CMB S-4: Telescope Design Considerations

August 23, 2016


Institutions
1 Introduction

Charge: Summarize the current state of the technology and identify R&D efforts necessary to advance it for possible use in CMB-S4. CMB-S4 will likely require a scale-up in number of elements, frequency coverage, and bandwidth.

May want to point to the Hanany et al 2013 review for background: http://arxiv.org/abs/1206.2402

1.1 Optics benchmarks

Describe and define important optical quantities.
2 Current CMB telescope designs and maturity

2.1 Current refractive and reflective optics designs

2.2 Table of current telescope/instrument designs

Possible items for table: aperture, f/#, min Strehl ratio, f-lambda at 150 GHz, A*Omega, ?

See Google Docs page linked here for current table status.
3 Design considerations for next generation telescopes

e.g. crossed-Dragone with reimaging optics (Niemack 2016)

3.1 Brief discussion of tradeoffs

3.2 New optics design concepts
4 Telescope engineering to improve systematics

CMB-S4 will require exquisite control of systematic errors, so the telescopes must be designed to have low pickup, stable optics, and good pointing while scanning fast enough to freeze atmospheric brightness fluctuations. It may also be necessary to measure systematic errors that are fixed relative to the instrument, e.g., by rotating the camera or the entire telescope about boresight. CMB-S4 will build on experience with existing telescope designs, but the scale of CMB-S4 may allow approaches that were deemed impractical for current experiments. Some of these approaches are described below; all will require design and manufacturing studies to assess their viability for CMB-S4.

Exactly what can be tolerated for pickup outside the main beam requires some investigation, but to give a sense of what will be needed, the EPIC 1.4m design has \(-80\) dB, \(-20\) dBi sidelobes, and gives \(0.1\) nK rms polarized pickup from the galaxy at 150 GHz (“Study of the Experimental Probe of Inflationary Cosmology - Intermediate Mission for NASA’s Einstein Inflation Probe,” NASA, 4 June 2009). There are two approaches for controlling pickup: (i) reduce scattering, which means low blockage in the obvious sense of off-axis optics, enough clearance to avoid sidelobes due to clipping the beam, and smooth optical surfaces to avoid scattering from gaps between mirror segments; and (ii) control what does get scattered, which requires reflecting shields and/or absorbing baffles to eliminate pickup in far sidelobes.

The pointing requirements for CMB-S4 will be stringent: something like beamwidth/100 or 1.5” (W. Hu, M. M. Hedman and M. Zaldarriaga, “Benchmark parameters for CMB polarization experiments,” Phs. Rev. D 67, 043004 (2003)), so the telescope structures must be stiff. Stable optics also require stiff structures, and schemes to keep the optical surfaces free of water, snow, and ice.

4.1 Monolithic mirrors

Fabrication of a monolithic, millimeter-wavelength mirror larger than a few meters in diameter is challenging, so all existing, large, CMB telescopes (i.e., ACT and SPT) have mirrors made of \(\sim 1\) m segments with \(\sim 1\) mm gaps between the segments. Scattering from the gaps generates sidelobes which account for \(\sim 1\%\) of the telescope response. It is difficult to make the gaps smaller because some clearance is needed for assembly and manufacturing tolerances. Various gap cover/filler schemes have been tried, but a robust solution has not been demonstrated.

Monolithic mirrors were not practical for the large, stage-3, CMB telescopes, but CMB-S4 will involve multiple telescopes, so the cost of developing a fabrication approach for large monolithic mirrors may be reasonable. There is obviously no point pursuing monolithic mirrors unless the rest of the telescope design is consistent with small sidelobes.

The key issues for monolithic mirrors are: (i) fabrication errors; and (ii) thermal deformation. Figure 1 shows surface error contributions for a monolithic, aluminum mirror, which is an obvious choice for low cost. A 5 m diameter, \(\lambda = 1\) mm mirror seems possible if thermal gradients through and across the mirror are \(< 1\) K, which is what the \(\sim 1\) m diameter \(\times 50\) mm thick CSO primary mirror segments achieve at night. Keeping thermal gradients below 1 K in a large aluminum mirror will require insulation on the back of the mirror, a reflective front coating for
daytime operation, and maybe active control (e.g., cooling the back of the mirror at night). A CFRP mirror would have an order of magnitude better thermal performance, but it might not be practical to fabricate a large monolithic CFRP mirror with the required surface accuracy.

