TEPCE: A Tethered Electrodynamic Propulsion CubeSat Experiment

Shannon Coffey, Cameron Crippa, Gil Dutchover, Matthew D. Brunner, Zachary Sibert, Scott Kindl, Ivan Gaylish, C. Lon Enloe, Joe Carroll, Eugene Levin

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  - Electronics Systems
- Flight Operations
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- Thrusting and Current Flow Results
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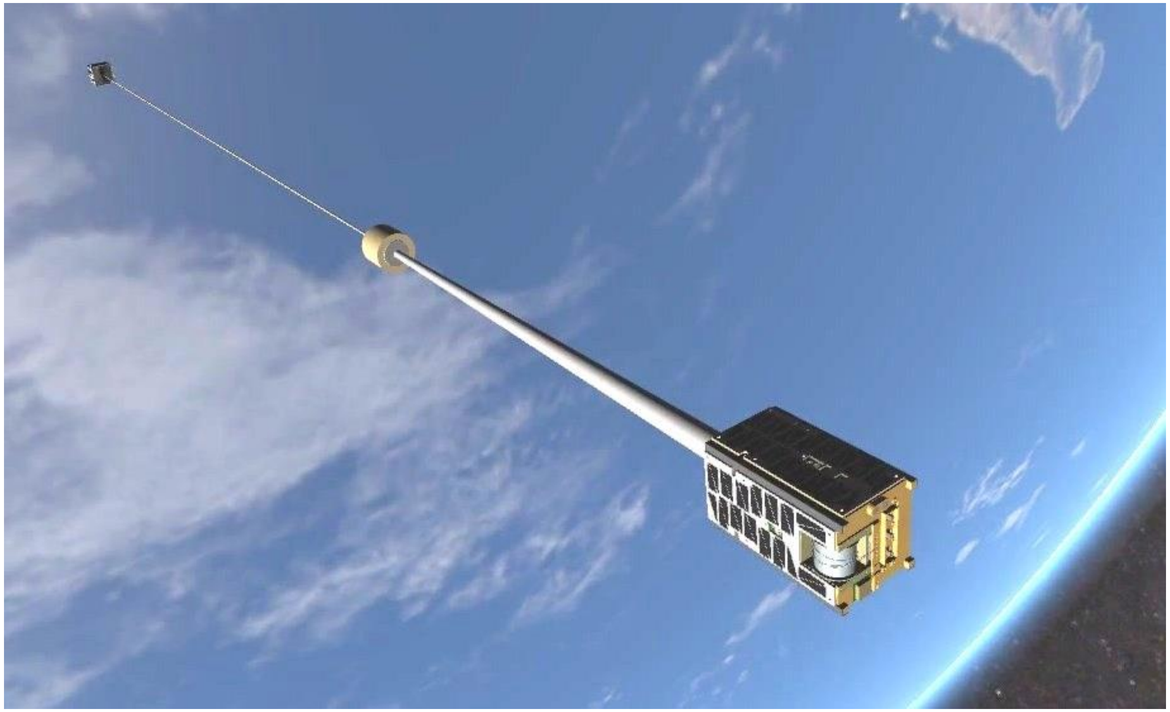

3D Rendering of Tether Deployment

Overview

TEPCE was a 3U CubeSat that was developed to explore the feasibility of using electrodynamic propulsion for spacecraft. Propulsion is generated by conducting an electric current along a long wire, called a tether, that connects two spacecraft end-masses. As the spacecraft moves along its orbital path, the Earth's magnetic field induces a Lorentz force between the magnetic field and the electrons in the tether that results in thrust for the spacecraft. It requires no chemical or other traditional fuel source. TEPCE was one of the first self-contained electrodynamic propulsion spacecraft. TEPCE was launched on a SpaceX Falcon Heavy rocket on June 25, 2019. It was a successful spacecraft that demonstrated mechanical and electrical systems that can enable a spacecraft to maneuver using electrodynamic principles.

Team Composition

- Systems Integration Branch, Spacecraft Engineering Division
  - Shannon Coffey
  - Cameron Crippa
- Dynamics and Control Systems Branch, Spacecraft Engineering Division
  - Gil Dutchover
  - Matthew D. Brunner
  - Zachary Sibert
  - Scott Kindl
- Advanced Space PNT Branch, Space Systems Development Division
  - Ivan Galysh
- Charged Particle Physics, Plasma Physics Division
  - C. Lon Enloe
- Tether Applications, Inc.
  - Joe Carroll

Program History

~10 year program from concept to completion

- 2010 - Initial research and development
- 2015 - Hardware finalized and patented
- 2018 - Ground station development and setup
- 2019 - Launch
  - **June 25, 2019** - TEPCE was launched from Cape Canaveral, FL, on Space Test Program (STP-2) mission via SpaceX Falcon Heavy
  - **July 16, 2019** - First Positive Contact
  - **November 16, 2019** - Tether Deployment
    - At approximately 0140 EST, the command was given to deploy the tether, separating the two end-masses
    - Acknowledgement of successful deployment was not obtained
    - Subsequent passes showed an increase in the rotation rate about the roll axis, consistent with the rate of the stacer unwinding per prelaunch tests
  - **November 17, 2019** - A six-fold increase to the drag term further confirmed separation of the spacecraft
  - **November 21, 2019** - Imagery further confirmed separation of the end-masses but showed separation of only about 270m
  - **November 22, 2019** - Commands were given to deploy the impedance probes (iProbes) and collector tapes for both end-masses.
    - Confirmation was received from Ren
    - Due to communication limitation with Stimpy, confirmation could not be determined
  - **November 27, 2019** - Further imagery showed a separation of 450 m but also a reflective area in the center of the tether
  - **February 1, 2020** - TEPCE reentered Earth's atmosphere
    - Analysis predicted a post-tether deployment orbital lifetime between 30 and 60 days
    - Post-tether deployment lifetime was 78 days
    - This longer-than-expected lifetime is attributed to a partial deployment of the tether and therefore a smaller area-to-mass ratio than expected.

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Hardware Systems

Hardware Systems

- Mechanical
  - Mechanical Description of Ren
  - Mechanical Description of Stimpy
  - Mechanical Description of Center Module
  - Tether Design, Winding and Testing
- Electronics
  - Battery Board
  - Electrical Power System (EPS)
  - Command Data Handling Board (CDH)
  - Sensor Board
  - Radio Board
  - High-Voltage Board

