TELEMETRIC INTERPLANETARY REGOLITH EXPLORER FOR SEISMIC INVESTIGATION OF ASTEROID SURFACES

CRITICAL DESIGN REVIEW

Aerospace Engineering Sciences
University of Colorado
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OUTLINE

 Project Overview
 Design Solution
 Communications System
 Power System
 Mechanical System
 Project Planning
 Appendix
PROJECT OVERVIEW
MISSION CONOPS

1. **Deploy Explosive Pods (red) and GeoPods (grey)**
   - 18 month travel time
   - 14 hour settling time

2. **Spacecraft Orbits Asteroid for 10 days**
   - 0.1-10 km Range
   - 20 minute contacts every 2.26 hours

**Deploy, Descent, and Landing**
- Accel is turned on; GeoPod is separated
- GeoPod records data while descending
- Touchdown with surface, data recorded while settling
- 300 min

**Surface Operations**
- Explosive Pod detonates; GeoPod collects data with Accel and Geophone
- Science data transmitted when link is available with the orbiting satellite
- 10 min

**TIRESIAS Focus:**
- GeoPod
  - Power
  - Communication
  - Internal Structure

- 10 days
- 14 hours
During this time, the power system must regulate and distribute power to all of the components.

Heaters are not necessary for ground testing. Representative loads will be used for simulation.

The internal structure must integrate the components and the power system into the GeoPod shell (provided by Ball).

- Thermoistors w/MUX
- Receiver
- ADC

PROJECT CONOPS

- Power
- Transmitter
- Receiver
- C&DH Board
- Internal Structure
- 1.5 ft
- 3 lb weight

- Antenna

- 1 ft

- Commands are received over the next 20 minutes to start transmissions of data.

20 minutes represents a contact window.

Our project will sample each axis of the accelerometer twice to simulate the GeoPhone, because commercial GeoPhones are too large, heavy, and expensive for our project.

- Ball is receiving a custom GeoPhone.

Communication System

- ADC converts 6 analog channels (2 signals for each accelerometer axis) into a digital signal.
- C&DH board samples and stores the digital data from the ADC at 500Hz.
- Data from the multiplexed thermistors (housekeeping data) is sampled at 500Hz and stored at 80 bits/s.
- The C&DH Board continues to sample both the accelerometer data and the thermistors for 15 minutes.

BASIX mission will use both the 3D GeoPod and the GeoPod shell. The GeoPod shell represents a contact window necessary for ground testing.
DESIGN SOLUTION
DESIGN OVERVIEW

Batteries  Internal Structure  Transmitter  Receiver  C&DH Board  ADC Board  Power Board  Accelerometer

Project Overview  Design Solution  Comm System  Power System  Mechanical System  Project Planning
<table>
<thead>
<tr>
<th>Element</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSN.1</td>
<td>Mass</td>
<td>Total mass of geopod shall be less than 5 kg</td>
</tr>
<tr>
<td>MSN.2</td>
<td>External Shell Integration</td>
<td>All subsystems shall be integrated into existing 3000 mL spherical external shell</td>
</tr>
<tr>
<td>MSN.3</td>
<td>Data Collection</td>
<td>The GeoPod shall collect and store accelerometer and housekeeping data</td>
</tr>
<tr>
<td>MSN.4</td>
<td>Transmission</td>
<td>The GeoPod shall be capable of transmitting all collected data to the Ground Station Equipment (GSE) within the mission duration</td>
</tr>
<tr>
<td>MSN.5</td>
<td>Thermal Range</td>
<td>The GeoPod shall be kept within the operating temperature range of GeoPod components</td>
</tr>
<tr>
<td>MSN.6</td>
<td>Power</td>
<td>The GeoPod shall be able to power itself for the mission duration</td>
</tr>
<tr>
<td>MSN.7</td>
<td>Path to Flight</td>
<td>The designed subsystems shall have no critical obstacles in their development toward a space-qualified system</td>
</tr>
</tbody>
</table>
MASS AND VOLUME

Mass Budget [kg]

- Margin, 0.66 kg
- External shell, 1.09 kg
- Batteries, 1.80 kg
- Internal structure, 0.95 kg
- Transmitter/Receiver, 0.22 kg
- Arduino Due, 0.04 kg

Volume Allocation
COMMUNICATIONS SYSTEM

- External Structure
- Temperature Monitoring
- Ground Support Equipment
- 2 kbps
- 437 MHz
- 32 kbps

- Internal Structure
- Power Board
  - Power Regulation, Distribution, and Monitoring
  - Switches
  - 20V
  - 5V
  - 12V
  - 27V
  - SPI 96 bit

- 12V Batteries
- 27V Batteries

- ADC Board
  - Condition Accel data and convert to digital
  - 3-axis 16 bit 500Hz

- Accelerometer
  - Piezoelectric

- Antenna
  - Transmit and Receiver
    - Sends data and receives commands
    - TTL
  - Comm Board
    - Processes commands and forwards data

