the Lower Limit of Detection. A threshold setting anomaly was discovered early in flight, where the threshold would fluctuate. This was resolved by sending

three threshold setting commands to the instrument. The first two commands were to set the threshold to an arbitrarily high value, and the third command was to set the threshold to the intended value. This workaround was only used once, but resolved noticeable threshold drift for the remainder of flight.

The second threshold circuit is used to determine the zero crossing of *outb*. When *outu1* is at it's peak, *outb* will have a zero crossing, and the ADC is triggered to begin recording. Figure 3-5 shows an example of all signal shapes.
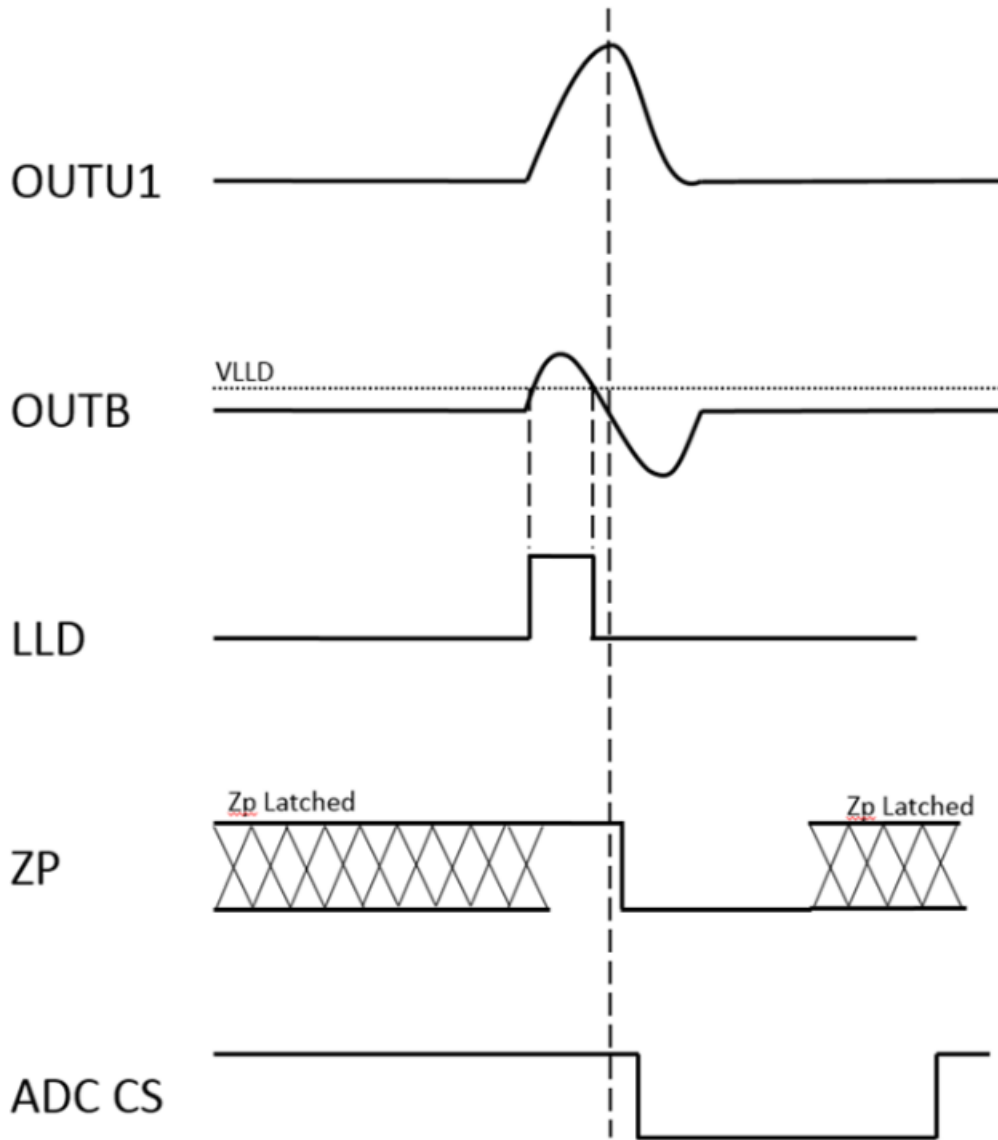
Figure 3-5: SXM signals at various points throughout the amplification chain.

3.2 Instrument Testing

As part of the instrument design process, the REXIS SXM was subject to numerous functionality tests on the ground. Testing was limited by time and financial constraints, but the testing framework was rigorous and proved the SXM ready for flight. The subsection on ground testing will focus on testing that aided in characterizing the SXM low count rate anomaly discussed in Chapter 4. A more thorough description of SXM ground testing can be found in Kevin Stout's thesis [14].

The SXM also underwent a series of flight tests between launch in 2016 and Orbital B, the first data collection phase, in July of 2019. Flight testing was primarily used to characterize the REXIS main spectrometer, whose CCD array required in-flight calibration, although the SXM was tested as well [7].

3.2.1 Ground Testing

The SXM was put through a battery of ground tests to ensure the instrument was ready for flight testing. The testing procedure followed NASA requirements for Risk Class D missions [11]. The focus of this subsection will be on SXM thermal tests, which provided a background for the root cause analysis outlined in Chapter 4.

The SXM was subject to thermal testing using thermal vacuum chambers built in the MIT Space Systems Laboratory and at MIT Lincoln Laboratory.

SXM Oven Test

The SXM MEB underwent an oven test at Lincoln Laboratory in November of 2015. The complete SXM flight assembly, including the preamp and SDD detector, were placed in a thermal chamber. The MEB remained connected to the SXM assembly, but outside the chamber. The MEB was held at a temperature of approximately 20°C. The temperature of the thermal chamber was then fluctuated between -40°C and 60°C with a ground calibration iron source to measure instrument performance as a function of temperature. This was a more drastic temperature fluctuation than was expected in flight, and was used to identify thermal vulnerabilities in the SXM.

An example histogram from the ground calibration source is shown in Figure 3-6.
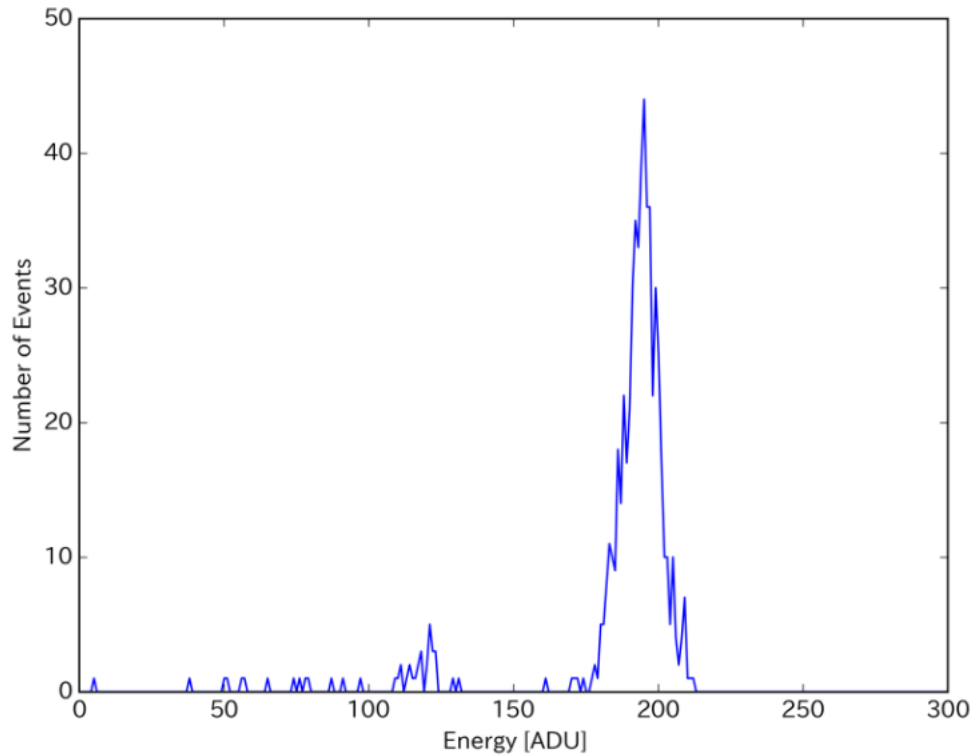
Figure 3-6: SXM Histogram of Ground Calibration Source. A strong iron line can be seen at around 200 ADU.

The preamp and SDD detector remained insensitive to temperature fluctuations over the test range. Additionally, it was discovered that both low and high energy artifacts set in at approximately 53°C. The results of this test are provided in Figure 3-7.

MEB Thermal Characterization

The SXM MEB was included in a similar thermal test. The MEB was placed in the thermal test chamber, where its temperature was then cycled between -40°C and 60°C, while the SXM was exposed to the Fe-55 ground calibration source. Figure 3-8 shows temperature changes in the SXM during testing.

At high temperatures, the SXM recorded lower source counts than at lower temperatures. Hysteresis effects were also seen in the MEB, and it was determined that
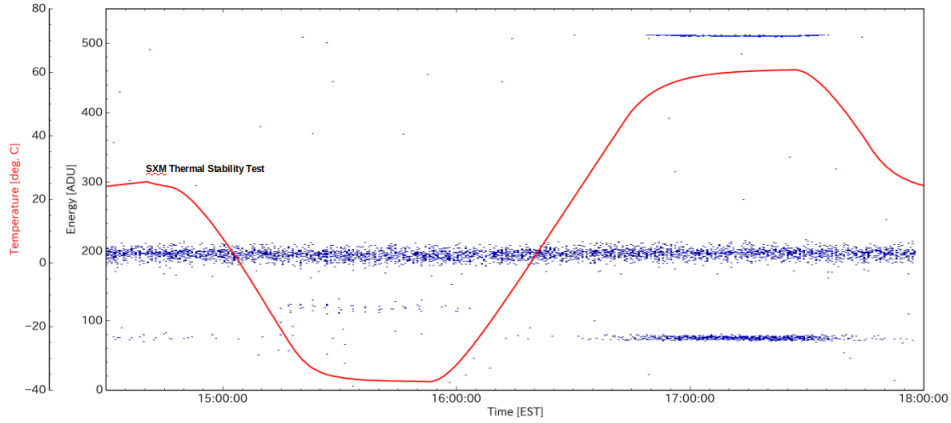
Figure 3-7:   Results of SXM Oven Test, November 2015.
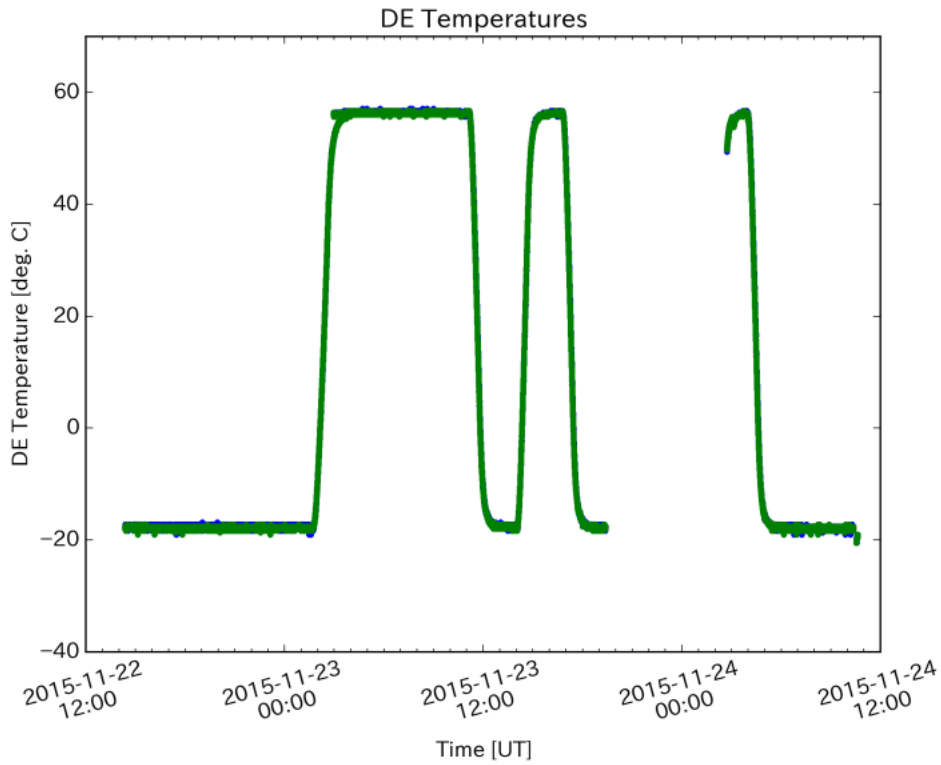
Figure 3-8:   Temperature Fluctuations during the MEB Thermal Characterization Test.

temperature changes in the MEB can result in changes to the SXM's low energy threshold. The results of this test are provided in Figure 3-9.

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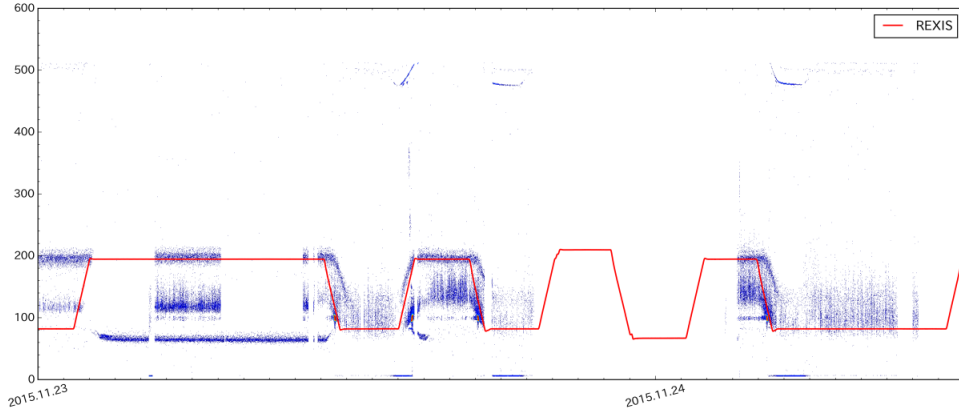
Figure 3-9: Ground Testing results of MEB susceptibility to temperature fluctuations.

3.3 Flight Operations

This section will describe the REXIS SXM during flight operations, from launch in September 2016 to planned shutdown in November 2019. The REXIS SXM operated over a period of approximately 3.5 years. The SXM was first powered on during L+14 days for a payload functions check. It was powered on at various times in flight during which it underwent calibration and additional functions checks. The SXM entered its first data collection phase in July, 2019 during Orbital B. Due to unanticipated low x-ray counts during Orbital B, it was powered on for an additional observation window in November, 2019 as part of the Orbital R mission phase.

3.3.1 Early Flight Operations

Early flight operations for the SXM were characterized by a series of functionality tests, which served as milestones towards the ultimate goal of data collection during the Orbital B mission phase. The first of these calibrations occurred during the L+14 days payload check. The SXM collected 3935 seconds of nominal x-ray data, and the instrument was determined to be working properly.

The next notable evaluation of the SXM occurred during L+30, which took place in January, 2019. L+30 was the first time that Bennu was in the field of view of the REXIS main spectrometer, and was a critical functionality check for the instrument.

The L+30 mission phase was divided into two distinct flight patterns. The first had the REXIS main spectrometer pointing nadir at the asteroid, while the second had the main spectrometer pointing away from the asteroid. During the second phase of L+30, the SXM recorded a low x-ray count rate from the sun, which was because the instrument was not directly facing the sun, as it was during the first phase of L+30. A comparison of L+30 flight data are shown in Figure 3-10. This example of off-pointing low x-ray counts became an important comparison data set with which to compare Orbital B data.

