Energetic Particle Detector

Colin Wilkins and Ryan Caron
Instruments Lead and Chief Engineer
June 7th, 2018
Agenda

0. The Team
1. Instrument specification
2. Post-CDR milestones
3. Post-CDR Assembly, Integration, and Test (AI&T)
4. Requirements validation
5. Responses to CDR RFAs and recommendations
6. Unverified failures and open risks
7. Conclusion
## 0. The team

<table>
<thead>
<tr>
<th>Name</th>
<th>Class</th>
<th>Responsibility</th>
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<tbody>
<tr>
<td>Colin Wilkins</td>
<td>Graduate student, EPSS</td>
<td>Instruments lead</td>
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<tr>
<td>Ryan Caron</td>
<td>Staff engineer</td>
<td>Chief Engineer</td>
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<tr>
<td>Matthew Nuesca</td>
<td>CS ‘18</td>
<td>Payload Software</td>
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<tr>
<td>Gary Zhang</td>
<td>Graduate student, EE</td>
<td>Electronics Support</td>
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<tr>
<td>Maxwell Chung</td>
<td>Graduate student, AE ‘16 (now at APL)</td>
<td>Instruments Lead (former)</td>
</tr>
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<td>Patrick Cruce</td>
<td>Staff programmer (now at Northrop)</td>
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</table>
1. Instrument specification

- Instruments Stack
- EPD-I
- EPD-E
- PRM
- Stacer
- Batteries
- Avionics
- He-82
- UHF
- VHF
- FGM

6/7/2018
ELFIN’s Energetic Particle Detector (EPD) serves to measure the pitch-angle resolved fluxes of energetic electrons and ions precipitating from the radiation belts.

ELFIN’s EPD is comprised of two sensor heads, one for electrons (EPD-E) and the other for ions (EPD-I).

Sensor heads and supporting electronics fit in a volume of approximately 1U.

PCBs are interconnected using a combination of card edges and vertical mezzanine connectors.

Supported by a stack of related payload boards.
• The EPD is supported by other payload subsystems, including:

  • **The Instrument Data Processing Unit (IDPU)**
    • Primary payload telemetry and control unit, responsible to command the EPD and telemeter its data
    • Composed of the IDPU FPGA and TI MSP430 microcontroller (synthesized “soft core” implementation)
    • In-house real-time operating system (RTOS) developed specifically for ELFIN
    • Responsible to perform EPD’s magnetic spin sectoring algorithm (discussed later)
    • Some EPD/payload software still being actively developed and tested

  • **The Switching Instrument Power Supply (SIPS)**
    • Provides EPD power at 1.5V, 2.5V, 3.3V, 5.0V, and 8.0V levels
    • Makes use of synchronized internal clocking at configurable frequencies; chosen to minimize EPD noise

  • **The Fluxgate Magnetometer (FGM)**
    • EPD’s companion science instrument
    • Used by the IDPU to determine the local pitch angle of EPD’s boresight at the time of data collection
    • 80 Hz output mode to provide high time resolution for pitch angle determination as S/C spins
• ProASIC3E 3000 FPGA
  • 56 KiB of RAM split between program & data memory
  • Embedded MSP430 16-bit microcontroller core
• 16.384MHz oscillator
  • Distributed via LVDS to EPD, FGM, & SIPS
• 2 x 256KiB FRAM ICs
  • Stores 4 MSP430 programs for easy in-flight reprogramming
• 4x 128MiB Flash ICs
  • Stores instrument data, data products, and housekeeping
• Board revisions stem from minor interface changes
  • DM->EM: always on 5V UART transceiver & alternate voltage regulator for FGM
  • EM->FM: Shifted connectors to reduce PCB cutout in SIPS
• Bulk of effort has been (and continues to be) on the MSP430 programs
Switching Instrument Power Supply (SIPS)

- Filtered power switches for different modes
- Housekeeping & overcurrent protection
  - Parameters in-flight configurable: threshold (mA), persistence (ms), and response (switches, s/c panic)
- EM suffered a thermal runaway during vac
  - Evaluate relation between bench temp (IR camera) and vac temps (GSE thermistors in select locations)
  - Retrofit w/ thermal epoxy to continue tests
- FM changes
  - Larger inductor family
  - Larger linear regulator package
  - Added buck-boost 5V regulator
    - less power AND less noise
  - Used EM’s bench→vac coefficients w/ FM bench tests to determine that it would pass TVAC
Instrument specification

Unchanged from CDR, the EPD is comprised of several interconnected PCBs. The majority of electrical and digital design choices are now locked in (next slide for reference).

