Interplay of Foregrounds and Systematics: The Case for Low-Frequency Observations

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TAKEAWAY MESSAGE

Given the systemic asymmetry between the low- and high-frequency polarized sky measurements that will be possible to conduct from a future single platform CMB space mission, e.g. PICO, it would be prudent to address the long standing and known problems at the low frequency range ahead of time.

We recommend to study a mission dedicated to those low frequencies, to determine whether such a mission, in combination with a higher-frequency mission, would be the most cost-effective way to obtain the low frequency data required by CMB science, and to help the future inflation probe project become a true pinnacle of effort in observational CMB cosmology.

What is the problem?

- This presentation is an extract from the Astro2020 APS White Paper "Planck-scale physics vs. Galactic astrophysics – addressing the need and requirements for the high-fidelity full-sky low-frequency microwave polarization survey to provide enabling support for the future CMB observations and their interpretation" by KMG, A.J. Banday, C.R. Lawrence, T. Gaier, T. Jaffe, and G. Rocha
- We discuss the importance of addressing a persistent problem in the field of CMB observations and their interpretation – the imbalance between the achievable measurement quality at the very low ($\lesssim$ 20 GHz) and high ($\gtrsim$ 300 GHz) frequency ranges. These measurements are essential for cleaning Galactic foregrounds, extracting cosmological signals, and achieving the demanding scientific goals of the future inflation probe space mission to measure and characterize the primordial gravitational wave background related polarized CMB anisotropies.

What is the problem, and why is it hard?

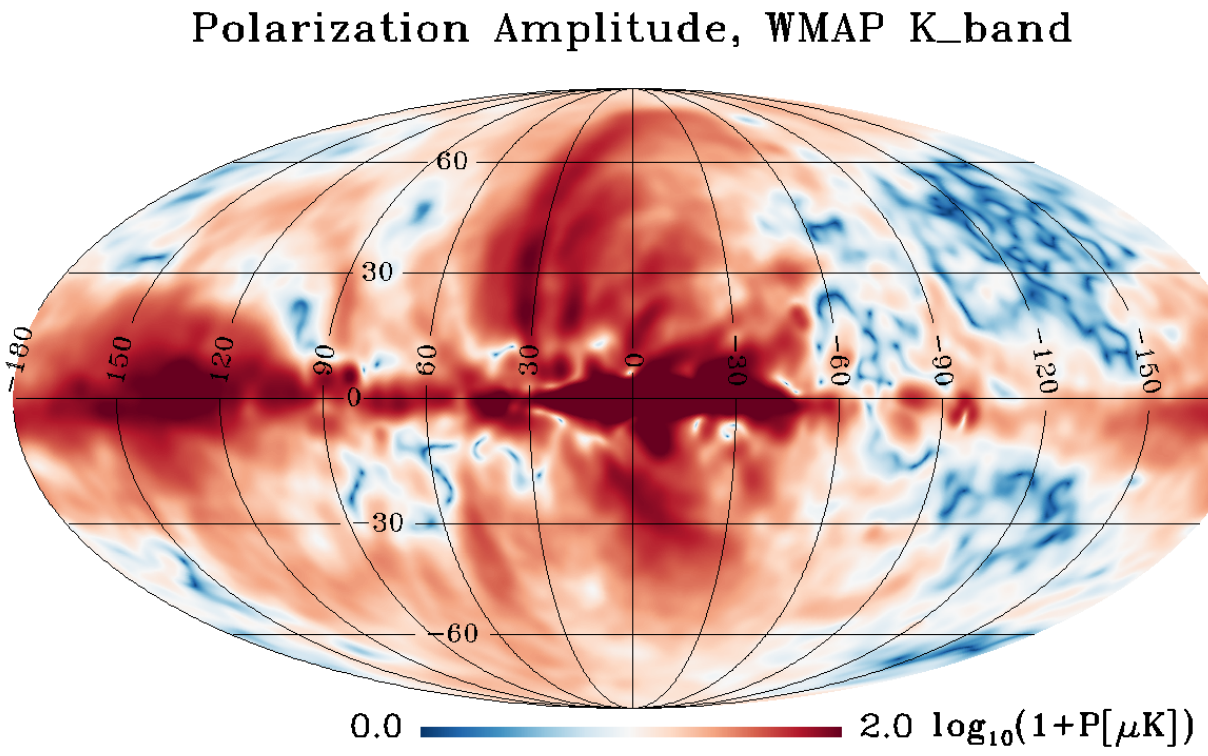
- CMB polarization anisotropies of cosmological origin are very faint.
- All CMB polarization anisotropy at large angular scales is strongly dominated by foreground emission from our Galaxy, by thermal dust at high frequencies and synchrotron emission at low frequencies.
- Primordial CMB B-mode anisotropy is very strongly foreground-dominated at all angular scales, and will only be reliably revealed if those dominant foreground emissions can be reliably removed from the maps of polarized sky.
- Presently the only polarized full sky surveys available for assessment of foreground emission from our Galaxy are those by WMAP at low frequencies, and by Planck Low- and High-Frequency Instruments.
- High-frequency polarized dust emission is now better known thanks to superior performance of *Planck* HFI.
- Low-frequency polarized synchrotron emission is known (in a quantifiable way) considerably less well.

