MASTERING AND REPLICATION OF REFLECTIVE VIDEODISCS

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INTRODUCTION

From the beginning the aim of MCA's videodisc development was to make a complete system for playing pre-recorded color programs over a home TV. Such a system was developed and was demonstrated publicly in late 1972, when a video player played a replicated disc into several standard TV sets.

Meanwhile the Philips company in Eindhoven, working quite independently but with similar goals, developed a similar system. After reviewing each other's work, the two companies agreed to make their discs and players compatible. At present, Philips and MCA plan to introduce Philips NTSC players and MCA discs on a regional basis in 1977.

Zenith Corporation and Thomson CSF also developed optical videodiscs and means for playing them.

DESCRIPTION OF MASTERING AND REPLICATION TECHNIQUES

Metal Film Mastering

Metal film mastering starts with a 14" diameter glass disc which is fine ground and optically polished to reduce the pit density to well under one pit per square millimeter. The disc is then washed, thoroughly rinsed in de-ionized water and spun dry. Then it receives a 200 to 300 Å metal coating in a thermal evaporator and is ready for mastering.

For mastering the disc is clamped to the spindle of the mastering machine and the cutting head is moved into position. An air bearing spindle is used. It is driven by a printed circuit type motor and is phase locked to the color subcarrier generated by a Tektronix color bar generator. The same subcarrier is also used as a reference by the VTR which supplies the program.

Cutting is accomplished with a microscope objective of 0.75NA which focuses an argon-ion laser beam to produce a small spot of light on the disc surface. The spot selectively melts the metal film to encode the disc. The high NA of the lens, required to produce the small (0.8 micron diameter) recording spot, makes the depth of the focus very shallow (±0.3 micron) so that the lens-to-metal film distance must be maintained constant to less than ±0.3 micron. This is accomplished by mounting the lens on a hydrostatic air bearing which rests on the disc surface. The bearing is loaded with enough force to make it follow disc wobbles as great as 25 microns.

The cutting head is driven radially by a lead screw which advances it 1.61 microns per turn of the spindle. Since the pitch uniformity of the finished recording depends on the steady advance of the head, care is taken to lap the lead screw, preload the nut which engages it and make the connection between the nut and the cutting head as stiff as possible.

The cutting process consists of melting holes in metal film which correspond to the positive half cycles of the FM recording signal. The ends of the holes mark the zero crossings of the FM and so contain all of the FM information.

Melting occurs when the power in the light spot exceeds a threshold characteristic of the composition and thickness of the metal film and the properties of the substrate. The spot power is modulated by a Pockels cell driven by the FM encoded video. The on-off transitions are kept short to make the location of the hole ends precise in spite of variations in

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the melting threshold.

The average power in the spot is of the order of 20 milliwatts. Since the FM carrier frequency is about 8MHz, $8x10^6$ holes are cut per second and the energy per hole is $2.5x10^{-9}$ joul.

Because the metal film solidifies rapidly after melting, it is possible to monitor the mastering process through the cutting objective by directing a low powered (1 milliwatt) reading beam through the objective at an angle to form a reading spot a few microns down stream from the cutting spot. The read spot is more strongly reflected by the metal than by the exposed glass so the reflected beam can be used to measure the recorded signal, noise, distortion and dropout frequency during cutting. This read-while-write feature is also used to check disc quality and machine adjustments while preliminary cuts are made inside and outside of the area reserved for the video program.

The essentially flat hole pattern produced by mastering could not be read if it were replicated by molding. The difference in height between the glass and the uncut metal (200-300Å) is too small to produce much optical interference or scattering at visible wavelengths. However, the height difference can be enhanced by coating the cut disc with a photoresist layer and exposing it through the holes. This exposure will polymerize negative resist at the hole sites and will leave bumps or mesas when the unexposed resist is developed away. (Positive resist will yield holes at the hole sites.) This bumpy surface can now be faithfully reproduced in metal by the same galvanic technique used in audio disc processing.

