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The Design and Implementation of the Dynamic Ionosphere Cubesat Experiment (Dice) Science Instruments

Steven Reed Burr
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Abstract

The Design and Implementation of the Dynamic Ionosphere Cubesat Experiment (DICE) Science Instruments

by

Steven R. Burr, Master of Science
Utah State University, 2013

Major Professor: Dr. Charles M. Swenson
Department: Electrical and Computer Engineering

Dynamic Ionosphere Cubesat Experiment (DICE) is a satellite project funded by the National Science Foundation (NSF) to study the ionosphere, more particularly Storm Enhanced Densities (SED) with a payload consisting of plasma diagnostic instrumentation. Three instruments onboard DICE include an Electric Field Probe (EFP), Ion Langmuir Probe (ILP), and Three Axis Magnetometer (TAM). The EFP measures electric fields from $\pm 8\text{V}$ and consists of three channels a DC to 40Hz channel, a Floating Potential Probe (FPP), and an spectrographic channel with four bands from 16Hz to 512Hz. The ILP measures plasma densities from $1 \times 10^4 \text{ cm}^{-3}$ to $2 \times 10^7 \text{ cm}^{-3}$. The TAM measures magnetic field strength with a range $\pm 0.5 \text{ Gauss}$ with a sensitivity of 2nT. To achieve desired mission requirements careful selection of instrument requirements and planning of the instrumentation design to achieve mission success. The analog design of each instrument is described in addition to the digital framework required to sample the science data at a 70Hz rate and prepare the data for the Command and Data Handling (C&DH) system. Calibration results are also presented and show fulfillment of the mission and instrumentation requirements.
Public Abstract

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Dynamic Ionosphere Cubesat Experiment (DICE) is a cubesat satellite project funded by the National Science Foundation (NSF) to study the ionosphere. Cubesats are small satellites in the shape of a cube around 10cm on a side, and allow better access to space. Three main properties of the ionosphere are measured by the DICE mission, which are electric field, magnetic field, and plasma density with an instrument for each. The limitation of power, mass, and volume contributes to the difficulty of cubesat design. Mission and instrumentation requirements must be carefully planned to ensure mission success. Each instrument’s requirements and design are described in detail from an electrical engineering and spacecraft design perspective. In addition, calibration results are provided for each instrument. DICE is an example of advanced satellite development and also pioneered mechanism and instrumentation methods due to the number and complexity of instruments in a small volume.
This thesis is dedicated to my parents, James and Michelle Burr, and also to Andrew C. Christensen whose educational outreach to a student eventually led the student to write this thesis.
Acknowledgments

There were many people who were involved with the DICE satellite project; it was a privilege to work with each one. Special thanks to both Chad Fish and Charles Swenson for tirelessly writing proposals so students can have top tier projects to work on such as DICE, and also for working with a bunch of students. Tim Nielsen helped write portions of the digital section and some of his work is featured there. Keith Bradford also contributed to the Electric Field Boom design and has a thesis featuring the mechanics of the design. Also, thanks to Dr. Swenson and Aroh Barjatya who helped develop many figures for the calibration section. None of this work would be possible without the staff of Space Dynamics Laboratory, especially as they allowed students to have access to their resources and knowledge.

Steven R. Burr
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Chapter 1

Introduction

1.1 Small Satellite Constellation Missions

The most significant advances in space science over the next decade are most likely to derive from new observational techniques. The connection between advances in scientific understanding and technology has historically been demonstrated across many disciplines and time. There are clear ties between advances in our understanding of the processes in the space environment and the deployment of new sensing techniques, from new vantage points, which fuel new discoveries. Newer sensing techniques, such as X-ray and UV-imaging, Global Positioning System (GPS) based measurements, energetic neutral atom imagers, and others, along with the ability to place these sensors above the atmosphere and within regions of interest, have revolutionized space science [1,2]. The study of the Sun and Earth system requires multi-point observations to develop understanding of the coupling between disparate regions: solar-wind, magnetosphere, ionosphere, thermosphere, mesosphere on a planetary scale. Changing environmental conditions in the near-Earth region of space are important to our technological civilization that relies in complex and unexpected ways on satellites and their proper function. The term “Space Weather” is growing in usage to describe the study of changes in the ambient plasma, magnetic fields, radiation, and the thin upper atmosphere that effect the health of satellites. Distributed multi-point measurements are needed to develop understanding of the space weather processes that occur across temporal and spatial scales. The need for this capability can be seen in the conceptual scientific investigations presented in National Aeronautics and Space Administration (NASA) roadmaps for science which call for various sizes of satellite constellations [3]. It is clear that the science and predictive capability of space weather will advance with the development of
satellites constellations that can provide multi-point measurements from within the space environment.

Remote imaging, or cameras, is one source of multi-point measurements of space weather processes. The field of view of the imager is a multi-point set of observations of the scene, but not all parameters of interest can be observed through this technique. Electric field patterns and currents flowing along magnetic field lines, both of which are important quantities for understanding the coupling of regions, cannot be sensed through remote imaging and must be sensed in situ by instrumentation. The global and distributed observations of these quantities require constellations of spacecraft. Even remote imaging data can be improved by multi-point observations from constellations to aid in understanding global phenomena such as atmospheric tides and auroral storms, or to improve the combined observations through advanced signal processing methods such as tomography. The development of satellites which enables both in situ and remote sensing from multiple points within the space environment is a high priority for the advancement of space weather.

The resources that will be available over the next decades for all areas of space weather research have limits, and it is therefore important to find ways to leverage the costs of developing new technologies to advance science. The high-cost of access to space, at first review, is a serious impediment to making multi-point measurements within the space environment or in other words in deploying constellations of traditional satellites. It is therefore desirable to develop much smaller and lower-cost sensor/satellite systems such that the largest number of distributed measurements can be economically made in the space environment. The smaller the mass and volume of the sensor/satellite the larger the number will be that can be deployed from a single launch vehicle. The space engineering community is creating miniaturized sensors and satellite systems by leveraging the enormous investment of commercial, medical, and defense industries in producing highly capable, portable and low-power battery-operated consumer electronics, in-situ composition probes, and novel reconnaissance sensors. The advancement represented by these technologies has direct application in developing small sensor/satellite systems for space weather research.
Within this thesis, we describe the development and testing of a miniaturized set of scientific instruments for space weather research. These instruments have been developed for the Dynamics Ionospheric CubeSat Experiment (DICE) which consists of two 1.5 unit Cube-Sats flying as a small constellation to demonstrate multi-point in-situ measurements of the space environment from a small sensor/satellite system.

1.2 DICE Mission Overview

The “Dynamic Ionosphere CubeSat Experiment” or “DICE” mission was selected and funded by the National Science Foundation in October 2009 in response to a cooperative proposal from Utah State University’s Space Dynamics Laboratory (USU/SDL), ASTRA Inc., and Embry Riddle University. DICE is one of several missions that have been flown or are currently in development under NSF’s CubeSat-based Science Mission for Space Weather and Atmospheric Research program. Launch was provided by NASA through the Educational Launch of Nano-satellites (ELaNa) program. DICE consists of two identical “CubeSats” deployed on October 27, 2011 as secondary payloads from a Delta II rocket. The National Polar-Orbiting Operational Environmental Satellite System Preparatory Project (NPP) was the prime payload of the launch. After NPP was placed into its Sun-synchronous polar orbit the upper stage of the Delta II was restarted and the two DICE spacecraft were released into an 809 to 457km at 102° inclination with one satellite following the other. Both spin stabilized satellites are expected to remain on orbit for about 15 years with the functional life of the spacecraft limited by the number of charge/discharge cycles the batteries can withstand. The scientific purpose of the mission is to study space weather phenomena that occur in the Earth’s ionosphere during geomagnetic storms. The payload of each CubeSat consists of three science instruments, an Ion Langmuir Probe (ILP) to measure in-situ ionospheric plasma densities, an Electric Field Probe (EFP) to measure DC and AC electric fields, and a Three Axis Magnetometer (TAM). Figure 1.1 illustrates the DICE spacecraft configuration and scientific instrumentation location. The two DICE spacecraft are identical in design and function, and conform to a 1.5U CubeSat form factor (10 x 10 x 17cm).
The four EFP wire booms, shown in partial deployment in Figure 1.1, extend 5m outward from the spacecraft including their probes. Centrifugal force due to the spacecraft spin is used to both deploy and hold them in proper orientation. The four shorter booms on the bottom-side of the spacecraft comprise the Ultra-High Frequency (UHF) communications turnstile antenna and are 0.2m in length. The UHF booms also provide balance for the controlled spin of the spacecraft about the axis along the Langmuir probes. The ILP sensor spheres are supported on the top and bottom of the spacecraft by extending scissor booms that extend 8cm away from the spacecraft. The electronics for the EFP, TAM, and ILP are housed in the spacecraft on as single, highly integrated, board. On-board GPS measurements provide daily navigational updates accurate to within 1µs and 10m. The DICE mission is using government radio bands that are consistent with a government funded mission. A new half-duplex UHF modem developed by L-3 Communications for DICE provides a 3 Mbit/s downlink and a 19.2 Kbit/s uplink. Both spacecraft share uplink
and downlink frequencies but have unique logical addresses decoded by the modem. The
ground stations are at Wallops Island on the East coast and at SRI on the West coast
where 18m UHF dish antennas are used to track and communicate with both spacecraft.
The DICE spacecraft can be considered a prototype for a small “space buoy” that would
be deployed in large numbers to observe electric fields, electron density, and magnetic fields
in the Earth’s ionosphere.

1.2.1 DICE Science Objectives

The distribution of plasma in the Earth’s ionosphere is dramatically different during
ggeomagnetic storms times than that found during quiet times. Many storm-time charac-
teristics have only been described recently, including the Storm Enhanced Density (SED)
bulge and plume features. Much of this storm-time morphology has only become apparent
with the recent availability of Two-Dimensional Total Electron Content (TEC) mapping
across the US using GPS receivers. Three-dimensional ionospheric simulations are helping
to reveal the corresponding vertical variation of electron density. An example of an SED
plasma plume occurring over North America during solar storms is shown in Figure 1.2.
Several important research questions are still unanswered. First, how exactly the greatly
enhanced plasma is formed over the southern USA (the SED bulge) and what is the source
of the plasma. Second, exactly what physical drivers are involved in the formation and
evolution of the SED plume, and what is their relative importance. Finally, the precise
relationship between the occurrence of penetration electric fields, the subsequent expan-
sion of the Appleton anomaly crests, and the development of SED is still an open research
question, particularly in terms of why there is an apparent preference for the USA geo-
graphic sector shown in Figure 1.2 [4,5]. Ultimately, the large redistributions of ionospheric
plasma interfere with radio communications and the SED plume causes GPS navigation
blackouts for users over North America. Since modern society has come to rely upon radio
and more increasingly GPS, the ability to understand and predict space weather effects on
these services is of importance.

The DICE mission will provide insight and measurements for further understanding
of the formation, evolution, and decay of SED and their related impact on space weather forecasting. In particular, the mission will provide simultaneous electric field and electron density measurements in the early afternoon sector where SED events seem to form. The DICE mission will focus on local times between about 12-17 LT, complementing the current Defense Meteorological Satellite Program data, and together provide dayside electric field measurements across a broad swath of local times.

The DICE science team developed a set of requirements to achieve the science goals and how those requirements trace down to instrument parameters and the mission concepts. A summary of these requirements and their flow down are presented in Table 1.1 [6]. The sub-requirements that pertain to each set of instrumentation derived from the mission concepts are available in the appendix. The three science objectives for the DICE mission are listed and correspond to questions about the SED bulge and plumes, their formation and motion. Table 1.1 also lists the minimum required measurement parameters of electric fields and density and basic instrument requirements for the investigation including the range and minimum sensitivity level for each science objective as determined by the DICE science team. In general, all of these minimum requirements were exceeded during the design phase of the mission.
Table 1.1: Science and mission functionality requirements traceability matrix.

| Science Objective 1: Investigate formation of the SED bulge over the USA |
| --- | --- | --- |
| **Measure RMS Fluctuations in Electric Field and Plasma Density:** |
| 1. Make co-located DC electric field and plasma density measurements at a ≤ 10 km on-orbit resolution |
| 2. Make AC electric field measurements at a ≤ 10 km on-orbit resolution |
| 3. Make measurements on a constellation platform of ≥ 2 spacecraft that are within 300 km |
| **Electric Field:** |
| 1. Max range of ± 0.6 V/m |
| 2. Min threshold of 0.6 mV/m |
| 3. Min resolution of 0.15 mV/m |
| 4. DC sample rate ≥ 4 Hz |
| 5. AC sample rate ≥ 4 kHz [Telemeter AC FFT power information at ≥ 1 Hz (3 points)] |
| **Plasma (Ion) Density:** |
| 1. Range of 2x10^9-2x10^13 m^-3 |
| 2. Min resolution of 3 x10^8 m^-3 |
| 3. Sample rate ≤ 1 Hz |
| 1. Constellation size ≥ 2 satellites |
| 2. Spacecraft spin ≥ 0.8 Hz |
| 3. Spacecraft spin axis aligned to geodetic axis to within 10° (1σ) |
| 4. Spacecraft spin stabilized to within 1° (1σ) about principal spin axis |
| 5. Spacecraft knowledge to within 1° (1σ) Constellation time synch knowledge ≥ 1s |
| 6. Orbital insertion inclination between 55 - 98° (ideally Sun-synchronous at 12-16LT) |
| 7. Orbital altitude between 350 - 630 km |
| 8. ‘Circular’ orbits (eccentricity of ≥ 0.2) |
| 9. Spacecraft ΔV speed of ≥ 50 km/month |
| 10. Storage/downlink ≤ 31 Mbits/day |
| 11. Lifetime ≥ 6 months |

| Science Objective 2: Investigate formation of the SED plume over the USA |
| --- | --- | --- |
| Same as Science Objective |
| Same as Science Objective |
| Same as Science Objective (downlink included in Objective 1) |

| Science Objective 3: Investigate correlation of PPE with formation and evolution of SED |
| --- | --- | --- |
| Same as Science Objective |
| Same as Science Objective |
| Same as Science Objective (downlink included in Objective 1) |

1.2.2 The DICE Satellite

The configuration of the DICE spacecraft are the result of a number of drivers and requirements including the limited resources of $1.2 M to build, test, launch, and operate two spacecraft. The most important driver was the need to conform to the Poly-Picosatellite Orbital Deployer (P-POD) containerized launch system for secondary payloads [7], which
both restricted the combined volume (10 x 10 x 17 cm) and mass (4 kg) of the mission. The major science driver was the need to deploy the electric field sensors, some 10 meters, from the spacecraft and spin them such that observational errors could be identified and removed from the data. This required a method to store a set of four booms 5 m in length from a compact volume (9.5 x 9.5 x 1.5 cm) which could later be released to their full length. A secondary science objective required the ILP density probes to be placed away from the spacecraft. This required a spring loaded boom or “scissor” booms to accomplish this task. The TAM was designed to be deployed on the scissor booms to reduce magnetic noise but was relocated to the top deck of the spacecraft during final integration. Issues with reliable deployment of the scissor booms made this adjustment to the spacecraft configuration prudent. A memory shape alloy Frangibolt locking mechanism developed by TiNi locks the ILP, EFP, and antennas in place during launch. Keeping design complexity to a minimum was a general rule (although where technical demands warranted this rule was ignored); off-the-shelf components were purchased to facilitate this philosophy. The GPS, L3 Cadet Radio, Clyde Space solar cells, Electronic Power System (EPS), and Pumpkin Command and Data Handling (C&DH) system were purchased. The Attitude Control and Determination System (ACDS), boom deployment system, satellite structure, and science payload were developed in house. The Attitude Determination and Control System (ADCS) system keeps the satellite in a spin stabilized attitude with torque coils based on information received from the Sun-sensor and GPS system. The GPS also synchronizes the spacecraft clocks for time-stamping measurements. A Command and Data Handling is the central means by which the spacecraft functions and means by which it is controlled. The C&DH system ensures that the spacecraft is operating correctly, creates housekeeping data, and organizes and compresses data from the payload. Both the radio and payload can be reset in the event of an upset. Commands from the ground station are received by the L3 cadet radio which sends them to the C&DH system for execution. The radio also stores up data packets that are prepared for downlink by the C&DH system, commands from the ground station start the downlink of data. The EPS provided by Clyde Space can store energy
from the solar cells and generates up to 1.8 Watts of power [8]. The EFP wire booms are released by the Frangibolt along with the antenna booms which are shown in Figure 1.3. Temperature is also recorded in housekeeping data by several temperature sensors located throughout the spacecraft. Primary means of keeping time are done by a Real-Time Clock (RTC) which is located on the science payload Field-Programmable Gate Array (FPGA) and synchronizes time with the GPS. The C&DH system then synchronizes time with the primary real time clock.