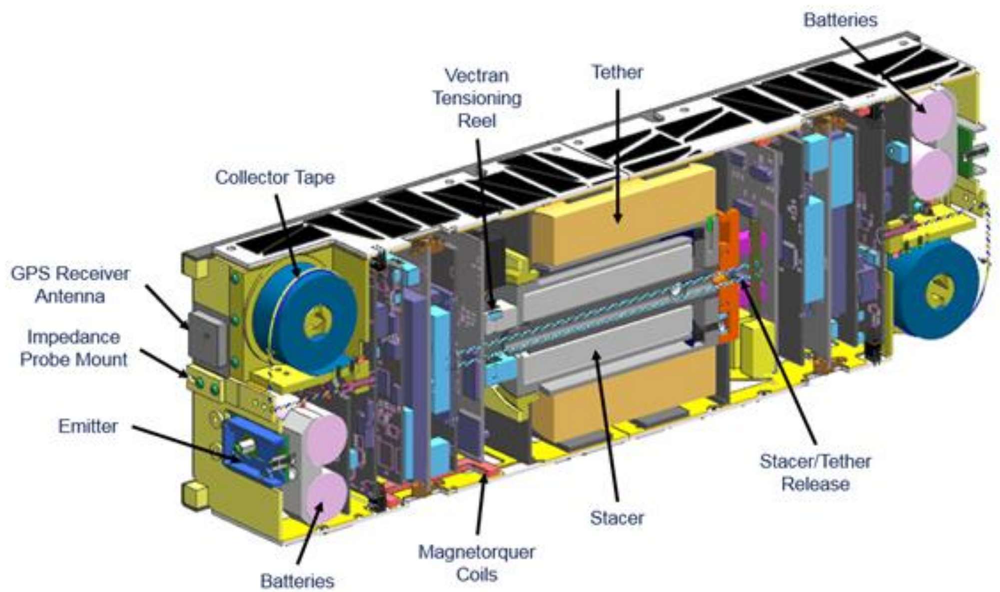
TEPCE in Flight Configuration

TEPCE Without Exterior Panels

Hardware Systems

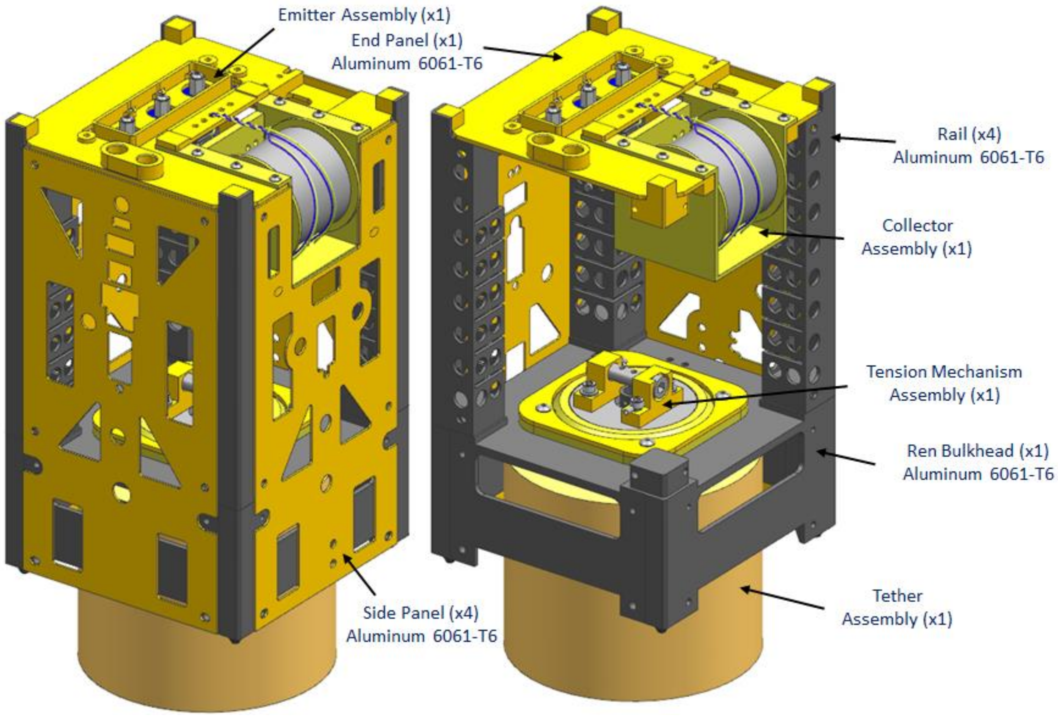
Mechanical Description of TEPCE

- 3U Small Sat
- Two Near-Identical 1.5U Sub-CubeSats
- Connected by a 1 km Conductive Tether
- Each End-Mass Contains Independent Systems
- The Center Module Houses the Conductive Tether and Release Systems
- The Two End-Masses Were Held Together By a Pretensioned Vectran Line



CAD Cutaway Drawing of TEPCE

- Ren
  - End Panel
  - Bulkhead
  - Connected by 4 side panels
    - Emitter and collector assemblies mounted to end panel
    - Tether Assembly and Tension Mechanism Assembly mounted to bulkhead
    - Electronic component cards mounted to the rails

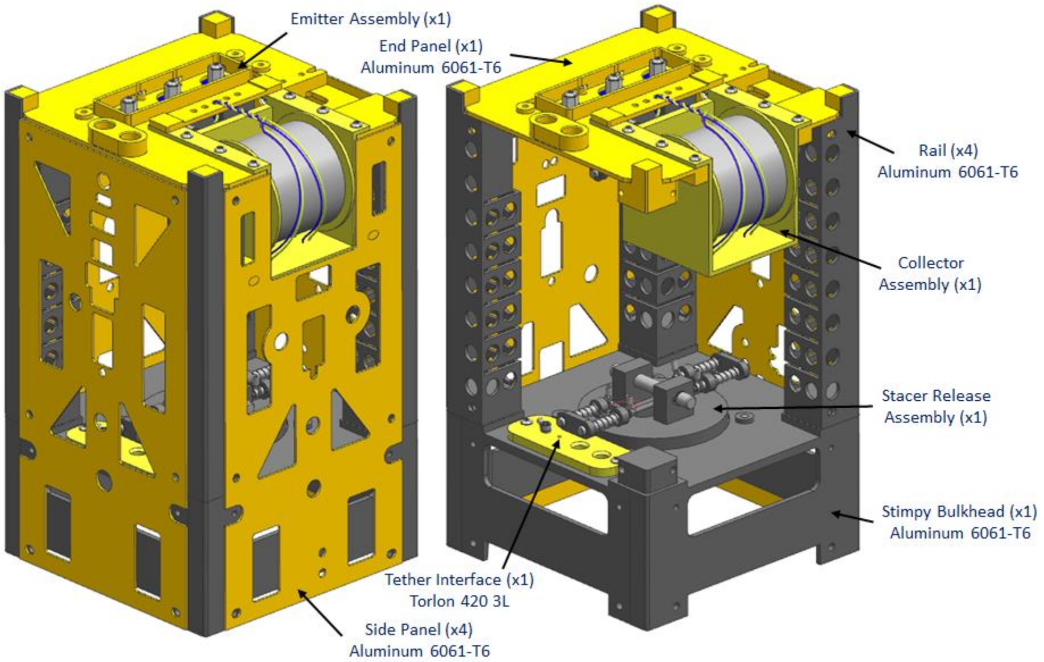


Ren Structural Components and Subassemblies

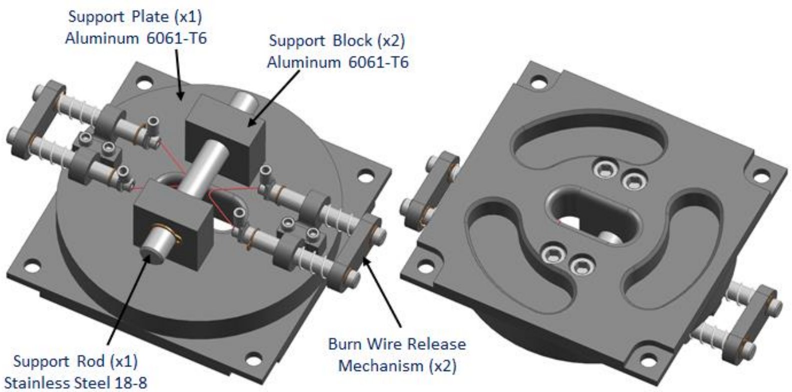
Hardware Systems

Mechanical Description of Stimpy

- Stimpy
  - Nearly Identical to Ren
  - Major differences
    - Stacer Release Assembly
    - Tether Interface