Photoresist Mastering

Photoresist mastering is carried out in a manner very similar to metal film mastering with the difference that the disc is coated with a thin, uniform layer of positive photoresist instead of metal. The photoresist is exposed directly by the laser spot and development produces pits at the exposed site since positive resist is used. At this point developed disc is ready for galvanic processing.

Photoresist mastering requires two fewer steps than metal film mastering: the disc is coated only once rather than twice and photoresist exposure takes place during mastering rather than in a separate operation. However, the read-while-write feature is lost so that the disc quality is unknown until the photoresist is developed and a metal film deposited on it.

Thermoform Replication

There are three distinct thermoform processes used to make videodiscs:

Compression Molding: A soft "patty" of warm plastic is placed between the open halves of the mold cavity. The mold is heated and the halves are pressed together forcing the plastic to assume the shape of the cavity. Some time after the mold is closed, it is cooled so as to solidify the plastic and then opened so that the disc can be removed. This technique is used to make audio LPs and is being used to make thick videodiscs.

Injection Molding: The halves of the mold cavity are first clamped shut, then hot plastic is injected at high pressure to fill the cavity. The mold is maintained at a constant temperature which will solidify the plastic. The plastic soon cools to the mold temperature, the mold is opened and the part is removed. This technique is used to make 45RPM audio discs and is being used to make thick videodiscs.

Embossing: A preformed sheet of plastic is placed in a press. A heated tool which bears the encoding is pressed against the surface of the sheet long enough to transfer the encoding without deforming the sheet. This technique is used to make thin "mailable" audio discs and thin videodiscs.

The tools used in the thermoforming techniques are electroformed nickel replicas of the photoresist surface.

Cast Replication

Videodiscs can also be made by a casting process: A thin film of liquid resin monomer is first applied to a preformed substrate and then the liquid resin is pressed against an encoded mold surface at relatively low pressure. After contact the resin polymerizes (either spontaneously or with the help of heat or radiation) and the disc may be separated from the mold.

The mold is derived from the photoresist in the same way the replica is made from the mold. A film of silicone (elastomeric) rubber monomer is applied to a glass disc and this is pressed against the photoresist surface. The elastomer is cured in contact with the photoresist and then the two are separated. The elastic properties of the cured mold make its separation from the photoresist and the separation of the replica from the mold relatively easy. A rigid mold would be more difficult to separate and distortion of the encoding could result.

Because of the low temperatures and pressure involved, the casting process introduces the least geometrical distortion of any of the replication techniques. The replicas are nearly as round as the masters and the encoded detail is faithfully reproduced. The flatness, however, depends on the substrate.

EXPERIMENTAL RESULTS FROM METAL FILM MASTERING AND REPLICATION BY INJECTION MOLDING

Mastering Signal Quality

In order to improve our understanding of the mastering process, test signals are routinely inserted in the recordings. Carrier amplitude, noise and intermodulation distortion are measured by recording the sum of an unmodulated 7.5MHz

