Multi-channel disk-based optical correlator

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ABSTRACT

Angularly multiplexed transmission holograms were recorded at multiple spots on a photopolymer coated disk. By imaging in the "along track" direction and Fourier transforming in the radial direction when recording and presenting images, disk rotation can be used to generate the 2-D correlation functions between stored templates and presented images. The correlation functions for holograms multiplexed at a given spot are generated line by line and detected in parallel. A theoretical model of operation was developed and experimentally verified.

2. INTRODUCTION

In recent years we have seen the implementation of several pattern recognition systems that use arrays of optical correlators to realize a variety of algorithms (e.g. template matching, radial basis fuctions, and neural networks). An array of correlators can be implemented by spatially multiplexing different filters on a 2-D medium, typically in a disk configuration [1,2,3,4]. Alternatively, 3-D holographic storage can be used by superimposing multiple holograms utilizing either wavelength [5] or angular [6,7] multiplexing to form the correlation between the input and any stored reference. Finally, spectral and time domains can be used to store multiple filters in 2-D spectral hole burning media [8]. In this paper we present a method that combines angularly multiplexed storage in 3-D media with spatial multiplexing to form a 3-D disk [9]. The 3-D disk allows us to store a very large number of grey scale templates (in excess of 100,000) whereas the disk rotation proves convenient for implementing the necessary shift in one of the two dimensions for the calculation of the image correlation function. The architecture we describe can be implemented with any holographic storage medium that can be fabricated into a thick slab (to allow volume holography) with sufficient area (to make a sizable disk). For instance, photorefractive crystals can be used [9]. The 3-D disk used in the experimental demonstration in this paper, is constructed with the HRF-150 Dupont photoplolymer [10]. In a previous publication [11] we have reported the storage of 10 angularly multiplexed holograms, and we have since stored 50 hololgrams on a sample approximately 200 μm thick.

0-8194-1275-9/93/$6.00

3. THEORY OF OPERATION

When a thick hologram is used to store the Fourier transform filter in a VanderLugt corelator, the shift invariance is destroyed in one of the two dimensions [12]. As a result, the output of such a system is simply one line of the 2-D correlation function. We can use angularly multiplexed holograms in a 3-D volume to store multiple templates and use the second dimension of the output plane to display in parallel one line of each of the 2-D correlation patterns between the input and the stored templates. By translating the input image, the 2-D correlation patterns are generated line by line with time [2,6,7]. Here we describe an alternative solution in which we translate the holographic medium instead. The reference holograms are stored by Fourier transforming in one direction and imaging in the other. Since the input is imaged onto the hologram in one dimension, translating the hologram produces the desired relative shift between input and reference that is necessary to compute the correlation function in 2-D. If the holographic medium is a 3-D disk, then this translation is provided by the disk rotation. Moreover, in this architecture, we can increase the number of templates by storing multiple sets of angularly multiplexed holograms at different locations on the disk. Disk rotation can also be conveniently used to access the different locations in sequence.

The optical setup is shown in Figure 1. The image f(x,y) to be stored is presented to the system on a SLM (an Epson LCTV). The first lens takes the Fourier transform of the image presented on the SLM. At the Fourier plane the image is filtered both to egde enhance and to remove the diffraction orders of the SLM. The second lens transforms this filtered signal back into an image that is demagnified by 1/5. Using three cylindrical lenses, the image is imaged in the along "track" (x) direction and Fourier transformed in the radial (y) direction. The spherical lenses , after the cylindrical lenses, demagnify the 1-D Fourier transform and 1-D image further. This pattern is then interfered with a plane wave with spatial frequency μ and stored in a optically thick photopolymer film on a glass optical disk. This results in the image of f in the x direction and complex conjugate of Fourier transform of f in the y direction ($f^*(M_1x', M_2v)$) being stored, where v is the spatial frequency in the y direction. More holograms can be multiplexed at this location on the disk by changing μ using the rotating mirror and a 4F system of lenses to change the incident angle of the reference beam without changing the beam location. The hologram can be written as $T(x', y') \approx f^*(M_1x', M_2v)e^{j2\pi\mu x'}$ where the M's are magnification factors.

