TELEMETRIC INTERPLANETARY REGOLITH EXPLORER FOR SEISMIC INVESTIGATION OF ASTEROID SURFACES

PRELIMINARY DESIGN REVIEW

Aerospace Engineering Sciences
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OUTLINE

- Mission Overview
- Baseline Design
- Critical Project Elements
- Feasibility
- Integration and Test
- Status Summary
MISSION BACKGROUND

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 interior and surface composition
ASTEROID MISSION CONOPS

Launch (29g load)  
18 month travel time

Deploy Explosive Pods (red) and GeoPods (grey)

Spacecraft Orbits Asteroid for 10 days

20 minute contacts every 2.26 hours

0.1-10 km Range

TIRESIAS Focus:
- Power
- Communication
- Internal Structure

Landing at 25 cm/s

Asteroid Surface

1

14 hour settling time

2

Deploy, Descent, and Landing

<table>
<thead>
<tr>
<th>Accel is turned on; GeoPod is separated</th>
<th>GeoPod records data while descending</th>
<th>Touchdown with surface, data recorded while settling</th>
<th>Accel and Geophone activated after settling</th>
<th>Explosive Pod detonates; GeoPod collects data with Accel and Geophone</th>
<th>Science data transmitted when link is available with the orbiting satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 min</td>
<td>14 hour</td>
<td>~5 min</td>
<td>10 min</td>
<td>10 min</td>
<td>10 days</td>
</tr>
</tbody>
</table>
TIRESIAS MISSION OBJECTIVES

- Development of the power, structures, and command and data handling (C&DH) subsystems for the BASiX GeoPod sensor probe
- Construction of the GeoPod prototype with components that demonstrate path-to-flight characteristics
- Verification and validation of the design via subsystem and integration tests
<table>
<thead>
<tr>
<th>Req.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSN.1</td>
<td>The GeoPod shall have full functionality after an impact of 25 cm/s with the asteroid surface.</td>
</tr>
<tr>
<td>MSN.2</td>
<td>The GeoPod structure shall withstand a static 29-g launch load.</td>
</tr>
<tr>
<td>MSN.3</td>
<td>The power system shall provide power to the accelerometer, avionics board, and radio for the 12 day deployment duration.</td>
</tr>
<tr>
<td>MSN.4</td>
<td>The GeoPod shall receive commands from the orbiting satellite to control power management and data handling.</td>
</tr>
<tr>
<td>MSN.5</td>
<td>The GeoPod shall transmit science and housekeeping data to the orbiting satellite during the 10 days of surface operations.</td>
</tr>
</tbody>
</table>
BASELINE DESIGN
SUBSYSTEMS

- C&DH
- Power
- Structure
**C&DH ARCHITECTURE**

**Payload:**
- 64 bit Accelerometer data at 500 Hz
- 64 bit Geophone data at 500 Hz

**C&DH:**
- Store & forward science and housekeeping data
- \( \leq 0.1 \) ms res clock
- Up to 512 stored commands (9 bit ID)
- Time-tagged command sequences
- Packetize data for transmission

**RF System:**
- 20 min contacts every 2.26 hrs during 10 days of surface operations
- GeoPods communicate at different times
- Range: 0.1-10 km

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Mission Overview  
Baseline Design  
Critical Project Elements  
Feasibility  
Integration and Test  
Status Summary
DATA STORAGE

- Provide sufficient memory for housekeeping and science data
- NAND Flash
  - Fast data transfer
  - Data maintained with no power
- Circular Buffer
  - Read and write rates non-equivalent
  - Size of buffer predefined, no dynamic memory allocation
  - Overwrites oldest data first
  - Provides a playback pointer for the possibility of retransmitting data
- Organize data to transmit to spacecraft
- Packet size 1024 bits
- 32 bit Header
  - Sync: Code signifying packet initialization
  - Frame ID: Packet number
  - Probe ID: Identifies probe
- Modular Checksum
  - Method of verifying integrity of transmitted packets
  - Detects all single-bit errors
  - Small likelihood of two-bit error going undetected

