Cosmic Microwave Background Science at Commercial Airline Altitudes

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ABSTRACT

Obtaining high-sensitivity measurements of degree-scale cosmic microwave background (CMB) polarization is the most direct path to detecting primordial gravitational waves. Robustly recovering any primordial signal from the dominant foreground emission will require high-fidelity observations at multiple frequencies, with excellent control of systematics. We explore the potential for a new platform for CMB observations, the Airlander 10 hybrid air vehicle, to perform this task. We show that the Airlander 10 platform, operating at commercial airline altitudes, is well-suited to mapping frequencies above 220 GHz, which are critical for cleaning CMB maps of dust emission. Optimizing the distribution of detectors across frequencies, we forecast the ability of Airlander 10 to clean foregrounds of varying complexity as a function of altitude, demonstrating its complementarity with both existing (Planck) and ongoing (C-BASS) foreground observations. This novel platform could play a key role in defining our ultimate view of the polarized microwave sky.

Key words: cosmology: cosmic background radiation – cosmology: early Universe – methods: statistical

1 INTRODUCTION

Measurements of the large-scale polarization of the cosmic microwave background (CMB) are central to two key goals of cosmology: detecting primordial gravitational waves and robustly measuring the summed neutrino masses. The limiting factor in achieving these aims, obscuration by polarized Galactic emission, can be controlled using the differing frequency dependence of the Galactic and cosmological components. Obtaining high-sensitivity, multi-frequency CMB polarization measurements on large scales is, however, a serious experimental challenge.

CMB polarization can be decomposed into E modes, sourced predominantly by scalar perturbations, and B modes, generated at arc-minute scales by gravitational lensing (Zaldarriaga & Seljak 1998) and potentially at degree scales by gravitational waves excited during inflation (Seljak & Zaldarriaga 1997; Kamionkowski et al. 1997). Though the inflationary signal could be undetectably small (or non-existent), its singular nature makes it an irresistible target. The primordial signal is potentially detectable at $\ell \lessim 200$ before it becomes subdominant to lensing. Large-scale E modes provide a direct handle on the optical depth to reionization, $\tau$, degeneracies with which fundamentally limit our ability to measure neutrino masses with the CMB (Smith et al. 2006).

Polarized foregrounds—-dominated by synchrotron and dust emission—overwhelm large-scale primordial B modes. These foregrounds can be reasonably captured with models described in Planck Collaboration et al. (2016c), although weak evidence is beginning to emerge for greater complexity, with spatially-varying frequency dependence (Planck Collaboration 2010) or multiple dust components (Meisner & Finkbeiner 2015; Draine & Lazarian 1998). Ground-based
observations of polarized dust emission are made difficult by
the opacity of the Earth’s atmosphere above 220 GHz. This
can be overcome by deploying a payload on a stratospheric
balloon or satellite.

The types of CMB observatories currently available—
ground-based observatories, stratospheric balloons, and
satellites—offer distinct pros and cons. Ground-based ob-
servatories allow the shortest construction timescales, the
use of cutting-edge technology, regular upgrades and repairs.
Telescope diameter is relatively unrestricted compared with
stratospheric and satellite instruments, making the ground
the location of choice for observing the smallest angular
scales. These observatories are, however, fixed at a partic-
ular location within Earth’s atmosphere, restricting the ac-
cessible portion of the sky and constraining observations to
atmospheric frequency windows centred on roughly 40, 100,
150, and 250 GHz (Hanany et al. 2013). Even within these
windows, measurements on the largest scales are subject to
location-specific systematic effects such as ground pickup,
wind, and turbulence, preventing ground-based experiments
from probing the largest angular scales.

By contrast, satellites can probe the entire CMB elec-
tromagnetic spectrum free from atmospheric contamination,
but they typically undergo 10–20 year development cycles.
The prospect of near-space-like conditions has pushed many
scientific collaborations to employ stratospheric balloons,
which typically operate at altitudes of 30–40 km. Their re-
duced cost results in shorter development cycles and ex-
ploration of more modern technology. Unfortunately, typi-
cal stratospheric balloon flights, so-called long-duration bal-
loons (LDB), have a mean flight time of 20 days. Further, be-
cause payloads sustain non-negligible damage during land-
ing, experiments normally do not fly more than once ev-
ery two years, yielding ∼10 days of integration per year.
Upcoming experiments hope to exploit newly developed
superpressure-balloons (SPB) which are expected to provide
∼100-day stratospheric flights with somewhat reduced lift
capacity (Eberspeaker & Pierce 2011).