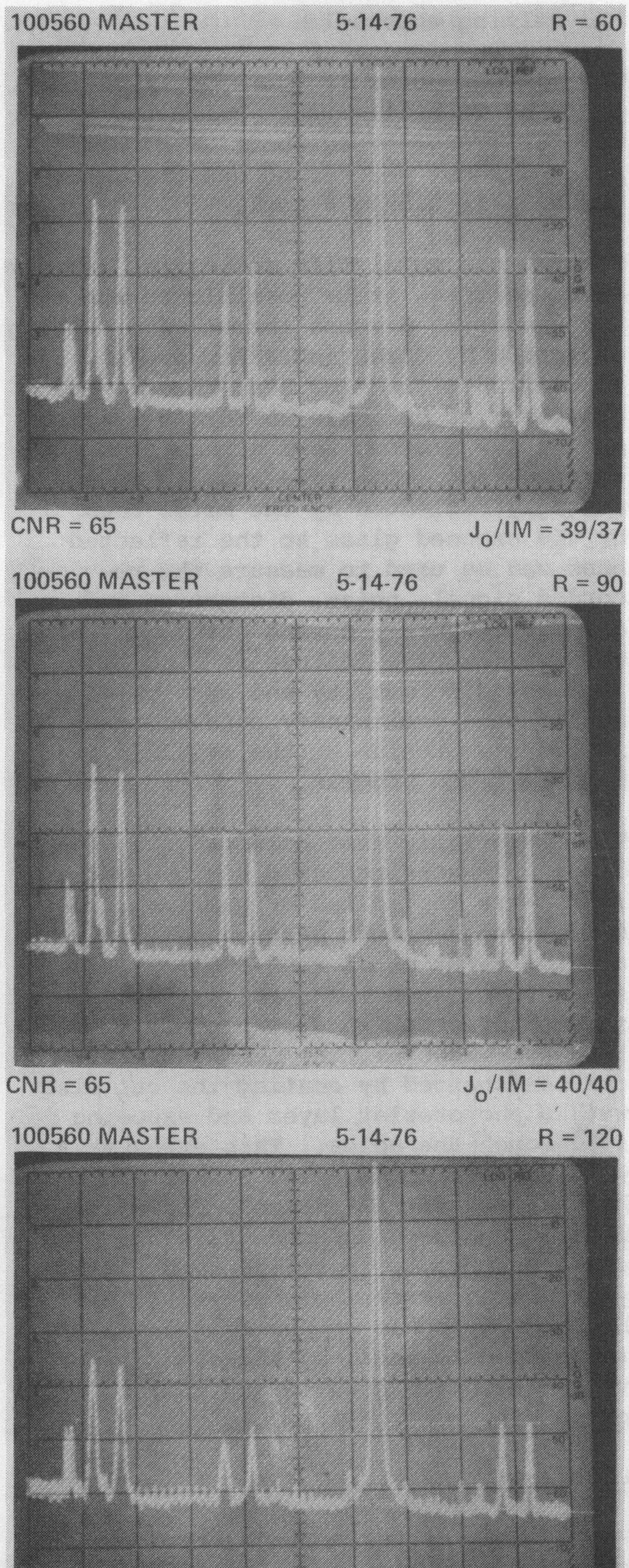


TABLE I

SIGNAL, NOISE AND INTERMODULATION PRODUCTS OF METAL FILM MASTERS MEASURED WITH A SPECTRUM ANALYZER

Recording Number	Radius (mm)	Carrier (dB)	Noise (dB)	CNR (dB)	Carrier to IM Product Ratios (dB)
	(60	-3	-65	62	37/34
553	(90	-3	-66	63	42/37
	(120	-1	-65	64	49/52
	(60	-4	-67	63	38/34
554	(90	+2	-64	66	45/42
	(120	+2	-62	64	49/50
555	(60	-4	-62	58	40/35
	(120	-2	-65	63	42/47
	(60	-3	-67	64	51/51
556	(90	-2	-65	63	48/52
	(120	-1	-64	63	52/56
	(60	-1	-66	65	39/35
560	(90	+1	-65	66	41/41
	(120	+1	-63	64	50/48
	(60	-2	-60	58	42/39
251	(90	0	-62	62	42/47
(0.75NA P/B)	(120	+1	-62	63	52/45
	(60	-9	-66	57	39/45
251	(90	-6	-67	61	39/45
(0.45NA P/B)	(120	-7	-68	61	41/43

NOTE: [1]Measurement made by feeding preamp output to HP Spectrum Analyzer.

[2]Analyzer settings: IF Bandwidth - 30KHz
Video Bandwidth - 100Hz
Sweep - 0.5 seconds/cm

[3]The recorded test signal is the sum of three unmodulated carriers: 7.5MHz at 0dB, 2.3MHz at -26dB, and 2.8MHz at -26dB.