<table>
<thead>
<tr>
<th>8</th>
<th>20</th>
<th>4</th>
<th>976</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sync</td>
<td>Frame ID</td>
<td>Probe ID</td>
<td>Data</td>
<td>Checksum</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1023</td>
</tr>
</tbody>
</table>
SUBSYSTEMS

C&DH

Power

Structure
POWER BOARD

- Monitor health and status of all components
  - Voltage, current, temperature
  - Communicates with avionics board
- Fault Response
  - Fault: Over-voltage, under-voltage, over-current, temperature range violation
  - Response: component power management, warning messages to avionics board
- Regulates voltage
- Distributes power
MODULAR BATTERY SYSTEM

- Subsystems have separate batteries tailored to the needs of each subsystem
  - High power: heaters and RF system
  - Low noise: sensors and avionics
- Increased efficiency
- Requirements on regulators relaxed
- Structural integrity for sustaining impact and launch loads
- Simple design promotes subsystem integration and accessibility
- Open architecture allows for heat management of electronics while decreasing weight
- Inner box suspended inside GeoPod
  - 8 Connectors to external Shell
  - ~1 U size
MATERIAL PROPERTIES

- Structure
  - Aluminum 7075-T6\(^5\)
    - Flight heritage in aerospace
    - Lightweight: 2.810 g/cm\(^3\)
    - Tensile Yield strength: 505 MPa
    - Modulus of Elasticity: 71.7 GPa
    - Shear Strength: 331 MPa
- Shell Surface Coating
  - BASiX GeoPod coating
    - Emissivity: 0.15
    - Absorptivity: 0.1
CRITICAL PROJECT ELEMENTS
C&DH CRITICAL ELEMENTS

- Interface with components
  - Accelerometer and Geophone data sampling
  - Power board health and status
  - I/O of RF system
- Uplink telemetry from all GeoPods to orbiting satellite
  - Science and housekeeping stored onboard until transmission
  - Uplink rate facilitates data transfer within 10 days of surface operations
- GeoPods receive and execute commands from orbiting satellite
POWER CRITICAL ELEMENTS

- Power board distributes regulated power
- Health and Status Monitoring
  - Verify power subsystem functionality
  - Define critical responses
  - Interface with avionics board
- Battery Survivability
  - 18 month cruise phase
  - Possibility of battery self-discharge
- Power System Capacity
  - Limited mass and volume budget
  - Batteries must have enough energy for mission operations
MECHANICAL CRITICAL ELEMENTS

- Withstand launch load
  - Vehicle launch loading of 29-g
- Integrate with GeoPod external shell
  - Form factor of external shell determined by Ball Aerospace
- Subsystem accessibility
  - Battery installment in pre-launch sequence
- Thermal response of structural subsystem
  - Power budget required to maintain operational temperature range
  - Thermal effects on structural elongation
FEASIBILITY
SUBSYSTEMS

C&DH

Power

Structure
DATA HANDLING

- All science and telemetry needs to be transmitted to the orbiting spacecraft
- 10 days of surface operations results in 100 contacts
- 96.6 MB transmitted over 100 contacts results in a data rate of 6.5kbps
- 32 kbps data rate sufficient
  - Packet sent in 0.032 sec

Data Storage 96.6 MB

Science
315 min @ 32 kbps
15 min @ 32 kbps
79.2 MB

Health & Status
12 days @ 100 bps
13 MB

Timestamps
12 days @ 34 bps
4.4 MB
Ball developed their own avionics board for C&DH
- Proprietary restriction
- PC-104 Field-Programmable Gate Array (FPGA)
  - Interface similar to space-grade components
  - Greater functionality
  - Limited experience increases complexity
- Arduino Uno microcontroller
  - 6, 10 bit ADCs available as required
  - SPI computer bus protocol
  - Memory: 32 KB (1G SD shield for additional)
  - Clock speed: 16 MHz
  - Meets minimum functionality
  - Experience and documentation
SUBSYSTEMS

