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SHARPENING STELLAR IMAGES

Real-time phase correction has permitted a ground based astronomical telescope to overcome atmospheric distortion.

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> *If the Theory of making Telescopes could at length be fully brought into Practice, yet there would be certain Bounds beyond which Telescopes could not perform. For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by the tremulous Motion of Shadows cast from high Towers, and by the twinkling of the fix'd Stars. But these Stars do not twinkle when viewed through Telescopes which have large apertures. For the Rays of Light which pass through divers parts of the aperture, tremble each of them apart, and by means of their various and sometimes contrary Tremors, fall at one and the same time upon different points in the bottom of the Eye, and their trembling Motions are too quick and confused to be perceived severally. And all these illuminated Points constitute one broad lucid Point, composed of those many trembling Points confused and insensibly mixed with one another by very short and swift Tremors, and thereby cause the Star to appear broader than it is, and without any trembling of the whole. Long Telescopes may cause Objects to appear brighter and larger than short ones can do, but they cannot be so formed as to take away that confusion of the Rays which arises from the Tremors of the Atmosphere. The only Remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds.*
>
> Sir Isaac Newton[1]

In the 250 years since these words were written, astronomers have been able to find neither a more succinct description of the "seeing" nor, until recently, a "Remedy" other than the one suggested by Newton. The speckled images of distant stars result directly from phase perturbations caused by propagation of the light through inhomogeneities in the atmosphere. The scintillation (intensity fluctuations) perceived by the eye as twinkling results from interference which also develops as the perturbed wave propagates down through the atmosphere. However, the image quality is primarily degraded by the phase perturbations rather than the amplitude variations. A time exposure averages together the speckles, yielding a blurred image whose size depends on the observatory location and the particular turbulence at the time. At most observatory locations, however, this image size is seldom less than one second of arc. Thus, the resolving power of large telescopes is no better than that achieved by a mere 10 cm aperture; larger telescopes simply gather more light for observing dimmer objects.

A number of methods have been employed which partially overcome this seeing limitation. Interferometer techniques were introduced by Michelson and Pease.[2] Intensity interferometry was invented and developed by Hanbury Brown and Twiss.[3] Speckle interferometry was developed by Labeyrie and co-workers,[4] and has recently yielded several newly separated binary star systems, and refined the measurements on others.[5] Knox and Thompson have suggested a method to extend speckle interferometry to non-symmetrical objects.[6] Their suggestion has been successfully simulated at Itek Corporation[7] and used to reconstruct solar features.[8] T. Brown has recently suggested a method which allows post-detection image retrieval through the use of non-redundant-array apodizing of the telescope aperture.[9] These techniques all require a narrow wavelength bandpass in recording the image, and the more powerful of them also require considerable computing for each image.

H. Babcock first suggested a system which could provide real-time correction of astronomical images.[10] He proposed that an active corrector plate be introduced into the telescope optics to compensate for the changing atmospheric phase shifts. In order to determine the amount of correction to apply to a given region of the telescope objective, he suggested performing a knife-edge test on each portion of the objective, using an unresolved nearby bright star as the light source. Unfortunately, practical atmospheric time constants and spatial distributions require that this nearby star be quite bright and not very far removed in angle from the objects under study. Such nearby stars are rare, and Babcock's scheme has never been used.

It now appears that real-time correction of astronomical telescope images is feasible, without the need for a nearby guide star.[11-13] In particular, if one defines an image-plane sharpness properly, this sharpness has been shown to reach an absolute maximum only when the atmospheric phase perturbations have been removed. The sharpness measurement, then, is a suitable source of feedback to the active, phase-shifting elements of the corrector plate. We have shown that such feedback causes rapid convergence to the true restored image.

A wide variety of suitable sharpness functions are available. Computer simulations and formal proofs have been carried out for several of these.[13] A selection of particularly useful functions is

$$S_1 = \int I^2(x,y)\,dx\,dy \qquad ,(1)$$

$$S_2 = I(x_o,y_o), \text{ the intensity at a single image point } (x_o,y_o) \qquad ,(2)$$

$$S_3 = \int I(x,y)\,M(x,y)\,dx\,dy \qquad ,(3)$$

$$S_4 = \int \left|\frac{\partial^{n+m} I(x,y)}{\partial x^n\,\partial y^m}\right|^2 dx\,dy \qquad ,(4)$$

$$S_5 = \int I^n(x,y)\,dx\,dy,\ n > 1 \qquad ,(5)$$

where (x,y) are image-plane coordinates, I(x,y) denotes image plane intensity, and M(x,y) is a mask which approximates the true restored image. In choosing an appropriate sharpness function for practical applications, one must consider both the ease with which the sharpness can be measured, and the type of object to be studied. For the simple case of a single unresolved star, perhaps with dim companions or structure nearby, or an object with a single bright "glint" on it, S_2 would probably be the best choice, since a single photomultiplier provides the measurements when placed behind an image-plane mask pierced by a hole the size of a diffraction-limited image. For a complicated object such as a tumbling asteroid or satellite, S_1 would probably be optimum although its use might require some difficult image-plane data processing. To view a planet, one would probably use a function of the type S_4, in which the sharpness of the edge of the planet drives the feedback. The rings of Saturn might be best recorded with a variant of S_3, however. One would use the best available Saturn photograph to generate a starting M(x,y), but then update the mask with newly sharpened images as they are recorded. These sharpness functions are successful because they single out some feature of the object which is known to be a maximum with the undistorted image, and use the amount of the feature present to provide a measure of the distortion.

In the last few years there has been considerable interest in real-time image correction. A number of groups are now actively engaged in constructing and testing telescope systems which put these new ideas into practice.[14-16] This article describes the results achieved with a prototype 1-dimensional system which uses a sharpness function of the type S_2 to determine the appropriate phase corrections for six adjustable mirrors.