Another sub-orbital platform, helium airships operating
at commercial jet altitudes, might emerge as a novel plat-
form for CMB observations. In this Letter, we explore the
possibility of mapping the high-frequency microwave sky at
degree scales from one such airship: the Airlander 10 hybrid
air vehicle.

2 AIRLANDER 10

Airlander 10, developed by the United Kingdom-based com-
pany Hybrid Air Vehicles (HAV), is the largest aircraft cur-
cently flying (see Fig. 1). Airlander 10 generates 60% of its
lift through helium buoyancy and the remainder through its
aerodynamic shape. Its four engines, with vectored thrust,
allow the aircraft to maintain position at a minimum air-
speed of 20 knots. Designed to meet the heavy lifting and
long-duration surveillance and communications needs of the
military and commercial aviation sectors, Airlander 10’s ba-
sic scope is to heavy lift cargo of up to 10,000 kg at altitudes
of up to 10,000 feet (3 km) or to carry a maximum surveil-
lance payload of 1,000 kg at altitudes of up to 20,000 feet (6
km) for up to three weeks (via remote piloting), without the
need for an airport. Its maximum flight altitude could po-
tentially be increased to 30,000 ft (9 km) with further mod-
ifications and testing, and careful operation from a suitable
8–10,000 feet operating base.

There are several features of Airlander 10 that lend it well
to CMB observations. Airlander 10’s potential payload
mass and flight duration are both comparable to LDB, but
the turnaround time for Airlander 10 flights could be days
rather than years, with minimal risk of payload damage dur-
ing landing. As a result, Airlander 10 has the potential to
carry LDB-esque CMB observatories, offsetting the reduc-
in altitude with increased integration time. HAV indi-
cate that Airlander 10’s basic design could be modified to
mount a CMB telescope on the aircraft’s lower fins, yielding
an instantaneous field of view of around a quarter of the
sky. Should civil regulations for remote piloting of Airlander
10 be in place by 2019, HAV anticipate that a remotely pi-
loted flight would be feasible within five years. We assume
such a scenario is plausible without attempting to assess the
technical challenges associated with deploying a telescope
on this platform. From here onwards, we refer to this mod-
ified aircraft as AirlanderCMB. AirlanderCMB’s utility in
obtaining large-scale polarization information rests on the
frequency range attainable at commercial airline altitudes:
here we investigate this in detail.

3 FORECAST METHODOLOGY

Our methodology is based on the CMB4CAST code (Errard
et al. 2016) which forecasts the ability of a given experimen-
tational configuration to isolate lensing and primordial B
modes in the presence of Galactic foregrounds and hence con-
strain cosmology. Foreground cleaning is assumed to be per-
formed by a parametric maximum-likelihood approach (Brandt
et al. 1994; Eriksen et al. 2006; Stompor et al. 2009), in
which the frequency dependence of each foreground compo-
nent (which may vary spatially) is estimated from multi-
frequency observations and then used to construct a cleaned
CMB map. The noise and foreground residuals in the result-
ing CMB map (Errard et al. 2011; Errard & Stompor 2012)
are propagated through the rest of the forecast (Verde et al.
2006), and projected constraints on cosmological parameters
are obtained with a power-spectrum-based Fisher formalism.

Our forecasts depend on two fundamental components:
a sky model and an instrument model. For the former, we
assume the polarized microwave sky takes the simplest form

Figure 1. Airlander 10’s first flight on August 17th, 2016.
supported by current data: the CMB obscured by Galactic synchrotron and dust emission. CMB4CAST requires spatial templates for each sky component, along with a parametric form for their frequency and angular-scale dependence. We source spatial templates from Planck Collaboration et al. (2016c,b), define the dust and synchrotron frequency dependences as a modified grey-body (temperature $T_d = 19.6$ K and spectral index $\beta_d = 1.59$) and a power law (spectral index $\beta_s = -3.1$), respectively, and model their multipole dependence as $C_{ℓd}^T \propto ℓ^{-2.4}$ and $C_{ℓs}^T \propto ℓ^{-2.6}$ (Planck Collaboration et al. 2015, 2016a). Spectral indices are assumed constant over $15^\circ$ patches. The CMB power spectra required by CMB4CAST are computed using CAMB (Lewis et al. 2000), assuming the best-fit cosmology from Planck’s “TT+lowP+lensing+ext” analysis (Planck Collaboration et al. 2016d).