TABLE II

SIGNAL, NOISE AND INTERMODULATION PRODUCTS OF COPPER COATED PHOTORESIST MEASURED WITH A SPECTRUM ANALYZER

Recording Number	Radius (mm)	Carrier (dB)	Noise (dB)	CNR (dB)	Carrier to IM Product Ratios (dB)
	(60	-9	-63	54	36/36
553	(90	-5	-62	57	40/37
	(120	0	-62	62	37/42
	(60	-8	-64	56	35/35
555	(90	-3	-65	62	37/37
	(120	-1	-63	62	43/40
	(60	-10	-67	57	30/30
560	(90	-5	-68	63	38/38
	(120	-6	-68	62	44/45

NOTE: Measurement conditions same as Table I.

carrier and the two sound carrier whose amplitudes are 26db below the main carrier. A few seconds of this signal are recorded at radii of 60, 90 and 120mm and played back into an HP Spectrum Analyzer. The playback is generally done in the read-while-write mode.

The results of these tests on representative masters are given in Table I. The spectrum analyzer bandwidth was set at 30KHz, the video filter at 100Hz, and the sweep at 0.5 seconds/cm. The 7.5MHz noise was estimated by interpolating the noise on each side of 7.5MHz. Spectra from a metal film master are shown in Fig. 1. The smallest IM-to-carrier ratio is -34db. In the worst case this IM signal could produce a peak demodulator output 32db below the maximum peak-to-peak video output.

There was some concern that playback with the 0.75NA cutting objective would give results significantly different from playback with the lower NA player lens. Accordingly, a master was cut and evaluated in the read-while-write mode. Then it was removed from the mastering machine and mounted on a test player with an 0.45NA lens and re-evaluated. (See the last entries on Table I for Disc No. 251.) These results show very little difference between the two playback modes. It was concluded, therefore, that the read-while-write results would, in general, be comparable with measurements done later in the process with 0.45 and 0.40NA lenses.

Photoresist Signal Quality

After mastering the discs are covered with positive photoresist, exposed and then developed so that pits are produced in the photoresist corresponding to the holes in the metal film. Next a thin (500Å) layer of copper is evaporated over the photoresist and the discs are played back on the test player with the 0.45NA lens. The measurements performed on the metal film master are repeated and the results are given in Table II.

Comparison of Tables I and II shows a drop in CNR going from the metal film to photoresist. In particular the drops for recording number 553 are 8db at 60mm, 6db at 90mm and 2db at 120mm. The drops in recording number 555 are less severe: 2db at 60mm and 1db at 120mm. The reductions in CNR were apparently due to a drop in signal rather than an increase in noise.

Baseband amplitude was measured on copper coated photoresist masters by playing back a chroma signal of 100 IRE peak-to-peak amplitude and 50 IRE luminance. On recording number 558 the sound carrier to baseband ratios were 10db at 60mm, 12db at 90mm, and 15 db at 120mm.

Replica Signal Quality

After the copper coated photoresist master has been tested, it is nickel plated to produce a mother and the mother is separated from the master. At this point the mother can either be used directly as a stamper for injection molding or it can be plated to make an intermediate piece of tooling which can in turn be plated to make stampers. For experimental work it is quicker to injection mold with the mother. The resulting replicas are then aluminum coated and tested on a Philips Tokyo player equipped with B system electronics.

Recording number 558 was processed in this manner: The copper coated photoresist was plated, a mother was made and a number of replicas were injection molded from the mother. The data taken on the photoresist and a typical replica are presented in Table III. These data show that the CNR is degraded very little by the replication process. (2db at 60mm.) The intermodulation products are more strongly degraded. (5db at 60mm.) The baseband is not significantly changed.

TABLE III

MEASUREMENTS OF CARRIER-TO-NOISE RATIO, INTERMODULATION PRODUCTS AND BASEBAND SIGNAL MADE ON PHOTORESIST MASTER 528 AND A TYPICAL INJECTION MOLDED REPLICA

	R	CNR(dB)	Carrier to IM Product Ratio (dB)	Sound Carrier to BB Ratio (dB)
Photoresist	60	54	28/35	9
Master[1]	90	56	34/36	12
528	120	58	40/45	12
Replica[2]	60	52	23[3]	9
528-000-65	90	56	30[3]	11
	120	58	42[3]	15

NOTE: [1]Measured on special player with 0.45NA lens.
[2]Measured on Philips Tokyo player with 0.40NA lens.
[3]Upper pair of IM products are significantly attenuated by the preamp.

