Lessons from Planck Calibration for Future CMB Experiments

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Introduction

- Focus on space anisotropy experiments
  - Planck was a space anisotropy experiment
  - Space — and specifically Sun-Earth L_2 — is the best environment for CMB measurements

    No atmosphere

    Unrestricted frequency coverage

    Sun, Earth, Moon all off in the same direction

    Continuous observing, multiple observations of same sky with same system. With no consumables, can last a long time.

    Great stability
  - Not trying to design an experiment, but to identify general lessons learned from Planck for the future
  - Need to have a rough idea of how ambitious to be. Take $r \leq 10^{-4}$ as a goal.
- Planck set new standards for calibration of CMB experiments. It was hard.
- Calibration of future experiments, which will require map noise levels whose appropriate units are nanokelvin, will be harder.
- Some lessons are quite harsh.

(Explain about figures)

Acknowledgment

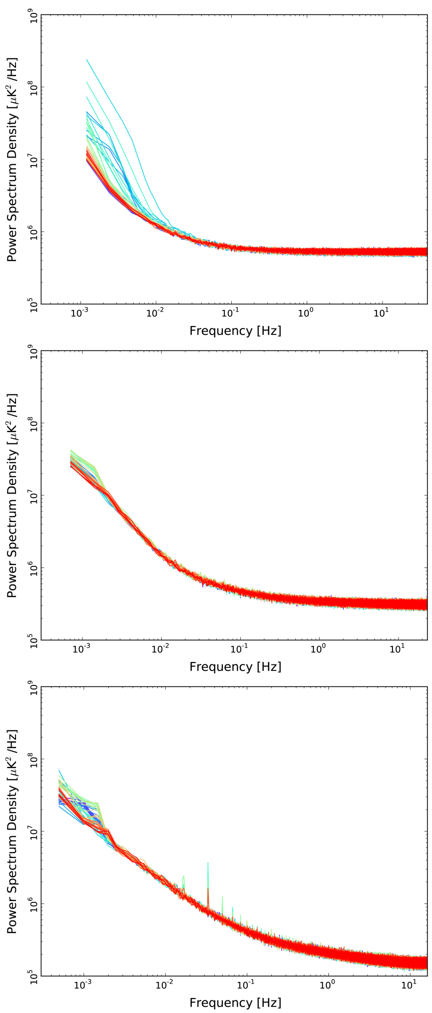
I thank Reijo Keskitalo, Bill Jones, Brendan Crill, and Marco Bersanelli for useful discussions and help.

What Do We Mean By "Calibration"?

- "Calibration" isn't a single thing
  - Noise
  - Gain
  - Bandpasses
  - Beams and time constants
  - Polarization angles