To fully specify an instrument model, CMB4CAST requires the observable fraction of sky ($f_{sky}$), the range of accessible multipole and the central frequency, bandpass, angular resolution and white noise level of each channel. The white noise level of an array of $N_{det}$ bolometers is given by $N_r = 4\pi f_{sky} s^2 (N_{det} t_{obs})^{-1}$, where $t_{obs}$ is the observation time and $s$ is the polarized detector sensitivity.

**Detector Modelling:** We adopt a relatively simple model to predict detector sensitivities as a function of altitude and therefore atmospheric loading. This model assumes that the detectors are cooled to 100 mK to minimize detector noise due to stochastic thermal fluctuations (phonon noise) and adopts optical properties similar to those deployed by the BICEP1 experiment (Takahashi et al. 2016) (see Table 1). The general detector performance assumed for our fiducial instrument can be extrapolated from the estimated properties of current and future instruments, including PIPER and CLASS (Gandilo et al. 2016; Essinger-Hileman et al. 2014).

We refer the reader to Mather (1982); Lamarre (1986); Irwin & Hilton (2005) for details of detector sensitivity modeling. For the six frequencies considered, noise contributions from thermal fluctuations and readout electronics are assumed to be constant: 3.8 and 6.0 aWs$^{1/2}$, respectively. Conversion from W to $K_{CMB}$ is performed using the properties in Table 1 assuming the detectors are single-moded. Using the Atmospheric Model package (Paine 2016) to produce an estimate of the atmospheric spectral radiance as a function of altitude, we vary detector loading due to atmosphere while fixing photon loading contributions from instrument emission and the CMB. Atmospheric loading is derived assuming 1 mm of precipitable water vapor (PWV) and 45° elevation angle. Since we provide location-specific results, we use model predictions pertaining to the atmosphere above the Atacama; however, results should not differ significantly for other locations if we ignore PWV variability. Note that 1 mm PWV is almost certainly greater than the median PWV value across any given year at the site of the Atacama Cosmology Telescope (Dünner et al. 2013). Fig. 2 shows the predicted detector sensitivity as a function of altitude for this model.

Our detector sensitivity model is generated assuming the sensitivity of suborbital instruments will continue to be limited by their optical components and not the statistical properties of incoming CMB photons. The predictions are based on a few basic assumptions about instrument performance: these assumptions can be contested, and should not be interpreted as statements of fact.

**Experimental Setup:** We assume a basic experimental setup of 10,000 detectors in total, comparable to proposed LDB missions such as EBEX-IDS and BFORE (Hanany 2015; Niemack et al. 2016). We consider six frequency bands, centred on 40, 94, 150, 220, 270, and 350 GHz, with Gaussian beams whose widths (FWHMs) are reported in Table 1. Bands with $ν \leq 220$ GHz can be observed from the ground without penalty (Fig. 2); indeed, AdvACT-Pol, BICEP-Keck, Simons Array and SPT-3G plan to. Here, we model all channels flying at altitude to avoid having to select a particular observatory to optimize against. We assume all experiments considered can scan half the sky and access multipole in the range $20 \leq ℓ \leq 2500$ unless otherwise stated. We do not explicitly treat systematic effects, which are highly experiment-specific; rather, we assume such effects will render unusable the modes on scales larger than the minimum multipole considered. The total mission ob-

### Table 1. Detector properties assumed for this analysis. Loading corresponds to the assumed total optical loading from instrument, before accounting for optical efficiencies.

| Band center [GHz] | Bandwidth [GHz] | FWHM [arcmin] | Opt. eff | Loading [pW] |
|-------------------|-----------------|---------------|----------|-------------|
| 40                | 10              | 90            | 0.30     | 5.7         |
| 94                | 23              | 43            | 0.30     | 5.7         |
| 150               | 36              | 30            | 0.30     | 10.0        |
| 220               | 66              | 21            | 0.30     | 16.7        |
| 270               | 81              | 15            | 0.30     | 15.7        |
| 350               | 28              | 14            | 0.30     | 7.3         |