The satellite structure was formed from one piece of 7075 aluminum by a wire electro-discharge machining process. Mass was reduced by cutouts in the structure. These cutouts also allowed access to the satellite bus during assembly. Four standoffs separated each board that consists of the satellite bus and are connected to the main structure by spacers. Aluminum plates with cutouts for mechanisms were installed on the top and bottom to form the rest of the structure. The ILP booms and antenna mechanisms are spring-loaded and released by a one-time release bolt. To release the mechanisms a bolt fires which is spring loaded, this causes the EFP spool to unlock and the ILP to unlock. By requirement only non-magnetic materials were allowed to avoid interference with the magnetometer. The satellite initial inertial state was a minor axis spinner of the z-axis. To turn the spacecraft into a major axis spinner around its z-axis, tungsten weights were added to the tips of each antennas and extending them up to 20 cm away from the spacecraft.

1.3 DICE Science Board

The electronics for all three science instrument are housed in the spacecraft on a single Printed Circuit Board (PCB) science board weighing 75 grams with a dimension of 90.2mm x 95.9mm as shown in Figure 1.4. Due to the compact nature of the board and components, a 6-layer PCB design was necessary. The analog and digital sections of the board were physically and electrically separated to reduce Electro-Magnetic Interference (EMI) near the instrumentation. A functional diagram is shown in Figure 1.5. While operating the board consumes <250 mW of electrical power with the majority (100mW) being consumed by the magneto-resistive devices of the TAM. The PCB included the digitization, time stamping,
and data formatting such that packets of data that passed to the on-board computer only needed to be stored in the telemetry buffer without additional processing.

The DICE EFP, ILP, and TAM data provided as products sampled simultaneously at either 35 or 75 of Hz each. Internally, the channels are oversampled at a rate of 17kHz and the EFP data is then subjected to an onboard Fast Fourier Transform (FFT) to produce four AC spectrometer channels up to 512Hz. The EFP (including AC FFT spectra) and ILP data is then co-added and decimated for improved Signal-to-Noise Ratio (SNR).

An Actel ALG600 FPGA was chosen for control of the instrumentation in the place of a microprocessor. This was done to reduce design time through simplification; in addition FP-GAs are well-suited to the measurement co-location requirements of the mission. Communication with the instrumentation is done by a Universal Asynchronous Receiver/Transmitter (UART) running at 56.2 kBaud. Several two byte commands change the three sampling modes (off, on 35Hz, and on 70Hz) and deployment commands. The FPGA also contains the control and electronics for the boom deployment system. The analog instrumentation required ±12V generated switching regulators and a 1.25V and 2.5V reference, which pulled power from a single 5.8V regulator connected to the 7V-8.2V unregulated battery bus. The digital electronics drew power from the EPS regulated 3.3V and 5V power busses and also generated 1.2V locally for the FPGA. The satellite bus contained both UART and power connections through a PC 104 connector. A PC 104 connector and four standoff mounts on the corners mechanically connected spacecraft and science payload.

1.4 Overview of Thesis

The rest of this document is organized in the following manner. The design and functionality of each instrument is then described in detail with a chapter for each in the following order: Chapter 2 details the Ion Langmuir Probe, Chapter 3 with the Electric Field Probe, and Chapter 4 with the Three Axis Magnetometer. Chapter 5 is about data management: the data processing of the FPGA and the formation of data packets sent down to the ground. Chapter 6 includes results on the testing and calibration result for the three instruments.
Fig. 1.3: DICE satellite structure and bus.

Fig. 1.4: DICE science payload.
Fig. 1.5: DICE functional diagram.
Chapter 2

Ion Langmuir Direct Current Probe

2.1 Ion Langmuir Probe Concept

An ILP measures the plasma density of the ionosphere by observing its electrical impedance. A voltage is applied to a probe, the change in the impedance can be used to measure the density and temperature of the ionosphere [9]. Plasma parameters such as electron density $N_e$, ion density $N_i$, and total electron temperature $T_e$ can be derived from the current measured by the probe [10, 11]. USU/SDL has flown many Langmuir probes on various missions in the past. The DICE ILP will need to use less power and volume than previous instrumentation. The density of the atmosphere is required to be measured from a range of $1 \times 10^4 \text{ cm}^{-3}$ to $2 \times 10^7 \text{ cm}^{-3}$ with a resolution of $1000 \text{ cm}^{-3}$ (for a total list of requirements see A.1). The ILP dynamic range has been determined by the science team to be $\pm 50 \mu$A to meet the density measurement which also defines a resolution of $1.525 \text{mA}$. A typical Direct Current Probe fixes the voltage at a single bias point; however, the DICE ILP is required to sweep its voltage from -4V to 2V to make measurements in the electron current region. A Digital-to-Analog Converter (DAC), controlled by the FPGA, allows for sweeping. The ILP probes rest atop two booms on the top and bottom of the spacecraft to prevent interference from the spacecraft’s plasma density wake.

2.2 ILP Mechanical

The DICE ILP mechanical probe design raises the booms above the plasma density wake region, as shown in Figure 2.1. Each probe consists of a 1.27cm in diameter gold plated aluminum probe, the center being located 13cm away from the top of the spacecraft and 21cm away from the center of the spacecraft. Deployable booms were required to stay within
Fig. 2.1: ILP mechanical and sensor map.
the launch envelope during launch. The probe assembly rests atop a delrin scissor boom which is stowed away in the top and bottom spacecraft panels. A locking mechanism holds the booms into place until they are released. Upon release, the ILP booms release, swing out, then spring forward to their final position. A tube built from G10 insulates the probe from the voltage guard and also holds the probe assembly together. Exposed potentials can create a problem with measuring density as it can create additional current into the probe. To mitigate this problem, no exposed potentials were permitted per requirement on the spacecraft structure, and a guard was placed at the base of the probe. A bias potential from the guard shields the plasma from electric fields that may come from potentials on the spacecraft.

2.3 Sweeping Langmuir Probe Instrument Design

The DICE ILP design had to conform to the sensitivity requirement of 1.525nA but also needed to be low-power. Only 40mW of power was allocated per requirement, which restricted component selection to those that were low-power and low-noise. An AD8622 operational amplifier was selected for these reasons; other desirable characteristics are shown in Table 2.1. Instead of using a two operational amplifier design for the difference amplifier, an INA129U instrumentation amplifier was selected to reduce usage of circuit board space. Setting the gain is another advantage because instrumentation amplifiers only require one gain resistor. The INA129 instrumentation amplifier is also a low-noise, high-precision part.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AD8622</th>
<th>INA129</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>-40 to 125</td>
<td>-40 to 125</td>
<td>°C</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>Vcc ±2.25</td>
<td>Vcc ±2.25</td>
<td>V</td>
</tr>
<tr>
<td>Quiescent Current</td>
<td>0.215</td>
<td>0.7</td>
<td>mA</td>
</tr>
<tr>
<td>Temperature Offset Drift</td>
<td>1.2</td>
<td>0.5</td>
<td>uV/°C</td>
</tr>
<tr>
<td>Output</td>
<td>Vcc ±1</td>
<td>Vcc ±1</td>
<td>V</td>
</tr>
<tr>
<td>Short Circuit Current</td>
<td>±40</td>
<td>+6/-15</td>
<td>mA</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>$10^9$</td>
<td></td>
<td>5.5</td>
</tr>
<tr>
<td>GBW</td>
<td>560</td>
<td>700</td>
<td>kHz</td>
</tr>
<tr>
<td>Voltage Noise at Input(1kHz)</td>
<td>11</td>
<td>10</td>
<td>nV/Hz$^{1/2}$</td>
</tr>
<tr>
<td>CMRR</td>
<td>120</td>
<td>100</td>
<td>dB</td>
</tr>
</tbody>
</table>
To understand how the system operates, a discussion on the circuit follows. A transimpedance amplifier measures the input current with a gain of $K_{trans}$ which is equal to 10000V/A. A voltage bias $V_{bias}$ is also applied to the probe through the transimpedance amplifier. The amplifier output equation is (2.1).

$$ (I_{in} \ast K_{trans}) + V_{bias} = V_{trans} \quad (2.1) $$

Biasing the probe and its resultant shift in the signal reduce the dynamic range of the system. To center the signal around 0V, the INA129U subtracts the voltage bias from the transimpedance signal. The INA129U is also used to gain the signal by $K_{diff}$ shown in equation (2.2).

$$ (V_{trans} - V_{bias}) \ast K_{diff} = V_{out-diff} \quad (2.2) $$

Noise is an issue within the system, by requirement the instrument shall limit bandwidth to 40Hz. A low-pass filter located after the instrumentation amplifier accomplishes this task. Lastly, an amplifier stage is used to center the $\pm$2.5V signal by adding an offset of 2.5V. This centers the input of the Analog-to-Digital Converter (ADC) around 2.5V with a range of 0V to 5V. The gain $K_{lpf}$ of the low-pass filter and the amplifier are 1V/V for frequencies below 40Hz. Upon further inspection of the schematics in the appendix, it should be noted that the low-pass filter was implemented improperly. This happened because a resistor was added between the low-pass capacitor and the last amplifier. To correct this mistake the resistors between the instrumentation amplifier and was lowered to a value of 402Ohms, and when added to the filter resistors that make up the low-pass filter is equal to a gain of 1.

### 2.4 Digital-to-Analog Converter for Sweeping Voltage

The DAC was added later to enable the probe to sweep its voltage instead of hold it at a fixed bias of -7V as originally planned. The key to the design was finding a DAC that would add less than 4mW of power to the system. The DAC7621 is a low-power (2.5mW),
12-bit DAC. The main feature is a simple parallel interface, more parameters are shown in Table 2.2. The DAC7621 has a settling time of 7uSec which is about 0.05% of the system sampling rate of 14.3mSec. It also has good accuracy and typically falls to within 50% of the desired voltage value.

With a range of only 0V to 4.096V, the DAC7621 output signal needs further amplification to meet a range of ±7V that is needed to cover any desired sweeping voltage. An AD8622 was used to convert the DAC signal with a 2.8V/V gain and 1.85V offset. A unity gain amplifier buffers the signal to provide the needed current for the other amplifiers and the voltage guard. The DAC system does contribute significant noise to the system mainly in the form white noise as shown in Table 2.3, this noise is gained up by factor of 2.8V/V from the amplifier. There is also noise added from the unity gain amplifier. The noise at the output of the system is 9.74uV-rms. The magnitude of the noise was not calculated until after the system was built.

2.5 Ion Langmuir Probe Sensitivity and Range

Noise limits the sensitivity in electronic systems. The noise level must be less than the desired signal sensitivity of the system. Dynamic range is determined by the most limiting point in the system that restricts the signal range. The ILP system amplifier stage was designed to make the ADC the most limiting factor of the dynamic range. Excluding protection diodes for simplicities sake, the ADC has a range of 5V. The dynamic range of the system is found by taking the ADC range and dividing it by each system gain shown in (2.3).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DAC7621</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling Time</td>
<td>7</td>
<td>uSec</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40 to 85</td>
<td>C°</td>
</tr>
<tr>
<td>Step</td>
<td>1</td>
<td>mV/Count</td>
</tr>
<tr>
<td>Output Current (Code 800h)</td>
<td>±7</td>
<td>mA</td>
</tr>
<tr>
<td>Relative Accuracy</td>
<td>±1/2 (2 Max)</td>
<td>LSB</td>
</tr>
<tr>
<td>Differential Nonlinearity</td>
<td>±1/2 (1 Max)</td>
<td>LSB</td>
</tr>
</tbody>
</table>
Table 2.3: DAC system parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Bandwidth</td>
<td>40</td>
<td>Hz</td>
</tr>
<tr>
<td>DAC White Noise Amplitude</td>
<td>0.55</td>
<td>uA/Hz(^{1/2})</td>
</tr>
<tr>
<td>DAC White Noise Amplitude</td>
<td>550</td>
<td>nV/Hz(^{1/2})</td>
</tr>
<tr>
<td>Total From DAC White Noise</td>
<td>3479</td>
<td>nV-rms</td>
</tr>
<tr>
<td>Gain of AD8622 on after output of DAC</td>
<td>2.8</td>
<td>V/V</td>
</tr>
<tr>
<td>Total Noise from AD8622</td>
<td>78.8</td>
<td>nV-rms</td>
</tr>
<tr>
<td>Gained up noise from DAC</td>
<td>97.39</td>
<td>nV-rms</td>
</tr>
<tr>
<td>Total Noise output from DAC System</td>
<td>9740</td>
<td>nV-rms</td>
</tr>
<tr>
<td>Total Noise output from DAC System</td>
<td>9.74</td>
<td>uV-rms</td>
</tr>
</tbody>
</table>

\[
\left( \frac{\text{ADC Range}}{K_{\text{diff}} \cdot K_{\text{trans}} \cdot K_{\text{lpf}}} \right) = (5V) \left( \frac{1A}{10000V} \right) \left( \frac{1 V}{5 V} \right) \left( \frac{1 V}{1 V} \right) = 100 \, \mu A = \pm 50 \, \mu A \tag{2.3}
\]

The system sensitivity is found by multiplying the inverse of the system gains and the ADC range (which is also the dynamic range) divided by the ADC counts as shown in equation (2.4) and numerically computed in equation (2.5).

\[
\left( \frac{K_{\text{diff}} \cdot K_{\text{trans}} \cdot K_{\text{lpf}}}{\text{ADC Range}} \right) (\text{ADC counts}) = \left( \frac{2^{16} \text{ counts}}{100 \, \mu A} \right) = \frac{655.36 \text{ counts}}{1 \, \mu A} \propto \frac{1.525 \, nA}{1 \, \text{ count}} \tag{2.4}
\]

\[
\left( \frac{2^{16} \text{ counts}}{100 \, \mu A} \right) \frac{655.36 \text{ counts}}{1 \, \mu A} \propto \frac{1.525 \, nA}{1 \, \text{ count}} \tag{2.5}
\]

The total noise of the system was calculated at the input of the probe for comparison with the input signal. The noise was found by taking the noise at the output of each amplifier and dividing it by the amplifier gain to find the equivalent noise at the amplifier input and added by the sum of the squares to the amplifier input referred noise. This process was repeated until the input noise of the last amplifier was found. The system SNR can then be found which is the total dynamic range divided by the total noise at the same point in the system. In the case of the ILP, the noise is a factor of 17 less than the signal assuming no contribution from the DAC system which was added later. A spice noise analysis was ran for the circuit and for the system bandwidth and is shown in Figure 2.2.
Total system performance and calculations can be found in Table 2.4.