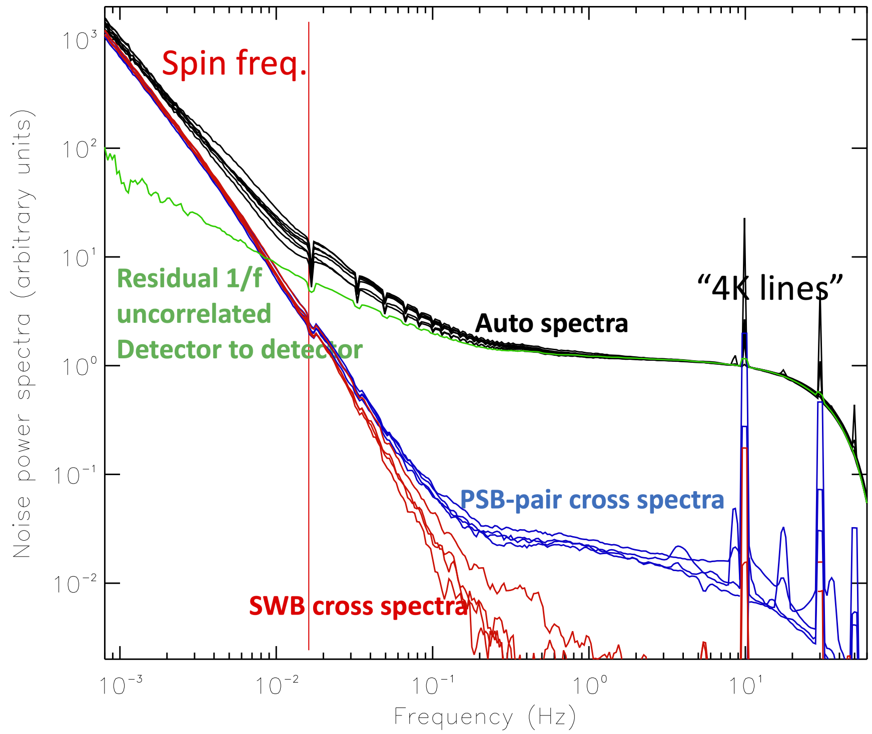
Noise — I

- Detector noise is and will be time-dependent
- Convenient analytical representations of the noise spectrum will be wrong, i.e., it's not $1/f^n$
  - Must determine from the data themselves



Evolution of noise spectra over the mission lifetime for radiometer 18M (70 GHz top), 25S (44 GHz middle), and 27M (30 GHz bottom). Spectra are colour-coded, ranging from OD 100 (blue) to OD 1526 (red), with intervals of about 20 ODs. White-noise levels and slope stability are considerably better than in the 2015 release, being at the 0.1 % level for noise, while knee-frequencies show variations at the 1.5 % level.