- Software
- Flash Memory
  - SPI
  - 3.3V
  - 9V
  - 27V

- Provided By:
  - Tiresias
  - Purchased
  - Ball

- Power
- Telemetry
- Commands
**Project Overview**

**Design Solution**

**Comm System**

**Power System**

**Mechanical System**

**Project Planning**

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**Comm Requirements**

**Max. Amplitude:** 0.2 g’s

**freq < 50 Hz**

**Expected Example Signal to ADC**

**Rotational Period = 2.4 hrs**

**Orbital Period = 124.1 hrs**

---

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Flows From</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COM.1</td>
<td>MSN.3</td>
<td>6 channels of science data shall be sampled at 500 Hz.</td>
</tr>
<tr>
<td>COM.2</td>
<td>MSN.3</td>
<td>Science data shall be recorded such that a range of -2g to 2g is quantized with a resolution of 0.002g</td>
</tr>
<tr>
<td>COM.3</td>
<td>MSN.3, MSN.4</td>
<td>The C&amp;DH board shall interface with ADC, memory, power board, and RF system.</td>
</tr>
<tr>
<td>COM.4</td>
<td>MSN.4</td>
<td>Uplink data rate shall ensure all stored telemetry is transmitted during the 20 min contacts over 10 days</td>
</tr>
</tbody>
</table>
**ACCELEROMETER - ICP 356M98**

**Driver**
- **COM.2** - 0.002g Resolution, 4g range

**Solution**
- Output range = 1.5V to 8.5V
- Data range = -5g’s to 5g’s
- Resolution = 0.0006g’s

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**Diagram:**
- Accelerometer
- ADC
- CCSC
- VD
- LPF
- 3-17V
- 20V
- 1.5-8.5V
- SPI Interface with C&DH Board

---

**Graph:**
- Noise Measured in Lab - Bias Removed
- Lab Noise
- Zero
- ADC LSB
- Noise RMS
TI ADS8555 ADC

**Driver**
- **COM.3** – Component interface

**Solution**
- SPI protocol
- Compatible with 3.3V logic levels

**Driver**
- **COM.1** – Sample 6 channels at 500Hz

**Solution**
- 6 channel ADC
- Max sampling rate of 450kHz
COMMAND & DATA HANDLING
**ARUDOINO DUE MICROCONTROLLER**

**Project Overview**
- **Design Solution**
- **Comm System**
- **Power System**
- **Mechanical System**
- **Project Planning**

**Temperature Sensor System**
- Analog Temp.
  - High or Low

**Component On/Off**
- High or Low
- SPI

**Flash Memory**
- SPI

**Driver**
- **COM.1** – Science data sampled at 500Hz
- **COM.3** – Component interface

**Solution**
- 84 MHz CPU Clock
- TTL interface with RF components
- Extended SPI library interface with ADC and DataFlash memory

**Analog to Digital Converter**
- Vref
- SPI
- TTL

**Transmitter**
- TTL

**Receiver**
- TTL

**ARDUINO DUE MICROCONTROLLER**

**Driver**
- **COM.1** – Science data sampled at 500Hz
- **COM.3** – Component interface

**Solution**
- 84 MHz CPU Clock
- TTL interface with RF components
- Extended SPI library interface with ADC and DataFlash memory
**Driver**

- **COM.1** – Science data sampled and recorded at 500Hz
- **COM.3** – Component interface

**Solution**

- 64Mb of data storage (Arduino Due only has 96 KB of SRAM)
- 66 MHz clock facilitates write speed
- SPI interface and 3.3 V compatibility with Arduino
- Data formatted and stored into packets based on CCSDS standard:

**Memory**

<table>
<thead>
<tr>
<th>Amount</th>
<th>Data Rate</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science</td>
<td>20 min</td>
<td>28.8 Mb</td>
</tr>
<tr>
<td>HK</td>
<td>15 min</td>
<td>0.072 Mb</td>
</tr>
<tr>
<td>Packets</td>
<td>1203 pkts</td>
<td>0.096 Mb</td>
</tr>
</tbody>
</table>

**Total:** 29 Mb  
**Margin:** 55%

<table>
<thead>
<tr>
<th>8</th>
<th>16</th>
<th>4</th>
<th>2</th>
<th>34</th>
<th>24000</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sync</td>
<td>Frame ID</td>
<td>Probe ID</td>
<td>VCID</td>
<td>Timestamp</td>
<td>Telemetry</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
RF SYSTEM

**Driver**
- **COM.4** – RF system transmits stored data to GSE in 20min contacts

**Solution**
- Ball provided UHF transmitter, receiver, and antenna
- 32 kbps data rate yields an FOS = 4.5

---

**Link Budget**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uplink (TX From GeoPod)</th>
<th>Downlink (RX To GeoPod)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>437 MHz (UHF)</td>
<td>437 MHz (UHF)</td>
</tr>
<tr>
<td>Range*</td>
<td>10 km</td>
<td>10 km</td>
</tr>
<tr>
<td>Bit Error Rate</td>
<td>$10^{-6}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Data Rate</td>
<td>32 kbps</td>
<td>2 kbps</td>
</tr>
<tr>
<td>RX Antenna Length</td>
<td>0.5 m</td>
<td>0.2 m</td>
</tr>
<tr>
<td>TX Power Output</td>
<td>0.25 W</td>
<td>0.5 W</td>
</tr>
<tr>
<td>Link Margin</td>
<td>25 dB</td>
<td>40 dB</td>
</tr>
</tbody>
</table>

*Addresses spacecraft orbit for power considerations, testing range is 10 m*
C&DH SOFTWARE