The frequency cutoff for the system bandwidth is at 40Hz integrating the spice noise figure from 0.1 to 40Hz yields a value of around 1.56µA for the noise floor level, however, this result also excludes DAC noise. The actual noise for the system should be somewhere in between these two values.

The ILP system is affected by temperature offsets. As per requirement the temperature of any instrument cannot exceed -10°C or 30°C. This results in a temperature differential of 40°C. The temperature error was calculated at the input of the ADC. The error (shown in Table 2.5) is calculated by finding the temperature error for each part and multiplying it by the gain of each successive amplifier until the ADC. All error is collectively summed to get total projected temperature error which is ±308µV at the input of the ADC and is ±0.006% of the signal.

![Fig. 2.2: ILP system noise calculations.](image-url)
Table 2.4: ILP system performance.

<table>
<thead>
<tr>
<th>Total Noise</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal input Range of System</td>
<td>100</td>
<td>uA</td>
</tr>
<tr>
<td>Noise from ADC ADS8343</td>
<td>20</td>
<td>uV-rms</td>
</tr>
<tr>
<td>Noise from ADC ADS8343</td>
<td>20000</td>
<td>nV-rms</td>
</tr>
<tr>
<td>Total Noise from AD8622</td>
<td>78.8</td>
<td>nV-rms</td>
</tr>
<tr>
<td>Total Noise from INA129U</td>
<td>259</td>
<td>nV-rms</td>
</tr>
<tr>
<td>Gain of 3rd amplifier stage AD8622</td>
<td>1</td>
<td>V/V</td>
</tr>
<tr>
<td>Gain from 2nd Amplifier Stage INA129</td>
<td>5</td>
<td>V/V</td>
</tr>
<tr>
<td>Gain of 1st Amplifier Stage AD8622</td>
<td>10000</td>
<td>V/A</td>
</tr>
<tr>
<td>Noise at input 3rd amplifier stage AD8622</td>
<td>20000</td>
<td>nV-rms</td>
</tr>
<tr>
<td>Noise at input 2nd amplifier stage INA129</td>
<td>4008</td>
<td>nV-rms</td>
</tr>
<tr>
<td>Noise at input 1st amplifier stage AD8622</td>
<td>4008</td>
<td>nA-rms</td>
</tr>
<tr>
<td>Noise at input 1st amplifier stage AD8622</td>
<td>5668</td>
<td>nA</td>
</tr>
<tr>
<td>Noise at input 1st amplifier stage AD8622</td>
<td>5.67</td>
<td>uA</td>
</tr>
<tr>
<td>SNR</td>
<td>17.64</td>
<td>Unitless</td>
</tr>
<tr>
<td>SNR</td>
<td>12.46</td>
<td>dB</td>
</tr>
</tbody>
</table>

Table 2.5: ILP temperature error.

<table>
<thead>
<tr>
<th>Temperature Error</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Temperature</td>
<td>30</td>
<td>°C</td>
</tr>
<tr>
<td>Lower Temperature</td>
<td>-10</td>
<td>°C</td>
</tr>
<tr>
<td>Temperature Coeff of AD8622</td>
<td>1.2</td>
<td>uV/°C</td>
</tr>
<tr>
<td>Temperature Coeff INA129</td>
<td>0.5</td>
<td>uV/°C</td>
</tr>
<tr>
<td>Gain of INA129</td>
<td>5</td>
<td>V/V</td>
</tr>
<tr>
<td>Temperature Differential</td>
<td>40.0</td>
<td>°C</td>
</tr>
<tr>
<td>Error of Trans. Amplifier AD8622</td>
<td>48.0</td>
<td>uV</td>
</tr>
<tr>
<td>Error of Trans. Amplifier With Gain</td>
<td>240.0</td>
<td>uV</td>
</tr>
<tr>
<td>Error of INA129</td>
<td>20.00</td>
<td>uV</td>
</tr>
<tr>
<td>Error of LPF Amplifier Stage AD8622</td>
<td>48.0</td>
<td>uV</td>
</tr>
<tr>
<td>Total</td>
<td>±308.0</td>
<td>uV</td>
</tr>
</tbody>
</table>
Chapter 3

Electric Field Probe

3.1 Electric Field Probe Concept

The electric field probe was part of DICE’s primary objective to measure gradients caused by the electric field in the ionosphere. Instrumentation is required to make power spectral measurements across 16Hz to 512Hz for high-frequency or Alternating Current (AC) measurements and 0Hz to 40Hz for low frequency or Direct Current (DC) measurements. The challenge was designing a system within the constraints of the requirements. Only 40mW of power and 16cm$^2$ of circuit board space for the electronics were allocated by requirement.

The DICE electric field concept uses the double probe technique to measure the ambient electric field $\vec{E}$ with a suite of instruments [10]. The Electric Field instrument suite has four separate instruments attached to the two probe sets consisting of two DC channels, a floating potential channel, and an Electric Field Alternating Current (EFAC) channel shown in Figure 3.1. The Electric Field Direct Current (EFDC) channels enable the measurement of the ambient electric field in two dimensions. The Floating Point Potential Channel was not initially proposed but later added to the EV12 channel to measure spacecraft charging potential. The EFAC channel obtains the AC component of the signal with a high-pass filter to measure the power spectral density of the plasma. Each instrument has an analog front end which consists of a precision instrumentation amplifier. The desired frequency range for each instrument is obtained by both passive and active filters, which also mitigate noise. To match the ADC voltage, the signal is gained and the signal level is offset on each channel. The FPGA controls the ADCs and simultaneously samples them. The FPGA then adds headers and sends the data to the C&DH system which process is discussed in
Chapter 5. To compute the power spectral density, the EFAC channel also requires digital signal processing which is also discussed in Section 3.8. The design and performance of the analog instrumentation sections is discussed in the following order: the EFDC channel, Floating Potential Probe (FPP) channel, and the EFAC channel.

3.2 Alternate Configurations

Alternate configurations exist for the Electric Field Instrumentation Set. In the past, two floating point potential probes were used instead of one differencing channel were used. This configuration would have increased the electric field power usage by 33%, and would also have required one additional ADC channel. Another option to save power is to digitally filter the signals, which was not done in this mission because of complexity and lack of FPGA resources. Passive filtering saved power with the exception of the high-pass filter on the EFAC channel, which will be discussed later. It should also be noted that volume was a consideration. Increasing part counts can affect volume since there is a limited amount of PCB space. A simple way to achieve a low-power, low-volume design is to eliminate active circuit elements where possible.

Fig. 3.1: Electric field system functional diagram.
3.3 Electric Field Probe Mechanical

The mechanical layout of the EFP consists of two boom sets with two probes each mechanically perpendicular to each other labeled Electric Field Set 1 consisting of sensors 1 and 2 and Electric Field Set 2 consisting of sensors 3 and 4 as shown in Figure 3.2. The Floating Point Potential Probe also shares sensor 1 and the other input is grounded.

The probes consist of gold-plated spheres with a 1cm diameter that are attached to wires and are initially stowed upon launch on a spool. They are later deployed through centripetal force and after deployment the booms measure 5m from the center of the spacecraft and a 10m tip to tip distance. More information on the boom deployment system can be found in this project thesis [12].

3.4 Guarding and Shielding

The current generated by the plasma on a 1 cm sphere is at most 10pA. Proper shielding and guarding techniques are used to prevent leakage. The 1pA input bias current of the INA116 must be supplied. This can be done in two ways: by placing a voltage guard.
around the wire with approximately the same voltage, and/or by using a very high-insulative material [13]. Shielding the boom wire was impractical because a minimal wire diameter was needed, so an insulative material was chosen. Teflon was used because it has one of the highest resistivity’s of $10^{18}$Ohms·cm. It is also durable and able to withstand the spacetime environment. This was also difficult because a joining connection had to be made on the top of the deckplate. The impedance issue was solved by insulating the solder joint with teflon tubing. Another point for leakage is between the signal input and the science board. The volume resistivity of the material in PCBs varies between $10^6$Ohms and $10^8$Ohms. If the signal is unguarded, most of the current would leak out at this point. The INA116 instrumentation amplifier has guarding pins that near the voltage of the input pins. Because of this leakage, capacitive effects are significantly reduced if proper shielding techniques are used.

3.5 Expected Signal

Because the EFAC and EFDC channels have different input amplitudes across their frequency range, it is necessary to ensure that saturation does not occur. Signal inputs are driven by physical processes which change with atmospheric variability. A model was created by the science team to determine the variability of the atmosphere and signal inputs shown in Figure 3.3. The information for the electric field input model was taken from several sources: data from previous missions, the fact that a spinning spacecraft will generate an electric field, and bounding the noise by modeling it as $1/f$ or pink noise. Spectrometer data from DE2 was used for the low bound case [14]. The VEFI instrument from CNOFS was used for the upper bound case. The spin rate of the satellite can also affect the electric field measurement because of the Lorentz force shown in equation (3.1) [10].

$$\vec{V}_{s/c} \times \vec{B} + E_0 = E_{input}$$ (3.1)

At the magnetic field strength of 0.5 Gauss and a tangential velocity of the probes approximately 30m/s creates an electric field E of about 400mV/m, shown in Figure 3.3.
The ambient electric field contributes 200mV/m. To model the minimum 1/f noise, the VEFI log chart was fitted with a line on its minimum frequencies which corresponds to quiet time values. The maximum of each model was taken on each frequency bin. The EFDC and EFAC channels are overlaid on the graph to show their respective frequency ranges. In this manner, a good model for the input of both the EFDC and EFAC channels was obtained.

3.6 Electric Field Direct Current Channels

The EFDC probe set measures large scale features in the ionosphere's electric fields. The maximum signal input was given by the science team as ±0.8V/m which comes from both the spinning of the spacecraft and the ambient electric fields. For more information on how electric field instruments interact with the plasma see “Design, Test, and Calibration of the Utah State University Floating Potential Probe” [15]. The main preamplifier which

![Amplitude Spectrum and E-field Instrument](image)

Fig. 3.3: Electric field system modeled inputs.
is essentially a voltmeter is the INA116 instrumentation amplifier as shown in Figure 3.4. It outputs the difference of the voltage of the probes which are connected to its inputs provided it has sufficient input bias current. The preamplifier is then followed by two more amplifiers which limit the system bandwidth at 40Hz with a low-pass filter and match the range of the ADC. The low-pass filter also attenuates the signal with a gain of 0.312V/V to bring the ±8V down to a ±2.5V range. The signal is then shifted by +2.5V to match the ADC range of 0V to 5V. The dynamic range calculation is shown in equation (3.2), and is calculated for the input of the instrument.

\[
\left( \frac{\text{ADC Range}}{K_{\text{lpf}}} \right) = (5 \text{V}) \left( \frac{1 \text{ V}}{0.312 \text{ V}} \right) = 16 \text{ V} = \pm8 \text{ V}
\] (3.2)

Lastly, a unity gain buffer isolates the load from the ADS8343 and the circuit. The system sensitivity (equation (3.3)) is found by dividing the dynamic range by the total number of counts.

\[
\left( \frac{\text{Dynamic Range}}{\text{ADC Counts}} \right) = \left( \frac{16 \text{ V}}{2^{16} \text{ counts}} \right) = \frac{244 \text{ uV}}{\text{count}}
\] (3.3)

It is important that the noise in the system is lower than the system sensitivity noise or the ADC will convert the noise to counts, and this will lead to a degradation of system sensitivity by rendering it unobservable. System noise was calculated in a similar manner as the ILP. The noise in Table 3.1 was found at the system input which makes it easier to compare to the system sensitivity. Each count is 5V/65536 which is equal to 76.2uV/bit.

\[
\text{Electric Field Direct Current Channel}
\]

Fig. 3.4: EFDC functional diagram.
the noise is 3764nV so the SNR is 21 or 13dB with additional noise reduction from the coadding.

3.7 Floating Potential Probe

The FPP measures spacecraft charging which occurs when materials are exposed to plasma in the spacetime environment such as the spacecraft body. The FPP measures the potential of the spacecraft ground and body relative to the plasma and the function is shown in Figure 3.5. The FPP is an aid to both the DC probe and the DC channels of the spacecraft. It is identical to the DC channels with the exception that one of its inputs is tied to ground. In this manner, the floating potential is the voltage measured between the spacecraft body and the plasma. Because the instrument is electrically equivalent to the EFDC channel, it has the same system sensitivity, dynamic range, and SNR. This reduces the complexity of the system as a whole.

3.8 Electric Field Alternating Current Channel

The EFAC captures noise or higher frequency information that is associated with waves or smaller scale features in the plasma and computes the spectral power. On previous mis-

<table>
<thead>
<tr>
<th>Table 3.1: EFP system performance.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Noise of EFP</strong></td>
</tr>
<tr>
<td>Signal input Range of System</td>
</tr>
<tr>
<td>System Bandwidth</td>
</tr>
<tr>
<td>Noise from ADC ADS8343</td>
</tr>
<tr>
<td>Noise from ADC ADS8343 Not Filtered</td>
</tr>
<tr>
<td>Total Noise from AD8622 Filtered</td>
</tr>
<tr>
<td>Total Noise from INA116</td>
</tr>
<tr>
<td>Unity Gain Amplifier AD8622</td>
</tr>
<tr>
<td>low-pass Filter Amplifier INA116 Gain</td>
</tr>
<tr>
<td>Effective Noise at input 3rd amplifier stage AD8622</td>
</tr>
<tr>
<td>Effective Noise at input 2nd amplifier stage AD8622</td>
</tr>
<tr>
<td>Effective Noise at input 1st amplifier stage INA116</td>
</tr>
<tr>
<td>Effective Noise at input 1st amplifier stage INA116</td>
</tr>
<tr>
<td>Effective Noise at input 1st amplifier stage INA116</td>
</tr>
<tr>
<td>SNR</td>
</tr>
<tr>
<td>SNR</td>
</tr>
</tbody>
</table>
sions, this has been done with analog instrumentation by separating the signal into several channels with a bandpass filter or by computing an FFT and integrating the frequency information into spectral bins [10]. The EFAC channel uses the same INA116 instrumentation amplifier and booms as the DC EV34 channel. This sharing contributes to power and volume reduction. DICE uses an FFT to compute four power spectral density channels in the frequency range of 16Hz to 512Hz, the digital computation will be discussed in Chapter 5. A high-gain of 100 is necessary for the EFAC channel, a lower frequency signals with such a gain 100 would lead to saturation of the ADC input and must be filtered out.

Spacecraft spinning up to 2Hz creates an artificial sine wave which can be seen as a spike of 400uV/m in Figure 3.6. To filter out the large spin signal, a high-pass filter was used. A butterworth filter was selected because they are known for their flat passband response [16]. It was necessary to try to place the poles as close to 16Hz as possible while maintaining a flat passband across the range of the FFT and having minimal phase shift. The slope of the filter is directly related to the SNR of the AC channel. To filter out the spin component a 60dB/Dec is necessary, a 7-pole butterworth was required. The signal dynamic range is ±50uV which needs a gain of 100 and offset of 2.5V to meet the range of the ADC which is 0 to 5V as shown in Figure 3.7. The signal is then sent to the FPGA where it is separated into different frequencies and summed up into four spectral bins.