To generate the correlation function between f and another function g, input $g(x, y)$ on the SLM. After going through the same optics before the disk, $g(x, y)$ is mapped into $g(M_1x', M_2v)$. The signal after the disk is given by $g(M_1x', M_2v)f^*(M_1x', M_2v)e^{j2\pi\mu x'}$. This signal is then Fourier transformed by a spherical lens, with focal length F, and detected a distance 2F away from the disk. Ignoring the reconstructed plane wave that ends up uniquely shifting (for each angularly multiplexed hologram) the result on the detector plane, the signal - to within angular selectivity limits - is given by

$$S(x_d, y_d) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(M_1x', M_2v)f^*(M_1x', M_2v)e^{-j\frac{2\pi}{\lambda F}(x'x_d+y'yd)}dx'dy'. \qquad (1)$$

Detecting the signal at $x_d = 0$ and taking the Fourier transform in the y direction results in the signal becoming:

$$S(O, y_d) \approx \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(M_1 x', y'') f^*(M_1 x', y'' - \frac{y_d}{M_2}) dx' dy''. \qquad (2)$$

This is a inner product in the x direction and correlation in the y direction or one line of the full 2-D correlation function of f and g.

Using disk rotation as approximately a linear shift ($(\theta(t))$) in x direction generates the full 2D correlation function with time.

$$S(O, y_d, t) \approx \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(M_1 x', y'') f^*(M_1 x' + \theta(t), y'' - \frac{y_d}{M_2}) dx' dy''. \qquad (3)$$

Since intensity at detector is $I(0, y_d, t) = SS^*$, the intensity detected is equal to the square of the correlation function. With a thick medium, multiple holograms can be recorded at a single spot on the disk using angle multiplexing. Therefore, different 2-D correlation functions for each hologram multiplexed at a spot can be generated one line at a time and detected in parallel.

4. DISK ROTATION EFFECTS

Hologram rotation during reconstruction results in a shift at the correlation detection plane. To analyze this effect, a 1-D image and 1-D Fourier transform of a single point ($S = sinc(\frac{A}{\lambda z_o}(x - x_o))e^{-j2\pi\beta y}$, $\beta = \frac{y_o}{\lambda F}$) – is stored with a plane wave with spatial frequency of α in the x direction ($R = e^{-j2\pi\alpha x}$, $\alpha = \frac{\sin\theta}{\lambda}$). In the expressions above, A is the aperture of the imaging lens, θ is the angle between the normal to the disk and the reference beam, F is the focal length of the Fourier transforming lens, x_o, y_o is the image point, and x, y are the coordinates at the disk (x along "track" direction, y radial direction). Ignoring the *sinc* function that simply weights the outcome, the recorded hologram is

$$RS^* = e^{-j2\pi\alpha x} e^{j2\pi\beta y}. \qquad (4)$$

The hologram is then rotated about the z axis by $d\theta$ resulting in the coordinates being tranformed according to the formulas: $x' \doteq x - y d\theta$, and $y' \doteq y + x d\theta$. Substituting these into equation 4,the hologram can now be written as

$$RS^* = e^{-j2\pi\alpha x} e^{j2\pi\alpha d\theta y} e^{j2\pi\beta y} e^{j2\pi\beta d\theta x}. \qquad (5)$$

Multiplying by S to generate the 1-D inner product and 1-D correlation, expand and simplify, results in

$$SRS^* = e^{-j2\pi\alpha x} e^{j2\pi\beta d\theta x} e^{j2\pi\alpha d\theta y}. \qquad (6)$$

In the above expression, the factors are:

$e^{-j2\pi\alpha x}$ is the reconstructed plane wave without rotation.

$e^{j2\pi\beta d\theta x}$ corresponds to a shift in x direction on the correlation plane.