4.2 Boresight rotation

A few experiments (e.g., DASI, CBI, QUAD, QUIET, BICEP, Keck Array) have included boresight rotation to measure systematic errors that are fixed with respect to the instrument (e.g., instrumental polarization) and vary slowly (e.g., on timescales of tens of seconds). All these experiments have or had small telescopes, or arrays of small telescopes; the largest boresight rotator was the 6 m diameter platform on the CBI. Large telescope projects have generally dismissed boresight rotation as impractical, but it may be needed to achieve CMB-S4 sensitivity levels, and may be reasonable given the scale of CMB-S4.

The key issues for boresight rotation are: (i) balancing the telescope structure while also providing adequate range of motion; and (ii) protecting the drive mechanisms from the weather.

A mount that supports boresight rotation can wrap around the outside of the telescope, which allows full range of motion with a naturally balanced structure (no counterweight), but results in a massive, expensive mount with large mechanisms that are difficult to protect. Alternatively, a compact, inexpensive, enclosed mount can be placed behind the telescope, but this requires a counterweight which results in limited range of motion because the counterweight interferes with the mount. Figure 4.2 shows a concept for a compact mount with boresight rotation. The design provides an optical bench that can support a single, large, off-axis telescope, or an array of smaller telescopes, inside a deep baffle. The compact drive mechanisms can be enclosed, with access from below, which is appropriate for a site that has severe snow storms or very low temperatures.

4.3 Shields and baffles

Deep, comoving, reflective shields and/or absorbing baffles will be needed to control pickup in the far sidelobes. Good shielding is a key reason for the success of small CMB telescopes in making measurements at low \(\ell\), but a full shield or baffle may also be practical for a large telescope, e.g., the mount in Figure 4.2 can accommodate a 5 m telescope inside a deep, cylindrical baffle that is supported by a light, CFRP spaceframe.

The key issues for shields and baffles are: (i) adequate mechanical stability, to avoid time-varying pickup, e.g., due to wind buffeting; (ii) keeping surfaces clear of water, snow, and ice, which change the optical loading; (iii) baffle temperature variations, which cause variations in optical loading; and (iv) survival of absorbing coatings.

Mechanical stability is more challenging for a reflective shield because any part of the surface that sees scattered light must be stable. For an absorbing baffle, the rim must be stable, but the rest of the baffle can move relative to the telescope beam as long as the baffle is truly black. There is no practical experience with large absorbing baffles, so the effect of temperature variations needs consideration. Some work must also be done to identify or develop a light, robust, weather-resistant absorber.
Figure 1: Surface error vs. diameter for a monolithic aluminum mirror with thickness = diameter/4. Temperature gradients across the mirror change the thickness, while a temperature gradient through the mirror causes cupping. The gravitational deformation model is the deflection of a simply supported plate, and wind-induced deformation is the gravitational deformation scaled by the ratio of wind pressure to mirror weight per unit area. The fabrication error model has 50 µm rms for a 10 m mirror, with error scaling as the square of diameter, combined in quadrature with a setup error of 5 µm rms. The model is based on the OVRO 10.4 m primary mirrors, which were machined as a single piece, and the 1 m segments for SPT. The horizontal dashed line corresponds to 80% Strehl ratio (λ/27 rms surface error) at λ = 1 mm.

Figure 2: Concept for a telescope mount with boresight rotation. The mount provides a large, flat optical bench that can accommodate various arrangements of cameras and off-axis mirrors. Standard, slewing-ring bearings allow fast scanning in azimuth and rotation about boresight to modulate/measure polarization. Zenith angle motion is controlled by a hexapod that provides a stiff connection between the azimuth and boresight slewing rings. The blue structure is a lightweight CFRP spaceframe that supports an absorbing baffle to reduce pickup. Dimensions in the diagram are based on a 6 m diameter optical bench and 2 m diameter slewing rings.
5 Potential future studies and development areas

5.1 Control of systematic uncertainties
Describe various systematic design considerations (polarization modulation, boresight rotations, ... )

5.2 Studies to inform telescope designs

5.3 Cost trends? Designing cheaper telescopes?
A Optics designs for current projects

A.1 Advanced ACTPol

Figure 3: Left: ACT telescope optics and mechanical structure. Right: Raytrace of Advanced ACTPol receiver optics, which includes three optics tubes: one on top and two symmetric tubes on bottom [1].