C&DH

Power

Structure
28 sensors required

- Voltage sensors for monitoring
  - Voltage: components receive adequate voltage
  - Current: power calculations, remaining battery, over-current protection
  - Temperature: Monitor operating temperatures of components

- 16:1 multiplexer allows for 16 sensors to 1 ADC

- Arduino Uno Microcontroller
  - 6 ADCs available: 2 ADCs required for 28 sensors
  - 14 digital outputs available: 4 required for multiplexers, 8 required for component on/off
  - SPI interface with C&DH board
### Battery Capacity Estimates

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>LiSO$_2$ (Space-Grade)$^3$</th>
<th>Spiral LiMnO$_2$ (COTS)$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Energy Density (W-hr/Kg)</td>
<td>203</td>
<td>150</td>
</tr>
<tr>
<td>Volume Energy Density (W-hr/L)</td>
<td>450</td>
<td>300</td>
</tr>
<tr>
<td>Max Out (A)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Discharge/yr</td>
<td>&lt; 2%</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Li$_2$ (Space-Grade)$^3$</th>
<th>Bobbin LiMnO$_2$ (COTS)$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Energy Density (W-hr/Kg)</td>
<td>329</td>
<td>329</td>
</tr>
<tr>
<td>Volume Energy Density (W-hr/L)</td>
<td>701.4</td>
<td>668</td>
</tr>
<tr>
<td>Max Out (A)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Discharge/yr</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

- **Spiral**: High output power, low mass/volume efficiency
  - RF system, heaters
- **Bobbin**: Low output power, high mass/volume efficiency
  - Sensors, electronic boards

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Mission Overview | Baseline Design | Critical Project Elements | Feasibility | Integration and Test | Status Summary
---|---|---|---|---|---
30
FUNCTIONAL REQUIREMENTS

- Max Subsystem Requirements
  - Communications – 9 V, 700 mA
  - Heaters – 3.6 V, 1 A
  - Avionics – 7 V, 50 mA
  - Accelerometer – 20 V, 3 mA
  - Geophone – 18 V, 16 mA
- Spiral batteries: Communications and Heaters
  - Three 3 V cells in series
  - Lithium cells provide up to 5 A
- Bobbin batteries: Avionics and Accelerometer Battery
  - Seven 3 V cells in series
  - Lithium cells provide up to 100 mA
TOTAL ENERGY

- **Spiral batteries: Communication and Heaters**
  - **Communications**: 6 W draw during contacts + 0.25 W for 10 days receiving = 64.2 W-hrs
  - **Heaters**: 3.6 W at 26% duty cycle = 223 W-hrs
- **Bobbin batteries: Avionics and Accelerometer**
  - **Avionics**: 0.5 W draw for probe life of 12 days = 101 W-hrs
  - **Accelerometer**: 0.25 W draw for 315 minutes = 1.4 W-hrs
  - **Geophone**: 0.3 W draw for 15 minutes = 0.075 W-hrs
- Total energy capacity: 389.3 W-hrs
- **Mass**: 2.225 kg
- **Volume**: 1.110 L

**Total Energy Distribution**

- **Communications**: 16.48%
- **Heaters**: 0.30%
- **Avionics**: 57.30%
- **Accelerometer**: 0.02%
- **Geophone**: 25.90%
SUBSYSTEMS

C&DH

Power

Structure
**DURABILITY: SHELL**

- **Theory**
  - Total Load: 29-g sustained launch acceleration on a 5 kg sphere
    - Aluminum 7075-T6
    - \( F = 1422.45 \text{ N} \)