3.3.2 Flight Operations during Orbital B

The SXM entered its primary data collection phase during Orbital B, which occurred in July, 2019. On 5 July, the SXM suffered a "bit flip" error, where each detection was saturated by an additional value of 34880. This was noticed when the daily histogram data was saturated at an extremely high count rate. The "bit flip" most likely occurred when the SXM was struck by a high energy cosmic ray, which shifted the reset value of the SXM from its minimum value to its maximum. This required a reset of the instrument from the ground, which reverted the SXM reset value to its designed minimum.

Once the "bit flip" had been resolved, the SXM remained operational for the rest of Orbital B. During Orbital B, the SXM recorded an x-ray count rate two orders of magnitude lower than what was previously seen during the first part of Internal Calibration. An example event rate histogram from Orbital B is shown in Figure 3-11.

Low x-ray counts persisted for the remainder of Orbital B, and were subsequently the focus of an anomaly report made to the OSIRIS-REx team. These low x-ray counts were unexpected, and highlighted anomalous performance in the instrument, give the spacecraft's heliocentric distance, and the solar state. While the Sun was recorded at a quiet A6.7 state, x-ray counts should have reflected a higher solar flux.
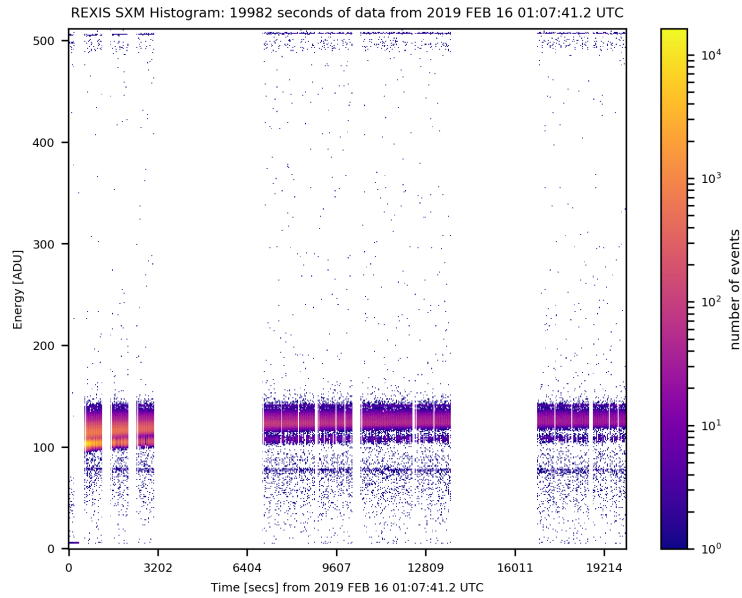
(a) Nadir Pointing REXIS Main Spectrometer
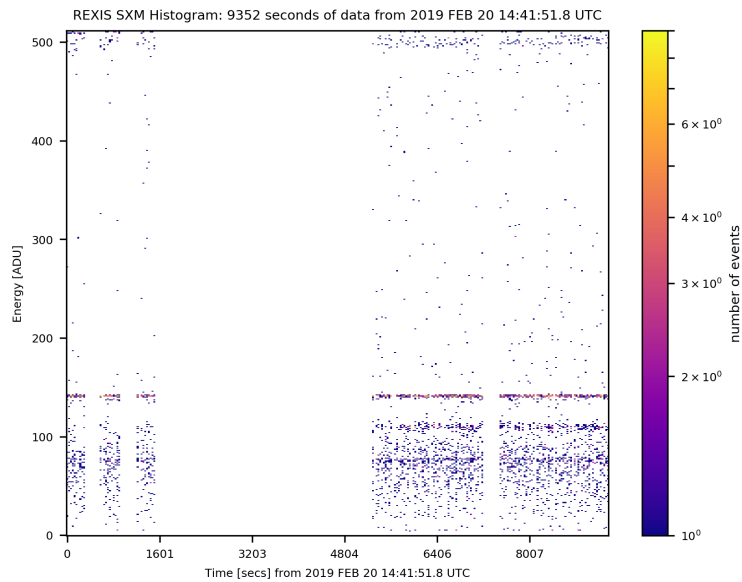
(b) Off-Point REXIS Main Spectrometer

Figure 3-10: SXM Event Rate Histograms during L+30

3.3.3 Flight Operations during Orbital R

The REXIS instrument team requested an additional observation due to lower than anticipated counts by the SXM and REXIS main spectrometer during Orbital B. The OSIRIS-REx mission operations team allowed the REXIS instrument to have an additional observation window during Orbital R, which took place during November
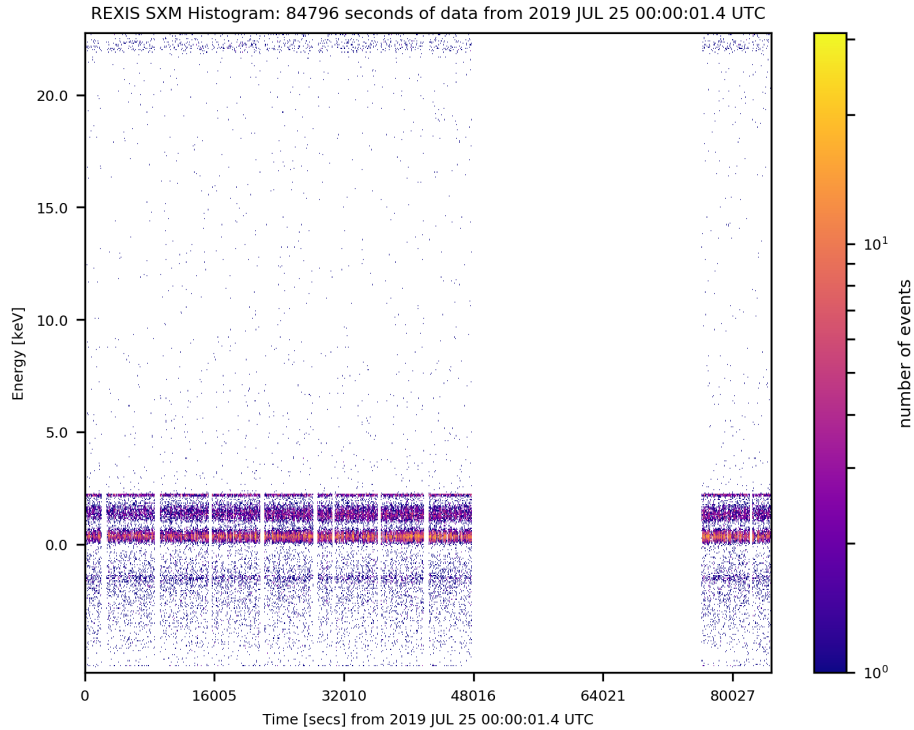
Figure 3-11: SXM Event Rate Histogram from Orbital B, 25 July 2019.

2019. It was hoped that when REXIS was powered on for Orbital R, the main spectrometer would detect higher flux counts from the asteroid, and the SXM would report x-ray counts at the expected rate.

During Orbital R, the SXM recorded low x-ray counts similar to those seen in Orbital B. An example Orbital R event rate histogram is shown in Figure 3-12.

As Orbital R progressed, the SXM event rate began to decline. This coincided with a change in temperature in the SXM MEB, which occurred on 18 November, 2019. The secondary count drop off occurred rapidly over the course of the day, and can be seen in Figure 4-4. The SXM recorded low counts for the remainder of Orbital R. An investigation of the cause of these low x-ray counts in described in Chapter 4.
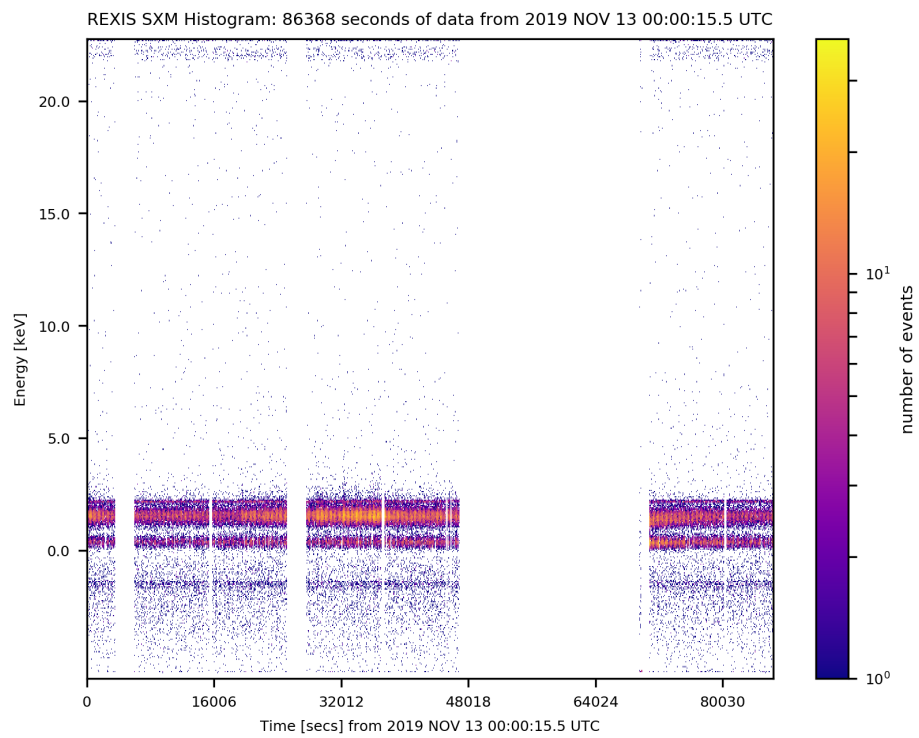
Figure 3-12: SXM Event Rate Histogram from Orbital R, 13 November 2019.

Chapter 4

SXM Root Cause Analysis

This chapter presents a preliminary root cause analysis of the SXM low count rate anomaly that began on 3 July, 2019, at the beginning of the Orbital B observation window. A root cause was chosen to examine the failure of the SXM as an instrument. It consists of an investigation into all possible causes of failure, which is the fourth probable cause described in a fishbone diagram (shown in Figure 4-1).
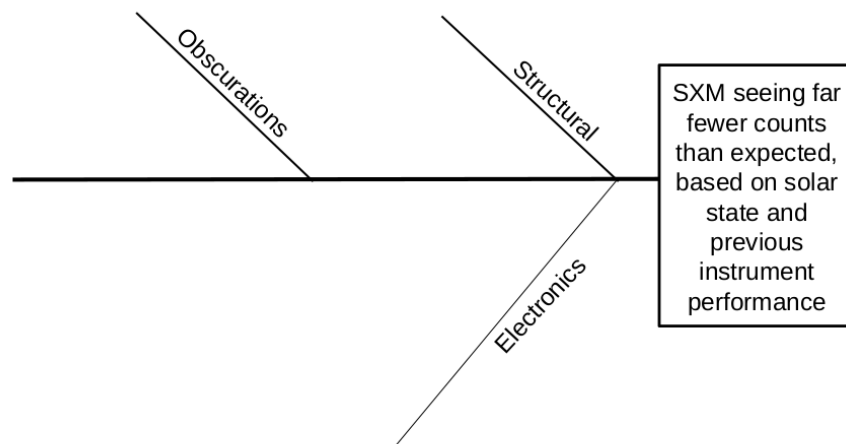
Figure 4-1: Example Fishbone diagram used to outline a Root Cause Analysis. Each bone is used to categorize the type of cause.

Based on evidence collected during a preliminary investigation by the instrument team, the most likely cause of low x-ray counts in the SXM was hypothesized to be due to a change in temperature in the signal amplification change. This thesis

will focus on the subsequent investigation of the thermal vulnerability of electronic components in the SXM. A brief explanation will be given for why other bones on the fishbone diagram have been discounted as the causes of failure.

In this chapter, an investigation report delivered to the OSIRIS-REx PI will be presented. A section will be devoted to how the anomaly was first identified, and the methods used to bound the problem. SXM response modeling to Orbital B data will be shown, and how it corresponds to deviations in the SXM's long-term temperature. LTSpice simulations show that modeling capabilities are limited by vendor simulation code, and leave a path forward for further research. A preliminary conclusion is offered, and a recommendation for future investigation is provided. As a point of reference, the terms "count rate" and "event rate" will be used interchangeably, as the SXM histogram data are recorded as counts (or particles striking the diode detector) per energy level, recorded in 32 second bins.

4.1   SXM Low Count Rate Anomaly

The SXM received lower than expected counts during its two observation windows. This problem was first identified in Orbital B, and was subsequently observed in all of Orbital R as well. It was an ongoing impediment to solar science using the SXM, and its exact cause remains an open area of investigation.

4.1.1   Orbital B

The SXM low count rate anomaly was first discovered during Orbital B, which took place in July and August of 2019. The SXM showed a decreased count rate that was atypical for the spacecraft's heliocentric distance. At this time, the spacecraft was located at a heliocentric distance of 1.3AU, and was showing a solar state of A6.7 as recorded by GOES15, a solar observatory located in Low Earth Orbit (LEO). An A6.7 solar state is relatively quiet from the sun, which at this time was near solar minimum, a period of low solar output. Orbital B data were two orders of magnitude lower when compared to signal data taken during Internal Calibration, during which

the spacecraft was at a comparable heliocentric distance.SXM data from Orbital R show a similar signal discrepancy, shown in Figure 4-2.
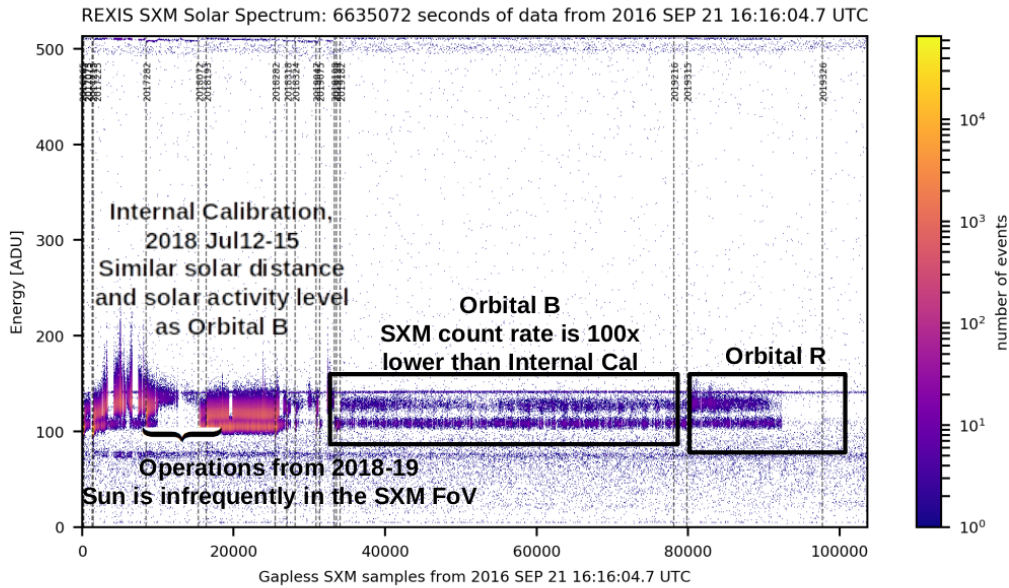
Figure 4-2: SXM count rate histogram from launch to Orbital R.