Stimpy Structural Components and Subassemblies



Stacer Release Mechanism

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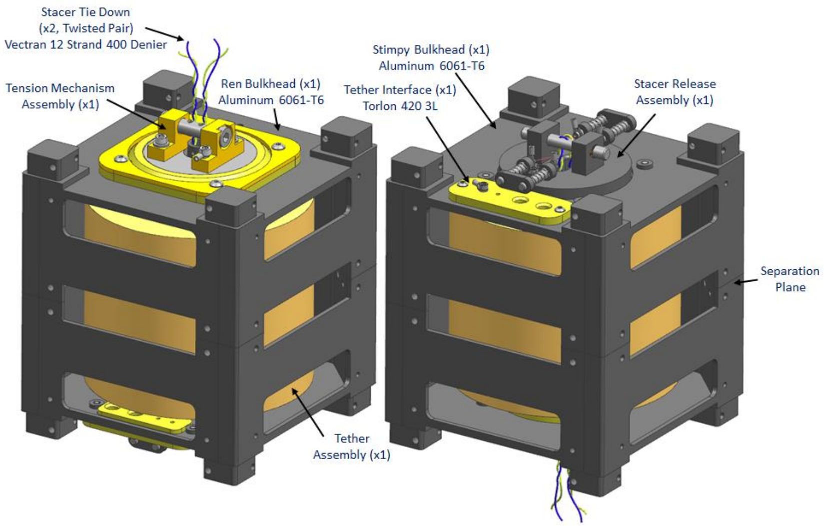
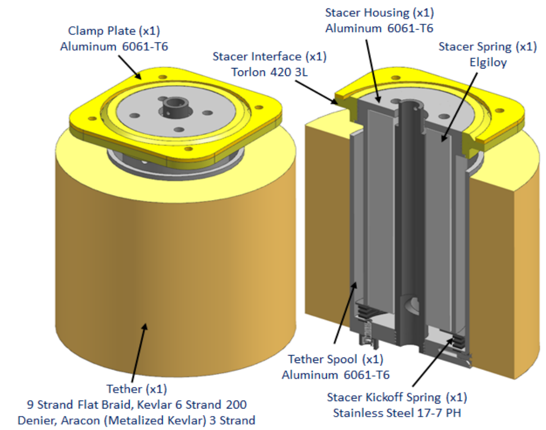
Hardware Systems

Mechanical Description of Center Module

- Center Module
  - Composed of Bulkhead Sections of Both Ren and Stimpy
  - Separation Interface of TEPCE
  - Contains Tether Mechanism
  - Tether Deployment Initiation
    - Current Applied to the Stacer Release Mechanism
    - Burn Wire Cuts the Vectran Tie Down
    - Stacer Spring Released
    - Loaded Spring Force Separates the Stacer Housing and the Tether Spool



TEPCE Center Module



Tether Assembly

- Tether
  - 9 Strand Flat Braid Kevlar
    - 6 Strand 200 Denier
    - 3 Strand Copper/Nickel/Copper Coated Kevlar Fiber (Aracon)
  - Bare Conductor
    - Insulation Would Have Added Stiffness and Bulk
    - Bare Conductors Allowed for Electron Collection from Emitters
  - 1.6mm Width x 0.25 mm Thickness x 1030m Length
  - Electrical Resistance of 1.6 Ω/m
  - Wind Direction Was Reversed Five Times During Winding to Reduce Angular Momentum Caused by Free Endwise Deployment
  - 36 AWG Magnet Wire Braking Hooks Were Added to Provide 0.1-0.5N of Braking Force to Control Deployment

Completed Tether Winding

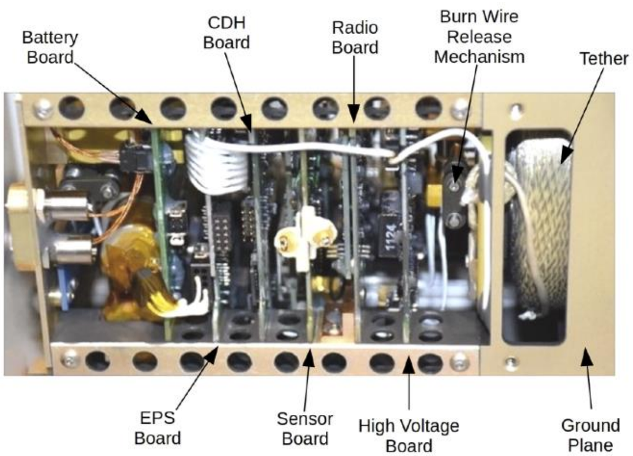
Tether Winding Reversal

Tether Braking Hooks

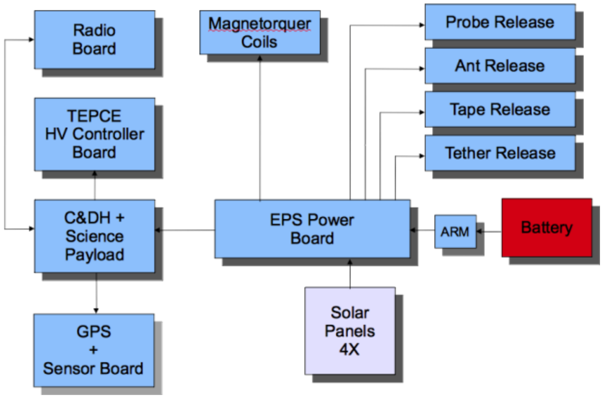
Hardware Systems

Electronic Description of TEPCE

- Both End-Masses Contained Six Identical Electronic Cards Mounted Directly to the Rails
    - Battery Board
    - Electrical Power System (EPS) Board
    - Computer Data Handling (CDH) Board
    - Sensor Board
    - Radio Board
    - High Voltage Board
- Boards Were Interconnected with Custom Harnesses

