

Diffraction, Chopping, and Background Subtraction for LDR

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LDR will be an extremely sensitive infrared telescope if the noise due to the photons in the large thermal background is the only limiting factor. For observations with a 3 arcsec aperture in a broadband at 100 μm , a 20-meter LDR will emit 10^{12} photons per second, while the photon noise limited sensitivity in a deep survey observation will be 3,000 photons per second. Thus the background subtraction has to work at the 1 part per billion level. Very small amounts of scattered or diffracted energy can be significant if they are modulated by the chopper.

This paper presents the results of 1-D and 2-D diffraction calculations for the lightweight, low-cost LDR concept developed at JPL that uses an active chopping quaternary to correct the wavefront errors introduced by the primary. Fourier transforms have been used to evaluate the diffraction of 1 mm waves through this system. The JPL concept tries to fit a badly aberrated image through a small hole in the quaternary mirror, and several percent of the energy in the sidelobes is lost. During the chopping cycle, the amount of sidelobe energy lost on one side of the throw differs from the loss on the other side, leading to a modulated signal in phase with the signal from astronomical sources. As the errors of the primary change due to thermal modulation or other causes, the aberrations of the intermediate image change, so that the unbalanced signal also changes, giving rise to an excess noise of up to 10^{10} photons per second in the example above.

CASE	TERTIARY	HOLE	SECONDARY
No Errors or Chop	0.011166	0.011498	0.000086
Errors, No Chop	0.033212	0.084272	0.000386
Errors, +0.5' Chop	0.033314	0.009161	0.000848
Errors, -0.5' Chop	0.032887	0.090453	0.000830

TABLE 1. Light Losses on Mirrors

TABLE 1 shows the fraction of the light lost off the edges of various mirrors for the 2-D calculation. The values for cases with errors are random variables whose range in principle includes the no error cases. As can be seen in photographs, using the quaternary to correct the errors of the primary converts the intermediate image at the quaternary hole from the diffraction pattern of the LDR as a whole, to a speckle pattern whose envelope is the diffraction pattern of a single segment. Far out in an Airy pattern the light lost outside an angle θ varies as $\lambda/D\theta$, so that changing D from 20 meters to 2 meters should increase the light lost by a factor of 10, which is observed. The

light loss should be 10 times smaller at $\lambda = 100 \mu\text{m}$, but this is still unacceptable. The hole in the quaternary should be much larger to reduce the light loss due to diffraction, but it needs to be at least ten times larger, giving a diameter of 1.4 meters. Since the quaternary is an image of the primary, this would require a quaternary diameter of 7 meters! An off-axis design for the tertiary-quaternary stage could allow a large clearance for the intermediate image without requiring such large mirrors.

The PHOTOGRAPHS of the illumination of the secondary show another effect of the small quaternary hole. The image of the primary in the strongly curved secondary is quite close to the secondary, so these pictures approximate the illumination on the primary. With no errors one has fairly uniform illumination, as expected. With large step-function phase errors, the illumination becomes quite nonuniform. The small quaternary hole allows only a low resolution image of the quaternary on the primary, so when the phase jump at an edge is close to π the complex amplitude goes through zero instead of achieving a sharp jump in phase at the panel edge. The width of the misilluminated strip can be estimated as:

$$w = (\lambda L_{qs} D_p) / (D_{qh} D_s)$$

where: L_{qs} is the distance from the quaternary to the primary image in the secondary,
 D_p is the primary diameter,
 D_s is the primary image diameter in the secondary, and
 D_{qh} is the quaternary hole diameter.

For the case evaluated here $w = 0.5$ meters! The sidelobes in the beam pattern produced by these misilluminated edges are large, time varying, and they cannot be reduced by tapering the illumination with the feed horn. Again, a very large quaternary hole is required to reduce the width of the misilluminated strips to the width of the cracks between segments.

Unbalanced signals due to dust and thermal gradients have also been studied. When the light from the sky is concentrated onto small mirrors before the chopper, the sensitivity to dust is greatly enhanced. As a result, focal plane choppers give poor performance in high background situations like the LDR. The chopping secondary design, on the other hand, has only the primary between the sky and the chopper. The light on the primary is not concentrated at all, so dust or nonuniformities on the primary are not a big problem.