APPARATUS

In this section we give a brief description of the design, calibration, and test of our apparatus; details have been published elsewhere.[16] Figure 1 shows a schematic diagram of the image sharpening system, and figure 2 shows the mechanical layout of the apparatus. This first telescope was designed to be as simple as possible, yet have a resolution fine enough to be capable of interesting astronomical measurements, such as the separation of double stars. It employs a 32 cm diameter primary mirror with an entrance aperture 30 cm x 5 cm, divided into six separately adjustable squares. The 2.5 m focal length primary focuses the incident light immediately in front of the projection lens. The light path is folded by two diagonal mirrors on its way to the primary image. The first diagonal mirror is mounted on three piezoelectric columns which allow steering of the image. The second diagonal mirror consists of six independently moveable elements which can change the optical pathlength of light passing through the six entrance-aperture squares by ±2.5 microns. The projection lens makes an enlarged image on a slit in front of the sharpness-defining photomultiplier PM-1, which measures sharpness of the type S_2. A bimetal strip system automatically keeps this projection lens properly focused as temperature changes occur. A portion of the light is diverted to the image-recording photomultiplier PM-2 with its slit. The image is moved across the slit either by mechanically translating the PM-2 assembly or by displacing the image by transmission through a rotating cube (not shown in the figure) placed between the beam splitter and the PM-2 slit. The balance of the light <u>not</u> passing through PM-1's slit is detected by photomultipliers PM-3 and PM-4 and is used to drive the first diagonal mirror at rates $\lesssim$50 Hz to keep the image centered on the sharpness-defining slit.

The 30 cm x 5 cm aperture, when corrected, has six times better resolution in one direction than the other. Rather than attempt to utilize the image information in the direction of poorer resolution, we have integrated over this direction by using slits both to define the sharpness and to record the image. Since we expect to use this instrument primarily for objects which consist of a few unresolvable bright points, the one-dimensionality of the recorded images is not detrimental. Our computer simulations[13] have shown that no fundamental difficulty stands in the way of making two-dimensional image-sharpening systems; the choice of one-dimensional imaging for this apparatus came primarily from the desire to keep the design simple.

The measurement of S_2 is given by the current from PM-1. This provides the feedback to drive the independently moveable mirrors making up the second diagonal. The six mirrors move as pistons perpendicular to their common plane. The method of making this "flexible mirror" and the alignment procedures which guarantee coplanarity of the six elements have been described previously.[16] The electronics providing the feedback link between PM-1 and the moveable mirrors is shown schematically in figure 3, along with the steering and data-recording systems. The program logic causes the mirror logic to introduce a small perturbation (typically 0.05 to 0.10 micron) into the position of one of the six moveable mirrors. The comparator determines whether this perturbation increased the sharpness reading in PM-1. If it did, the perturbation is left in place; otherwise it is removed. The circuits cycle through each of the six mirrors in turn, continually building up the value of S_2 through successful introduction of perturbations. Opposite signs of perturbation are used on successive passes through the mirrors, to prevent the adjustments from eventually working the mirror motions to the extremes of their ranges.

The length of time the system takes to pass through a complete cycle of six mirror adjustments depends on the integration time chosen for the comparator to decide whether to replace a perturbed mirror. The integration time can be less than 0.1 msec for many of the brightest stars in the sky, but has to be several milliseconds for a typical fifth magnitude star, in order that photoelectron statistical fluctuations not confuse the decisions. The cycle time can be varied from a minimum of about one msec (the time it takes to perturb six mirrors and replace on the average half of them) to about 30 msec, depending on the integration time selected. It takes about three cycles through the mirrors to produce an adequately sharpened image.

The apparatus was first tested with laser light viewed horizontally along a 250 m path. Figure 4 shows the result on a day when the atmosphere had spread the image to about 3 arc sec, but the speckle change time was quite long. The recorded and expected images are in good agreement. The wings of the diffraction pattern are about half due to the expected pattern in the absence of any atmospheric perturbation, and half due to residual errors because the incident phasefront was corrected by six discontinuous pistons rather than a smoothly deformable mirror. The series of bumps on either side of the main diffraction peak, at multiples of 2.6 arc sec, are caused by the regularly spaced gaps between the six moveable mirrors.

The rapidity of the speckle changes at the sharpness slit determines the dimmest object that can be corrected by this system. A measure of the speckle change time is given by

$$A(\tau) = \int_0^T dt\, I(t)\cdot I(t+\tau) \quad , \quad (6)$$

where I(t) is the current from PM-1 with feedback off. The integral is performed by a Hewlett-Packard Correlator Model 3721A, with $T >> \tau$ and A(0) normalized to unity. We define the characteristic coherence time τ_c to be the value for which $A(\tau)$ has dropped to half of A(0). For the horizontal-path tests, τ_c varied from several milliseconds to nearly 100 milliseconds. Since $A(\tau)$ gives the time structure for speckles drifting and changing at the sharpness slit, τ_c is an indication of how rapidly the phase adjustments must be completed in order to achieve a corrected image. We have found empirically, for perturbations of 1/5 to 1/10 wavelength, that the system must be able to complete about three cycles through the six mirrors within τ_c in order to achieve a well-corrected image. Thus the measurement of a particular τ_c at some observing location and time determines the maximum permissible length of the electronics cycle time, and hence the longest permissible sharpness integration time. This integration time in turn determines the dimmest correctable object limited by photon statistics. The integration adjustment for our instrument, from 10 microseconds to 4 milliseconds, matches the shortest possible integration time for the brightest star in the sky, and the longest coherence time (50 to 100 msec) we thought might ever be encountered at observatories. We have used this instrument to measure the coherence time τ_c at our laboratory site in Berkeley, at nearby Leuschner Observatory, at Lick Observatory on Mt. Hamilton, and at Hale Observatory on Mt. Wilson. Figure 5 shows the distributions.

Since seeing conditions frequently vary with time, we found it important to gate the image-recording system using the sharpness signal from PM-1. The gate circuit permits recording the image only when the measured sharpness in PM-1 exceeds a preset value. Thus when τ_c suddenly deteriorates to a small value, and then slowly recovers, the data recording is switched off until the image sharpening system is again able to "keep up" with the speckle changes, as indicated by a return to large signals detected in PM-1.

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The apparatus has been operated attached to other telescopes at Leuschner and Lick Observatories, and with its own equatorial mount at the Lawrence Berkeley Laboratory and at Mt. Wilson Observatory. Some of the earlier results have already been reported.[17] Figure 6 shows the first sharpened stellar image obtained with this apparatus. The image-recording gate was not available at the date of this image; based on subsequent experience with the gate, it would have reduced the underlying background in figure 6b. The peak riding upon the background is nearly diffraction limited for this size of telescope. To our knowledge, this is the first time that image sharpening has succeeded in producing a diffraction limited stellar image.

Figure 7 shows other images, taken more recently at Mt. Wilson Observatory, with the gate operational and using the rotating cube system for image recording. This figure demonstrates the ability of the gate to reduce the background of the ungated curve, although this background was less severe than it was on the image in figure 6b. One might wonder whether the gate alone could allow recording of a good image like that of figure 7c, without needing the image sharpening provided by the moveable mirrors. In principle this might be the case since the gate could detect those moments when the seeing permitted a diffraction-limited image and placed it upon the PM-1 slit. However, when we tried using the gate alone, the resulting images were substantially broader than those achieved with the full image sharpening in operation. A gate-only system might be successful, however, if the seeing were such that it primarily moved the image from side to side rather than disrupting it into speckles.