- Possible to command into three different modes
- Will not listen for additional commands until commanded mode(s) are completed
- Command Link Transmission Units (CLTUs) based on CCSDS standard

<table>
<thead>
<tr>
<th>8</th>
<th>Sync</th>
<th>4</th>
<th>Probe ID</th>
<th>Command Word(s)</th>
<th>9</th>
<th>Parameters</th>
<th>...</th>
<th>24</th>
<th>x33</th>
<th>3</th>
<th>Tail Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**POWER SWITCHING**

- Extracts command words/parameters
- Determines component (of 5)
- Parameter signifies on/off
- Switches power high/low

**DATA COLLECTION MODE**

- Samples ADC for science data
- Samples Mux for HK data
- Packetizes data in buffers
- Writes buffers to DataFlash

**TELEMETRY PLAYBACK MODE**

- Extracts command words/parameters
- Determines packet from parameter
- Reads packet from DataFlash
- Writes packet to TX
SOFTWARE LIMITATIONS

Driver
- **COM.1** – Science data sampled at 500Hz

Solution
- Computations of data collection algorithm critical path must execute within 2ms
- Limiting factors
  - 84 MHz CPU clock
  - Chip select handled by Arduino Due SPI library
  - Flash data transfer speed based on 66MHz clock
- Possible to implement algorithm accommodations
  - Store less samples in buffer before writing to DataFlash

![Diagram showing computational times and process complete]
## Risk Assessment

<table>
<thead>
<tr>
<th>Risk</th>
<th>Description</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSK.C1</td>
<td>Unable to design software interface</td>
<td>Register settings designed, currently working with ADC and DataFlash</td>
</tr>
<tr>
<td>RSK.C2</td>
<td>Software computational time greater than 2 ms (500 Hz)</td>
<td>Safety margin of 0.78 ms, possible software algorithm accommodations</td>
</tr>
<tr>
<td>RSK.C3</td>
<td>Unable to solder ADC board</td>
<td>Practicing soldering, alternative soldering methods available</td>
</tr>
</tbody>
</table>

### Risk Matrix

<table>
<thead>
<tr>
<th></th>
<th>Negligible</th>
<th>Marginal</th>
<th>Critical</th>
<th>Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probable</td>
<td>RSK.C2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occasional</td>
<td>RSK.C1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improbable</td>
<td>RSK.C3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Inconsequential**
- **Acceptable w/mitigation**
- **Unacceptable**
POWER SYSTEM
Critical Components

- Batteries
  - Mass and Volume (Complexity)
- Power Regulation and Distribution
  - Efficiency

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Flows From</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS.1</td>
<td>MSN.3, MSN.4</td>
<td>The power system shall output voltage lines at 5, 9, 20, and 12 volts</td>
</tr>
<tr>
<td>EPS.2</td>
<td>MSN.5</td>
<td>The batteries shall supply power for 12 days of operations</td>
</tr>
<tr>
<td>EPS.3</td>
<td>MSN.1</td>
<td>Power Distribution board shall fit on 4x4 in PCB</td>
</tr>
<tr>
<td>EPS.4</td>
<td>EPS.1, EPS.2</td>
<td>The Power Distribution board must be &gt;90% efficient</td>
</tr>
</tbody>
</table>
# BATTERIES

**Driver**
- **EPS.1** - Have voltage lines of 5, 9, 12, and 20V
- **EPS.2** - Provide Power for 10 days outlined in the Power Budget
- **MSN.7** – Provide a path to flight

**Solution**

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Battery Pack 1</th>
<th>Battery Pack 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form Factor</td>
<td>AA</td>
<td>9V</td>
</tr>
<tr>
<td>Number of Strings</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>Voltage</td>
<td>12</td>
<td>27</td>
</tr>
<tr>
<td>Output Lines</td>
<td>12, 9, 5</td>
<td>20</td>
</tr>
<tr>
<td>Energy Density (Wh/kg)</td>
<td>259</td>
<td>199</td>
</tr>
<tr>
<td>Energy Density (Wh/L)</td>
<td>469</td>
<td>315</td>
</tr>
<tr>
<td>Total Amp Hours</td>
<td>37.5</td>
<td>0.75</td>
</tr>
</tbody>
</table>

**Power Budget**

<table>
<thead>
<tr>
<th>Component</th>
<th>Amp Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter</td>
<td>0.424</td>
</tr>
<tr>
<td>Receiver</td>
<td>5.333</td>
</tr>
<tr>
<td>Heaters</td>
<td>22.000</td>
</tr>
<tr>
<td>Avionics</td>
<td>8.640</td>
</tr>
<tr>
<td><strong>Battery pack 1</strong>:</td>
<td><strong>36.398</strong></td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td>0.050</td>
</tr>
<tr>
<td><strong>Battery pack 2</strong>:</td>
<td><strong>0.050</strong></td>
</tr>
</tbody>
</table>

---

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REGULATION & DISTRIBUTION

Driver

- **EPS.1** - Have voltage lines of 5, 9, 12, and 20 volts
- **EPS.4** – Power board must be >90% efficient

Solution

- Switching Regulator on highest load path
  - 90.9% efficient on entire board
  - Linear regulator would yield 62.7% efficiency
- Accurate Linear Regulator for sensitive accelerometer
  - 1% Voltage accuracy
  - 25 μA Ripple Current

