Systems Engineering of the Double-Probe Instrumentation for Measuring Electric-Fields Cubesatellite

Seven M. Grover

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SYSTEMS ENGINEERING OF THE DOUBLE-PROBE INSTRUMENTATION
FOR MEASURING ELECTRIC-FIELDS CUBESATELLITE

by

Steven M. Grover

A report submitted in partial fulfillment
of the requirements for the degree
of
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in
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Logan, Utah
2013
Abstract

Systems Engineering of the Double-probe Instrumentation for Measuring Electric-fields
CubeSatellite

by

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This report presents the general mission overview of the Double-probe Instrumentation for Measuring Electric-fields (E-fields) (DIME) program. The Lessons learned from a previous program are summarized, and the subsequent changes to the main science instrument and overall satellite bus design are presented. The trade-studies, design, and systems engineering of the Double-probe Electric Field (E-field) science instrument is described. This report also outlines the overall mechanical design of a 1.5U CubeSatellite and its deployable mechanisms for use on the DIME program.

(49 pages)
I would like to thank Chad Fish for providing the opportunity to work on this project, as well as the support he has given throughout this work. I would also like to thank Drs. David Geller, Charles Swenson, and Stephen Whitmore for their guidance and support throughout my academic career.

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Chapter 1

Introduction

1.1 Mission Overview

The effects that space weather and high energy densities in the ionosphere have on radio frequency systems is a vital area in which to gain an increased understanding. The effects of the sun and the associated processes within the Earth’s magnetic field environment, as well as other disturbances, can have major detrimental effects on communications, navigation, and surveillance. While ionospheric electron density has been extensively studied with ground-based and space-based facilities, this has not been the case for the difficult to measure electric field. Ionospheric electric fields were recently identified as a high priority by the Department of Defense (DoD) Joint Requirements Oversight Council (JROC). Picosatellites (e.g. CubeSatellites or CubeSats) may play a key role in the future measurement and characterization of the Earth’s E-field, because of their low cost and the ability to deploy them rapidly. The low cost also enables multiple payloads to be placed in various orbits, forming constellations of satellites that are able to provide more comprehensive measurements. A satellite following another is able to make measurements at the same spatial location in the magnetic field at a different time, which is key to understanding variations in the electric field with respect to time. This ability is necessary in developing space weather models that can more accurately predict space weather. Space weather prediction can be used to anticipate impacts on communications and navigation.

The DIME mission as well as the preceding Dynamic Ionospheric CubeSat Experiment (DICE) mission is to measure the electrical field for high and low inclination Low Earth Orbit (LEO) orbits. DICE consisted of two identical CubeSatellites, each with a suite of science instruments that enable in-situ measurement of the Earth’s electric field, plasma density, plasma temperature, and the Earth’s magnetic field. The electric field is measured
using the double probe technique [4]. This technique has been used for several years [1], and was used recently on previous missions such as the NASA THEMIS and NASA FAST missions. This is accomplished using a miniature wire boom system that deploys 4 spherical sensors in a 10 meter tip-to-tip configuration. The electric potential between the opposite sensors provides the electric field measurement, which accomplishes the primary mission objective. The greater the distance between the sensors, the better the measurement.

Fig. 1.1: NASA THEMIS Mission used the double-probe technique

Because use of the double probe technology on a CubeSat platform is relatively new, and to raise the Technology Readiness Level (TRL) level of the instrument, its operation in different environments, such as variable plasma density and temperature, needs to be demonstrated. The double probe instruments respond differently depending on the plasma environment, specifically the plasma density and temperature. In addition, the motion of the satellite through the Earth’s magnetic field induces an electric field that is larger than the ambient electric field of the target measurement area. This induced electric field needs to be removed from the field of measurement. Thus, the Earth’s magnetic field must also be known. To make these measurements of plasma density, temperature, and magnetic field, each spacecraft is equipped with two Langmuir Probes (LP) (to measure plasma density and temperature), and a magnetometer (to measure the magnetic field).
The DICE mission successfully placed two CubeSats with these three science instruments into a high inclination LEO orbit on October 28, 2011. DIME is beginning phase II of an Air Force Small Business Innovation Research (SBIR), and is another important step in the development and demonstration of this technology on a picosatellite platform. The DIME instrument will improve upon the DICE design, and will demonstrate the feasibility of using CubeSats for unique and relevant science missions.

1.2 DICE Spacecraft Overview

To understand the changes that have been made in the DIME design, it is necessary to first have a general idea of the DICE spacecraft design and configuration. The DICE design will briefly be summarized. The E-field instrument used on the DICE spacecraft will be discussed in detail in Section 1.3.

The DICE spacecraft consists of a 1.5U (10x10x17 cm) form factor CubeSat. It contains a power system (i.e. batteries, 4 non-deployable solar panels, power regulating electronics), communication system (i.e. radio, turnstile antennas), command and data handling system (C&DH), attitude control system (ACS) (i.e. sun-sensor, magnetometer, torque coils, mass trim booms), a suite of science instruments and electronics, and a release mechanism for all deployable instruments. Though small, the complexity of the deployment mechanism and the concepts of instrument deployments is great. The deployed science instruments include the E-field instrument and the two LP’s on opposite faces of the spacecraft. The E-field system consists of 4 spherical sensors attached to 5 meter long booms. These sensors deploy using the satellite’s angular momentum to unwind the booms from a spool that is free to rotate about the spacecraft’s spin axis. The LP’s are deployed on two “scissor booms” to move them away from the body of the spacecraft. The turnstile antennas with attached mass trim booms are also deployed. The deployment is achieved by using a miniature titanium nickel actuator that breaks a frangible bolt. This allows a lever to move in the spacecraft, which simultaneously releases the two LP’s, the antenna/mass trim booms, and unlocks the rotation of the E-field instrument spool. The deployed spacecraft is shown in Fig. 1.3. The E-field instrument is located within the satellite where the gold-plated spheres
can be seen in Fig. 1.2.

