An Optical Guide Camera for BICEP (Background Imaging of Cosmic Extragalactic Polarization)

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ABSTRACT

BICEP is a bolometer array dedicated to the measurement of B-mode Cosmic Microwave Background polarization on scales of approximately 1 degree. BICEP should be able to detect B-mode polarization with T/S ¿ 0.05. To achieve the desired sensitivity it is necessary to maintain pointing accuracy on the order of ¡5 arcsec. It is therefore necessary to use an optical guiding camera which will be able to periodically observe stars in the BICEP field and derive the pointing model for the telescope.

Subject headings:

1. Introduction

Cosmic Microwave Background polarization provides the ability to understand the nature of inflation by searching for the signature and magnitude of the Gravitational Wave Background predicted by inflation theories. Linear CMB polarization is the result of Thompson scattering of quadrupolar incident radiation. Depending on the source of the anisotropy, the polarization pattern takes on different characteristics. In particular, the tensor perturbations produced by the Gravitational Wave Background generated during inflation leave a polarization vector field that can be described as the curl of a vector potential(1). Scalar perturbations produced by compressional plane waves produce a vector field that can be described as the gradient of a scalar potential.

2. BICEP Design

BICEP aims to observe this signal of polarization, which will be found at the 10 ppb level. The optical design of BICEP is that of a refractor with an f/2.3, 20 cm aperture. The focal plane contains 48 Polarization Sensitive Bolometer pairs (PSBs) at 100 and 150 GHz. The beam patterns for the bolometers are designed to be diffraction limited, 1 degree for 100 GHz and 0.7 degrees for the 150 GHz pixels.

In order to measure non-local properties of the CMB polarization map on the sky (i.e. curl and gradient components of the vector field) it is necessary that the the cross-correlations between each 1 degree patch of sky be well understood. Therefore it is critical to understand the beam size and pattern in order to know the noise covariance matrix. At the minimum it is necessary to know the beam size to 10 percent precision, and desirable to attain an order of magnitude greater than this. In order to make use of this information, pointing must be therefore be known to even greater precision and this suggests a desire for pointing on the 5-10 arcsec level.

BICEP will nominally operate at the South Pole during the Austral Winter. However, installation of the mount and cryostat will occur during the Austral Summer necessitating the ability to solve for the pointing model while the Sun remains above the horizon during December and January. Therefore an optical camera is required that has 5 arcsec accuracy and can maintain this during daylight.

3. Design Considerations

The pointing model for a telescope includes approximately 9 dynamic parameters, in addition to the longitude, latitude and altitude that can be determined without the need of a guide scope. Those parameters include the azimuth and elevation zero points, flexure of the telescope, offsets between the azimuthal axis and the vertical and the collimation error between the telescope boresight and the guide camera. In order to calculate the 9 parameters, it is desirable to fit the model to data that has twice that many observations - it is necessary to be able to observe 20 stars. Star catalogs show that to view 20 stars with 40 degrees of the South Celestial Pole (BICEP's elevation limit), stars of magnitude 3.0 must be viewable.

In order to view stars during the daytime, the best strategy seemed to be to use the fact that the sky spectrum, due to Rayleigh Scattering, which has a spectral dependence proportional to $\lambda^{-}4$. So the first task was to find a camera with good NIR viewing - the Astrovid StellaCAM-EX. The camera has parameters shown in Table 1.

To get the necessary resolution we demand that:

$$\frac{1.22*206265\lambda}{d} < 5arcsec \tag{1}$$

which requires $d > 2$ inches. Additionally, the focal length must be chosen so that, ideally, the diffraction spot falls entirely on a single pixel. That requires

$$f < \frac{pixelsize*206265}{5} \tag{2}$$

which suggests a focal length of 400 mm is appropriate. So, a standard f/5 400 mm telescope, a NIR filter and the camera were taken up to the 14" on the Robinson roof, strapped to the side of the telescope and we conducted a bunch of experiments to determine whether this was good enough.

Table 1: Parameters for the StellaCAM-EX.

Pixelsize	8.4 μm x 9.8 μm
No. Pixels	768 x 494
Max λ	1100 nm

4. 14" Results

The ability to look at stars during the daytime depends on maintaining a very stable pointing solution from night into daylight and proved exceedingly difficult, since it turned out our 'mounting' of the 400 mm scope to the 14" was unable to achieve no better than 1 degree collimation. Since the FOV of the scope was a little less than 1 degree, this meant that, depending on the azimuth and elevation, stars were often on the edge or outside the FOV. Occasionally Venus was visible which allowed some re-pointing, but not with desired accuracy and Venus is still difficult to find in broad daylight.

Results showed that we were able to view stars up to a magnitude of about 1.0, but no better. It should be noted that many of these observations were undertaken in Pasadena, in July, and during mid-day, while the conditions at the South Pole are expected to have better seeing, and sky brightness corresponding to early morning or late evening. In addition, I believe it is possible to achieve better baffling than the commercial scope contained. Another improvement to be made was finding a lens with smaller chromatic aberration.

Still, I concluded that a longer focal length, reducing the amount of ambient sky falling on each pixel was necessary to increase the contrast. The next easily available lens was a 900 mm, f/11 lens designed to be apochromatic in the NIR (being used for a similar device on the South Pole Telescope.) This should offer a 4-fold improvement in lowering the amount of sky to contrast with. Including the improvements above, this should be enough to move our sensitivity into the necessary range.