- **Digital 1/2 (D1/D2):** ADC reference and sampling from pre-amp outputs; HV biasing control; binning, histogram processing, and time-series processing

- **Extended Front End (EFE):** Detector biasing and front-end analog output electronics

- **Preamp:** Preamps to boost detector outputs from EFE as well as provides input pulse-shaping for particle event detection
**ELFIN EPD Tech Specs**

**Extended Front-End (EFE)**
- High voltage biasing for detectors
- Low output bias drive for 500um detectors (nom. 80V)
- High output bias drive for ≥1000um detectors (nom. 140V)
- Configurable clock-based H-bridge driving from D1 FPGA (nom. 683 kHz)
- Housekeeping for bias voltages and board temperature
- Provides analog LP-filtering to reduce SIPS and bias CLK noise

**Electron detector stack**
- 6x Si detectors
- 500um: E1, E6
- 1000um: E2, E3
- 2000um: E4, E5
- E6 for anti-coincidence

**Ion detector stack**
- 2x Si detectors
- 500um: P1, P2
- P2 for anti-coincidence

**Preamp Board**
- Amplify and shape detector outputs to ADC-detectable levels
- Provide nominal mV-to-MeV ratio

**Digital 1 (D1)**
- Primary FPGA controlling EPD subsystem (16.384 MHz clock)
- 4x ADCs sampling detector outputs P1, P2, E1, E6 at 2.048 MHz, at 13 bit resolution
- Mux in remaining 4x ADCs from D2 to read all detector channels
- Provide driving bias clock for EFE, reference voltages for ADCs
- Responsible to analyze and process real-time ADC data for energetic pulse events
  - Anti-coincidence logic to reject out-of-field particle events
  - Digital low-pass filtering post-preamps
  - Threshold filtering and detector masking
- Generates the low-resolution (LR) histogram data product
  - Supports up to 16 bins at 24 bits/bin for each sensor (I/E)
  - Dedicated capture banks for EPD-I, EPD-E
  - Double-buffered to allow for simul. capture and readout
- Can generate high-rate ADC time-series data for calibration (FFTs)
- Can generate high-resolution energy histograms for calibration
  - Internal FPGA block ram used for this purpose
  - Spin sectoring events raised by IDPU trigger LR histo. captures
  - UART TX/RX at 1Mbaud with IDPU payload FPGA (C&T)
  - EPD configured through addressed register interface
  - Commanded by IDPU MSP payload OS interface

**Digital 2 (D2)**
- Secondary FPGA (clock and control from D1)
- 4x ADCs sampling detector outputs E2, E3, E4 (2.048 MHz, 13 bit)
- Provides low-pass filtered power to preamps

**Key:**
- High-voltage bias
- Filtered power
- Analog signal(s)
- Digital signal(s)
- I/O to external device

**SIPS mezzanine power interface (to all boards):**
- 1.5V
- 2.5V
- 3.3V
- 5.0V
- 8.0V
- AGND
- DGND

**UART to IDPU FPGA (C&T)**
Since CDR, a number of important tests and milestones were achieved:

- Finalization of electrical design and FPGA gateware
- Development and test of the magnetic spin sectoring algorithm
- Successful assembly, integration, and testing of the FM-A/FM-B/EM3 units
- Successful preliminary instrument characterization, including the complete or partial closure of all requirements
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Since CDR, the EPD electrical and FPGA implementations have been finalized

• **Electrical changes/notes**
  • SIPS now uses multi-frequency buck boost power in lieu of linear regulators (significant power and noise savings)
  • Various component swaps on SIPS, D1 due to thermal issues discovered in EM2 TVAC and elsewhere
  • Various component swaps on all boards to minimize AC noise and balance preamp output gain
  • High-voltage bias: EPD now operating thin detectors (500um) at 80V, thick (1000um+) at 140V
    • This is due to EFE bias ladder maximum range being reduced by parasitics
    • Detectors remain fully depleted; confirmed operating voltages by scope and housekeeping

• **FPGA changes/notes**
  • D1 now supports the capability to ignore the output of specific detectors by command
    • Useful to inspect individual EPD detector performance post-integration and on-orbit
    • Can be used to bypass detectors should they fail on-orbit
  • Magnetic spin sectoring module now implemented as MSP430 C code in lieu of dedicated D1/FGM FPGA modules
  • SIPS modified to support a wider range of configurable operating frequencies
    • Each rail has its own adjustable operating frequency; allows for minimization of EPD-sensitive frequencies
    • Has also been extremely helpful in tracking down noise sources affecting EPD
Since CDR, a number of important tests and milestones were achieved:

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Milestone: Development and test of the magnetic spin sectoring algorithm

The magnetic spin sectoring algorithm has been developed, simulated, and tested

- Magnetic field along FGM stacer axis is used to determine real-time orientation of EPD relative to Earth’s magnetic field (i.e. pitch angle)
- Algorithm makes use of either “Bact” or “Bdot”; found in simulation to correctly identify spin period and phase even in presence of 3500 nT noise added to Earth’s field (bottom)
- FGM 80 Hz output provides 2.25 deg of angular spin resolution at fastest S/C spin rate
  - Factor of 10 better than required (22.5 deg = 1 spin sector)
- **Change:** Implemented algorithm in the MSP payload OS in lieu of FPGA modules
  - External timer modules on IDPU utilized to ensure reliable sector boundaries
- Tested on essential hardware with a sinusoidal magnetic field driver (top right) and with FM ELFINs on a rotating platform (bottom right) over the range of expected spin rates

![Graph showing magnetic field data](image-url)
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Detectors have always been ELFIN’s critical path

- 06/16: Initial order placed
- 12/16: Original delivery date
- 03/17: Received mechanical models (not calibration or flight)
- 04/17: Additional order placed for ELFIN-STAR (-B) units
- 01/18: Received all detectors
- Accelerated AI&T schedule
  - Prebuilt aperture & mag stage assemblies to max extent possible

Delays caused by:

