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# Digital Simulation Applied to a Photo-Optical System

**Abstract:** The validity of the Image Forming Systems Simulator, IMSIM/1, as a means of simulating multiple-stage photo-optical systems has been determined. IMSIM/1 was used to simulate a three-stage system consisting of a microfilm camera (first stage), followed by the photo-optical subsystem of a developmental image storage and retrieval system (second and third stage). Fine line targets were processed through the camera and the storage and retrieval system. Microdensitometer scans of the targets were then processed through the simulator. To compare the output of the real system with the output of the simulator, it was necessary to measure carefully those system and camera data used in the simulator. After this was done, a satisfactory agreement between experimental result and simulator output was achieved.

## Introduction

When analyzing the design of a complex photo-optical system, it is often helpful to simulate its operation by means of a digital computer. A recently reported digital simulation program,[1] the Image Forming Systems Simulator, IMSIM/1, is intended for such use. But to assess the validity of any simulation scheme, it is necessary to compare the performance of a simulated system with the performance of the system it represents. It is the intent of this paper to demonstrate the validity of IMSIM/1 by describing its application in the simulation of a multiple-stage photo-optical system.

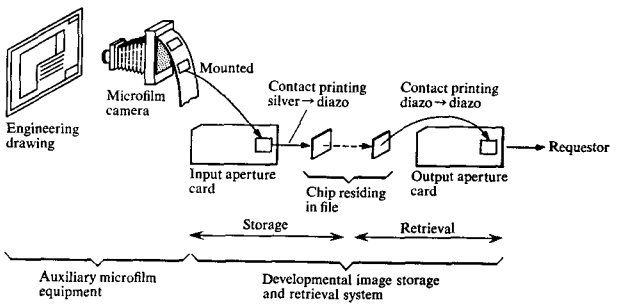
This system consisted of a microfilm camera and the photo-optical subsystem of a developmental system for storage and retrieval of microfilm images. Since the photo-optical subsystem was already operable at the time simulation took place, a comparison between simulated and actual performance could readily be made.

The simulated photo-optical system consists of three stages: microfilming, storage, and retrieval (Fig. 1). In the first stage, the original document (an engineering drawing) is photographed by a microfilm camera onto a fine-grain, silver halide film. The camera uses an f/8 lens of 50 mm focal length, reducing the linear dimensions of the document by a ratio of 20:1. After development, the film is cut, and each image is mounted on an aperture card.

In the second stage, each card is brought to a printing station where the microimage is contact-printed onto the storage material, a photographic film "chip" made of diazo. Diazo is a positive material; hence, the microimage on the chip is a negative of the orginal. After development, this chip resides permanently in the file.

In the retrieval stage, the chip containing the requested microimage is transported to another printing station. Here the microimage is contact-printed onto a diazo material, different in kind from the file material. This output material forms part of another aperture card. After development of the diazo, the requestor receives this card from the system for further use in a magnifying reader or hard copy printer. Because the photographic material in the aperture card is again a positive material, the requestor actually receives a negative microimage of the original document.

**Figure 1** Microfilming, storage and retrieval phases.

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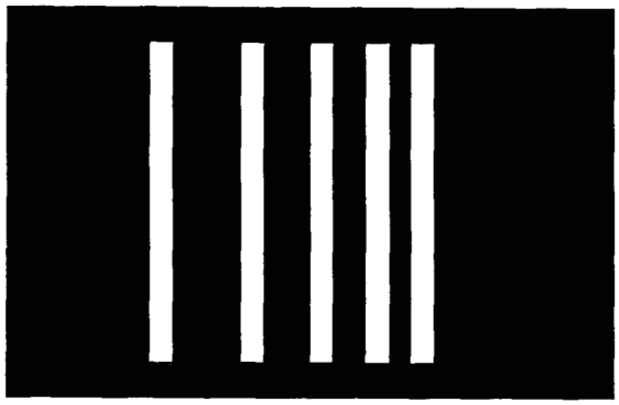
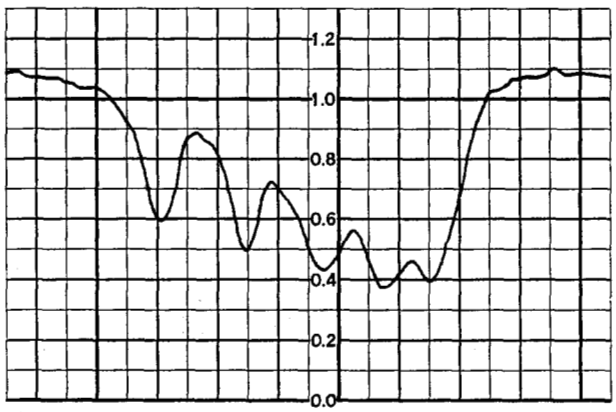


**Figure 2** The 0.1 mm group of the fine line test target.

**Figure 3** Microdensitometer scan of the 0.1 mm group on the diazo output material (length of the scan as in Fig. 12a).