Planck 2018 results. II. 2020

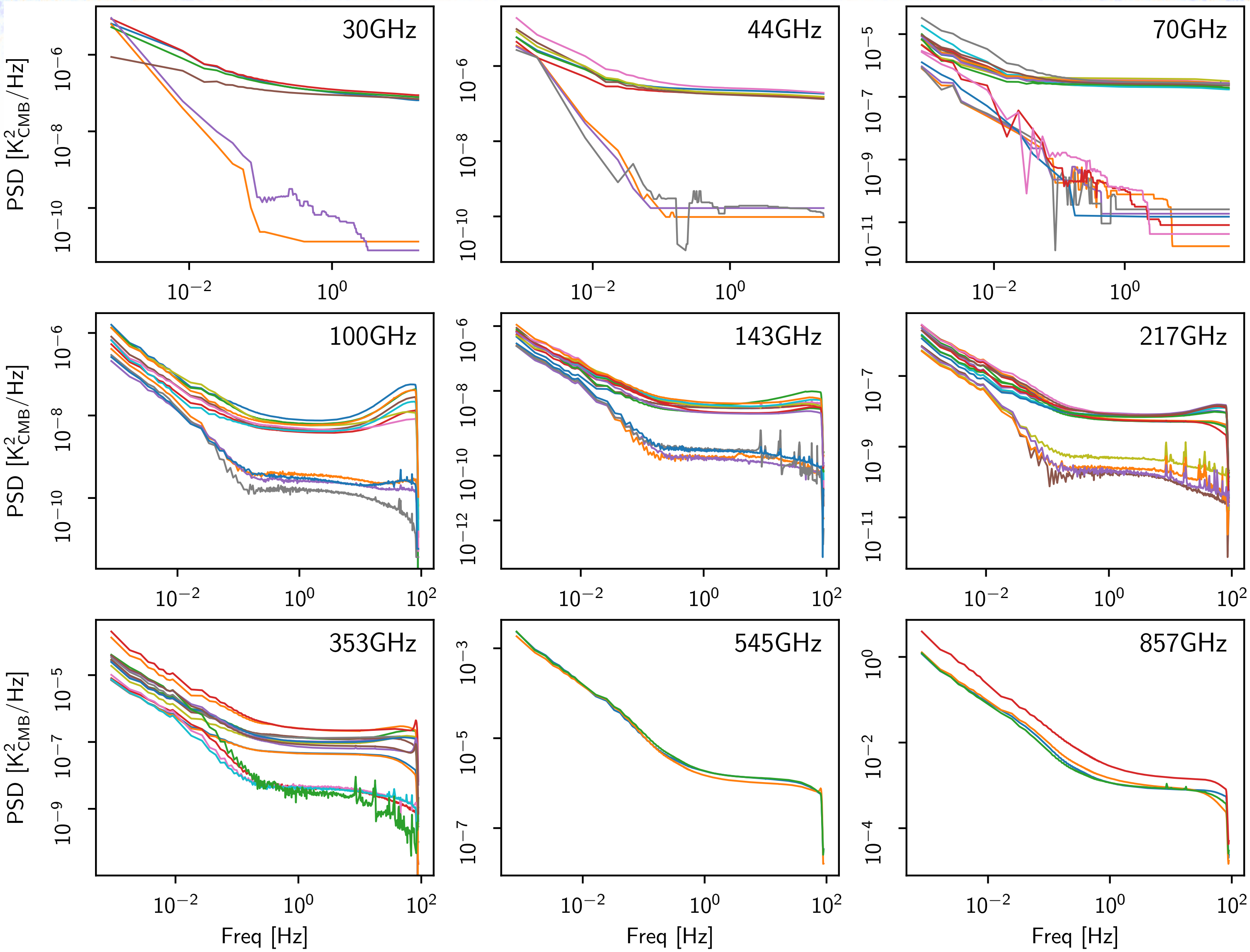


Noise cross-power spectra of the 143-GHz bolometers, with the unpolarized spider-web bolometers (SWBs) in red and the polarization-sensitive bolometers (PSBs) in blue. The low-level correlated white noise component of the PSB noise is associated with common glitches below the detection threshold. Auto-spectra are shown in black. The uncorrelated noise is in green.

Planck intermediate results. XLVI. 2016

Annotations by Brendan Crill

Noise — II



Averaged noise PSDs for each detector (upper curves) and correlated-noise modes for each polarized horn (lower curves). The total noise power is the sum of the correlated and uncorrelated modes. These noise PSDs are measured from the data by subtracting a signal estimate and then evaluating the sample-sample covariance function. The HFI noise is suppressed near the Nyquist frequency (≈ 90 Hz) by the bolometric transfer function filtering. The PSDs are used for simulating the $1/f$ noise fluctuations, and as inputs to the `Madam` noise filter for destriping.

Planck intermediate results. LVII. 2020

General Principle

- Simplifying assumptions are OK for a start, but do not assume that anything is simple, that first or second or n^{th} order is good enough without demonstration.
- If you can think of a complication that will make your life harder, it will happen. Nature is much cleverer than we are, and is merciless.

"Gain" Calibration — I

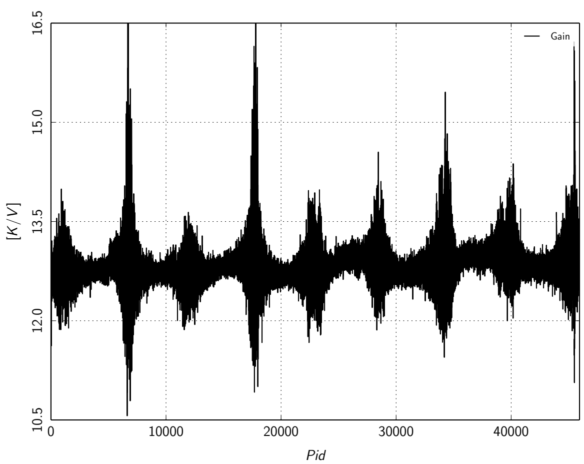
- Gains are and will be time-dependent
  - The gain of amplifiers depends on bias and temperature, and lots of solid-state physics things,
  - Bolometer responsivity depends on geometry and material properties, optical background, temperature, bias power...

$$S(\omega) = -\frac{1}{\sqrt{1+(\omega\tau)^2}}\frac{1}{G_{\rm eff}}\frac{R}{2T}\sqrt{\frac{\Delta}{T}}\frac{V_b}{(R_L+R)}\left(1-\frac{R}{R_L+R}\right)$$