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**Figure 2.** Simulated sensitivity of a single detector in each frequency channel as a function of altitude above the Atacama plateau (mountain). Solid lines are power-law fits to the discrete model predictions, plotted as diamonds. Estimates are produced assuming 1 mm PWV and a viewing angle of 45°.
Fig. 2 shows that the sensitivity of the 40, 94, and 150 GHz channels only changes by a factor of 3. The optimal distributions are plotted in Fig. 4 (left), with corresponding parameter constraints reported in Table 2. For both altitudes, the main effect is to concentrate detectors into fewer bands: the 150 GHz channel is dropped. At 6 km, however, adding C-BASS FGs results in marginalizing over the foreground residuals; the noisy 350 GHz channel is noise- rather than lensing-limited, and the detectors at frequencies up to 220 GHz are distributed roughly as 1:10:2.5:1. Beyond 220 GHz, however, the impact of altitude is apparent: the 350 GHz channel is 3 or 50. The optimal distributions are plotted in Fig. 4 (centre). The impact of the additional frequency coverage is clear, as the constraints tighten by a factor of 2.3 flying at maximum altitude compared to Atacama: over 60% of the improvement of space.

We now optimize the frequency coverage as a function of altitude, following Errard et al. (2011). Using these optimal detector distributions, we further investigate the ability of AirlanderCMB to clean our fiducial foregrounds and constrain cosmology as a function of its minimum multipole, $\ell_{\text{min}}$. Our baseline is that all modes with $\ell \geq 20$ can be observed reliably; we also consider scenarios in which $\ell_{\text{min}}$ is 3 or 50. The optimal distributions are plotted in Fig. 4 (left), with corresponding parameter constraints reported in Table 2. Focusing initially on the detector distributions, we note that the differences between altitudes are largely confined to the highest frequencies. In both cases the bulk of detectors are placed in the most sensitive channel, 94 GHz, and the detectors at frequencies up to 220 GHz are distributed roughly as 1:10:2.5:1. Beyond 220 GHz, however, the impact of altitude is apparent: the 350 GHz channel is the main dust monitor at 9 km, but not 6 km.

Turning to the parameter constraints, we find that AirlanderCMB can place one-sigma limits of $\sigma_{r}=1.6 \times 10^{-3}$ when operating at 6 km, or $1.1 \times 10^{-3}$ at 9 km. The limits do not change greatly if $\ell_{\text{min}}$ is reduced to 3—the experiment is foreground-limited on large scales—but degrade by 20% if modes with $\ell < 50$ are unusable. Constraints on $\tau$, which are sourced by large-scale $E$-mode measurements, are insensitive to AirlanderCMB’s altitude but depend strongly on $\ell_{\text{min}}$. If AirlanderCMB can access modes with $\ell \geq 3$ it will constrain $\tau$ with an uncertainty of 2.7 $\times$ 10$^{-3}$; if $\ell_{\text{min}}$ is beyond the reionization bump, the uncertainty grows to $4.2 \times 10^{-3}$.

Since AirlanderCMB’s strength is its high-frequency observations, we investigate its complementarity with an experiment offering superb low-frequency data: C-BASS (King et al. 2010). C-BASS is gathering full-sky observations at 5 GHz (Irifan et al. 2015) with a 45 arcmin beam and 4500 $\mu$K-arcmin noise; here we assume it can cover the AirlanderCMB patch down to $\ell_{\text{min}} = 20$. The results of combining with C-BASS and Planck are reported in Fig. 4 (centre) and Table 2. For both altitudes, the main effect is to concentrate detectors into fewer bands: the 150 GHz channel becomes obsolete, its detectors redistributed to the 94 and 220 GHz bands. Since the 150 GHz band is less sensitive to the CMB than 94 GHz, it is disfavoured when C-BASS is present to regulate residuals. There are again interesting differences between baseline and maximum altitudes. At 6 km, the number of 40 GHz detectors increases, which aids in marginalizing over the foreground residuals; the noisy 350 GHz channel is dropped. At 9 km, however, adding C-BASS prioritizes 94 GHz over 40 GHz (reducing the noise of the detection.