Advanced ACTPol (AdvACT) is the third instrument upgrade for the 6 m Atacama Cosmology Telescope (ACT). The 6 m primary and 2 m secondary are arranged in a compact off-axis Gregorian configuration to give an unobstructed image of the sky. The details of the telescope optics design are presented in [2], while the ACTPol and Advanced ACTPol receiver optics designs are presented in [1, 3]. Figure 3 shows a raytrace through the ACT mechanical structure as well as through the Advanced ACTPol receiver optics. To minimize ground pick-up during scanning, the telescope has two ground screens. A large, stationary outer ground screen surrounds the telescope and a second, inner ground screen connects the open sides of the primary mirror to the secondary mirror, and moves with the telescope during scanning.

ACTPol and Advanced ACTPol use the same receiver with three independent optics tubes. Both use large silicon lenses with two and three layer metamaterial antireflection (AR) coatings for silicon lenses [4]. These coatings offer the advantages of negligible dielectric losses (< 0.1%), sub-percent reflections, polarization symmetry equivalent to isotropic dielectric layers, and a perfect match of the coefficient of thermal expansion between coating and lens. Each optics tube focuses light onto a two-frequency multichroic detector array at one of the following frequency pairs: 28&41 GHz, 90&150 GHz, or 150&230 GHz [5]. The AdvACT reimaging optics have f/1.35 at the array focus. A pixel-to-pixel spacing of 4.75 mm in the recently deployed 150&230 GHz array leads to approximately 1.8&2.5 f-λ spacing. A UHMWPE vacuum window is used combined with metal mesh filters to control out of band radiation.
Figure 4: Left: BICEP2/Keck Array ray trace Right: Bicep3 raytrace.

A.2 BICEP3

BICEP3 is a cryogenic refractor of aperture 0.52m, with 2 alumina lenses ([6][7]) in an f/1.6 system. The main cryostat volume is 29in in diameter x 95in high. It operates at 95 GHz on a 3-axis mount at the South Pole. The field used is 14.1° half-opening angle, nearly the unvignetted field of view. At 2mm wavelength the design gives Strehl > 0.96 over the full unvignetted field (top-hat illumination assumed).

The lenses are 99.8% pure alumina. The lenses and stop are at 4K. The window is HDPE, filters consist of metal mesh filters at (nom.) ambient, alumina filter at 50K, another mesh filter below that, 2 Nylon filters at 4K, and Ade edge filters at 250mK over each detector module. The window, alumina components, and Nylon filters are single-layer AR coated; the alumina AR is an epoxy mix. A co-moving absorptive forebaffle and a reflective groundshield mitigate ground source contamination.

2016 95 GHz light detector count is 2400. Pixels are Bock phased slot antenna arrays with tapered weighting to approximate Gaussian beams ([8]). The 1/f noise knee after atmospheric common-mode rejection from detector pair differencing is well below the degree-scale science band ([9][10]). Beam systematics are averaged down by boresight rotation and residual temperature to polarization beam leakage is removed by deprojection ([11]). Thus, a (fast) polarization modulator is not used in BICEP3 (as with BICEP2 and Keck).

The mount (originally built for BICEP1) provides EL down to ~ 50°, full AZ, and boresight
rotation $255^\circ$. The latter provides for two $45^\circ$ offset pairs of $180^\circ$ complement boresight angles (4 angles total) for full Q/U discrimination and cancellation of several beam related systematic errors. Mapping is performed with a sequence of constant EL scans at $2.8^\circ/s$ in AZ.

The BICEP-Array receivers will be substantially the same as BICEP3.

### A.3 CLASS

![CLASS System Overview](image)

The Cosmology Large Angular Scale Surveyor (CLASS) consists of four telescopes sharing similar optical layouts [12]. One telescope operates at 40 GHz, two at 90 GHz, and the final telescope is a dichroic 150/220 GHz, hereafter the high-frequency (HF) telescope. A 60-cm-diameter variable-delay polarization modulator (VPM) is the first element in the optical chain, providing $\sim 10$ Hz front-end polarization modulation [13]. Ambient-temperature, off-axis, elliptical, 1-meter primary and secondary reflectors reimage the cold stop of the receiver at 4 K onto the VPM. Cryogenic reimaging lenses, one at 4 K and one at 1 K, focus light onto the focal plane of feedhorn-coupled transition-edge-sensor bolometers. The CLASS design emphasizes per-detector efficiency and sensitivity with 10 dB edge-taper illumination of the cold stop. The CLASS telescopes provide diffraction-limited performance over a large, $20^\circ$ field of view with resolutions ranging from 90′ at 40 GHz to 18′ at 220 GHz. Three-axis mounts give azimuth, elevation, and boresight rotations, with two telescopes on each of two mounts (See Figure 5). Co-moving ground shields and baffles reduce ground pickup.