$e^{j2\pi\alpha d\theta y}$ corresponds to a shift in y direction on the correlation plane.

Therefore, as the disk is rotated, the correlation is shifted in both the x and y directions on the output correlation plane. Because α was much larger than β in our experimental setup, due to geometrical constraints, the shift is predicted to be almost entirely in the y direction.

5.0 EXPERIMENTAL RESULTS

Using the system shown in Figure 1, 300 transmission holograms were stored on one 5 cm radius "ring" of a holographic (6 cm radius) 3D disk. Using DuPont's HRF-150 film and exposing with 488 nm light, three holograms (image plane in the along "track" direction and Fourier transformed in the radial direction) were angularly multiplexed at a given spot on the disk using the methods presented in reference 7. The disk was then rotated to expose a total of 100 different spots; at each spot, three holograms were recorded for a total of 300 holograms stored. The object size was approximately .9x.6 mm with 13 μW intensity recorded with a 1 cm x 1.5 mm plane wave reference beam with 300 μW intensity. After each spot had been sensitized with pre-illumination with the reference beam for 25 seconds, each hologram was exposed for 10 seconds. Disk rotation between spots was 3.5° and the angular separation of the three multiplexed holograms was 1.5°. The holograms were made with an image of four boxes as shown in Figure 2. The peak diffraction efficiency for the three hundred holograms is shown in Figure 3. The 3D disk was made by pressing (laminating) the 38 μm thick photopolymer film onto the glass disk. In addition, spin coating the photopolymer onto the disk is possible.

To test the correlator, an experimental autocorrelation squared of the four boxs was measured using the correlator setup in Figure 1. Figure 4 is an experimental plot of the autocorrelation function squared of the four boxes of Figure 2 and roughly agrees with the theoretical autocorrelation of this image. Figure 4 was generated by storing the image on the disk as explained above, and then presenting the image to the system. The correlation plane was sampled by a line detector. The detector was read out, the disk was rotated, and the detector was read out again. This procedure was repeated until the entire 2-D autocorrelation function squared was generated. Since the boxes occupy a large portion of the input plane (SLM), Figure 4 demonstrates that the correlation ability exists across most of the input plane. In addition, Fugure 5, is the grey scale image looking straight down from the top of Figure 4. Notice the shift in peak location due to disk/hologram rotation. The shift produced by the experimental setup was mostly in the y direction as predicted.

6. CONCLUSION

We have demonstrated a multi-channel disk-based optical correlator using both angular and spatial multiplexing of volume holograms. The full 2-D correlation function of a presented image against stored images is generated by using disk rotation to shift one image over the other, thus reading out one line of each correlation function in parallel. 300 holograms, in the required 1-D image and 1-D Fourier transformed format, were stored on a single ring of an optical disk. The correlation generation was experimentally verified and compared to theory.

The current system stores three holograms at a single spot and uses most of one ring around the disk resulting in 300 holograms stored. The effective thickness of the material was about 38 μm. Using the spin coating technique, a photopolymer film thick enough ($\approx$ 350 μm) to store more than 50 holograms in one spot has been made. Using the whole area of the disk and leaving enough blank space between spots, approximately 3000 spots can be stored on a 5 cm radius disk. This results in a $\sim$ 150,000 hologram storage capacity. The speed of the current correlator is limited by the speed of the linear detectors. A line detector is needed for each angular multiplexed hologram position. For example, if 50 holograms are multiplexed at each spot then 50 line detectors are needed. With the 50 holograms per spot, and linear detectors running at 30 MHz, the correlation rate is about 12,000 correlations per second. This system can be realized with off the shelf technology. For example, small parallel detector arrays, SLM's, and photopolymer films that can use existing red light sources, are all currently available.

7. ACKNOWLEDGMENTS

The authors gratefully acknowledge Northrop's support for this work. Kevin Curtis acknowledges the Northrop Fellowship for supporting his Ph.D. studies at the California Institute of Technology. The photopolymer was graciously made available to us by DuPont; in particular, the authors wish to thank Jay Calio of DuPont. In addition, we appreciate the many helpful discussions with Sidney Li.

