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ABSTRACT:

The image-sharpening telescope described in the preceding article was installed and operated on equatorial mounts at both Leuschner Observatory and Lick Observatory. We present measurements of the characteristic speckle change times for stars observed at these locations. We also present sharpened images of Sirius and Arcturus.

I. INTRODUCTION

In the preceding article[1], we described an image-sharpening telescope and its initial tests using laser light and white light viewed horizontally through 250 meters of turbulent atmosphere. Here we describe the performance of the apparatus as installed on equatorial mounts at both Leuschner Observatory in Lafayette, California, and Lick Observatory at Mount Hamilton, California. At both locations we encountered angular "seeing" discs of about the expected size (3 to 5 sec of arc for Leuschner, 1.5 to 5 sec of arc for Lick), but with characteristic speckle change times that were usually shorter than the minimum correctable time for our apparatus. As described in the preceding article, the apparatus must cycle through the six phase-correcting mirrors about three times in order to produce a reasonably well-corrected image. During a single cycle, typically 0.3 msec is used carrying out the steps listed in Table I of the previous article, 1.5 msec is used moving and replacing the mirrors, and 1.1 msec is used integrating photoelectrons for the sharpness decision to replace the moved mirrors. Of these three times, only the last is a fundamental limitation, and even this could be substantially reduced by improving the efficiency of the apparatus. In spite of the short speckle change times encountered, however, we were able to record dramatically improved stellar images on nights when the speckles changed relatively slowly.

II. CHARACTERISTIC STELLAR SPECKLE CHANGE TIMES

As described in the previous article, the image we obtain with our apparatus has an autocorrelation function $A(\tau)$ given by

$$A(\tau) = \int_0^T dt\, I(t)\cdot I(t+\tau), \qquad (1)$$

where $I(t)$ is the signal observed by the sharpness-defining photomultiplier S_1. $A(\tau)$ decreases for $\tau > 0$ as the speckles move and change at the sharpness slit.

We define the characteristic speckle change time to be that value $\tau_{1/2}$ for which $A(\tau)$ has dropped to half. We had originally expected $\tau_{1/2}$ to be typically 20 milliseconds[2], but found the values at both observatories to be substantially shorter than this. Figure 1 presents the observed distributions of $\tau_{1/2}$, where all measurements for a given night have been averaged together. Although Lick is somewhat better than Leuschner, both locations usually have speckle change times that are too short for an instrument which requires typically 10 msec to correct the image. Nevertheless, when the feedback for image sharpening was turned on and the characteristic $\tau_{1/2}$ was longer than 7 or 8 msec, it was possible to observe significant image sharpening in the eyepiece.

We found $\tau_{1/2}$ generally fluctuates by a wide range on a time scale of seconds. Averaged over several minutes, its mean value still might vary by a factor of two with a time constant of several hours. No strong dependence on color or on zenith angle out to 60^o was observed. Surface winds in excess of 20 mph were generally associated with small values of $\tau_{1/2}$.

III. SHARPENING STELLAR IMAGES

We first observed stellar image sharpening at Leuschner Observatory on 21 January 1976, when $\tau_{1/2}$ was between 11 and 12 msec. Figure 2 shows the image of Sirius recorded that night. Observation at the eyepiece showed that successful image sharpening was taking place about 1/3 of the time. A narrow peak, whose width is close to the diffraction limit of the telescope, rides upon an uncorrected background. To our knowledge, this is the first time image sharpening has been used to produce a diffraction-limited stellar image.

To help remove the background under the diffraction-limited image, we installed a gate circuit which allows image data to be recorded only when the measured image sharpness exceeds a preset value. After the gate circuit was available, we became discouraged waiting at Leuschner for another night as good as 21 January. We therefore arranged to move the equipment to Lick Observatory, where we hoped longer values of $\tau_{1/2}$ would be more common.