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Project Overview
Design Solution
Comm System
Power System
Mechanical System
Project Planning
Driver

**EPS.3** – Subsystems must integrate on the internal structure

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>12V Batts</td>
<td>Power Board</td>
<td>2 Pin Molex</td>
</tr>
<tr>
<td>27V Batts</td>
<td>Power Board</td>
<td>2 Pin Molex</td>
</tr>
<tr>
<td>Power Board</td>
<td>Heaters</td>
<td>2 Pin Molex</td>
</tr>
<tr>
<td>Power Board</td>
<td>Transmitter</td>
<td>9 Pin Serial</td>
</tr>
<tr>
<td>Power Board</td>
<td>Receiver</td>
<td>9 Pin Serial</td>
</tr>
<tr>
<td>Power Board</td>
<td>Arduino</td>
<td>2.1 mm Barrel</td>
</tr>
<tr>
<td>Power Board</td>
<td>ADC Board</td>
<td>5 Pin Header</td>
</tr>
<tr>
<td>Power Board</td>
<td>Temp Sensors</td>
<td>32 Pin Header (4 each)</td>
</tr>
<tr>
<td>Accel</td>
<td>Power Board</td>
<td>4 line coax to (3) BNC</td>
</tr>
<tr>
<td>ADC Board</td>
<td>Arduino</td>
<td>4 Pin Header SPI</td>
</tr>
<tr>
<td>Memory</td>
<td>Arduino</td>
<td>6 Pin Header SPI and power</td>
</tr>
<tr>
<td>Arduino</td>
<td>Receiver</td>
<td>20 AWG to BNC</td>
</tr>
<tr>
<td>Arduino</td>
<td>Transmitter</td>
<td>20 AWG to SSMA</td>
</tr>
<tr>
<td>TX/RX</td>
<td>Antenna</td>
<td>SMA</td>
</tr>
</tbody>
</table>
Driver

- **EPS.3** Power distribution board must fit within form factor (4in x 4in)

Solution

- Initial layout of power distribution components shows ability as well as margin for the design of the PCB
# Risk Assessment

<table>
<thead>
<tr>
<th>Risk</th>
<th>Description</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSK.E1</td>
<td>Unable to construct PCB</td>
<td>Margin in schedule and budget</td>
</tr>
<tr>
<td>RSK.E2</td>
<td>Power system does not meet efficiency</td>
<td>LDO’s can be replaced with SR’s</td>
</tr>
<tr>
<td>RSK.E3</td>
<td>Charge amplifier will not give correct accelerometer output</td>
<td>Prebuilt laboratory charge amplifiers available</td>
</tr>
<tr>
<td>RSK.E4</td>
<td>Wiring in batteries shorting</td>
<td>Detailed assembly procedure for battery pack</td>
</tr>
<tr>
<td>RSK.E5</td>
<td>Battery pack overheat</td>
<td>Accept</td>
</tr>
</tbody>
</table>

## Frequency vs. Severity Matrix

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Negligible</th>
<th>Marginal</th>
<th>Critical</th>
<th>Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent</td>
<td></td>
<td></td>
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<td>Probable</td>
<td></td>
<td>RSK.E2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occasional</td>
<td>RSK.E3, RSK.E4</td>
<td>RSK.E1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improbable</td>
<td>RSK.E5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Green: Inconsequential
- Yellow: Acceptable w/mitigation
- Orange: Unacceptable
MECHANICAL SYSTEM
## MECHANICAL REQUIREMENTS

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Flows From</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCH.1</td>
<td>MSN.2</td>
<td>The internal structure shall integrate with the manufactured GeoPod shell</td>
</tr>
<tr>
<td>MCH.2</td>
<td>MSN.2</td>
<td>The power and electrical subsystems shall be accessible for extraction without the removal of other components</td>
</tr>
<tr>
<td>MCH.3</td>
<td>MSN.5</td>
<td>A thermal model shall be created to ensure subsystems are within operating temperatures in the testing environment</td>
</tr>
<tr>
<td>MCH.4</td>
<td>MSN.7</td>
<td>All internal structural components shall be manufacturable using on campus resources</td>
</tr>
</tbody>
</table>
SUBSYSTEM INTEGRATION

Driver

- **MCH.1** – The internal structure shall integrate with the manufactured GeoPod shell
- **MCH.2** – The power and electrical subsystems shall be accessible for extraction without the removal of other components

Solution
THERMAL MODEL

**Driver**

- **MCH.3** – A thermal model shall be created to ensure subsystems are within operating temperatures in the testing environment.
**Solution**

- Calculated board temperatures for each subsystem
- Material choice not dependent on thermal concerns
- Subsystems remain in operational range

**Material comparison:**

<table>
<thead>
<tr>
<th>Internal Structure Material: Aluminum 6061</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subsystem</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Arduino Due</td>
</tr>
<tr>
<td>Power Board</td>
</tr>
<tr>
<td>Battery Pack</td>
</tr>
</tbody>
</table>

**Battery Pack Thermal Response**

<table>
<thead>
<tr>
<th>Change in Subsystem Surface Temp. [K]</th>
<th>7075</th>
<th>5052</th>
<th>2024</th>
<th>6061</th>
<th>7068</th>
<th>6063</th>
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<tbody>
<tr>
<td>8</td>
<td>8.5</td>
<td>9</td>
<td>9.5</td>
<td>10</td>
<td>8.5</td>
<td>9</td>
</tr>
</tbody>
</table>