8. REFERENCES

[1] Demetri Psaltis, Mark A Neifeld, and Alan Yamamura,"Image correlators using optical memory disks", Optics Lett. **14**, no. 9, 429 (1989).

[2] Demetri Psaltis, Mark A Neifeld, Alan Yamamura, and Seiji Kobayashi, "Optical memory disks in optical information processing", Applied Optics, **29**, no. 14, 2038 (1990).

[3] Askar Kutanov, Boktybek Abdrisaev and Sagynbek Dordoev, "Holographic disked-based optical neural network", Optics Lett. bf 17, no. 13, 952 (1992).

[4] E$'$ Kh. Gulanyan, A.L. Mikaelyan, L.V. Molchanova, V.A. Sidorov, and I.V. Fedorov, "Use of a photothermoplastic disk in memories based on one-dimensional holograms," Sov. J. Quan. Elect. **19**, no 8, 1124-26 (1989).

[5] Francis T.S. Yu, Shudong Wu, Andrew W. Mayers, and Sumati Rajan,"Wavelength multiplexed reflection matched spatial filters using $LiNbO_3$", Optics Comm., **81**, no. 6, 343 (1991).

[6] F.H. Mok, M.C. Tackett, and H.M. Stoll, “Massively parallel optical template matcher/ correlator”, OSA Annual Meeting ThII4, Boston, Massachusetts (1990).

[7] Claire Gu, John Hong and Scott Campbell,“2-D shift-invariant volume holographic correlator”, Optics Comm.,**88**, 309 (1992).

[8] X.A. Shen and R. Kachru,“High speed pattern recognition by using stimulated echoes”, Optics Lett., **17** no. 7, 520 (1992).

[9] Demetri Psaltis,“Parallel optical memories”, Byte, **17**, no. 9, 179 (1992).

[10] W.K. Smothers, T.J. Trout, A.M. Weber, and D.J. Mickish,“Hologram recording in DuPont's new photopolymer material,” 2^{nd} Int. Conf. on Holographic Systems, Bath, UK (1989).

[11] Kevin Curtis, Demetri Psaltis,“Recording of multiple holograms in photopolymer films”, Applied Optics, **31**, (1992).

[12] Jeff Yu, Fai Mok, and Demetri Psaltis,“Capacity of optical correlators”, SPIE, **825-22**, San Diego, CA (1987).

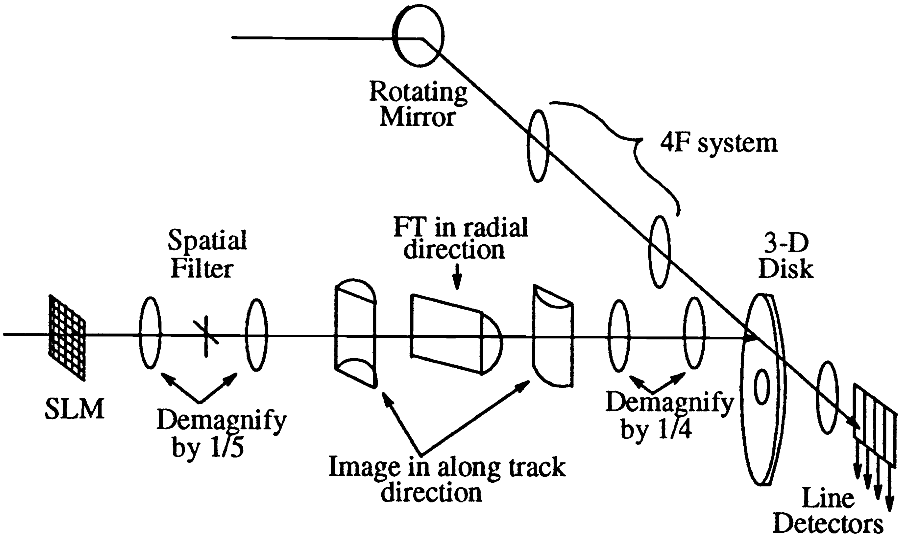


Figure 1: Optical Setup.