1.3 E-field Instrument Design Overview

It is useful to examine the E-field instrument which was developed and implemented on the DICE program. The experience gained through the DICE program is useful only when applied. By examining the lessons learned from the DICE design, DIME can provide a more reliable and robust design, which can result in a simpler, more cost-effective assembly.

The design described in this section and shown in Fig. 1.4 is one of the original
designs from the DICE program [3], and represents a baseline by which lessons learned and improvements to the new design are derived from. The final configuration of the DICE E-field instrument will also briefly be summarized. The E-field instrument is a mechanical platform with 9x9x2.5 cm dimensions. These small dimensions allow it to fit within the CubeSat form factor. It is composed mostly of non-magnetic materials to avoid contamination of the sensitive magnetometer on the spacecraft that is used to measure the magnetic field of the earth. Some fasteners and springs are made of stainless steel series 304 and 316, which exhibit magnetic properties that are mild enough to avoid degradation of the magnetometer measurements.

1.3.1 Spool Assembly

The spool is a multi-layered assembly that four booms, each one being 5 meters in length, are wound around. The spool consists of an outer rotating component, and an inner stationary component. Each boom consists of a 24 AWG wire with a gold plated tungsten spherical sensor attached at the end. Each of the four booms is wrapped on the outer-spool in a clockwise direction. There are spacers of a specified thickness between layers that allow for one single layer of wire to be wound around the spool. This avoids cross over and tangling
of the wires in their respective layers. The inner-spool is a non-rotating component that is fixed to the spacecraft body. A counter-wrapped ribbon cable with 5 strands connects to the respective booms on the outer-spool. The fifth wire of the inner-spool ribbon cable is used as a common electrical ground.

After ejection from the Poly-PicoSatellite Orbital Deployer, (PPOD) and after successful completion of system checkouts, the spacecraft aligns itself in the desired configuration with respect to the earth’s magnetic field, and spins up to a specified rate about its z-axis. The outer-spool (rotating component) is allowed to move using a braking mechanism that will be described in Sections 1.3.2 and 2.1. The rotational inertia of the 4 spherical sensors enables the booms to deploy. As the outer-spool rotates and the booms deploy, the wire on the inner-spool unwinds. After completely unwinding, the inner-spool wire begins re-winding in the same direction as the outer-spool wire. This principle is illustrated in 1.5. This allows a direct point-to-point electrical contact from the spherical sensors to the science electronics. As the booms deploy, the angular velocity of the rotating spacecraft decreases as the moments of inertia change. After the booms have completely deployed, the spacecraft will be at some nominal final spin rate, which allows the booms to remain taut. An exploded view of the spool assembly is shown in Fig. 1.6.

Fig. 1.5: Concept of Instrument Deployment using Counter-Wrapped booms
1.3.2 Brake Assembly

The original E-field instrument design for DICE controlled the spool deployment using a friction brake that constricts a fiber (Dyneema or Kevlar string) about a brake ring. The brake is actuated by a mechanism driven by a linear piezoelectric motor developed by New Scale technologies. The piezoelectric motor moves a lever that constricts the fiber around the ring. This enables the use of friction to control the deployment rate of the wire booms, and also to prevent the booms from unwinding during the spacecraft’s spin-up phase. The braking mechanism on the underside of the deck plate is shown in Fig. 1.7. Because the linear motor has a limited range of travel, and is not capable of relatively significant loading, the length of the lever used for the actuation is necessary to achieve the required amount of motion to actuate the brake. The issues that were experienced with this design, as well as the final design used for DICE will be discussed in Section 2.1.

1.3.3 Corner Mount Assembly

The corner mounts serve as the interface for the spherical sensors. Each mount consists of an aluminum block with a spherical cutout, in which the spherical sensors sit. The mounts are gold plated, and serve as an electrical ground for the sensors to the spacecraft until they are deployed. The mounts also provide secure stowing of the sensors during launch.
One of the potential issues in deploying long wire booms from a rotating spacecraft with imperfect moments of inertia (MOI) is oscillations of the booms during deployment. This and other general stability topics will be discussed further in Sec. 5. In order to dissipate any oscillations of the boom as it is deployed, each mount also has a damping washer which provides damping friction to remove oscillations over time. As the boom oscillates, the washer moves within its socket. The contact between the washer and the corner mount assembly produces a very small amount of friction. The corner mount assembly is shown in Fig. 1.8.
1.3.4 Deck Plate

The spool assembly, braking mechanism, and corner mount assemblies are mounted on a printed circuit board (PCB). This board serves as the platform or deck plate of the E-field instrument. The deck plate is the interface to the CubeSat via a mounting bracket. The PCB has some integrated electronics (e.g., optical encoder to track rotation of the spool), but its main purpose is to be an interface. Mounting is made possible by using threaded nuts soldered directly onto the PCB. The deck plate is shown in Fig. 1.6.

1.4 Report Overview

In this project, design concepts based on lessons learned from a previous project were developed for a 1.5U CubeSat that has an E-field instrument, LP’s, and a magnetometer. The project develops the design to have improved dynamic stability and less complexity. This decreases the probability of mission failure.

Moving forward in the report, Chapter 2 presents the various issues and lessons learned from the DICE program that were considered as the DIME design was developed. Chapter 3 details the improved design of the DIME E-field mechanism. Chapter 4 similarly talks about improvements to a satellite bus that serves as the platform for the E-field instrument. Both Chapters 3 and 4, which summarize the new DIME design, are based on the discussions in Chapter 2. Chapter 5 discusses the impact that changes to the DIME design have on spin stability. The inertia matrices and nutation of both DICE and DIME are compared.

