CENTER FOR ELECTRONIC IMAGING SYSTEMS

HALFTONING ALGORITHMS AND SYSTEMS

FINAL PROGRESS REPORT

4 APRIL 1994 — 31 MAY 1996

DAAH04-94-G-0062
32936-PH

U.S. ARMY RESEARCH OFFICE
ATTN: AMXRO-ICA-L
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AUGUST 1996

NICHOLAS GEORGE
PRINCIPAL INVESTIGATOR

THE INSTITUTE OF OPTICS
UNIVERSITY OF ROCHESTER
ROCHESTER, NY 14627

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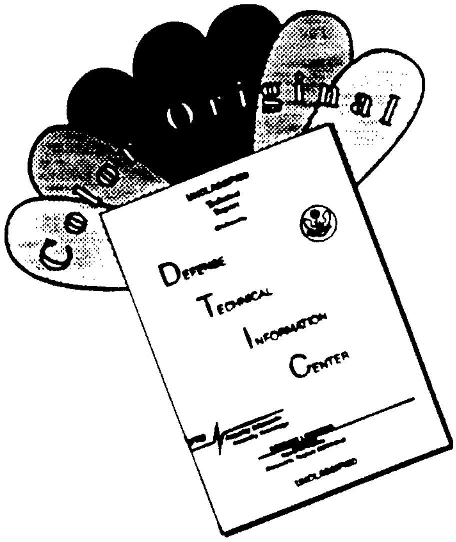

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13. ABSTRACT *(Maximum 200 words)*

Theoretical and experimental research is being conducted on topics related to monochrome and multicolor halftone printing systems. Our goal is to make contributions to improve the understanding of printing for higher image quality, better gray-scale and color reproduction, and faster printing speed. Major aspects of our proposed research include the following three topics. First, we have devised a new sampling method, i.e., a new centering concept, for computing the overlapping correction in digital halftoning. This novel concept will greatly reduce the complexity in making the measurement-based overlapping correction. We propose to investigate corresponding halftoning algorithms and built-in-printer hardware for real-time monitoring and calibration in order to maintain the optimum performance of hard-copy devices. Secondly, we plan to extend the new centering concept to multicolor halftoning studies. For the third topic, we propose to conduct system research for multiplexed output devices. The research will be focused on architectures which provide support for a multi-output system. This program of research is heavily leveraged by participation from the ARO-URI in Optoelectronic Systems, the new Center for Electronic Imaging Systems, and industrial sponsors including several U.S. Corporations who are leaders in imaging.

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HALFTONING ALGORITHMS AND SYSTEMS

ABSTRACT

Theoretical and experimental research is being conducted on topics related to monochrome and multicolor halftone printing systems. Our goal is to make contributions to improve the understanding of printing for higher image quality, better gray-scale and color reproduction, and faster printing speed. Major aspects of our proposed research include the following three topics. First, we have devised a new sampling method, i.e., a new centering concept, for computing the overlapping correction in digital halftoning. This novel concept will greatly reduce the complexity in making the measurement-based overlapping correction. We propose to investigate corresponding halftoning algorithms and built-in-printer hardware for real-time monitoring and calibration in order to maintain the optimum performance of hard-copy devices. Secondly, we plan to extend the new centering concept to multicolor halftoning studies. For the third topic, we propose to conduct system research for multiplexed output devices. The research will be focused on architectures which provide support for a multi-output system. This program of research is heavily leveraged by participation from the ARO-URI in Optoelectronic Systems, the new Center for Electronic Imaging Systems, and industrial sponsors including several U.S. Corporations who are leaders in imaging.

HALFTONING ALGORITHMS AND SYSTEMS

TABLE OF CONTENTS

Halftoning Algorithms and Systems

Technical Progress Report

Statement of the Problem

The goal of the research conducted under this grant was to improve the output quality of halftone printing devices. Improvements in image quality were made through a novel resampling of the output image, which lead to an improved algorithm for the calibration of the printing device. The resampling of the output image shifts the output pixels 1/2 of the dot pitch both horizontally and vertically. This resampling results in the physical printed dot being placed at the intersections of four output pixels. The significant result of the output image resampling is a significant reduction in the complexity of the calibration procedure. The novel resampling concept has yielded excellent results for both monochrome and multicolor printing.