During Orbital B, the SXM also suffered an unrelated "bit flip" error, which caused each histogram bin to increase by a value of 34880. The bit flip was most likely caused by a strike from a stray high energy particle, which caused the 16-bit reset value to wrap around from 0 to 34880, the maximum value. This was first observed on 5 July, 2019, and resulted in a saturated event rate histogram. When this value was subtracted from these data, the corrected histogram showed values similar taken the previous day. A comparison of the saturated and corrected histogram is shown in Figure 4-3. The bit flip was corrected by manually resetting the histogram minimum value, which could be done from the ground. There were no issues with saturation in the SXM event rate for the remainder of Orbital B. The reset of the SXM offset did not impact the low count rate issue previously identified.
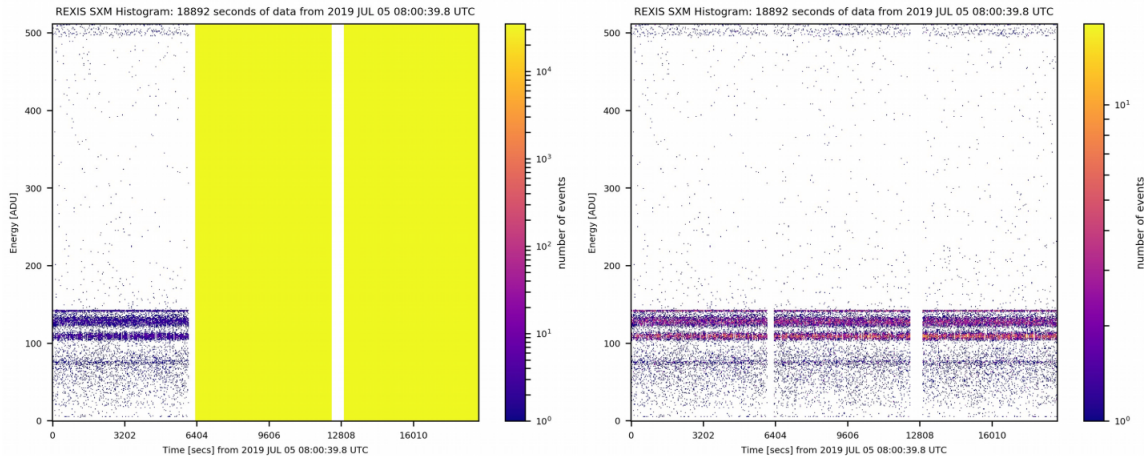
Figure 4-3: SXM Saturated Histogram (Right) and Corrected Histogram (Left)

4.1.2 Orbital R

Due to low counts during Orbital B, REXIS was allotted an additional 15 day observation window during November, 2019. On 18 November, 2019, SXM signal during Orbital R decreased beyond the low count rate seen in Orbital B, which can be seen in Figure 4-4. This decrease in signal is distinct from the previous six days observation in Orbital R, and demonstrates a departure from the previous low-count issue. This second decrease in signal persisted for the remaining 7 days of Orbital R.

A notice was provided to the OSIRIS-REx PI following the first instance of a lower than anticipated count rate during Orbital B. A subsequent incident, surprise, anomaly report (ISA) was requested, which was the formal directive for a root cause analysis into the instrument anomaly.

4.2 Constraining the Problem

Once the low count-rate anomaly had been identified, it became necessary to provide boundaries on the investigation. The following section begins with an overview of the ISA report and provides a fishbone diagram of the five likely root causes, as well as the rational behind selecting thermal variability in the SXM Main Electronics Board (MEB) amplification chain as the most likely root cause.
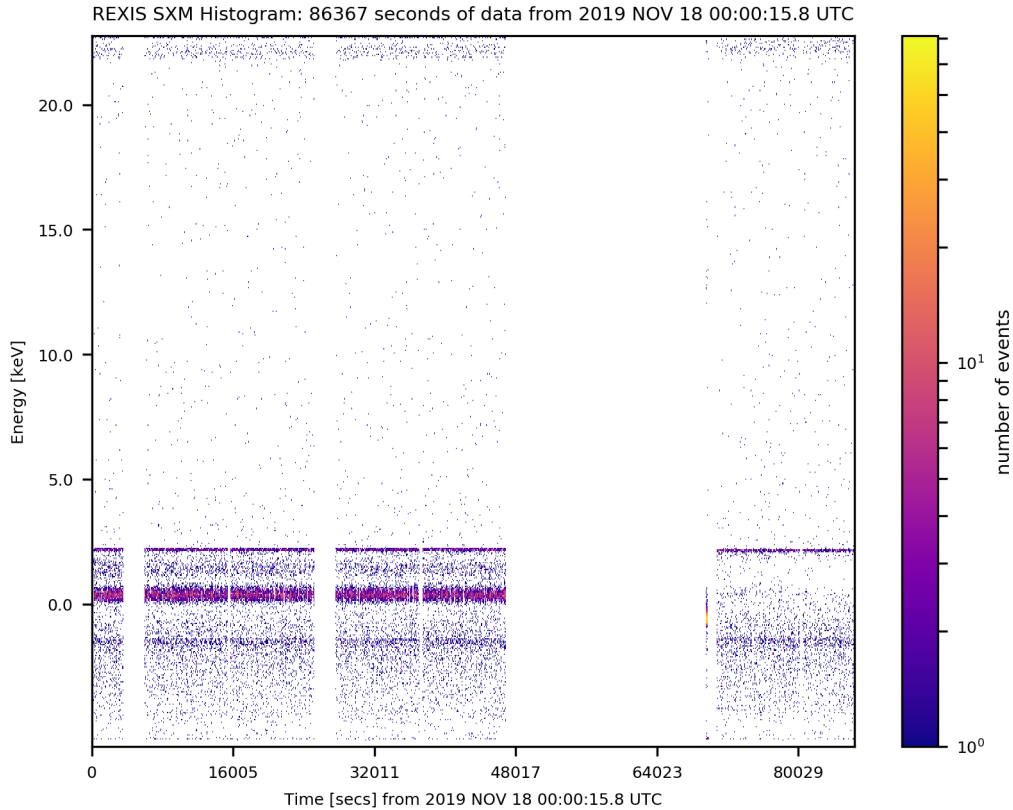
Figure 4-4: SXM count rate histogram on 18 November, 2019. The gap in the histogram is when the instrument was not recording data, and is unrelated to the low count rate anomaly in Orbital R.

4.2.1 ISA #10939

The OSIRIS-REx PI's office opened a formal Incident, Surprise, Anomaly (ISA) investigation into the SXM low count rate. At the conclusion of Orbital B, this investigation was not time sensitive, as REXIS had completed its only observation phase, collected all possible data, and had been powered off according to OSIRIS-REx power mission design.

A fishbone diagram was created to illustrate the possible causes of a low instrument count rate in the SXM. The fishbone diagram included in the SXM low count rate ISA is shown in Figure 4-5.

Each potential cause of the SXM low count rate shown in the fishbone diagram will be explained briefly.
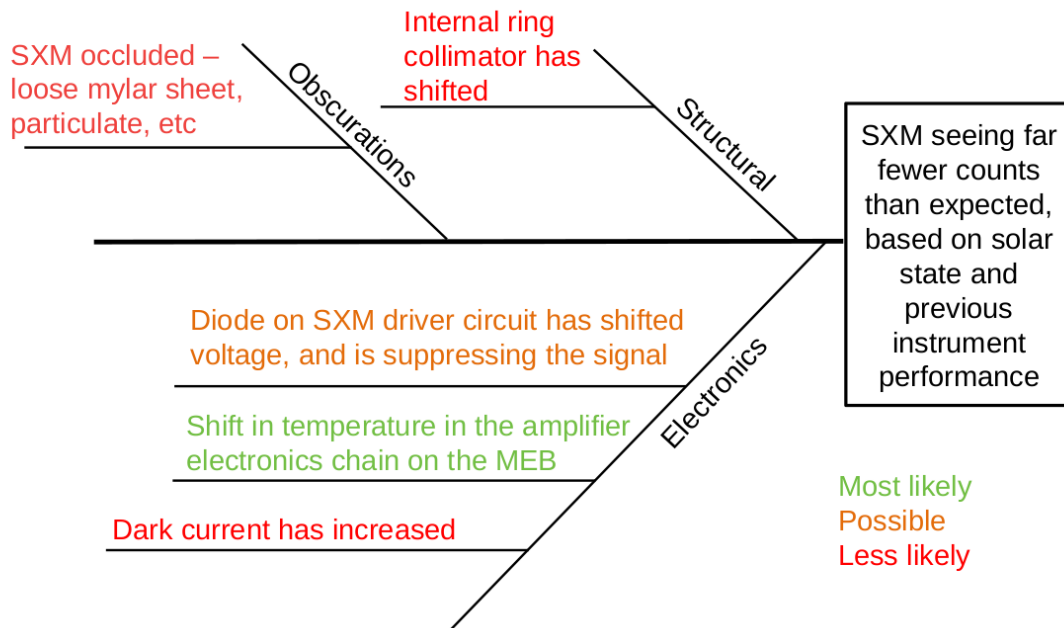
Figure 4-5: Fishbone diagram constructed for OSIRIS-REx ISA #10939

SXM SDD Detector was Occulted

The SXM SDD detector being occulted was a natural concern for the instrument team. The OSIRIS-REx team discovered that Bennu is an "activated asteroid," which is characterized by dust ejecta from the asteroid's surface [3]. If particulate matter partially or completely occulted the SXM field of view, then the instrument would receive lower counts than predicted. However, it is unlikely that particulate blockage occurred, as the SDD detector is small, and the spacecraft took extreme care to avoid ejecta.

Another way that the SXM might have been physically occulted is if part of the spacecraft, for example foil used to insulate sensitive electronics, became dislodged and migrated to cover the detector. Parts of the spacecraft are lined with mylar, which acts as a thermal insulator. This too is unlikely, as the spacecraft's guidance and control team would notice a change in spacecraft motion.

Internal Collimator Shifted

The Internal Ring Collimator is attached to the exterior of the preamp housing, and acts as a pinhole for solar x-ray flux. The collimator is attached to the preamp in such a way that if the collimator shifted, it would disconnect critical SXM wiring. This would appear as a total loss of signal in the instrument, rather than as reduced x-ray counts.

It was determined that the SXM did not suffer a complete loss of signal after the SXM observed a solar flare. The timing of the flare detected by the SXM coincided with flare data observed by one of the GOES satellites (Figure 4-6). GOES is an Earth-orbiting satellite constellation that monitors solar phenomena and provides persistent solar observation.
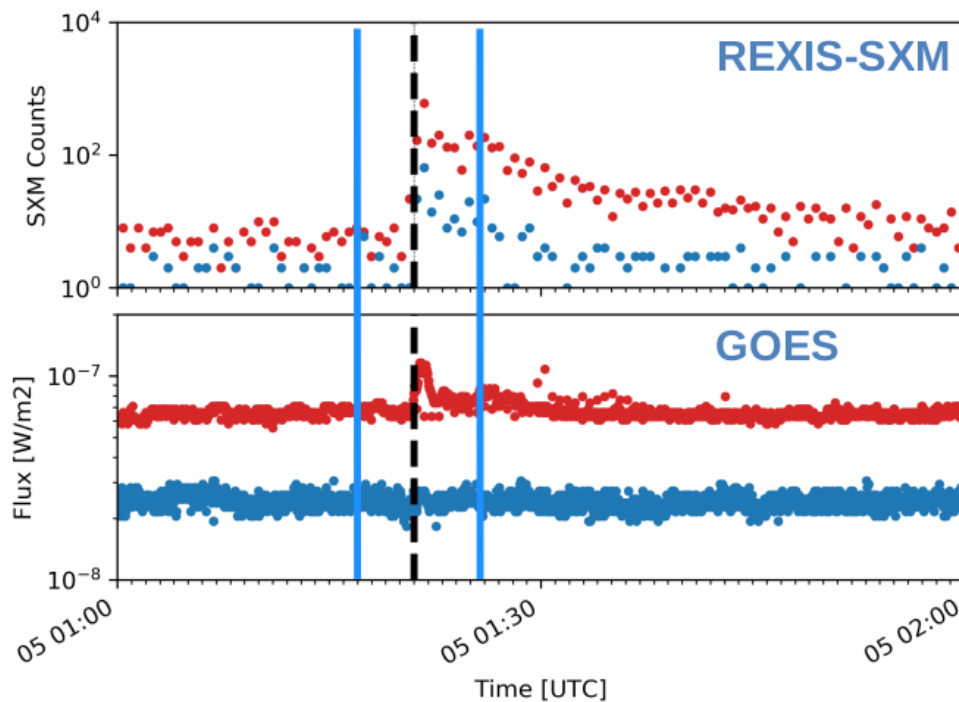
Figure 4-6: Flare Coincidence between the SXM and GOES15.

Voltage Shift in SXM Driver Circuit

Another possibility considered was that the SXM driver circuit's voltage had shifted. The driver circuit was directly linked to the Analog-to-Digital Converter (ADC) at

Figure 4-7: SXM longterm HV for its operational lifetime.

the end of the amplification chain. A departure from the designed driver voltage would cause the ADC to convert less analog signal. SXM long-term High Voltage (HV) did not deviate by more than ± 1 V, as seen in Figure 4-7. Thus, a voltage shift in the driver circuit can be eliminated from the list of possible root causes for the low count anomaly.

Dark Current Increase

It is unlikely that dark current increased in the SXM during Orbital B. Ground testing indicated that dark current was not a significant concern for the SXM when it was cooled to operational temperature. Dark current was found to cause more frequent resets when the SDD detector was warm [6].

Temperature Shift in the Amplifier Electronics Chain

The most likely possibility remaining unaccounted for in the fishbone diagram was a temperature change in the signal amplification chain located on the Main Electronics Board (MEB). The SXM showed sensitivity to temperature changes in the MEB during ground testing, which included suppressing low energy signal at higher temperatures. Figure X shows an SXM oven test that illustrates ground test thermal susceptibility.

58

Additionally, the second decrease in SXM signal during Orbital R coincided with a thermal change on the spacecraft. Inertial Measurement Unit 1 (IMU1) was switched off, and IMU2 was powered on. The inertial measurement units provide the OSIRIS-REx navigation team with the exact position of the spacecraft, and where it is located with respect to Bennu. When the IMU changeover occurred, the SXM entered a new phase space (shown in Figure X), where the Thermo-Electric Cooler (TEC) temperature decreased, and the temperature doubled in the Detector Electronics (DE), where the REXIS main spectrometer's video board is housed. The SXM backpack electronics were not effected by this thermal change.
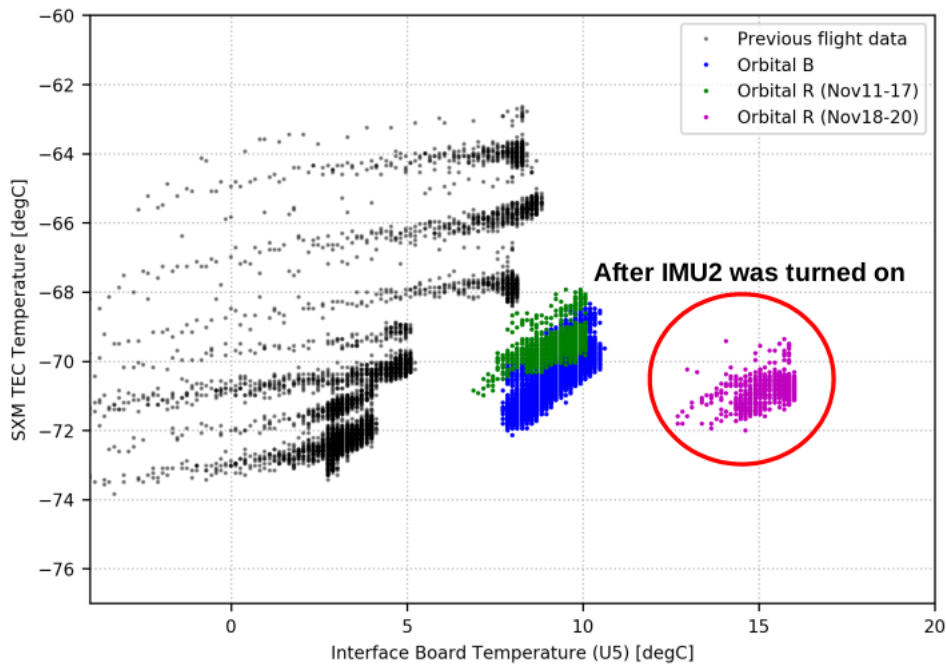
Figure 4-8: SXM Temperature Phase Space.