Noise is also an issue with the EFAC system if not eliminated the noise is summed into the four frequency bins along with the signal. Because of the difficulty of the noise
calculations, only a spice noise analysis is needed to understand how the noise affects the signal. The noise was calculated at the input of the ADC; additional input referred noise was simulated by using a 4MΩ resistor. The instrument’s frequency range is from 16Hz to 1024Hz. Figure 3.8 shows the noise at the input of the ADC (green line and small amplitude signal). The noise amplitude of the EFAC is roughly 2000uV which is many times over the bit range of the ADC which is 76.2uV/count. The red line (large amplitude signal) shows the noise at the input of the last gain stage and also suggests that the main noise contributor is from the gain stage in the EFAC system.
Fig. 3.8: EFAC spice noise simulation.
Chapter 4

Three Axis Magnetometer

4.1 Magnetometer Concept

Magnetic field measurements are secondary science objectives for the DICE mission. The science magnetometer implemented was an experimental small volume, low-power sensor. The science team felt that there was great value in demonstrating that a magnetometer could be included along with the other instruments. The sensing technique selected was based on the Anisotropic Magneto Resistive (AMR) effect which can be fabricated into extremely small packages. Honeywell has a line of AMR bridging sensors and integrated magnetometers that are small in volume, relatively low-power, and sensitivity down to the nT range. These sensors have been flown on other cube sat missions such as Radio Aurora Explorer [17, 18]. The HMC5363 magnetometer was selected and integrated as the attitude determination magnetometer for DICE. This is a 12-bit magnetometer providing sensitivities down to 700nT. The desire for the DICE science magnetometer was to create a device with 1nT resolution and matching sensitivity. None of the integrated Honeywell devices approached this level of performance with the closest being the HMC2003 which is an analog sensor incorporating the most sensitive magneto resistive sensors, the HMC1001 and HMC1002, into a hybrid module as shown in Table 4.1. The concept was to construct a similar magnetometer using a highly-integrated, precision, 24-bit Analog-to-Digital convert circuit. The entire TAM would be incorporated into the available space on the science board of DICE along with the other instruments. The sensor would be deployed externally on a boom to remove it from the immediate magnetic contamination of the DICE Spacecraft and was connected via cable to the science board. Because the magnetometer was of value for secondary science and as a backup attitude magnetometer a best effort was made to
achieve the highest sensitivity and lowest noise operation. A summary of the M1 science requirement (see Appendix A.1) states that the magnetometer shall return 1nT with a SNR of $\leq 3$ over the $\pm 50,000$ nT range of the Earth’s magnetic field. This requirement formed the basis of which the TAM was designed around.

4.2 Magnetometer Mechanical Layout

The DICE magnetometer needed to be situated as far away from the spacecraft as reasonably possible to reduce noise on the sensor from the spacecraft. The magnetometer was mechanically incorporated into the ILP boom. This, however, created a risk that the boom might not deploy properly. Different options were provided in the event that the mechanical system could not be proven. The DICE magnetometer has two options, one internal on the science board itself and an external option to reduce the effects of electrical noise from other electronic processes such as the EPS board. Jumpers select between the internal and external options. A temperature sensor is adjacent to the magnetometer packages on both options. The internal option shown in Figure 4.1 mounts the HMC1001 and HMC1002 directly to the science board near the middle of the board and occupies approximately 4cm² of space. The internal option was intended mostly for prototyping, and if the measured environment was not too noisy, then it could be used. The external option was to be used in the event that magnetic noise from other processes reduced the sensitivity of the magnetometer. The sensors are mounted on a PCB board which is small in volume being only (1.6 x 1.8 x 0.5cm). There is also an ADS590kf temperature sensor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HMC1001</th>
<th>HMC1002</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axis</td>
<td>One</td>
<td>Two</td>
<td>N/A</td>
</tr>
<tr>
<td>Board Orientation</td>
<td>Perpendicular</td>
<td>Parallel</td>
<td>N/A</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>3.2</td>
<td>3.2</td>
<td>mV/V/Gauss</td>
</tr>
<tr>
<td>Range</td>
<td>$\pm 6$</td>
<td>$\pm 6$</td>
<td>Gauss</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-55 to 150</td>
<td>-55 to 150</td>
<td>$^\circ$C</td>
</tr>
<tr>
<td>Noise Density @ 5V</td>
<td>48</td>
<td>48</td>
<td>nV/Hz</td>
</tr>
<tr>
<td>Temperature Stability</td>
<td>0.3</td>
<td>0.3</td>
<td>$^\circ$C</td>
</tr>
<tr>
<td>Package</td>
<td>20-Pin SOIC</td>
<td>8-Pin SIP</td>
<td>N/A</td>
</tr>
<tr>
<td>Size</td>
<td>13x10x2.6</td>
<td>1.6x11x7</td>
<td>mm</td>
</tr>
</tbody>
</table>
mounted to calibrate out temperature effects on orbit. A delrin enclosure encases the PCB board and the parts to help shield them from the environment. In the end the external option was not placed on the boom due to mechanical concerns with deploying the Langmuir probes and the bulky 24-wire harness that attached to the external magnetometer science board. The magnetometer was then attached to the –Z plate which is situated near the base of the –Z DC Probe boom (shown in Figure 4.2) and located -3.34cm in the X-axial direction, -1.26cm in the Y-axial direction, and -8.14cm in the Z-axial direction from the center in the spacecraft body coordinate system. The spacecraft (black) and magnetometer (blue) coordinate systems are also shown in Figure 4.2.

4.3 Magnetometer Implementation

There are three design issues associated with the magnetometer. Magnetoresistive sensors have sensitivity reduction that decreases with time or exposure to high magnetic fields. The material can cause offsets that can decrease or change the dynamic range of the
instrument which produces measurement error. Lastly, a large potential temperature range from the thermal environment causes bridge voltage offsets.

AMR technology is sensitive to high magnetic fields. Magnetic field domains line up incorrectly and oppose the field when exposed to high magnetic field. To reverse this effect, an S/R strap is provided to realign the domains; a pulse greater than 4V will consistently reset the device to its ground state. Figure 4.3 shows a consistent degauss pulse that requires a 4V pulse [19, 20]. The DICE magnetometer had all of the S/R resistors in series which created a problem because the voltage was divided across each 1.5Ohm resistor. A 12V signal was needed to generate the required 4V per resistor and 3A per circuit and requires a retooling of the degauss circuit on the board. A better approach would be to put the S/R resistors in parallel since it was a challenge to generate a 12V pulse for 20uSec with the series resistors. The large amount of current also necessitates proper cabling to ensure
a low-resistance pathway. The S/R pulse is activated by a command that can be sent from the ground station to reset the magnetometer on orbit.

Offsets are a common problem with AMR sensors. Manufacturing processes cause resistor mismatches which lead to a constant voltage imbalance [19]. This can lead to an offset up to 15mV as shown in Figure 4.4.

The DICE magnetic sensor has an output of ±8mV, with an offset up to 15mV; it could offset the dynamic range by almost half of its value. This would also cause an offset in the range of magnetic sensitivity resulting in mostly the positive or negative side of the values to be detected or railing of the signal. There are two methods used to correct offset problems, offset straps and external parallel resistors. The offset straps are resistors that create a magnetic field but also require 2mW of power. A lower-power option is using resistors in parallel with the larger resistor value of the bridge to match them. For example: if the bridge resistors are 800Ohms and 810Ohms, this will cause an offset of 12mV. If a 65KOhm resistor is placed in parallel with the 810Ohm resistor, it will reduce the offset in the micro-Volt range and use 0.15mW of power. DICE had the option to use the parallel resistor method. Due to project time constraints, this method was not used, instead the

Fig. 4.3: Set/reset voltage for AMR bridge.
dynamic range was increased by a factor of 3.8 to mitigate the offset problem at a cost of sensitivity.

Another challenge associated with AMR bridges is changes in resistance caused by temperature. This is caused by resistance changes in the material of the bridges and can vary from device to device. The HMC1001 and HMC1002 have a change in resistance of 0.25%/°C. Temperature changes also cause bridge voltage offsets to vary by ±0.05%/°C. Temperature effects can be removed from the final measurement if the devices are calibrated across a temperature range and if the operating temperature is known by sensing it. The temperature sensor chosen for DICE had to be able to monitor temperature both on the science board itself and the external magnetometer module. The AD590 temperature sensor used for temperature compensation offers electrical and mechanical advantages as well as a temperature range of -55°C to 150°C. The AD590 has a linear current output of 1uA/°K and does not require amplifiers or support circuitry while maintaining a ±0.3°C linearity across its temperature range. The AD590 also has three different package options which made it ideal for the internal and external options of the magnetometer. The standard
TO-52, or can-package, was used on the science board itself while the two-lead CQFP was small and flat enough to be used for the external magnetometer module.

4.4 Electrical Design of Magnetometer

The electrical design of the magnetometer needed to be low-power and meet the requirement of 1nT sensitivity. To meet the requirement of 1nT with a range of \( \pm 50,000 \) nT an ADC with at least 18-bits was needed. To make a better measurement an ADC with greater precision was desired. An ADS1248 was selected because it was a low-power, precision, low-noise, and 24-bit ADC. It was also built specifically to differentially measure wheatstone bridges such as the one found in the magnetometer. The ADS1248 is a Delta-Sigma ADC and also has other features including a digital filtering and Programmable Gain Amplifier (PGA). The digital filtering is dependent upon the sampling rate of the ADC and usually has a -3dB cutoff at half the sampling rate. The PGA operates in powers of two from 1 up to 128. Another analog option was provided in the circuit to differentially measure the bridge with the use of an instrumentation amplifier so the gain could be adjusted linearly instead of powers of 2. The INA129 is low-noise precision instrumentation amplifier that was selected for this option and also because of its dual use in the ILP design. Jumpers were also provided to select between the selectable gain of the instrumentation amplifier option or between using the PGA gain and a differential measurement in the ADC. The expected magnetic field signal input range supplied by the science team is \( \pm 50,000 \) nT which is the planned dynamic range of the instrument. The AMR wheatstone bridge, shown in Figure 4.5, is simplified by viewing its differential output \( V_{\text{bridge}} \), which is equal to the positive input terminal subtracted by the negative input terminal. The bridge has a sensitivity of \( 16 \) mV/\( 10^5 \) nT. When multiplying this by the signal input of \( \pm 50,000 \) nT, the bridge differential output is \( \pm 8 \) mV. Measuring the bridge differential voltage is done by subtraction by the instrumentation amplifier which also gains the signal by 20.5 for an output value of \( \pm 164 \) mV. Shifting by an offset of 2.5V gives a value of \( \pm 164 \) mV+2.5V at the output of the instrumentation amplifier. The signal is then digitized by the ADS1248 which also has the ability to gain, offset, and digitally filter the signal. By setting the gain to 4 with no
offset, the dynamic range of the ADC to narrows to ±625mV. The signal is not truncated by the ADC to a 24-bit and until the offset and gain are implemented. The ADC also has a +2.5V reference which centers the digital range around that voltage giving an effective range of ±625mV (1.250V total) and $2^{24}$-bits. A 6-bit truncation is then necessary, and the resultant count range of the system is $2^{18}$. An oversight (or lack of attention) to the system filtering resulted an incorrect system bandwidth. It was later realized the ADC filtering was fixed to its sampling rate, and the sampling rate had to equal that of 3 times 70Hz to sample all three channels. The next highest sampling rate is 320Hz, which also had an undesirable digital filter with -3dB cutoff point at 152Hz.

### 4.5 Magnetometer Sensitivity and Dynamic Range

Noise limits the sensitivity in electronic systems. The noise level must be less than the desired signal sensitivity. The magnetometer system was required to have a sensitivity of 1.5nT. The circuit needed the appropriate gains and filtering to reduce system level noise and also to maintain the signal at the input voltage range of the ADC. The greatest determining parameter of gain the system sensitivity is the AMR bridge sensitivity. The bridge sensitivity is dependent on voltage which increases power demands. The bridge has a sensitivity of 3.2mV/V/Gauss. To find the sensitivity, the bridge voltage can be multiplied by the bridge sensitivity to get the system sensitivity in equation (4.1).

**Magnetometer**

![Magnetometer functional diagram](image)

Fig. 4.5: Magnetometer functional diagram.
\[
\text{Bridge Voltage} \times \text{Bridge Sensitivity} = (5 \text{ V}) \times \left( \frac{3.2 \text{ mV/V}}{1 \text{ Gauss}} \right) = \frac{16 \text{ mV}}{1 \text{ Gauss}} = \frac{16 \text{ mV}}{10^5 \text{ nT}} \tag{4.1}
\]

Power is saved at the cost of sensitivity; a lower bridge voltage will yield a lower bridge sensitivity. The total system sensitivity was found at the input of the bridge. To achieve a 1nT sensitivity, the system noise at the bridge input needed to be less than 160nV. To find the total system sensitivity equation, the bridge sensitivity was multiplied by the inverse of the gains and the ADC voltage and counts shown in equation (4.2).

\[
\left( \frac{10^5 \text{ nT}}{0.016 \text{ V}} \right) \times \left( \frac{1 \text{ V}}{20.5 \text{ V}} \right) \times \left( \frac{1.250 \text{ V}}{218 \text{ counts}} \right) = \frac{1.454 \text{ nT}}{1 \text{ count}} \tag{4.2}
\]

The total system noise was also calculated at the bridge output. Three devices are the main noise contributors in the magnetometer, the resistive bridge, the INA129, and the ADS1248. Both the INA129 and the resistive bridge have 1/f noise as well as white noise. Both noise sources need to be modeled accurately for the total system noise; nV can make a difference in the SNR final calculation. A method to easily find the contribution from 1/f noise from a chart is to find the amplitude at the 1Hz crossing mark \( V_{1Hz \text{ Amplitude}} \), then find the corner frequency \( F_{\text{Corner}} \), and the desired frequency of the lower limit of integration \( F_{\text{Int-Limit}} \). The result can be computed in equation (4.3).

\[
V_{\frac{1}{f}} (\text{rms}) = (V_{1Hz \text{ Amplitude}}) \sqrt{\log \left( \frac{F_{\text{Corner}}}{F_{\text{Int-Limit}}} \right)} \tag{4.3}
\]

Effects from the filter were ignored since both corner frequencies were well below the filter cutoff of 150Hz which in this case is the system bandwidth. The white noise source contribution is found by finding the white noise amplitude (measured in Root-Mean Squared (RMS) volts) in equation (4.4).

\[
V_{\text{whitenoise}}(\text{RMS}) = (V_{\text{noiseamplitude}}) \times \text{SQRT}(\text{SystemBandwidth}) \tag{4.4}
\]
The last noise source in the system is the ADS1248, which is also a Gaussian white noise source as shown by the distribution. However, the datasheet only lists the total noise in Volts-rms at the output. The PGA gains are set at four while the noise at the input of the ADC1248 is a factor of four less. The total system SNR is found at the output of the bridge; this makes accounting the total gain and dynamic range less difficult. For example: the INA129, with a gain of 20.5, multiplies the noise from the output of the bridge by 20.5. Similarly, the equivalent noise contribution from the ADC can be found at the input of the bridge by dividing it by the INA129’s gain of 20.5. To find the total system noise, the contribution of each of the Gaussian sources from the bridge, INA129, and ADS1248, is divided by 20.5 plus the 1/f noise sources. The SNR is calculated at the sensor. The smallest signal is 160nV and the noise spectral power summed is 209nV; dividing the signal by the noise yields a SNR of 0.762 or slightly over 1nT for the system sensitivity. A excel chart listing these parameters and other system parameters is found in Table 4.6.