- **Analysis**
  - Attachment hole loading
    - \( F/8 = 177.8 \text{ N per hole} \)
  - Distributed load over half of shell
    - \( F = 1422.45 \text{ N} \)

- **Conclusion**
  - Shell thickness: 0.125 in
  - FOS = 1.7
  - Attachment hole loading
    - Safety Margin: 2000%
  - Distributed load over half of shell
    - Safety Margin: \( 17.5 \times 10^3 \%

Yield Strength: 505,000,000 N/m^2

Deformation Scale: 3988.68:1

Deformation Scale: 238898:1
DURABILITY: INDEX FRAME

- **Theory**
  - Maximum load concentration
    - Total Load through diagonal axis:
      - $F = 1422.45 \text{ N}$
  - Horizontal beam stress
    - Total load applied to entire frame with fixed vertices
      - $F = 1422.45 \text{ N}$

- **Conclusion**
  - X-Sectional Area: 0.0625 in$^2$
  - FOS = 1.7
  - Maximum load concentration
    - Safety Margin: 695%
  - Horizontal beam stress
    - Safety Margin: 1050%

Yield Strength: 505,000,000 N/m$^2$

Deformation Scale: 746.4:1

Deformation Scale: 427.1:1
THERMAL ANALYSIS

- **Purpose**
  - Determine heat transfer from sphere
  - Find required power draw for heaters

- **Theory**
  - GeoPod surface energy balance
  - Types of heat transfer
    - Radiation & conduction

- **Results**
  - Average consumption of 3.92 W
  - Close to Ball’s design of 3.6 W
  - Elongation/ Max Temp Range
    - 0.0010611 in/in

- **Graph**
  - Heater Power Required to Maintain $T_{\text{surface}}>0^\circ\text{C}$

**Mission Overview**

- Baseline Design
- Critical Project Elements
- Feasibility
- Integration and Test
- Status Summary

36
SUBSYSTEM INTEGRATION

- **Purpose**
  - Compatibility with existing shell
  - Ensure batteries and other subsystems are accessible

- **Theory**
  - CAD model developed under existing constraints

- **Conclusion**
  - Index frame core assimilates all subsystems
  - Manufacturable with available resources
  - Batteries are accessible
INTEGRATION AND TEST
COMMUNICATION TESTING

- Subsystem Benchmarks (not shown)
  - Hardwired handshake without antennas
  - Downlink of sample data packet without antennas
  - Downlink of sample data packet over RF with antennas
- Subsystem Pre-Integration Test
  - RF transmission of multiple data packets on request
POWER SYSTEM TESTING

- Subsystem Benchmarks (not shown)
  - Single-cell battery discharge characterization
  - Unloaded power supply regulation verification – over-current/voltage protection, temperature triggered responses
- Subsystem Pre-Integration Test
  - Ensure proper voltage, current, temperature measurements with representative loads

Mission Overview | Baseline Design | Critical Project Elements | Feasibility | Integration and Test | Status Summary
---|---|---|---|---|---
STRUCTURAL TESTS

- Subsystem Benchmarks (not shown)
  - Instron axial stress testing of structure standoff posts – interface to internal and external structures
  - Battery installment timed accessibility test
- Subsystem Pre-Integration Test
  - Tension and compression of each hemisphere at half expected launch load
Bench-top test of system to verify connections