This dramatic shift in SXM temperature phase space indicated that low count rate was related to a change in MEB temperature. The SXM operated in a new phase space for both Orbital B and Orbital R when compared to previous data, which coincided with lower signal counts. This sensitivity was reported in the ISA #10939 briefing, and it was determined that the SXM was still functional above 3 keV. The low count anomaly presented no threat to any other spacecraft system, and it was recommended that additional work focus on further isolating the root cause.

4.2.2 Modeling SXM Instrument Response

Once it had been established that SXM signal was reduced below its expected value, rather than totally lost, efforts were made to recover the signal. If it was possible to recover the signal, SXM data could still be used to measure solar temperature. Solar temperature measurements can be used to calculate solar output, which in turn makes it an essential step in characterizing the Sun's input to Bennu's surface.

The most prominent of these attempts involved rebinning SXM data. Since the SXM was reporting a 100x loss in signal, it was thought that signal could be amplified by rebinning 100 histograms together. The original SXM histograms showed 32 seconds of data. Rebinned histograms combined 3200 seconds of data into a single histogram. Rebinning histogram data required writing additional code to interface with the existing Data Pipeline. Data were separated by collection phase, with Orbital B consisting of one dataset, and Orbital R divided into two, differentiated by which IMU was employed.

Data were rebinned using a sliding bin technique, which used a 3200 second window of data and took averages of the energies of the individual histograms and produced a stacked histogram. Sliding binning was employed to prevent individual high-count histograms from skewing binned data. A limitation to rebinning was that it raised the high energy noise as well as improved signal, which is shown in Figure 4-9. Rebinning also amplified instrument artifact, which binned at an disproportionate rate when compared signal.

Rebinning was ultimately unsuccessful at extracting SXM signal from the low count rate data. Rebinning recovered artifacts back to levels seen in the Internal Calibration, but failed to recover signal to the same levels. Signal could not be recovered to the levels of previous quiet sun data, and further rebinning attempts were abandoned, and efforts were focused on identifying thermally susceptible electronics.
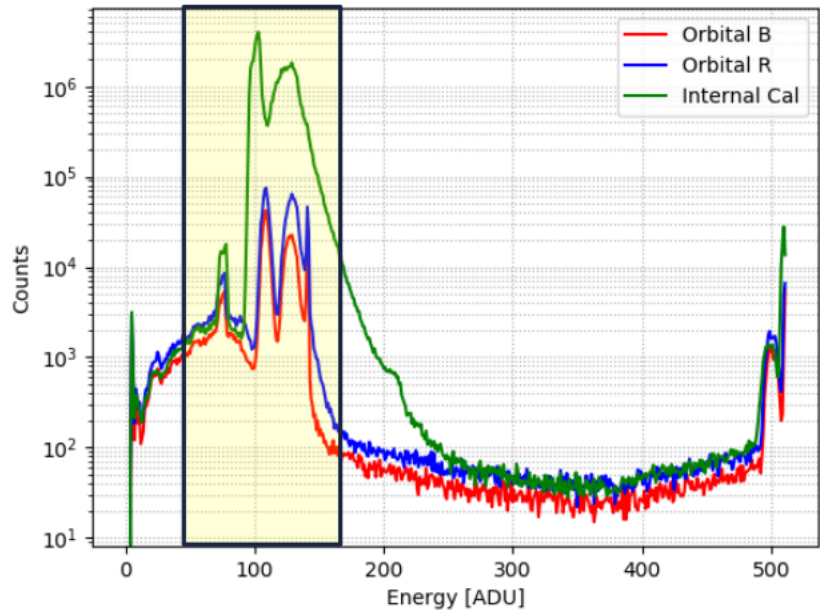
Figure 4-9: SXM Histogram Rebinning. The boxed area surrounds the SXM's main signal peaks. The peaks at the outer edges of the figure are instrument artifacts.

4.3 LTSpice Simulations of Amplification Chain

The SXM amplification chain proved to be the most promising path towards isolating a root cause of the low count anomaly. As was previously explained in Section 4.2.1, the SXM was susceptible to temperature changes in the MEB. This temperature vulnerability was not seen in the ground spare unit, and MIT's closure due to COVID-19 prevented any further ground testing. Computer simulation of the SXM electronics using LTSpice was chosen as an alternative to physical testing. LTSpice can simulate circuits across multiple temperatures and signal inputs, making it an excellent choice to investigate thermal vulnerability.

LTSpice is a free software distributed by Analog Devices, which allows a user to build and test circuits. LTSPice allows a user to upload proprietary component models, which are produced by electronics hardware companies. These proprietary models incorporate existing LTSpice modeling code and data from a component's spec sheet.

The opamps used in the SXM amplification chain are produced by MAXIM In-

tegrated, an electrical components company that produces analog and mixed-signal integrated circuits. MAXIM Integrated offers LTSpice models for their components on their website, which are free to download and developed by their engineering staff.

LTSpice has two simulation modes: a netlist, and a schematic. A netlist utilizes Spice syntax and works similar to common coding languages. Components and their values are added to a netlist, and connections to other components are written in LTSpice's netlist syntax. LTSpice schematics are drawn or imported by the user, and have a more robust visual interface. LTSpice schematics are nearly identical to KiCAD and other schematic design software. Both a netlist and schematic can be used to simulate the same circuit.

4.3.1 Thermal Variability in Components

The SXM had an existing netlist from previous simulation, which required minor changes due to software updates. The simulation procedure involved running the circuit for 10ms, with a global electronics temperature range from 0°C to 30°C, run at steps of 5°C. A voltage pulse was used as the input signal, which represented a single detection by the SXM. However, the simulation would not run when given the stepwise temperature procedure. LTSPice refused to run at the upper and lower bounds of the simulation.

The range of testing was modified to run between 20°C and 30°C, within the range of temperatures seen by the MEB during Orbital B and Orbital R. Again, temperatures at the extremes of the range were unable to be simulated by LTSpice. The simulation worked at a temperature of 27°C, but the total time to simulate the circuit increased as the temperature moved closer to 20°C and 30°C.

The increased simulation time was considered to be a result of high-frequency noise, which was believed to indicate that the amplification chain had components that were highly vulnerable to noise, near operational temperatures. This could not be well established with the netlist, as the netlist could not simulate flight temperatures seen in Orbital B, Orbital R, or from any previous flight data with which to compare.

The validity of the existing netlist was called into question, and it was decided

to try to create a schematic of the amplification chain from scratch, to avoid any preexisting errors that could have propagated from the updating of the old netlist.

The amplification chain was recreated in LTSpice using the electronics schematic for the SXM. The MAX4416ESA opamp model was placed in the electronics chain to provide an accurate simulation of signal amplification. The LTSpice schematic of the amplification chain is provided in Figure 4-10.

The simulation was conducted with the same reduced range as the netlist, and again faced the same challenges as the simulation run from the netlist. To eliminate the possibility that the simulations were failing due to computing limitations, the circuit was broken up into five distinct sections, and each contained only one opamp.

Each subcircuit was tested within the same 10°C temperature range. The simulation crashed at same temperatures seen in prior simulations. Consistent simulation failures at the same temperature across multiple configurations was hypothesized to be the result of faulty opamp code. A simulated test circuit was constructed, where the MAX4416ESA opamp was given a generic input and output within its range of operation. The test circuit was run with the same 10°C temperature range, and the range at which the simulation ran properly was constrained to between 22°C and 29°C. This pointed to a limitation in the opamp Spice model, which was confirmed through a series of emails with MAXIM Integrated. The thermal constraint is a known limitation from the manufacturer, which was not published with the Spice model. This was unknown to the REXIS team until April 2020. Additionally, efforts to freeze the opamp model at a local temperature, and run the LTSpice simulation at a different global temperature were unsuccessful.

This revelation made further thermal investigation with LTSpice a fruitless endeavor. The temperatures seen by the MEB during Orbital B and Orbital R were out of range of the model of the opamp used in the amplification chain. While these results are inconclusive, there is further work that can be done towards isolating the root cause of the low count rate anomaly.
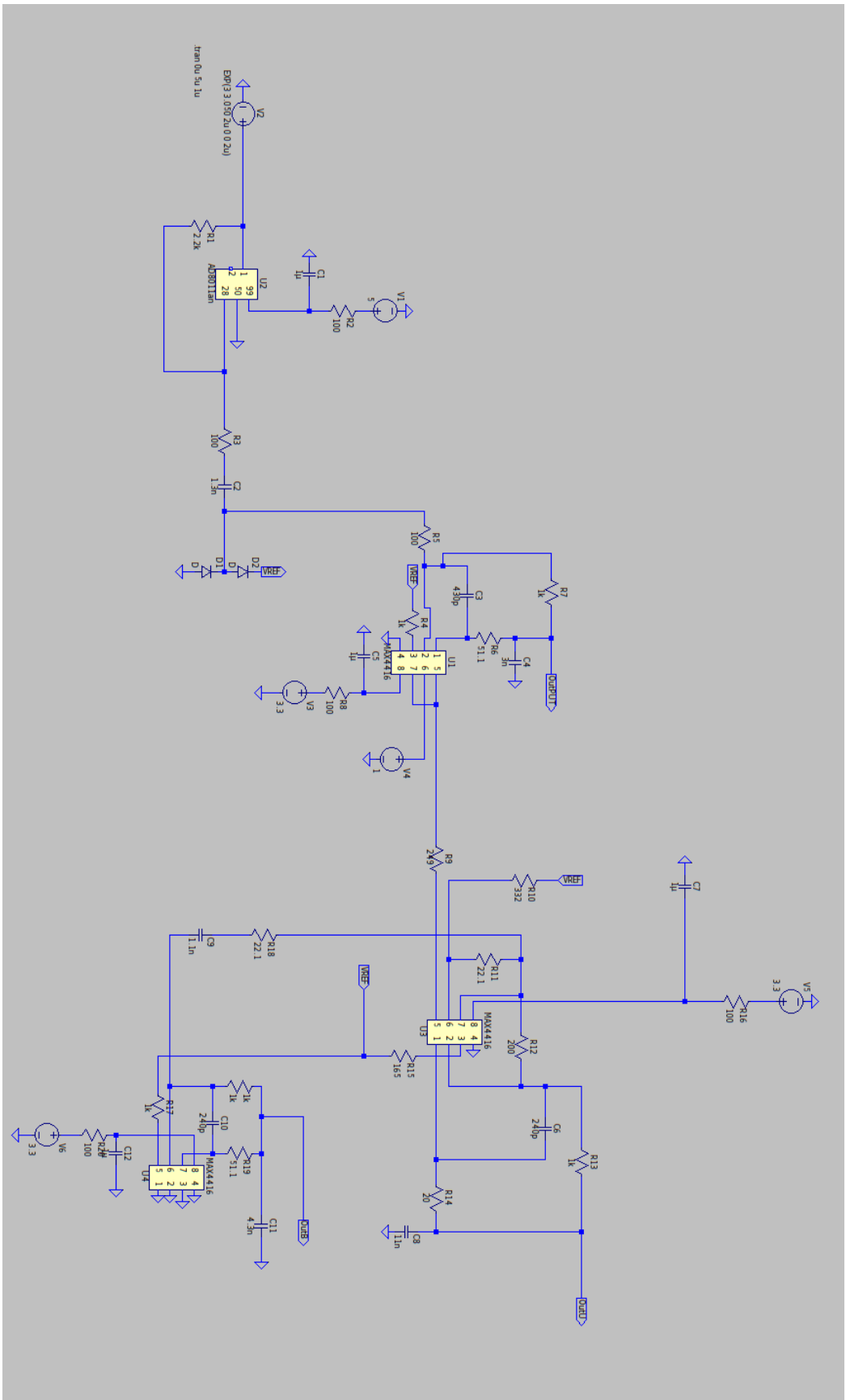
Figure 4-10: The SXM Signal Amplification Chain.

4.4 Root Cause Next Steps

The SXM low count rate anomaly remains an open area of investigation. The SXM is a model instrument for other Class D missions, and instrumentation and programmatic lessons learned will allow other instruments to learn and improve from the SXM.

Despite the limitations of circuit simulation, there are avenues to continue the root cause analysis. This section will describe two areas of future work, a continued root cause investigation, and a CAST analysis, which will together serve as the crux of my Master's thesis.

4.4.1 Identification of Vulnerable Components

There is still work to be done on a root cause investigation into the low count anomaly. The hypothesis that there are temperature-sensitive components in the SXM amplification chains has not yet been proven wrong. Identifying vulnerable components is important for the NICER team, from which the SXM amplification chain schematic was derived. There is a possibility that NICER is operating with the same vulnerability in their detector chain, and a known vulnerability could be planned for, or worked around by the instrument team.

4.4.2 CAST Analysis

Another approach to isolating the cause of the low count rate anomaly is through a Causal Analysis based on System Theory (CAST) investigation. CAST is used to examine the programmatic and control factors that may have influenced an event. While this will not provide further information towards which components in the SXM amplification chain are thermally vulnerable, it offers a way to document lessons learned at a programmatic level. This includes decisions to prioritize some ground tests over others, and decisions made in instrument development. CAST also documents successful control measures that were implemented throughout the project that guarded against other accidents. The goal of this future CAST investigation is to produce a definitive list of lessons that can be used by future instrument teams in their design

and testing process.

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Appendix A

SXM Circuit Schematics

The following Appendix contains the circuit diagrams of all sections of the REXIS SXM. This Appendix also serves as a means through which to document the design of the SXM.