**Project Overview**

- Design Solution
- Comm System
- Power System
- Mechanical System
- Project Planning
MANUFACTURABILITY

Driver

- **MCH.4** - All internal structural components shall be manufacturable using on-campus resources

Solution

- Modular manufacturing to ensure proper integration
- Brace plate clip manufactured from 2in x 1in x 0.5in aluminum block
### Risk Assessment

<table>
<thead>
<tr>
<th>Risk</th>
<th>Description</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSK.C1</td>
<td>Unable to manufacture internal structure components</td>
<td>Structural component design reviewed by aerospace manufacturing staff</td>
</tr>
<tr>
<td>RSK.C2</td>
<td>Component wiring will not assimilate correctly</td>
<td>Component placement to ensure shortest length between electrical components</td>
</tr>
<tr>
<td>RSK.C3</td>
<td>Unable to isolate thermal resistances</td>
<td>Accept</td>
</tr>
</tbody>
</table>

#### Frequency vs. Impact Matrix

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Negligible</th>
<th>Marginal</th>
<th>Critical</th>
<th>Catastrophic</th>
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<tbody>
<tr>
<td>Frequent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probable</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occasional</td>
<td>RSK.C3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improbable</td>
<td>RSK.C1, RSK.C2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Inconsequential**
- **Acceptable w/mitigation**
- **Unacceptable**
Project Overview
Design Solution
Comm System
Power System
Mechanical System
Project Planning
WORK BREAKDOWN STRUCTURE

**Project Management**
- CDR
- FFR
- Work Flow Schedule
- Cost Budget
- PFR
- SFR

**Comm System**
- Link Budget
- Transmitter and Receiver
- Antennas
- Accelerometer
- Configured ADC
- C&DH SW Sketches
- Stored Data
- Mothership Simulation (GSE)

**Power System**
- Power Budget
- Schematics
- Power Distribution PCB
- Housekeeping Monitoring PCB
- ADC PCB
- Wiring Harness

**Mechanical System**
- CAD Models
- Thermal Model
- Mass and Volume Budget
- MSR
- Battery Pack
- Shell Integration Structure
- Subsystem Mounting Frame

**Integration and Test**
- TRR
- Safety Protocols
- Interface Control Documents
- As Run Procedures
- Results Documents
### Financial Plan

<table>
<thead>
<tr>
<th>Part</th>
<th>Cost</th>
<th>Contingency</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals and Fasteners</td>
<td>$264</td>
<td>20%</td>
<td>$317</td>
</tr>
<tr>
<td>Batteries</td>
<td>$294</td>
<td>20%</td>
<td>$353</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>$47</td>
<td>100%</td>
<td>$94</td>
</tr>
<tr>
<td>Cables/Adapters</td>
<td>$209</td>
<td>30%</td>
<td>$272</td>
</tr>
<tr>
<td>PCBs</td>
<td>$132</td>
<td>300%</td>
<td>$528</td>
</tr>
<tr>
<td>Integrated Circuits</td>
<td>$57</td>
<td>300%</td>
<td>$226</td>
</tr>
<tr>
<td>Resistors, Capacitors, Inductors, Diodes, Transistors</td>
<td>$91</td>
<td>30%</td>
<td>$118</td>
</tr>
<tr>
<td>Breakout Boards and other testing necessities</td>
<td>$143</td>
<td>30%</td>
<td>$185</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>$2093</strong></td>
<td></td>
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<tr>
<td><strong>Budget</strong></td>
<td><strong>$5000</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>Margin</strong></td>
<td><strong>58%</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TESTING PLAN

Project Overview
Design Solution
Comm System
Power System
Mechanical System
Project Planning

Timeline:

- Feb 9: Data Collection Test
- Feb 16: Pre-integration Telemetry Playback Test
- Mar 2: Battery Discharge Characterization
- Mar 23: Pre-integration Test with Simulated Loads
- Mar 30: Fully Integrated Pod Assembly
- Apr 6: Validate Subsystem Integration
- Apr 13: Validate Thermal Model
- Apr 20: Final Fully Integrated Project Validation
- Apr 27: Testing Results Documents
DATA COLLECTION TEST

- Goal: Measure data collection rate and characterize signal conditioning output

- 3-channel Accelerometer
  - 10 min.
  - 15 min.

- 6-channel Accelerometer
  - 5 min.

- Temperature Sensors
  - 15 min.
  - 3.6 MB
  - 1203 pkts.

Measure ADC conversion frequency, Verify sampling rate

Measure data stored, Verify recording rate

Measure SNR and bias of data, Verify signal conditioning output

3 lb. weight
Sand Box

Vibrations

1 ft.

