The First Flight of SPIDER
Hunting B-Modes from the Edge of Space

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ILLINOIS
B-Mode From Space
18Dec2019
Outline

Instrument Overview

2015 In-Flight Performance
Data, Calibration, Systematics

The View From Above
Sky maps and current status

Up Next: SPIDER-2
B-modes: Goals and Challenges

**PRECISION**
Approach photon noise limit
Few photons, many detectors

**ACCURACY**
Rigid control of polarized systematics
Instrument symmetry

**CLARITY**
Isolation of CMB from polarized foregrounds (dust, synchrotron…)

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**Density perturbations**

**Quantum Fluctuations**

**Primordial gravitational waves**

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**Tensor-to-Scalar Ratio**

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**Planck DUST polarization**

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**Planck 2015 polarization**

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**Half-wave plate**

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**Density perturbations**

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**Inflation**
The SPIDER Program

A balloon-borne payload to identify primordial B-modes on degree angular scales in the presence of foregrounds

1. Verify angular power spectrum
   Observe many modes
   High fidelity from $\sim 10 < l < 300$

2. Verify statistical isotropy
   Large ($\sim 10\%$) sky coverage

3. Verify frequency spectrum
   Multiple colors, (esp. 200+ GHz)

Rahlin+ Proc. SPIE (2014)
Fraisse+ JCAP 04 (2013) 047
… and more …
Antarctic Ballooning

The Good

• **High sensitivity** to approach CMB photon noise limit
• Access to **higher frequencies** obscured from the ground
• Retain **larger angular scales** due to reduced atmospheric fluctuations (*less aggressive filtering*)
• **Technology pathfinder** for orbital missions

The Bad

• Limited **integration time** (~weeks)
• Stringent **mass, power** constraints
• Very limited bandwidth demands **nearly autonomous operations**
• Elevated cosmic ray flux

**Excellent proxy for space operations!**
Payload Overview

- Large shared LHe cryostat
  - 1284L main tank (4K)
  - 16L vented, capillary-fed superfluid tank (1.6K)
- 6 monochromatic refractors
  - SPIDER 2015: 3x95 GHz, 3x150 GHz
- Lightweight carbon fiber gondola
  - Azimuthal scanning: reaction wheel
  - Stepped elevation: linear drives
- 24h solar power: 2200/1440W peak/avg
- Launch mass: ~6500 lbs (3000 kg)
SPIDER Receivers

- Monochromatic 2-lens refractors
  *Cold HDPE lenses, 264mm stop*
- Emphasis on **low internal loading**
- Predominantly reflective filter stack
  *Metal-mesh + one 4K nylon*
- Inter-lens 1.6K absorptive baffling
- Thin vacuum window (3/32” **UHMWPE**)
- Reflective wide-angle fore baffle
- Polarization modulation with **stepped cryogenic HWP** *(AR-coated sapphire)*
- Dedicated $^3$He sorption coolers (0.3K)
Bolometer Arrays

- **JPL antenna-coupled TES arrays**
  *Also used in BICEP2 / 3 / Keck Array*
  *SPIDER-2: NIST platelet horn arrays*

- Planar antenna synthesized via microstrip network
- Lumped element band-defining filter
- Meandered isolation legs (G~12-20 pW/K)
- Dual TES: science (Ti, 0.5K) and lab (Al, 1.3K)
- Time-division SQUID multiplexer
  *NIST cold electronics, warm UBC MCE*

<table>
<thead>
<tr>
<th>Band center</th>
<th>Optical eff.</th>
<th>N_{TES}</th>
</tr>
</thead>
<tbody>
<tr>
<td>94 GHz</td>
<td>30-45%</td>
<td>864</td>
</tr>
<tr>
<td>150 GHz</td>
<td>30-45%</td>
<td>1536</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>2400 TESs</td>
</tr>
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Half-Wave Plate

- Birefringent single-crystal sapphire, anti-reflection coated at 4K in each receiver