REXIS MAIN ELECTRONICS BOARD ENGINEERING MODEL SCHEMATICS

TI 8:1 ANALOG TO DIGITAL CONVERTER

U41

+3.3V

+3.3V

IN0
IN1
IN2
IN3
IN4
IN5
IN6
IN7
SCLK
CS
DIN

VA
VD

DOUT

AGND
DGND

HK_ADC_MISO

+1.0V HK
HTR TEMP
+3.3V HK
+5V HK
+12V HK
+24V HK
-5V HK
-12V HK
HK_ADC_SCK
HK_ADC_SS_N
HK_ADC_MOSI

ADC128S102WGBQV

R62
S1

C27

C41
1uF

C42
1uF

GND

GND

GND

J21

GND

SPACECRAFT COMM INTERFACE

RS422 TRANSCEIVERS, OPTOCOUPLERS

+3.3V

R241
124
PLACEHOLDER

J23

J24

DE_POWER_EN_FPGA

R240
124

U21

CO
EM
BAS

66171-300

CA

DE_POWER_EN

EMI_COMMON

GND

+3.3V

+3.3V

CL4
1uF

GND

U2

EN
EN
AIN
AIN
BIN
BIN
CIN
CIN
DIN
DIN
GND

VDD

AOUT
BOUT
COUT
DOUT

CMD_A

CMD_B

CMD_A_POS
CMD_A_NEG
CMD_B_POS
CMD_B_NEG

J76
SQ50TP

RS9-26CLV32RH-Q

GND

GND

+3.3V

+3.3V

CY7
1uF

GND

R315
5.1K

R64
5.1K

R65
5.1K

R66
5.1K

U3
HPCL_6751

CA1
AN1
CA2
AN2
CA3
AN3
AN4
CA4

VCC
NC1
VO4
VO3
VO2
VO1
NC2
GND

TIMETICK_A_RET
TIMETICK_A_IN
SIDESELECT_A_IN
SIDESELECT_A_RET
TIMETICK_B_RET
TIMETICK_B_IN

R204   1K

R70   1K

R69   1K

TIMETICK_B_N
SIDESELECT_A_N
TIMETICK_A_N

HCPL-6751

GND

GND

GND

SIDE A

J2

CMD_A_POS
CMD_A_NEG

TELEM_A_POS
TELEM_A_NEG

TIMETICK_A_IN
TIMETICK_A_RET

SIDESELECT_A_IN
SIDESELECT_A_RET

MNT1
MNT2

SND15SMSR700G

CGND

SIDE B

J3

CMD_B_POS
CMD_B_NEG

TELEM_B_POS
TELEM_B_NEG

TIMETICK_B_IN
TIMETICK_B_RET

SND15SSR700G

+3.3V

+3.3V

CY3
1uF

GND

U1

EN
EN
AIN
BIN
CIN
DIN

VDD

AO
BO
CO
DO

R71   45.3
R72   45.3
R74   45.3
R73   45.3

TELEM_A_POS
TELEM_A_NEG
TELEM_B_POS
TELEM_B_NEG

TELEM_A

TELEM_B

RS9-26CLV31RH-Q

GND

GND

72

EXTERNAL CONNECTORS - SXM AND PRTS

TO PREAMP/SDD

+5V_SXM   -5V

J79
SQ50TP

J78
SQ50TP

J5
1   HV
2   TEC-
3   TEC+
4
5   PREAMP_TEMP
6   TEC_DIODE
7
8
9
10
11
12
13
14
15

J80
SQ50TP

GND

TO PRTS AND LIMIT SWITCH

J6
1   PRT_1P
2   PRT_1N
3   PRT_2P
4   PRT_2N
5   PRT_3P
6   PRT_3N
7
8
9
10
11 RADCOVER_LIMITSWITCH
12
13
14 FRANGIBOLT_PWR
15

J81
SQ50TP

J77
SQ50TP

EMI_COMMON

GND
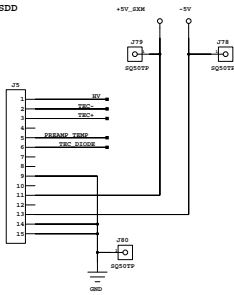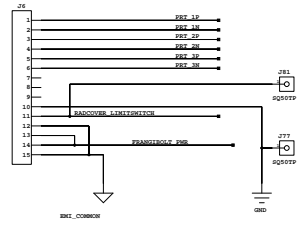
FRANGIBOLT RADIATION COVER RELEASE MECHANISM ACTUATION

MSK5055RHS SWITCHING REGULATOR CONTROLLER
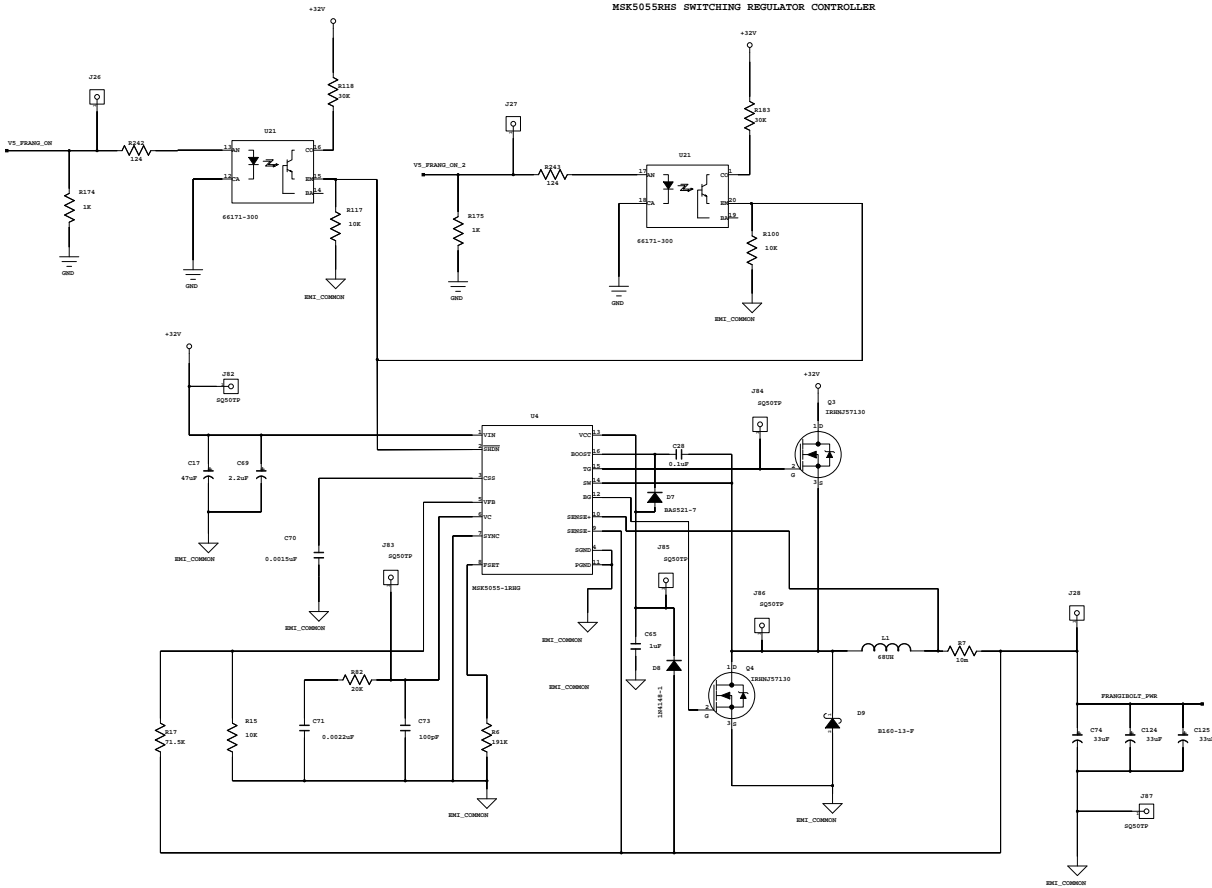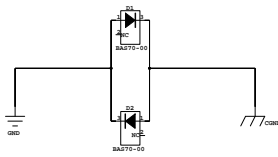
POWERS
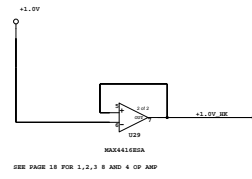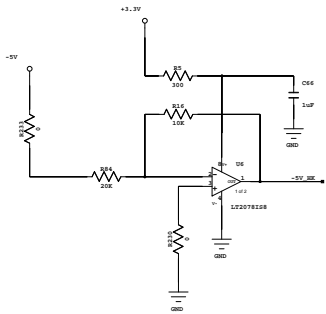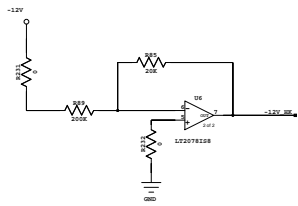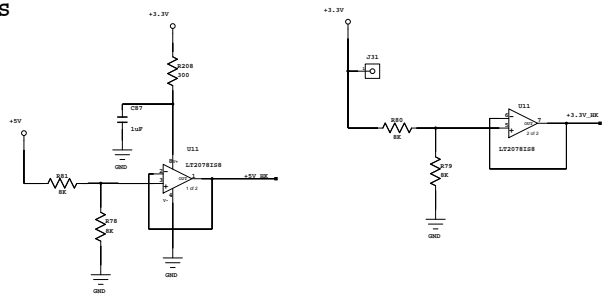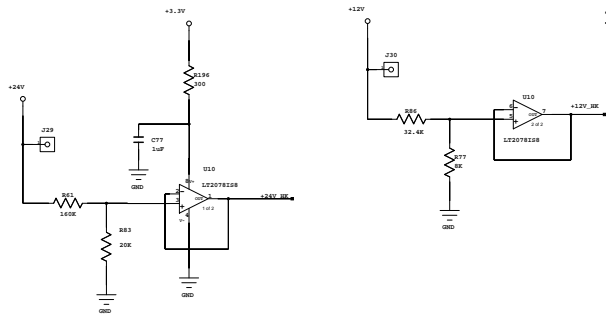
AEROFLEX 64MBIT NOR FLASH
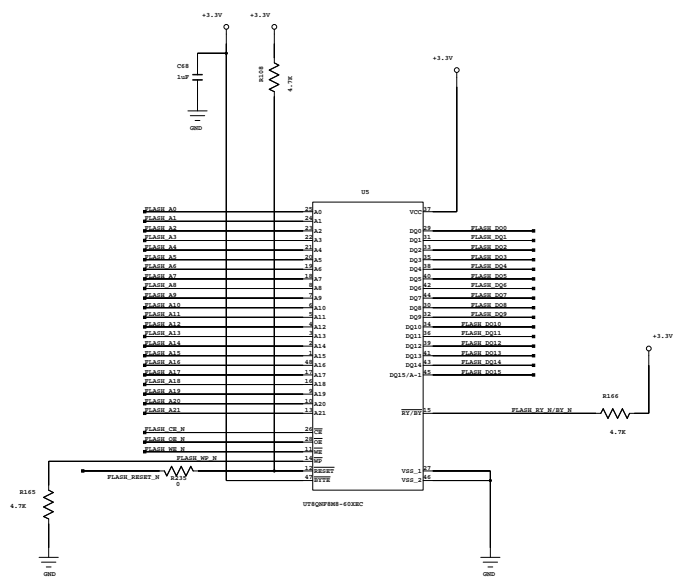
PRIMARY POWER

EMI FILTER, +5V, +12V, +24V, -12VDC

+32V

J34
SQ50TP

+32V

D5
JANTXV1N5806US

D6

D3
JANTXV1N5806US

D4

JANTXV1N5806US

JANTXV1N5806US

J1

SMD9M5R600G

U14
1 +VIN   +VOUT 2
5 INCOM   OUTCOM 4
           CASE   3
SFMC28-461EH

R101
2

C75
22uF

CGND

J33
SQ50TP

TIE CASES (CHASSIS) OF EMI FILTER AND DC CONVERTERS
TOGETHER, AND KEEP TRACES AS SHORT AND WIDE AS POSSIBLE

EMI_COMMON

+32V

C29
1uF

EMI_COMMON

U15
+IN   +OUT
INH
IN_CON   NC
SYNC   OUT_CON
        CASE
SMHF2805S/KR

+5V   +5V
R40   R39

+5V_PWR

CGND

GND

+32V

C30
1uF

EMI_COMMON

DE_POWER_EN

U16
+IN   +OUT
IN_CON   OUT_CON
INH   -OUT
       CASE_GND
SLH2812D/KR

+12V   -12V
R38   R37

+12V_PWR
-12V_PWR

CGND

GND

J36
SQ50TP

+32V

J35
SQ50TP

C31
1uF

EMI_COMMON

DE_POWER_EN

U17
+IN   +OUT
IN_CON   OUT_CON
INH   -OUT
       CASE_GND
SLH2812D/KR

+24V
R28

+24V_PWR

CGND

GND

78

1.0V POWER

2.5V POWER

+3.3V POWER

-5V POWER

+3.3V

C25
0.1uF

GND

C84
220uF

GND

R111
4.32K

J43
SQ50TP

R18
806

C72
100pF

GND   GND

+5V

C83
220uF

C24
0.1uF

GND

U18

VOUT_1   VIN_1
VOUT_2   VIN_2
VOUT_3   VIN_3
VOUT_4   VIN_4
VOUT_5   VIN_5
VOUT_6   VIN_6

OCP   BYP
VADJ   EN
PG
GND

ISL75051SRHQF

3.3V_ENABLE

C85
0.18uF

GND

J44
SQ50TP

R95
1K

5.49K
R114

GND   GND   GND

GND

-12V

R94
DEPOP

C40
1uF

U20

VIN   OUT

ADJ

RH137H

J45
SQ50TP

J46
SQ50TP

R112
357

C41
1uF

GND

R113
120

-5V

81

3D-PLUS 1GBIT DDR SDRAM

MOSFET SWITCH

DECTECTOR ELECTRONICS 5V RAIL

SOLAR X-RAY MONITOR 5V RAIL
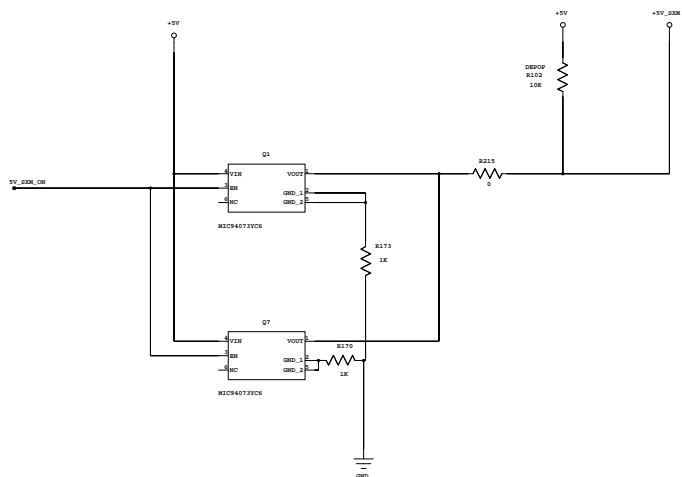
SOLAR X-RAY MONITOR DAC & ADC
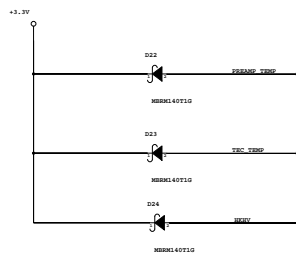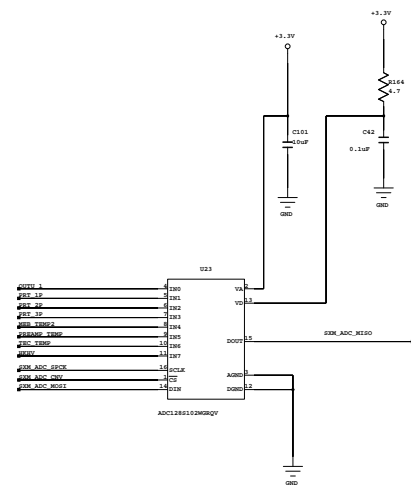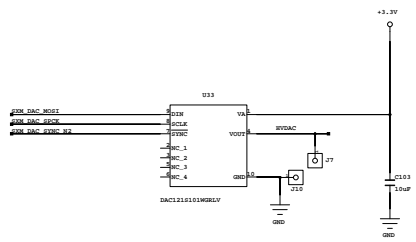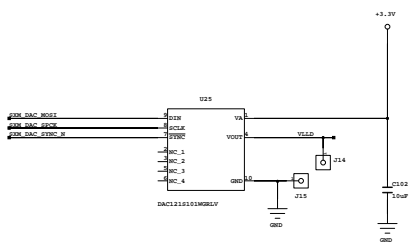
SOLAR X-RAY MONITOR AMPLITUDE CAPTURE

+3.3V

+3.3V

R145
100

R137   R104
1K   10K

C43   C51
1uF   1uF

GND   GND

U30   U30

VB   R180
OUTU   R127   R119   1K   22   OUTU 1
        1K   IN+
                                              MAX4416ESA
              MAX4416ESA
                                              SPARE
        GND
                                 GND