Figure 8 shows double star images. The brighter of the two stars (the left hand one) was placed on the sharpness-defining slit, and the steering circuit was biased to keep the image centered that way. It is clear that the pair of stars is much better resolved by this system than it could have been without image sharpening. Figure 8 also shows, at the Mt. Wilson Observatory site where it was recorded, that most of the "seeing" perturbations on that night did not originate high in the atmosphere, since there is little discernible shape difference between the two peaks. Had all of the phase perturbations originated further away than 5 km from the telescope, we would expect the second peak to be completely degraded relative to the first, because light from the two different stars passed through different atmosphere on its way to each of the segments of the telescope mirror. The lack of discernible shape difference between the two peaks indicates that the bulk of the phase perturbations originated within 2 km of the telescope.

DISCUSSION

The apparatus described in this article was matched for seeing with a characteristic angular size of several arc seconds. For uncorrected images of this size and somewhat larger we have shown that dramatic improvement results when image sharpening is applied. Such improvement holds the promise of better resolving power at existing observatories, allowing both discernment of finer details, and use of narrower slits in spectrometers without the loss of light. For multiple star systems, this would allow separate spectral measurements with the individual stars. If the seeing is much worse than several arc seconds, diffraction-limited performance is no longer achieved and a large uncorrected background results, rather like the ungated images shown in figures 6b and 7b. Gating cannot remove this background since it is caused by phase changes in the incident wave front of much more than a radian within a single moveable mirror. The acceptable size of seeing disk that a given system can correct depends on the particular type of measurement one wants to perform; for a close (but still resolvable) pair of stars with comparable intensities, the presence of the two peaks could still be seen above the background. On the other hand, for resolving a dim companion star, one may require that the uncorrected background be minimized. In some cases the companion star may be so dim that even absence of any seeing distortion (attainment of the unperturbed diffraction pattern) might not allow resolution, and the presence of the faint star would then have to be inferred through other means.

The telescope simultaneously corrects all light wavelengths, which is vital for spectroscopic applications. In those cases which require maximizing the light through a narrow slit, large tails on the diffraction pattern may not matter at all. Then, use of image sharpening improves the photon flux through the slit as the seeing worsens, until the transverse distance for a radian of phase change becomes significantly smaller than the size of one of the moveable mirrors. For seeing worse than this, diffraction-limited performance is no longer possible, and the amount of light in the central peak diminishes inversely as the diameter of the seeing disc. However, image sharpening can still provide an image whose peak intensity is roughly N times that of the background, where N is the number of mirror segments.

The magnitude of the dimmest objects correctable by this technique is intimately bound up with the particular speckle change time. The apparatus described here would be able to correct objects down to 5th magnitude if τ_c were 25 to 30 msec. If the photon efficiency of the apparatus were maximized, this limit would be improved to 7th or 8th magnitude. The philosophy we have adopted here of moving the mirrors one at a time limits us to a dimmest correctable object whose brightness is proportional to the square of the N moveable elements.[13] This limitation occurs because both the sharpness change produced by moving a single mirror and the time available to do it diminish in proportion to 1/N. Different mirror-moving strategies (moving mirrors in groups or at different frequencies) and different telescope configurations (shearing interferometer or multi-image telescopes) exist, however, which hold the promise of more efficient image correction for dim objects. We presently believe that substantial resolution improvement is probably possible on objects as dim as 9th or 10th magnitude. Many interesting astronomical objects are brighter than this. For example, it should be possible to increase further the number of visually separated binary star systems. A particularly interesting system is μ Cassiopeia, which has been suggested as a means of determining the primordial He abundance.[18] An adaptation of the techniques described here to a somewhat larger telescope aperture (say 1 m) should permit observation of μ Cassiopeia's dim companion, even if the magnitude difference is as great as $\Delta M \approx 5$. Increased telescope angular resolution should also extend substantially the sample of stars whose masses can be determined by their being members of visually separated binary systems.

SUMMARY

Atmospherically induced phase perturbations have for years limited the resolution of large optical astronomical telescopes. A prototype telescope system with six moveable elements has successfully corrected these phase perturbations. This use of real-time image sharpening has restored stellar images to the diffraction limit (in one dimension) for a 30 cm telescope. The double star image presented indicates that the bulk of the atmospherically induced wavefront phase change occurred within 2 kilometers of the telescope. This implies that, at least for conditions similar to those of our measurement, real-time correction can be accomplished simultaneously for a region at least several arc seconds in angular size. With the present apparatus, the technique should be practical for objects as dim as 5th magnitude, and with improvements the technique holds the promise of active image restoration for objects as dim as 10th magnitude.

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19. A. J. Schwemin and R. G. Smits contributed much to the design and construction of the apparatus. The observatory measurements would have been impossible without the enthusiastic support of the Astronomy Department staff at Berkeley, the Lick Observatory staff, and the Mt. Wilson Observatory staff. We are pleased with the continuing interest and support of L.W. Alvarez, H.W. Babcock, R.W. Birge, P.B. Boyce, and D.E. Osterbrock. D.D. Cudaback made several important contributions. We have enjoyed interesting conversations with L.V. Kuhi, J.E. Nelson, J.A. Tyson, G. Wallerstein and E.J. Wampler. This work was supported by the Department of Energy, and by grants from the National Science Foundation and the National Aeronautics and Space Administration.

FIGURE CAPTIONS

Figure 1. Schematic diagram of the image sharpening system. Arrow heads indicate the relative phase of the wave. The adjustable phase shifter corrects the phase of the incoming wave. (from reference 13).

Figure 2. Mechanical layout of the apparatus. The telescope mount (not shown) allows rotation of the entire telescope about the axis of its barrel, thus permitting orientation of the direction of good resolution. (from reference 16).

Figure 3. Block diagram of the electronics. The incident light reflects off the first and second diagonal mirrors and then proceeds to the four photomultipliers. PM-1 is used to define the image sharpness and provide feedback to the six moveable elements of the second diagonal mirror. PM-2 receives a portion of the light to record the image. PM-3 and PM-4 receive the light not passing through the sharpness slit, and drive the first diagonal mirror to keep the image centered upon the sharpness slit. When viewing stars, the average steering correction is fed to the telescope mount drive motor which then corrects the speed of the drive to keep the first diagonal steering centered within its range. This permitted the use of a crude spur gear telescope drive, but nonetheless provided sub-arc-sec stellar tracking. The image is scanned over the PM-2 slit by a rotating cube, which also provides synchronization signals for the image recording system. Image recording is permitted only when the sharpness signal from PM-1 exceeds a preset value.