![Magnetometer System Parameters](image)

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Fig. 4.6: TAM system parameters.
Chapter 5
Payload Digital System

5.1 Data Subsystem Overview

The data collection system consists of all the hardware that processes data including the payload Data Acquisition Subsystem (DAS), C&DH system, the radio, and ground station as shown in Figure 5.1. The DAS collects the data, processes the data, and returns the data to the ground. The DICE payload digital subsystem needed to be low-power but also allow for the control of the payload board and the ability to process and return data to the C&DH system. The data can then be processed and stored in the radio which sends the data via downlink to the ground station. First, the data is sampled by the ADCs which are controlled by the FPGA through multiple serial data links. The data is then time-stamped by the FPGAs RTC. The RTC is a precision clock synchronized with GPS time, to achieve time accuracy close to the GPS time system. Each instruments’ data is separated into a “granule” of data. The granules are collected in a First-In-First-Out (FIFO) buffer which continually sends packets to the C&DH system when possible. Processing of the granules is done by the C&DH system which rearranges and condenses the data into radio packets and sends them to a queue in the radio. When the ground station contacts the satellite, the data is down-linked and copied to a database that stores Level 0 (or raw, uncorrected) data.

Additional tasks are also carried out by the DICE digital subsystem, such as the ability to control the sweeping voltage for the ILP with a DAC. The digital subsystem also had the option of being augmented by a Digital Signal Processor (DSP). At design time the method to compute the FFT was unknown, and three options were provided. Other tasks of the digital subsystem will not be discussed, such as the control of the electric field
boom deployment subsystem. Power modes of the instrumentation are also controlled via command and can switch the instrumentation on and off but the system will not be discussed here.

5.2 Digital Requirements

A summary of the most important requirements that relate to the data collection system are listed here. Without meeting these requirements, the data collection system fails to produce results that are acceptable to the mission. The requirements fall into two different categories: sampling requirements and the separation of the digital and analog subsections.

Electro-Magnetic Interference (EMI) is most prevalent in digital systems to prevent this noise from affecting the analog instrumentation. The boards were separated into different sections for each. To meet requirement SI4 and also to mitigate noise power, planes, and ground planes were separated into respective digital or analog areas. Digital lines were not allowed to be routed through analog areas.

The DAS was required to be able to reliably sample data and time-stamp data. The sampling rate was determined by the science team. Requirement SI2 states, “The maximum sampling rate for any science data channel shall be 100Hz.” Requirement S1 further states,
“Measure RMS Fluctuations in Electric Field and Plasma Density: S1. Make co-located DC electric field and plasma density measurements at a 10km on-orbit resolution.” The science team also determined that the sampling rate should be more than 0.7Hz to meet spatial sampling requirements. The telemetry budget was not limited by rates up to 70Hz and a higher telemetry rate was chosen. Another lower rate of 35Hz was added in the case that 70Hz consumed too much power or telemetry resources. Requirement SI2 stated that the “maximum sampling for any channel needed to be 100Hz.” This meant a 10ms time stamping requirement. However, because the RTC resolution was 1ms, the requirement was exceeded by a factor of 10. Time-stamping is discussed in Section 5.3.8 of this document. Requirement E15 states that the “EFAC spectrometer shall have at least three points of frequency data from 16Hz to 512Hz.” Another channel was added to be consistent with previous missions [21]. The FFT method was chosen to compute the spectral power.

5.3 Payload Controller and Data Acquisition Subsystem

The several goals of the DAS are: data must be sampled reliably, a method to accept commands from the C&DH subsystem must be provided, and the subsystem must control all functions of the science board. The payload digital system consists of all of the digital hardware on the science board including the FPGA, ADCs, and DAC. These are discussed in depth in their respective sections.

5.3.1 Field-Programmable Gate Array

The design of the DAS needed a low-power controller to poll the ADCs and control the payload systems. The ability to do things simultaneously is an advantage of an FPGA over a microprocessor. The linear nature of microprocessors necessitates the need for much software design. To ensure the device met real-time constraints at design time, an FPGA was chosen over this option. An Actel Igloo FPGA series was selected for a controller for properties of low-power, precise control, and previous use in cubesat designs at SDL. This limited risk and shortened design time by having a previously implemented hardware design and VHDL code reuse. Actel FPGAs have advantages and disadvantages. One advantage
is that they are very low power operating in the tens of mW range and have a low operating voltage of 1.2V. They require no boot up time and are ready the instant power is applied (or a few ns later). Actel Igloo FPGAs are disadvantaged by the fact that they have no built in DSP hardware such as adders or multipliers, functions have to be implemented on a gate level and take more FPGA resources. Because of this, less digital filtering can be utilized by design. Multipliers and other complex digital circuitry have to be avoided. Actel FPGAs also have memory resources as shown in Table 5.1. An AGL600k gate part was selected initially with the option of moving to a 1000k gate part since both parts were pin compatible. Each of these devices are available in a 256 Pin BGA. Both Parts also have a small footprint of 1.7cm by 1.7cm and have 177 in/out pins. These pins can operate at a standard digital switching voltage of 3.3V or lower voltages.

5.3.2 FPGA Firmware

The FPGA firmware has many different functions as shown in Figure 5.2. The system has to be able to receive and respond to commands from the C&DH. The FPGA also interfaces with external devices. Firmware design is broken down into these separate tasks. The C&DH UART interface turns incoming serial data into parallel data to the Payload Controller which then decodes the data and sends out appropriate commands to other functions in the system. A timekeeper has a free-running clock that counts milliseconds from the FPGA 12mHz system clock. Time is synchronized from the GPS by a register which can be updated from an external source. For time-stamping, the GPS time is also received by the DAS. Sampling and processing is done solely by the DAS which is the interface to the ADCs. Data is sent to the C&DH system through a UART. The DAS is discussed in depth in Section 5.1 of this chapter. The DAS can also relay other important

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AGL600</th>
<th>AGL1000</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Gates</td>
<td>600k</td>
<td>1000k</td>
<td>gates</td>
</tr>
<tr>
<td>RAM</td>
<td>108k</td>
<td>144k</td>
<td>bits</td>
</tr>
<tr>
<td>Flash-ROM</td>
<td>1024</td>
<td>1024</td>
<td>bits</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>1.2, 1.5</td>
<td>1.2, 1.5</td>
<td>V</td>
</tr>
</tbody>
</table>
information to the C&DH system from the deployment controller such as motor and encoder data recorded by the boom deployment system. Lastly, there are some auxiliary circuits such as the degauss pulse for the TAM instrumentation and the ability to switch the analog power from the instrumentation on and off to conserve power in the event of a low battery event. These two systems will not be discussed in this thesis.

5.3.3 Payload Controller Commands

The commands received through the UART are processed by the Payload Controller. Most missions support many different telemetry modes, or the rate in which data is collected. In the case of DICE, a simplistic approach was used with only four planned modes in the

![Diagram](image-url)

**Fig. 5.2: FPGA firmware.**
beginning. These commands, as shown in Figure 5.3, originally were to update the time and set the DAS sampling frequency. The DAS frequency command also controls the analog power. Power is enabled by sending a 35Hz or 70Hz command. The complexity of the commands grew as commands were added later as needed such as the ability to control the motor and encoder power, control the motor position, degauss the magnetometer, and set the sweep mode for and ILP sweeping voltage. All commands are one byte sent with Most Significant Bit (MSB) first; two commands have additional bits. The 0x41 and 0x54 commands have two additional bytes and one additional byte, respectively, that are sent after the command to set registers for their particular function.

5.3.4 Analog-to-Digital Converters

The ADC selection process was important because the quantization error can be the main factor in determining system performance. The ADCs need to meet the resolution requirement, but minimize use of system resources, especially power. The ADC selection process is difficult due to the amount of parameters involved including: number of bits,
sample speed, sampling scheme, power, number of channels, and digital interface. The instrumentation required different sampling rates, the EFDC, ILP, and Magnetometer needed a low rate of 70Hz, but the EFAC needed a rate over 1024Hz. A method to sample multiple ADC channels while making a lower rate conversion is to oversample and interleave. The magnetometer, however, also needed 18-bit precision. Measurements made by the ILP, EFDC, and EFAC channels are 16-bit. There are two main types of low-power ADCs to choose from—both have advantages and disadvantages. The two main types of ADCs are: Successive Approximation Register (SAR) and Delta-Sigma converters. SAR converters typically have higher-power, respectively, but have a higher sampling rate. Delta-Sigma converters tend to filter out high frequencies and take longer to convert, but have better accuracy and have built-in noise reduction. Oversampling and interleaving also saves power by reducing the number of ADCs that are used by combining channels into the same ADC. This method works best on SAR ADCs because of their fast conversion times. A Texas Instruments ADS8343 16-bit ADC was selected for low-power properties because it was a SAR. The ADS8343 can sample at 100kHz which is well beyond the highest needed 1024Hz sampling rate of the system. These ADS8343 properties helped fulfill requirements of the EFP and ILP instruments. A differential reference scheme is used, meaning that the output in counts is in a two’s complement binary format. The reference was set 2.5V to center the ADCs zero-point around the midpoint ADCs counting system and to match the full scale of the 5V analog signal. For the magnetometer, the ADS1248 Delta-Sigma ADC was used, because it supported the required 18-bit precision of the TAM instrument. Sampling of this ADC has a 2kHz limit. The multiplexer on the front end can be configured as two differential pair inputs or seven single-ended inputs. The TAM ADC also has a reference of 2.5V and a 5V input with a 24-bit also in a two’s complement binary format; however, the values are later truncated to 18-bits.

5.3.5 Sampling Methods

The sampling methods for the DAS are different depending on the sampling scheme and the ADC. The interleaved sample conversion allows for simultaneous spatial sampling
in a 70Hz window by the instrumentation. Differences in the timing and the amount of co-adding vary by instrument. The ADS8343 both make many 256 conversions and then sleep for a time to save on power. Interleaving is still preformed by the ADS1248 channels, but the limited sampling rate prohibits co-adding. The conversion system, shown in Figure 5.4, is driven by a 70Hz clock which marks the start of each sample. Each instrumentation channel is sampled at different rates, but aligns on the same 70Hz boundary. Channels that consist of the ILP Z+, ILP Z-, and FPP form a set from the same ADS8343 ADC, which also performs conversions of these channels in that order. Each instrumentation channel is oversampled and co-added 256 times to reduce noise. Once 256 conversions have taken place on all three channels, a sample is completed, and the ADC enters a sleep mode until the next 70Hz clock. The electric field ADS8343 consists of the EF12, EF34, and EFAC channels. Sampling of the first two channels is done in the same manner as the ILP channels with 256 conversions per sample; however, the EFAC co-adds every eight conversions to increase its sampling frequency. The electric field sample has a slower conversion interval which is 14.5us for the ILP versus 18us per conversion of the electric field. Three magnetometer channels from the ADS1248 ADC rely on a completely different scheme because of the nature of Delta-Sigma ADCs. The samples start on the same 70Hz boundary as the other channels. Because samples cannot be interleaved, they are preformed sequentially on each axis in this order X, Y, and then Z. Sampling by the ADS1248 ADC which takes 3.125ms at 320Hz to complete. This TAM sample set takes 9.375ms to complete. The ADC then sleeps until another 70Hz clock is detected. Each 70Hz measurement from the EFDC, ILP, FPP, and Magnetometer are grouped into granules, and the values are stored as explained in the Data Flow Down (Section 5.4).

5.3.6 EFAC Spectrometer FFT

At design time, it was not known how the FFT would be computed; different options were designed into the hardware for testing purposes. Initially, the prototype had three options which were available for the FFT: two digital co-processors and a firmware FFT. The micro floating point unit (uM-FPU) by Micromega is a floating point emulated mi-
A coprocessor that was also used on the ACDS board of the satellite for processing floating point values and also floating point other mathematical functions. The um-FPU could only compute a 64-point FFT and consumed 30mW (60mW at 5V) by power but was included because of knowledge of its functionality. The second co-processor was a C5000 series chip built by Texas Instruments which had a built in hardware capable of performing a 1024-point FFT. The C5500 had a low-power usage 30mW and even lower if duty cycled, but was expensive in time and complexity due to needed software and hardware development. A firmware FFT from opencores.org, comprised the last option, but was not available at design time. Later in the project, it was available for use and was chosen as the final method to compute the FFT. Utilization of the FPGA by the firmware FFT is approximately 30-

Fig. 5.4: DAS sampling scheme.
40% of the total gates, and the larger 1000k gate device was needed to accommodate the firmware. Values from the EFAC channel are oversampled at 17920Hz by the firmware from the ADS8343. The data is then co-added by a factor of eight, each sample is loaded into a FIFO as shown in Figure 5.5. Once 1024 values are stored, the FFT computes and returns the data one sample out at a time which equates to 1Hz amplitude of information. As each sample is computed, it is summed together in each of the frequency bins shown in Table

![Fig. 5.5: DAS functional data plot.](image-url)
5.2. Each of the four values then form a granule and are released to the C&DH system at 1Hz.

5.3.7 ILP Sweep Mode

The ILP is required to sweep its voltage; this voltage sweep occurs from -4V to 2V every 120 seconds and is digitally controlled with a DAC and interrupts the normal mode 0 sampling scheme of the ILP and FPP instruments. The main difference between mode 1 and mode 0 is co-adding is the reduction from 256 to 32 times per sample. A reduction of timing from 3.712ms to 464us per sample enables the sweep to complete faster. Both ILP channels and the FPP channel are interleaved to produce a sample every 1.5ms. The DAC also changes voltage at the beginning of each sweep step. Starting at -4V, the DAC increments 11.2mV per step the sweep mode samples until 512 samples of each channel have been completed; the DAC also completes 512 steps during this time. Figure 5.6 illustrates the digital timing of the sweep.

5.3.8 Sample Timing

Additional clock information is included for further understanding of the DAS sampling. The section describes how timing calculations for the DAS are and results are shown in Table 5.3. Each ADC has a 2MHz or 500ns Clock. The time taken to complete one conversion is listed as clock per conversion. The conversion time is determined by the base clock multiplied by the clocks per conversion. The sample time is the time taken to complete 1 sample. However, for a set this is multiplied by the number of instruments in the set, which is 3, for each interleaved channel set. The DAS has clocks that determine the start

<table>
<thead>
<tr>
<th>Table 5.2: EFAC spectrometer channels frequency bins.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrometer Channels</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>EFDC</td>
</tr>
<tr>
<td>Ch-1</td>
</tr>
<tr>
<td>Ch-2</td>
</tr>
<tr>
<td>Ch-3</td>
</tr>
<tr>
<td>Ch-4</td>
</tr>
</tbody>
</table>
of each conversion and start the sampling until the appropriate time. After this period of sampling the ADCs are put in low-power sleep mode. This waiting period allows slightly different co-adding schemes. The ADC sleep time is defined numerically as the difference between the clock time and sample time. The EFAC contributes to the FFT timing and is a singular instrument that is not part of a set, taken 1024 measurements which happen every 1Hz. The ILP sweep has the same conversion time but co-adds 32 times instead of 256; this decreases the timing by 1.39ms and has a 1.5ms or 667Hz clock until to completion. 512 measurements of the ILP Z+, ILP Z-, and FPP channels which takes 768ms. Table 5.3 shows the coadding and differences between the channels.