- **Stepped** by 22.5° twice daily
  Full Q/U coverage every 2 days

- Inevitable non-idealities yield sensitivity to **circular** (V) polarization

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![Diagram of Half-Wave Plate](image)

**Graph:**

*VV Limit Comparison (95% C.L.,)*

- MIPOI Limit: 33 GHz
- SPIDER Limit: 95 GHz
- SPIDER Limit: 150 GHz

*J.M. Nagy+
Antarctica 2014-15
• January 1-18, 2015
• ~36 km altitude
• All systems functional (except dGPS, no science impact)
• All HWPs turned reliably
• Full hardware and data recovery with help of British Antarctic Survey personnel
Scanning the Sky

- **Sky coverage**: ~12% (geometric), 6.3% hit-weighted
- Full map each sidereal day
- Complete Q/U map for each bolometer every 2 days

- Back-and-forth **sinusoidal** azimuth scan (max ~3.6 dps) stepped in elevation
- Scan tracks map center, width limited by sun/galaxy, elevation by balloon/earth
- HWPs stepped by 22.5° every 0.5 sidereal day (timed to minimum sky rotation)

**Pointing reconstruction**

In-flight (~1’ accuracy)
- Magnetometer
- Pinhole sun sensors

Post-flight (~6” accuracy)
- 3-axis gyroscopes
- Orthogonal star cameras on deck
- Fixed boresight star camera
Autonomous Detector Operations

SQUID tuning
- Retuned (~5 min) after every fridge cycle
- Compares to pre-flight examples, adjusts parameters as needed

Detector responsivity
- Electrical bias step response used as proxy for optical gain variation
- 2s bias step every few turnarounds gives ~0.1% uncertainty
- Monitor loop adjusts TES biases occasionally if needed

Fully automated
- Downlinks minimal statistics to verify functionality

A.S. Rahlin
Detector Performance

- 1.56 TB data set
- Very low internal loading!
- Substantial flagging due to RFI
  - Transmitter handshake every ~1 minute
  - ~10% data loss in good channels
- Negligible flagging due to cosmic rays

See poster for more on cosmic rays in SPIDER!

<table>
<thead>
<tr>
<th>Band center</th>
<th>Absorbed power</th>
<th>Optical eff.</th>
<th>N_{TES}</th>
<th>N_{TES} (w/cuts)</th>
<th>NET</th>
</tr>
</thead>
<tbody>
<tr>
<td>94 GHz</td>
<td>≤0.25 pW</td>
<td>30-45%</td>
<td>864</td>
<td>675</td>
<td>~7.1 μK-√s</td>
</tr>
<tr>
<td>150 GHz</td>
<td>≤0.35 pW</td>
<td>30-50%</td>
<td>1536</td>
<td>1184</td>
<td>~5.3 μK-√s</td>
</tr>
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Gain Stability Revisited

**Problem**: bias steps stopped on some receivers about halfway through flight!

  - TES bias adjustments not performed
  - Bias step results were not downlinked during flight, so we didn’t notice

Careful use of DC signal level as an alternate proxy for TES bias state

**Conclusion**: No evidence that we needed to re-bias so often after all!

Anne Gambrel
RFI Challenges

**DC level losses** ("flux slips") during RFI glitches as SQUID loses lock

Difficult to recover, may include small crosstalk to other channels

"**Reaction wheel noise**": signal seen in some detectors synchronized with reaction wheel angle (*not* payload orientation)
Scan-Synchronous Noise

Comparable to CMB dipole
Complex dependence on detector, boresight elevation, time, ...