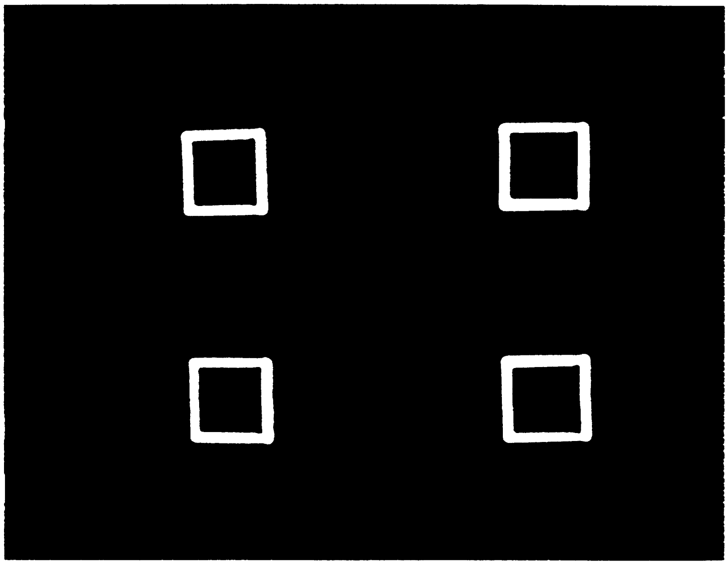


Figure 2: Image of four boxes.