Direct contributions to the project are the review of lessons learned from DICE and development of design improvements to address those lessons learned. These improvements include the design of rigid, simple deployables and mechanisms, design and engineering of a system that is inherently dynamically stable for spinning about a specific axis on the spacecraft, design and development of deployable solar panels with spring-loaded hinges, and incorporation of balancing masses that can be used to align the spacecraft’s principle moments of inertia with the spacecraft’s rigid body axes. An innovative approach for the deployment of the E-field booms, LP’s, and magnetometers is also developed.
Chapter 2

DICE Lessons Learned

The final assembly, integration, and testing of the two DICE spacecraft occurred mainly over the summer of 2011, the same year that the spacecraft were launched into orbit. Sections 2.1 through 2.6 outline several of the lessons learned during this critical time period. The final designs of the braking mechanism and bushing used on the DICE spacecraft are also described in Section 2.1 and 2.4, respectively.

2.1 Braking Issues

Many of the early issues of the DICE E-field instrument were related directly to the braking system. The linear piezoelectric motor and associated mechanical system in the original DICE design did not meet the braking force requirement. The design went through several iterations using various brake levers and constricting fibers, all in conjunction with a brake ring. However, performance was not sufficient. The spool tolerance stack-up, which is demonstrated in Fig. 2.1, resulted in enough tilting and radial play in the rotating spool that when the braking mechanism was actuated, the constricting fiber pulled the spool to the side. In other words, the braking mechanism first had to take up the slack in the system due to loose tolerances before any effective braking could occur. However, the braking mechanism, comprised of the mechanical lever and the linear motor, did not have enough linear travel to fully actuate the brake. The brake ring also had problems with circularity, which contributed to varying and non-repeatable braking forces. The braking force required for the controlled deployment was not met, nor were test results of the braking mechanism repeatable.

Because of the issues associated with the constricting friction brake described in Section 1.3.2, the final design included a rocker arm with teeth on both ends of the arm that engage
Fig. 2.1: Impact of spool tolerance stack up

A brake ring with teeth. Rather than a friction brake, it acts similarly to an escapement mechanism such as one might find in a watch or clock. This escapement mechanism concept is shown in Fig. 2.2. The motor rapidly travels back and forth, alternatively pivoting the rocker arm in both directions, which allows the spool to rotate approximately 3.5 degrees per stroke of the motor. This meant that the spool released a maximum of 0.1 inches of boom wire per motor stroke. In this manner the booms can be released in a controlled, but slow, deployment. The releasing motion of the spool is dependent on the presence of a sufficient amount of angular momentum of the spheres (i.e., the satellite must be rotating about its nominal spin axis at a predetermined spin rate). The original spool bushing was also modified to reduce the rocking/tilting of the spool, as well as remove some of the radial play. This was the design used on the DICE E-field instruments at the time of launch. It is a complex assembly with sensitive tolerances, which required laborious fine tuning. Even though the spool tilt and radial play were not completely corrected, the mechanism performed the controlled deployment as required, albeit very slowly.

A simpler, more robust and reliable solution to this issue is to use a rotary piezoelectric motor which can act as the brake. Rotary piezo motors have a common characteristic of a zero-power holding torque. When the motor is not powered, it will not rotate unless the minimum holding torque is overcome. This eliminates the need for a complex braking
mechanism with several parts and pieces, and also relaxes (to an extent) the requirements for reduced spool rocking and tilting. The reason for this is that introduction of a rotary motor would effectively reduce spool rocking and tilting, because the motor itself would become the bearing for the spool assembly. Care must still be used for tolerance analysis and stack-up.

Fig. 2.2: Final DICE Braking mechanism design

Fig. 2.3: Braking Issues
2.2 Winding Issues

The winding of the 4 booms on the spool involved a complex process. Each boom had to be precisely measured. The spool was attached to a winding jig with 4 aluminum reels and weights. Each boom is inserted through its respective slot and attached to the top of the outer-spool, which is where the boom wires interface directly with the inner-spool ribbon cable, which leads directly to the science electronics. The boom is then wound, using the weights on each boom to provide approximately constant tension winding on each boom. The fixture used to wind the DICE spool is shown in Fig. 2.4. Despite these efforts, uneven boom lengths were observed during winding. One of the reels had a broken bearing, which may have resulted in different tension from the other booms. Variable tension on the wires could cause uneven packing of the booms on each spool layer. Then, if wire tension is relieved when the spool is removed from the winding jig, the spool wires can “unwind” slightly, causing variable lengths during final assembly. There could also be variability in the material properties of the boom which could result in uneven lengths. If the spool was correctly wound with no observable difference in initial boom lengths, after testing, one of the booms was consistently a different length after attempting to rewind the spools without disassembling the spool. In order to address this issue, spring loaded corner-mount assemblies were used. These are shown in Fig. 2.2. This allowed the boom wires to remain under tension after winding and prior to deployment of the spool.

The solution to this problem requires consistency. The winding jig used for the boom winding should be fully functional, with bearings and reels having similar friction properties. There also seems to be an optimal tension for the booms that results in consistent packing of the booms on the spools. There also must be a means to apply a consistent tension on the wires as the spool is removed from the winding jig.

2.3 Wire Issues

During integrated vibration testing of the DICE CubeSat, the locking mechanism of the spool failed, and the spool on the E-field instrument lost tension. The booms came out of the spool around the spool radius, much like Christmas ribbon on a spool will unroll from
a spool if it is not taped down. The result is a big tangle of wires that must be carefully untangled, and the spool must be rewound. The aftermath of this incident is shown in Fig. 2.5. The satellite had to be partially disassembled to reach the E-field instrument. The E-field instrument then had to be completely disassembled. The boom wires were then carefully disentangled. The spool had to be completely rebuilt. This was a very labor intensive operation, and the risk of damaging the boom wires was high.