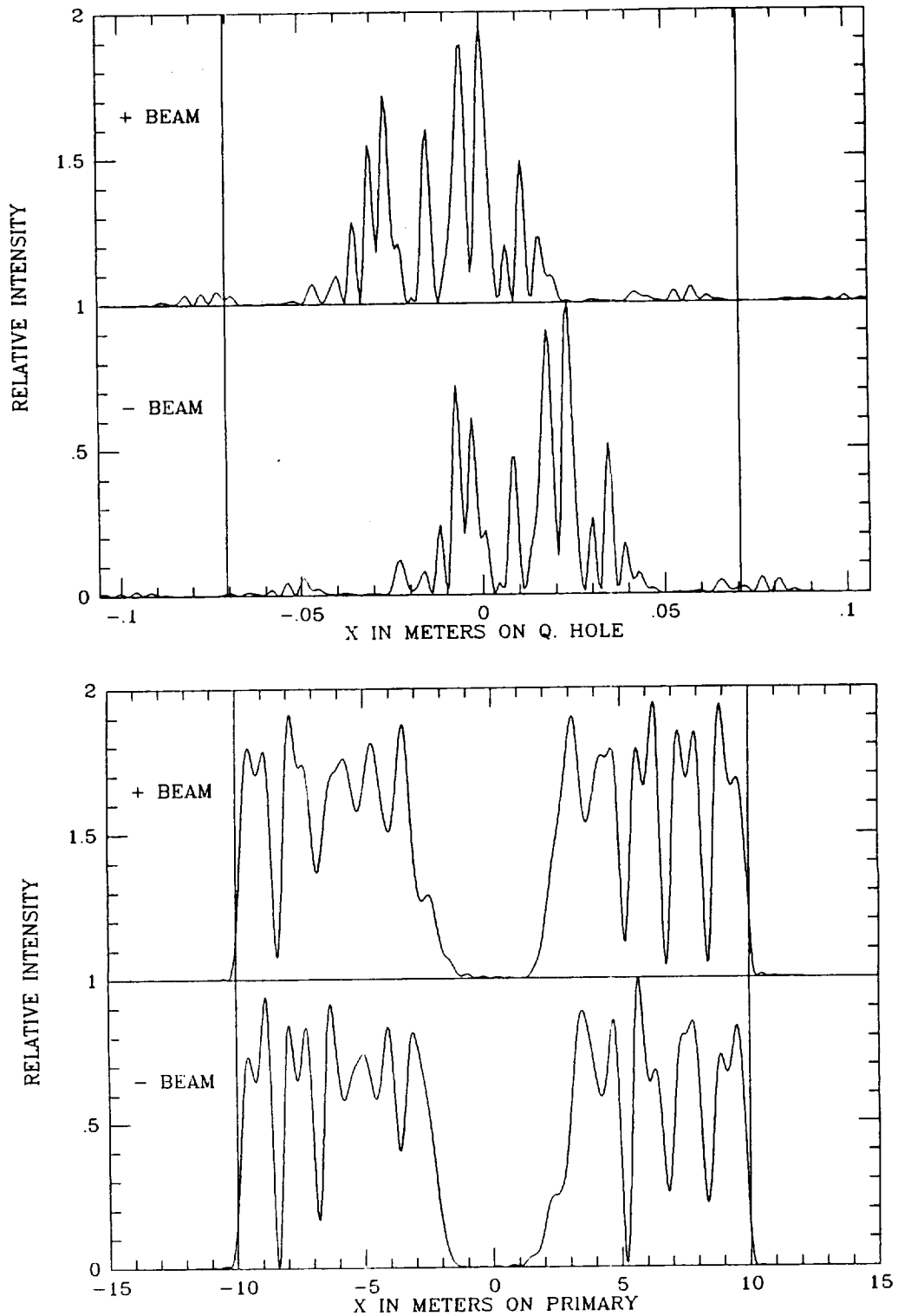
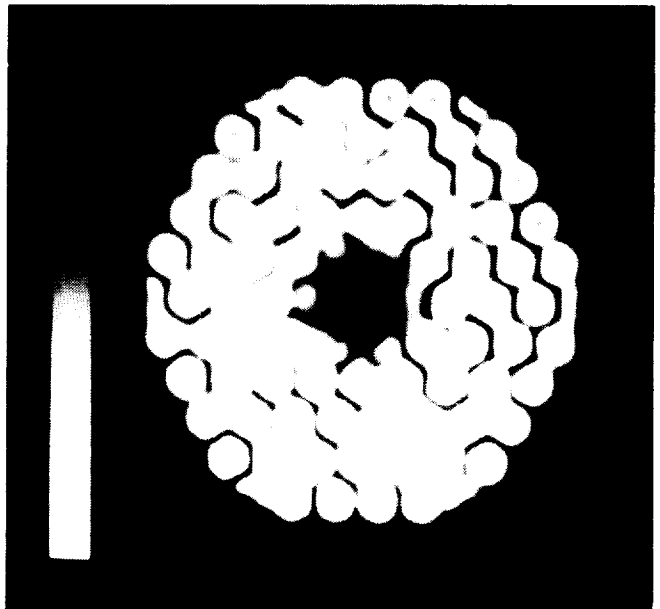
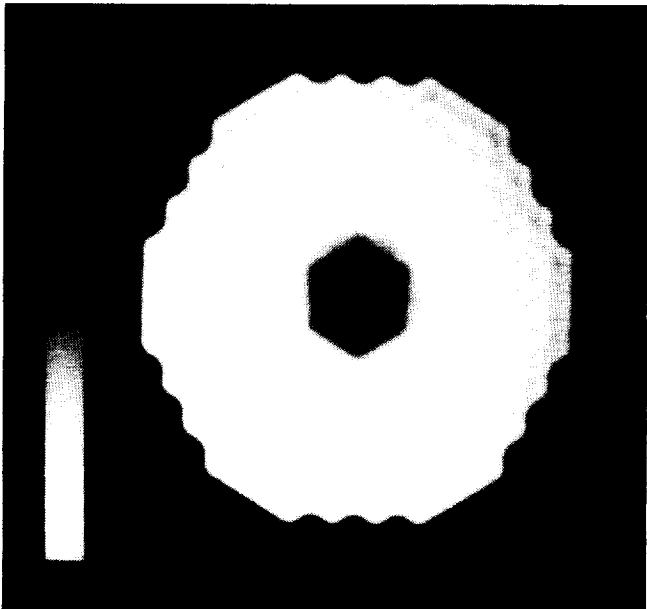
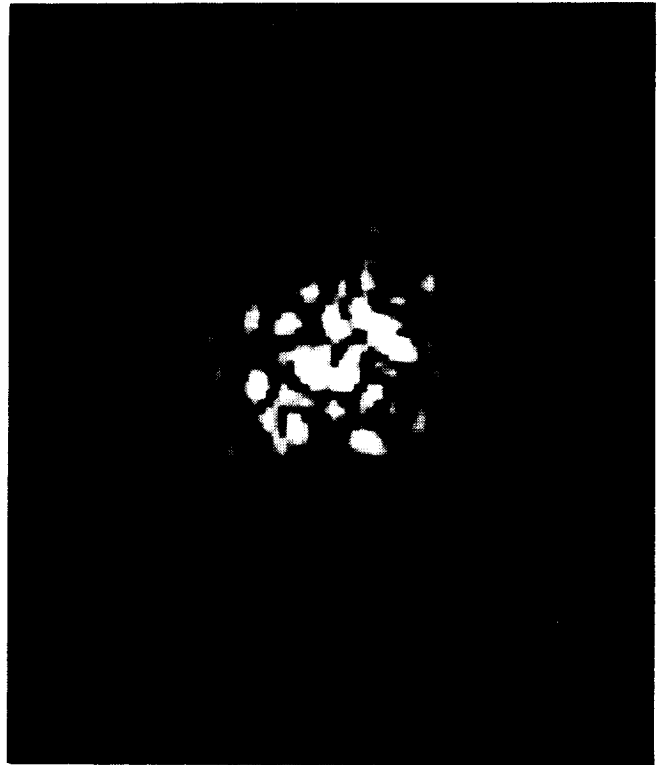
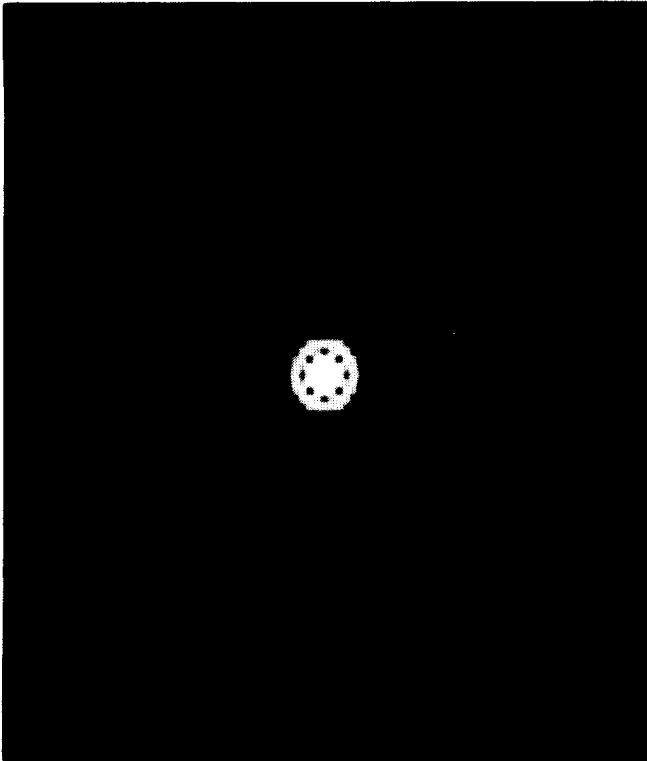


FIGURE 1. The intensity due to a source at the detector position for the on-axis, active chopping quaternary concept: (above) at the intermediate focus in the central hole of the quaternary, and (below) on the surface of the primary, for a 1-D diffraction calculation assuming $290 \mu\text{m}$ RMS wavefront errors on the primary, and a wavelength of 1 mm.



PHOTOGRAPHS: Results from a 2-D diffraction calculation for the on-axis active chopping quaternary concept at wavelength of 1 mm. Top: The illumination due to a source at the detector position at the quaternary hole; without errors (left) and with 290 μm rms wavefront errors (right). Bottom: The illumination on the secondary without errors (left) and with 290 μm rms wavefront errors (right).