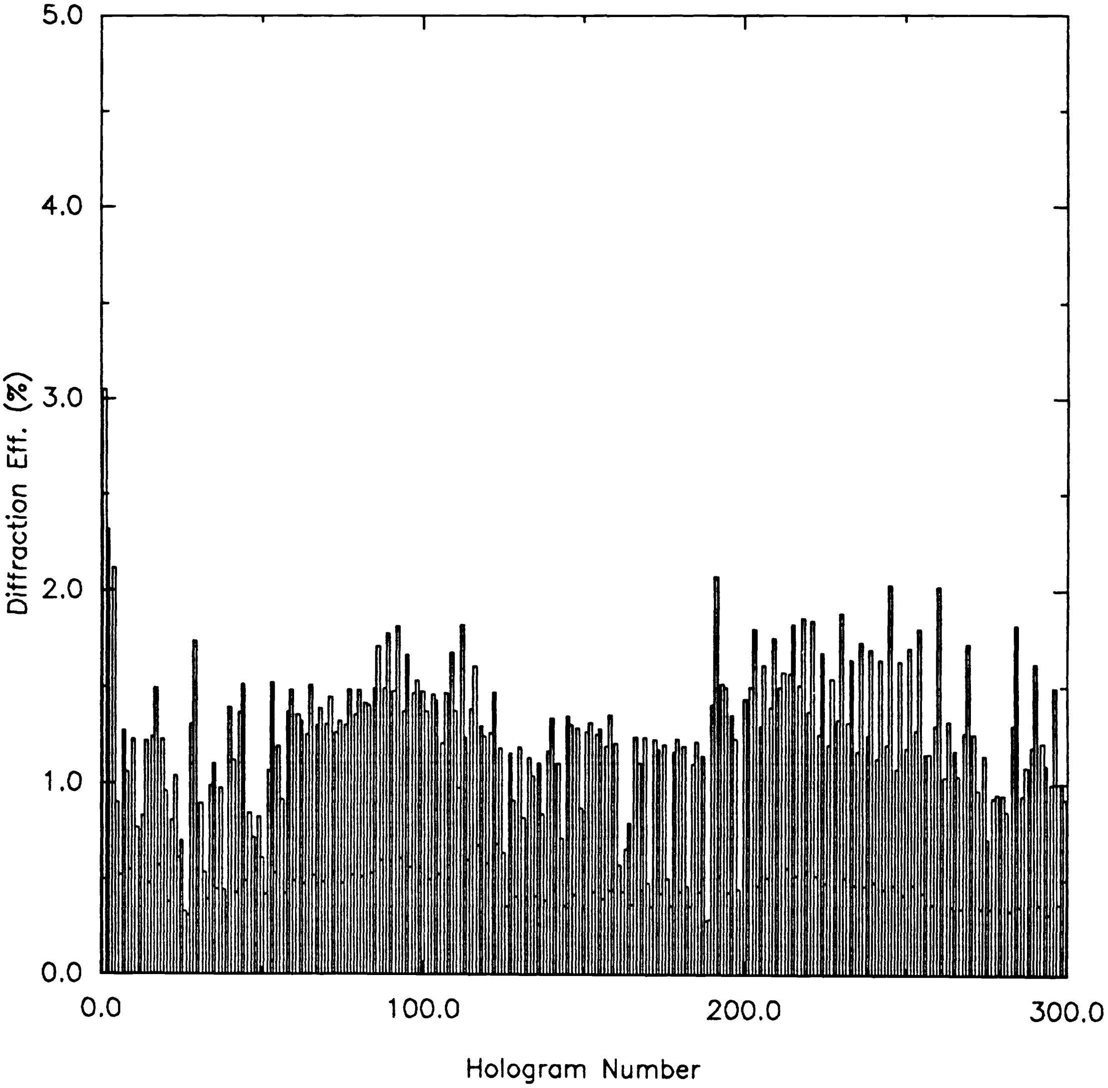
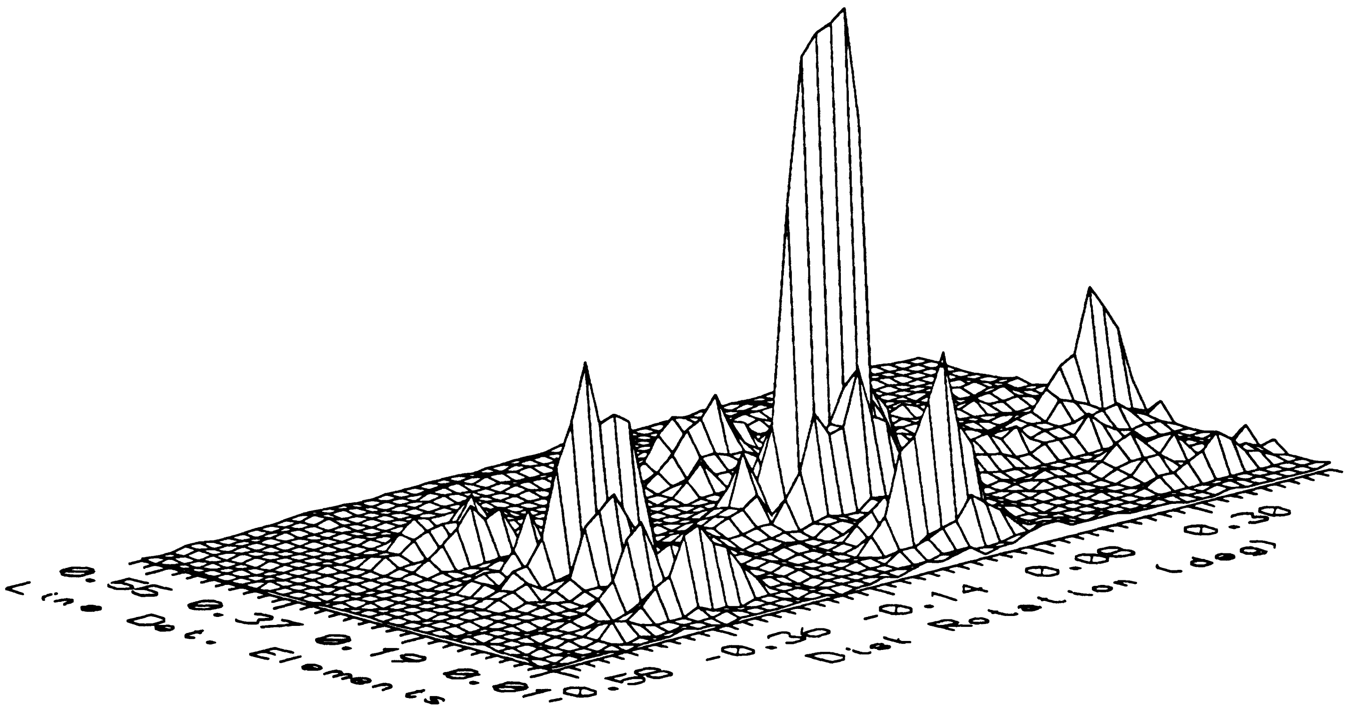