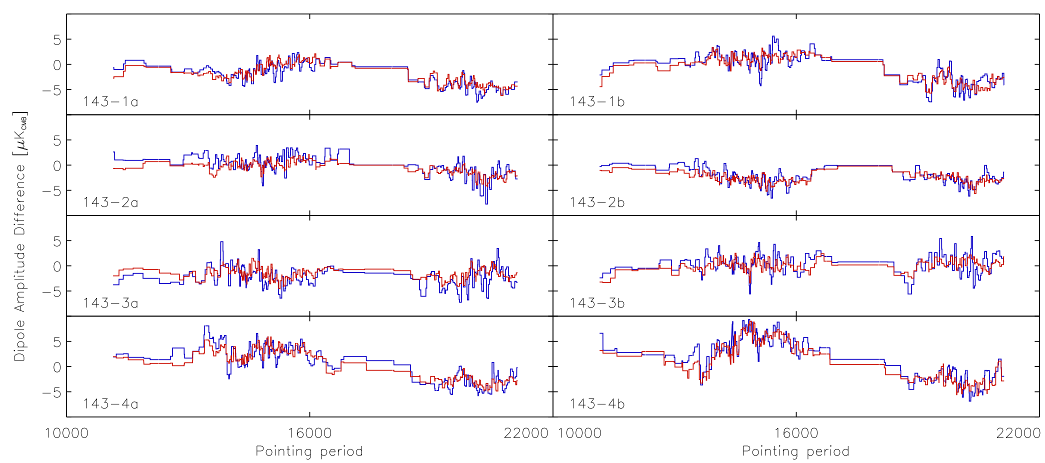
$$G_{\rm eff} = G(T) + \left(1-\frac{2R}{(R_L+R)}\right) I^2_{\rm bias}\left|\frac{\partial R}{\partial T}\right|$$

where S is signal [V] for a fluctuation in optical power [V/W]
Δ is the doping parameter for the NTD
T is the bolometer temperature
R_L is the load impedance, from capacitors in HFI case
R is the bolometer impedance

...plus all the time-dependent effects in the readout electronics, which in the case of Planck dominated