To mitigate the risk of tension loss, a cover can be put in place that physically prevents
the wire from coming off of the spool. The cover needs to be close enough around the radius of the spool to prevent the wire coming off. A radial clearance of .006 inches would prevent the wire (approximate diameter of .020 inches) from falling off of the spool. The cover is also light (approximately 10 grams), and fits within the required space. The circularity and perpendicularity of the inner radius of the cover would be critical to avoiding interference with the rotating spool. If needed the inner radius could be coated with a thermal set lubricant, as referenced in Section 2.5.

2.4 Tolerance Issues

On the DICE instrument, standard tolerances caused assembly and performance issues, which can be seen in Fig. 2.6. With the initial brake ring concept, the non-concentricity of the ring combined with the radial play and range of tilting motion of the spool caused braking issues, as discussed in Section 2.1. The tolerance stack-up also resulted in difficult assembly because of hole misalignment between the several layers (14 layers). Each layer has several holes in a circular pattern that interface with adjoining layers. 3 alignment pins were used in three of these holes to build up the layered spool. In some orientations, the pins would not fit through the interfaces holes of all 14 layers, and a new configuration, achieved by rotating individual layers was necessary.

The optical encoder was also impacted by the tilting of the spool during braking operations. The encoder required the spool to rotate at a certain height and angle above the sensor. This issue was improved by using an aluminum bushing with less clearance than the previous design. There still remained an undesirable amount of tilting in the spool, however. The final DICE bushing had +/- 0.005 inches of radial play, and 0.72 degrees of tilt.

It will be necessary on a final design to perform a tolerance analysis to provide better parts for overall instrument assembly, and for instrument performance based on mission requirements.
2.5 Shielding and Lubricant Issues

At one point in the DICE program, graphite was considered for use as a shielding material for the boom wires, as well as a lubricant for the spool bushing. However, use of graphite presented several problems and risks. Graphite is electrically conductive. Graphite powder from the wires would get on the electronics during assembly and testing, as shown in Fig. 2.7. Graphite can also be corrosive to aluminum. Also, after applying the graphite coating to the boom wires, it was observed that the wires became much stiffer, making it difficult to bend them around sharper radii.

A wire that is already shielded and insulated is the optimal solution, as it reduces the time required to prepare the boom wires, and reduces particulate contamination. A wire that is shielded using stranded mesh wires can be purchased. This wire will retain a large amount of flexibility, allowing the wire to bend around sharp radii.

It was also learned that graphite does not function as a lubricant in a vacuum environment, due to the lack of moisture and air. Molybdenum Black Magic spray on lubricant was used in the final design. A thermal set Black Magic lubricant would be more robust than a spray-on lubricant. Another solution is to use a commercial bearing that does not require lubricant.
2.6 Bus Stability and Power Issues

The DICE spacecraft has potential stability issues. Because the E-field instrument is located well above the spacecraft’s center of mass, any mutation of the spacecraft, as well as any oscillation of the booms with respect to the other booms places uneven moments on the spacecraft. If these moments are large enough, they could cause the spacecraft to lose a stable spin about the desired spin axis. This is a result of the relatively large moment arm from the boom wires to the spacecraft’s center of mass. Another stability issue stems from the DICE mass trim booms. The complex deployment of these booms has a moderate risk of partial deployment. This would result in uneven moments of inertia, which would prevent the spacecraft from entering into a stable spin about the desired spin axis.

Another general issue faced by the DICE is insufficient power budget margin. The DICE spacecraft has a total of 12 solar cells. There are 3 solar cells on each of the 4 long panels on the exterior of the spacecraft. Because the DICE spacecraft is almost in a polar orbit, as the spacecraft orbit precesses around the Earth, there are periods of time when the spacecraft is in eclipse for a large portions of time during several weeks. There are times during which power on the spacecraft drops low enough to cause a reset of the spacecraft, and spend large amounts of time in a mode that does not allow ground contact with the satellite.
2.7 Dime Solutions

All of these lessons-learned from DICE presented in this report have been considered in the DIME design, and provide a baseline for improvements to the instrument design and the overall spacecraft design. A summary of potential solutions to the issues described in Section 2 is given here:

- Apply minimum tension necessary during boom wind, and provide means to maintain tension when removing from the winding jig to avoid wire coming off of the spool
- Use spring loaded cams/levers to maintain tension on the booms during assembly and to securely stow the sensors in corner mounts
- Implement a spool guard to prevent the boom wire from uncoiling from around the spool radius if loss of tension should occur
- Perform tolerance analysis to reduce undesirable play in the spool that causes mechanism braking issues
- Purchase a commercial precision bearing to reduce spool tilt and play, and to reduce complexity of assembly
- Purchase wire that already has shielding to have the best balance of wire strength and flexibility, and to reduce assembly time by not having to coat wire with shielding material
- Implement a rotary piezo motor to actively control spool deployment, allow for faster deployment testing of the E-field instrument, and also reduces required assembly time by replacing a complex braking mechanism
- Locate E-field instrument at the plane where center of mass is located to minimize disturbance torques resulting from satellite nutation
- Include deployable solar panels to provide margin to the power budget and to improve moments of inertia about the spin axis
• Use embedded antennas on deployable panels to avoid complex antenna deployment

The goal of these improvements is to increase ease of assembly, reliability, and functionality of the instrument and satellite.
3.1 Motor Trade-study

The previous design from the DICE program used an escapement braking mechanism, which was composed of a linear piezo electric motor and mechanical linkage to actuate the mechanism. The close tolerances and small movements of the mechanism meant that a great amount of fine-tuning was needed for reliable operation. An optimal solution that simplifies the assembly and the operation of the spool is to implement a rotary motor, which can act as the braking mechanism. It is necessary to use a piezo electric motor to avoid magnetic contamination of the science magnetometer. This narrowed the possibilities. The search was further refined by performing a trade-study evaluating several rotary piezo-electric motors. The trade-study is shown in Fig. 3.1. The motors in the trade-study are shown in Fig. 3.2.