- Chemical incompatibility of epoxy ruined first batch of detectors
  - junction oxide damaged, causing excessive leakage current (noise)
  - caused by reformulation & repackaging of epoxy - correlated with corporate merger
- Substitute epoxy identified, hadn’t been used in a long time
  - Mfr had to relearn - presented plenty of its own mechanical challenges (delamination)
  - Some evidence of continued junction oxide damage, but not to the same degree
EPD detector stack cross section

Foil frame (EPDE)
Tantalum front (EPDI)

P1
P2

Tantalum Back Wall (fixed)

Spacer
Kapton
Epoxy
Silicon

Pusher
Plate
Wave Washer (spring)
Back Block

EPD-I shown above. EPD-E has 6 detectors (2 ganged, 8 total layers of silicon)
• First shock of EPD
  • thin foils, like EPDE’s 10um ion filter, traditionally considered shock sensitive
  • Foil OK, but did have detector damage
  • Initially believed to be overcompression
    • Seen before on Lomo (2011)
      • exceeds Si ultimate strength during test, resulting in cracked/fractured detectors
  • Determined to be undercompressed
    • re-evaluation of spring force and thickness stack-up for test
    • Failure mode is silicon chipping around perimeter

• Mitigations:
  • Component cleaning (laser cut slag on spacers)
  • Precise component stack-up measurements (ratcheting micrometer 0.0001” 5-10N)
  • Wave washer uncompressed height & compressed force assessment
EPD Spring Compression

- Inherent imprecision of wave washers
- Mfr spec: 37 lbf/in, but +/-7 thou in uncompressed height
- Needed precise height measurements
  - Same jig can also get spring force coefficient
  - Jig prevents plastic deformation ("crushing") of springs by limiting compression height
  - AA battery packs are a convenient weight
- Actual coefficients 4-16x higher than spec’d
  - typical for industry - nearly all mfr’s do not perform upscreening since it is too customer specific
- Purchased 6 models from 3 vendors & test all 200 pieces
- We found 3 each of 22 lb/in (EPDI) and 120 lb/in (EPDE)
  - Used for EM3, FMA, FMB
Detectors selection

- Seating selection based on dark current curves for optimal seating assignments
  - Mechanical suitability (surface flatness, delamination, previous vibe/shock)
  - Dark current stability
  - Uniformity between EM, FM A, & FM B
  - Better performing detectors prioritized to the front
    - MSX03-500s: E1, P1, P2, E6
    - MSX03-1000s: E2, E3
    - MSX03-2000s: E4, E5 (1000-ganged)
- FFTs provide a similar quality assessment of the detectors once they’re integrated into the sensor and prove that they are stable and have survived environmental testing (TVAC cycling, bakeout, vibe, & shock)
Detector cleaning

• Particulate contamination
  • Kapton is slightly smaller than 13x13mm chip
  • Both junction and ohmic metalizations (aluminum) are susceptible to flaking off & loosely sticks to kapton
  • All kapton surfaces wiped down & inspected - small pressure points need to be avoided

• Epoxy residue
  • Some kapton surfaces have excess epoxy exposed
  • Rubbed off with broad/round side of tweezers

• Surface residue contamination
  • Some detectors had this out of the box, others after handling despite nitrile gloves, facemasks, & flow bench
  • Gently removed with IPA & kim-wipe (more lint-free than the “lint-free” wipes)
Component cleaning

• PEEK spacers (0.010”)
  • laser cutting “slag” slightly thicker than rest of surface
• Tantalum components
  • Surprisingly soft - easy to scuff & displace material
  • Fresh xacto blades best
• PEEK insulator sides
  • Substantial cleanup required - outside shop didn’t use a finishing pass. Lots of “fibers” despite being unfilled PEEK. probably not optimal feeds & speeds
  • Failed fit check (walls too thick, would squeeze detectors), requiring substantial sanding & re-cleanup
  • Used 300 & 600 grit to fix, along with sanding bar and alternating direction for even wear
  • Modified 5 pairs on insulators and used the best 3
Detector vault grew to accommodate MSX03-2000 loops

- Used leftover tantalum walls from Lomo due to expense & lead time
- Arced geometry made filler components difficult to manufacture
  - ruled out epoxy fill due to alignment challenges & inability to rework
- Used 5mil + 2mil (not incl adhesive) kapton sheets, cut with Sizzix CNC, to dial in gaps
- Brass plates also used where possible to minimize shielding degradation
Kapton spring hinge

- PEEK insulator sides out of tolerance
  - Walls too thick in many places
  - Too thin in others, making a gap
- Lomo had metal debris enter from this region - many mitigations put in place since (anodization, tighter tolerances, etc)
  - Still a vulnerable region but did not want an airgap here
- Rounded corners to force kapton to take the corner and not delaminate
- Advantageous spring hinge - two insulator halves pushed all other vault components outboard simultaneously
  - Allowed for an hands-off visualization to see if all parts were aligned
  - Toggle-clamped and vac-baked overnight to “cure” adhesive
Foil Alignment

- Too fragile to add layers to foil frame
- Instead added layers added on top of one insulator side frame
- Small protrusion into optics, but overlapping kapton region (not active area) so negligible impact
- Top of foil frame needs to stick up beyond vault by spring compression height prior to front wall install
  - If not, add more PEEK spacers
EFE & Bias Supply