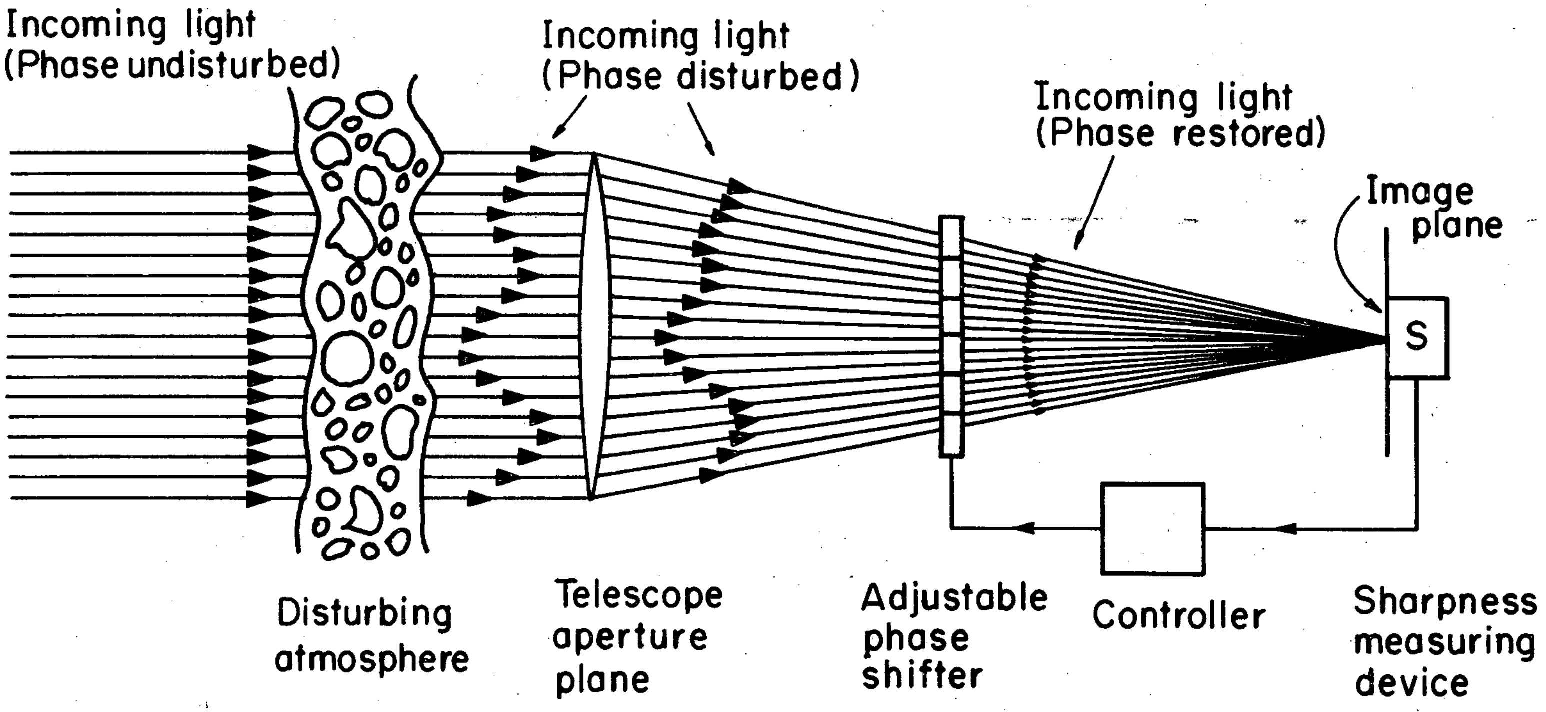
Figure 4. Images of laser light viewed horizontally along 250 m of turbulent atmosphere. (from reference 16).

Figure 5. Characteristic speckle change times at four observatory locations. All measurements during a night have been averaged together. The above data may be misleading because there are seasonal variations in the seeing and the data for the observations were collected at different times of the year. Furthermore, the histogram contains only the average seeing for the night. At Mt. Wilson, in particular, there were nights when τ_c was greater than 15 milliseconds for a substantial portion of the time, but the whole night still averaged less than 10 milliseconds.

Figure 6. Images of Sirius recorded at Leuschner Observatory on the evening of 12 January 1976. (from reference 17).

Figure 7. Images of Capella recorded at Mt. Wilson on 3 November 1977. The gating fraction in (c) was the best 40%. τ_c was about 13 msec for these images. Since two of the moveable elements were inoperative for these images and those of figure 8, the images are for a telescope with an aperture size of 5 x 20 cm and only four moveable elements. The peaks are still close to the diffraction limit for this smaller aperture.

Figure 8. Images of Castor recorded at Mt. Wilson on 3 October 1977. The gating fraction in (b) was the best 50%. The good resolution direction of the telescope was oriented about 50° from the line between the two stars, so the two peaks appear somewhat closer to each other than their actual 2 arc sec separation. τ_c was about 20 msec for these images.