5.4 Data Flow Down

5.4.1 Real-Time Clock

Clock accuracy and the ability to associate instrumentation data with time is essential for the science measurements. The time-stamp enables the ability to associate the data in a spatial frame and cross referencing it with data from other missions. An incorrect time-stamp can affect analysis as it is used for spatial reference; therefore, it is important that the clock be as accurate as possible. A method was needed to sync the spacecraft clock with another clock and time-stamp the data with 1ms resolution as shown in Figure 5.7. The GPS system has a clock that can offer resolutions down to 1ns depending on the receiver and the GPS signal. Once the GPS clock is synchronized with GPS time, DICE has a GPS
system that is used for attitude and time keeping purposes. The GPS receiver sends out a
digital pulse called the Pulse Per Second (PPS) signal. After the signal is sent, the GPS
system updates the GPS week and millisecond registers in the C&DH system. The C&DH
updates a pre-clock register in the timekeeper module of the FPGA with the value of the
next PPS time. Upon the detection of the PPS, the register synchronizes its time with the
GPS and is the master clock for the satellite due to the poor accuracy of the C&DH’s clock.
All DICE data is time-stamped from the FPGA clock at the beginning of a sample.

5.4.2 Data Packets and Granules

The data is grouped by sampling rate before it is sent down to the ground. By pack-
etizing the data, it enables a scheme by which the data can be managed and processed
through the satellite systems as it flows through several before it reaches the ground sta-
tion. Granules are groups of data, the three types are: science, sweep, and EFAC granules
as shown in Figure 5.8. Each granule has a 1-byte header to delineate the granule type
to the C&DH system. The header is then followed by a 4-byte time-stamp, and is time-
stamped with the current time from the FPGA RTC with a time resolution of 1ms at the
moment the sampling started. Science granules are sent at a rate of 70Hz or 35Hz. In the

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Base Clock</th>
<th>Clock Per Conv.</th>
<th>Conv. Time</th>
<th>Co-adds</th>
<th>Sample Time</th>
<th>Clock Time</th>
<th>ADC Sleep Time</th>
<th>Meas. Num.</th>
<th>Meas. Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFDC ch. 1</td>
<td>500ns</td>
<td>36</td>
<td>18us</td>
<td>256</td>
<td>4.6ms (13.8ms)</td>
<td>14.28ms</td>
<td>461us</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>EFDC ch. 2</td>
<td>500ns</td>
<td>36</td>
<td>18us</td>
<td>256</td>
<td>4.6ms (13.8ms)</td>
<td>14.28ms</td>
<td>461us</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>ILP Z-</td>
<td>500ns</td>
<td>29</td>
<td>14.5us</td>
<td>256</td>
<td>3.7ms (11.1ms)</td>
<td>14.28ms</td>
<td>3.15ms</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>ILP Z+</td>
<td>500ns</td>
<td>29</td>
<td>14.5us</td>
<td>256</td>
<td>3.7ms (11.1ms)</td>
<td>14.28ms</td>
<td>3.15ms</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>FPP</td>
<td>500ns</td>
<td>29</td>
<td>14.5us</td>
<td>256</td>
<td>3.7ms (11.1ms)</td>
<td>14.28ms</td>
<td>3.15ms</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>EFAC</td>
<td>500ns</td>
<td>36</td>
<td>18us</td>
<td>8</td>
<td>4.6ms</td>
<td>N/A</td>
<td>461us</td>
<td>1024</td>
<td>N/A</td>
</tr>
<tr>
<td>ILP Z+ Sweep (Mode 1)</td>
<td>500ns</td>
<td>29</td>
<td>14.5us</td>
<td>32</td>
<td>0.464 (1.39ms)</td>
<td>0.5ms</td>
<td>108us</td>
<td>512 (1536)</td>
<td>256ms (768ms)</td>
</tr>
<tr>
<td>ILP Z- Sweep (Mode 1)</td>
<td>500ns</td>
<td>29</td>
<td>14.5us</td>
<td>32</td>
<td>0.464 (1.39ms)</td>
<td>0.5ms</td>
<td>108us</td>
<td>512 (1536)</td>
<td>256ms (768ms)</td>
</tr>
<tr>
<td>FPP (Mode 1)</td>
<td>500ns</td>
<td>29</td>
<td>14.5us</td>
<td>32</td>
<td>0.464 (1.39ms)</td>
<td>0.5ms</td>
<td>108us</td>
<td>512 (1536)</td>
<td>256ms (768ms)</td>
</tr>
<tr>
<td>TAM X Axis</td>
<td>3.12ms</td>
<td>1</td>
<td>3.12ms</td>
<td>0</td>
<td>3.12ms (9.37ms)</td>
<td>14.28ms</td>
<td>4.91ms</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>TAM Y Axis</td>
<td>3.12ms</td>
<td>1</td>
<td>3.12ms</td>
<td>0</td>
<td>3.12ms (9.37ms)</td>
<td>14.28ms</td>
<td>4.91ms</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>TAM Z Axis</td>
<td>3.12ms</td>
<td>1</td>
<td>3.12ms</td>
<td>0</td>
<td>3.12ms (9.37ms)</td>
<td>14.28ms</td>
<td>4.91ms</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
event that the 35Hz mode is selected, the data is still collected but only every other packet is sent. Processes such as the EFAC and sweep functions take a few seconds to complete. Each time-stamp is then followed by data which is in Little-Endean format with the MSB of the data being the MSB of the byte. Granules are sent out in 1-byte boundaries but are generally aligned on a 16-byte boundary. The first packet in a sweep contains time stamp information, whereas the other 64 packets in a sweep have a sequence number for order. This 1-byte sequence number indicates the packets set number. Each granule channel has a FIFO buffer that stores the granules and sends them through the UART when allowed by the traffic controller which ensures that only one granule at one time is sent to the serial data stream.

5.4.3 Packet Formation and the C&DH

The C&DH system receives the granules from the FPGA and converts them to a telemetry specification called Consultative Committee for Space Data Systems (CCSDS), packets that can be sent to the radio [22]. The CCSDS packets add some overhead to
the telemetry, but also have important functions such as a check sum for error correction and serve as a wrapper for the science granules. The granules form the main body of the CCSDS packet but redundant data is compressed. The granule header is not included to save space as shown in Figure 5.9. Because of the linear monotonic nature of the GPS time signal, only the delta time is sent for most granules. The first packet header contains the full time-stamp, and each subsequent CCSDS packet is referenced from the time header of the first. This method saves telemetry because for all but one of the packets only 1-byte out of the three bytes is sent via the telemetry stream. The number of granules in a packet is 70, which number corresponds to 1 second of data, and the total packet size is 542 bytes. There are also 16 ILP Sweep granules, the packets of which are 542 bytes in length.

5.4.4 Radio-to-Ground Station

DICE uses a novel software radio receiver for the ground station as shown in Figure 5.10. The antenna for the ground station consists of an 18.3m dish at Wallops, VA. The radio is only half duplex, to switch between Tx or Rx modes, an amplifier\switch by single sideband carrier ensures only one channel is talking at a time. The radio uplink consists of a CC1101 made by Texas Instruments. The downlink is a WBX demodulator which then feeds the data into a USRP2 software defined radio—this radio converts the data to a digital stream. It is then processed by the GS computer and stored in a data base in its raw, Level 0 bit form.

Fig. 5.8: DAS granule types and byte sequences.
Fig. 5.9: Science granules in a CCSDS packet.

Fig. 5.10: Ground station functional diagram.
Chapter 6
Calibration and Testing Results

The ideal instrumentation explained in the previous chapters varies because imperfections in analog instrumentation. Analog components are composed of smaller circuit elements that are susceptible to temperature changes and nonlinearities. Each device is also different due to manufacturing, no two components function in exactly the same way. Because of these differences, error is introduced which affect performance in two ways: 1) Offsets are created which shift the center range of the signal away from zero; 2) Changes in dynamic range result from gain differences. Both parameters can also vary over temperature which introduces a third source of error. Calibration is necessary to form a model of these differences by measuring error in the output with respect to a reference input. Functional testing and verification were simultaneously conducted to save time and ensure that the instrumentation meets the limits specified by the requirements. Figure 6.1 shows the functional temperature testing of DICE.

Fig. 6.1: Temperature chamber.
6.1 Instrumentation Testing and Calibration

The DICE instrumentation was tested by applying a linear signal with a known amplitude and frequency to the input of the instrumentation. This was either done by stepping the parameter by hand or by generating a linear waveform. The output was recorded in digital counts and a linear fit applied to the waveform. System error can be measured by finding the residual created by subtracting the linear fit from the output. On orbit data can later be corrected with the characterized error.

Testing was done with the backplane of the satellite built up inside of the chassis. Control was provided by ground station software which sent commands to control the instrumentation and received the testing data. The data was automatically recorded in a database, which also simultaneously tested the end-to-end performance and functionality of the satellite, software, and ground station. Each performed test name and statistics were recorded in an excel spreadsheet for documentation purposes. The tests were conducted both inside and outside of the temperature chamber, shown in Figure 6.2. The details of the testing will not be described in this thesis, the interested reader should obtain the calibration documents for further information. However, a short description of testing done for each instrument will be reviewed. Calibration was conducted on two different timeframes, 14-15 of Mar., 2011 and 11-24 of Sept., 2011. Because the ILP and EFP September calibration runs were not processed at the time of writing, only the data from the March runs will be included.

6.2 Ion Langmuir Probe Testing and Results

6.2.1 Ion Langmuir Probe Calibration

The ILP instrument essentially records current and outputs the quantized value from the ADC. Resistors were used to calibrate the current into the ILP. The resistor values used for this test were 92k, 110k, 130k, and 920k. Each resistor was placed in an aluminum block to keep a constant temperature and calibrated so the resistance value was known at that temperature. The test was conducted by starting a voltage sweep on the ILP which sweeps
Fig. 6.2: Yhatzee in temperature chamber ready for calibration.

from -4V to 2V. The change in current was then observed by recording ILP counts from the ADC. This test was conducted at three different temperature points -12°C, 22°C, and 35°C.

6.2.2 Ion Langmuir Probe Calibration Results

The simplest way to calibrate the data is to find the first-order linear fit for voltage versus counts. The data for the sweeps was obtained and a linear fit was applied to each. By fitting the output data two main factors of the system are shown, the dynamic range and gain. The dynamic range can be found in the graph where the full scale points of 0 and 65535 are on the graph. Gain is found by the slope of the line, error in the form on nonlinearities can be found in the residual of the data as shown in equation (6.1). Another system performance measure is offset which is the value of the output of the system at the y-intercept of the zero-point of the x-axis. This can also be found in the residual at the zero-point of the input signal.

\[ V_{counts-out} = (K_{gain}) (I_{in}) + V_{offset} \]  

(6.1)

The results are shown in Figure 6.3 from six runs, two each for each temperature point. The gain on each channel is related to the slope of the line, the higher the slope the higher the gain. The residuals of the linear fits to the data, shown in Figure 6.4, also
give information about the linearity of the system and its accuracy. The channels do have inconsistencies on a fine scale that change with temperature, most likely due to offsets in the instrumentation. An unexpected result was the highly nonlinear nature of the ILP number two channel as shown in Figure 6.4. A probable cause of this problem results from a zero crossing on the ADC or the last offset amplifier in the system.

The linear fits of Figure 6.5 show temperature differences in the ILP data with about 100 counts of error in some cases. This results in a one sigma uncertainty of 30nA and was a factor of 20 worse than anticipated. The resolution of the ILP will be lower than expected at $10^4 \text{ cm}^{-3}$. More than a simple linear fit will be needed for the ILP data calibration.

For a more exact picture of the noise, a $10^{th}$ order fit was applied to the data to subtract any polynomial effects, and the worst case error at $22^\circ C$ shows about 10 counts of error. This equates to an amplitude of 381uV noise which suggests that DAC system noise is of
concern and noise mitigation should have been employed for that system.

6.3 Electric Field Probe Testing and Results

6.3.1 Electric Field Probe Calibration

The EFP is much simpler to test since the system is converting voltage to counts. The testing consisted of sweeping a voltage on each channel from -7V to 7V and recording the counts out. This testing was done in conjunction with the ILP testing in March with two runs at each -13°C, 22°C, and 35°C temperature points. The testing followed in this manner:

1. The voltage was swept across a ±6.5V range across input channels V12 and V34 to avoid the voltage limits of the instrumentation;

2. The results were recorded in a database by the ground station software;

3. The testing occurred at the same time as the ILP testing and was done for three different temperature points -12°C, 22°C, and 35°C.

6.3.2 Electric Field Probe Calibration Results

The same methods used to analyze the ILP data was applied to the EFP data, a linear fit and residual were found for each channel. The equation is similar to the previous equation, also as shown in (6.2).
\[ V_{\text{counts}-\text{out}} = (K_{\text{gain}})(V_{\text{in}}) + V_{\text{offset}} \] (6.2)

The EFP was more well behaved and had less nonlinearities across temperature. The gain and offsets were more consistent than the ILP stayed close to a ±2mV tolerance. The same nonlinear crossover effect that shown in the ILP residuals are also present in the EFP V34 channel residuals shown in Figure 6.6. This error is either caused by the second channel of the ADS8343 or by the AD8622 amplifier which are present in both instruments. The limits of the dynamic range of the instrumentation by extrapolating the voltage and hit full scale at ±7V. The horizontal lines represent one sigma standard deviation after calibration. For V12, Standard Deviation (STD) is 1.72mV, and for V34, STD it is 2.43mV.