## Experimental procedure

A test target master was selected, consisting of six groups of five transparent lines each. All groups were similar to Fig. 2. Within each group, line width remained constant, and spacing between lines varied. For the series of six groups, the line widths were 0.1, 0.15, 0.2, 0.3, 0.4, and 0.5 mm. The actual test target was made by contact-printing the master onto photographic paper. To provide necessary data for the subsequent simulation, a photographic density step tablet, made of the same paper, was mounted side-by-side with the fine line target. The combination target/step tablet was then used as an input document to the storage and retrieval system. According to the procedure outlined in the Introduction, a silver halide microimage, storage chip, and output aperture card were created.

The microimages of the fine line targets on the aperture card were then scanned with a microdensitometer. The effective width of the microdensitometer slit was 0.001 mm, a width that was found to have no noticeable influence on the result. Figure 3 shows as an example the scan of the 0.1 mm group. The plots of density as a function of distance obtained by scanning across the microimages on the output aperture card served as measures of system performance against which the performance of the simulated system could be compared.

## Data acquisition

Before using IMSIM/1 to simulate the photo-optical system, it was necessary to obtain the following measurements:

1. Description of the fine line test target.
2. Modulation transfer function (MTF) of the camera lens.
3. MTF and H & D curve* of the silver halide emulsion.
4. MTF of the contact-printing processes.
5. MTF and equivalent print density curve of the diazo file material; MTF and H & D curve of the diazo output material.
6. Exposure data for each of the three photographic stages.

A detailed description of the procedures used in acquiring the above data follows.

- *Fine line target*

The fine line targets used as input to the system were scanned by a microdensitometer. These scans were corrected to represent the densities that would actually be seen by the microfilm camera. Correction was necessary for two reasons. First, the illumination geometry of the microdensitometer may differ from that of the microfilm camera. Second, the photographic paper reflects the light nonuniformly in different directions, and this requires correction of the scans if the microdensitometer and the microfilm camera have different relative apertures (this is usually the case). Thus, the two instruments may collect different amounts of light when looking at the same spot in the target; and the two densities seen will then be different.

In order to compensate for this discrepancy, a calibration curve was obtained by two sets of density measurements. The densities of the step tablet in the target assembly were first measured with the microdensitometer. Then the target assembly was placed in the object plane of the microfilm camera, and the densities of the same steps were now measured in the focal plane of the camera, using an ordinary diffuse densitometer. The resulting calibration curve is shown in Fig. 4.

- *Lens*

The modulation transfer function of the lens was determined experimentally on a lens test bench. This function, shown in Fig. 5, represents the performance of the lens on-

* The H & D (Herter-Dreifield) curve is the conventional means of characterizing photographic materials. It is a graph of the density of the exposed and developed photographic material as a function of the $\log_{10}$ of the exposure.

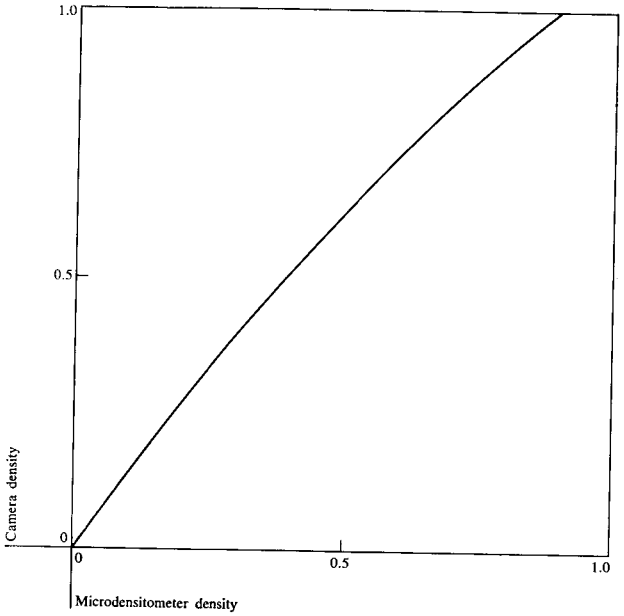



**Figure 4** Calibration curve for converting microdensitometer densities into densities as seen by the microfilm camera.