The lenses for the 40 and 90 GHz telescopes are made of high-density polyethylene (HDPE), while the HF telescope employs silicon lenses. All of the lenses are anti-reflection (AR) coated...
with simulated dielectrics cut directly into the lens material. The receivers have vacuum windows approximately 50 cm in diameter made of ultra-high molecular-weight polyethylene (UHMWPE). A combination of capacitive-grid metal-mesh filters and absorptive PTFE and nylon filters reject infrared radiation.

### A.4 EBEX

![EBEX optical design raytrace schematic](image)

Figure 6: EBEX optical design raytrace schematic consisting of two ambient temperature reflectors in an off-axis Gregorian configuration and a cryogenic receiver (left). Inside the receiver (right), cryogenically cooled polyethylene lenses formed a cold stop and provided diffraction limited performance over a flat, telecentric, 6.6° field of view. A continuously rotating achromatic half-wave plate placed near the aperture stop and a polarizing grid provided the polarimetry capabilities.

The EBEX telescope was a balloon-borne CMB polarimeter observing at 150, 250, and 410 GHz. It was required to have flat telecentric focal planes, a large diffraction limited field of view defined as Strehl ratio > 0.9, a cold stop to control sidelobe response, as well as a continuously rotating achromatic half-wave plate and polarizing grid to provide polarimetry, all while remaining sufficiently compact to fit on a balloon payload.

To achieve this the EBEX optical system consisted of a 1.05 m, f/1.9, ambient temperature, Gregorian Mizuguchi-Dragone reflecting telescope and a cryogenic receiver containing 5 ultra-high molecular weight polyethylene re-imaging lenses, see Figure 6. The mirrors were oversized to suppress sidelobe pick-up; the illuminated aperture is 1.05 m while the physical aperture is 1.5 m. The reimaging lenses preserved the f-number of the system while forming a 1 K cold stop, the location of the continuously rotating achromatic half-wave plate, enlarging the diffraction limited field of view to 6.6°, and forming two flat, telecentric focal planes. On the focal planes conical feedhorns coupled the detectors, TES bolometers, to free space. Each focal plane
consisted of 7 wafers, 4 at 150 GHz, 2 at 250 GHz, and 1 at 410 GHz. Each wafer contained 128 usable detectors; the system was readout limited [19]. Observing bands were defined by reflective filters above the feedhorns and cylindrical waveguides between the feedhorns and bolometers. Reflective IR filters and one absorptive Teflon filter were used to reduce load on the cryostat [20].

A.5 Keck/Spider

Keck and SPIDER are close relatives of BICEP2. Both consist of multiple cryogenic refractors of aperture \( \sim 250 \text{mm} \) and f/2.2 of essentially the same optical design as BICEP2 ([21]). Both use JPL dual-polarization slot antenna array coupled TES bolometers ([8]).

Keck consists of 5 telescopes co-aligned in their ground-based mount at the South Pole, each in its own independent vacuum jacket. Individual telescopes have been assigned each observing season to different frequency bands from 95 to 230 GHz ([22]). Apertures are 264mm and fields of view 15° ([23]).

The Keck telescopes have 12cm thick Zotefoam windows, 50K PTFE and Nylon filters, 4K HDPE lenses and a Nylon filter, and Ade edge filters ([22, 23]). The lenses and filters (except the edge filter) are single-layer AR coated, matched to the frequency band of the detector in use. The stop is at 4K, on the bottom of the first lens. Absorptive comoving forebaffles surround each telescope aperture, and along with a reflective groundscren minimize ground pickup.