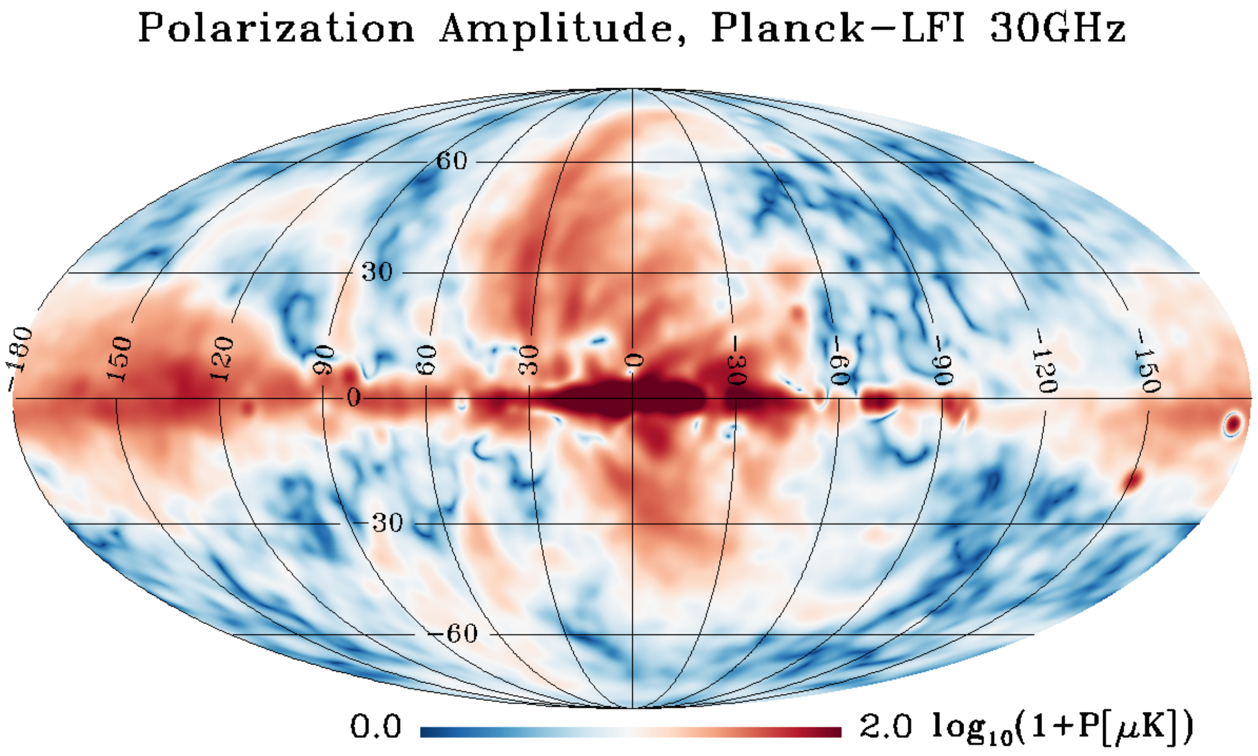
What is the problem, and why is it hard?