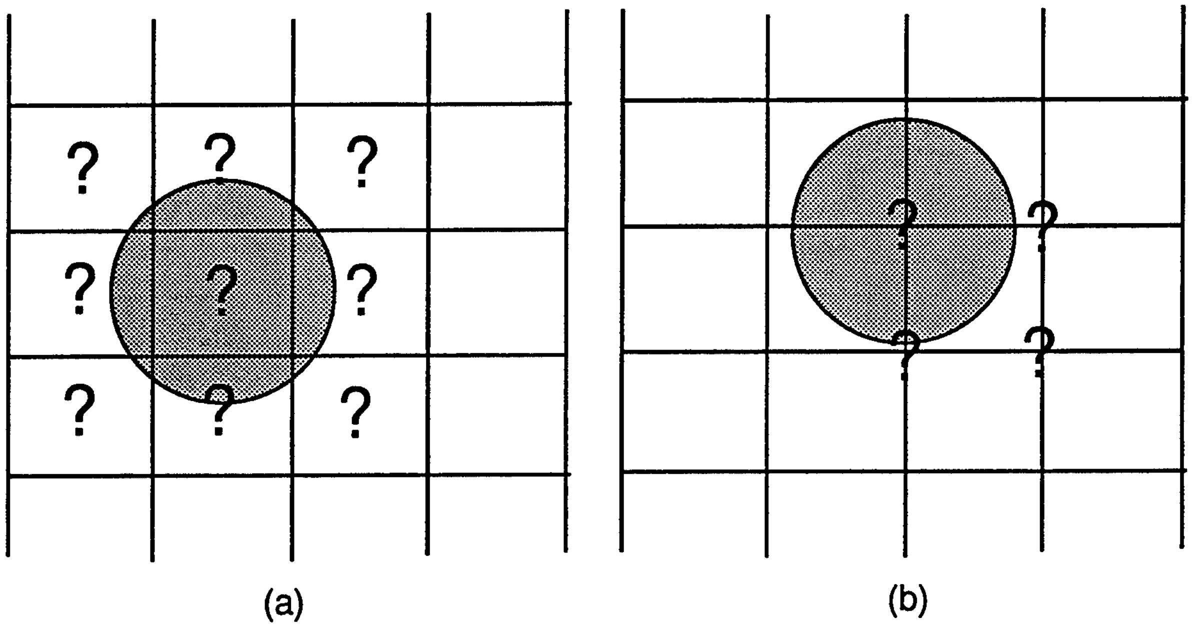

Fig. 1. a) Conventional definition of output pixels where output pixels are coincident with printer dots; b) Novel redefinition of the output pixel such that printed dots lie at intersection of four pixels.

Summary of Important Results

There are several drawbacks to current monochrome, binary printing algorithms. The common approach of conventional halftone algorithms is to assume that the output pixels are coincident with the printer dots (see Fig. 1a.) Under these conditions the output graylevel in any given pixel is dependent upon the state of nine pixels, the eight nearest neighbors and the output pixel itself. The most significant result of this research is the concept of resampling the output pixels such that the physical printed dots lie at the intersection of four output pixels (see Fig. 1b.) One key advantage of this new approach is that the output graylevel of any given pixel is dependent upon only four dots. Therefore, in the worst case, the calibration table requires 16 entries whereas the calibration table for the conventional approach requires 512 entries.

The second advantage of the output resampling approach is that the dot patterns required to generate the calibration table form isotropic patterns. For example, a small portion of the pattern consisting of an alternating vertical pattern of ones and zeros is shown in Fig. 3a for the 2x2 test cell based on the novel resampling approach. The replication of this pattern to produce a large scale test patch, as shown in Fig. 2b, appears invariant to the exact location within the patch. On the other hand, the same set of alternating ones and zeros for the conventional 3x3 test cell is shown in Fig. 3b. The resulting test patch created by the replicating the test cell is indeed dependent upon the exact location within the test patch. This result is significant in reducing the complexity of the calibration procedure and calibration test patterns.