The Keck array is on a 3-axis mount (built for DASI). Mapping is performed by a sequence of constant EL scans at each of 8 boresight rotation angles, 4 pairs of 180° complements for complete Q/U discrimination and mitigation of beam systematics. AZ scan speed is 2.8° /s. The 1/f noise knee after atmospheric common-mode rejection from detector pair differencing is well below the degree-scale science band ([9, 10]). Beam systematics are averaged down by boresight rotation and residual temperature to polarization beam leakage is removed by deprojection ([11]). Thus, a (fast) polarization modulator is not used in Keck (as with BICEP2 and BICEP3).

SPIDER is a balloon experiment with 6 co-aligned telescopes in one large vacuum jacket ([24]). It has some optical differences from Keck (and BICEP2) due to the lower sky loading at altitude (as well as mechanical and thermal differences due to weight and cooling system requirements).

Here some specific differences – predominantl reflective (vs. absorbptive) filter stack for low cryogenic loading, 1.6K sleeve and stop, lower-G detectors, very aggressive magnetic shielding.

The SPIDER telescope have apertures of 250mm and 20° fields of view. The window is 1/8in UHMWPE. Metal mesh filters at ambient, 120K and 30K are above a 4K sapphire half wave plate, Nylon filter, and HDPE lenses ([24]). Between the lenses is a 1.5K cooled sleeve with optical baffles. Between the 2nd lens and the 300mK focal plane is a low pass filter at 1.5K. The dielectrics are single-layer AR-coated.

The detectors (for the first circum-Polar flight in January, 2015) are JPL slot antenna array-coupled TES bolometers, with 95 and 150 GHz bandpasses. The detector 1/f noise knee is low ([24]), the science goals for 10 < \( l < 300 \) are accommodated with available scan rates (see below), and fast polarization modulation is not needed, as with Keck and the BICEP2 and 3 instruments (see also [25]).

The second circum-Polar flight is planned to include NIST feedhorn arrays and OMT-coupled detectors ([26]).
The gondola provides for AZ and EL scanning. It does not have boresight rotation, so depends on the cryogenic waveplates for Q/U discrimination and slow polarization modulation, with a contribution as well from sky rotation. The scan strategy ([24, 27, 28]) is quite different from Keck and the BICEP telescopes due to gondola inertial limitations; a sinusoidal scan was adopted in both AZ and EL with variable amplitudes. The waveplates are stepped 22.5° every 12 sidereal hours. This generates good mapping coverage, Q/U discrimination, and cross-linking.

### A.6 Piper

![Image](image.jpg)

**Figure 7**: PIPER. Left: Raytrace of original PIPER optics design. Right: Current PIPER implementation.

PIPER is a balloon-borne instrument to observe CMB polarization at 200, 270, 350 and 600 GHz [?]. Twin co-pointed telescopes survey Stokes $Q$ and $U$. Like CLASS, the first optical element of each telescope is a variable-delay polarization modulator (VPM). The VPM separates sky signal from instrument drifts by modulating the incoming polarized signal at 3 Hz, aiding reconstruction of the polarized CMB sky on largest angular scales. The VPM efficiently mitigates instrument polarization systematics by being the first optical element. Each of the PIPER VPMs have a 40 cm clear aperture with 36 $\mu$m wires at 115 $\mu$m pitch. PIPER uses the bucket dewar from ARCADE, which carries 3000 L of liquid helium. Helium boiloff allows operation without emissive windows. Superfluid fountain effect pumps draw LHe to cool all optics to 1.4 K. Cold optics and the lack of windows reduce photon noise and allow PIPER to take full advantage of the float conditions (especially at high frequencies) and to conduct logistically simpler, conventional flights from Palestine/Ft. Sumner and Alice Springs. Each flight is optimized for one band, and flights from the northern and southern hemispheres cover 85% of the sky.

Two aluminum mirrors image a 12 cm diameter cold aperture stop (1.4 K) onto the central region of the front-end VPM. The entrance pupil is 29 cm in diameter and is undersized to limit edge illumination of the VPM (33 dB edge taper). The stop is a corrugated stack of Eccosorb. The 1.4 K environment of the bucket dewar mitigates stray light and acts as a comoving ground screen.
The reflective fore-optics feed silicon re-imaging optics that use metamaterial anti-reflection layers [?]. The off-axis nature of the fore-optics creates aberrations that can be corrected by de-centering the reimaging lenses. The reimaging lenses remain planar to the stop and are oversized to retain cylindrical symmetry for diamond turning. The final lens focuses light onto a $32 \times 40$ free-space backshort-under-grid detector array at $f/1.6$. The resolution at 200 GHz is $21'$ and its Airy disk spans approximately six bolometers. The minimum Strehl ratio within the $6 \times 4.7$ degree FOV is 0.97 [?]. PIPER uses a common detector array for all frequencies. Between flights, the VPM throw, band-defining filters, and (when necessary) lenses are swapped. This strategy is facilitated by a backshort that is optimized for 200 GHz and is less efficient at high frequencies where the atmosphere and dust emission are brighter. A narrower passband toward higher frequency also limits loading.