- Designs for space missions use a single telescope to illuminate a focal plane populated with detectors apportioned to the entire spectral range of the experiment. Consequently, the lowest frequency channels always are constrained to observe the sky with the poorest angular resolution.
- Foreground signals get brighter at lower frequencies, hence it is usually considered sufficient for the lowest frequency channels to operate at higher detector noise levels.
- Low frequency detectors are large, and take up focal-plane space that could be filled with many more smaller ones at the higher frequency channels that are critical for maximization of the overall instrument's sensitivity to cosmological perturbations.
- These points invariably drive design toward minimization of the precious resources of the space instrument that are allocated to low frequency observations. The lowest frequency channels of WMAP and Planck (23 and 30 GHz, respectively) had just four detectors each, placed at the edge of the focal planes and subject, in addition to the points made above, to significant beam distortions.
- All these considerations illustrate a specific issue encountered while designing a CMB space instrument: low frequency channels end up with the lowest resolution, high noise, and typically less favorable placement in the focal plane – and, they collaterally diminish performance of higher frequency channels by taking the valuable focal-plane space.

Still, currently the best full sky polarization amplitude maps are WMAP K-band, and *Planck* LFI 30 GHz

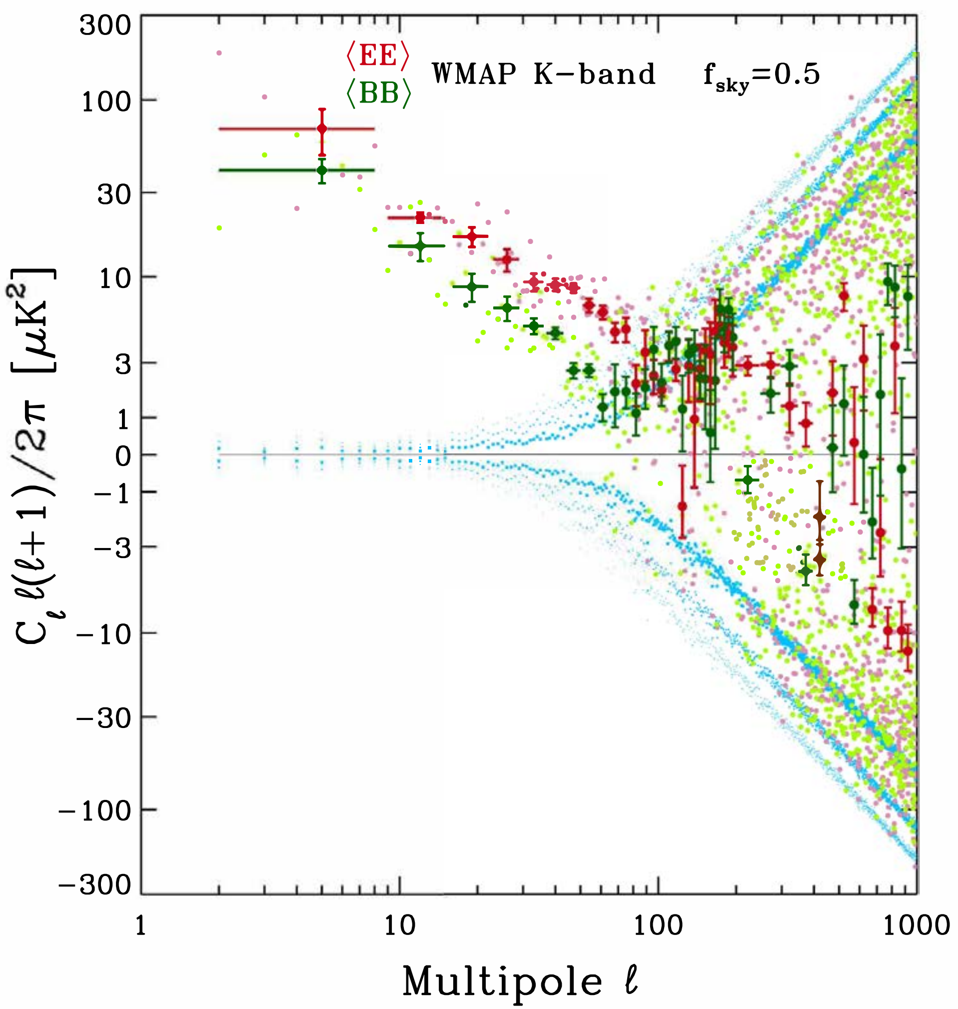
These maps are smoothed to $FWHM = 4$ deg, and pixelized at 14 arcmin.
Polarization amplitude (in μK) is plotted non-linearly as $(\log_{10}(1+P))$, and saturated at $P = 100\mu$K.