Conversion
Start Pin

Logic Analyzer

MATLAB

Dual (20/5V) Power Supply

9V Power Supply

3-axis 16 bit 500Hz

Accelerometer

Piezoelectric

ADC Board

Condition Accel data and convert to digital

External Structure

Heaters

3.3V

Temperature

monitoring

Antennas

27V Batteries

software

Comm Board

Processes

commands and

and forwards

Flash Memory

12V Batteries

3.3V

SPI

3.3V

SPI
TELEMETRY PLAYBACK TEST

- Goal: Measure effective data transmission rate and identify bit errors
- Pre-integration
- Verify ability to transmit 3.6 MB of data in 20 min. and receive transmit commands

Measure delay between command and transmitter activation, Verify response to command

Calculate packet errors from checksums, Verify BER

Measure data transmitted, Verify 32 kbps transmission rate
Goal: Measure regulation accuracy and power board efficiency
Additional 8-cell prolonged discharge test for capacity
THERMAL VERIFICATION

- Goal: Isolate and measure modeled thermal conductive resistances
  - Resistances independent of thermal loads, symmetric
  - Integrated, with battery power

Measure steady-state temperatures over representative orthant of pod
Verify modeled thermal resistances
Project Overview

Design Solution

Comm System

Power System

Mechanical System

Project Planning

---

**Data Collection**

<table>
<thead>
<tr>
<th>Task</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command power on and data collection</td>
<td>&lt; 5 min</td>
</tr>
<tr>
<td>Sample accel. channels 1-3 and HK data</td>
<td>10 min</td>
</tr>
<tr>
<td>Sample accel. channels 1-6 and HK data</td>
<td>5 min</td>
</tr>
</tbody>
</table>

**Data Transmission**

<table>
<thead>
<tr>
<th>Task</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Send transmission request</td>
<td>&lt; 1 min</td>
</tr>
<tr>
<td>Transmit all collected data, measure critical device voltages and currents</td>
<td>~ 20 min</td>
</tr>
<tr>
<td>Estimate TX rate, EPS efficiency</td>
<td></td>
</tr>
</tbody>
</table>

---

**Sample accelerometers channels 1-6 and HK data**

- Sand Box
- Vibrations
- 3 lb. weight

- Receiver
- Connected during commanding
- Lab Station
ACKNOWLEDGMENTS

Customer – Ball Aerospace
- Joseph Hackel

Course Coordinator
- Dr. Dale Lawrence

Faculty Advisor
- Dr. Scott Palo

Principal Investigator
- Dr. Daniel Scheeres
5. “Arduino Due” http://arduino.cc/en/Main/arduinoBoardDue
Didymos 65803 Asteroid

- Binary system
- Primary asteroid rotates every 2.4 hrs
  - Equatorial microgravity environment

Mission Objective

- Determine driving forces holding the surface together
  - Van der Waals
- Characterize asteroid composition
  - Planetary dynamics
<table>
<thead>
<tr>
<th>Item</th>
<th>Acquisition Method</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter</td>
<td>Ball provided</td>
<td>DT-15</td>
</tr>
<tr>
<td>Receiver</td>
<td>Ball provided</td>
<td>RC-75</td>
</tr>
<tr>
<td>Antenna</td>
<td>Ball provided</td>
<td>Custom Ball Antenna</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>Ball provided</td>
<td>PCB 356M98</td>
</tr>
<tr>
<td>External Shell</td>
<td>Ball provided</td>
<td>Custom Ball Structure</td>
</tr>
<tr>
<td>Comm. Board</td>
<td>Purchased</td>
<td>Arduino Due</td>
</tr>
<tr>
<td>Internal Structure</td>
<td>Manufactured</td>
<td></td>
</tr>
<tr>
<td>Power Board</td>
<td>Manufactured</td>
<td></td>
</tr>
</tbody>
</table>
COMMUNICATIONS SYSTEM
ACCELEROMETER FILTERING

- Tested environment noise in Trudy’s lab
  - Need data sampled at higher rate
  - No low-frequency peaks
  - Filtered noise expected to allow for SNR > 10 for initial burst and ringing
- First-order op-amp filter selected
  - Simple calibration curve
  - Low phase delay
  - Simple design
  - Small footprint
ADC SPI Timing Diagram

- SPI Clock
- ADC Conversion starts on high
- SPI Chip Select
- SPI MISO - Digital data output
- SPI MOSI - 32 bit settings register
MEMORY BUFFER USE

Max: 40.0 ms

Max: 1.2 ms
22.1 Buffer Write

Max: 0.12 ms
(1024 byte transfer)

BINARY PAGE SIZE
14 DON'T CARE + BFA9-BFA0

22.2 Buffer to Main Memory Page Program (Data from Buffer Programmed into Flash Page)

Max: 40 ms
### MEMORY READ TIMING

#### 23.1 Main Memory Page Read

Max: 0.125 ms (1024 byte transfer)

#### 23.2 Main Memory Page to Buffer Transfer (Data from Flash Page Read into Buffer)

Max: 400 us
ADC OVERALL TIMING

Figure 1. Serial Operation Timing Diagram (All Three SDOs Active)
ADC OUTPUT FORMAT

2 SDO’s: NOT USED

1 SDO: USED

Figure 30. Serial Interface: Data Output with One or Two Active SDOs
DT15 Transmitter

- Frequency: UHF support
- Data rate: <10Mbps
- Power: up to 2W RF output
- Voltage: 9-16 V\textsubscript{DC}
- Dimensions: 3.175x8.89x0.97 cm
- Mass: 48.2 grams
- Temperature: -20C to 50C
- Acceleration: 100g, 3-axis