Integrate system into GeoPod, conduct drop weight test
## SUMMARY: COMMUNICATION

<table>
<thead>
<tr>
<th>Critical Project Elements</th>
<th>Feasibility Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>C&amp;DH board must interface with all other components</td>
<td>All components utilize a compatible interface protocol with an Arduino</td>
</tr>
<tr>
<td>Data is stored onboard until transmission</td>
<td>-96.6 MB is sufficient for science data, timestamps, and health/status data</td>
</tr>
<tr>
<td></td>
<td>-Circular buffer allows for store and forward routine and available retransmission of data</td>
</tr>
<tr>
<td>Uplink data rate facilitates data transfer in 10 days</td>
<td>32 kbps determined sufficient through consideration of contact window time, number of contacts available, and amount of data to be transferred</td>
</tr>
</tbody>
</table>
### Critical Project Elements | Feasibility Verification
--- | ---
Batteries must not self discharge during 18 month flight to asteroid | All batteries had < 2% discharge/year. Maximum discharge of 3% in 18 months
Energy | Basic energy balance utilizing the predicted energy for each subsystem component was completed (Accelerometer, C&DH Board, etc.)
Power board monitors the voltage, current, and temperature of internal devices | Arduino interface capable of managing sensor outputs using multiplexer
## SUMMARY: MECHANICAL

<table>
<thead>
<tr>
<th>Critical Project Elements</th>
<th>Feasibility Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Withstand 29-g launch load</td>
<td>Static load analysis determined the maximum possible stress was acceptable for aluminum 7075-T6</td>
</tr>
<tr>
<td>All components must integrate with GeoPod shell</td>
<td>CAD model was produced using the exact dimensions of the GeoPod shell</td>
</tr>
<tr>
<td>Design must allow for battery installment in pre-launch sequence</td>
<td>CAD model clearly shows easy access is provided to the central battery housing</td>
</tr>
<tr>
<td>Temperatures must remain in operating range for components</td>
<td>Energy loss was computed through energy surface balance, sufficient energy will be allocated for heaters by the power system</td>
</tr>
<tr>
<td>Thermal expansion of structural materials must not compromise GeoPod</td>
<td>Surface temperature range is 45°C, thermal expansion is negligible</td>
</tr>
</tbody>
</table>
Comm. Remaining Studies

- Accelerometer for testing purposes
  - Ball can provide accelerometer
  - Possible second to represent a geophone
- Further understand antenna options
  - Ball UHF patch antennas mounted on half shells available
- Radio selection
  - Ball willing to provide military grade transmitter/receiver
  - Consider alternative radio systems
- C&DH board
  - Satisfy functionality requirements
  - Provides path-to-flight
- Strategy for remaining studies
  - All further considerations require discussion
  - Work with advisor and customer to identify exact feasibility
POWER REMAINING STUDIES

- Choice of power board
  - Several viable options available including the Arduino Uno
- Voltage regulator selection
  - Passive: Simple design, no interface with processor
  - Active: Requires a processor interface, more customizable
- Power System Fault Response
  - If problems are detected, determine appropriate responses
- Data storage
  - Determine format of housekeeping data required for transmission
- Strategy for remaining studies
  - Trade study and performance verification to down-select solution
  - Develop fault tree and responses
STRUCTURE REMAINING STUDIES

- Sizing and configuration of internal structure
  - Battery pack attachment for ideal power distribution
  - Design to Ball GeoPod form factor
- Manufacturing consideration
  - Assess manufacturability of prototype
- Finite element analysis on GeoPod assembly
ACKNOWLEDGMENTS

Customer – Ball Aerospace
- Joseph Hackel

Course Coordinator
- Dr. Dale Lawrence

Faculty Advisor
- Dr. Scott Palo

Principal Investigator
- Dr. Daniel Scheeres
QUESTIONS?
Definition: Remaining work to allow for deployment of GeoPod in space as part of the BASiX mission

Existing Device Replacement
- Device to perform same function already exists, verification of device function unnecessary
  - Antenna, transmitter/receiver, avionics board

Similar Device Replacement
- Device has flight-quality analog with similar interfaces and performance
  - Geophone, accelerometer, batteries

Refinement/Alteration
- Some components of device must be replaced to ensure flight quality
  - Power board, internal structure, avionics software
# Requirement Verification