Because of the requirement that the motor be non-magnetic, a piezo-electric technology is the best fit. The motors considered in the trade-study were all rotary piezo motors. The parameters considered were drive direction (uni/bi-directional), travel range, maximum speed, stall torque, zero-power holding torque, dimensions, operating temperature,
maximum power, mass, and cost.

It is desirable to have a bi-directional motor, because the motor can then be used to re-stow/re-wind the booms, rather than having to manually rewind the spool. Manual rewinding of the spool can result in uneven packing of the boom wires. Also, if the spool is being tested while integrated in the CubeSat bus, the spool can simply be rewound without removing the instrument from the CubeSat interior. This results in time/cost-savings, and less risk of damaging the spool wires.

Maximum speed was simply a parameter that was considered, but there is no firm requirement regarding the speed of boom deployment. Because the centripetal reactive force on the E-field sensors is great enough to unwind the booms from the spool, the motor is only acting as a brake. Operation of the motor only controls the speed of the deployment by releasing the holding force exerted on the spool. However, a slower deployment allows time for oscillations in the booms to dampen, which results in less induced moments on the spacecraft body, and less rotational instability.

The zero-power holding torque is one of the key parameters of the trade-study, and indicates the force available to prevent the booms from releasing during spacecraft spin-up. The holding torque is a key part of the ability to actively control the boom deployment. The maximum expected torque/force occurs shortly after initial boom deployment. Figure
3.3 shows the force on a single boom throughout deployment, using an initial spin-rate of 2 Hz. The maximum torque exerted on the spool by the deploying booms is approximately 91.5 N-mm.

The size of each motor was also an important factor in the trade-study. Most of the motors available are too large for use in the CubeSat, and would extend far below the desired envelope for the instrument. This would require extensive changes to other components in the spacecraft, and result in less available volume for electronics and hardware. Especially with a desire to eventually use the E-field instrument in a 1U CubeSat, these larger motors are not feasible.

The clear choice from the trade-study is the PCB motor, because of its low profile, zero-power holding torque, and ability to rotate the motor in both directions. The motor profile is shown in Fig. 3.4. The stator of PCB motor is slightly thicker than a PCB (0.063

![Fig. 3.3: Deployment Forces in E-field Boom Wire](image1)

![Fig. 3.4: PCB Motor Profile of Stator and Rotor Base](image2)
inches), and uses a ring of small piezo components mounted on two sides of a stator ring that is milled onto a PCB, as shown in Fig. 3.5. The stator ring has different dynamic response than the rest of the PCB. It is this dynamic response that makes the operation of the motor possible. The rotor is completely defined by the user, and generally consists of two discs pressed around the stator. A standing ultrasonic wave form is then generated on the stator, which induces a rotary motion of the rotor. This directional vibration of the stator occurs at approximately 45 KHz. This concept is shown in Fig. 3.6. The zero-power holding torque is determined by the compressive force of the rotor discs upon the stator ring, and upon the friction properties of the rotor against the PCB. This technology would need to be verified through testing of an actual prototype PCB motor.

Fig. 3.5: PCB Motor Components

Using PCB motor technology, a custom designed PCB could potentially include electronics for driving the motor, data processing (although this will probably still take place on a separate electronics board), interfaces for fasteners and mechanisms, and encoder electronics (if required). The spool will act as the rotor for the DIME application.

The PCB motor concept for DIME is shown in Fig. 3.7. Two disks will be machined from G10 or FR4. These disks will have a radial pattern of curved beams which will allow the center of the disks to deform vertically. The center ring of each disk will be attached to the opposite disk via three fastener holes. Each faster will use a combination of shim
washers to obtain the required amount of disk deflection. These two disks will then be pressing down upon the PCB motor stator with a specified amount of force needed for the motor’s operation. The DIME spool will be built upon the top disk.

3.2 Precision Bearing Trade-study

The DICE E-field mechanism used an aluminum bushing as a bearing interface between the rotating outer-spool and fixed inner-spool. The final design of the bushing allowed for tilting of the spool spin axis up to 0.72 degrees, and radial translation of the spool of approx-
imately 0.005 inches. The combination of tilt and radial play negatively affects the braking mechanism performance and encoder operation. Because of this, the braking mechanism required fine tuning for proper performance of the encoder and reliable deployment of the booms. The encoder missed approximately 1 out of 1680 ticks per revolution on the final configuration. Though this was sufficient to meet the requirements on the DICE spacecraft, use of a more precise bearing part will improve spool deployment and retraction during test operations, as well as allow for more repeatability in the assembly and testing operations. Use of a precision bearing reduces spool play and tilting.

Because there is no room for vertical growth, the bearing considered needs to have a low axial profile. The bearing must also be able to support both a radial and axial load to withstand the loads that are present during the launch phase of the mission. The combination of these constraints narrows the types of bearings that may be considered.

The optimal type of bearing for this mission is a full ceramic radial ball bearing, which is well-suited for both axial and radial loads. There are several different tolerance levels available which satisfy a large range of different requirements. The bearing selected in the trade-study has a specification of ABEC Grade 5P, which has radial translation of approximately .0005 inches to .0008 inches. This is an order of magnitude less that occurred with the DICE bushing. With radial play specification P13, the free angle of misalignment (tilt) is 0.24 to 0.42 degrees. The final tilt and play in the spool also depends largely upon the interface of the bore and the shaft elements that the bearing is mounted to. This bearing sufficiently reduces play in the spool, which allows the brake and encoder to function correctly.