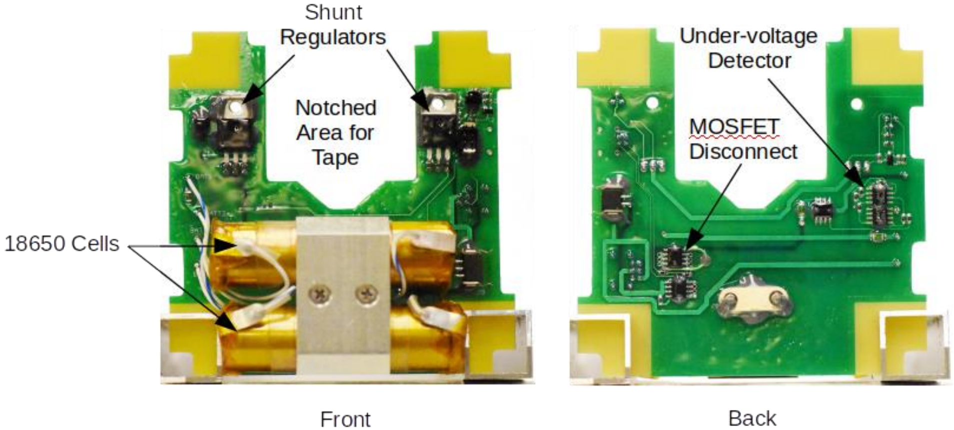


TEPCE Board Stack, Tether, Collector Tape, and Filaments

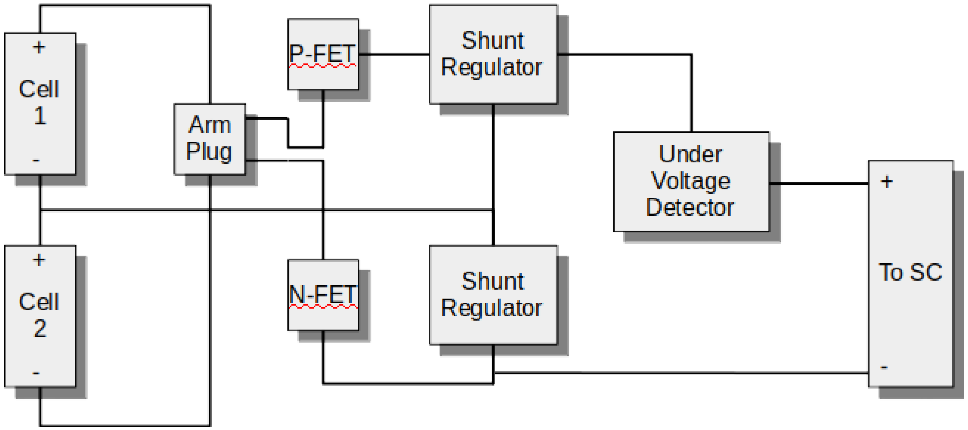


End-Mass Electronics Block Diagram

- Two 18650 Lithium Ion Cells (LG Brand)
  - 3.6V
  - 2600 mAH
  - Provided a Maximum of 3.75 A
  - System Required 2A
- Shunt Regulator Clamped Maximum Voltage to 4.1V Per Cell
- Field-Effect Transistor
  - Disconnected Battery Systems from the Satellite if Total Voltage Below 6V
  - Allowed Charging via Solar Panel
- Release Switch
  - Activated Upon Ejection from PPOD
  - Turned on Transistors Connecting Battery Cells to Protection Circuits



Battery Board

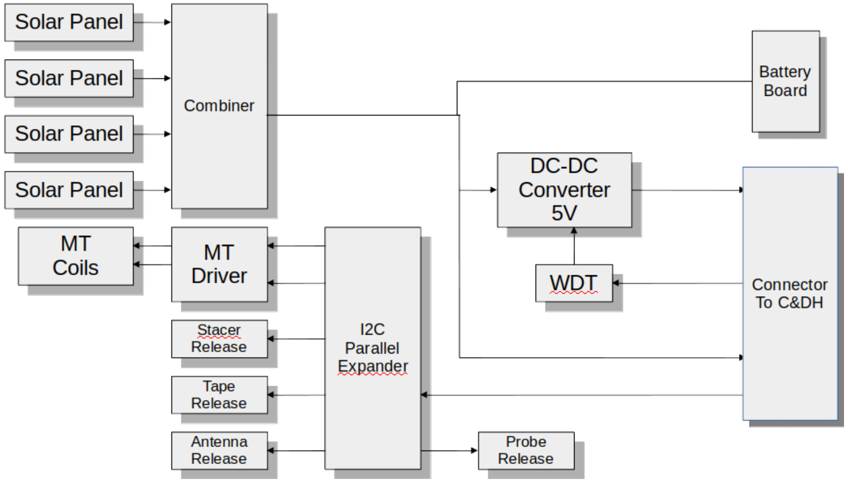


Battery Board Block Diagram

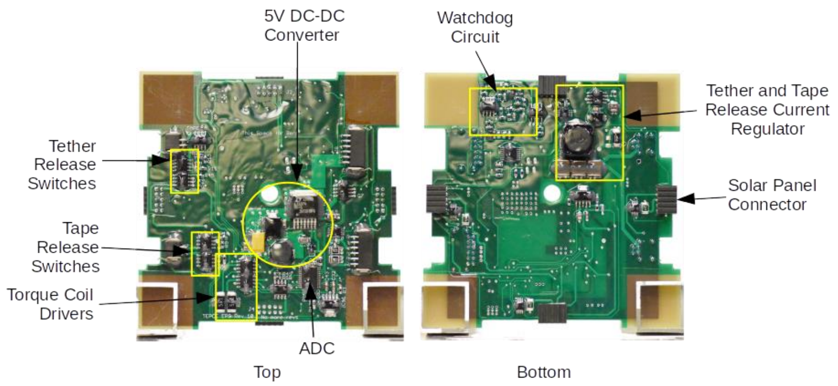
Hardware Systems

Electrical Power System (EPS)

- Provide Consistent 5V Supply to the Command Data Handler, Sensor, Radio, and High-Voltage Board
- Included Watchdog Timer to Power-cycle Satellite in the Event of Software Error or Radiation Event
- Solar Panel Regulation
- Magnetic Torque Coil Controls
- System Deployment (Cutter) Controls
    - Antennas
    - iProbe
    - Tether
    - Collector Tape