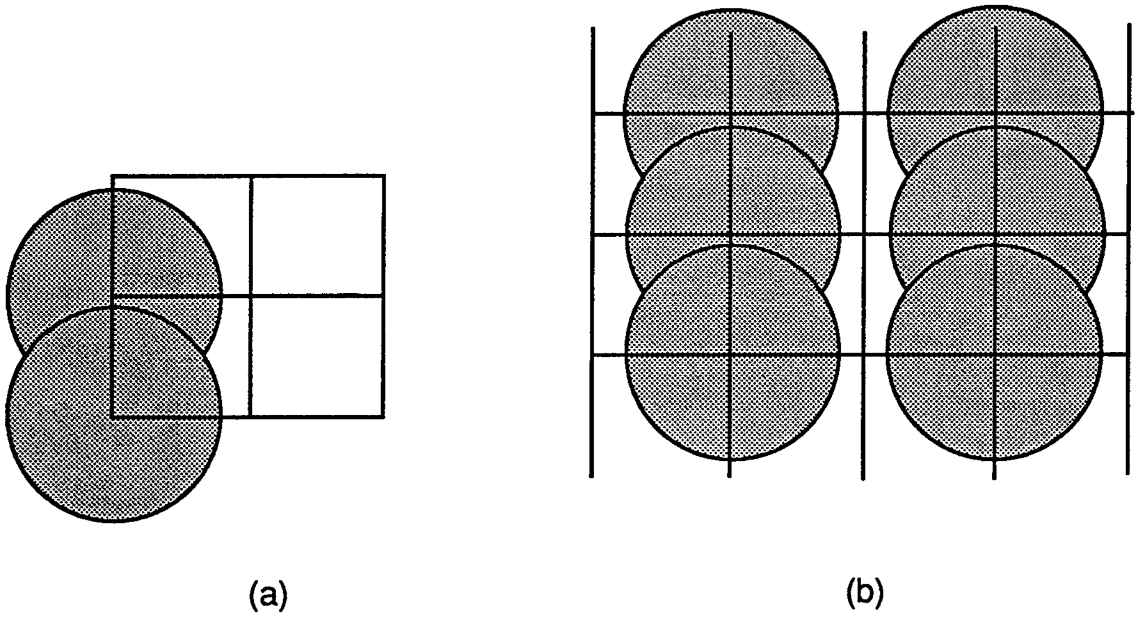

Fig. 2. a) Test pattern of alternating vertical lines using 2x2 test cell based upon novel resampling approach. b) Resulting large scale test patch create by replicating test cell . Local dot pattern is independent of absolute position within the patch.