TABLE IV

DISC STATIC IMBALANCE, FLATNESS, VERTICAL ACCELERATION AND BIREFRINGENCE MEASUREMENTS ON INJECTION MOLDED REPLICAS OF THE 528-000 SERIES

Disc	Static Imbalance (gmcm)	Flatness[1] (Static Deflection) (mm)	Vertical[2] Acceleration (g's)	Birefringence[3] (nanometers) (R=60, 90, 120)
48	3.5	1.5	5.9	14.1, 12.0, 6.5
49	2.8	2.0	4.3	15.8, 13.7, 6.3
50	3.5	1.8	5.9	16.3, 14.2, 6.1
51	4.0	1.6	4.3	16.7, 14.0, 5.5

NOTES: [1]Flatness measures the sag of the edge of a horizontal disc below the clamp plane.

[2]Peak acceleration measured at R=138mm.

[3]Single pass through disc.

Track Geometry and Time Displacement

The ideal information track would be a circular spiral of constant pitch which makes exactly one turn per TV frame. The deviations from this ideal which occur in mastering and replication are discussed below.

The circularity of the tracks on a master disc is generally extremely good compared to the limits imposed by keeping the radial acceleration below 2g. The largest source of unroundness is the molding step where improper removal of a part from the mold can distort it. An out-of-roundness plot for an injection molded replica is shown in Fig. 2. The maximum deviation from roundness is ±12 microns and the maximum acceleration is 0.9g. These data were taken at the outside edge of the encoding and are therefore a worst case.

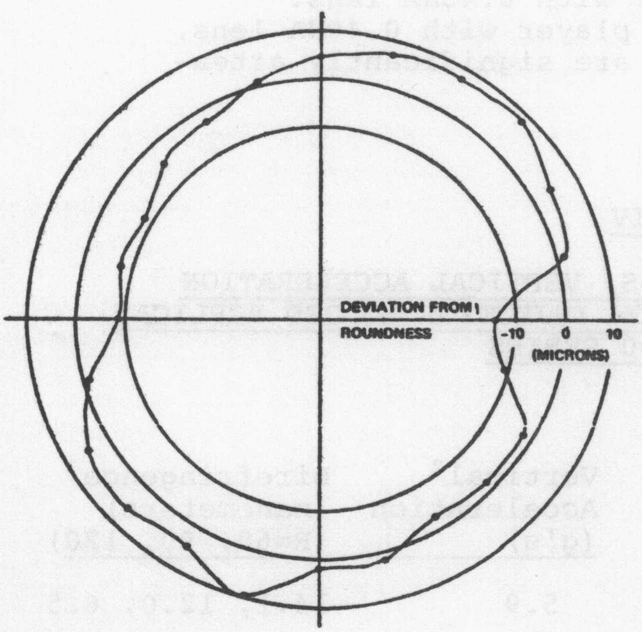


FIG. 2: OUT-OF-ROUNDNESS OF INJECTION MOLDED REPLICA 558-000-134 MEASURED AT R=146mm. MAXIMUM RADIAL ACCELERATION: 0.9g.

Changes in track-to-track spacing are determined entirely by the mastering process; replication can neither improve or degrade the master in this respect. Seismic vibrations during mastering and stick-slip in the lead screw are the chief cuases of changes in spacing. As a precaution against a large source of vibration going unnoticed or the lead screw getting rough, pitch measurements are made periodically on master discs at three radii. Thirty center-to-center distances are measured at each radius and the results are tabulated as a histogram. A significant widening of this histogram is considered a warning that something is going wrong.

Measurements made on replica 558-000-39 gave a standard deviation of .06 microns about the 1.61 micron mean. Deviations larger than .16 microns do not in general appear in these samples; however, a survey of 90 tracks gives little chance of spotting an isolated pitch catastrophe in the 54,000 tracks of a disc: Playback must be relied on to catch these defects.