Electrical Power System Block Diagram

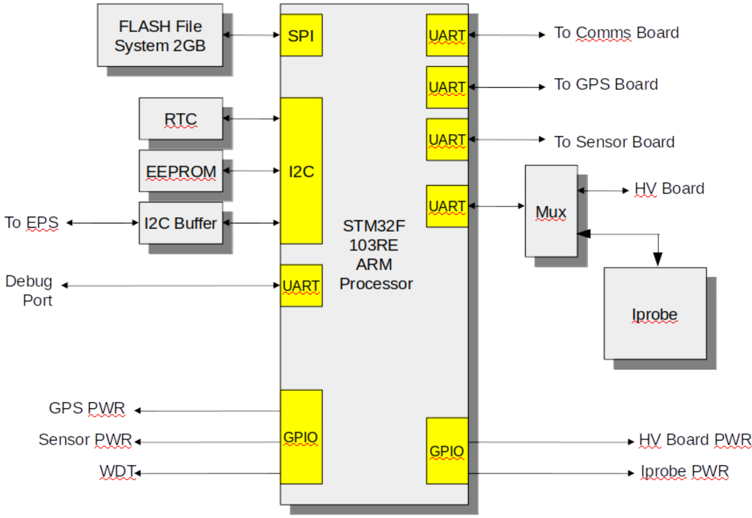


Electrical Power System Board

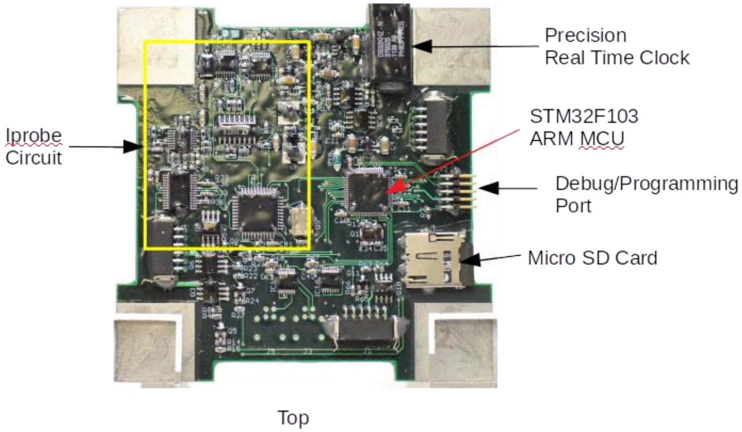
Hardware Systems

Command Data Handling Board (CDH)

- STM32F103 Arm-Based 32-Bit Microcontroller
- Real-time Clock
- EEPROM IC to Store State Information
- P-Channel MOSFETS to Switch Power
  - GPS Receiver
  - Sensor Board
  - High-Voltage Board
- 2 GB microSD card
- 5 Serial Ports
  - Sensor Board
  - Radio Board
  - High-Voltage Board
  - GPS Board
  - iProbe Circuitry
    - Generated a Frequency Swept Signal to Measure Probe Impedance
    - Measured Plasma Field Density



CDH Board Diagram

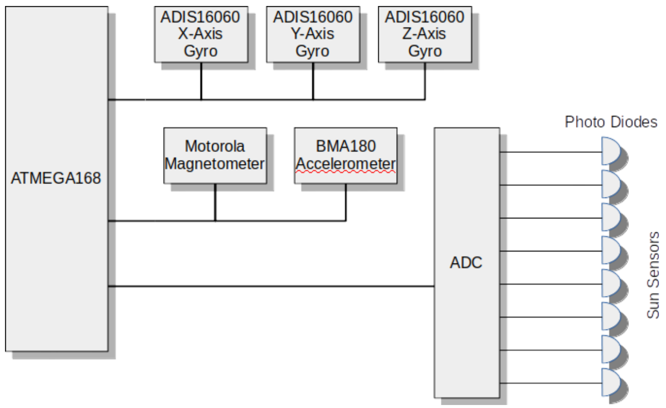


CDH Board

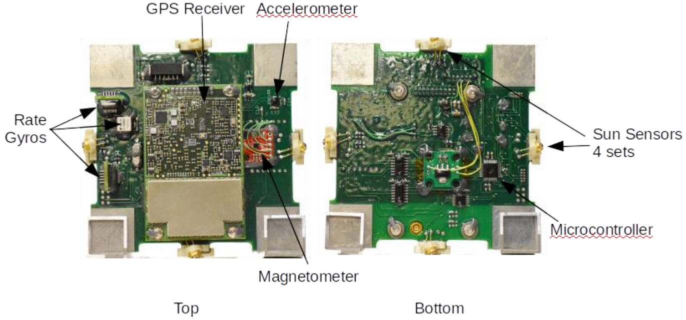
Hardware Systems

Sensor Board

- ATMEGA168 AVR Microcontroller
- Interfaced with On-Board Sensors
  - Three-Axis Magnetometer (Motorola)
  - Three-Axis Accelerometer (Bosch BMA180)
  - Three Gyro Rate MEMS Sensors (ADIS16060)
  - Eight Photodiodes (Sun Sensors)
    - Two Per Side
    - Angle Offset to Allow for Calculation of Sun Direction
  - GPS Receiver
    - Independent Receiver Mounted to Sensor Board
    - Novatel Receiver

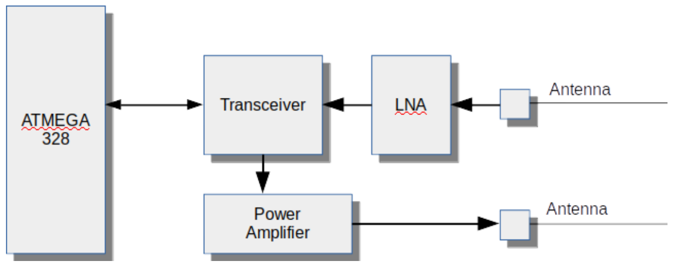


Sensor Board Diagram

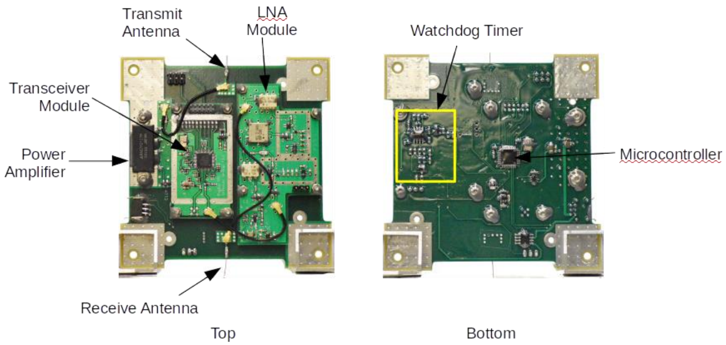


Sensor Board

- ATMEGA328 AVR Microcontroller
- Interface to Radio
    - Half-Duplex GMSK Radio Module
    - ADF7020-1 Transceiver
    - Low Noise Amplifier
    - Power Amplifier (1-4W)
    - Transmit and Receive Antenna (Nitinol Wire) Directly Connected
- 297.7 MHz
- 253 MHz