- EFE designed for 5V->200V
- Ringing stressed driver & masked rectification issue
- Snubber fixed ringing, lost 100V instead of 10V
- Reassessed needs now that actual detectors were tested
  - Need 159V (Margin 186V)
- Switched caps & diodes
  - Less $V_f$ & $I_r$ losses in caps
  - Larger caps preserve $V_{ac}$
  - Benign radiation, thermal, and voltage applied
- Got 173V – good enough
Mag Stage

- Original design SmCo magnets yielded 2.5 kG
- InteMag N3621 becomes ~4.7 kG channel field
- Dipole measured to be roughly 0.008 A m^2
- Electron contamination on ion detector reduced

Sims show Ji/Je = 0.1, then i/e contamination is:
- 250-400 keV: 2.42 → >12.80
- 300-500 keV: 1.75 → >5.77
- 450-600 keV: 1.11 → >2.60
Since CDR, a number of important tests and milestones were achieved:

- Finalization of electrical design and FPGA gateware
- Development and test of the magnetic spin sectoring algorithm
- Successful assembly, integration, and testing of the FM-A/FM-B/EM3 units
- Successful preliminary instrument characterization, including the complete or partial closure of all requirements
Since CDR, have completely or partially verified all instrument requirements.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Num. of Requirements</th>
<th>Num.Verified</th>
<th>Num. Partially Verified</th>
<th>Failure/Waived</th>
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</thead>
<tbody>
<tr>
<td>FM-A EPD</td>
<td>17</td>
<td>12</td>
<td>5</td>
<td>0</td>
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<tr>
<td>FM-B EPD</td>
<td>17</td>
<td>12</td>
<td>4</td>
<td>1</td>
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<tr>
<td>EM-3 EPD</td>
<td>17</td>
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<table>
<thead>
<tr>
<th>Req ID</th>
<th>Description</th>
<th>Status</th>
<th>Expected Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLD-09</td>
<td>The EPD-E shall be able to measure electrons with an energy range of 0.5-4 MeV</td>
<td>Verified in simulation, partially verified by test. Demonstrated 0.5-2.4 MeV; have shown 5.5 MeV on front detector of all EPDs. FM-B has a failed detector and so shall be permanently reduced in energy range to 0.5-~3 MeV (presumed).</td>
<td>Pre-launch (FM-A only)</td>
</tr>
<tr>
<td>PLD-08</td>
<td>The EPD-I shall be capable of deflecting electrons less than 500 keV</td>
<td>Verified in simulation, partially verified by test. Observed 300 keV electrons completely attenuated over operating timescales. Will test using an electron source in the 300-500 keV range.</td>
<td>Pre-launch (FM-A/B)</td>
</tr>
<tr>
<td>PLD-11</td>
<td>The EPD-E shall be capable of measuring 16 sectors per spin</td>
<td>Verified in simulation, partially verified by test. Have measured accurate spin periods on the bench with S/C rotating in Earth’s field; testing in-progress with EPD data collection simultaneously performed.</td>
<td>Imminent (FM-A/B)</td>
</tr>
<tr>
<td>PLD-17</td>
<td>The EPD-I shall be capable of measuring 16 sectors per spin</td>
<td>Identical to PLD-11 above.</td>
<td>Imminent (FM-A/B)</td>
</tr>
<tr>
<td>PLD-15</td>
<td>The EPD-I shall be able to measure ions with an energy range of 50-300 keV</td>
<td>Verified in simulation, partially verified by test. Showed can pick up low-energy gammas near 50 keV and alphas near 5.5 MeV.</td>
<td>Possibly pre-launch (FM-A/B)</td>
</tr>
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</table>
Requirements involving detection of particle energies

- Many of the EPD requirements stem from the need to measure particle energy spectra.
- Testing this aspect of the instrument is achieved in-house using a number of radioactive isotopes ("sources").

- **For EPD-E, we use a number of electron-emitting isotopes:**
  - **Sr-90/Y-90:** broad emission with energies up to 2.4 MeV
  - **Ba-133:** conversion electron source with several narrow peaks in the 200-400 keV range
  - **Tc-99:** vacuum-compatible with broad emission up to 300 keV
  - **Ru-106 (soon):** Wide energy emission up to 3.6 MeV

- **For EPD-I, in addition to electron sources, we use a single ion source:**
  - **Am-241:**
    - Alpha particle emitter (He$^{2+}$) with high-energy emission around 5.4 MeV
    - Also has a gamma ray emission near 59 keV (useful for calibration)
    - Vacuum-compatible
Requirements and test validation

Bench testing with Sr-90/Y-90 electron source
PLD-09: The EPD-E shall be able to measure electrons with an energy range of 0.5-4 MeV

- Status: Verified in simulation, partially verified by test

Justification:

- Showed early on that could meet 0.5 MeV
- Verified as low as 50 keV with Tc-99 (see figures)
- Highest electron source on-hand goes to ~2.4 MeV (Sr-90/Yr-90), have successfully measured 0.5-2.4 MeV
- Will verify with electrons up to 3.6 MeV in a stacked configuration with Ru-106 source
- Have resolved 59 keV Am-241 gamma peak and low energy Tc-99 features down to 50 keV (top right)
- Have resolved ~5.5 MeV Am-241 alpha on front detectors

Figure: Sample Tc-99 EPD-E integration (top) vs. theoretical curve (bottom). The peak energy ~300 keV of Tc-99 is observed by EPD around 75 mV (assuming 240 mV/MeV with some noise). Red line is the noise floor of ~10 mV, which translates to 42 keV. [Note that the theory prediction is integrated over an arbitrary timescale so counts should not be directly compared.]
PLD-15: The EPD-I shall be able to measure ions with an energy range of 50-300 keV