XBL741-2267

Figure 1

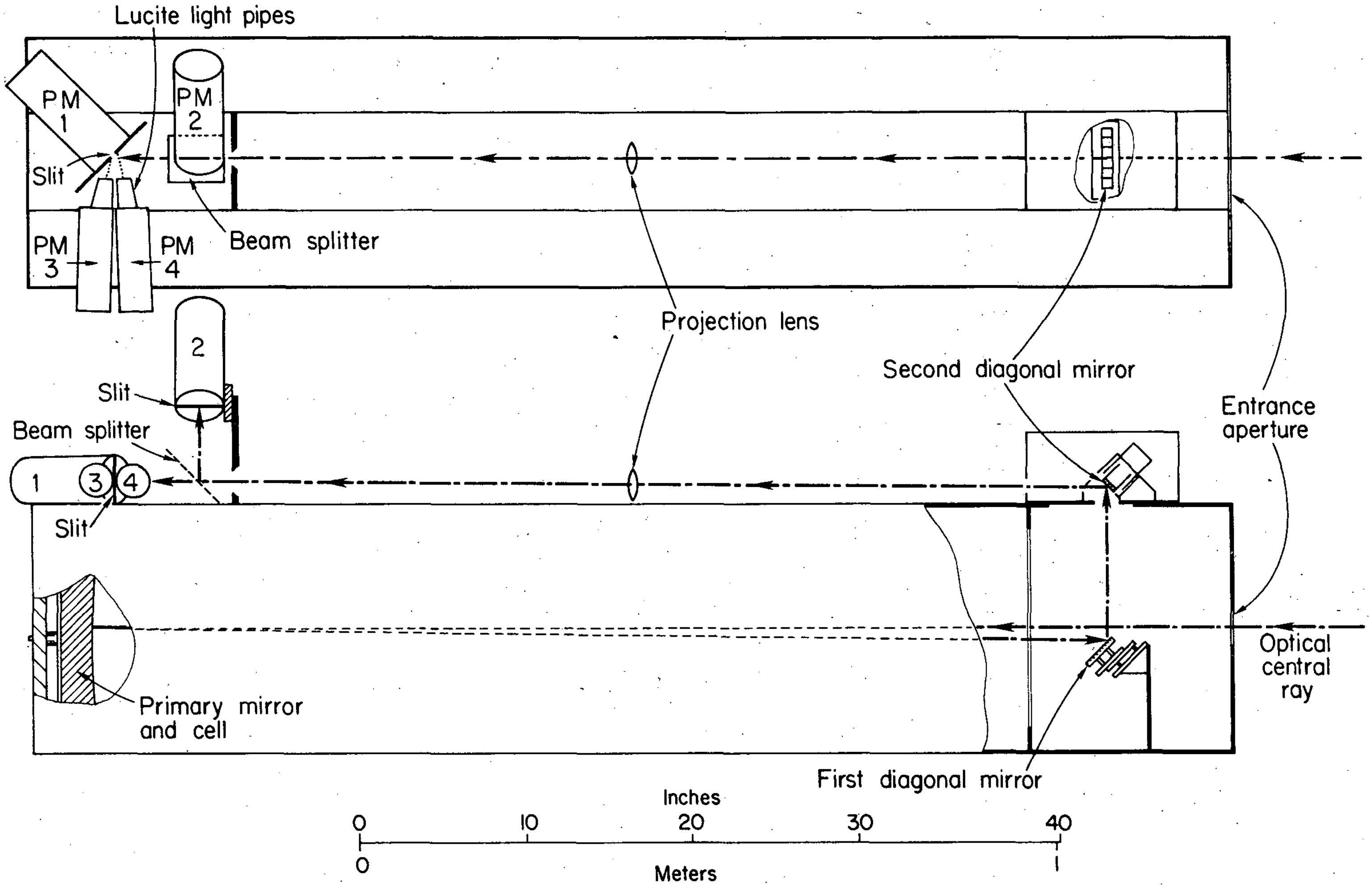


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Figure 2