Radio Board Diagram

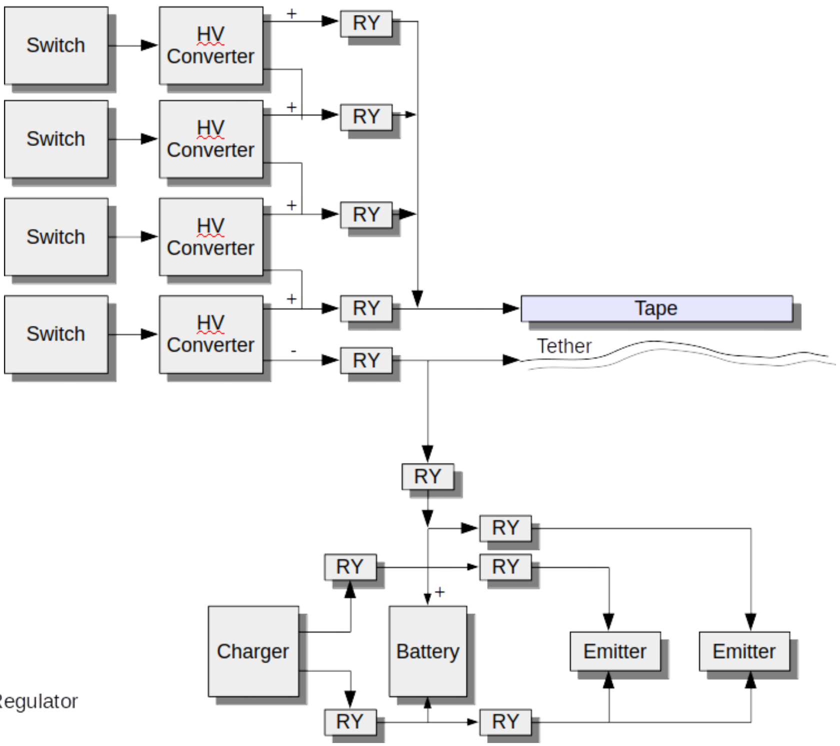


Radio Board

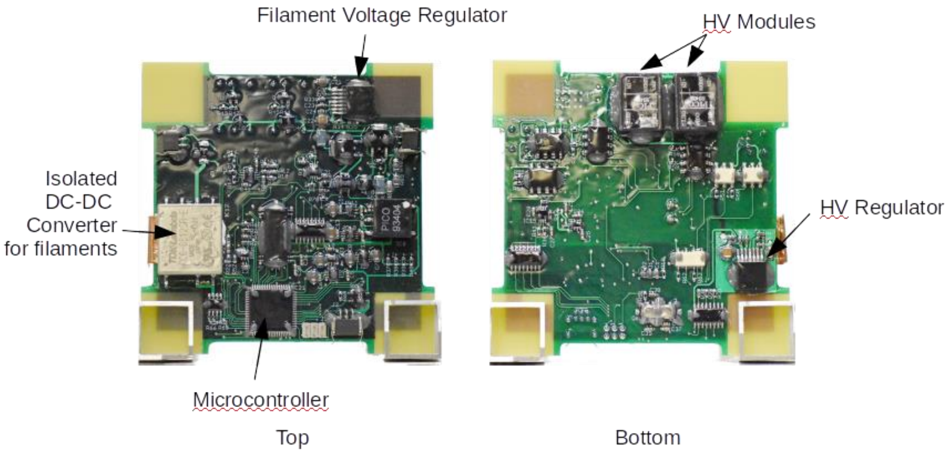
Hardware Systems

High Voltage Board

- ATMEGA128 AVR Microcontroller
- Routed High voltage to Tether and Collector Tape
- Measured Current Through Tether
- Two HV Modules Generating 150V and 300V (Total Combined Maximum of 450V)



High Voltage Diagram



High Voltage Board

Flight Operations

Flight Operations

- Ground Station
- Launch
- Subsystem Checkout
- End-Mass Deployment
- Communication Lessons Learned

Mission Operations

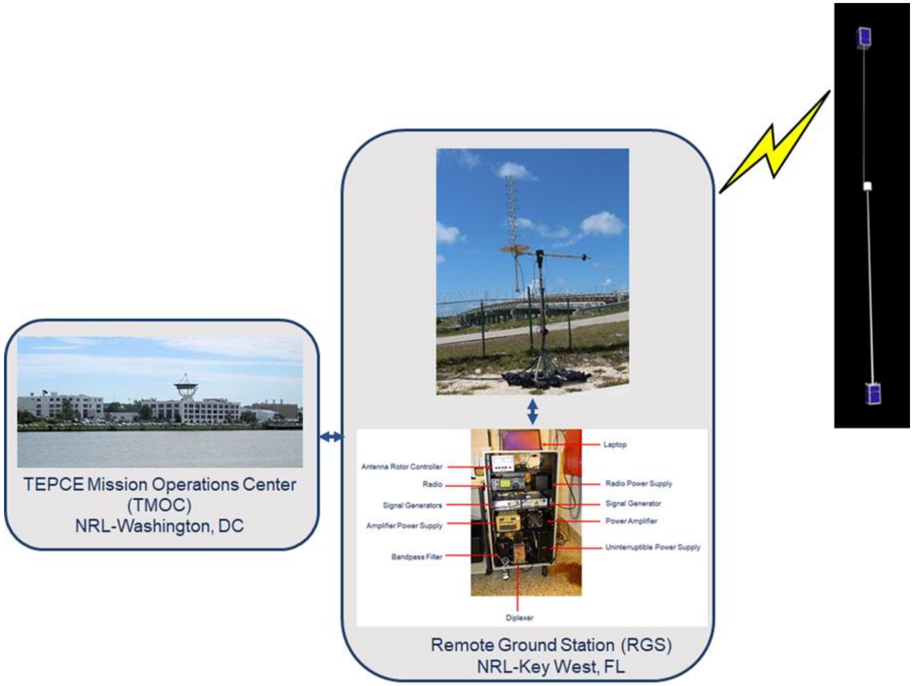
Ground Station

- Tracking/Communication Challenges
  - TEPCE Team Based Out of Washington, DC
  - Interface software was proprietary
    - Limited Tracking to DoD Controlled Systems
    - Software Not Approved for Public Release
  - TEPCE was Planned for a Low Inclination Orbit
    - Visibility Over Washington DC Was Minimal or Nonexistent
    - Link budget established that TEPCE had insufficient transmit power to secure downlink to a ground station located in the Washington DC Area

- Solutions
  - Establish and Operate Our Own Ground Station
  - Install Remote Ground Station at DoD Site at Lower Latitude
    - Utilize Space at NRL Installation at the Naval Air Station Trumbo Point, Key West, FL
      - High-Elevation Passes Over Key West
      - Low Range Passes Over Key West
    - DoD Network Systems Allowed for 22 Mbps Communication Between DC and Key West

- Ground Station Hardware
  - M2 Antenna Systems Inc. 2.4-m helical antenna
  - 10-foot-tall antenna mount
  - YAESU G-5500 antenna azimuth-elevation rotators & controller
  - On Site Computer (Ubuntu 16.04 LTS)
    - Motor Controls Via Custom Rotator Controller
    - The on-site laptop provided azimuth and elevation input based upon a custom-built tracker program that received input from an open-source satellite position tracking program called PREDICT[5].
    - A custom motor controller and tracking program was built utilizing the PREDICT data, which allowed for automated control of the azimuth and elevation motor,
    - A custom-built satellite control program was developed to generate transmission signals and to process received data. Figure 37e shows the TEPCE graphical user interface used during operations.
    - Weather-Proof HD Camera