Use of a ceramic bearing avoids magnetic contamination of the science magnetometer. The outer and inner races are zirconium oxide ceramic, and the balls are silicon nitride ceramic. Because of the properties of these materials, the bearing may be used without lubrication. While there are lubricants that have low-outgassing characteristics and function well in a vacuum environment, it greatly simplifies assembly and cleanliness requirements if a lubricant is not needed. Ceramic materials are very hard, and at slow to moderate speeds
do not require a lubricant. The ceramic balls also increase the stiffness of the bearing. The outer race will be press-fit in the stationary inner-spool interface, and the inner race will have a loose-fit interface with a shaft that connects to the rotating outer-spool. The bearing in the spool assembly is shown in Fig. 3.8. The outer-spool can be attached to the bearing interface with a fastener, which allows the outer-spool to be removed without removal of the bearing itself.

When this bearing is used in conjunction with the PCB motor, the tilt is not as critical. The outer-spool will be pressed against the piezo elements on the PCB, which effectively removes tilting from the assembly. Radial play of the outer-spool is still fairly critical, because the spool needs to remain concentric within other parts on the E-field instrument (e.g. the spool cover), and within the CubeSat.

![Cross-section of bearing in the DIME E-field Spool Assembly](image)

**Fig. 3.8: Cross-section of bearing in the DIME E-field Spool Assembly**

### 3.3 Boom Wire Trade-study

Several factors were taken into consideration in the boom wire trade-study. The wire was required to be shielded, have sufficient strength to withstand launch loads and deployment loads, and also needed to be no larger than the wire used on the DICE program. Using the same overall diameter of wire allows the height of the spool to remain unchanged. The wire also needed to have very little memory, and be very flexible. This will reduce the risk of damaging the wire during assembly and testing, and will also enable the booms to
be as straight as possible after deployment on orbit.

The wire selected is a Calmont 38 AWG silver-plated stainless steel stranded wire. This wire was selected because of its small size, shielding, tensile strength, and flexibility. The shield is a braided stainless steel. The insulation is Teflon. The overall diameter of the wire is approximately 0.020 inches, which is equivalent to the overall diameter of the wire used on the DICE program.

![Fig. 3.9: Layers of an insulated, shielded wire](image)

### 3.4 Spool Guard Concept

A spool guard, such as the one shown in Fig. 3.10, addresses the issue described in Section 2.3 that was experienced during assembly and testing of the DICE E-field instrument. This guard would provide a physical barrier that prevents the wire from coming off of the spool. With a clearance of 0.006 inches, the wire cannot physically come off of the spool. The concentricity and circularity of the entire assembly become critical with the spool guard in place, since the clearance between the rotor and guard is minimal. It may be desirable to apply a thermal set lubricant (Black Magic) to the interior of the spool guard to mitigate the risk of increased friction between the spool and the spool guard. Tolerance analysis would be necessary. It will also be critical to avoid sharp edges in the guard which have the potential to damage the wire.

The spool guard may also be broken up to consist of 4 separate pieces, which could be adjusted using slotted holes. This would address some of the manufacturing issues of achieving tight concentricity on a single piece spool guard.
Fig. 3.10: Spool Guard Concept
Chapter 4

DIME CubeSat Bus

A 1U and 1.5U CubeSat bus concept have been developed for the use of the DIME of E-field instrument. Although the remainder of this study will focus on the 1.5U bus, there are advantages with using the 1U bus architecture, such as improved stability. This results from having a CubeSat that is “short and squat” rather than “long and skinny”. Some of the broader improvements to the CubeSat bus are based on observations of the DICE bus. These include considerations for improving moments of inertia, power budget, and instrument location. The 1.5U concept is shown in Fig. 4.1.

![Fig. 4.1: 1.5U DIME Spacecraft Concept](image)

4.1 Power

The DICE spacecraft has a power budget that occasionally results in reset of the satellite when the battery voltage drops too low. To remedy this, the DIME CubeSat bus has four deployable solar panels that have high efficiency solar cells on both sides of the
deployable panel. The DICE CubeSat has 12 solar cells. The DIME Cubesat has more than 24 solar cells. Prior to launch and deployment, the deployable panels are held in place by a frangible-bolt (e.g., TiNi Aerospace’s Frangi-bolt) or string-cutter release mechanism. After the mechanism releases, the 4 panels each rotate 135 degrees about a line parallel with the spin-axis (Z-axis) of the satellite. The panels each have two spring-loaded hinge mounts attached adjacent to the CubeSat rail. While it may be possible to incorporate some kind of locking mechanism that will lock the panels into their final deployed position at the appropriate angle, because of the small size of the spring-loaded hinge mounts, this feature has not yet been added. Enough torque will be available to prevent the panels from moving in and out of the final position.

The panels also will provide a platform for the science instruments, antennas, and spin balance mass elements, as shown in Fig. 4.3.

4.2 Moments of Inertia

To improve the moments of inertia on the DICE spacecraft, mass trim booms were
Fig. 4.3: DIME Deployable Solar Panel

added as extensions to the live antenna segments of the turnstile antenna. The mass trim booms are spring-loaded brass tube segments that can be folded up and stowed (similar to segmented tent poles), as shown in Fig. 4.4. The final element consists of two brass tubes, each with a tungsten rod inserted permanently in the tube. Spring margins of the boom hinges were analyzed and determined to be large enough to deploy the booms in a microgravity environment while in orbit. Data from one of the spacecraft indicate that one of the booms may have only partially deployed. Because the spacecraft will always rotate about the greatest primary moment of inertia [2], the spacecraft will never be able to maintain a passive spin about the desired spin axis unless the boom does fully deploy. The deployed configuration of DICE is shown in Fig. 4.5.