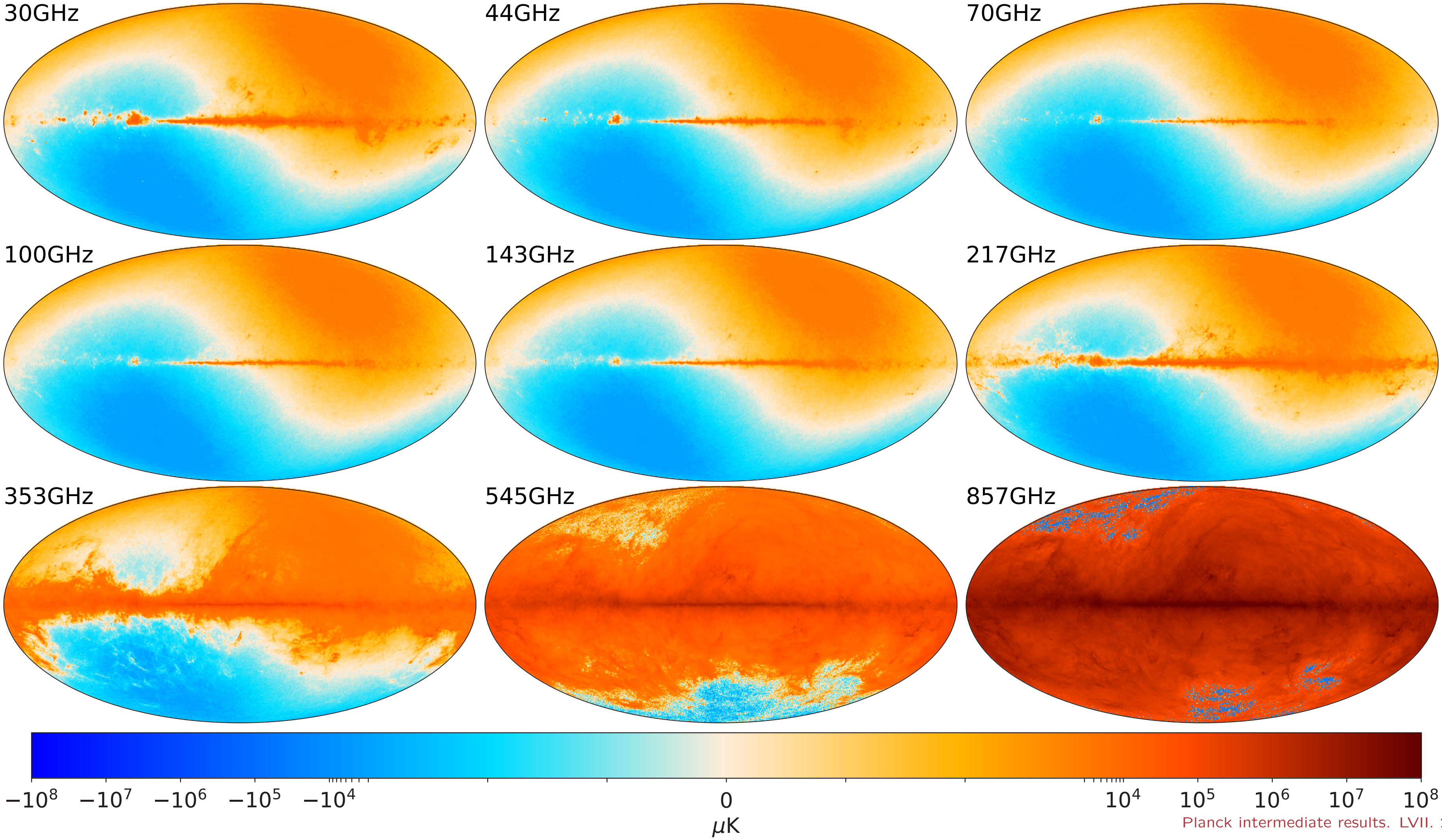
Raw gain from radiometer 27M throughout 4 year mission. $P_{\rm id}$ is a counter for pointings of the spin axis, which had an average duration of about 45 minutes (planck2013-p01). The increase of noise corresponding to the periods of "minimum dipole" (see text) are clearly visible for each of the eight surveys. Survey 2 ($P_{\rm id}$ range approximately $5\,200-10\,000$) and Survey 4 ($P_{\rm id}$ approximately $15\,700-20\,600$) exhibit a significantly higher noise, as expected from the unfavourable alignment of the spacecraft spin axis with the Solar dipole in those two surveys. Planck 2015 results. II. 2016.



Dipole amplitude difference on the rings observed twice, one year apart, for each of the 143-GHz polarization-sensitive bolometers. This detects the time-dependent response associated with the excursions of the signal on the ADC. The blue curve shows the dipole differences in units of μK after ADC correction in the TOI processing, with no other processing. The red curve shows the measured dipole amplitude solved by `Sroll`, demonstrating the reliability of the model, which can then be applied to small signals.
Planck intermediate results. XLVI. 2016

Gain Calibration — II

- The ultimate goal is to determine the response of each detector to a known input signal for each integration period
- What is the only possible "known" input? The time-dependent I, Q, U sky itself..



Planck intermediate results. LVII. 2020

Gain Calibration — III

- The time-dependence of the sky that matters on the time-scale of experiments is due to the orbital motion of the spacecraft around the Sun.
  - This "orbital dipole" is the best absolute calibrator in all of astrophysics
  - Planck scan strategy far from ideal for measuring the orbital dipole, as the timescale of gain variations was much shorter than the timescale of alignment/misalignment of the scan circle with the dipole
- Obviously we don't know the sky in advance, as that's what we're trying to measure
- Obviously have to iterate.
- Obviously time-consuming and computer-intensive, but inescapable
  - Do the best you can, and don't pretend there is a shortcut!