5. Camera Design

The physical design of the camera was the most difficult portion of the project. BICEP is designed with a thin inner ground shield cylinder of height and diameter each 1 m. This structure is too flimsy to support a telescope. Therefor the guide scope must be mounted on the top of the cryostat. This requires the camera to fit into a space that is approximately 25" x 14" x 6", and the window must be placed in the center of this area so it can see through the bottom of the groundshield. This is shown in Figure 1.

Consequently, the optical path needed to be folded twice. Guide scopes generally do not include folds since mirror angular motions are amplified by a factor of 2 and multiple mirrors cascade this effect. However, the setup requires this and the mirrors can be glued in place and bolted down rigidly, which should minimize errors.

The next step involved selecting materials for the mirrors, mounts and adhesives. The extreme thermal conditions at the South Pole require that the mirrors and metal mounts be matched closely in Coefficient of Thermal Expansion. Research done by the KIRMOS team indicated that Pyrex and fused silica could be glued to Invar if done carefully, and this would be stable (Echols).

At this time the parts are being fabricated by the Physics Machine Shop and should be ready for test on the BICEP mount in early October.

REFERENCES

Hu, W. and White, M. 1997, New Astronomy, 2, 323

Echols, C. "Kirmos Adhesive Qualification Tets" http://www.astro.caltech.edu/oir/kirmos/

This 2-column preprint was prepared with the AAS LaTeX macros v5.2.

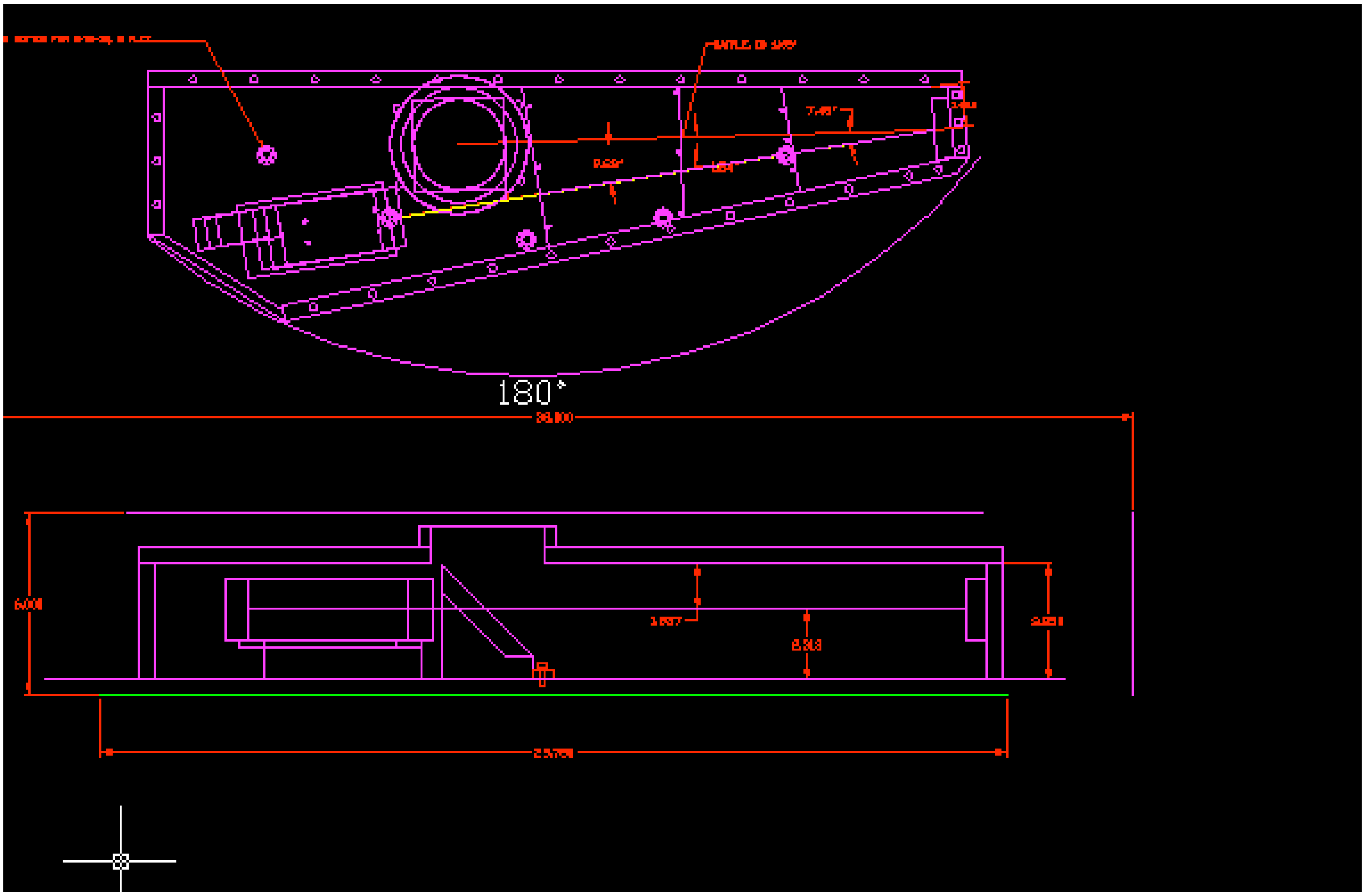

Fig. 1.— Layout for BICEP Optical Camerafig1