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Determining the Alignment of HiRes Optics Using a CCD Camera.

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Abstract. The pointing direction of each HiRes mirror and photomultiplier tube cluster was determined using a CCD camera to record the images of stars projected onto the cluster by the mirror. The precision of the technique is limited by the image quality and the exposure time; we estimate a precision of 1–2 minutes of arc for most of our measurements. Using our 4 m^2 mirrors with a field of view of 220 square degrees and a 4 second exposure time, we were sensitive to stars down to fifth magnitude.

1 Introduction

For HiRes to be able to reconstruct the position and direction of extensive air showers, we must have a good knowledge of the direction each mirror is pointing and what part of the sky each photomultiplier tube (PMT) sees. While each mirror and PMT cluster was surveyed in place as they were installed, one would like to corroborate this survey with another measurement with different systematic uncertainties. We chose to capture the images of stars on the face of the cluster box with a CCD camera, using the known time to map the position on the cluster box, and hence each PMT, to a given direction in the sky.

Our task was complicated by the fact that the cluster boxes are slightly in front of the focal plane of the mirrors and that the mirrors are spherical rather than parabolic. Thus, the light from a star was spread over a fairly large number of CCD pixels making it difficult to pick out stars from background light and to find the "center" of the star. Nonetheless, with each PMT viewing about one square degree of the sky, arc-second accuracy is not necessary, and we did achieve arc-minute accuracy.

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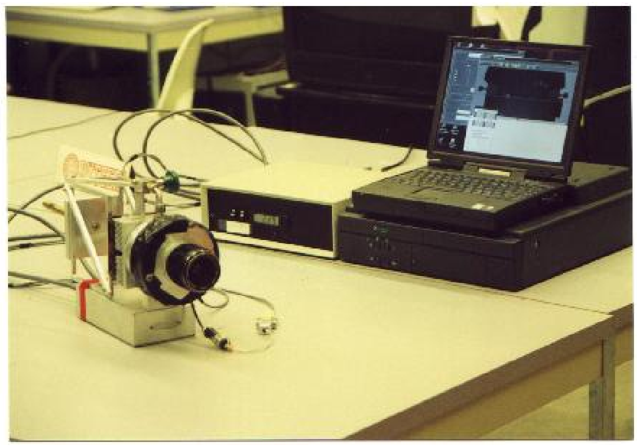

Fig. 1. A picture of the CCD camera showing the camera, lens mount and electronics. Behind the camera is the power supply (left) and data acquisition computer (lap-top and docking station, right).

2 The Camera

We borrowed the CCD camera, which had been built at Rutgers for other purposes and we were fortunate to be able to use it for these measurements. The camera consisted of the CCD chip itself, a vacuum housing, a cooling fan, the shutter, the lens and some controlling electronics. A picture of the camera and associated electronics is shown in figure 1.

The CCD chip had an array of 1184×330, back illuminated pixels, originally meant for use as a spectrometer on an optical telescope. With our roughly square PMT clusters, we only used about half of the pixels. The CCD chip was thermoelectrically cooled to reduce electronic noise. Light entering the camera was focused onto the CCD plane by a standard wide-angle (35 mm) SLR camera lens. Between the lens and the CCD plane was an electronically controlled shutter.

There were two other devices associated with the camera, the power supply for the thermoelectric cooling and the data

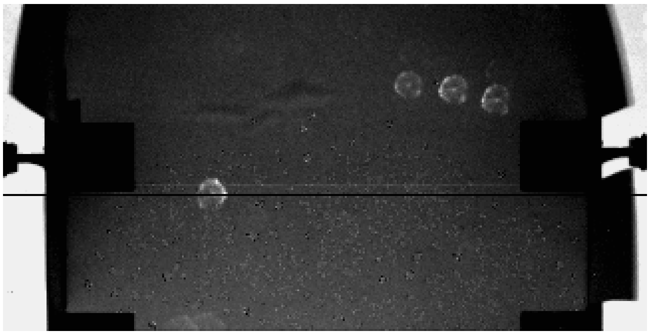

Fig. 2. A picture taken by the CCD camera. The stars on the screen come from the constellation Orion. At the upper-right are the three stars of the "belt". At the center-left is γ Orionis, the "left shoulder". The holes in the screen are clearly visible, and the PMT edges could be made out by changing the brightness and contrast of the picture.

acquisition computer. The data acquisition computer was a Windows PC lap-top with a docking station for the CCD interface card. CCD exposure, shutter control and CCD readout were handled by a specially written program running on this computer.

3 The Pictures and Analysis

The camera was mounted on a post which fit into a socket at the center of each mirror, with the camera focal plane approximately 200 cm from the PMT cluster. Two exposures of four seconds each were taken of each PMT cluster, one with and one without a screen in front of the PMT's. The screen was cut from a standard projection screen roll with optimized reflection normal to its surface. The screen had holes cut into it to allow one to see a few PMT's even when the screen was in place. This allowed for a mapping between the PMT's and a elevation-azimuth coordinate system deduced from the star images.

Because the PMT plane was slightly in front of the focal plane of the mirror, stars were not perfectly focused. This offset was intentional and designed to equalize spot sizes across the face of the cluster. With the spacing between the camera and the PMT plane, this turned out to be a circle of about 25 pixels in diameter. The center of each star image was found by eye from an on-screen display. By repeatedly measuring the same star image, it was determined that the center could be consistently picked to about one pixel. We did not try to fit the image because of the complicated shape of the image. A sample picture showing a portion of the constellation Orion is shown in figure 2.

With three or more stars in a picture, a model consisting of the pointing direction of the center of the PMT cluster, the angle of the CCD camera with respect to the PMT cluster and the scale size of each pixel in degrees could be overconstrained. Each star in a given image was assigned to a celestial object whose azimuthal and elevation angles at the time of the exposure were known. Then, the distance between the expected position and the observed position, in pixels, was minimized to determine the parameters of the model.

This model related pixel coordinates to azimuthal and elevation angles on the sky. Since we could also see several of the PMT's in the same image, we used the model to determine where on the sky these tubes were viewing. The viewing angles of obscured tubes were inferred by interpolation.

4 Results and Conclusion

Interpreting the squared distance of the expected and observed positions of stars in the CCD pixel plane as a χ^2, we find that we can determine the pointing direction of the center of our PMT clusters to about two arc-minutes. This is reasonable given the quality of the stellar images we were measuring and our four second exposure time (which corresponds to one arc-minute of motion across our fixed telescope).

While we are grateful to have had a ready-made CCD camera in hand to use, commercial systems for amateur astronomical use are also available.

We were limited in this survey by the ability to pick out stars over the background level in the CCD. In a system where the stars could be imaged closer to the focal plane, we would have been able to pick out much fainter stars. In addition, we used minimal baffling and shielding either of the camera lens or the projection screen. Adding these would help to lower the background level of the CCD images.

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We would also like to thank Ted Williams and Chuck Joseph of Rutgers University for allowing us to use their CCD camera and for helping us to get it working; and Al Vogel of Dugway Proving Grounds for accompanying us through the long nights of viewing.