### Table 2. Parameter constraints for AirlanderCMB as a function of altitude, $\ell_{\text{min}}$, additional data, and foregrounds. We consider fiducial (fid.), flat and complex (comp.) foregrounds; the model assumed during optimization (opt. FGs) may be incorrect.

| Alt. [km] | $\ell_{\text{min}}$ | Inc. | Opt. FGs | True FGs | $\sigma_{r}=0$ $[10^{-3}]$ | $\sigma_{r}$ $[10^{-3}]$ |
|----------|---------------------|------|----------|----------|----------------|----------------|
| 6        | 20                  | fid. | fid.     | 1.64     | 4.21           |                |
| 3        | 20                  | fid. | fid.     | 1.59     | 2.66           |                |
| 50       | 20                  | fid. | fid.     | 1.95     | 4.21           |                |
| 50       | 20                  | fid. | fid.     | 1.16     | 4.21           |                |
| 20       | ✓                   | fid. | flat     | 1.35     | 4.41           |                |
| 20       | ✓                   | fid. | comp.    | 32.9     | 72.5           |                |
| 20       | ✓                   | comp. | comp.  | 21.8     | 64.6           |                |
| 20       | ✓                   | comp. | fid.    | 1.41     | 4.21           |                |
| 9        | 20                  | fid. | fid.     | 1.14     | 4.20           |                |
| 3        | 20                  | fid. | fid.     | 1.14     | 2.62           |                |
| 50       | 20                  | fid. | fid.     | 1.40     | 4.20           |                |
| 20       | ✓                   | fid. | fid.     | 0.856    | 4.18           |                |
| 20       | ✓                   | fid. | flat     | 0.947    | 4.39           |                |
| 20       | ✓                   | fid. | comp.    | 33.5     | 72.0           |                |
| 20       | ✓                   | comp. | comp.  | 16.6     | 59.1           |                |
| 20       | ✓                   | comp. | fid.    | 1.02     | 4.18           |                |
main CMB channel) and moves all detectors from 270 GHz to 220 GHz (allowing better control of foreground residuals).

There is considerable uncertainty in current foreground models, so we investigate the impact of optimizing using incorrect foregrounds. First, we optimize using the correct model but incorrect parameter values. We run a single forecast (without reoptimizing) in which the foreground spectral indices are flattened (within their one-sigma Planck limits) to be closest to the CMB ($\beta_\ell = 1.55$, $\beta_\ell = -2.7$). In this case, constraints on $r$ degrade by only 10–16%. Next, we consider the case in which the model itself is incorrect, and the spectral indices vary rapidly, requiring estimation in each pixel. In this case, the failure is catastrophic: constraints degrade by a factor of 30–40. If we reoptimize assuming the complex foreground model we find minima in which all channels are populated (Fig. 4, right), though constraints on $r$ are still heavily degraded, with $\sigma_{r=0}$ in the range $1.7–2.2 \times 10^{-2}$. However, these configurations are still able to place constraints on the simple foreground model of $1.0–1.4 \times 10^{-3}$: only a 20% penalty. Operating at altitude is essential in this case: dropping the three highest frequency channels penalizes constraints by 63%.

5 CONCLUSIONS

With limited information about the nature of polarized foregrounds, the size, location and optimal frequency coverage of the ideal sky regions for B-mode observations remain largely unknown. To some extent, current and future experiments must gamble on these critical design parameters (Kovetz & Kamionkowski 2015, 2016). With relatively fast turnaround times, airships like AirlanderCMB offer a modular platform that can be quickly optimized for varied sky regions and frequency ranges.

Optimizing AirlanderCMB’s frequency coverage for a range of altitudes, foreground scenarios and complementary datasets yields two important conclusions. First, realization of AirlanderCMB’s maximum altitude is not critical to the success of the platform, though, if possible, constraints on $r$ improve by 35%. Second, optimizing for the most pessimistic foreground scenario does not significantly penalize performance if foregrounds are more benign. By contrast, constraints degrade by a factor of over 30 if the foregrounds are incorrectly assumed to be simple. As bands below 270 GHz will be observed from the ground, AirlanderCMB need carry only 1300–3000 detectors to realize this performance.

High-altitude observations represent a critical step in preparing the ground for a space mission tasked with delivering the ultimate CMB polarization data. In addition to demonstrating detector technology, such observations will characterize polarized foregrounds in the detail required to ensure the design of the space mission suits the science requirements. Given the cost and development time of a space mission, novel platforms such as AirlanderCMB could play a very important role in defining our ultimate view of the polarized microwave sky.

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