Gain Calibration — IV

- The Planck sequence
  - Use WMAP dipole
  - With enough data in hand, use orbital dipole
  - Eventually, determine frequency-by-frequency tweaks to improve foreground-fitting residuals

Gain Calibration — V

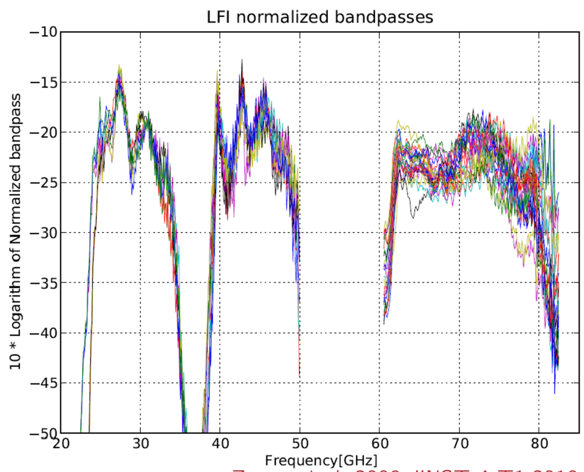
- How well can we do?

- Now possible to track gain variations using the sky/cmb on "smallish scales" combining "largish numbers of detectors" (Bill Jones)
  - Easy-to-use proxies for gain variations may be found that help the process (Filippini et al. *In-flight gain monitoring of SPIDER's transition-edge sensor arrays* under review at the Journal of Low Temperature Physics)

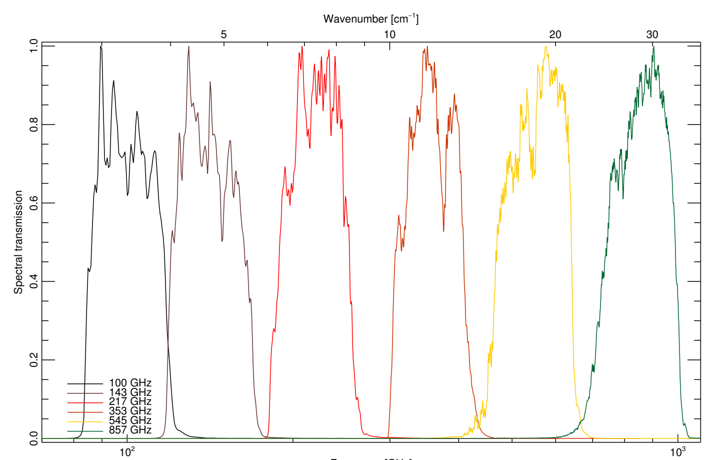
- Hierarchical, iterative processes can be imagined to push gain calibration further and further

Bandpasses — I

- There are no good bandpass calibrators in the sky
- Bandpasses are hard to measure, and good ones are hard to build
- Even with perfectly known bandpasses, one can only correct for the known sky, which is what we are trying to measure
- So bandpass mismatches and sky model/measurements are intertwined
- Planck was handicapped by its inability to produce individual detector maps in polarization
  - Two or more detectors had to be combined to map polarization. Bandpass mismatches then produced temperature-to-polarization leakage
  - A scan strategy that gives complete polarization angle coverage so that polarized maps of the sky can be produced detector by detector eliminates this problem
- The better the ground starting point, the better



Zonca et al. 2009 JINST 4 T1,2010



Planck 201? results. ??. 20??

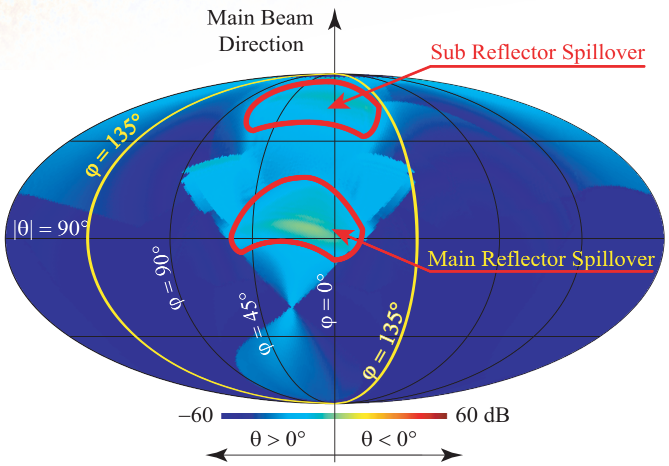
Bandpasses — II

- Design and build the best (most rectangular) ones you can
- Measure them on the ground better than you think you can
- Hope for the best, and determine band "center" tweaks to improve component separation