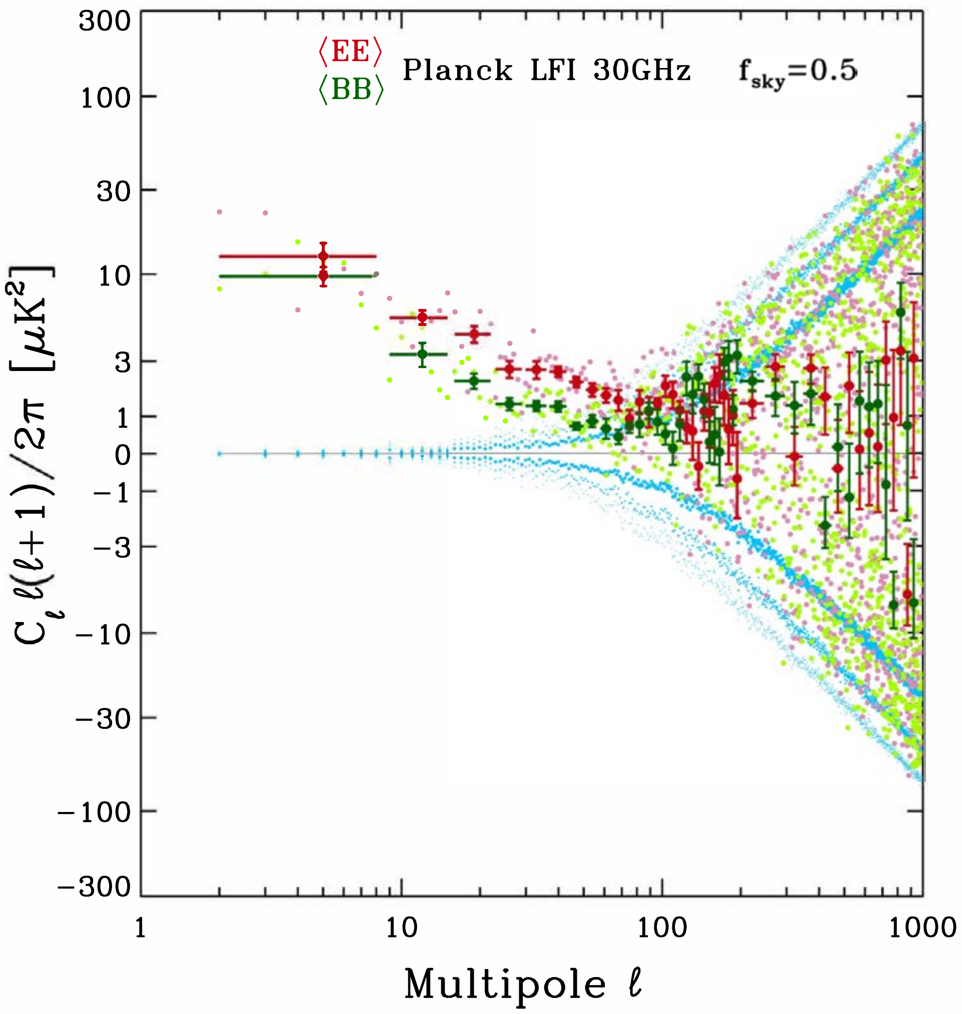




EE and BB pseudo-cross-spectra of the WMAP K-band and Planck LFI 30 GHz Q and U sky maps.