A.7 Simons Array

![Ray tracing diagram of the POLARBEAR-2 and the Simons array optics. Secondary mirror and cryogenic receiver are shown. Length of cryogenic receiver is 2-meters. Diameter of three cryogenic lenses are 500 mm.](image)

The three telescopes that comprise the Simons Array are identical o-axis Gregorian designs that utilize a 2.5m monolithic primary mirror [29]. The telescope and receiver optics are designed to provide a at, telecentric focal plane over a wide direction-limited eld of view. The angular resolution of the telescope is 5.2, 3.5, and 2.7 at 95, 150 and 220 GHz respectively. Relative positions of the primary mirror and the secondary mirror obey Mizuguchi-Dragone condition to minimize instrumental cross-polarization [30]. Each telescope has a co-moving shield to prevent
side lobe pickup from ground emission and an optical bae around prime focus to block stray light from reaching the window and scattering into the receiver. The rst telescope comprising the Simons Array - the Huan Tran Telescope (HTT) - was installed in Chile in 2011 and has been operating nearly continuously with the POLARBEAR-1 experiment since. The second and third telescopes were installed in early 2016.

The receivers have windows made out of laminated 10-inch thick Zotefoam. Radio-Transmissive Multi-Layer Insulation (RT-MLI) and 2-mm thick anti-reflection coated alumina plate are anchored to 50-Kelvin stage as infrared filter [31, 32]. First POLARBEAR-2 receiver, the POLARBEAR-2a, will deploy with the ambient temperature continuously rotating half-wave plate (HWP) [33]. Second and third POLARBEAR-2 receivers, the POLARBEAR-2b and the POLAEBEAR-2c, will have cryogenically cooled HWP at 50-Kelvin stage. All three receivers have three 500 mm diameter alumina re-imaging lenses cooled to 4-Kelvin. High index of refraction of alumina allowed for optics design with lenses that have moderate radius of curvature. The first lens is double convex lens. The second lens and the third lens are plano-convex lenses. Optics design has a cold stop between the second lens (aperture lens) and the third lens (collimator lens). Meta-material infrared blocking filters and Lyot stop are mounted at the stop. Final F/# of at the focal plane is 1.9. Optics design proves diffraction limited illumination that extends over 365 mm diameter of the focal planes. Strehl ratio at the edge of focal plane is 0.95 for 95 GHz and 0.85 for 150 GHz.

A.8 SPT-3G

B Recent projects using crossed-Dragone telescopes

B.1 ABS

The Atacama B-Mode Search (ABS) telescope consists of 60-cm, cryogenic primary and secondary reflectors in a crossed-Dragone configuration held at the 4 K stage of the receiver (Figure 9) [34]. This optics design was chosen for its compactness for a given focal-plane area and low cross-polarization. The reflectors were machined out of single pieces of aluminum. A 25-cm stop at 4 K limits illumination of warm elements. The reflectors couple the 25-cm-diameter array of 240 feedhorn-coupled, polarization-sensitive, transition-edge-sensor bolometer pairs (480 detectors) operating at 145 GHz to the sky with 33' FWHM beams over a 20° field of view. The telescope is an f/2.5 system. The polarization directions of the detectors within groups of ten adjacent detectors were oriented to minimize cross-polarization and each group was tilted to minimize truncation on the cold stop. Although neither the orientation of the ten elements within a group nor the orientation of different groups was parallel, the detectors are largely sensitive to polarizations ±45° to the symmetry plane of the optics.