For now, impose **aggressive filtering** (5th order polynomial per half scan), exploring better options
Optical Characterization

Pre-flight measurements of passband (FTS) and mid-field beams
Characterize beams in-flight by fits to Planck maps (analog of BICEP2 “deprojection”)
Adjust beam centroids; other fitted beam anomalies are inputs to systematic studies
Simulate effects of known non-idealities

- Differential beams, gain drift (deprojected)
- Full physical optics beam convolution
- Beam ghosts, crosstalk above known levels

Known beam and readout systematics should have negligible effect at current sensitivities.
Seeking LCDM

Reobservation: Simulate SPIDER’s beam, scan, filtering on external map for fair comparison to SPIDER

Close agreement with reobserved Planck maps

LCDM E-mode structure dominates polarization maps, clearly visible in stacked (hot-cold) spots in temperature map

…but also plenty of dust!
Power Spectrum Estimators

Empirical noise modeling is hard: data redundancy is limited relative to Pole instruments (though high relative to Planck!)

Noise Spectrum Independent (NSI):
• PolSPICE pseudo-Cl Monte Carlo
• Signal-only simulation library
• Covariances from cross spectra among 14 data subsets (interleaved 3-min chunks)
  91 crosses/band, 378 total crosses
• J.M. Nagy, J. Hartley, …

X Faster: Hybrid maximum-likelihood
• Iterative quadratic estimator in the isotropic, diagonal approximation used by MASTER
• Solves for binned bandpowers using signal and noise simulation library
• Adapted for null tests, foreground sep in progress
• C. Contaldi, D. Mak, A.E. Gambrel, A.S. Rahlin, …
Null Tests

Construct difference maps between (near-) equal data halves

10 data splits, 3 spectra considered
- Left / right-going scans
- 2 mission time splits
- 7 detector splits
  - 6 spatial, hi/lo band center

Estimate power spectra of difference maps

Subtract simulated signal residual

Present status: Most null tests look good
but some work ongoing on stats, 150 GHz
Raw Power Spectra

- Good consistency between distinct power spectrum pipelines
- Good consistency with Planck 100/143 when restricted to common sky patch (with higher S/N!)
- Clear frequency-dependent excess above LCDM -> Dust
Foreground Strategies

How can we effectively **clean** foregrounds from our data while **quantifying the error** on what we’re doing?

- **Spatial template subtraction**
  Decorrelation across frequencies?
  Chance correlations?

- **Harmonic domain** - per-bandpower or multipole model
  Non-gaussian sample variance
  Spatial variation of SED?

- **Spatial / harmonic variants** - SMICA, NILC

- **Per-pixel** joint component estimation - Commander
Spatial Template Removal

- Regress Planck-derived dust templates (P353-P100, P217-P100) out of SPIDER maps (can also be done for synchrotron, S/N low for now)

- 353 GHz: $\alpha = 0.043 \pm 0.004$ (0.015 $\pm$ 0.004) at 150 (95) GHz
  Additional work on 217 GHz template
Harmonic Domain

- **SMICA**: fit components to map auto/crosses
- No multipole model required: fit each band power separately
- Optional SED model: modified blackbody dust
- SPIDER (95/150), Planck pol HFI (100/143/217/353)

Good agreement in SMICA $\beta_D$ between 95 and 150, and $E$ and $B$ ($E/B$ constrained to match in NSI template work)
SPIDER Mission Goals

TARGET: $r<0.03$ (95% CL) in the presence of foregrounds

Commander foreground estimate

Proposal sensitivity - 2 flights

$C_{\ell}\bigl((\ell+1)/2\bigr)\mu K^2_{\text{equ}}$
SPIDER-2

- Second flight targeting 2018/19, 2019/20, 2020/21 austral summer

- Expanded frequency coverage to resolve foregrounds with post-Planck sensitivities
  3x 280 GHz receivers, new optical design
  Best 95/150 receivers from first flight

Avoid galactic CO lines

FTS measured

NIST platelet horn array
AlMn science TES

Hubmayr+ SPIE 2016
Bergman+ LTD 2017
Conclusions

**SPIDER** performed well during its first flight

- Successful automation, pointing, detector operations
- Minimal impact from cosmic rays, RFI more significant

95/150 polarization analysis nearing completion

- Ongoing work on foregrounds: rich and interesting!

**SPIDER-2** will soon map the sky at 280 GHz