- Status: Verified by simulation, supported by test

Justification:

- Tested the EPD-I in TVAC with Am-241 alpha source, showed that energies up to 5.5 MeV could be resolved, with a lower cutoff around 37 keV

- Historically the DM unit successfully observed Am-241 at various distances in air (attenuates energies), which showed can measure energies in the in-between range
  - Will repeat this before launch

Figure: EPD-I Am-241 integration from FM-A TVAC showing characteristic 5.5 MeV alpha peak (red) and 59 keV (green) gamma emission. The noise floor is observed to be ~37 keV (purple).
PLD-08: The EPDI shall be capable of deflecting electrons less than 500 keV

- Status: Verified in simulation, partially verified by test

Method/Justification:

- Magnetic broom stage ("mag stage") sweeps electrons out of the field of view via the Lorentz force
- **Change:** Impact surface for deflected electrons is serrated, providing an energy dissipation mechanism
- Verified using Tc-99 source in TVAC that electrons up to 300 keV are deflected
- Also verified using Geant4 simulations to trace the trajectory of deflected electrons out of field
- Even if mag stage doesn’t deflect, electrons with energies above 500 keV are ignored by anti-coincidence with P2
Requirements and test validation

PLD-11: The EPD-E shall be capable of measuring 16 sectors per spin, &

PLD-17: The EPD-I shall be capable of measuring 16 sectors per spin

- Status: Verified in simulation, bench tests on-going

Justification:

- Have shown algorithm works in simulation even in extremely noisy magnetic environments (>3500 nT random noise added)
- FGM 80 Hz mode provides time resolution to a factor of 10 of required 16 sectors/spin
- Bench testing with IDPU+FGM shows can determine spin period reliably
  - Separately tested with magnetic field drivers and turntables to simulate ELFIN’s magnetic spin conditions
- Histogram capture and readout at nominal rates currently being tested; successful in initial cases
5. RFAs and recommendations

From the EPD dCDR, the following RFAs and recommendations were accepted:

RFA: Quantify effect of atomic oxygen deposition on epoxy surfaces
  • Status: Resolved [see backup slides]

RFA: Quantify bias circuitry noise while in a proper Faraday cage
  • Status: Resolved

Rec.: Measure/calculate stray magnetic fields
  • Status: Completed [see AI&T section]
RFA: Quantify bias circuitry noise while in a proper Faraday Cage

Description: The noise caused by the EPD biasing circuitry (and other electrical sources) could not be accurately quantified because of EMI from surrounding devices. Perform the quantification.

Response:

- Fully assembled EPDs are effective Faraday cages; tests were performed in this configuration
- High rate EPD ADC time-series data (2 MHz sampling) was used to reveal the bias ripple as well as other sources of noise in the system
- The frequency content of the noise was analyzed by inspecting Fourier transforms (FFTs) of the time-series data
- All major sources of noise were accounted for based on their frequency content
  - Found to correlate directly with SIPS operating frequencies and the EFE bias clock
  - The front detectors E1 and P1 are most susceptible to these effects because they measure low energies
- Subsequent analysis shows current scheme nonetheless meets science requirements
RFA: Quantify bias circuitry noise while in a proper Faraday Cage

- Now have a more complete understanding of noise sources in the system
  - Amplified EPD detector outputs see primarily sinusoidal noise; affects measured energies
  - Noise frequencies correspond mainly to EPD bias clock and SIPS operating frequencies
- Noise manifests itself as uncertainties in both pulse amplitude and phase
- Amplitude effects:
  - Particle energies are determined by measuring the difference between peak and base of a preamp pulse output
  - Noise signals sum onto preamp outputs; “line broadening” effect due to AC nature
  - Amplitude of 240 mV = 1 MeV; 10 mVpp noise is +/- 21 keV spread on average; 20-30 mV on thicker detectors
  - Each detector makes a noise contribution to total energy of any particles passing through it

Noise summing causes deviations of preamp pulse height from the true value (deviation from 1.0)
**RFA: Quantify bias circuitry noise while in a proper Faraday Cage**

**Phase effects:**

- EPD uses derivative-based triggering to determine base and peak time of pulse events
  - Pulse height (i.e. energy) determined by subtracting the amplitude of the pulse at these two times
  - Errors in derivative knowledge mean an incorrect sampling choice for the pulse peak
- Even though noise is typically small compared to the pulse height, the noise derivatives may not be since they are sinusoidal (get multiplied by their large frequencies)
- Effect is most pronounced at the SIPS/EPD bias clock frequencies (see next slide)
- Minimized by digital filtering and configurable tuning of SIPS frequencies to best align with filter

Frequency content of noise causes the derivative-based zero crossing trigger to occur at an incorrect time (phase). This also gives rise to deviations from the true value.
RFA: Quantify bias circuitry noise while in a proper Faraday Cage

- Phase effects:

![Fourier Transform of noise signal observed at preamp output](image)

Derivatives of the signals in orange interfere with the zero-slope feature of the pulse height peak. This gives rise to errors in determining the timing (phase) of the pulse peak. Lowest energy channels are most affected, although testing shows that we remain below 50 keV noise floor on all front detectors.
Unverified Failure: *The E5 detector on FM-B failed following assembly of the sensor head*

**Description:** Following assembly of the FM-B EPD sensor, the E5 detector on FM-B began to exhibit anomalous electrical performance. Its operational peak-to-peak noise level rose from ~30mV to ~250mV (~1 MeV energy width) with considerable wideband noise not corresponding to any known frequencies in the system. The detector is now considered unusable and its output will be ignored in science data collection.