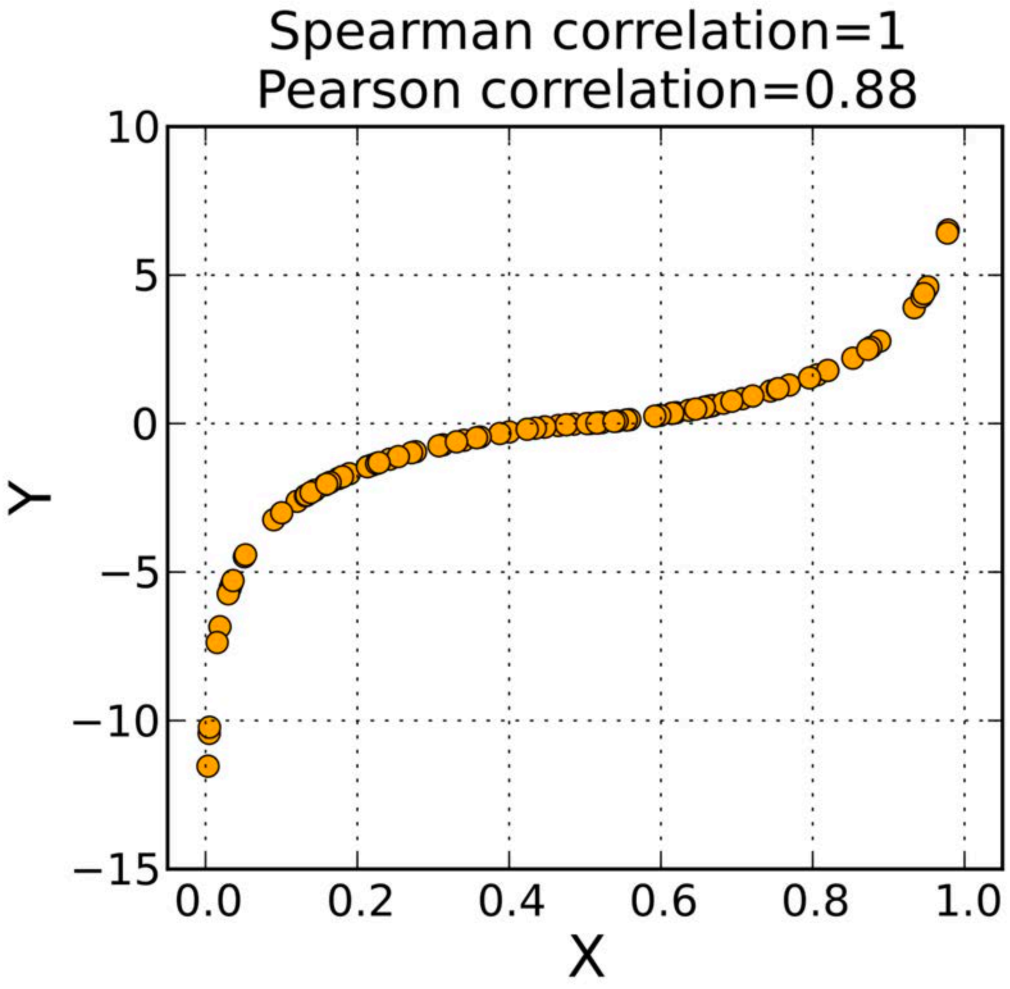
These spectra are evaluated on Galactic polar caps at $|b| > 30$ deg, i.e. for $f_{sky} = 50\%$.





- Pink/lime dots – all EE/BB multipoles.
- Red/green dots/bars for the values binned over the range of $\Delta l = 7\ (50)$ below (above) $l = 200$.
- Error bars show the rms spread within the bins.
- Three light blue bands indicate the 1, 2, and 3σ ranges of the distribution of cross-spectrum noise evaluated in the empirical model based on intrinsic data splits (half-ring maps for LFI 30 GHz, and 4, and 5 coadded yearly maps for WMAP K-band).