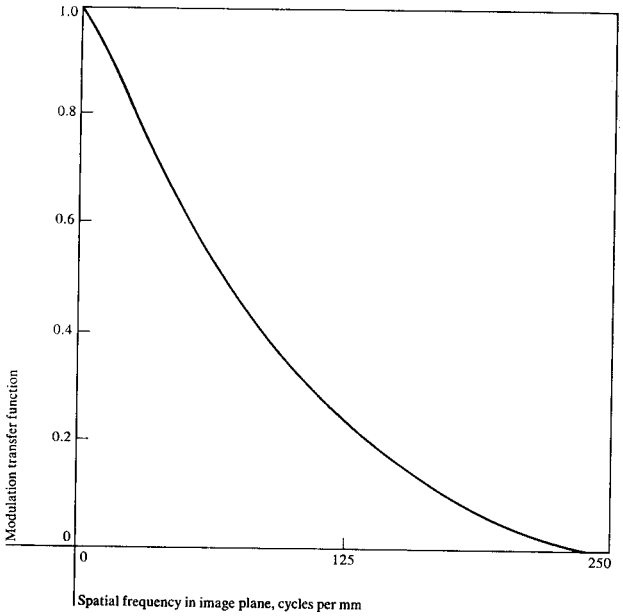



**Figure 5** On-axis modulation transfer function of the camera lens.

axis for a 20:1 reduction. The spatial frequencies were measured in the image plane. The small size of the target image after the reduction ensured that the lens performance was sufficiently well described by the on-axis MTF.

- *Silver halide emulsion*

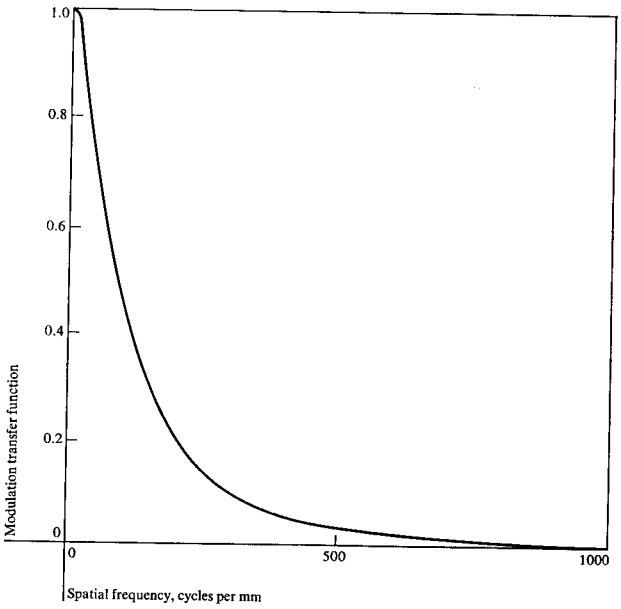
The modulation transfer function of the silver halide emulsion was taken from data published by the manufacturer and extrapolated up to a frequency of 1000 cycles/mm (see Fig. 6). The H & D curve was determined from the microimage of the step tablet on the silver halide emulsion. The fact that the stage immediately following the silver halide emulsion was a contact-printing process (Fig. 1, storage phase) required measuring the diffuse densities of the emulsion. The light absorption in the silver halide emulsion is almost wavelength independent; hence, it was sufficient to measure the diffuse densities with an ordinary densitometer. These densities were determined for the step tablet image on the emulsion.

After removal of the microfilm from the camera, the log exposure values were measured with the same densitometer. This was done in the image plane of the microfilm camera, where the aerial image of the step tablet is located. The resulting H & D curve is shown in Fig. 7.

- *Contact printing*

The degrading influence of the contact-printing processes had been investigated by M. Rabedeau.[2] He found that, for the range of the target sizes employed in the simulation, this influence is negligible.