Figure 3 presents images of Arcturus recorded with and without the gate on the night of 13-14 July, 1976 at Lick. The uncorrected image (figure 3a) is quite broad and is typical of the type of image recorded without phase correction feedback at both observatories. Feedback alone produced significant image sharpening as shown in figure 3b, but the peak is not as narrow as achieved earlier with Sirius (figure 2). The gate was subsequently set to allow data recording only during the 5 to 10% of the time that the sharpness value was twice its typical value. The gated image (figure 3c) is dramatically improved over the 4 to 5 arc sec uncorrected seeing disc. Although the 0.6 arc sec full-width-at-halfmaximum of the corrected image is somewhat larger than the 0.4 arc sec width expected for a diffraction-limited image, we feel the results presented in figures 2 and 3 clearly demonstrate the feasibility of our image-sharpening system. We have not, of course, resolved any features of Sirius or Arcturus, whose total angular extent is expected to be much less than the diffraction-limited resolution of this telescope.

We are currently improving the efficiency of the system to enable observation of dimmer stars, and are speeding up the electronics so diffraction-limited performance can be achieved with speckle change times less than 10 msec. For a system limited by photoelectron statistics and not by mirror cycle time, the dimmest correctable object should still be within a magnitude or so of the limit indicated in the preceding article.

IV. ACKNOWLEDGEMENTS

The rapid progress in moving from fixed horizontal-path measurements to stellar observations would have been impossible had it not been for the enthusiastic cooperation of L.V. Kuhi, T. Forster, and the staff of the Astronomy Department of the University of California at Berkeley, and of M.L. Walker, R. Stone, R. Laub, and D. McKenna of Lick Observatory, University of California at Santa Cruz. S.M. Pollaine helped with the final data analysis and he and T.S. Mast helped with preparation of this manuscript. We are pleased with the continuing interest of L.W. Alvarez, R.W. Birge, P.B. Boyce, D.D. Cudaback, J.E. Nelson, A.G. Opp, D.E. Osterbrock, and E.J. Wampler. This work was supported by the Energy Research and Development Administration, and by the National Aeronautics and Space Administration (grant NGR-05-003-553).

V. REFERENCES

(1) "Correction of Atmospheric Distortion with an Image-Sharpening Telescope", A. Buffington, F.S. Crawford, R.A. Muller, A.J. Schwemin, and R.G. Smits, Journal of the Optical Society of America, the preceding article.

(2) R.A. Muller and A. Buffington, J. Opt. Soc. Am. 64, 1200 (1974).

FIGURE CAPTIONS

FIGURE 1. Observed distributions of characteristic speckle change times at (a) Leuschner and (b) Lick Observatories. All measurements during a night have been averaged together.

FIGURE 2. Images of Sirius recorded at Leuschner Observatory on the evening of 21 January 1976. The typical value of $\tau_{1/2}$ was 11 to 12 msec. The two curves are normalized to the same area.

FIGURE 3. Images of Arcturus recorded at Lick Observatory on the night of 13-14 July 1976. The typical value of $\tau_{1/2}$ was 10 msec. In (c) the gate threshold was set at twice the average feedback-ON sharpness and allowed data recording during the best 5 to 10% of the time. To simulate the averaging effect of a long exposure, the above curves were smoothed by eye with resolution functions of widths ~1/2, 1/10, 1/10 arc sec respectively.