R138   R103
10K   1K   J16

                C109
                1nF

GND   GND
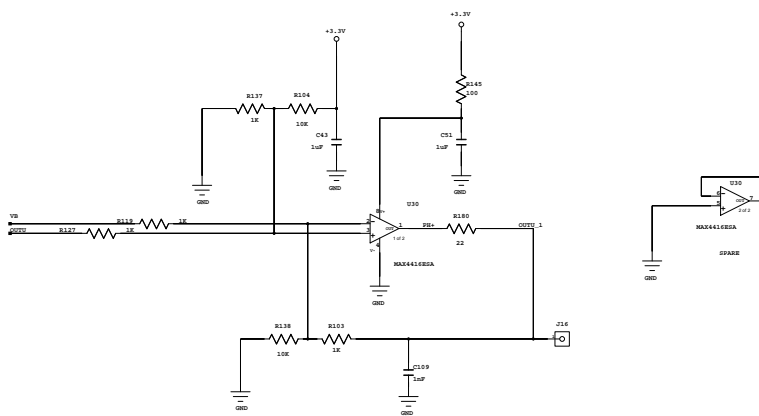
SOLAR X-RAY MONITOR COCKCROFT WALTON HIGH VOLTAGE GENERATOR

SOLAR X-RAY MONITOR SHAPING AND AMPLIFICATION

U29 PINS 5,6,7 IS ON PAGE PAGE 7 (SX)
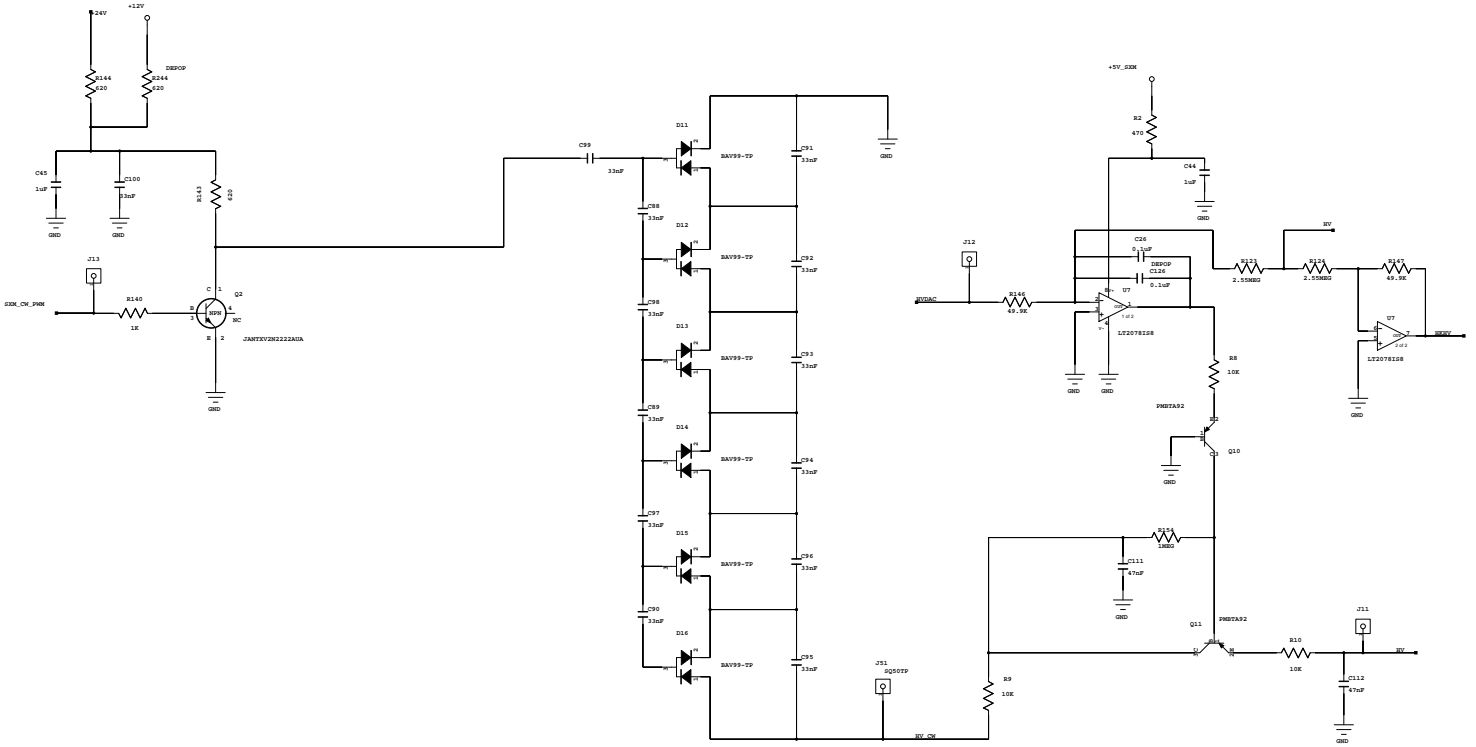
SOLAR X-RAY MONITOR TEC DRIVER

+32V

L7
MPZ2012S102A

L8
22UH
SPD62R-223M

C50
1uF

C104
10uF

EMI_COMMON   EMI_COMMON

Q13
PNP
2SB1316

R203
3.9K

J58
SQ50TP

SXM_TEC_ENABLE

R238
124

U21

66171-300

GND

EMI_COMMON

+32_TEC

L4
MPZ2012S102A

J61
SQ50TP

D19
NSRK140T1G

L5
MPZ2012S102A

C105
10uF

C106
10uF

EMI_COMMON

DEPOP
R98
10K

+3.3V

R179
30

C49
1uF

GND

J18

SXM_TEC_PWM

U35
CD74AC00M96

U35
CD74AC00M96

R239
124

+32V

J60
SQ50TP

R172
200K

U24

66171-300

GND

R1
10K

EMI_COMMON

Q14
IRFL014PBF

L9
100UH

L6
MPZ2012S102A

C107
10uF

C108
10uF

TEC-

EMI_COMMON

GND

U35
CD74AC00M96

+3.3V

R11   15K

U35
CD74AC00M96

J59
SQ50TP

U24

66171-300

GND

R171
1

EMI_COMMON

SOLAR X-RAY MONITOR TEC TEMPERATURE INTERFACE
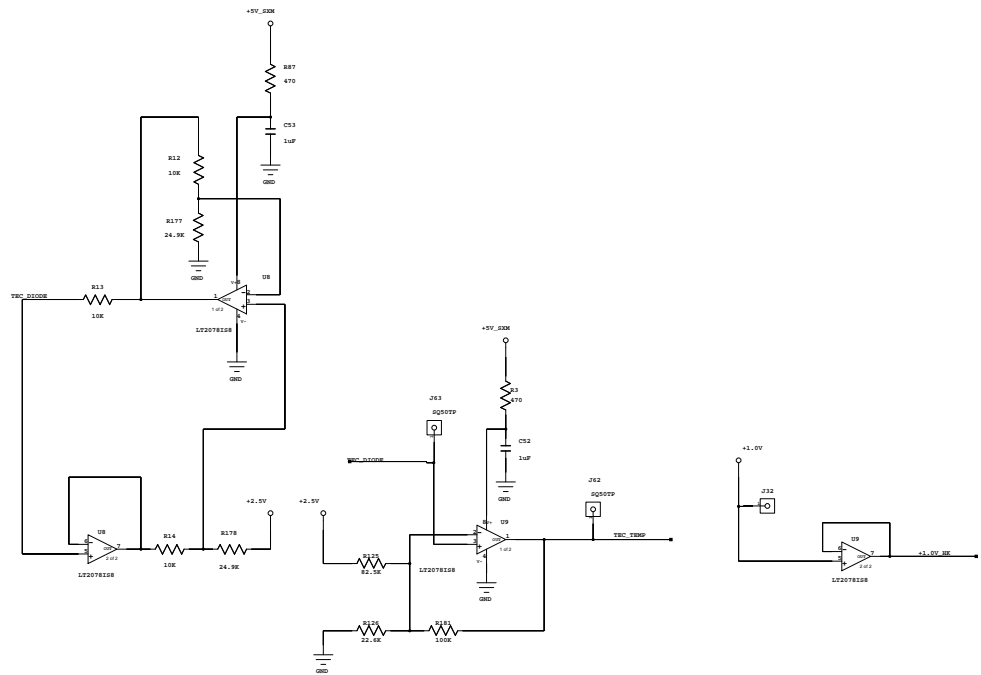
SOLAR X-RAY MONITOR THRESHOLD CONTROL

+3.3V

R96
1K

C120
47uF

GND

VB

D18
BAV99-TP

C55
1uF

GND

GND
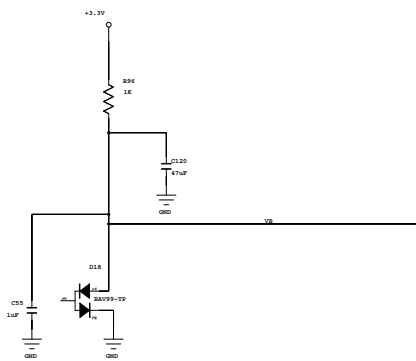
SOLAR X-RAY MONITOR TRIGGER AND TIMING
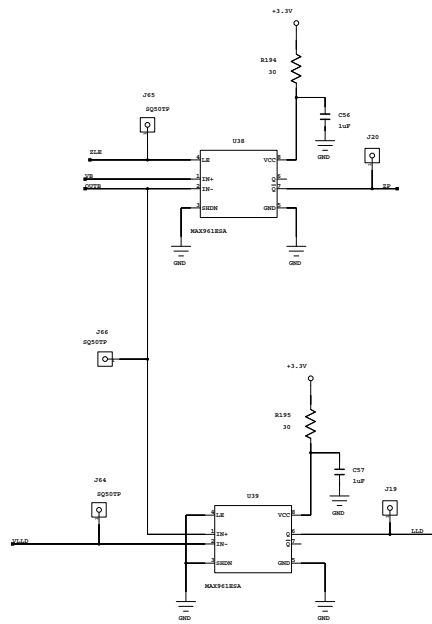
PRT TEMPERATURE MEASUREMENT INTERFACE

+3.3V

R185
200

PRT_1P

PRT_1N
R186
200

GND

+3.3V

R205
200

PRT_2P

PRT_2N
R133
200

GND

+3.3V

R206
200

PRT_3P

PRT_3N
R207
200

GND

+5V

U27

NC

AD590LH

R248
1.15K

WEB_TEMP2

R167
2.2K

GND

+5V

U26

NC

AD590LH

R245
1.15K

WEB_TEMP

R76
2.2K

GND
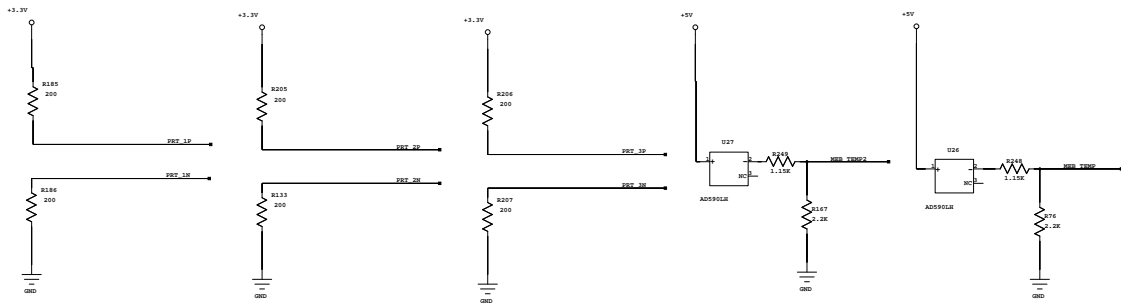
VIRTEX-5 BANKS 0-4

CONFIGURATION ADDRESS

OSCILLATOR

U22

BANK 0 - 4

XQ5VFX130T-1EF1738I

+3.3V +3.3V +3.3V +3.3V +2.5V +3.3V +3.3V

R201 4.7K
R200 4.7K
R236 4.7K
R237 4.7K
R197 4.7K
R198 4.7K
R105 4.7K
R106 4.7K
R99 4.7K
R110 4.7K
R130 4.7K
R4 4.7K
R122 4.7K
R156 4.7K
R132 4.7K
R131 4.7K
R245 4.7K
R246 100
R199 4.7K
R247 100
R202 4.7K
C121 0.1uF
R134 10.1
R128 4.7K

J8
87833-1421

GND

TMS_0
TCK_0
TDO_0
TDI_0

AC22 DXP_0
AC21 DXN_0
AA22 VP_0
AB21 VN_0
R29 PROGRAM_B_0
P15 HSWAPEN_0
B15 D_IN_0
T30 CS_B_0
B30 RDWR_B_0
AH30 M0_0
W1 M1_0
A28 M2_0
AG29 TCK_0
AH16 TDI_0
AH15 TDO_0
AH15 TMS_0

H25 IO_L0P_A19_1
P25 IO_L0N_A18_1
P18 IO_L1P_A17_1
P17 IO_L1N_A16_1
P26 IO_L2P_A15_D31_1
N26 IO_L2N_A14_D30_1
N16 IO_L3P_A13_D29_1
N16 IO_L3N_A12_D28_1
P27 IO_L4P_A11_D27_1
P28 IO_L4N_VREF_A10_D26_1
H15 IO_L5P_A9_D25_1
N14 IO_L5N_A8_D24_1
N28 IO_L6P_A7_D23_1
N29 IO_L6N_A6_D22_1
M14 IO_L7P_A5_D21_1
M13 IO_L7N_A4_D20_1
N30 IO_L8P_CC_A3_D19_1
M29 IO_L8N_CC_A2_D18_1
M13 IO_L9P_CC_A1_D17_1
P13 IO_L9N_CC_A0_D16_1

AK12 IO_L0P_CC_RS1_2
AK13 IO_L0N_CC_RS0_2
AJ30 IO_L1P_CC_A25_2
AK30 IO_L1N_CC_A24_2
AK15 IO_L2P_A23_2
AK14 IO_L2N_A22_2
AL30 IO_L3P_A21_2
AM29 IO_L3N_A20_2
AL14 IO_L4P_FCS_B_2
AK13 IO_L4N_VREF_FOE_B_MOSI_2
AM28 IO_L5P_FWE_B_2
AL29 IO_L5N_CSO_B_2
AH13 IO_L6P_D7_2
AP13 IO_L6N_D6_2
AK28 IO_L7P_D5_2
AK29 IO_L7N_D4_2
AN14 IO_L8P_D3_2
AM14 IO_L8N_D2_FS2_2
AK27 IO_L9P_D1_FS1_2
AJ26 IO_L9N_D0_FS0_2

FLASH_A19
FLASH_A18
FLASH_A17
FLASH_A16
FLASH_A15
FLASH_A14
FLASH_A13
FLASH_A12
FLASH_A11
FLASH_A10
FLASH_A9
FLASH_A8
FLASH_A7
FLASH_A6
FLASH_A5
FLASH_A4
FLASH_A3
FLASH_A2
FLASH_A1
FLASH_A0