Figure 3: Peak diffraction efficiency of 300 holograms -- 3 holograms at a spot with 100 spots on a ring of a 3-D disk.



Experimental Correlation Plane

Figure 4: Experimental autocorrelation squared generated using optical disk-based correlator.

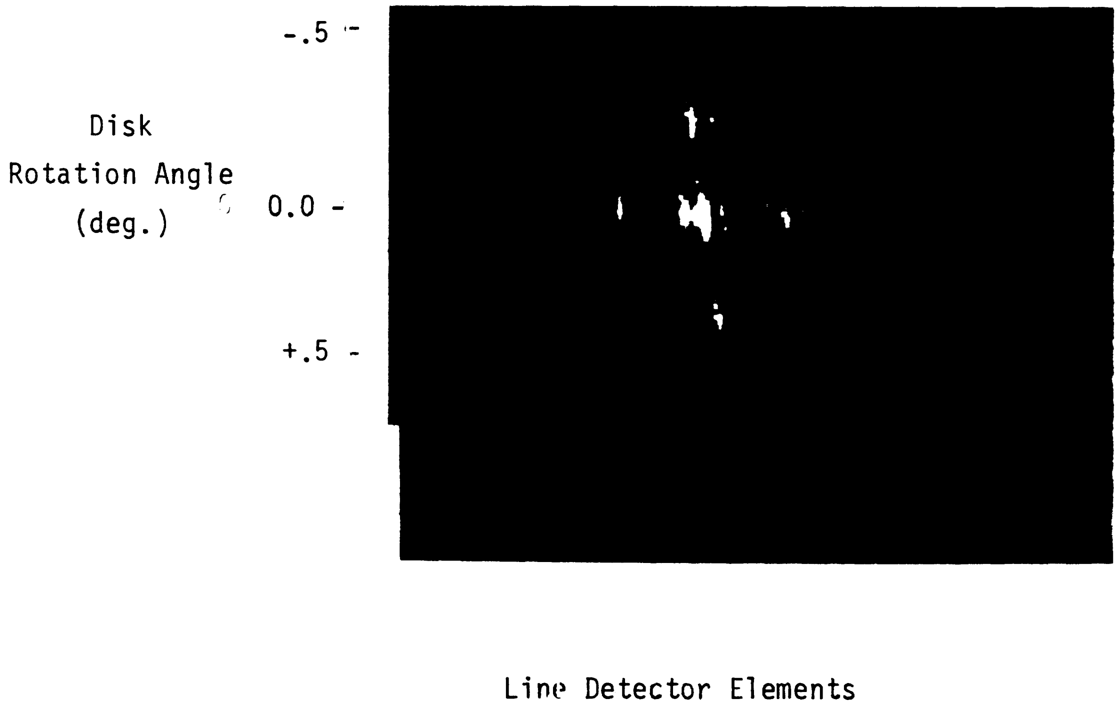


Figure 5: Grey scale of experimental autocorrelation squared.