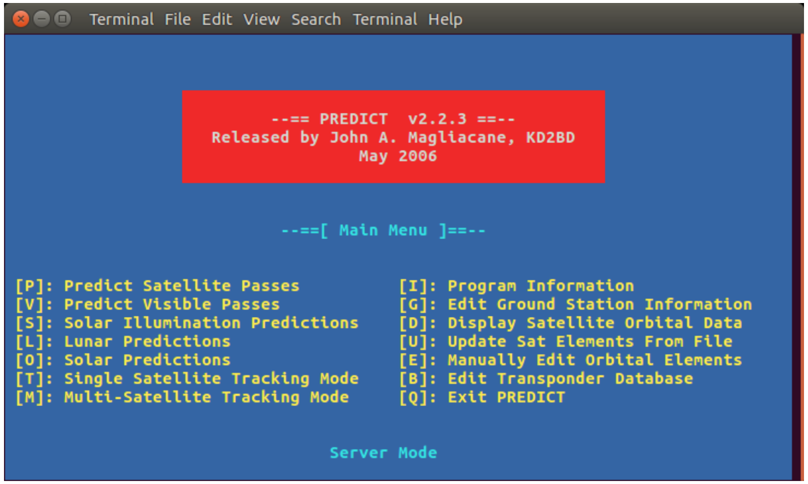
- TEPCE Mission Operations Center (TMOC)
  - Received Remote Video of the Ground Station
  - Remotely Accessed Ground Station Laptop to Update, Command, and Control RGS
  - Transferred Downlinked Data for Analysis



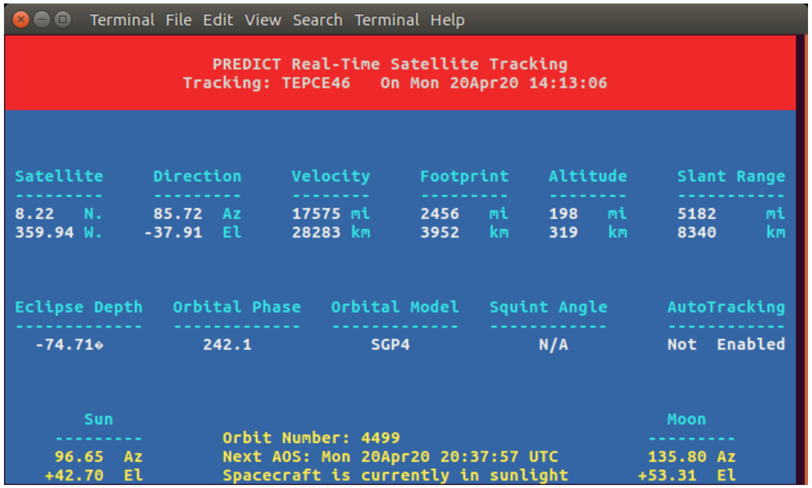
TEPCE Ground Architecture

Mission Operations

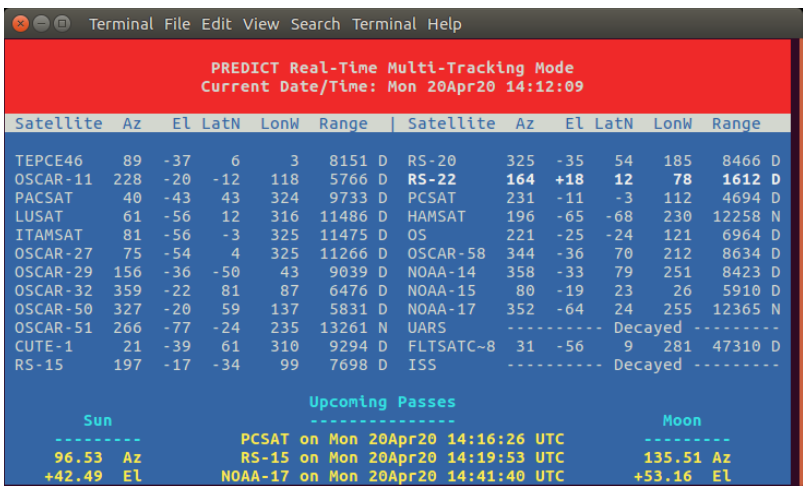
Ground Station (cont.)



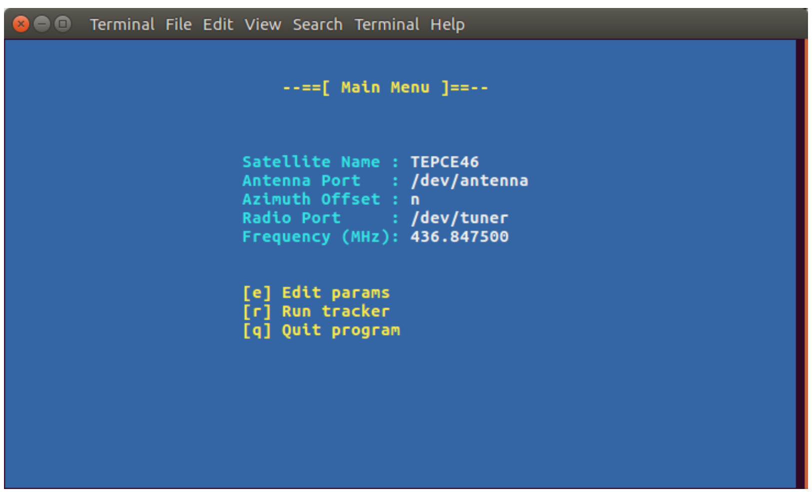
PREDICT Software Used for TEPCE Tracking



PREDICT Software Single-Tracking Mode



PREDICT Software Multi-Tracking Mode



Custom-Built Motor Controller/Tracking Software

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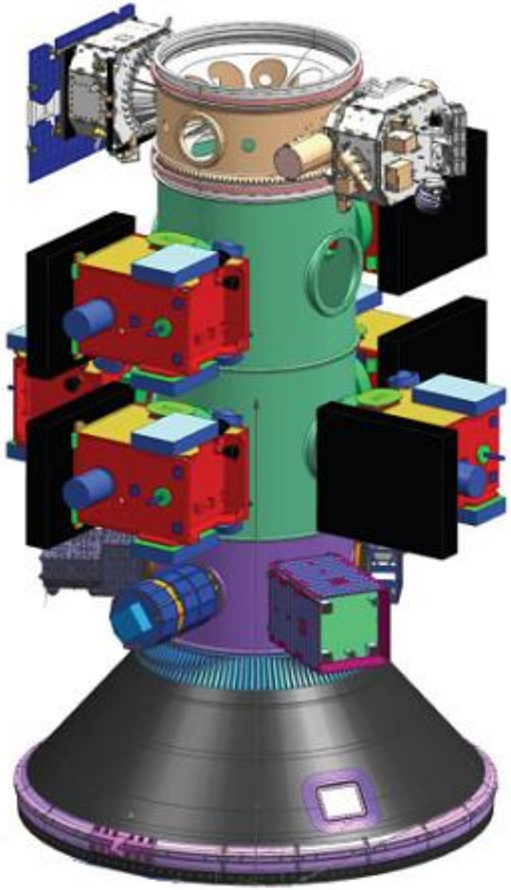
Mission Operations

Ground Station (cont.)