**Impact:**
- E5 covers the range beyond 3 MeV; primary science on FM-B will take a hit
- FM-A E5 remains functional; at least one of the satellites will perform the primary science
  - sufficient to achieve the goals of the mission
- FM-B will instead provide spatio-temporal information in a reduced energy range

**Suspected causes:** Junction oxide contamination
Comparison between functional FM-A E5 time-series and FM-B E5

**UVF: E5 detector**

- **FM-A E5**, 12.5 mVpp high-frequency noise (expected performance)
- **FM-B E5**, 250mVpp low-frequency noise (anomalous)
Open risk: *Leaving radioactive source testing of detectors E4-E6 to last minute*

**Description:** At present we have not attempted to directly observe particles with the E4, E5, and E6 detectors with any of the EPD units. This is because we lack a sufficiently high-energy electron source to penetrate into these layers (need >3 MeV). A Ru-106 source (3.6 MeV max energy) has been ordered which will allow for the characterization of E4 and E5 detectors in the summer before launch.

**Perceived risk:** low

**Potential impact:**

- Detectors could be non-functional, resulting in reduced measurable energy range (E4, E5) and/or anti-coincidence capabilities (E6)

**Mitigation:**

- Characterization of detectors before selection by measuring dark current response to high voltage stimuli (IV curves)
- IV curves of E4-E6 detectors are compared with E1-E3, found to be qualitatively similar; suggests proper performance
- Spectral noise content of E4-E6 detectors are compared with E1-E3, observed to also be qualitatively similar
- E4-E6 can be tested using cosmic ray inputs; will do this before launch
Open risk: *Late payload software development*

**Description:** As a result of an aggressive development and test campaign, payload software has not been subjected to a formal review since CDR. Additionally, a subset of planned on-board MSP430 payload utility routines have been deprioritized and will not be completed until near or after launch.

**Perceived risk:** low

**Potential impacts:**

- Undiscovered bugs in core functionality
- Delays in science data collection upon launch due to utilities (e.g. data compression) having not yet being implemented

**Mitigation:**

- Regular use of payload software in testing greatly increases likelihood of finding bugs
- A peer review will be scheduled for payload software prior to launch
- Employ best-practices techniques in flight software development
- Regular discussions at instruments team meetings to address status and prototypical implementations of incomplete features
• Despite various challenges and setbacks, the ELFIN EPDs delivered on time, verified most requirements, and are ready to fly! Woohoo!

• Summer Test Recap
  • Partial Vac Am-241 Test
    • Prove we can measure 50-300 keV ions
    • Determine ion energy losses due to dead layers
  • Strontium on EPD-I Test
    • Prove mag stage attenuates up to 500 keV electrons
  • Ru-106 and Cosmic Ray Tests
    • Test E4, E5, E6 functionality

Any questions?
Thank you to all of our sponsors, stakeholders, and contributors!

Shaun Murphy @ Northrop Grumman
Katharine Gamble @ UT Austin
Jim White WD0E @ Colorado Satellite Services
Mark Spencer WA8SME @ ARRL
Tony Monteiro AA2TX & Bob Davis KF4KSS @ AMSAT-NA
Backup slides
Extended Front End (EFE)

- Detectors must have HV to operate
  - All HV is on the EFE but driven by D1
- D1 Housekeeping perpetually “backburnered”
  - Means only HV measurements were taken by hand in an unassembled state & therefore infrequent
- Early EFE tests showed a better-than-expected voltage ceiling of 206V (200V target)
- Ringing caused by high slew rate of MAX256 driver combined with parasitic PCB effects
  - Stresses driver and generates noise on 5V rail
  - 200Ω snubber simulated to remove ringing with an acceptable (~10V) hit on ceiling
  - Once implemented, observed a 100V drop...
Design flaw means that voltage multiplier ladder was only rectifying half the wave
  - Ringing masked the problem
  - As did the lack of housekeeping
Reassessed voltage requirement now that detectors arrived
  - 186V desired - better detector would have needed less
Reduced parasitic effects
  - New diode array with less reverse leakage current
  - Also provided lower forward voltage drop
  - Larger capacitor array to preserve AC signal
  - Substitutions exceed ELFIN’s component rules
    - Diodes no longer have a radiation testing paper
      - Heavily shielded by EPDE & EPDI apertures
    - Capacitors no longer part of S-311-P-829 sizing
      - Benign temperatures & ~¼ of derated AC voltage
Achieved 173V - enough for most of mission
  - High temperature / elevated noise trade-off
Latent D1 schematic error fed the reference voltages to D2 incorrectly
- D1 used divided references to determine both mid-scale and span
- D2 was fed an *undivided* mid-scale but a *divided* span
- D1 is the only payload PCB that hadn’t recently gone through a revision, and there wasn’t enough time left in the schedule to do so