6.4 Three Axis Magnetometer Testing and Results

6.4.1 Helmholtz Coil Calibration

To calibrate the TAM system, a DICE used Helmholtz method to drive the input of the instrument. The DICE Helmholtz coil was built to test the TAM, shown in Figure 6.7. Because of the near straight magnetic field lines Helmholtz coils are ideal for testing magnetometers. The coil frame was fabricated with a 3D rapid prototype fabrication printer. Each copper coil was formed by wrapping wire into six coils, two for each axis. Each pair of coils is wired in series with 10 turns of 26 American Wire Gauge (AWG) wire for each

![Electric Field Probes - Six Linearity Tests](image_url)

![Error in EFP measurement after calibrations with temperature](image_url)

Fig. 6.6: EFP linear fit and residuals.
coil. The radii for the coils are 4.49cm, 5.15cm, and 5.81cm from the inner coil to the outer coil. To avoid confusion each axis was labeled to correspond to each axis. Helmholtz coil equation (6.3) shows the predicted magnetic field for a given current.

\[ B = \left( \frac{4}{5} \right)^{\frac{3}{2}} \frac{\mu_0 n I}{R} \]  

(6.3)

The calibration for the Helmholtz coil was done in the following manner. Each channel was calibrated individually with a FVM-400 test magnetometer that had an accuracy of 1nT. To reduce magnetic environmental noise the Helmholtz coil was calibrate in a zero-Gauss chamber which reduces external magnetic fields to near zero. Care was taken to align the test magnetometer and place it close to the center of the coil. A current was driven into each channel and the magnetic strength recorded. The current and magnetic field strength were measured at 15 points and compared with its theoretical performance. For brevity only the results at 250mA are shown in Table 6.1, but the errors were similar for each current measurement. These results were factored into the magnetometer calibration. The Helmholtz coil was also calibrated for rotation in a similar manner described below.
Table 6.1: Helmholtz coil calibration results.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Diameter</th>
<th>Magnetic Field (nT) @250mA</th>
<th>Calculated Drive Field (nT)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner X</td>
<td>4.32cm</td>
<td>52060</td>
<td>51100</td>
<td>-1.90%</td>
</tr>
<tr>
<td>Middle Z</td>
<td>4.95cm</td>
<td>48758</td>
<td>45440</td>
<td>6.81%</td>
</tr>
<tr>
<td>Outer Y</td>
<td>5.59cm</td>
<td>45691</td>
<td>40180</td>
<td>12.13%</td>
</tr>
</tbody>
</table>

6.4.2 Three Axis Magnetometer Testing and Calibration

The TAM testing and calibration needed to calibrate both the gains and offsets, but position error from misalignment from both construction and placement of the system which resulted in sources of error. The system can be thought of as three independent linear systems when corresponding axes are perfectly aligned and orthogonal to one another. Real world situations prevent this and cross-terms must be used to characterize misalignments between axes by substituting a coordinate transfer matrix A for the gain term as shown in equation (6.4).

\[
\mathbf{V}_{axis} = \mathbf{A}_{gain} \mathbf{B}_{axis} + \text{Offset} \tag{6.4}
\]

Misalignment of the axes causes them to be rotated which can be represented by matrix A as shown in equation (6.5):

\[
\mathbf{\vec{V}} = \begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
A_{31} & A_{32} & A_{33}
\end{bmatrix}
\begin{bmatrix}
\mathbf{B}_x \\
\mathbf{B}_y \\
\mathbf{B}_z
\end{bmatrix}
+ \begin{bmatrix}
\mathbf{O}_1 \\
\mathbf{O}_2 \\
\mathbf{O}_3
\end{bmatrix} \tag{6.5}
\]

Perfect alignment results in zero values for the terms which results in equation (6.6). Each channel is multiplied by its own gain. Only one set of calibration equipment existed only which meant only one axial magnetic source could be active at one time. However, by calibrating each channel independently simplifies the linear cross gain problem.

\[
\mathbf{\vec{V}} = \begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
A_{31} & A_{32} & A_{33}
\end{bmatrix}
\begin{bmatrix}
\mathbf{B}_x \\
0 \\
0
\end{bmatrix}
+ \begin{bmatrix}
\mathbf{O}_1 \\
\mathbf{O}_2 \\
\mathbf{O}_3
\end{bmatrix} \Rightarrow
\begin{bmatrix}
\mathbf{V}_x \\
\mathbf{V}_y \\
\mathbf{V}_z
\end{bmatrix}
= \begin{bmatrix}
A_{11} & B_x \\
A_{21} & B_x \\
A_{31} & B_x
\end{bmatrix}
+ \begin{bmatrix}
\mathbf{O}_1 \\
\mathbf{O}_2 \\
\mathbf{O}_3
\end{bmatrix} \tag{6.6}
\]
After calibration linear fits are then applied to each channel three of the cross-gains may be found because they are separate linear systems. It should be noted that the Helmholtz coil also had a coordinate transfer matrix associated with its own calibration; these differences were removed from the data at the time of DICE TAM calibration.

TAM testing was conducted in the following manner with two separate input signals. The Helmholtz coil was used to input a known magnetic field around the magnetometer, a singular axis of the Helmholtz coil was energized at any moment in the test. The magnetometer and Helmholtz coil were placed inside of the zero-Gauss chamber to minimize EMI from outside sources. A stepped input was applied to the magnetometer first stepping from -125mA of current to 125mA of current. This tested the offsets, gains and alignment of the TAM. A second wave form used to drive the input with a square, sine, or triangle wave into the Helmholtz coil with a waveform generator with a known frequency and amplitude as shown in Figure 6.8.

This simplified testing because only the amplitude and frequency were recorded as opposed to the difficult task of aligning to different data sets and their time series. Matlab was used to fit the wave form and produce a model that could reconstruct the original waveform. The two were then subtracted and a residual obtained. Figure 6.9 shows the TAM output and both sets of waveforms; in this figure misalignment can be where a driven channels signal can be seen in the un-driven channels. Each of these tests were done over three temperature points near -12°C, 21°C, and 35°C.

Fig. 6.8: Triangle wave input for TAM calibration.
6.4.3 TAM Calibration data

Figure 6.10 shows data and fits for the TAM, as well as the residuals of those fits, which shows data from the September Yhatzee sine wave calibration. This example is shown for driving the x-axis of the Helmholtz coil. The response of the magnetometer is shown mostly from counts on the x-axis of the TAM. This slope of is also the gain factor A11. When cross terms have low values it suggests better alignment.

Offsets are found by locating the magnetic field zero-point and recording the number of counts at that point. Table 6.2 is shown for all of the Yhatzee cross terms and offsets while Figure 6.11 shows the variation in temperature.

A considerable amount of noise was found in the residuals of the waveform fits subtracted from the data shown in the left of Figure 6.10. At 20 counts of noise, this was 10 times more than expected, however, on orbit and testing suggest that this is due to noisy test equipment or fitting methodology. This supports the predicted value of three counts and a sensitivity of 1.5nT characterizes the magnetometer and that the requirements were achieved.

The offsets and gains over temperature are shown for the linear fits done over testing. The calibration is linear over temperature for Farkel. Yhatzee, however, seems to reach its
The magnetic field (nT) vs. ADC Counts for the response to Helmholtz X-axis is shown in the figure. The fit residuals are also displayed.

Table 6.2: Gain matrix for Yhatzee calibration.

<table>
<thead>
<tr>
<th>X-axis</th>
<th></th>
<th>Y-axis</th>
<th></th>
<th>Z-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>A11</td>
<td>A12</td>
<td>A13</td>
<td>A21</td>
<td>A22</td>
</tr>
<tr>
<td>0.5796</td>
<td>-0.0139</td>
<td>0.02712</td>
<td>-0.0551</td>
<td>0.6494</td>
</tr>
<tr>
<td>Offset1</td>
<td>Offset2</td>
<td>Offset3</td>
<td>Offset1</td>
<td>Offset2</td>
</tr>
<tr>
<td>7929.6</td>
<td>32547</td>
<td>-33150</td>
<td>8060.8</td>
<td>32539</td>
</tr>
</tbody>
</table>

The temperature span of the magnetometer could be a bit higher than 35°C due to its external location.
Fig. 6.11: TAM gain and offset variations over temperature.
Chapter 7

Conclusion

7.1 DICE Comparison

7.1.1 Initial Mission Success

The DICE mission was launched at 09:48 UTC on October 28th 2011 from Vandenberg, CA as an auxiliary payload on the NPP mission and reached its orbit successfully. The lead DICE spacecraft was ejected with close to a 6mm/s delta-V imposed upon it by a separation spring between the two spacecraft along the velocity vector. Over a period of five months, the along-track separation between the spacecraft had grown to approximately 6,000km, most likely due to slight differences in attitude, orbit, and resulting drag. The EFP locking mechanisms, antennas, and ILP booms were successfully deployed by each spacecraft 50min after ejection. Communications with both spacecraft was first achieved on October 30th 2011 or a few days after launch when valid two line orbital element sets became available from the United States Space Surveillance Network. Tracking and ground station interference problems delayed the commissioning of the spacecraft which consisted of de-tumbling the vehicles, aligning them with the geomagnetic axis, and spinning them up for stabilization and deployment of the wire booms of the EFP science instrument. The spacecraft attitude control system will be switched into a 0.1Hz spin maintenance stabilization mode when the spacecraft is fully deployed. At the time of writing downloading data proved difficult due to radio noise in the ground station vicinity which resulted in limited amounts of data for retrieval. This also resulted in a delay of the EFP booms being deployed fully. Problems aside, both spacecraft were functioning correctly and housekeeping, ILP, and TAM data being collected. The DICE mission and instrumentation demonstrates that low-power, low-
volume plasma diagnostic instrumentation can be developed for cubesats and stand the rigors of the space time environment. By meeting the mission requirements and by its performance on orbit, DICE shows that cubesats are viable means for gathering vital space weather data.

7.1.2 Instrumentation Performance and Comparison

A comparison of DICE mission and the Communications/Navigation Outage Forecasting System (C/NOFS) mission which have instruments that are functionally similar; a comparison is shown in Table 7.1. Instrumentation parameters were either similar or exceeded by DICE, while using much less resources. A schematic for the instrumentation is shown in Appendix A.2.

Although C/NOFS are not similar missions because C/NOFS has much more instrumentation and differed from DICE in the reliability requirements and construction. An example of this is C/NOFS, which used more expensive radiation tolerant parts, whereas DICE used commercial off-the-shelf parts which cost less and are less reliable. However, the instruments DICE used were comparable in sensitivity and sampling rate while conserving mass and power. Another factor to consider is cost C/NOFS budget was 153 million dollars, while DICE mission costs were 1.2 million dollars [23]. Many small satellites could be purchased for the price of a larger mission and provide greater coverage.

7.2 Future Work

7.2.1 ASSP

The DICE mission paves the way for cubesats and other missions by proving new technologies and methods in the rigors of the spacetime environment. A DICE successor that will build off of these technologies is a sounding rocket mission called Auroral Spatial Structures Probe (ASSP) which will spin out ten instrumentation packages functionally similar to DICE and measure the Electric field, Magnetic field, and density of the auroral region. The advantage of smaller instrumentation package is more multipoint measurements
Table 7.1: DICE performance and comparison.

<table>
<thead>
<tr>
<th>EFAC</th>
<th>Parameter</th>
<th>DICE</th>
<th>C/NOFS</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>0.002</td>
<td>0.005</td>
<td>mV/m</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>50</td>
<td>45</td>
<td>mV/m</td>
<td></td>
</tr>
<tr>
<td>Frequency Range</td>
<td>16-512</td>
<td></td>
<td>Hz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DC Electric Field</th>
<th>Parameter</th>
<th>DICE</th>
<th>C/NOFS</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>400</td>
<td>300</td>
<td>uV/m</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>700</td>
<td>45</td>
<td>mV/m</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>&lt;0.1</td>
<td>&gt;1</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>50</td>
<td>&gt;50</td>
<td>mW</td>
<td></td>
</tr>
<tr>
<td>Sampled Rate</td>
<td>70</td>
<td>1</td>
<td>Hz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FPP</th>
<th>Parameter</th>
<th>DICE</th>
<th>C/NOFS</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>400</td>
<td>300</td>
<td>uV/m</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>700</td>
<td>45</td>
<td>mV/m</td>
<td></td>
</tr>
<tr>
<td>Sampled Rate</td>
<td>70</td>
<td>1</td>
<td>Hz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnetometer</th>
<th>Parameter</th>
<th>DICE</th>
<th>C/NOFS</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>1.5</td>
<td>50</td>
<td>nT</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>±196000</td>
<td>45000</td>
<td>nT</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>&lt;0.1</td>
<td>&gt;1</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>110</td>
<td>&gt;50</td>
<td>mW</td>
<td></td>
</tr>
<tr>
<td>Sampled Rate</td>
<td>70</td>
<td>1</td>
<td>Hz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ILP/PLP</th>
<th>Parameter</th>
<th>DICE</th>
<th>C/NOFS</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>10</td>
<td>500</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>3000</td>
<td>3.5</td>
<td>cm⁻³</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range Low</td>
<td>10⁴</td>
<td>10⁵</td>
<td>cm⁻³</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range High</td>
<td>10⁸</td>
<td>10⁸</td>
<td>cm⁻³</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>&lt;0.1</td>
<td>&gt;1</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>50</td>
<td>&gt;50</td>
<td>mW</td>
<td></td>
</tr>
<tr>
<td>Sampled Rate</td>
<td>70</td>
<td>1</td>
<td>Hz</td>
<td></td>
</tr>
</tbody>
</table>

which increases the resolution of spatial and temporal scales. The differences of ASSP are: it is smaller because the power and ACDS systems will be reduced, the electric field booms will be 3m of length, and it will spin faster to release the booms.

### 7.2.2 Satellite Constellations

DICE is amongst the first cubesat constellations by launching two satellites that make ionospheric measurements. Launching a single satellite makes it difficult to see small scale variations or global variations. Constellations overcome these problems and give a better view of space weather phenomena. Instead of building one single expensive satellite, several smaller inexpensive satellites may be deployed that have the same functionality but not necessarily the same level of redundancy and reliability. In the future, many small satellites could be deployed in the same mission to give global coverage as shown in Figure 7.1.
7.3 Lessons Learned

7.3.1 Science Board

Because of limited space in volume for the payload, the science board layout had a high part density that made it very complex. Future missions should work to lower part densities by increasing board space or by lowering part count. The science board PCB was a 6-layer design which made it expensive, in future designs using the same volume in two separate 4-layer boards could be used to house the same parts and lower part density. Analog and digital sections could be separated on different boards as well as isolating the power electronics from sensitive analog electronics. Space could also be saved by using a battery bus voltage greater than 12V, this would allow for DC-DC regulators instead of charge pumps. This approach would also lower design costs by giving more board space for designers to work with and lowering the cost of board changes. FPGAs make digital design more flexible, if a pin needs to be changed the FPGA can re-route the signal. Another problem is the envelope needs to be defined early on for the payload. In the case of DICE the Sun-sensors cut into the board which trimmed off additional space which resulted in
the 6-layer PCB design and increased the cost and design time of the board.

7.3.2 Ion Langmuir Probe

The ILP did not meet its resolution requirement of 1x10^3 cm^-3 because the dynamic range was adjusted from being a fixed bias probe with a range of 700pA to 7μA to being a dual sided ±50μA signal for input current. A better approach would be to use a logarithmic amplifier or to make the channel have a high gain and a low-gain stage to compensate. Another major problem with the instrument was not performing a system analysis of the noise for the DAC system which contributed noise amplitudes up to 10μA at the input of the system. This problem can be solved by putting a low-pass filter before the unity gain stage of the DAC system. The low-pass filter of the ILP also needed modification. Low-pass filters typically have an impedance buffer to separate them from the rest of the circuit. In this case, there was a resistor accidently placed between the output of the low-pass filter and the input of the next amplifier stage. This turned the low-pass filter into more of a band-pass filter. This was corrected by the pole is not exactly at 40Hz. Future designers should refer to the EFDC low-pass filters for correct schematics of a low-pass filter stage.

7.3.3 Electric Field Probe

The EFP met its goals. However, power could have been saved by downsizing the high-pass filter on the EFAC channel. The spin rate range at design time was 400mV/m at 1Hz to 9Hz, so the high-pass filter was designed to accommodate any signal across that range. The ending spin rate was around 2.5Hz max and the 60dB/decade filter was overdesigned. However, future missions should take care in modifying the design if they have a higher spin rate. An undiscussed problem belonging to the EFDC channel is the shielding of the boom wires. The capacitance between the wires and the plasma create undesirable signal effects. An attempt to compensate with a graphite spray to shield the wires. This attempt was not able to coat the wires evenly enough to provide continuous conduction. Future missions should use a small gauge wire with an inner or shielding conductor.
7.3.4 Magnetometer

The magnetometer met its goal of 2nT, however, there is room for improvement in future revisions of this instrument. The system bandwidth of the magnetometer had been set too high which added a considerable amount of noise to the system, reducing the bandwidth to 40Hz from 150Hz could reduce the noise amplitude by a factor of 2.5. To also improve sensitivity the bridge offsets could be compensated for as described in Section 4.5. The dynamic range could then be reduced 2 to 4 times in doing so, this would also improve system sensitivity. Better shielding on the cable could also reduce noise on the instrument since the cable runs down the length of the satellite and is susceptible to EMI. Further analysis of the on orbit data reveled spikes of up to 10nT which are probably caused by the power electronics. Placing the magnetometer greater than 6cm away from the center of the spacecraft could reduce the noise to a level lower than the sensitivity of the instrument. The instrument was not moved on DICE because of potential mechanical issues.
References


Appendices
Appendix A

A.1 Science and Mission Instrumentation Requirements

This section contains the mission requirements, instrument requirements, and also derived instrument requirements from which the instrumentation was developed.