<table>
<thead>
<tr>
<th>Req.</th>
<th>Concept</th>
<th>Verification Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSN.1</td>
<td>Shock loads and impact</td>
<td>Conduct a 3 mm drop test to achieve 25 cm/s. Controlled shock impact with specialized mallet tool and accelerometer readings.</td>
</tr>
<tr>
<td>MSN.2</td>
<td>Launch load</td>
<td>Static tension and compression loading test. Worst case scenario testing.</td>
</tr>
<tr>
<td>MSN.3</td>
<td>Power System Capacity</td>
<td>Battery full discharge benchmark test. Integrated current consumption during day-in-life scenario.</td>
</tr>
<tr>
<td>MSN.4</td>
<td>Command Receipt</td>
<td>Commanded C&amp;DH benchmark test. Day-in-life integrated scenario</td>
</tr>
<tr>
<td>MSN.5</td>
<td>Data Transmission</td>
<td>All C&amp;DH benchmark tests. Integrated day-in-life testing.</td>
</tr>
</tbody>
</table>
SUBSYSTEMS

C&DH

Power

Structure
Geophone

- 3-axis analog output
- Measures either velocity or acceleration of vibrations using springs and current generation
- Ideal for slow vibrations (2Hz - 110 Hz)
- Typically used for mineral resource detection
RF SYSTEM

ANTENNA
- Communication independent of landing orientation
- Monopole and Dipole antennas have microsatellite heritage
  - Deployment electrically and mechanically complex
- Patch antenna alternative solution
  - Low profile, external configuration
  - Inexpensive to fabricate and customize

RADIO
- Provides uplink and downlink capabilities
- Supporting frequency and data rate
- Receiver 100% duty cycle
  - Always listening
  - Low power consumption
- Transmits science and housekeeping during contacts
- Demonstrate path to flight
COMMAND AND DATA HANDLING

HARDWARE
- Computer bus protocol
- Reliable data acquisition and storage
- Pin-outs represent space grade
- Small form factor
- Clock with 0.1ms resolution
  - Satisfies science sampling rate
  - 34bit integer

SOFTWARE
- Tracks recorded data for playback
  - Store and forward routine
  - No processing required
- Packetizes data for transmit
- Executes stored and real time commands
  - 512 commands (9 bit ID)
**ANTENNA CONFIGURATION**

- Isotropic gain pattern required
- Simple square patch considered
- 3dB beamwidth of 69.1°
- 9dB gain
- Omnidirectional visibility achieved with two antennas mounted on opposite sides of GeoPod
- Characteristic length: $L \approx c/2f$
  - UHF: 435 MHz $\Rightarrow L \approx 34.5$cm
  - S-Band (ISM): 2.4GHz $\Rightarrow L \approx 6.25$cm
- UHF not feasible based on probe surface area

*Typical radiation pattern of a simple square patch.*
PATCH ANTENNA

- Dual-band transmit and receive UHF patch antennas
- Antennas at each pole orientated 90° apart provide 95% spherical coverage
  - Gain pattern designed and tested
  - Minimized interference pattern
- Antennas mounted on half shells available from Ball
- Demonstrated with radio system
DT15 Transmitter
- Frequency: 340.0 – 399.9MHz (UHF)
- Data rate: <10Mbps
- Power: up to 2W RF output
- Dimensions: 3.175x8.89x0.97 cm
- Mass: 48.2 grams
- Temperature: -20C to 50C
- Acceleration: 100g, 3-axis

DR75 Receiver
- Frequency: 340.0 – 399.9MHz (UHF)
- Data rate: <10Mbps
- Current draw: 275mA
- Dimensions: 6.35x8.89x2.159 cm
- Mass: 170.1 grams
- Temperature: -20C to 50C
- Acceleration: 100g, 3-axis
## Antenna Selection