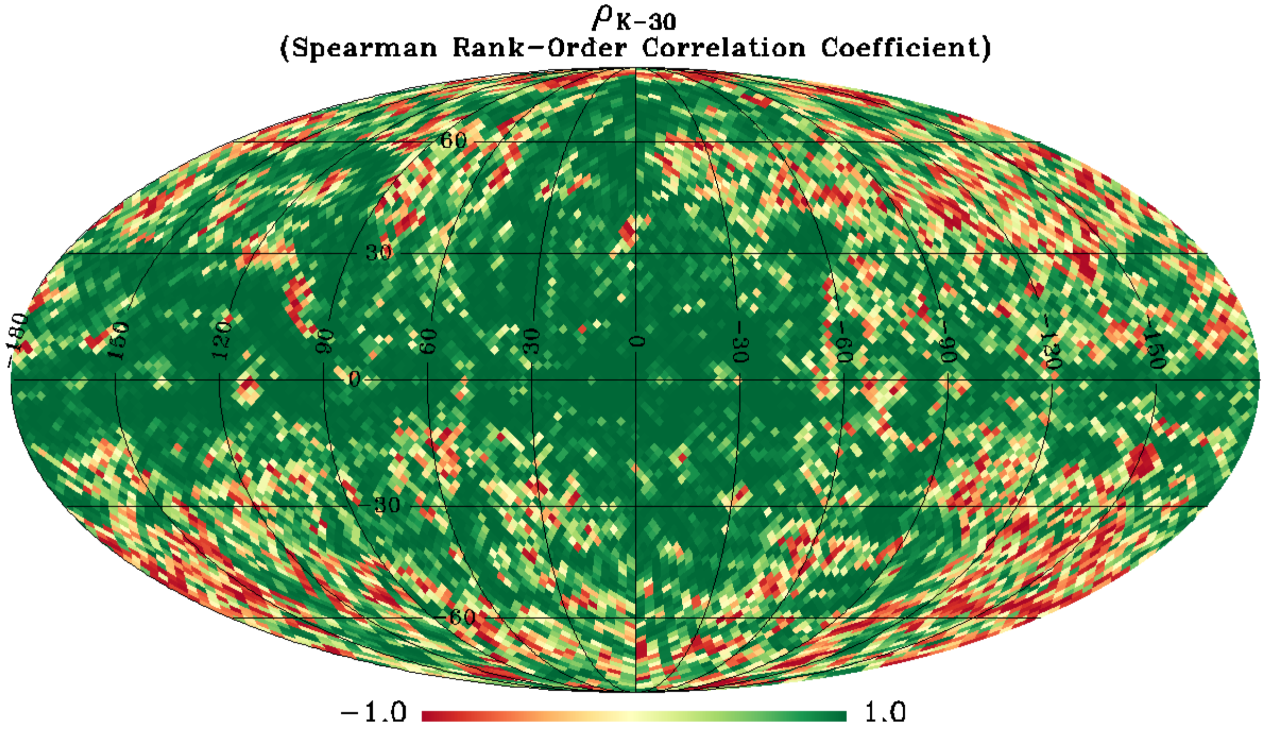
Spearman Rank-order correlation coefficient - a nonparametric measure of the strength and direction of association between two variables