An ambient-temperature, 33-cm-diameter continuously-rotating half-wave plate (HWP) is placed at the entrance aperture of the receiver [35]. The HWP is made of 3.15-mm-thick α-cut sapphire anti-reflection (AR) coated with 305 µm of Rogers RT-Duroid 6002, a fluoropolymer composite. An air-bearing system provided smooth rotation of the HWP at 2.55 Hz and polarization modulation in the detector timestreams at 10.20 Hz. Infrared blocking is provided by capacitive-grid
metal-mesh filters patterned on 6-μm mylar with grid spacings of 150 and 260 μm, along with absorptive 2.5-cm PTFE filters AR coated with porous PTFE at 4 K and 60 K. A 0.95 cm nylon filter AR coated with porous PTFE at 4 K provides additional filtering below 1 THz. The receiver has a 3-mm thick ultra-high molecular weight polyethylene (UHMWPE) vacuum window AR coated with porous PTFE. A reflective baffle, shown in Figure 9 and a co-moving ground shield reduce ground pickup.

**B.2 QUIET**

QUIET was a crossed Dragone telescope and receiver sited in Chile with 1.4m mirrors [36, 37]. It operated with 42 and 90 GHz receivers using corrugated feedhorns (19 and 91 feeds, resp.) and no tertiary optics. It did not have a stop above the primary mirror; the absorptive entrance aperture was large enough to miss any ray-traced beam from the receiver and only intercepted scattered or strongly diffracted radiation. Above the entrance aperture an absorptive fore-baffle caught several known sidelobes.

At a wavelength 2.0mm, the design would give a Strehl > 0.8 field size (assuming uniform illumination at f/1.65) of ~ 6.6° half-angle. When considering realistic detector beams the Strehl-limited field size is considerably larger.

The receivers had slow feeds to minimize spillover through the telescope, with FWHM of 7 – 8.6° (for the two edges of the 90 GHz band, similar for the 42 GHz band). The resulting beam sizes on the sky were 0.5° for the 42 GHz band and 0.22° for the 90 GHz band. The unvignetted f-ratio for the 90 GHz receiver’s feed locations was 1.65 (full angle 33.7°), resulting in less than 0.25%
spillover for any feed in the 91 pixel 95 GHz receiver (modeled, not measured). The telescope was surrounded by a box of Eccosorb (HR-10 on sheet aluminum, protected by Volara foam), so all spillover was intercepted at ambient temperature except the small percentage that made it through the entrance baffle onto the sky or back into the receiver itself.

Cross-polar response of both the telescope and the feed horns was also exceptional [38].

A larger receiver with 397 identical feeds in the same hex pattern on an unmodified QUIET telescope would reach $\sim 2.2\%$ spillover for the edge feeds. However, redistributing the feed pattern and widening the mirrors out of the plane of symmetry would reduce that number. The design is not Strehl-limited.

The QUIET telescope was operated on the CBI mount, with 3 axes including boresight rotation.
C Telecon notes

C.1 July 20, 2016

On the call: Shaul, Adrian, Toki, Keith, Mike, Nils, Steve, Jeff, John R.
Make separate section for new designs. First part is brief discussion of tradeoffs, second section is new designs.

Alternatively could change name of section 2 to simply ”CMB telescope designs”.
Nils suggests splitting 2.3 & 2.4 into new section. Section 2 becomes concrete reporting and new section becomes commentary, maybe named ”Design considerations for next generation telescopes”

Discussion of Charge:
Shaul points out that we may want to add ”control of systematic uncertainties”. We should enumerate the future studies that are needed related to systematics.
Adrian emphasizes that we should mention various systematic design considerations (polarization modulation, boresight rotations, ...)
Jeff suggests that we have a sub-section called benchmarks at the beginning of the paper/introduction to help people track the important optical quantities.
Nils suggests getting a ray trace figure from each experiment and a paragraph from each project.
Goal will be to combine these into a coherent discussion of different telescope types.

ABS - Tom?
CLASS - Tom?
EBEX - Shaul
AdvACT - Mike
SPT-3G - Nils
BICEP3 - Keith, Zeesh
Keck/SPIDER - Keith, Zeesh
Simons Array - Toki
Piper - Al?

Additional Metrics: lens materials, temperature of each optical component, FOV, optical loading?, beams on the sky per frequency, ”multichroic-ness”, window materials,

Ask people to comment on recommendations for studies for developing telescope designs for S4.

After we have this information, we will meet again and make final assignments.
Should talk generally about cost trends, but we should be careful about not putting specific numbers in.

Would be useful to discuss how could we design/develop things to make them cheaper?

Executive summary may be the most important part of this document. Keep that in mind for finishing work at the end.
Could send out a good example later.