Workaround is to not use a divider for the mid-scale, but we still needed a lower mid-scale voltage than what 2.5V provided by the AD780 to maintain resolution
- Replaced AD780 with the ADR420 (2.048V)
  - good radiation spec, even lower noise
- Divided span voltage revised from 2.0V to 1.847V as part of workaround
One D1 PCB showed high noise

- Unusual since it was correlated to D1, not the usual suspects (preamps, EFE, detectors)
- Thankfully had adequate populated spares to just substitute the whole board
- Still needed to chase down root cause
  - Voltage reference suspected
  - Common across all channels, ruling out a particular ADC failure
  - Reference replaced and problem resolved
  - Presumed “toasted” reference during population - both the the ADR420 and the original AD780 have demanding soldering reqs
- Highlights some of the difficulty in checking out EPD components on a component level - this was only revealed as an assembled instrument
  - Assess whether toasted reference noise is observable with oscilloscope & add it to board checkout

Voltage reference suspected
Common across all channels, ruling out a particular ADC failure
Reference replaced and problem resolved
Presumed “toasted” reference during population - both the the ADR420 and the original AD780 have demanding soldering reqs

Highlights some of the difficulty in checking out EPD components on a component level - this was only revealed as an assembled instrument
- Assess whether toasted reference noise is observable with oscilloscope & add it to board checkout
1. Objectives of the EPD PSR

The primary objectives of the EPD PSR are to:

1. Present relevant EPD-centric developments since CDR, with the aim of gaining useful feedback drawing upon the diverse and extensive experience of the reviewers

1. Demonstrate through testing and analysis that the FM-A and FM-B EPDs meet their requirements, and are ready to ship

1. Present and discuss perceived risks and unverified failures
PLD-07: The EPDE shall be capable of rejecting ions less than 500 keV.

- Status: Verified by simulation

Justification:

- Al foil placed over EPD-E entrance aperture to absorb all incident ions 500 keV and below
- Simulation shows this configuration works while minimizing electron energy losses [see backup slides for CDR presentation]
- Possibly before launch will test using low energy ion sources
PLD-06: The EPDs shall be capable of rejecting side penetrating particles through a combination of shielding and coincidence logic.

- Status: Verified by simulation

Justification:

- Using a combination of Tantalum and brass parts to deflect energetic penetrating particles; CASINO simulations show to be sufficient.
- Anti-coincidence logic verified in simulation and using test pulser to emulate particle events on the bench.
- We opted not to test for this because >10 MeV sources are required
PLD-10: The EPD-E shall have a dE/E ≤ 60%

- Status: Verified by inspection, supported by test

Justification:

- Choose digital histogram bin sizes such that the condition is met
- FWHM noise at low energy also observed to be within this tolerance
Requirements and test validation

PLD-20: The EPD-I shall be capable of measuring the flux of ions in the range $10^2 - 10^7$ counts/(cm$^2$-s-sr)

- Status: Verified by analysis

Justification:

- Geometric factor of the instrument coupled with maximum electronics count rate show the instrument can meet the required range of count rates

6/7/2018
PLD-18: The EPD-I shall be capable of measuring ion counts from 10,000-50,000 counts/second

- Status: Verified by test

Justification:

- Test pulser was used to produce an input rate exceeding 150,000 counts/sec. Count rates were shown to be reliably determined.
- Do not have access to high rate sources, so likely will never test directly
PLD-12: The EPD-E shall be capable of measuring electron counts from 10,000-50,000 counts/second

- Status: Verified on the bench

Justification:

- Test pulser was used to produce an input rate exceeding 150,000 counts/sec.
- Count rates were shown to be reliably determined
Requirements and test validation

PLD-14: The EPD-E shall be capable of measuring a flux in the range $10^2$-$10^7$ counts/($cm^2$-$s$-$sr$)

- Status: Verified by analysis

Justification:

- Flows down to the count rate and geometric factor design; this is met by definition if those are
RFA: Atomic oxygen

Description: Atomic Oxygen (AO) may remove epoxy over time causing degradation of exposed metal. Investigate.

Response:

- The effect of atomic oxygen was investigated
- Previous studies show this to be a non-issue for our case as the layer eroded is an order of magnitude smaller than the thickness of the epoxy
- Analysis presented in backup slides
Atomic Oxygen Impact at LEO

- Source: residual atmosphere;
- Damaging effect: oxidation, molecule bond damage;
- Density at 500 km altitude: 1e7 - 1e8 cm⁻³
- Kinetic temperature at 500 km altitude ≈0.08 eV;
- Kinetic energy due to spacecraft motion at 500 km altitude, 25 degr inclination: 4.5 eV (highly inclined orbits would result in much greater impact energies)

- AO flux at LEO (not attenuated): ≈2.0e12 atoms/cm²/s
- ELFIN 90 min orbit: AO flux at surface is 5400*2.0e12 atoms/cm²/s ≈1.0e16 atoms/cm² (per orbit)
- A depth of erosion in material is equal to the product of the erosion yield of the polymer and the atomic oxygen fluence.