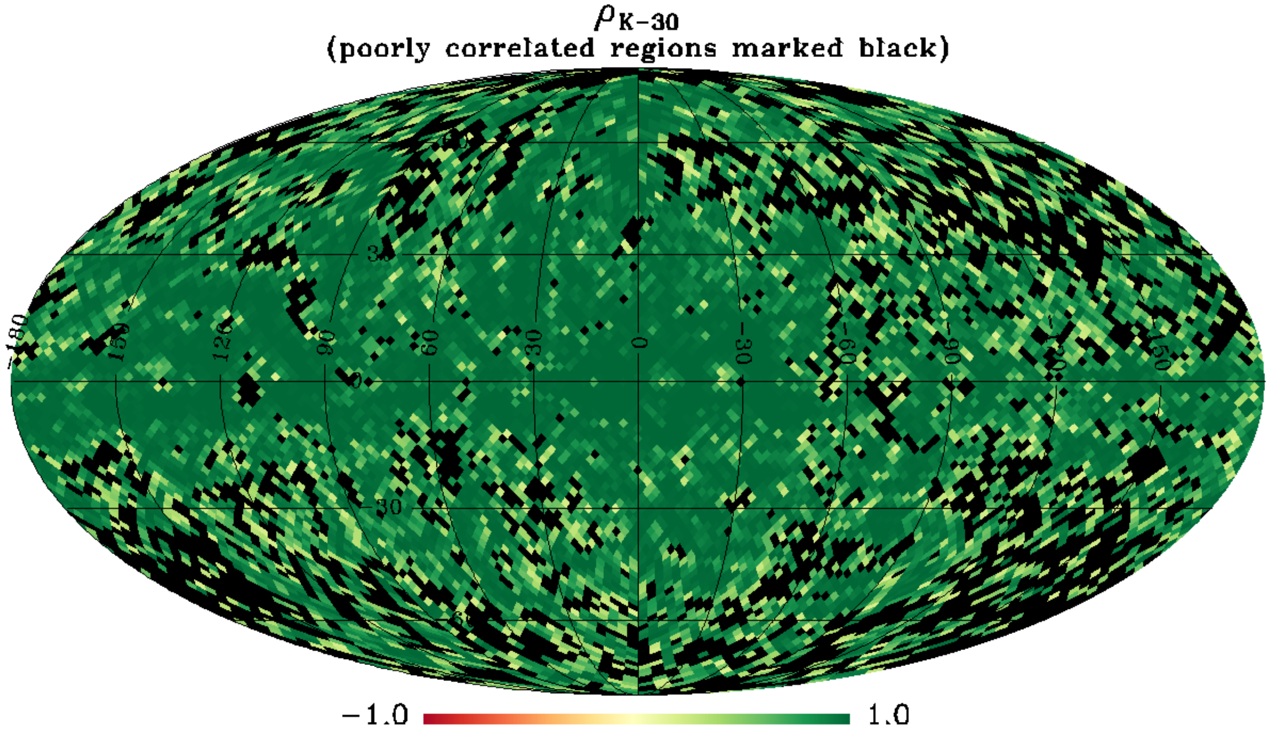


A Spearman correlation of 1 results when the two variables being compared are monotonically related, even if their relationship is not linear. This means that all data points with greater *x* values than that of a given data point will have greater *y* values as well. In contrast, this does not give a perfect Pearson correlation.

Non-parametric, Spearman correlation testing of consistency between WMAP K-band and LFI 30 GHz polarization amplitude maps

- The input maps are smoothed to $FWHM = 4$ deg, and pixelized at 14 arcmin.
- Left: Spearman rank-order correlation coefficient ρ_{K-30} evaluated within the large, 1.83 deg pixels, each comprising 16^2 original maps' small pixels.
- Right: Regions where signal correlations are significant are retained, and those where ρ_{K-30} indicates either weak- or anti-correlation are masked in black. Full sky fraction occupied by the poorly correlated regions is 23.5%.
- At $|b| > 30$ deg (1/2 full sky), the bad pixel sky fraction is 32%!
- WMAP maps "static", some improvement of Planck LFI maps in the making.
- This is "it" for the knowledge of the low frequency, polarized full sky for a while …