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| 2.4 GHz Square Patch     | - Industrial, Scientific, and Medical (ISM) band reserved for scientific purposes  
                        | - COTS transceiver availability                                        | - Limited experience with antenna design  
                        |                                                                       | - Antenna does not mount well with spherical form factor unless customized  
                        |                                                                       | - Less direct path to flight                                            |
| Ball UHF Patch Antenna   | - Willing to provide                                                | - Permit to radiate at 437Hz                                           |
|                          | - UHF demonstration has Cubesat heritage                           | - Transceivers not readily available                                   |
|                          | - Gain pattern achieved through design and testing                  |                                                                       |
|                          | - Integrated with shell                                             |                                                                       |
|                          | - Reduces complexity and resources                                  |                                                                       |
SPACECRAFT CONTACTS

- Spacecraft orbiting period: \( T = 2\pi \sqrt{\frac{a^3}{\mu}} = 124.1 \text{ hrs} \)
  - \( T \) – orbital period
  - \( a \) – semi-major axis of orbit (5.25 km)
  - \( \mu \) – gravitational parameter (28.68 m\(^3\)/s\(^2\))
- Rotation rate of asteroid (2.4 hrs)
- Rotation rate \( << \) Orbital period
  - Rotation rate determines contact times between GeoPod and orbiting satellite
  - Results suggest 20 min passes every 2.26hrs
CHECKSUM CALCULATION

- Assume Bit Error Rate (BER) of $1 \times 10^{-5}$
- Chance of 2 bit error is $\sim 1 \times 10^{-7}$
- Chance of 2 bit error going undetected with a 16 bit modular checksum is $< 6.25$
- The likelihood of a 2 bit error occurring in a given packet and going undetected is $\sim 6 \times 10^{-9}$
- The total number of packets during the GeoPod mission is $\sim 2 \times 10^6$ (200 MB)
- The likelihood of an undetected 2 bit error occurring during the mission lifetime is $\sim 1\%$
SUBSYSTEMS

- C&DH
- Power
- Structure
BATTERY DESIGN OPTIONS

- Central Battery System
  - Single Battery source used to power all components
  - Simplicity of single connection to power board
  - Full discharge depth: Everything runs out of power at the same time

- Modular Battery System
  - Subsystems have separate batteries tailored to the needs of each subsystem
    - Either high power or low noise
    - Increased efficiency
    - Requirements on regulators relaxed by customizing load
BATTERY DESIGN SELECTION

Power System Trade Study

<table>
<thead>
<tr>
<th>Features</th>
<th>Weight</th>
<th>Central Battery</th>
<th>Modular Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>20%</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Reliability</td>
<td>15%</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Design Complexity</td>
<td>20%</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Volume</td>
<td>15%</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Mass</td>
<td>15%</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Cost</td>
<td>15%</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100%</strong></td>
<td><strong>6.1</strong></td>
<td><strong>6.2</strong></td>
</tr>
</tbody>
</table>

- **Modular Battery System**
  - Highest efficiency
  - Can also provide greater reliability
  - Fits within the volume/mass budget (discussed more in feasibility analysis)
Modular Battery System

- Spiral Cell Battery
  - 9 V, 5 Ω internal resistance
  - Hardware controlled switch

- Bobbin Cell Battery
  - 21 V, 12 Ω internal resistance
  - Hardware controlled switch

Power Board

- Voltage Regulation
  - 5 V
  - Command controlled switch

- Voltage Regulation
  - 9 V
  - Command controlled switch

- Voltage Regulation
  - 7 V
  - Command controlled switch

- Voltage Regulation
  - 20 V
  - Command controlled switch

- Voltage Regulation
  - 18 V
  - Command controlled switch

Radio

Heaters

Avionics

Accelerometer

Geophone
For feasibility Lithium manganese dioxide (LiMnO$_2$) were analyzed because of their commercial availability.