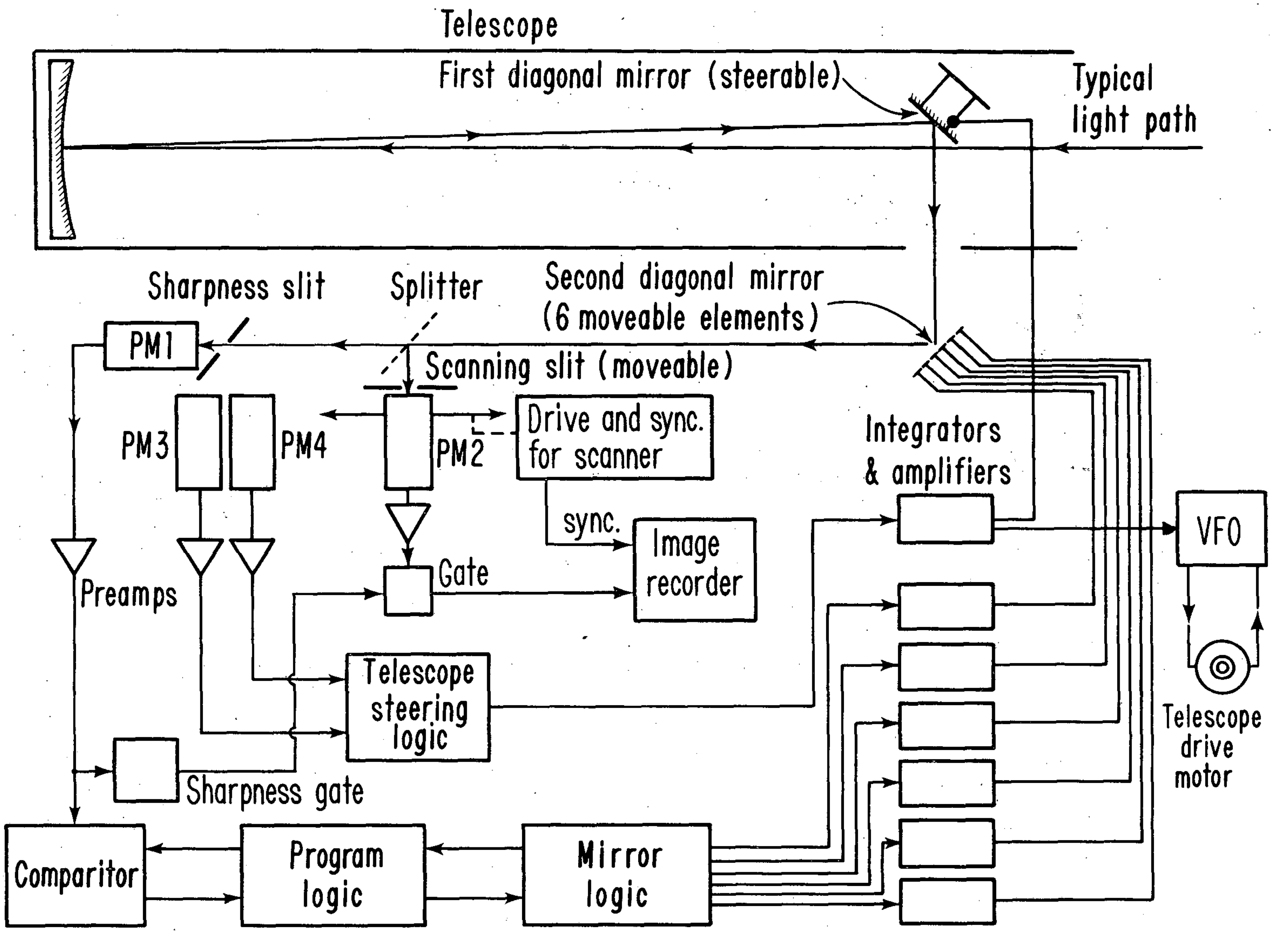

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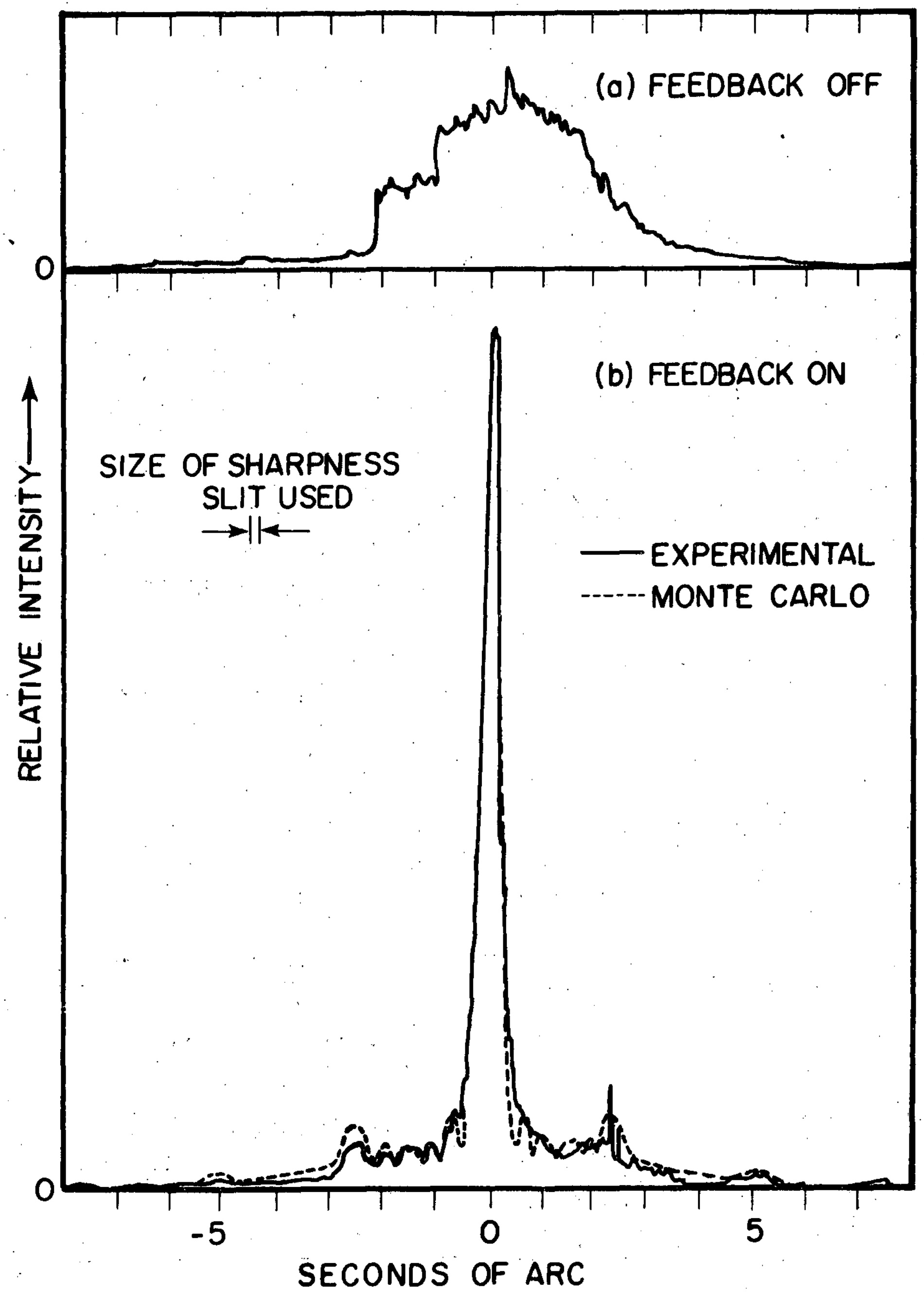
Figure 3