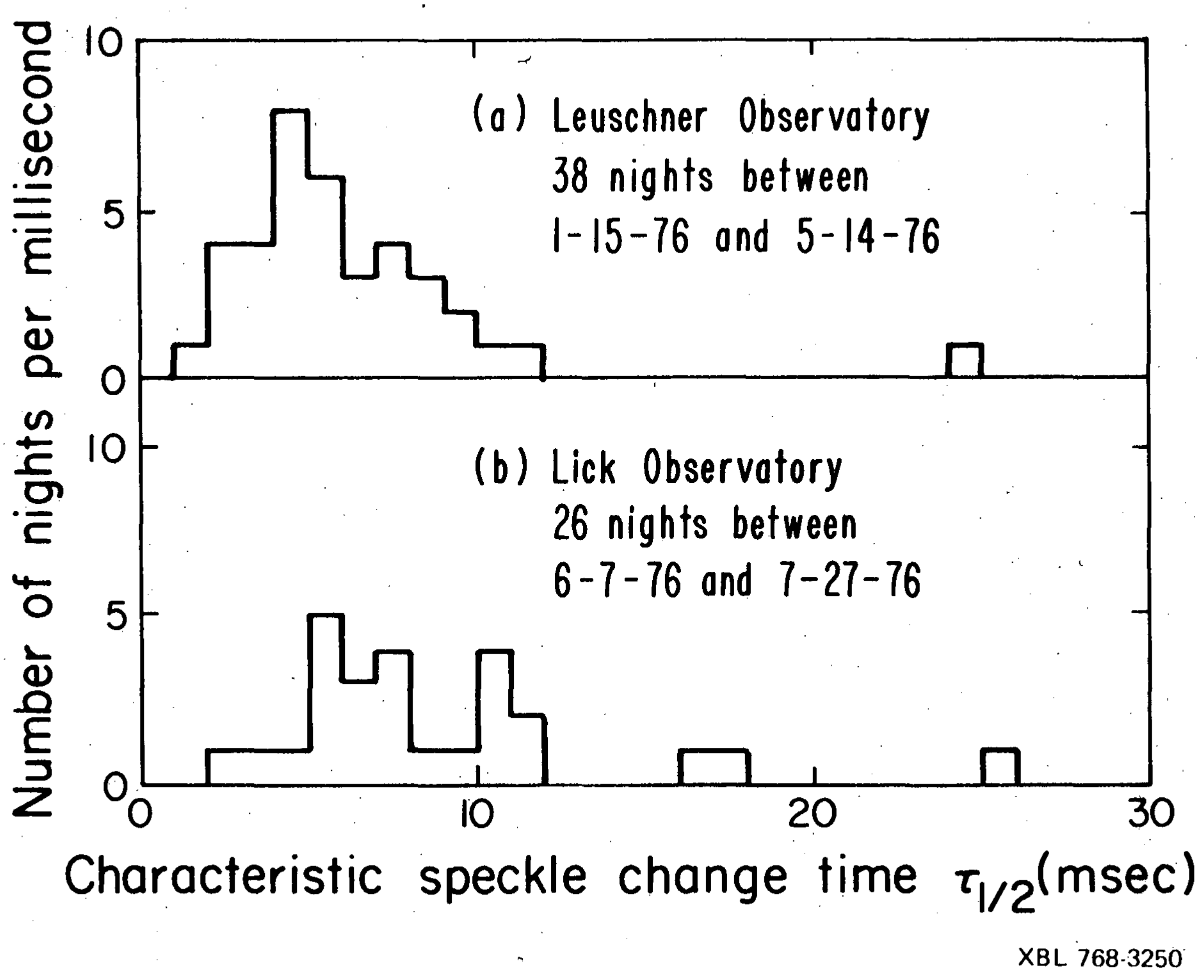
Number of nights per millisecond
10
5
0
(a) Leuschner Observatory
38 nights between
1-15-76 and 5-14-76
10
5
0
(b) Lick Observatory
26 nights between
6-7-76 and 7-27-76
0
10
20
30
Characteristic speckle change time $\tau_{1/2}$(msec)
XBL 768-3250