**Figure 6** Modulation transfer function of the silver halide emulsion (manufacturer's data and extrapolation).




- *Diazo materials*

The degrading influence of the modulation transfer functions of the diazo materials is negligible because, contrary to silver halide materials, diazo does not scatter the light at all.

The characteristic curves of the diazo materials required special attention. Diazo is a photomaterial which is sensitive to ultraviolet light. Unlike that of conventional silver halide materials, the absorption of exposed and developed diazo is significantly wavelength dependent. Hence, the density of diazo depends not only on exposure, but also on the light source and the receptor used in the densitometer.

Because the file material was to be printed onto the output material, the equivalent print density curve[3] of the file material was needed for the simulation. This curve was measured for the diazo file material as "print-through" material with the diazo output material as receptor (Fig. 8).

The H & D curve of the diazo output material was determined by first exposing an ordinary (silver halide) step tablet onto a piece of the output material. After development, the various densities in the image of the step tablet were measured with the same microdensitometer as was used for scanning the output microimages of the fine line targets. This ensured that the image graph of the simulation might later be compared with the scans of the target images. The H & D curve of the diazo output material is shown in Fig. 9.

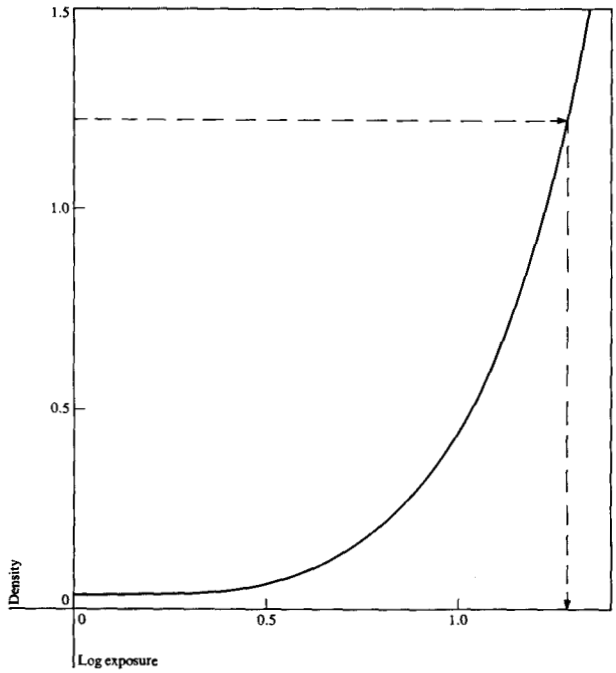
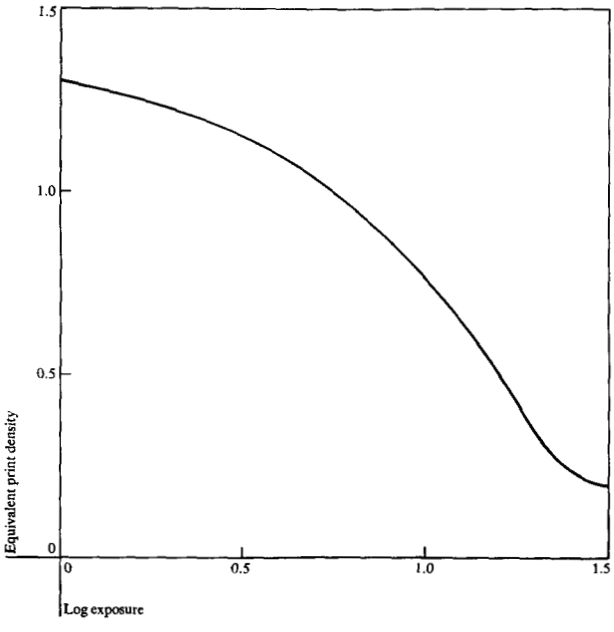



**Figure 7** H & D curve of the silver halide emulsion.

**Figure 8** Equivalent print density curve for the diazo file material as "print-through" material with the diazo output material as receptor.