XBL 762-2228

Figure 4

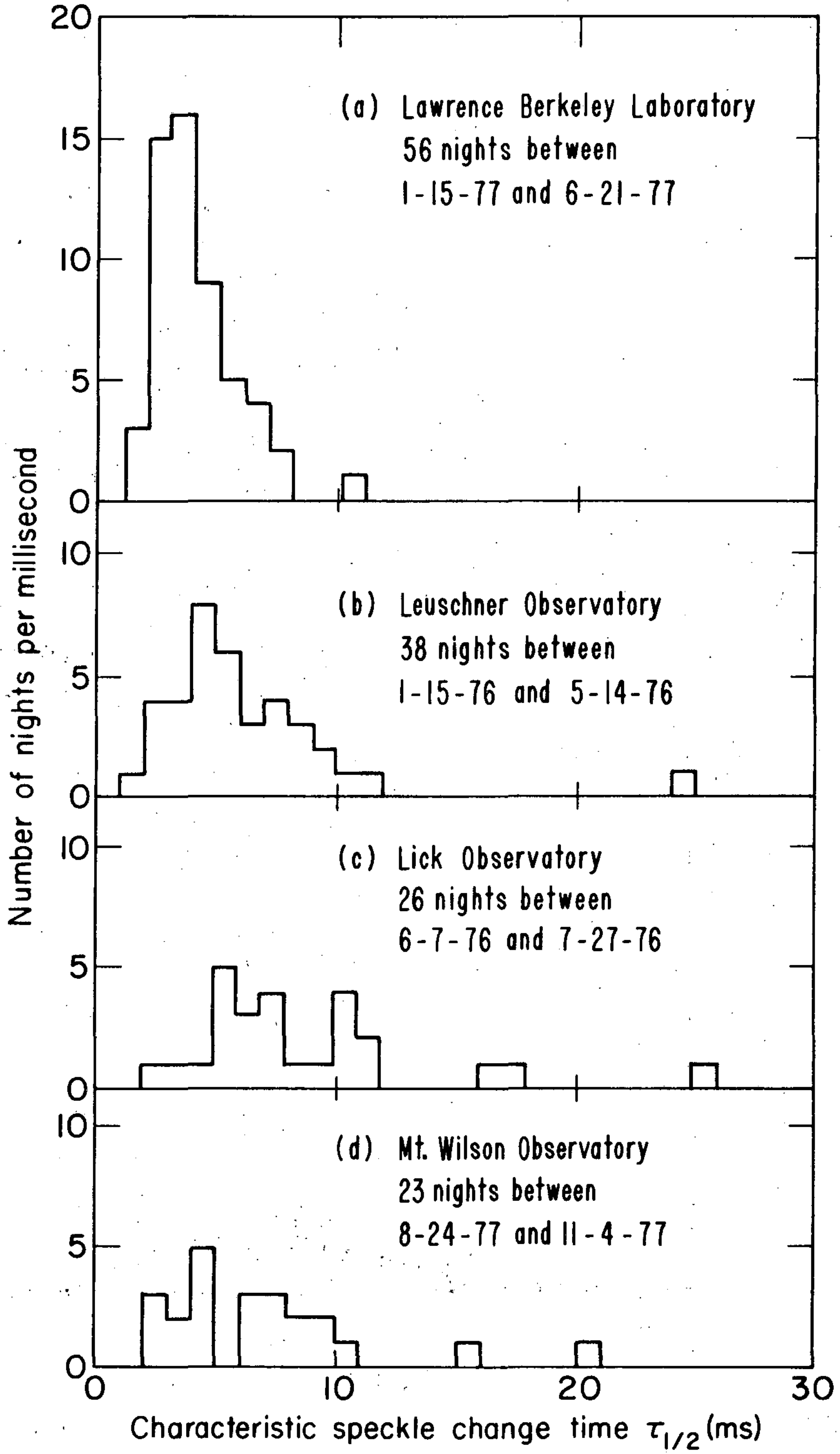


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Figure 5

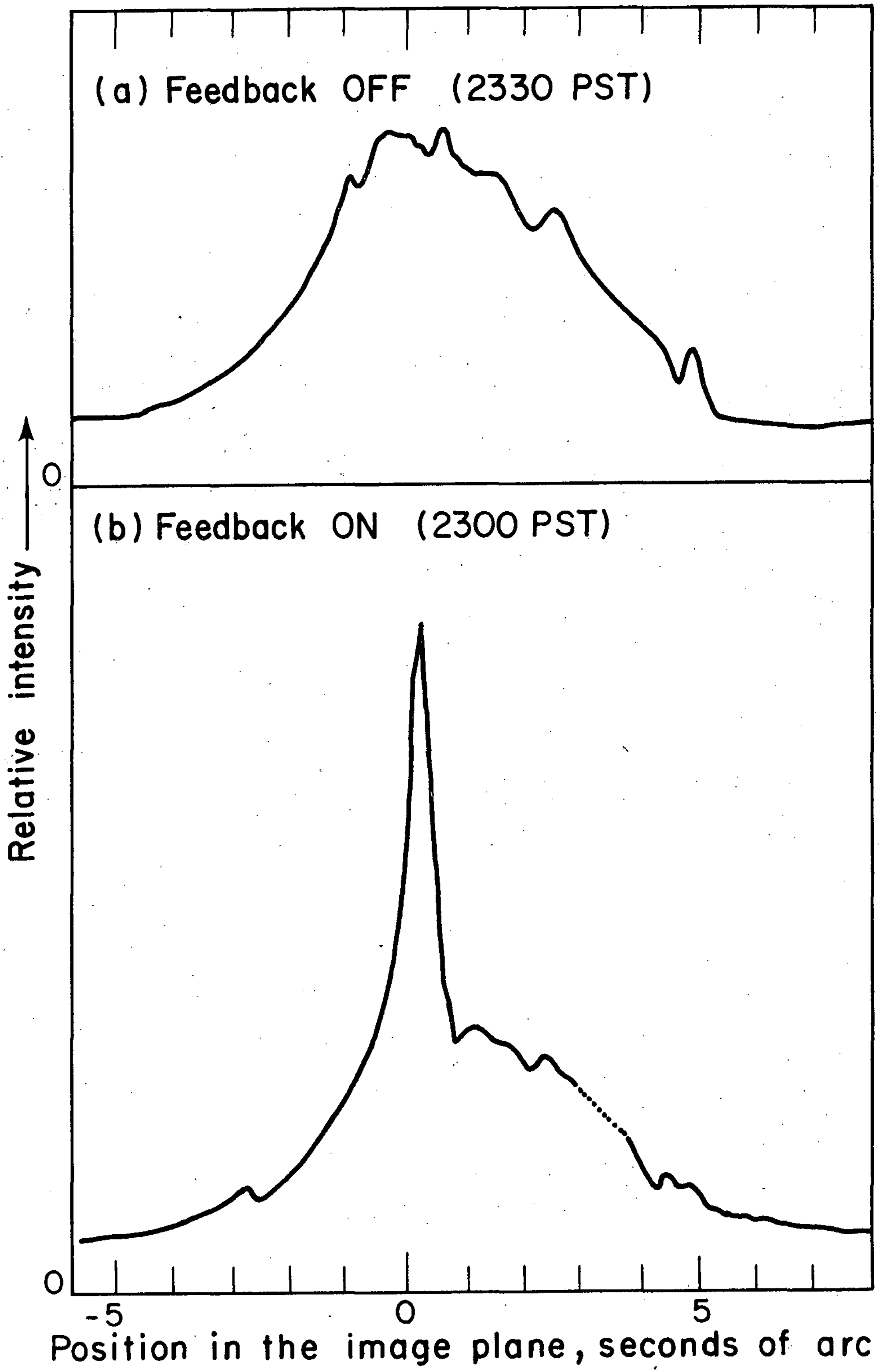

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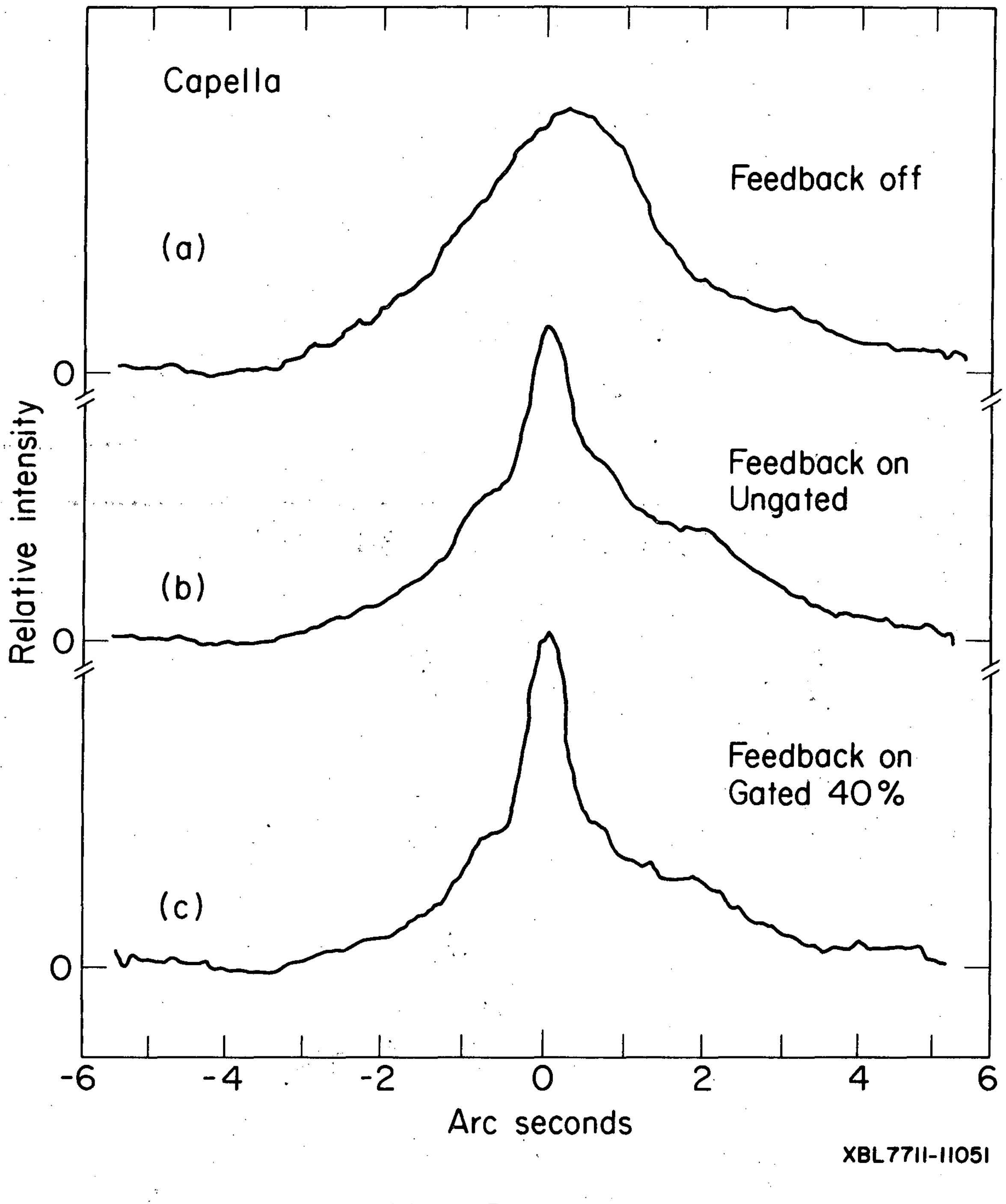
Figure 6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Feedback off