The DIME spacecraft uses a similar method of improving moments of inertia to achieve the desired spin axis. Rather than using segmented booms with large masses on the end, however, DIME takes advantage of the deployable solar panels. These panels are deployed in an X-wing configuration. Each panel has mass elements along the edge that is farthest from the spacecraft’s center of mass, providing the greatest possible increase of inertia about the spin axis. These spin balance mass elements could potentially be composed of a dense material, such as a tungsten alloy. The size of the masses can be adjusted to obtain different margins in the moments of inertia. Prior to deployment of the E-field instrument,
it is desired to have a moment of inertia about the spin axis that is 25% greater than the other minor axis moments of inertia. This simply provides margin, and ensures that one axis has the greatest moment of inertia. This approach is much more simple than segmented booms, and the risk of a failed deployment is much less.

4.3 Instrument Deployment

On the DICE spacecraft, the E-field instrument is located just below the top of a 1.5U CubeSat. As the booms deploy, the moments of inertia drastically change. In a perfect
world, as the instrument deploys, the major axis (spin axis) moment of inertia would increase greatly as the spherical sensors and booms become farther away from the center of mass. However, small disturbance torques resulting from imperfect assembly and tolerances create unequal moments about the center of mass. If these disturbance torques were great enough, they could potentially cause the spacecraft to fall out of the desired spinning orientation, which would result in erratic motion of the booms. The erratic motion of the booms would result in constantly changing moments of inertia. Eventually, the spacecraft will find a minimum energy configuration, about which it will spin indefinitely. At this point, it would be impossible to retract the booms and attempt a second deployment.

A better configuration is to locate the center of the E-field instrument approximately at the CubeSat’s center of mass. Then, as the 4 booms deploy, disturbance torques would have a much smaller moment arm to react through. It is much easier for the spacecraft to remain in its low energy state with the spin axis being the desired spin axis of the instrument.

Because the DIME CubeSat has deployable solar panels, these can become the platform from which the E-field sensors are deployed. The instrument is located at the satellite’s center of mass, and the four sensors are stowed in the sockets that are attached to the solar panel edge farthest from the center of mass. After deployment of the solar panels, the major axis of the satellite is the desired spin axis of the craft, and the satellite can begin its alignment and spin-up maneuvers using embedded torque coils in the solar panels, and the Z-axis torque coil. The PCB motor is then utilized to allow the booms to release slowly. The torque that the sensors/booms exert on the spool should never exceed the holding torque of the PCB motor. The deployment sequence is shown in Fig. 4.6.

The DIME spacecraft simplifies the deployment of the science instruments that it supports. All deployable mechanisms and assemblies on the spacecraft can be stowed by a pair of wire-cutters or Frangi-bolt actuators, with one on the top panel of the satellite, and the other on the bottom. The wire-cutter concept is shown in Fig. 4.7. The string (similar to fishing line) is used to constrain the 4 deployable solar panels, as well as 2 stowing levers that constrain the magnetometer and LP. The wire-cutter is an assembly consisting
of a fiberglass fixture wrapped with Nichrome wire. When a current is passed through the
Nichrome wire, the string that passes over the loops melts, which allows the solar panels
to swing out, once the string on both top and bottom panels has been cut, and also allows
the stowing levers to rotate, freeing the LP and magnetometer booms.

The solar panels serve multiple purposes, including increasing the power budget, pro-
viding a surface on which balancing masses can be placed, as well as providing a mounting
point for the E-field sensors. These mounts consist of 4 sockets that are placed on the
center outer edge of each deployable panel. The boom wires come off of the spool, exit the
spacecraft chassis through 4 apertures, and run along the interior edge of the stowed solar panels. The wire booms are protected inside of a small Delrin or Nylon raceway. Each raceway terminates at the base of the sensor socket. As the panels deploy, the E-field boom wires need to remain in tension. The solar panel deployment decreases the length of wire needed to span from the E-field spool to the E-field sensor. In order to keep the E-field wire booms in tension, there is a tensioner for each respective wire, as shown in Fig. 4.8. As the panel swings out, the spring-loaded tensioner maintains a force on the wire, which keeps it in tension.

![Fig. 4.8: E-field Tensioner Assemblies](image)

Each deployable solar panel is rotated to its deployed configuration by two spring-loaded hinges. These hinges are required to have a very low profile of approximately 0.0625 inches when stowed in order to meet general CubeSat specifications. Each hinge has two 270 degree torsion springs mounted on a small pin that extends across the hinge. Each hinge also has flanges that prevent the hinge from opening more than 135 degrees. The springs have sufficient torque at the end of the movement to hold the panels in their deployed configuration as the satellite spins up in preparation for the deployment of the E-field booms.

The LP’s are deployed on a single rigid boom on the edges of the deployed solar panels. The magnetometer booms use an identical deployment technique. When in the
stowed configuration, the LP and magnetometer booms lay slightly recessed into the top and bottom panels. Two spring-loaded levers hold them in this position. Each boom is attached at the base to a socket mounted on the vertical edge of a deployable solar panel. An extension spring is fixed to the bottom of the socket, and the other end of the spring is fixed inside the base of the boom. Thus, in the stowed configuration, the extension spring is extended, and wraps around the edge of the socket to the base of the stowed boom. Upon release of the levers that constrain the booms, the extension springs pull each boom up from the panel on which it lay, and down into each boom’s respective socket, as shown in Fig. 4.10. The extension spring will fully contract, seating each boom at a specified distance within the socket, much like a segmented tent pole with an elastic stretched between segments. As the spacecraft begins to spin-up, the booms cannot flex or deform. This ensures that the spacecraft’s moments of inertia will remain constant during spin-up. This is a great simplification from the “scissor booms” used on the DICE spacecraft, which had over 9 moving parts. The simple design provides a more repeatable, robust, and reliable design.

4.4 Embedded Antennas

DICE used deployable turnstile antennas for UHF downlink and uplink. The DICE antenna/mass trim booms consisted of 4 brass tube segments. Each brass tube first had to
be soldered to a brass hinge joint. The final segment had two brass tubes soldered together, each with a tungsten rod encased in the tube. Each tube then had to have holes drilled, pins and springs inserted, and then the pin/solder joint had to be ground down.