Fig. 1

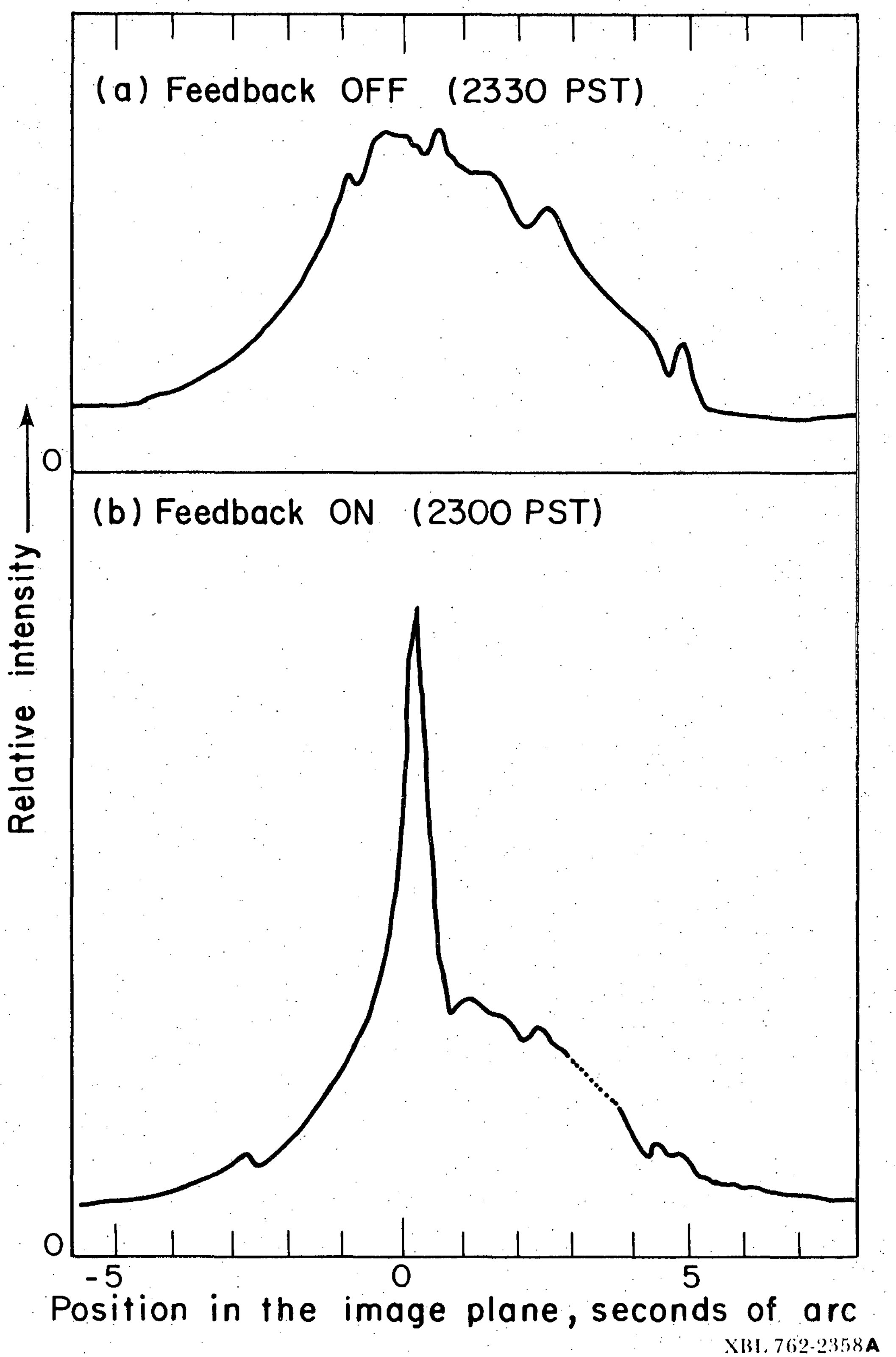
(a) Feedback OFF (2330 PST)
(b) Feedback ON (2300 PST)
Relative intensity
0
0
-5
0
5
Position in the image plane, seconds of arc
XBL 762-2358A