But, the microwave sky at low frequencies is accessible from the ground …

Indeed …, but …

- Frequencies below 45 GHz relevant for CMB foreground separation can be observed from the ground, with sizeable antennas, but
- Requirements for such surveys include multiple frequencies of observation, large or all-sky coverage, and extreme levels of sensitivity and systematic control, hence there are numerous difficulties to be resolved.
- The obvious issues are the limited sky availability for any given suborbital telescope (hence the need to stitch together heterogeneously-generated data, which requires extraordinary intercalibration accuracy), lengthy observing campaigns required to achieve the requisite survey sensitivities (while assuring measurement stability and calibration consistency), exquisite control of instrumental systematic errors (e.g., imperfectly known beam responses, including far-side lobes), sufficient shielding from ground pick-up, atmospheric effects, and RFI.
- Even though the need for quality low frequency sky surveys to support the CMB component separation is manifest, and declared to be less costly to conduct with telescopes on the ground, precious few efforts of this nature are being conducted. The relevant ongoing experiments are C-BASS (5 GHz, see e.g. Dickinson et al. 2019), S_PASS (~2.3 GHz, Carretti et al. 2019), QUIJOTE (10-20 GHz, Genova-Santos et al. 2015), and the forthcoming ones are AdvACT (~30GHz, Koopman et al. 2018), GreenPol (10-44 GHz, Fuskeland et al. in preparation), and SKA-MPG/S-band (1.7-3.5 GHz, Basu et al. 2019). All of these are spectacular, and very hard efforts, subject to difficulties listed above. Specifically, regarding the observed sky area, other than C-BASS that aims for aggregating measurements from two sites, at most about 50% of the sky can be surveyed by any of these experiments.
- Therefore, it is fairly safe to state that the prospect for a *full sky, uniformly high-quality* polarized radio survey, preferably at several frequency channels in the range of 2-20 GHz (advocated as the best range to target for Galactic synchrotron mapping post Planck data analysis), are fairly slim, and we may not see such data products made available to CMB community even on a time scale of more than a decade.

Desiderata

Given the difficulties that persistently challenge ground-based efforts, we advocate a consideration of the space mission option for generation of the survey of the polarized low frequency foregrounds, including the following:

- Conduct a design study, driven by science requirements, for an optimized low frequency CMB polarimeter (neither WMAP nor Planck were designed to be that) to observe the full sky from the Lagrange point L_2, to generate sky maps at the frequency channels near ~10 GHz, and at angular resolution no worse than ~30 arcmin at 10 GHz. Target sensitivity for such polarized synchrotron emission measurements, and cost ramifications would be the objective of such a study.
- Study the options for launching of a large aperture telescope required for such experiment with a focus on the already available options for deployable radio antennas.
- Define requirements on a satellite bus that could provide support for a large aperture telescope, and power supply sufficient to support the required system cooling.
- Assess feasibility of mission strategy for operations at L_2 that would involve full sky scanning with a large aperture, continuously moving dish w.r.t. spacecraft dynamics, far side lobe pick up control, and experiment duration.
- Support continued development of improved component separation methods and of the required inputs for realistic modeling and simulations of the foreground and cosmological signals – this must be done to assess realistically the necessities in the area of polarization measurement strategy and the actual quality demands at low frequencies that have to be met in order to support future efforts in cosmology and CMB polarimetry. Current state-of-the-art techniques addressing the inseparable challenges of simulation and separation of foregrounds are unlikely to be sufficient and should see dedicated and synergistic effort toward their improvement (as illustrated with the discussion of the necessary linking of the fields of CMB foreground simulation, Galactic magnetic field modeling, and CMB component separation).

What difference would it make? What would be the possible benefits?

- Present studies of future CMB instruments postulate deploying bolometric detectors across very wide frequency range (e.g. down to 20 GHz in the case of PICO). Significant technology demonstrations are required to ensure that this would be possible. Relieving the instrument design from the requirement to use bolometers in that low frequency regime would be a simplification for the future CMB space mission focal plane development.
- A related point is that a large fraction of the focal plane area of the future instrument(s) that presently is typically allocated to low frequency detectors would be freed up, and could be used for higher frequency detectors allowing very considerable sensitivity gains (many smaller high-frequency detectors to replace fewer, larger low-frequency ones in the relevant part of the focal plane). In PICO design ~20% of the focal plane area is given to the 21, 30, 43 GHz detectors, and ~50% thereof to 25, 36, 52 GHz detectors. **NOTE:** This point does NOT imply any criticism of PICO design study's vision of the focal plane layout; if there is no potential for provision of sufficiently good quality ancillary data at low frequencies prior to flight, PICO design concept is very powerful and very likely as good as can be conceptualized now; our point is that further optimization studies of PICO-type space mission would benefit from splitting the low and high frequency instruments between dedicated experiments.
- Potentially fewer sources of systematic effects (per fewer frequency channels) would need addressing in either effort - both PICO, and a dedicated low frequency experiment.
- The opportunity for design optimization of the low-frequency polarimeter, including increasing the angular resolution and improving the optical performance, e.g., and most importantly, the symmetrization of beam response.

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