(a)
Feedback on
Ungated
(b)
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Gated 40%
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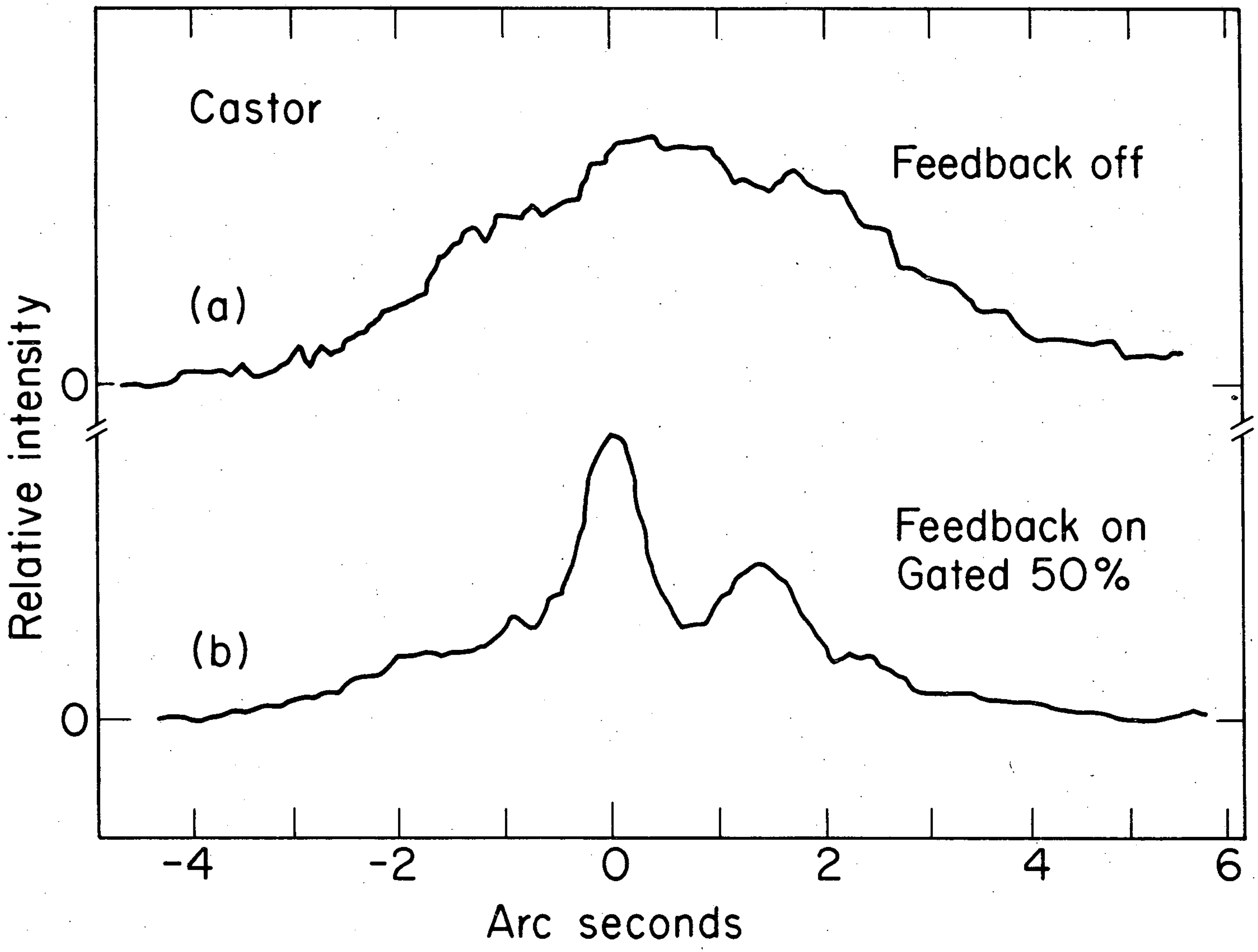
Figure 7



XBL 7711-11052

Figure 8

TECHNICAL INFORMATION DEPARTMENT
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