Table A.1: Mission and instrumentation requirements.

<table>
<thead>
<tr>
<th>Req.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission Objectives</strong></td>
<td></td>
</tr>
<tr>
<td>MO1</td>
<td>Investigate the physical processes responsible for formation of the geomagnetic storm enhanced density bulge in the noon to post-noon sector during magnetic storms.</td>
</tr>
<tr>
<td>MO2</td>
<td>Investigate the physical processes responsible for the formation of the geomagnetic storm enhanced density plume which forms at the base of density bulge and the transport of the high density plume across the magnetic pole.</td>
</tr>
<tr>
<td>MO3</td>
<td>Investigate the relationship between the penetration electric fields and the formation and evolution of the storm enhanced density bulge and plume.</td>
</tr>
<tr>
<td><strong>Science Requirements</strong></td>
<td></td>
</tr>
<tr>
<td>S01</td>
<td>Return continuous observations of the ionosphere using two spacecraft that are within the same orbital plane and within 1-min to 6-min of each other.</td>
</tr>
<tr>
<td>S02</td>
<td>Return observations of the ionosphere from $\geq 55^\circ$ latitude with a preference of observations $\geq 80^\circ$ latitude.</td>
</tr>
<tr>
<td>S03</td>
<td>Return 90 days of observations of the ionosphere from the 13 to 17 local time sector using two spacecraft that are within the altitude range of 350km to 800km with a goal of 180 days. Run</td>
</tr>
<tr>
<td>S04</td>
<td>Return observations of co-located electric fields, magnetic field fluctuations, and plasma density at a $\leq 10$km on-orbit spatial sampling with a $\leq 0.1$km goal and that are absolute time located to within $\leq 1$ms UT.</td>
</tr>
<tr>
<td>S05</td>
<td>Return observations of the presence of electric fields fluctuations in the 10 to 1000Hz range at a $\leq 10$km on-orbit spatial sampling.</td>
</tr>
<tr>
<td><strong>Instrumentation Requirements</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Electric Field Instrument</strong></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>The spacecraft shall return post-flight, post-analysis, observations of the ambient electric fields perpendicular to the local magnetic field with and accuracy of $\leq 2$mV/m and with a goal of 0.1mV/m over a range of $\pm 200$mV/m.</td>
</tr>
</tbody>
</table>

Continued on next page...
### Table A.1 – continued from previous page

<table>
<thead>
<tr>
<th>Req.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>E2</td>
<td>The electric field instruments shall provide two double probe observations with sensors deployed 90° ±0.1° relative to each other and simultaneously sampled.</td>
</tr>
<tr>
<td>E3</td>
<td>Each electric field sensors shall be spherical, ≥ 0.75cm diameter and deployed ≥ 2 meters from the spacecraft with a goal of 10m tip to tip distance.</td>
</tr>
<tr>
<td>E4</td>
<td>The location of each of the electric field sensors in the spacecraft body coordinate shall be known to within 1/1000 of the boom length when the sensors are fully deployed.</td>
</tr>
<tr>
<td>E5</td>
<td>The electric field sensors shall be rotated about the axis perpendicular to the deployed plane of the sensors with a frequency, f, such that 0.1 ≤ f ≤ 10Hz and at the geometric center point of the sensors to within 1/1000 of the boom length.</td>
</tr>
<tr>
<td>E6</td>
<td>The electric field booms shall be deployed to be perpendicular to the Earths geodetic axis of rotation to ≤ 30°.</td>
</tr>
<tr>
<td>E7</td>
<td>The post-flight attitude knowledge of the electric field boom orientation shall be ≤ 0.1° with a goal of ≤ 0.01°.</td>
</tr>
<tr>
<td>E8</td>
<td>The electric field instrument shall provide measurements under the environmental conditions for ambient plasma density of 10^2 Ohms to 10^8 Ohms/cm^-3.</td>
</tr>
<tr>
<td>E9</td>
<td>The electric field instrument shall provide measurements under the environmental conditions for temperature ranging from -10 to 30°C.</td>
</tr>
<tr>
<td>E10</td>
<td>The electric field instrument shall operate from power supplies of +5V and the unregulated spacecraft battery bus (7.4 ±0.8V)). IT shall have a total power usage of ≤ 50mW .</td>
</tr>
<tr>
<td>E11</td>
<td>The electric field instrument shall require no more than 4.0 x 4.0cm of circuit board space.</td>
</tr>
<tr>
<td>E12</td>
<td>The input impedance of the electric field instrument shall be ≥ 10^{13} Ohms and the instrument shall be in a short to ground configuration until deployed.</td>
</tr>
<tr>
<td>E13</td>
<td>The electric field probe shall be able to accommodate an induction field, VxB, plus ambient field of ≥ 600mV/m without saturating.</td>
</tr>
<tr>
<td>E14</td>
<td>The electric field instrument shall provide two 16-bit two’s complement values to the telemetry system representing the double probe measurements, V12 and V34, of the observed fields.</td>
</tr>
<tr>
<td>E15</td>
<td>The electric field instrument shall provide at least 3 points of electric field spectral information from the frequency range of 10 to 1000Hz at a ≤ 10km on-orbitspatial sampling rate.</td>
</tr>
</tbody>
</table>

#### Magnetic Field Science Instrument

<table>
<thead>
<tr>
<th>Req.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>The science magnetometer shall return post-flight, post-analysis observations of ambient magnetic fields with an accuracy of 2 nT and a signal to noise ratio of ≥ 3 over a range of ≥ ±50,000nT.</td>
</tr>
<tr>
<td>M2</td>
<td>The science magnetometer z-axis shall be aligned with the spin axis of the spacecraft to within 2°</td>
</tr>
<tr>
<td>M3</td>
<td>The science magnetometer x and y-axis shall be aligned to the electric field boom axis to within 2°.</td>
</tr>
</tbody>
</table>

Continued on next page...
<table>
<thead>
<tr>
<th>Req.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td>The spacecraft shall have residual and stray magnetic fields of rms amplitude of ( \leq 2 \text{nT} ) at the location of the science magnetometer.</td>
</tr>
<tr>
<td>M5</td>
<td>The science magnetic field instruments shall operate with a power supply of +5V with a total power usage of ( \leq 100 \text{mW} ).</td>
</tr>
<tr>
<td>M6</td>
<td>The science magnetometer shall provide measurements under the environmental conditions for temperature ranging from -10°C to 30°C</td>
</tr>
<tr>
<td>M7</td>
<td>The science magnetometer shall require no more than 4.0 x 4.0cm of circuit board space.</td>
</tr>
<tr>
<td>M8</td>
<td>The science magnetometer shall provide three 18-bit two's complement values to the telemetry system representing Bx, By and Bz of the measured field.</td>
</tr>
</tbody>
</table>

**Ion Langmuir Probe**

<table>
<thead>
<tr>
<th>Req.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>The Ion Langmuir Probes shall return post-flight, post-analysis plasma density observations over the range of ( 2 \times 10^3 \text{ to } 2 \times 10^7 \text{ cm}^{-3} ) with a resolution of ( 350 \text{ cm}^{-3} ).</td>
</tr>
<tr>
<td>L2</td>
<td>The voltage on the sensor shall be ( \leq -5 \text{V} ) relative to the spacecraft structure with a goal of -8V.</td>
</tr>
<tr>
<td>L3</td>
<td>The Ion Langmuir Probe shall be aligned with the spacecraft spin axis and return observations of the ion ram current in wake free regions.</td>
</tr>
<tr>
<td>L4</td>
<td>The Ion Langmuir Probe shall provide two observations with sensors deployed ( 180^\circ \text{C} \pm 0.1^\circ \text{C} ) relative to each other and simultaneously sampled.</td>
</tr>
<tr>
<td>L5</td>
<td>Each Ion Langmuir Probe sensor shall be spherical, ( \geq 1.27 \text{cm} ) diameter and deployed ( \geq 5 \text{cm} ) from the spacecraft such that one of the sensors shall be outside of the spacecraft wake at all times.</td>
</tr>
<tr>
<td>L6</td>
<td>The Ion Langmuir Probe shall provide measurements under the environmental conditions for temperature ranging from -10°C to 30°C.</td>
</tr>
<tr>
<td>L7</td>
<td>The Ion Langmuir Probe instrument shall operate from power supplies of +5V and the unregulated spacecraft battery bus (7.4V ( \pm 0.8 \text{V} )). It shall have a total power usage of ( \leq 50 \text{mW} ).</td>
</tr>
<tr>
<td>L8</td>
<td>The Ion Langmuir Probe shall require no more than 4.0 x 4.0cm of circuit board space.</td>
</tr>
<tr>
<td>L9</td>
<td>There shall be no exposed potentials on the spacecraft to the space environment aside from the Ion Langmuir Probe. All solar panel interconnects shall be isolated from the plasma and all connectors shall similarly be covered during operation of the spacecraft.</td>
</tr>
<tr>
<td>L10</td>
<td>The surface of the Ion Langmuir Probe shall be cleaned prior to flight.</td>
</tr>
<tr>
<td>L11</td>
<td>The surface of the Ion Langmuir Probe will be goldcoated.</td>
</tr>
</tbody>
</table>

**Science Instrument Interface**

<table>
<thead>
<tr>
<th>Req.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI1</td>
<td>The science Instruments will interface to the rest of the spacecraft using a single SPI interface</td>
</tr>
<tr>
<td>SI2</td>
<td>The maximum sampling rate for any science data channel shall be 100Hz</td>
</tr>
<tr>
<td>SI3</td>
<td>Science preamplifiers must be located as close as possible to the sensor mechanical interfaces.</td>
</tr>
</tbody>
</table>

Continued on next page...
<table>
<thead>
<tr>
<th>Req.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI4</td>
<td>Digital control lines may not be routed through the areas allocated to the Electric Field Instrument, Science Magnetometer, and Ion Langmuir probe.</td>
</tr>
</tbody>
</table>

### Derived Instrumentation Requirements

#### Electric Field Instrument

| ED1  | The input voltage range of the Electric field instrument shall be ±8V for a 10 meter tip to tip boom length. This requirement is derived from E1, E3, E13 and includes a 30% margin. |
| ED2  | The telemetry rate for the V12 and V34 channels shall be 80Hz giving a spatial resolution of 93m at 350km altitude and 96m at 800km. This requirement is derived from SO3, SO4, SI2. |
| ED3  | The input bias current of the instrument shall be lower than 1pA and input impedance more than 10^13Ohms. This requirement is derived from E8 and E12 |
| ED4  | The frequency response for the channels V12 and V34 shall be a DC low-pass response with a near linear phase response within the pass band and with at least a 20 dB/decade roll-off for out of band signals. The 3dB cutoff frequency shall be 35Hz. This requirement is derived from ED2. |
| ED5  | The electric field instrument response shall be calibrated over the temperature range of -10 to 30°C using a polynomial. This requirement is derived from E1 and E9 |
| ED6  | The temperature of the electric field instrument electronics shall be known to within 0.2°C while collecting science data and telemetered at ≥ 17mHz . This requirement is derived from ED5 |
| ED7  | The electric field spectrometer shall consist of four channels which cover the spectral ranges of 16-32Hz, 32-64Hz, 64-128Hz and 128-512Hz. The gain for these channels shall be 500 . This requirement is derived from SO5 and E15 |
| ED8  | The electric field spectrometer shall employ a high pass filter to reduce the VxB spin induced signal. The roll off of the filters shall be at least 60dB per decade for the out of band signals with a cutoff frequency of no more than 12Hz. |
| ED9  | The insulation on the electric field wire booms shall have a volume resistively of more than 10^17Ohms/cm. |

#### Ion Langmuir Probe

| LD1  | The input current range of the Ion Langmuir Probe shall be from 700pA to 7uA referenced as positive current to the probe surface from the space environment. This operating range shall be quantized with at least 16-bits. The operating range is calculated for a 1.9cm diameter spherical sensor. This requirement is derived from L1 and L5. |
| LD2  | The telemetered rate for the ILP1 and ILP2 data shall be 80Hz. This rate results in a spatial resolution of 93m at 350km altitude and 96m at 800km. This requirement is derived from SO3, SO4, SI2. |

Continued on next page...
Table A.1 – continued from previous page

<table>
<thead>
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<tbody>
<tr>
<td>LD3</td>
<td>The frequency response for the channels ILP1 and ILP2 shall be a DC low-pass response with a near linear phase response within the pass band and with at least a 60 dB/dec roll-off for out of band signals. The 3dB cutoff frequency shall be 35Hz. This requirement is derived from LD2.</td>
</tr>
<tr>
<td>LD4</td>
<td>The Ion Langmuir Probe response shall be calibrated over the range of -10°C to 30°C using a polynomial. This requirement is derived from L6.</td>
</tr>
<tr>
<td>LD5</td>
<td>The Ion Langmuir Probe electronics temperature shall be known to within 0.2°C while collecting science data and telemetered at $\geq 17$ mHz. This requirement is derived from LD4.</td>
</tr>
</tbody>
</table>

**Magnetic Field Science Instrument**

| MD1  | The science magnetometer sensor head shall be kept at least 15cm away from the power supply conditioning electronics. This requirement is derived from M1 and M3. |
| MD2  | The telemetered rate for the Magnetic Field Instrument shall be 80Hz giving a spatial resolution of 93m at 350km altitude and 96m at 800km. This requirement is derived from SO3, SO4, SI2. |
| MD3  | The Magnetic Field Instrument response shall be calibrated over the range of -10°C to 30°C using a polynomial. This requirement is derived from M6. |
| MD4  | The Magnetic Field Instrument electronics temperature shall be known to within 0.2°C while collecting science data and telemetered at $\geq 17$mHz. This requirement is derived from MD3. |

### A.2 Science Board Schematics

The following section contains the Science Board schematics taken from SDL document 141-0007 which is the electrical design of the science instrumentation.
DICE Stack Connector

Deck Plate Connector
E-Field Instrumentation

- Temp Spec
- Op
- Temp Vcc/Vee Vin
- Iq Ib Ioff Voff Voff Drift Vout
- Iout
- Capacitance
- Stability
- Input Impedance
- Output Impedance
- GBW (G = 1)
- Slew Rate
- Settling Time
- (0.01%) Vn
- (RTI) In
- PSRR
- Channel Isolation
- Digital Level
- Data Format
- Throughput Channels
- –95 dB
- 100 kHz
- Binary
- 2s
- Multiplexed
- 16
- THD
- Cont.
- Current Forward
- Surge Current
- Reverse Leakage Current
- Total Capacitance
- Reverse
- Recovery Time
- Temperature Range
- –55 to +125
- Resistance
- Input
- No
- Missing
- Codes
- ILE Bipolar
- Error
- Gain
- Noise
- PSSR
- –95 dB
- 100 kHz
- 5.5V
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- THD
- Cont.
TI Coprocessor (option B)

FPU Coprocessor (option A)

DICE Science Payload Board

T. Neilsen

1.05VD Generation