FLASH_A21
FLASH_A20
FLASH_CE_N
FLASH_WE_N

FLASH_DQ7
FLASH_DQ6
FLASH_DQ5
FLASH_DQ4
FLASH_DQ3
FLASH_DQ2
FLASH_DQ1
FLASH_DQ0

AVDD_0 Y22
AVSS_0 Y21
VBATT_0 P30
VREF0_0 AB22
VREF0_0 AA21

INIT_B_0 T14
D_OUT_BUSY_0 A716
DONE_0 R14
CCLK_0 AH14

RSVD_1 V31
RSVD_2 AF30

IO_L0P_CC_GC_3 J16
IO_L0N_CC_GC_3 J15
IO_L1P_CC_GC_3 M26
IO_L1N_CC_GC_3 L27
IO_L2P_GC_VRN_3 J17
IO_L2P_GC_VRP_3 H17
IO_L3P_GC_3 M27
IO_L3N_GC_3 L28
IO_L4P_GC_3 L17
IO_L4N_GC_VREF_3 M17
IO_L5P_GC_3 L29
IO_L5N_GC_3 K28
IO_L6P_GC_3 L16
IO_L6N_GC_3 L15
IO_L7P_GC_3 K29
IO_L7N_GC_3 J30
IO_L8P_GC_3 L14
IO_L8N_GC_3 K15
IO_L9P_GC_3 K30
IO_L9N_GC_3 L30

IO_L0P_GC_DQ15_4 AN30
IO_L0N_GC_DQ14_4 AP30
IO_L1P_GC_DQ13_4 AF17
IO_L1N_GC_DQ12_4 AN29
IO_L2P_GC_DQ11_4 AN29
IO_L2N_GC_DQ10_4 AP28
IO_L3P_GC_DQ9_4 AL15
IO_L3N_GC_DQ8_4 AL16
IO_L4P_GC_4 AP29
IO_L4N_GC_VREF_4 AN28
IO_L5P_GC_4 AH16
IO_L5N_GC_4 AM17
IO_L6P_GC_4 AN27
IO_L6N_GC_4 AN26
IO_L7P_GC_VRN_4 AM15
IO_L7N_GC_VRP_4 AN16
IO_L8P_GC_4 AL27
IO_L8N_GC_4 AK26
IO_L9P_CC_GC_4 AP16
IO_L9N_CC_GC_4 AP15

FLASH_DQ15
FLASH_DQ14
FLASH_DQ13
FLASH_DQ12
FLASH_DQ11
FLASH_DQ10
FLASH_DQ9
FLASH_DQ8

FLASH_RY_N/BY_N
FLASH_WP_N

J67
SQ50TP

J69
SQ50TP

U42
1116R36M0000SBF
EN_D
VCC
OUT
GND

IMPEDANCE CONTROL 50 OHM

GND

U22

BANK 11 - 12

XQ5VFX130T-1EF1738I

GND

GND

U22

BANK 13 - 15

XQ5VFX130T-1EF1738I

GND

GND

U22

BANK 31 - 34

XQ5VFX130T-1EF1738I

GND

GND

VIRTEX-5 BANKS 17, 18 AND 19

DETECTOR ELECTRONICS CAMERA LINK INTERFACE

NOT CONNECTED (FORMER CONNECTION TO J9)

+12V
+3.3V
-12V
+24V
+5V

J9
1
2
3
4 CAMLINK_SERTFGN
5
6 CAMLINK_SERTCN
7 CAMLINK_X1N
8 CAMLINK_XCLEN
9 CAMLINK_X2N
10
11 CAMLINK_X2N
12
13 CAMLINK_X1N
14 CAMLINK_X0N
15
16 CLINE_RESET_N
17
18 CAMLINK_SERTFGP
19
20 CAMLINK_SERTCP
21
22 CAMLINK_X1P
23
24 CAMLINK_XCLEP
25
26 CAMLINK_X2P
27
28 CAMLINK_X1P
29
30 CAMLINK_X0P

J70
SQ50TP

GND

U22
BANK 17 - 19

AB34 IO_L0P_17
AC34 IO_L0N_17
AC35 IO_L1P_17
AB36 IO_L1N_17
AD36 IO_L2P_17
AD35 IO_L2N_17
AE36 IO_L3P_17
AE37 IO_L3N_17
AE37 IO_L4P_17
AD38 IO_L4N_VREF_17
AB39 IO_L5P_17
AE38 IO_L5N_17
AF39 IO_L6P_17
AG38 IO_L6N_17
AG37 IO_L7P_17
AF37 IO_L7N_17
AN40 IO_L8P_CC_17
AP40 IO_L8N_CC_17
AR40 IO_L9P_CC_17
AT40 IO_L9N_CC_17
AV40 IO_L10P_CC_17
AU39 IO_L10N_CC_17
AT39 IO_L11P_CC_17
AH39 IO_L11N_CC_17
AH39 IO_L12P_VRN_17
AH39 IO_L12N_VRP_17
AJ38 IO_L13P_17
AK39 IO_L13N_17
AK38 IO_L14P_17
AK37 IO_L14N_VREF_17
AJ37 IO_L15P_17
AH38 IO_L15N_17
AL39 IO_L16P_17
AM39 IO_L16N_17
AM39 IO_L17P_17
AP38 IO_L17N_17
AN38 IO_L18P_17
AM37 IO_L18N_17
AL37 IO_L19N_17

AJ7   IO_L0P_18
AK7   IO_L0N_18
AB11 IO_L1P_18
AC10 IO_L1N_18
AL5   IO_L2P_18
AK5   IO_L2N_18
AB9   IO_L3P_18
AB8   IO_L3N_18
AJ5   IO_L4P_18
AC8   IO_L4N_VREF_18
AC9   IO_L5P_18
AH6   IO_L5N_18
AH5   IO_L6P_18
AD10 IO_L6N_18
AD11 IO_L7P_18
AB4   IO_L7N_18
AB4   IO_L8P_CC_18
AB4   IO_L8N_CC_18
AB7   IO_L9P_CC_18
AB6   IO_L9N_CC_18

XQ5VFX130T-1EF1738I

IO_L10P_CC_18   AC5
IO_L10N_CC_18   AC6
IO_L11P_CC_18   AF5
IO_L11N_CC_18   AE6
IO_L12P_VRN_18 AD6
IO_L12N_VRP_18 AD7
IO_L13P_18   AG6   CAMLINK_SERTFGP
IO_L13N_18   AG7   CAMLINK_SERTFGN
IO_L14P_18   AE5
IO_L14N_VREF_18 AD5
IO_L15P_18   AF7   CAMLINK_X1P
IO_L15N_18   AE7   CAMLINK_X1N
IO_L16P_18   AD8
IO_L16N_18   AE8
IO_L17P_18   AF9
IO_L17N_18   AF10
IO_L18P_18   AE9   CAMLINK_X2P
IO_L18N_18   AE10 CAMLINK_X2N
IO_L19P_18   AF11
IO_L19N_18   AF12

IO_L0P_19   J34
IO_L0N_19   K35
IO_L1P_19   H35
IO_L1N_19   J36
IO_L2P_19   H37
IO_L2N_19   M37
IO_L3P_19   M36
IO_L3N_19   J36
IO_L4P_19   L36
IO_L4N_19   L36
IO_L5P_19   K35
IO_L5N_19   K35
IO_L6P_19   H35
IO_L6N_19   J36
IO_L7P_19   K37
IO_L7N_19   J37
IO_L8P_CC_19   J34
IO_L8N_CC_19   J35
IO_L9P_CC_19   J33
IO_L9N_CC_19   J33
IO_L10P_CC_19   K35
IO_L10N_CC_19   J36
IO_L11P_CC_19   J36
IO_L11N_CC_19   J36
IO_L12P_VRN_19 M36
IO_L12N_VRP_19 J37
IO_L13P_19   J36
IO_L13N_19   J36
IO_L14P_19   J37
IO_L14N_VREF_19 J37
IO_L15P_19   K38
IO_L15N_19   J37
IO_L16P_19   K35
IO_L16N_19   K34
IO_L17P_19   J33
IO_L17N_19   M33
IO_L18P_19   J33
IO_L18N_19   M32
IO_L19P_19   J32
IO_L19N_19   AA32

CAMLINK_SERTCP
CAMLINK_SERTCN

CAMLINK_X1P
CAMLINK_X1N

CAMLINK_X0P
CAMLINK_X0N

R216
4.7K

GND

CAMLINK_XCLEP
CAMLINK_XCLEN

J71
SQ50TP

GND

R217
4.7K

GND

GND

95

VIRTEX-5 BANKS 20 AND 21

DDR SDRAM DATA

U22

BANK 20 - 21

Pin	Signal		Signal	Pin
N9	IO_L0P_20		IO_L0P_21	AR33
N8	IO_L0N_20		IO_L0N_21	AR32
E9	IO_L1P_20		IO_L1P_21	AC33
E8	IO_L1N_20		IO_L1N_21	AD32
P7	IO_L2P_20		IO_L2P_21	AD33
P8	IO_L2N_20		IO_L2N_21	AE32
D7	IO_L3P_20		IO_L3P_21	AE33
H7	IO_L3N_20		IO_L3N_21	AE34
R7	IO_L4P_20		IO_L4P_21	AV39
R8	IO_L4N_VREF_20		IO_L4N_VREF_21	AV38
F7	IO_L5P_20		IO_L5P_21	AU38
F6	IO_L5N_20		IO_L5N_21	AU37
R9	IO_L6P_20		IO_L6P_21	AT37
T9	IO_L6N_20		IO_L6N_21	AR38
E5	IO_L7P_20		IO_L7P_21	AR37
F5	IO_L7N_20		IO_L7N_21	AT36
V9	IO_L8P_CC_20		IO_L8P_CC_21	AE35
V10	IO_L8N_CC_20		IO_L8N_CC_21	AF34
F9	IO_L9P_CC_20		IO_L9P_CC_21	AF35
G9	IO_L9N_CC_20		IO_L9N_CC_21	AF36
G7	IO_L10P_CC_20		IO_L10P_CC_21	AH34
G8	IO_L10N_CC_20		IO_L10N_CC_21	AG34
U8	IO_L11P_CC_20		IO_L11P_CC_21	AH35
U9	IO_L11N_CC_20		IO_L11N_CC_21	AG36
H8	IO_L12P_VRN_20		IO_L12P_VRN_21	AP37
H9	IO_L12N_VRP_20		IO_L12N_VRP_21	AP36
T10	IO_L13P_20		IO_L13P_21	AP35
T11	IO_L13N_20		IO_L13N_21	AN36
J8	IO_L14P_20		IO_L14P_21	AM36
J7	IO_L14N_VREF_20		IO_L14N_VREF_21	AN35
U11	IO_L15P_20		IO_L15P_21	AN34
V11	IO_L15N_20		IO_L15N_21	AM34
K8	IO_L16P_20		IO_L16P_21	AM36
K9	IO_L16N_20		IO_L16N_21	AJ36
K7	IO_L17P_20		IO_L17P_21	AJ35
L7	IO_L17N_20		IO_L17N_21	AL36
M7	IO_L18P_20		IO_L18P_21	AL35
M8	IO_L18N_20		IO_L18N_21	AL35
M9	IO_L19P_20		IO_L19P_21	AL34
L9	IO_L19N_20		IO_L19N_21	AK34

XQ5VFX130T-1EF1738I

SDRAM_DQ0
SDRAM_DQ1
SDRAM_DQ2
SDRAM_DQ3
SDRAM_DQ4
SDRAM_DQ5
SDRAM_DQ6
SDRAM_DQ7

SDRAM_VREF

SDRAM_DQ8
SDRAM_DQ9
SDRAM_DQ10
SDRAM_DQ11
SDRAM_DQ12
SDRAM_DQ13
SDRAM_DQ14
SDRAM_DQ15
SDRAM_UDQS
SDRAM_UDM
SDRAM_LDQS
SDRAM_LDM

R221   4.7K
R220   4.7K

GND   GND   GND

VIRTEX-5 BANKS 23,24,25 AND 26

DDR SDRAM ADDRESS/CONTROL

U22

BANK 23 - 24

XQ5VFX130T-1EF1738I

SDRAM_A0
SDRAM_A1
SDRAM_A2
SDRAM_A3
SDRAM_A4
SDRAM_A5
SDRAM_A6
SDRAM_A7
SDRAM_A8
SDRAM_A9
SDRAM_A10
SDRAM_A11
SDRAM_A12
SDRAM_A13

SDRAM_CK
SDRAM_CK_N
SDRAM_BA0
SDRAM_BA1
SDRAM_CKE

SDRAM_CAS_N
SDRAM_WE_N
SDRAM_CS_N
SDRAM_RAS_N

SDRAM_VREF

U22

BANK 25 - 26

XQ5VFX130T-1EF1738I

GND

VIRTEX-5 BANKS 5,6,7,8,27, 29

3.3V I/O

+3.3V

+3.3V

+3.3V

U22 — BANK 27 - 29

Left signals	Pin
GND_A	D31
ZELEN_A	C31
GND_B	C30
ZELEN_B	B31
DE_POWER_EN_FPGA	A30
TIMETICK_A_N	A31
TIMETICK_A_N	A32
TIMETICK_B_N	B32
8K_ADC_MOSI	B33
8K_ADC_MISO	C33
8K_ADC_SS_N	D32
5V_SXM_ON	D33
2P	B34
SXM_ADC_SPCK	A34
SXM_ADC_MISO	A35
8K_ADC_SCK	D35
SXM_ADC_CNV	D36
SXM_DAC_MOSI	C36
SXM_DAC_SPCK	C35
SXM_DAC_SYNC_N	A37
SXM_TEC_PWM	A36
SXM_CM_PWM	B37
2LS	B36
FLASH_RESET_N	C38
SXM_ADC_MOSI	D38
V5_FRANG_ON	C39
SXM_TEC_ENABLE	C40
RADCOVER_LIMITSWITCH	B39
V5_FRANG_ON_2	B38
	A39
	A40
	A41
	B41
	B42
SXM_DAC_SYNC_N2	C41
CLINK_RESET_N	D40
	D41
	D42
	D42

XQ5VFX130T-1EF1738I

U22 — BANK 5 - 6

Left signals	Pin
	L24
	M24
	M23
	H17
	K24
	J23
	F16
	F17
	K25
	J25
	G15
	H16
	H15
	G16
	G17
	J28
	J27
	J26
	E18
	K27
	L26
	F20
	G27
	F21
	M19
	G28
	N17
	M18
	N16
	F22
	L20
	L19
	M25
	H30
	G26

XQ5VFX130T-1EF1738I

U22 — BANK 7 - 8

Left signals	Pin
	M23
	M22
	M21
	L21
	N24
	N23
	N22
	N21
	K21
	J21
	J20
	K20
	L22
	K23
	K22
	J22
	G22
	G21
	G23
	E22
	F24
	G23
	E19
	D18
	J23
	H23
	H20
	F20
	G24
	F19
	G19
	F26
	H19
	H20
	H25
	G26

XQ5VFX130T-1EF1738I

GND   GND   GND   GND   GND

J72 SQ50TP
J73 SQ50TP
J74 SQ50TP
J75 SQ50TP
J88 SQ50TP
J89 SQ50TP

VIRTEX-5 MGT I/O AND GND BANKS

U22

XQ5VFX130T-1EF1738I

U22

XQ5VFX130T-1EF1738I

GND

GND

GND

GND

VIRTEX-5 VCC +1.0V, +2.5V, +3.3V

U22
MGT

+1.0V +2.5V

+2.5V +3.3V

+1.0V

+1.0V

XQ5VFX130T-1EF1738I

GND

VIRTEX-5 DECOUPLING

+2.5V

C58 C59 C60
33uF 33uF 33uF
GND

GND

+1.0V

C119 C122 C123
330uF 330uF 330uF

GND

Appendix B

Simulation Code

The following Appendix contains python code developed for SXM data analysis.