TEPCE GUI – Controlling Stimpy

- Launch
  - TEPCE was Launched from Cape Canaveral, FL, on June 25, 2019, as a Part of the Space Test Program (STP-2) Mission Onboard a SpaceX Falcon Heavy
  - TEPCE was Stored Inside of a Poly Picosatellite Orbital Deployer (PPOD) Mounted to the Payload Attachment Fitting of the Upper Stage
  - TEPCE was Deployed from the PPOD Approximately 19 Minutes After Liftoff.
  - The STP-2 Mission Included the COSMIC-2 Constellation (Six Satellites) and 18 Other Satellites

- Tracking
  - Due to the Large Volume of Satellites Deployed, It Took Almost 2 Weeks to Positively Identify TEPCE
  - Trial-And-Error Communication of All Deployed Objects From the List of TLEs Published to Space-Track.org
    - Tracked Each TLE During Passes Over the RGS
    - Sent "Find State" Commands
    - Awaited Response Before Moving to Next Available Object
  - Developed Program to Send a Signal to Each End-Mass in Alternating, 3-second Bursts
    - Command to Increase Transmitter Power to Maximum
    - Return State Telemetry
  - Satellite Number 44346 Consistently Caused the Control Software to Crash
  - Errors in the Software were Mishandling Positive Signals from TEPCE
  - Code was Corrected and Positive Contact was Made to Satellite Number 44346 on July 16, 2019
    - Contact First Was Made With the Ren End-Mass
    - Contact Was Made With the Stimpy End-Mass on July 22, 2019.



STP-2 Payload Stack

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Mission Operations

Subsystem Checkout

- Following Successful Contact, a Series of System Checks Were Initiated
  - Synchronization of Onboard Clocks
  - Activation of Attitude Control Systems
  - Activation of GPS Receivers
  - Download of Telemetry and Sensor Data
  - Upload of Configuration Files
- ACS Showed TEPCE was Tumbling End-Over-End at a Rate of 4.4 Revolutions per
  - Far Above the Maximum Acceptable Rate
  - Magnetorquers Engaged to Slow Tumble Below One RPM
- TEPCE's Orbit Encountered the South Atlantic Anomaly Causing Frequent System Resets
  - Likely Due to Non-Hardened Electronic Components
  - Flight Data Recorded to Correlate TEPCE's Resets to SAA Models

Mission Operations

End Mass Deployment

- At 0147 EST on November 16, 2019 the Command was Given to Deploy the Tether
  - Acknowledgement was Not Obtained
  - Increase in Rotation About the Roll Axis was Consistent with Stacer Unwinding per Prelaunch Tests
  - A Sixfold Increase to the Drag Term on November 17, 2019, Further Confirmed Separation
- On November 22, 2019, Commands were Given to Deploy the Impedance Probes (iProbes) and Collector Tapes
  - Confirmation was Received from Ren
  - Confirmation was Not Received From Stimpy
- Imagery on November 21, 2019, Confirmed Separation but Showed Separation of Only About 270 m.
- Further Imagery on November 27, 2019, Showed a Separation of 450 m
  - Also Showed an Anomalous Reflective Area in the Center of the Tether
  - Suspected to Be a Snag in the Tether or a Rebound
  - Possible Causes
    - Braking Hooks Did Not Release
    - Braking Hooks Did Not Slow Release
    - Snag of a Piece of Hardware
    - Memory Effect Within the Tether.

Image of TEPCE After Tether Deployment Taken at the Air Force Maui Optical and Supercomputing Site

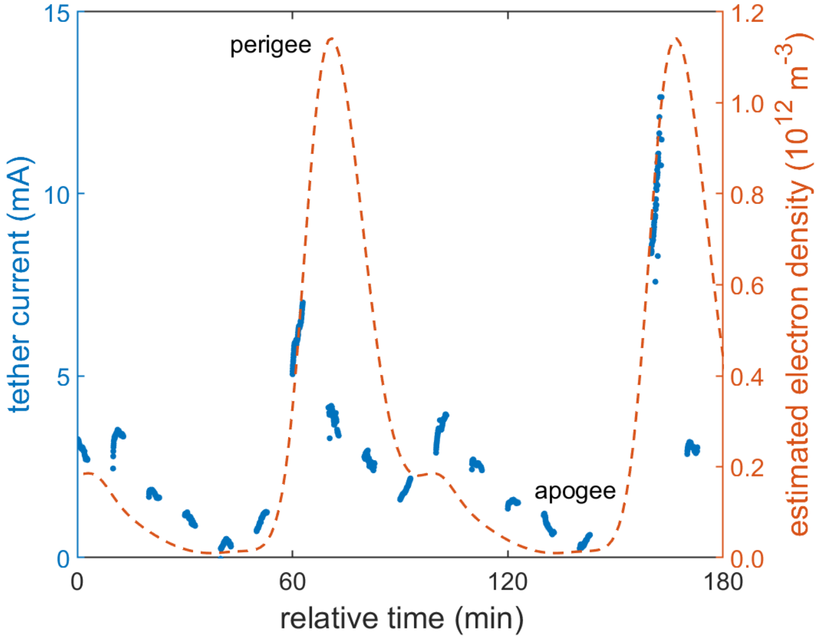
Mission Operations

Communication Lessons Learned

- TEPCE Suffered From Varying Communication Issues
  - Communication Difficulties Between the TMOC and RGS Computers (Resolved Prior to Launch)
  - Difficulties Closing the Link With the Satellite
  - Tracking Issues with the Ground Station
  - Power Management Issues
- Spacecraft Design and Construction Began Almost 10 Years Before Launch
  - Many Parts Were Outdated by Launch Date
  - Many Parts Could Not Be Changed Due to Budgetary Reasons
- Closing the Downlink With Stimpy Became Very Difficult Post-tether Deployment
  - Gravity Gradient Caused Stimpy to Remain at a Higher Altitude
  - It Was Hypothesized That the Tether May Have Modified the Antenna Pattern
  - Cause Could Not Be Definitively Determined
  - Operations Team Made 1,230 Communication Links with Ren, But Only 41 to Stimpy

Thrusting and Current Flow Results

- Tether Operations Limited By Power and Communication Issues
- Tests Involving Stimpy's Collection Tape Were Not Viable
- Tests Utilizing Ren Were Conducted
  - Tether Was Conductive
  - Ren Was Situated on the Negative End of the Tether
  - Ignition of Electron-Emitting Filament Allowed Flow in the Electrodynamic Circuit Driven by the Naturally Occurring Potential Drop in the Tether
- On December 6, 2019 Ren Was Able to Collect Data for a Significant Portion of Two Orbits
  - Due to Natural Negative Bias on Ren, the iProbe Was Not Able to Measure Electron Density
  - Electron Density Estimates Based on International Reference Ionosphere (IRI) Models Were Used and Behavior of Current in the Electrodynamic Circuit Was Consistent With the Estimated Level of Variation



Measured Tether Current and Estimated Plasma Electron Density Over Approximately Two Orbits, Taken Dec 6, 2019

Summary

- TEPCE demonstrated the feasibility of electrodynamic propulsion
- Data from the electrodynamics experiments demonstrated significant electron flow along the tether

- The tie-down mechanism and the stacer spring executed successfully
- The shortened distance between the end-masses is an area for future research for future missions

- The communication system was designed for a short-duration mission, but evidently, non-radiation-hardened components exhibited decreased performance as time went on

Questions?

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