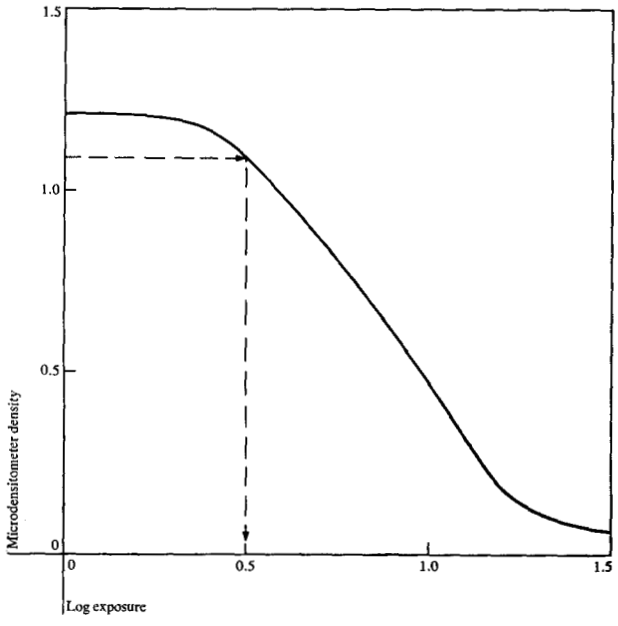



### • *Exposure*

The step tablet was processed together with the fine line target through the microfilm camera and the image storage and retrieval system to provide a means for determining exposure data at each of the three photographic stages in the simulated system. The general procedure for determining exposure data was as follows:

1. Measure the density $D_1$ of a specific step of the tablet in the object; that is, in the target assembly or transparency which was to be imaged or contact-printed onto the next photomaterial.

**Figure 9** H & D curve of the diazo output material.



2. Measure the density $D_2$ of the corresponding step on the image material after exposure and development, and find from the applicable H & D curve the corresponding log exposure value, $\log_{10} E_2$.

The two quantities described above are related by:

$$\log_{10} E_2 = -D_1 + C.$$

The value $C$, as determined from the equation, is the exposure constant which specifies the exposure point on the H & D curve to the simulation program.

For example, assume that $D_1$ was measured with the microdensitometer for a specific step of the step tablet in the original target/tablet combination. After converting this value by using the calibration curve (Fig. 4), the value $D_1 = 0.05$ was obtained. The corresponding density in the silver halide image was found to be $D_2 = 1.24$, which corresponds to log $E_2 = 1.27$ (Fig. 7). This led to a value for $C$ equal to 1.22.

A similar procedure was used to determine the constant $C$ for the contact-printing process of silver halide to file diazo. This process is described by an equivalent print density curve rather than an ordinary H & D curve. Measuring the density $D_2$ of the diazo file material then requires the use of the diazo output material as an effective densitometer. Because this method is rather tedious, a simpler means was used to determine $D_2$.

Boone and Todd[4] have shown that in this particular case it is permissible to approximate the equivalent print density curve by measuring the density of the diazo file material with an ordinary densitometer in combination with a particular set of filters. This was the method used to determine the density $D_2$ of the diazo file material.

For the third exposure (file to output printing), $D_2$ must be measured with the same microdensitometer which was used before for determining the H & D curve of the output material. $D_1$ must be measured with a densitometer having the same spectral sensitivity as the output material. To avoid this complication, an option provided in the simulation program was used. This option is explained in the next section.