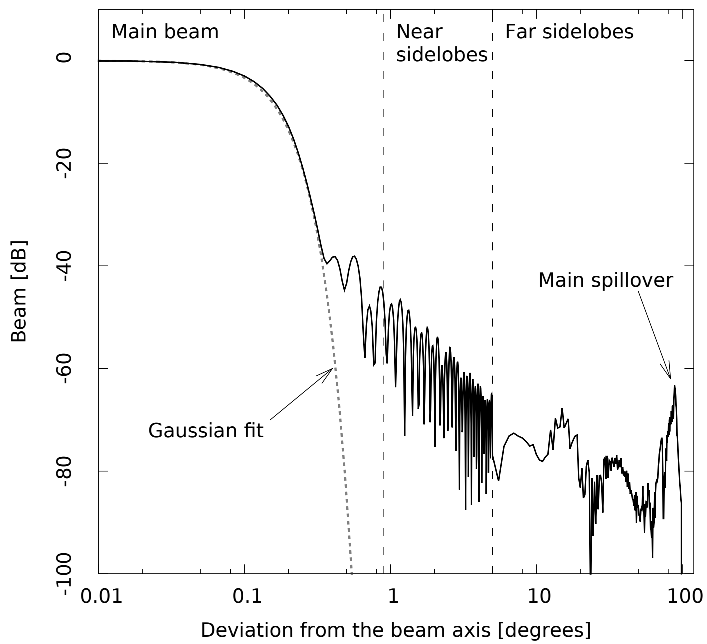
Beams — Definitions

- Instantaneous ≡ optical beams
- Smeared by radiometer response and scanning ≡ scanning beams
- Integrated by scan strategy, therefore varying over the sky ≡ effective beams