DR75 Receiver

- Frequency: UHF support
- Data rate: <10Mbps
- Current draw: 275mA
- Voltage: 9-16 V\textsubscript{DC}
- Dimensions: 6.35x8.89x2.159 cm
- Mass: 170.1 grams
- Temperature: -20C to 50C
- Acceleration: 100g, 3-axis
PATCH ANTENNA

- Transmit and receive UHF patch antennas
- Antennas at each pole orientated 90° apart provide 95% spherical coverage
- Gain pattern designed and tested
- Antennas externally mounted on half shells available from Ball
- Demonstrated with radio system
TELEMETRY FORMAT

- Organize data to transmit to spacecraft
- Based off CCSDS standard (NASA)
- Packet size 24080 bits
- 64 bit header
  - Sync: Packet initialization code
  - Frame ID: Packet number
  - Probe ID: Identifies probe
  - VCID: Packet type
    - 00 – housekeeping
    - 01 – accelerometer
    - 10 – geophone
- Timestamp: 0.1 ms resolution every second for 12 day range
- Telemetry
  - 1 second of science
  - 5 minutes of housekeeping
- Modular Checksum: verifies integrity of transmitted packet
- Represented by 3 pages on DataFlash

<table>
<thead>
<tr>
<th></th>
<th>8</th>
<th>16</th>
<th>4</th>
<th>2</th>
<th>34</th>
<th>24000</th>
<th>16</th>
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</thead>
<tbody>
<tr>
<td>Sync</td>
<td>Frame ID</td>
<td>Probe ID</td>
<td>VCID</td>
<td>Timestamp</td>
<td>Telemetry</td>
<td>Checksum</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24079</td>
<td></td>
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</tbody>
</table>
### Command Format

- **Expected command format to be received by GeoPod**
- **Based on CCSDS standard (NASA)**
- **Command link transmission unit (CLTU) size 48 bit**
- **12 bit header**
  - **Sync**: Command initialization code
  - **Probe ID**: Identifies probe
- **Command word(s)**
  - 9 bit length allows for 512 possible commands as per customer requirement
- **Ex. Playback telemetry, power switches, initiate science collection**
- **Parameters**
  - **Possible command options**
  - For playback, request Frame ID and VCID
- **Tail sequence**: Signifies end of uplink transmission
  - Allows for a block of multiple command words and parameter segments per CLTU

<table>
<thead>
<tr>
<th>8</th>
<th>4</th>
<th>9</th>
<th>24</th>
<th>x 33</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sync</td>
<td>Probe ID</td>
<td>Command Word(s)</td>
<td>Parameters</td>
<td>...</td>
<td>Tail Sequence</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**DATA COLLECTION MODE**

- **Control Loop**
  - For 15min
    - Increment File IDs
    - Determine Timestamp
    - Define File Headers
  - True
    - SPI DataFlash Transfer
    - SPI Science Transfer
      - Analog HK Read
      - Store in Buffers
      - Write Pkt to Pages
  - False
- For 500 Samples
  - False
Control Loop

For Cmd Playback

Extract Cmd Word

Extract Parameters

File ID = 0

File ID = Pointer

File ID = Parameter (for retrans)

Increment Pointer

Read Pkt DataFlash

Write Pkt to TX Serial

File ID = 0

False

True

False

True
POWER SYSTEM
# Power Connections

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Connector</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery 1</td>
<td>2 Pin Molex</td>
<td>12</td>
</tr>
<tr>
<td>Battery 2</td>
<td>2 Pin Molex</td>
<td>27</td>
</tr>
<tr>
<td>Heaters</td>
<td>2 Pin Molex</td>
<td>12</td>
</tr>
<tr>
<td>Transmitter</td>
<td>9 Pin Serial</td>
<td>9</td>
</tr>
<tr>
<td>Receiver</td>
<td>8 Pin Serial</td>
<td>9</td>
</tr>
<tr>
<td>Arduino</td>
<td>2.1 mm Barrel</td>
<td>9</td>
</tr>
<tr>
<td>ADC</td>
<td>2 Pin Header</td>
<td>9, 5</td>
</tr>
<tr>
<td>Temperature Sensors</td>
<td>8 Pin Header</td>
<td>5</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>4 line coax to (3) BNC</td>
<td>Variable</td>
</tr>
<tr>
<td>Constant Current Conditioner</td>
<td>Wire via on PCB</td>
<td>20</td>
</tr>
</tbody>
</table>
**BATTERIES**

- **Operational Discharge:**
  - **Battery 1**
    - Discharge/string: 8.4 mA (average) 60 mA (max)
  - **Battery 2**
    - Discharge/string: 20 mA (average) 40 mA (max)

---

![10mA Continuous Discharge](image1)

![100mA Continuous Discharge](image2)