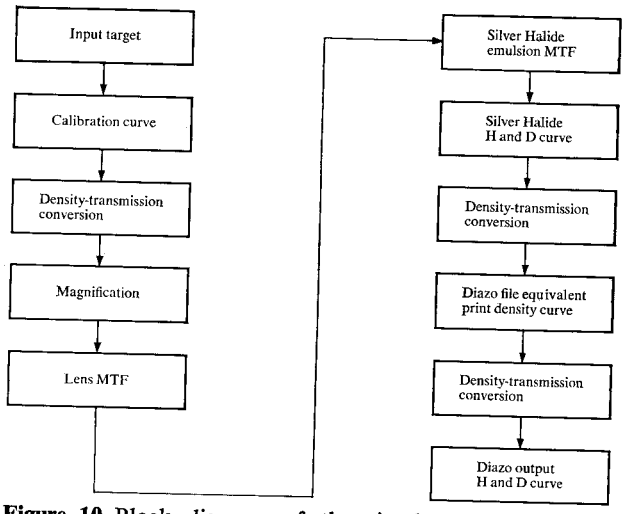



**Figure 10** Block diagram of the simulated photo-optical system as shown in Fig. 1.

**Figure 11** IMSIM/1 statements describing the simulation of the system shown in Fig. 10.

```
JOB  1   PHOTO-IMAGE SYSTEM SIMULATION   --   0.1  MM GROUP
APERIODIC TABLE (7, 2, .06, 2.5)
NONLINEAR FUNCTION (1)
DENSITY TRANSMISSION CONVERSION
MAGNIFICATION (0.05)
OPTICAL TRANSFER FUNCTION TABLE (250, 2)
OPTICAL TRANSFER FUNCTION TABLE (1000, 3)
CHARACTERISTIC CURVE (4, 1.22)
DENSITY TRANSMISSION CONVERSION
CHARACTERISTIC CURVE (5, 1.55)
DENSITY TRANSMISSION CONVERSION
CHARACTERISTIC CURVE (6, .5, -1)
PLOT SPACE
TABLE (1,3)  (0,0) (.1,.13) (.2,.26) (.3,.39) (.4,.51) (.5,.62)
             (.6,.72) (.7,.82) (.8,.91) (.9,1) (1,1.09)
TABLE (2,3)  (0,1) (.1,.813) (.2,.626) (.3,.467) (.4,.346) (.5,.253)
             (.6,.173) (.7,.1) (.8,.05) (.9,.015) (1,0)
TABLE (3,3)  (0,1) (.005,.999) (.01,.997) (.015,.99) (.02,.98) (.03,.88)
             (.04,.79) (.07,.62) (.1,.49) (.15,.33) (.2,.22) (.3,.1) (.4,.06)
             (.5,.04) (.75,.018) (1,0)
TABLE (4,3)  (0,.06) (.1,.06) (.2,.06) (.3,.06) (.4,.07) (.5,.08) (.6,.1)
             (.7,.14) (.8,.22) (.9,.32) (1,.45) (1.1,.64) (1.2,.94)(1.3,1.37)
TABLE (5,3)  (0,1.3) (.1,1.28) (.2,1.26) (.3,1.23) (.4,1.2) (.5,1.16)
             (.6,1.1) (.7,1.03) (.8,.94) (.9,.85) (1,.75) (1.1,.63) (1.2,.5)
             (1.3,.35) (1.4,.25) (1.45,.22) (1.5,.2)
TABLE (6,3)  (0,1.2) (.1,1.2) (.2,1.2) (.3,1.19) (.4,1.16) (.5,1.08) (.6,.97)
             (.7,.86) (.8,.74) (.9,.61) (1,.48) (1.1,.33) (1.2,.18) (1.3,.12)
             (1.4,.09) (1.5,.08)
TABLE (7,1)  (0,0) (.13,.07) (.15,.3) (.16,.28) (.178,.46) (.187,.4)
             (.215,.08) (.225,.03) (.32,.03) (.35,.18) (.362,.44) (.37,.36)
             (.38,.52) (.39,.44) (.405,.08) (.445,.04) (.487,.08) (.5,.2)
             (.507,.42) (.537,.48) (.557,.12) (.575,.06) (.612,.1) (.625,.221
             (.635,.4) (.65,.5) (.67,.48) (.687,.12) (.72,.14) (.735,.39)
             (.765,.4) (.775,.3) (.787,.05) (.812,0) (1,0)
END
```

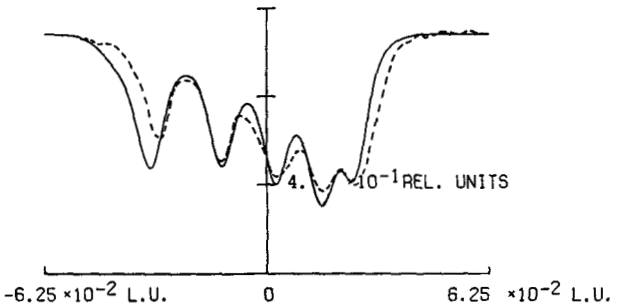
## The simulation

In IMSIM/1, the system to be simulated is described by a set of statements, whose sequence is determined by the sequence of the system components.* Figure 10 shows a block diagram of the system, and Fig. 11 shows the IMSIM/1 statements corresponding to the blocks, together with an output statement and various data for the simulation of the 0.1 mm group.