Time displacement error is largely dependent on the precision of the mastering spindle and the degree of control of eccentricity and unroundness in replication. The spindle in our mastering machine is phase locked to the color subcarrier so that on the average it makes exactly one turn per TV frame. To check on how much variation occurs from frame to frame, the subcarrier frequency was doubled and used to cut holes in a master. This frequency corresponds to exactly 238,875 cycles per TV frame; hence the holes should line up radially if the spindle is accurate. Fig. 3 shows a 1000X enlargement of a portion of this disc. The holes line up to within 10% of the hole-to-hole spacing so the spindle time error is under 14 nanoseconds when sampled at 30Hz.

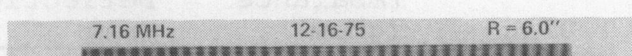


Fig. 3: Photo micrograph of master disc cut with frequency doubled color subcarrier. The track-to-track alignment implies that the rotation period of the spindle repeats itself to better than 14 nanoseconds.

Disc Flatness, Vertical Acceleration, Static Imbalance and Birefringence

A group of four consecutively injection molded discs were tested for static imbalance, flatness, vertical acceleration and birefringence. The data are summarized in Table IV.
Static imbalance was measured with respect to the die punched hole in the disc. All discs measured less than 4.2gm cm, the imbalance which would produce the specified maximum force of 1.5 Newton at 1800RPM.

Flatness or static deflection is the distance the edge of a horizontal disc sags below the clamp plane. The four measured discs were well below the 3mm specification.

Vertical acceleration was measured optically by reflecting a laser beam from the disc surface and measuring its angular velocity. The peak accelerations reported in Table IV fall within the 10g specification. The acceleration peaks are infrequent and last less than 1 millisecond.

Birefringence was measured by transmission before the discs were aluminized.

APPENDIX I

THE NOISE SPECTRUM PRODUCED BY RANDOM VARIATIONS IN DISC REFLECTIVITY

When a spot of light falls on a master disc or replica, the amount of reflected light will depend on the position of the encoding with respect to the spot and on the number and size of the random blemishes which fall within the spot. As the disc moves, new blemishes will enter the spot and old ones will leave causing a random variation in the reflected light. In tests made to determine the amount of correlation between noise and encoding, the noise of an uncut metal master was first measured, the master was encoded and then the noise was measured again. There was relatively little change in the noise due to the encoding so that in this analysis the distribution of blemishes is considered to be independent of the encoding.

Let the random component of the reflected light at time t be $y(t)$. At an earlier time, $t-\tau$, the reflected component will be $y(t-\tau)$. Then the noise spectral density of the function y, $S^2y(f)$, is equal to the Fourier transform of the expected value of the product $y(t)y(t-\tau)$. (See, for example, Reference Data for Radio Engineers, firth edition, p.39-11, 12.)

For mathematical simplicity, assume that the light spot intensity distribution is Gaussian:

$$I(x,y)=\exp[-2(x^2+y^2)/r^2]$$

where x and y are, respectively, the coordinates along and perpendicular to the direction of motion and r is the radius at which the spot intensity drops to $\exp(-2)$.

If the spot moves with velocity v, I will take the form:

$$I(x,y,t)=\exp\{-2[(x-vt)^2+y^2]/r^2\}$$

The noisy portion of the reflected signal $y(t)$ will be given by integrating the product of the randomly varying component of the reflectivity, (x,y), and the intensity distribution $I(x,y,t)$:

$$y(t)=\int\int_{-\infty}^{\infty}\rho(x,y)\exp\{-2[(x-vt)^2+y^2]/r^2\}dxdy$$

If $y(t)$ is a stationary random process, $Ry(\tau)$, the expected value of $y(t)y(t-\tau)$, is given by the integral:

$$Ry(\tau)=(T^{-1})\int_{-\infty}^{\infty}y(t)y(t-\tau)dt$$

Substituting the expression for $y(t)$ into the formula for $Ry(\tau)$, interchanging the order of integration and factoring out the function which does not depend on the variables of integration gives:

$$Ry(\tau)=\exp[-(v\tau)^2/r^2](T^{-1})\int\int\int_{-\infty}^{\infty}\rho^2(x,y)\cdot \exp\{-4[(x-vt+v\tau/2)^2+y^2]/r^2\}dxdydt$$