The concept for DIME is to use embedded antennas that run along the edges of the deployable solar panels. With an embedded antenna, the trace for the antenna could be printed directly onto the PCB substrate for the deployable solar panel. The antenna is shown in Fig. 4.3. This allows for a simpler deployment sequence. The assembly is also simplified. In fact, with deployable solar panels that serve as mounting points for the LP’s, magnetometers, and E-field sensors, embedded antennas become necessary in order to keep the CubeSat within the envelope used in the CubeSat specifications and standards for deployment in a PPOD.
Chapter 5
Simple Dynamic Stability

One of the greatest improvements that can be made to the DIME spacecraft is the ability to achieve an inertia tensor that results in a more stable passive spin. The concept of dynamic stability is key in the deployment of the E-field instrument. The satellite will be put in a controlled spin via three mutually orthogonal torque coils. When the satellite reaches the required spin rate about the spacecraft’s long axis (Z-axis), the torque coils will no longer be used. The four E-field booms will be deployed in a controlled manner, using the PCB motor as a braking mechanism. Deploying the booms in a slow, controlled manner will provide time for any oscillations of the deploying booms to dampen out. As the booms move away from the spacecraft’s center of mass, the moments of inertia will dominate the inertia tensor, which will further stabilize the spin about the Z-axis.

The DICE spacecraft, in a deployed configuration, has the moments of inertia shown in Table 5.1. The ratio between Izz/Ixx, and Izz/Iyy are both 1.14. With an initial spin-rate of 2 Hz, this results in a nutation angle that ranges from 0.04 degrees to 0.53 degrees. Because the E-field instrument is located at the top of the satellite, slight nutation of the satellite during boom deployment can result in disturbance torques that lead to an unstable deployment. If the disturbance torques are large enough, it may cause the satellite to spin about an undesirable axis. This would result in a failure to properly deploy the booms in the desired orientation.

Table 5.1: DICE Inertia Tensor

<table>
<thead>
<tr>
<th>Moments of Inertia</th>
<th>Products of Inertia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ixx = 0.050288 kg-m^2</td>
<td>Ixy = 0.000005 kg-m^2</td>
</tr>
<tr>
<td>Iyy = 0.050273 kg-m^2</td>
<td>Ixz = 0.000015 kg-m^2</td>
</tr>
<tr>
<td>Izz = 0.057435 kg-m^2</td>
<td>Iyz = 0.000032 kg-m^2</td>
</tr>
</tbody>
</table>
Table 5.2: DIME Inertia Tensor

<table>
<thead>
<tr>
<th>Moments of Inertia</th>
<th>Products of Inertia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ixx = 0.013503 kg-m²</td>
<td>Ixy = 0.000195 kg-m²</td>
</tr>
<tr>
<td>Iyy = 0.013573 kg-m²</td>
<td>Ixz = 0.000044 kg-m²</td>
</tr>
<tr>
<td>Izz = 0.017216 kg-m²</td>
<td>Iyz = 0.000009 kg-m²</td>
</tr>
</tbody>
</table>

The DIME spacecraft has several advantages over the configuration of the DICE spacecraft, in terms of the flexibility to distribute mass around the satellite bus as to be most beneficial for an inertia tensor resulting in a stable passive spin. The DIME spacecraft in semi-deployed configuration, has the moments of inertia shown in Table 5.2. The ratio between Izz/Ixx, and Izz/Iyy are 1.28 and 1.27, respectively. With an initial spin-rate of 2 Hz, this results in a nutation angle that ranges from 0.15 degrees to 1.30 degrees. The DIME E-field instrument is located at the satellite’s center of mass. Even with slight nutation of the spacecraft body, the disturbance torques are minimal due to a very small moment arm about the center of mass.

In comparing the moment of inertia ratios between the DICE and DIME spacecraft, and the placement of the E-field instrument in the satellite bus, it can be seen that the DIME spacecraft has a much lower risk of dynamic instability. The nutation is slightly greater for the DIME spacecraft because of the larger products of inertia, which are present because of the magnetometer booms and LP booms.
Chapter 6
Conclusions & Future Work

The design of the DIME CubeSat takes several lessons learned from DICE into account. The design now needs to be validated by building, testing, and ultimately successful insertion into LEO. The configuration of the DIME spacecraft should enable a lower risk mission than the previous DICE spacecraft.

Future work could include further development of a 1-U bus, as shown in Fig. 6.1. Additional improvements to the E-field instrument, such as the feasibility of using slip-rings or platters to replace the inner-spool ribbon cable could also be investigated. Alternate configurations of the LP’s and magnetometers could also be considered to improve the satellite’s products of inertia. A trade-study should also be conducted to consider the feasibility of using the walls of the deployment device to constrain the deployable structures on the CubeSat, rather than having a holding mechanism (e.g. wire cutter or frangi-bolt actuator).

Fig. 6.1: 1U DIME Concept
As the design becomes more developed, actual materials are selected, and parts are fabricated, analyses will need to be performed to ensure the feasibility of the design. Some of the analyses that will need to be completed in the future are a thermal analysis, structural analysis, and tolerance analysis. One of the key things that will need to be analyzed thermally are the deployable panels and attached mechanisms. The deployable panels may experience large temperature swings, and thermal margins of the components should be quantified.

Another future improvement includes development of a CubeSat bus that can be used in Planetary Systems Canisterized Satellite Dispenser (CSD). This new CubeSat launcher physically constrains the satellite during the launch phase by pre-loading the payload to the CSD, which reduces non-linearities in the launch environment loads that are normally seen in a PPOD. This allows for more accurate dynamic modeling.

The DIME CubeSat is a complex satellite with multiple deployable instruments. It also serves as a platform for cutting-edge technology that performs a valuable science mission. It proves that CubeSats can play a viable role in the world of satellites.
References