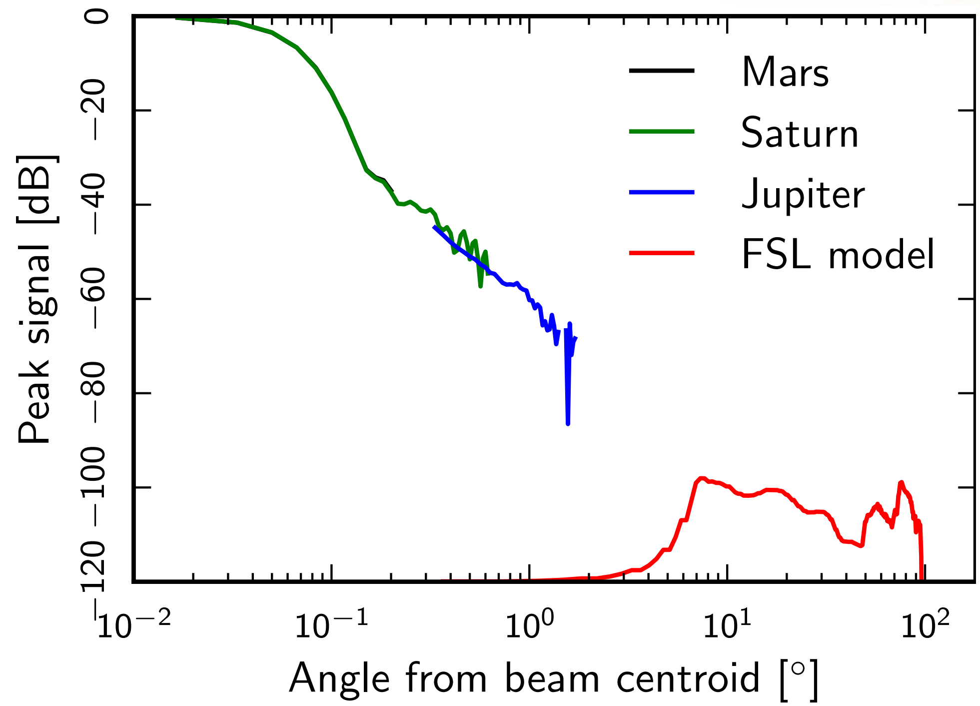
Examples



Calculated LFI beam at 30 GHz. Planck 2015 results. IV., 2016



Calculated LFI beam cross section at 70 GHz. Planck 2015 results. IV., 2016



Azimuthally averaged profiles of measured beams of channel 353-1 compared to the azimuthal average of the far sidelobe physical optics model. Planck 2013 results. VII., 2013

Instantaneous or Optical Beams — I

- Determined solely by hardware
- 4π beams could be calculated almost exactly if the post-launch position of "everything" were known to small fractional wavelength, and radiation properties were known accurately, ...
  - ...and enough computing power were available, and significant software advances were made
- Hard to measure accurately on the ground, and essentially impossible at large angles to the telescope boresight, i.e., far sidelobes, which are typically highly polarized
  - In any case, things may well change on the scale of small fractional wavelengths during launch
- Far sidelobes are nearly impossible to measure in space, either

  Launch a separate spacecraft with multifrequency sources? So many problems with that I don't know where to begin.
- Even main beams cannot be well-represented by polynomials or other nice basis functions
  - Need 2-D pixel representations
- What to do?
- For a good starting point, plan on extensive physical theory of diffraction (*not* physical optics or geometrical theory of diffraction!) calculations from the beginning
  - Individual feeds, I, Q, U
  - Multiple (10?) frequencies across all bands

Instantaneous or Optical Beams — II

- To recap:
  - Beams vary detector to detector, and with frequency across the band
  - You can't know your beams too well. (*explaination...*)
  - You can't measure them well enough on the ground
  - You can't measure them well enough in space
  - You can't yet calculate them well enough
  - But in principle beams can be calculated, then validated/verified in space

$\Rightarrow$ need serious work to develop PTD codes to run on massively parallel HPCs, without license problems

Scanning Beams

- Are what would be measured in flight
- Optical beam + radiometer time response + satellite motion
- There's a lovely degeneracy between optical beams, radiometer time response, and satellite motion

$\Rightarrow$ Measurements of time response on the ground are important

Effective Beams

- Scanning beams + scanning beam orientation + scanning strategy
- A given radiometer has the same number of effective beams as there are pixels in the observed sky map
- If scanning beams are known, effective beams can be calculated from the known scanning history

Polarization Angle

- Planck never found a sky source that provided polarization angle calibration free of systematics
- Have to assume there isn't one
- Measure on ground, maybe good to a degree or so
- If each detector maps the whole sky, use the polarization angle differences between detectors over the whole sky to get the relative angles
- Then there's just one (arbitrary?) angle to be determined/specified

Scan Strategy

⇒ Scan strategy should allow every individual detector to make I, Q, and U maps of the sky

It's a matter of complete polarization angle coverage

Putting It All Together

- The full sky itself (I, Q, U) is the best and ultimately the only thing to calibrate on
- Giant simultaneous fit of everything to everything
- But the sky can only be determined with a fully-calibrated instrument
- And degeneracies in a blind, unconstrained simultaneous fit guarantee it will explode
- The better the starting point for individual components, the better the global fit will work
- Start noise, gain, bandpasses, beams and time constants, polarization angles with the best that can be measured or calculated on the ground
- Refine with data
- Identify and connect systematics to specific sources, verify, only then can they be mitigated
- Eventually iterate global fit until it converges
- Then you have both calibration and sky

Constraints

- "Do better" is what I've been saying so far
- But there are always constraints, and "good enough is" remains to key to success in the space business
- Serious calculations and simulations will be required to establish criteria, requirements, and priorities
- This will be a major effort

ThinK