---

Functionality Limit
BATTERIES

- Battery chemistry were chosen based on energy density
  - **Lithium Iron Disulfide** – 259 Wh/kg, 469 Wh/L
  - Largest consumer grade form factor: AA
  - **Lithium Manganese Dioxide** – 199 Wh/kg, 315 Wh/L
    - Higher voltage cells (9V) available for high voltage systems
  - Space grade **Lithium Sulfur dioxide**, more efficient, but more casing for flight
    - Total energy density: 329 Wh/kg, 460 Wh/L
<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Connector</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery 1</td>
<td>Power Board</td>
<td>2 Pin Molex</td>
<td>12</td>
</tr>
<tr>
<td>Battery 2</td>
<td>Power Board</td>
<td>2 Pin Molex</td>
<td>27</td>
</tr>
<tr>
<td>Power Board</td>
<td>Heaters</td>
<td>2 Pin Molex</td>
<td>12</td>
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<tr>
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<td>Transmitter</td>
<td>9 Pin Serial</td>
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<tr>
<td>Power Board</td>
<td>Receiver</td>
<td>8 Pin Serial</td>
<td>9</td>
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<td>Power Board</td>
<td>Arduino</td>
<td>2.1 mm Barrel</td>
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<tr>
<td>Power Board</td>
<td>ADC</td>
<td>2 Pin Header</td>
<td>9, 5</td>
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<tr>
<td>Power Board</td>
<td>Temperature Sensors</td>
<td>8 Pin Header</td>
<td>5</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>Power Board</td>
<td>4 line coax to (3) BNC</td>
<td>Variable</td>
</tr>
<tr>
<td>Power Board</td>
<td>Constant Current</td>
<td>Wire via on PCB</td>
<td>20</td>
</tr>
</tbody>
</table>
TEMP. SENSOR SETUP

- 3.3 V
- GND
- Control (Shutdown)
- 0 V – 2.7 V
- Pin 2 (GND)
HEATER SELECTION

- FreezeStop 12V Heat Cable
  - Model: 17FLV1-CT
  - Representative load for power subsystem
  - 12 V Input
    - From Battery Pack 1
  - 5 W/ft
    - Only 1 foot required
SCHEMATICS - BOARD
MECHANICAL SYSTEM
THERMAL ASSUMPTIONS

- Steady state conditions
  - $T_{\infty} = 21^\circ C$
- Subsystems have uniform temperature on outer surface
- Convection
  - Free convection
  - $h_{\text{air}} = 5 \text{ W/(m}^2\text{K)}$
- Radiation
  - Radiation from remaining subsystems ignored (excluding batteries)
- Conduction
  - Internal structure only provides conductive heat transfer
  - Ground conduction assumed to be dry sand
    - $K = 0.15 \text{ W/(m*K)}$
  - Air Conduction
    - $K = 0.026 \text{ W/(m*K)}$
COMPLETE THERMAL MODEL

\[ R_1 = \frac{L_{PCB}}{k_{PCB}A_1} \quad R_2 = \frac{L_1}{k_{AL}A_1} \quad R_3 = \frac{L_2}{k_{AL}A_2} \quad R_4 = \frac{L_3}{k_{AL}A_3} \]
\[ R_5 = \frac{L_4}{k_{air}A_4} \quad R_6 = \frac{1}{h_{air}A_4} \quad R_7 = \frac{A_4 \varepsilon \sigma (T_B + T_{Sin})(T_B^2 + T_{Sin}^2)}{1} \]
\[ R_8 = \frac{L_5}{k_{AL}A_{shell}} \quad R_9 = \frac{L}{k_{ground} \frac{1}{2} A_{shell}} \quad R_{10} = \frac{L}{k_{air}(0.5 A_{shell})} \]
\[ R_{11} = \frac{1}{h_{air}A_{shell}} \quad R_{12} = \frac{A_{shell} \varepsilon \sigma (T_{out} + T_{\infty})(T_{out}^2 + T_{\infty}^2)}{1} \]

Conduction
Convection
Radiation
THERMAL PLOTS

Battery Pack

Power Board

Arduino Due

Transmitter/Receiver
MATERIAL SELECTION

- Type of aluminum not significant based on thermal analysis
- Main Structure: Aluminum 6061-T6
  - Lightweight
    - Total mass of internal structure: 0.93 kg
  - Increased availability and low cost
    - Low cost ≈ $11/kg in small quantities
  - Strong aerospace flight heritage
- Battery support bracket: Aluminum 5052 H-32
  - Maintains structural integrity with 90° bending
  - Similar cost and availability to 6061 T-6
# Tapped Hole Tolerances

Internal Thread Sizing  
Unified: Class 2B  
ISO Metric: Class 6H

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Tolerance</td>
<td>Min</td>
</tr>
<tr>
<td>#5-44</td>
<td>UNF</td>
<td>0.1004</td>
<td>0.1079</td>
<td><strong>0.0075</strong></td>
<td>0.1102</td>
</tr>
<tr>
<td>#10-32</td>
<td>UNF</td>
<td>0.156</td>
<td>0.164</td>
<td><strong>0.008</strong></td>
<td>0.1697</td>
</tr>
<tr>
<td>M3 X 0.5 F</td>
<td></td>
<td>0.1054</td>
<td>0.1092</td>
<td><strong>0.0038</strong></td>
<td>NA</td>
</tr>
<tr>
<td>M4 X 0.7 F</td>
<td></td>
<td>0.1396</td>
<td>0.1442</td>
<td><strong>0.0046</strong></td>
<td></td>
</tr>
</tbody>
</table>
PATH TO FLIGHT STRUCTURE

Cubesat: Humsat–D
Vehicle: Dnepr-I Rocket
Date: 21 Nov. 2013

Cubesat: HawkSat-I
Vehicle: Minotaur-I rocket
Date: 19 May 2009