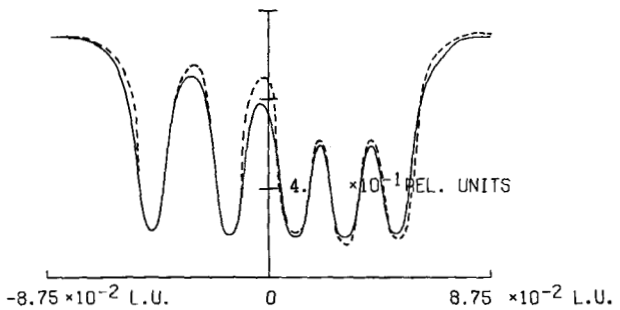
Each statement in Fig. 11 is equivalent to one block in the block diagram of Fig. 10. The first statement (in association with TABLE 7) describes the input target in terms of the photographic density values which were obtained by the microdensitometer scan. The next statement (in association with TABLE 1) converts these data according to the calibration curve (Fig. 4). The following statement converts the data, still representing photographic densities, into transmittances. These data can now be used in subsequent transfer function statements.

TABLES 2 AND 3 in Fig. 11 represent the modulation transfer functions of the lens and the silver halide emulsion (Figs. 5 and 6). The MAGNIFICATION statement must appear

* The program is available from the IBM Program Information Department, Hawthorne, New York, 10532.




(a)




(b)

**Figure 12** Output graphs for the 0.1 and 0.2 mm group as produced by the program of Fig. 11. The dotted curves represent the microdensitometer scans of the corresponding microimages. (Ordinates are in density units; L. U. stands for millimeters.)

before the lens statement: the lens performs a reduction of dimensions so that the image plane becomes the side of the short conjugate; and it is in this plane that lens transfer function data are usually measured.

The CHARACTERISTIC CURVE statements, together with TABLES 4, 5, and 6, represent the H & D and equivalent print density curves of the photomaterials (Figs. 7, 8, and 9). The output data of the first and second statements, which represent density, must be converted into transmittances: the input to the CHARACTERISTIC CURVE statement must be proportional to exposure or intensity. The exposure constants $C$ appear as parameters in the parameter lists of the CHARACTERISTIC CURVE statements.

In the last CHARACTERISTIC CURVE statement, the option of a third parameter permits exposing either the maximum (positive parameter value) or the minimum (negative parameter value) of the exposure distribution at a given point on the H & D curve. There is, therefore, no need to determine $D_1$ (see previous section).

In our example, the background density in the final image was also the maximum density (Fig. 3). Hence, this background density ($D_2 = 1.08$) corresponded to the minimum exposure value in the exposure distribution. Therefore, a negative parameter value (its magnitude is irrelevant) was specified. In using this option, the meaning of the exposure constant $C$ is modified: it is equal to log $E_2$, that is, the log exposure corresponding to $D_2$. From the H & D curve of the diazo output material, $C$ was found to equal 0.5 (Fig. 9).

It should be mentioned that the three consecutive CHARACTERISTIC CURVE statements (including the two conversion statements) can be replaced by a single statement—once the exposure constants are known. A single statement, however, would describe only the combined action of the three characteristic curves. The ability to insert transfer function statements for the printing processes or the emulsions as well as additional PLOT statements would be lost. It would also be difficult to change individual characteristic curves or exposure constants.

The PLOT SPACE statement provides a graph of the density values that occur in the final image; that is, the image on the diazo output material. Figs. 12a and b show the plot produced by the simulation program for the 0.1 mm and 0.2 mm targets, respectively. The densities of the output images produced by the actual system are superimposed on these plots. As can be seen, the results agree quite well.

## Conclusions

For multiple-stage photo-optical systems, the feasibility of performance prediction by computer simulation has been demonstrated. Accurate determination of all data needed in the simulation was found to be extremely important. This applied particularly to the H & D curves of the photographic materials and the exposure data. Once all data were established, the output images of the real system agreed well with the output graphs obtained by digital simulation.

## Acknowledgments

The authors wish to express their gratitude to M. Rabedeau for much valuable advice, as well as for measurement of the lens transfer function. Also greatly appreciated are G. King's skillful execution of the necessary photographic experiments, and W. McDougall's careful microdensitometer work.

## References

1. D. P. Paris, *Phot. Sci. Eng.* **10**, 69 (1966). See also D. P. Paris, *IBM Journal* **10**, 407 (1966).
2. M. Rabedeau, IBM Development Laboratory, San Jose, California, private communication.
3. J. W. Boone and H. S. Todd, *Proceedings of the Twelfth Annual Meeting*, The National Microfilm Association (1963), p. 140.
4. *Ibid.*, p. 142.

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