**Spiral Type Lithium cell** [1]
- Specific Energy: 150 Wh/Kg, 300 Wh/L (At coldest temperature of $-60^\circ$ C)
- Max Current: 5A

**Bobbin Type Lithium cell** [1]
- Specific Energy: 329 Wh/Kg, 668 Wh/L (Varies little with temperature)
- Max Current 100 mA
### Energy Distribution

<table>
<thead>
<tr>
<th>Component</th>
<th>Total Energy (Wh)</th>
<th>Energy Density (Wh/kg)</th>
<th>Energy Density (Wh/L)</th>
<th>Mass (kg)</th>
<th>Volume (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communications</td>
<td>64.16</td>
<td>150</td>
<td>300</td>
<td>0.428</td>
<td>0.214</td>
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<tr>
<td>Heaters</td>
<td>223.01</td>
<td>150</td>
<td>300</td>
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<tr>
<td>Spiral Cell Battery</td>
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<td></td>
<td></td>
<td>1.914</td>
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<tr>
<td>Avionics</td>
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<td>329</td>
<td>668</td>
<td>0.306</td>
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<tr>
<td>Accelerometer</td>
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<td>329</td>
<td>668</td>
<td>0.004</td>
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<tr>
<td>Geophone</td>
<td>0.075</td>
<td>329</td>
<td>668</td>
<td>0.001</td>
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<tr>
<td>Bobbin Cell Battery</td>
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<td></td>
<td></td>
<td>0.310</td>
<td>0.153</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>389.2</strong></td>
<td></td>
<td></td>
<td><strong>2.225</strong></td>
<td><strong>1.110</strong></td>
</tr>
</tbody>
</table>

- Mass is within preliminary budget of 3 kg (34% Margin)
- Volume is within preliminary budget of 1.5 L (35% Margin)
POWER REGULATORS

- Synchronous switching voltage regulator chosen over Linear dropout regulator (LDO)
  - Higher efficiency
  - Large accuracy with synchronous rectifier
  - Customizable active circuit

- Feasibility
  - Linear Technology switching regulator LTC3612
    - 2.25-5.5V range with up to 3A output current
    - ±1% Output Voltage Accuracy
    - Up to 95% efficiency
  - Linear Technology switching regulator LTC3646 for larger voltage loads

- Remaining Studies
  - Understand complex circuitry
SUBSYSTEMS

C&DH

Power

Structure
## Design Selection

### Internal Configuration Trade Study

<table>
<thead>
<tr>
<th>Features</th>
<th>Weight Score</th>
<th>Weighted Score</th>
<th>Score</th>
<th>Weighted Score</th>
<th>Score</th>
<th>Weighted Score</th>
<th>Score</th>
<th>Weighted Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Access</td>
<td>15%</td>
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<td>1.05</td>
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<tr>
<td>Cost</td>
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<td>Manufacturability</td>
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<td>1.05</td>
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<tr>
<td>Integration</td>
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<td>Maintenance</td>
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<td>7</td>
<td>0.35</td>
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<tr>
<td>Mass</td>
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<td>1</td>
<td>7</td>
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<tr>
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<td>0.8</td>
<td>6</td>
<td>0.6</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100%</strong></td>
<td><strong>5.45</strong></td>
<td></td>
<td><strong>6.25</strong></td>
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<td><strong>6.4</strong></td>
<td></td>
<td><strong>6.8</strong></td>
</tr>
</tbody>
</table>
THERMAL ANALYSIS CONT’D

- Energy Balance
  - \( \dot{q}_{\text{Net}} = \dot{q}_{\text{absorbed}} - \dot{q}_{\text{emitted}} + \dot{q}_{\text{load}} - \dot{q}_{\text{cond}} \)
  - Assume \( \dot{q}_{\text{Net}} = \frac{\Delta q}{\Delta t} \), where \( \Delta t \) is step size
  - \( \Delta T = \frac{\Delta q}{mC} \), allows for energy storage
  - Load dependent on time (mission segment)
  - Position on surface dependent on time
    - Solar absorption
    - Conduction values provided by ball
- Heater Power
  - Assume for \( T < 0^\circ \text{C} \), \( \dot{q}_{\text{Net}} = \dot{q}_{\text{heater}} \)