Fig. 2

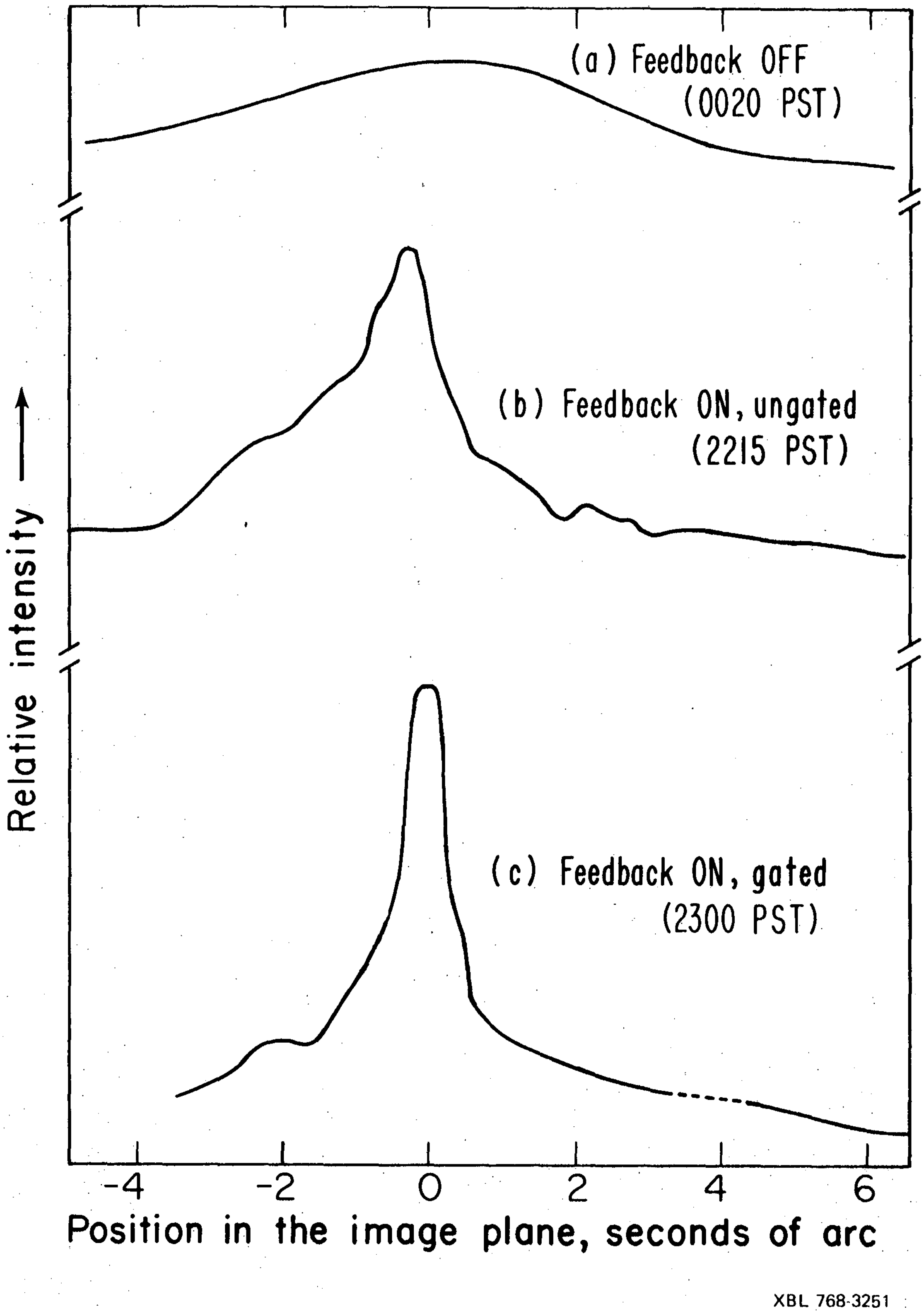
(a) Feedback OFF
(0020 PST)
(b) Feedback ON, ungated
(2215 PST)
(c) Feedback ON, gated
(2300 PST)
Relative intensity
-4
-2
0
2
4
6
Position in the image plane, seconds of arc
XBL 768-3251

Fig. 3

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