Figure 1: From: Low Earth Orbital Atomic Oxygen Interactions With Spacecraft Materials by Bruce A. Banks, Kim K. de Groh, and Sharon K. Miller (National Aeronautics and Space Administration)

<table>
<thead>
<tr>
<th>Material</th>
<th>Erosion yield [cm³/atom]</th>
<th>Damage depth of 1 cm² surface per flight year [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton H</td>
<td>3.0e-24</td>
<td>1.8e-4</td>
</tr>
<tr>
<td>Black Kapton</td>
<td>2.2e-24</td>
<td>1.3e-4</td>
</tr>
<tr>
<td>PEEK</td>
<td>3.7e-24</td>
<td>2.2e-4</td>
</tr>
<tr>
<td>Epoxy</td>
<td>2.7e-24</td>
<td>1.6e-4</td>
</tr>
<tr>
<td>Lexan</td>
<td>2.9e-24</td>
<td>1.7e-4</td>
</tr>
</tbody>
</table>
Expected flux determines the optimal geometric factor of EPD-e and EPD-i:
Optimal geometric factor = (maximum count rate) / (max expected flux)
## Detector Stack Design: EPD-E Requirements

<table>
<thead>
<tr>
<th>REQ ID</th>
<th>Requirement</th>
<th>Parent(s)</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLD-07</td>
<td>The EPD-E shall be capable of rejecting ions less than 500 keV</td>
<td>SCI-02</td>
<td>0.5μm AL, 10μm Lexan, 0.5μm AL foil in front of detectors (THEMIS heritage); stops p+ up to 500 keV</td>
</tr>
<tr>
<td>PLD-09</td>
<td>The EPD-E shall be able to measure electrons with an energy range of 0.5 to 4 MeV</td>
<td>SCI-02</td>
<td>Geant4 modeling verifies our detector configuration below</td>
</tr>
<tr>
<td>PLD-10</td>
<td>The EPD-E shall have a ΔE/E ≤ 60%</td>
<td>SCI-01</td>
<td>6 detectors with pulse height analysis</td>
</tr>
</tbody>
</table>

6/7/2018
Major changes to EPD-e detector stack

- Previously used a combination of different detectors with unequal circular and square areas utilizing three bias levels (L, M, H)
  - Active areas at front detectors were smaller (circular) to avoid saturation
- All detectors now have same 1 cm² square area to take advantage of higher count rate electronics; saturation not a concern based on testing
- Ganging allows for elimination of a bias, now using only two bias levels (L, H)
- New detector width ordering in this configuration
  - E1 and E6 0.5mm, E2 and E3 1.0mm
  - E4 and E5 are each 1.0mm ganged in parallel (effective 2.0mm)
0.5μm AL, 10μm Lexan, 0.5μm AL foil:
- Foil stops all p+ up to 500 keV (foil-penetrating protons have many orders of magnitude lower flux than <500 keV electrons measured at E1)

Simulators: Stopping and Range of Ions in Matter (SRIM) and Transport of Ions in Matter (TRIM)
e- Energy Loss in Ion Stopping Foil is Small

Simulator: Monte Carlo Simulations of Electrons in Solids (CASINO)
<table>
<thead>
<tr>
<th>REQ ID</th>
<th>Requirement</th>
<th>Parent(s)</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLD-08</td>
<td>The EPD-I shall be capable of deflecting electrons less than 500 keV</td>
<td>SCI-03</td>
<td>Single magnetic deflector using two 8.3 mm x 8.3 mm pole faces (deflecting field = 0.2 T) can deflect electrons &lt; 500 keV; proven in simulation to lose very little low-energy ion flux</td>
</tr>
<tr>
<td>PLD-15</td>
<td>The EPD-I shall be able to measure protons with an energy range of 50 to 300 keV</td>
<td>SCI-03</td>
<td>Geant4 modeling verifies our detector configuration below</td>
</tr>
<tr>
<td>PLD-16</td>
<td>The EPD-I shall have a $\Delta E/E \leq 60%$</td>
<td>SCI-03</td>
<td>P1 detector with pulse height analysis</td>
</tr>
</tbody>
</table>
Broom magnet removing electrons <500 keV

- Two quadrupole magnets in octupole configuration
  - SmCo matched magnets
  - Vacoflux saturated yokes
- \(0.2 \, \text{T} = 2 \, \text{kG} \) field at center

Detector Stack Design: EPD-T
30-50 keV protons lose 6-7 keV at 500 Å Si dead layer

Simulators: Stopping and Range of Ions in Matter (SRIM) and Transport of Ions in Matter (TRIM)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>11.65</td>
<td>5.82</td>
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<tr>
<td>40</td>
<td>12.32</td>
<td>6.16</td>
</tr>
<tr>
<td>50</td>
<td>12.53</td>
<td>6.26</td>
</tr>
</tbody>
</table>

IONIZATION
IONS
RECOILS

Depth vs. Y-Axis

Energy Loss [eV/Angstrom]

0 A -- Target Depth -- 500 A

+250 Å

-250 Å

0 Å
At 500 keV, electrons begin to pass the broom magnet field but also pass through P1, into P2; when recognized on both P1 and P2, they are eliminated by anticoincidence.
11 MeV ions stop completely in 1 mm of silicon, so 0.5 mm will have a range up to ~5 MeV, well above our desired maximum of 300 keV.

Simulators: Stopping and Range of Ions in Matter (SRIM) and Transport of Ions in Matter (TRIM)
Ray tracing with specular reflection verifies design:

- Electrons tested went up to 575 keV
- Only one ray enters the stack with a vanishingly small geometric factor, making the event unlikely

<table>
<thead>
<tr>
<th>RFA ID</th>
<th>Requirement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Verify that particles can't bounce through our magnetic deflector</td>
<td>Resolved</td>
</tr>
</tbody>
</table>