The value of the integral is a constant. Since $Ry(0)$ must equal σ^2, the mean square value of y, then:

$$Ry(\tau)=\sigma^2\exp[-(v\tau)^2/r^2] \quad (\text{volts}^2)$$

The noise spectral density $S^2y(f)$ is given by the Fourier transform of $Ry(\tau)$:

$$S^2y(f)=4\sigma^2\int\exp[-(v\tau)^2/r^2]\cos(2\pi f\tau)d\tau$$

$$=2\sqrt{\pi}\sigma^2\Theta\exp[-(\pi f\Theta)^2] \quad (\text{volts}^2/\text{Hz})$$

where f = the frequency in Hz
$\Theta = r/v$, the time required for a point on the disc to move one spot radius in seconds

The spot radius r, the point at which the intensity drops to $\exp(-2)$ is given approximately by:

$$r=\lambda/2(NA)$$

where λ is the wavelength of the illumination in meters and (NA) is the numerical aperture of the objective.

The velocity v is given by:

$$v=\omega R$$

where R = the radius in meters
and $\omega = 60\pi$ radians/sec in this case.

Combining these expressions gives:

$$\Theta=\lambda/120\pi R(NA) \quad (\text{seconds})$$

$$\pi f\Theta=\lambda f/120R(NA)$$

Noise spectral densities calculated from this expression for $\lambda=0.632$ micron and NA=0.45 are plotted in Fig. A-1. Experimental data taken from an uncut metal film master for the same λ and NA are plotted on the same figure. All of the experimental points were translated by the same number of db to make the measured and calculated values of $S^2(0)$ for R=60mm the same. No other adjustments were made. The measured and calculated values agree to better than 2db except for the 3db discrepancy at f=10MHz and R=60mm where the preamp noise made the measured value too large.

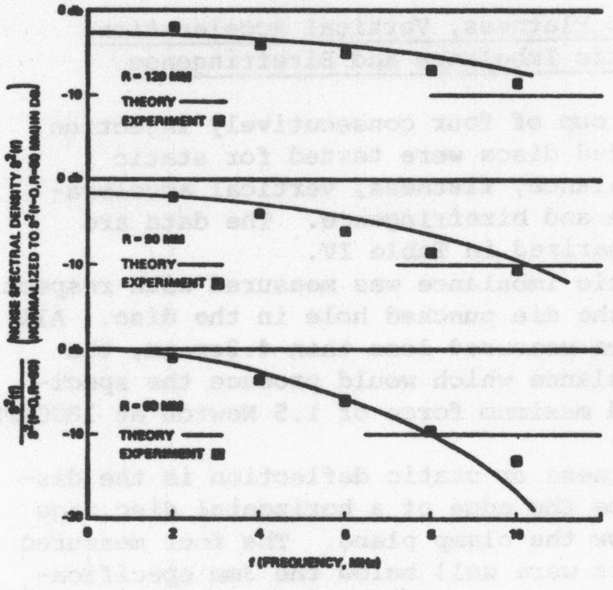
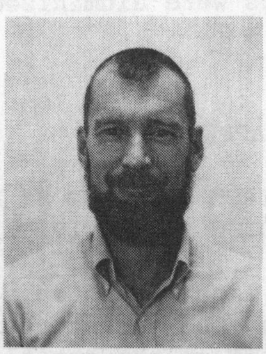


FIG. A-1. THEORETICAL AND MEASURED NOISE SPECTRAL DENSITY FOR A DISC OF RANDOMLY VARYING REFLECTIVITY. (λ = 0.633 MICRON, NA = 0.45)

BIOGRAPHY



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John S. Winslow was born in Altadena, California in 1931. He received a BS in Physics in 1953 and an MS in Electrical Engineering in 1958 both from Cal Tech.

He did preliminary engineering on instrumentation tape recorders at CEC in Pasadena, worked on solid state devices including image panels and storage tube at EOS, designed and built an underwater lamp for making photographs in the presence of back scatter and has worked on videodisc mastering for MCA since 1969. Member IEEE.