B.1 SXM Simulated Instrument Response Code

The following section contains SXM simulated response code used to attempt to fit SXM flight data to Chianti solar abundance models. This code implements SXM Data Pipeline code written by the REXIS Science Team.

```python
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
Created on Fri Jun 28 09:26:40 2019

@author: andrewcummings
"""

import ChiantiPy.core as ch
import ChiantiPy.tools.filters as cf
import matplotlib.pyplot as plt
import numpy as np
```

```python
#temp1 = np.arange(1.e+6,625e+4,25.e+4)
#temp2 = np.arange(65.e+5,10.e+6,5.e+5)
#temp3 = np.arange(10.e+6,21.e+6,1.e+6)
#temp12 = np.concatenate((temp1,temp2),axis=None)
#T = np.concatenate((temp12,temp3), axis=None)


"""file name"""
def chianti_spectra_generation(file,abundance):
        file ='sun_photospheric_1998_grevesse_highres.npz'
        #abundances:
                # sun_photospheric_1998_grevesse,
                sun_photospheric_2015_scott_ext,
                sun_coronal_feldman_1992_ext,
                sun_coronal_2012_schmelz_ext


        E= np.arange(0.0495, 25.0005,  0.005)
        T = np.array([  0.5,    0.6,    0.7,    0.8,    0.9,    1. ,
1.1,    1.2,    1.3,
            1.4,    1.5,    1.6,    1.7,    1.8,
            1.9,    2. ,    2.1,    2.2,
            2.3,    2.4,    2.5,    2.6,    2.7,
            2.8,    2.9,    3. ,    3.1,
            3.2,    3.3,    3.4,    3.5,    3.6,
            3.7,    3.8,    3.9,    4. ,
            4.1,    4.2,    4.3,    4.4,    4.5,
            4.6,    4.7,    4.8,    4.9,
            5. ,    5.1,    5.2,    5.3,    5.4,
```

5.5 ,   5.6 ,   5.7 ,   5.8 ,

5.9 ,   6. ,   6.1 ,   6.2 ,   6.3 ,

6.4 ,   6.5 ,   6.6 ,   6.7 ,

6.8 ,   6.9 ,   7. ,   7.1 ,   7.2 ,

7.3 ,   7.4 ,   7.5 ,   7.6 ,

7.7 ,   7.8 ,   7.9 ,   8. ,   8.1 ,

8.2 ,   8.3 ,   8.4 ,   8.5 ,

8.6 ,   8.7 ,   8.8 ,   8.9 ,   9. ,

9.1 ,   9.2 ,   9.3 ,   9.4 ,

9.5 ,   9.6 ,   9.7 ,   9.8 ,   9.9 ,

10. ,   10.1 ,   10.2 ,   10.3 ,

10.4 ,   10.5 ,   10.6 ,   10.7 ,   10.8 ,

10.9 ,   11. ,   11.1 ,   11.2 ,

11.3 ,   11.4 ,   11.5 ,   11.6 ,   11.7 ,

11.8 ,   11.9 ,   12. ,   12.1 ,

12.2 ,   12.3 ,   12.4 ,   12.5 ,   12.6 ,

12.7 ,   12.8 ,   12.9 ,   13. ,

13.1 ,   13.2 ,   13.3 ,   13.4 ,   13.5 ,

13.6 ,   13.7 ,   13.8 ,   13.9 ,

14. ,   14.1 ,   14.2 ,   14.3 ,   14.4 ,

14.5 ,   14.6 ,   14.7 ,   14.8 ,

14.9 ,   15. ,   15.1 ,   15.2 ,   15.3 ,

15.4 ,   15.5 ,   15.6 ,   15.7 ,

15.8 ,   15.9 ,   16. ,   16.1 ,   16.2 ,

16.3 ,   16.4 ,   16.5 ,   16.6 ,

16.7 ,   16.8 ,   16.9 ,   17. ,   17.1 ,

17.2 ,   17.3 ,   17.4 ,   17.5 ,

17.6 ,   17.7 ,   17.8 ,   17.9 ,   18. ,

18.1 ,   18.2 ,   18.3 ,   18.4 ,

18.5 ,   18.6 ,   18.7 ,   18.8 ,   18.9 ,

```
      19.  ,    19.1,    19.2,    19.3,
      19.4,    19.5,    19.6,    19.7,    19.8,
      19.9,    20.  ])


      T=T*1.e6
```

```
#T= np.logspace(5, 7, 50)
        s= ch.spectrum(T, wavelength= 12.4/E, eDensity= 1e9,
        em= 1e27, filter= (cf.gaussianR, 10000),
        abundance='sun_photospheric_1998_grevesse',
        minAbund= 1e-6,verbose=1)
```

```
        I= s.Spectrum
#plt.plot(E, I['intensity'][1])
#plt.xlabel('Energy [keV]')
#plt.ylabel(I['ylabel'][:-2])
        np.savez_compressed(file, I,E=E,T=T,
        wavelength = 12.4/E)
        f = np.load(file)
        s= dict(f['arr_0'].tolist())
        wvl = s['wavelength']
        T=f['T']
        T=T/1.e6
        E = 12.4/wvl
        intensity= s['intensity']
        for i in range(len(T)):
```

```
              intensity[i,:] = intensity[i,:]*4.06*1.e6*(wvl)**3
          data = intensity
          np.savez_compressed(file, E=E,
          data=data.T,T=T)
```

B.2   SXM Histogram Rebinning

Code used to rebin Orbital B and Orbital R flight data to attempt to recover x-ray
signal. SXM flight data was loaded manually into the rebinner because of x-ray count
rate differences that existed between the two sections of Orbital R. Level 0 SXM flight
data is delineated by "YYYYDDD," where DDD is the day of the year that data was
recorded.

```
import h5py as h
import math as m
import numpy as np



'2019182_L0.h5','2019183_L0.h5','2019184_L0.h5',
'2019185_L0.h5','2019186_L0.h5',
                '2019187_L0.h5','2019188_L0.h5','2019189_L0.h5',
'2019190_L0.h5','2019191_L0.h5',
                '2019192_L0.h5','2019193_L0.h5','2019194_L0.h5',
'2019195_L0.h5','2019196_L0.h5']
file=[   '2019197_L0.h5','2019198_L0.h5','2019199_L0.h5',
'2019200_L0.h5','2019201_L0.h5',
                '2019202_L0.h5','2019203_L0.h5',
                '2019204_L0.h5','2019205_L0.h5','2019206_L0.h5',
                '2019207_L0.h5','2019208_L0.h5',
```

```
                    '2019209_L0.h5','2019210_L0.h5','2019211_L0.h5',
                    '2019212_L0.h5','2019213_L0.h5',
                    '2019214_L0.h5','2019215_L0.h5','2019216_L0.h5',
                    '2019217_L0.h5','2019218_L0.h5']


#dtype([('sxm_period', '<u2'), ('TotalEventsCnt', '<u2'),
('underflowEventCnt', '<u2'), ('overflowEventCnt', '<u2'),
('bin', '<u2', (512,)), ('scTime(subsecs)', '<f8'),
('scTime(secs)', '<f8'), ('scGlobalCount', '<f8')])
#dtype([('Sync', 'S30'), ('Length', '<u4'),
('PacketID', '<u4'), ('GlobalCount', '<u4'),
('Time(secs)', '<u4'), ('Time(subsecs)', '<u4'),
('LocalCount', '<u4'), ('LocalTotal', '<u4'),
('SpacecraftTime', '<u4')])


def concatenate_hdr(ENTRY):
        f000 = h.File(file[0],'r')
        b000 = f000['data/tlm_sxm_data/hdr'][ENTRY]
        for i in range(1,18):
        # NEED TO CHANGE THIS TO range(1,len(file)) [this currently
        throws an error for 18th or 19th entry in file]
                f_now = h.File(file[i],'r')
                b_now = f_now['data/tlm_sxm_data/hdr'][ENTRY]
                if i == 1:
                        c_now = np.concatenate((b000,b_now),0)
                        current = c_now
                else:
                        c_now = np.concatenate((current,b_now),0)
                        current = c_now
        return current
```

```python
def concatenate_prehdr(ENTRY):
        f000 = h.File(file[0],'r')
        b000 = f000['data/tlm_sxm_data/pre_hdr'][ENTRY]
        for i in range(1,18):
        # NEED TO CHANGE THIS TO range(1,len(file)) [this currently
        throws an error for 18th or 19th entry in file]
                f_now = h.File(file[i],'r')
                b_now = f_now['data/tlm_sxm_data/pre_hdr'][ENTRY]
                if i == 1:
                        c_now = np.concatenate((b000,b_now),0)
                        current = c_now
                else:
                        c_now = np.concatenate((current,b_now),0)
                        current = c_now
        return current
s = concatenate_prehdr('SpacecraftTime')


def binner(data,bins):
        while len(data) > bins:
                #if len(data)%2==0:
                data2 = ([(a+b)/2 for a,b in
                zip(data[::2], data[1::2])])
                data = np.asarray(data2)
        #print(data)
        return data


def create_data_prehdr(width):
        sync_data = concatenate_prehdr('Sync')
        #BINNED_bin_data = binner(sync_data,width) ->
```

```
#binner function doesn't work with binary data

length_data = concatenate_prehdr('Length')
BINNED_length_data = binner(length_data, width)

PacketID_data = concatenate_prehdr('PacketID')
BINNED_PacketID_data = binner(PacketID_data, width)

GlobalCount_data = concatenate_prehdr('GlobalCount')
BINNED_GlobalCount_data = binner(GlobalCount_data, width)

Time_secs_data = concatenate_prehdr('Time(secs)')
BINNED_Time_secs_data = binner(Time_secs_data, width)

Time_subsecs_data = concatenate_prehdr('Time(subsecs)')
BINNED_Time_subsecs_data = binner(Time_subsecs_data, width)

LocalCount_data = concatenate_prehdr('LocalCount')
BINNED_LocalCount_data = binner(LocalCount_data, width)

LocalTotal_data = concatenate_prehdr('LocalTotal')
BINNED_LocalTotal_data = binner(LocalTotal_data, width)

SpacecraftTime_data = concatenate_prehdr('SpacecraftTime')
BINNED_SpacecraftTime_data = binner(SpacecraftTime_data, width)

dtp  = np.dtype([
        #('Sync'              , 'S30'   ),
        ('Length'            , '<u4'   ),
        ('PacketID'          , '<u4'   ),
```

```python
            ('GlobalCount'              , '<u4'   ),
            ('Time(secs)'              , '<u4',) ,
            ('Time(subsecs)'           , '<u4'   ),
            ('LocalCount'          , '<u4'   ),
            ('LocalTotal'              , '<u4') ,
            ('SpacecraftTime',         '<u4')
            ])


    bpdata= np.rec.fromarrays([
            #sync_data, #SHOULD BE BINNED DATA but
            # there's a bug currently (binner function not
            #compatible with binary files)
            BINNED_length_data,
            BINNED_PacketID_data,
            BINNED_GlobalCount_data,
            BINNED_Time_secs_data,
            BINNED_Time_subsecs_data,
            BINNED_LocalCount_data,
            BINNED_LocalTotal_data,
            BINNED_SpacecraftTime_data], dtype= dtp)


    return bpdata


create_data_prehdr(1)


def create_data_hdr(width):
    ''' hard coding this since for now '''
    bin_data = concatenate_hdr('bin')
    BINNED_bin_data = binner(bin_data,width)
```

```
sxm_period_data = concatenate_hdr ( 'sxm_period')
BINNED_sxm_period_data = binner (sxm_period_data, width)


TotalEventsCnt_data = concatenate_hdr ('TotalEventsCnt')
BINNED_TotalEventsCnt_data = binner (TotalEventsCnt_data,
width)


underflowEventCnt_data = concatenate_hdr ('underflowEventCnt')
BINNED_underflowEventCnt_data = binner (underflowEventCnt_data,
width)


overflowEventCnt_data = concatenate_hdr ('overflowEventCnt')
BINNED_overflowEventCnt_data = binner (overflowEventCnt_data,
width)


scTime_subsecs_data = concatenate_hdr ('scTime(subsecs)')
BINNED_scTime_subsecs_data = binner (scTime_subsecs_data,
width)


scTime_secs_data = concatenate_hdr ('scTime(secs)')
BINNED_scTime_secs_data = binner (scTime_secs_data,
width)


scGlobalCount_data = concatenate_hdr ('scGlobalCount')
BINNED_scGlobalCount_data = binner (scGlobalCount_data,
width)


dt  = np.dtype ([
        ('sxm_period'             , '<u2'   ),
        ('TotalEventsCnt'             , '<u2'   ),
```

```python
                   ('underflowEventCnt'            , '<u2'   ),
                   ('overflowEventCnt'             , '<u2'   ),
                   ('bin'            , '<u2',(512,)),
                   ('scTime(subsecs)'          , '<f8'   ),
                   ('scTime(secs)'           , '<f8'   ),
                   ('scGlobalCount'                    , '<f8')
                   ])

        bdata= np.rec.fromarrays([
                BINNED_sxm_period_data,
                BINNED_TotalEventsCnt_data,
                BINNED_underflowEventCnt_data,
                BINNED_overflowEventCnt_data,
                BINNED_bin_data,
                BINNED_scTime_subsecs_data,
                BINNED_scTime_secs_data,
                BINNED_scGlobalCount_data], dtype= dt)

        return bdata


def create_file(width,filename):
        bdata = create_data_hdr(width)
        bpdata = create_data_prehdr(width)
        with h.File(filename, 'w') as f:
                grp = f.create_group("data")
                subgrp = grp.create_group("tlm_sxm_data")
                sub2 = subgrp.create_dataset("hdr",data=bdata)
                sub3=subgrp.create_dataset("pre_hdr",data=bpdata)
                f.close()
        return
```

```
create_file(500,'rebinned_data.h5')
```

B.3 LTSpice Simulation Readout

This code is used to analyze LTSpice simulation data. LTSpice software was updated between the time early LTspice readout code written by Dr. Branden Allen, and the SXM low count rate root cause investigation. The code was updated to take .txt files instead of .raw files, which was the old LTSpice file output.

```python
#!/usr/bin/env python
#-*-encoding=utf-8-*-
'''
A library for loading the output spice simulations

Author: Branden Allen
Date: 2015.06.18
Edited: Andrew Cummings
Date: 2019.01.30
'''
from __future__ import print_function

#Numerical
import numpy as np

#Standard
import struct
import re

################################################################################################
```

```python
def open_spice(filename, dtype='f'):
    with open(filename, 'rb') as f:
        d= f.read()
        div= re.search('Binary:'.encode(), d)
        data= d[div.end()+1:]
        hdr= d[:div.end()+1]


        #Extract the data
    size= [re.search(i.encode(), hdr).span() for i in
    ['No._Points:\s+\d+', 'No._Variables:\s+\d+']]
    nrow, ncol= [int(hdr[i[0]:i[1]].split(':'.encode())[-1])
    for i in size]
    #print(nrow,ncol)
    d= np.reshape(struct.unpack(nrow*ncol*dtype, bytearray(5952)),
    (nrow, ncol)) #[1:]



        #Retrieve the data keys
    start= re.search('\nVariables:', hdr.decode()).end()+1
    end= re.search('\nBinary:', hdr.decode()).start()
    keys= [i.split() for i in hdr[start:end].decode().split('\n')]


        #Generate record array
    d= np.rec.fromrecords(d, names= [i[1] for i in keys])
    return d


# Andrew's Version for txt files
def open_text(filename):
    with open(filename, "r") as readfile:
        x=[]
```

```python
y = []

for line in readfile:
    Type = line.split("\t")
    x.append(Type[0])
    y.append(Type[1])
xlabel = x[0]
ylabel = y[0]
x.pop(0)
y.pop(0)
time = np.array(x, dtype=np.float32)
time = time * 1.e6
value = np.array(y, dtype=np.float32)
print(xlabel, ylabel)
return time, value


################################################################################
```