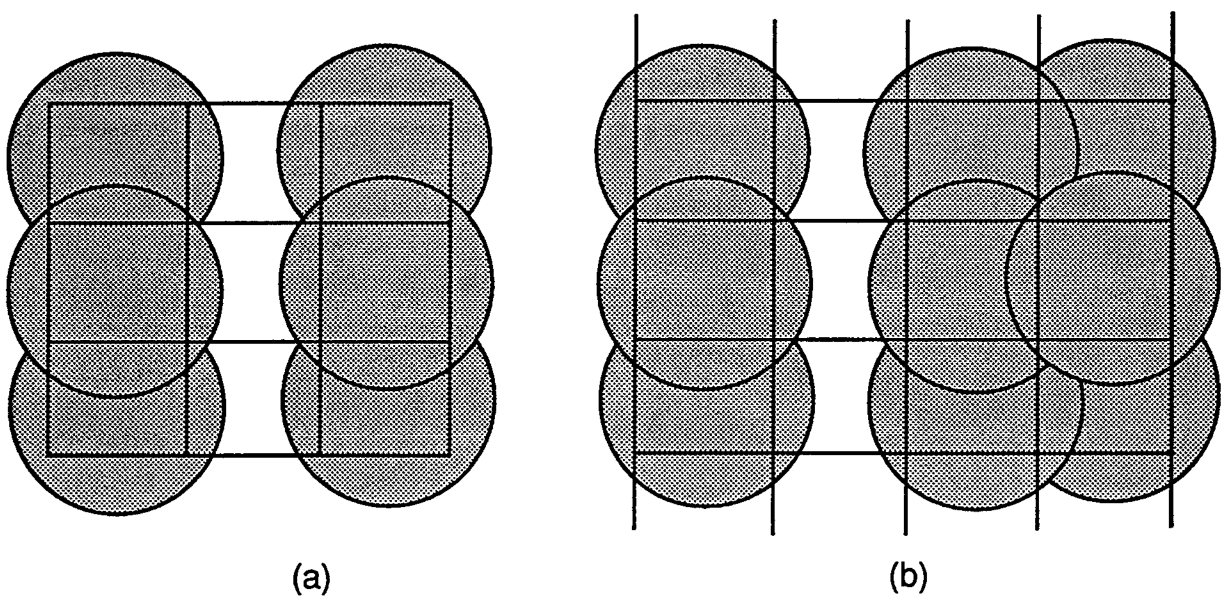

Fig. 3. a) Test pattern of alternating vertical lines using conventional 3x3 test cell. b) Resulting large scale test patch create by replicating test cell . Local dot pattern is dependent upon absolute position within the patch.

The new centering concept has been incorporated into both ordered and stochastic halftone algorithms. For the case of screen-type halftone algorithms where a threshold mask is placed over the input image to determine the output halftone pattern, the calibration procedure using the new centering concept has the effect of redesigning the halftone screen to obtain the proper graylevels for each screen level. In the case of error diffusion algorithms, the calibration procedure using the new centering concept manifests itself as a correction to actual graylevel within the current pixel based on the state of the previously printed dots. In all cases excellent results were obtained with both grayscale step wedges and complex imagery. For the case of the grayscale step wedges, the desired aim was to create perceived graylevels that were linear with input grayscales. Excellent experimental results were obtained for a variety of printers, including both laser and ink-jet printers.

While the new resampling approach yields a reduction in the complexity of monochrome printing systems, the most significant advantage is seen in the case of multicolor printing. For the case of multicolor printers, the resulting color within any given pixel still depends on the state of the nearest neighbors. The calibration of multicolor printers is complicated by the fact that the state of each neighboring pixel may attain any one of eight different hues as compared to just two for the monochrome case. The calibration procedure must account for the fact that the overlap of dots of different hues can produce a third hue. For the case of the new resampling concept, the resulting set of test patches consists of 4096 different dot patterns. While this is a large number of color patches to measure, it is certainly a manageable number, whereas the total number of possible test patterns for the conventional approach is equal to 8^9. Obviously the new centering concept results in a significant reduction in the complexity of the calibration procedure. Experimental results have shown that excellent color reproductions are obtained using the new centering approach.

PUBLICATIONS AND INVENTIONS

PUBLICATIONS

"The blurred bird," Nicholas George and Bryan J. Stossel, Technical Note, 1993.

"Neural networks applied to diffraction pattern sampling," Nicholas George and Shen-ge Wang, Appl. Opt. **33**, 3127-3134, (1994).

"Automatic image quality assessment," David M. Berfanger and Nicholas George, IS&T's 47th Annual Conference/ICPS 1994, 436-438 (1994).

"Novel centering method for overlapping correction in halftoning," Shen-Ge Wang, Keith T. Knox, and Nicholas George, IS&T's 47th Annual Conference/ICPS 1994, 483-486 (1994).

"Controlled blurring in image processing," Bryan J. Stossel and Nicholas George, IS&T's 47th Annual Conference/ICPS 1994, 534-535 (1994).

"Backscattering cross section of a roughened sphere," Donald J. Schertler and Nicholas George, J. Opt. Soc. Am. A. **11**, 2286-2297 (1994).

"Ultrafast pulse propagation in periodic optical media: a generalized finite-difference time-domain approach," Stojan Radic and Nicholas George, Opt. Lett. **19**, 1064-1066 (1994).

"Holographic contouring by using tunable lasers," Nicholas George and Wenjun Li, Opt. Lett. **19**, 1879-1881 (1994).

"Optical switching in l/4-shifted nonlinear periodic structures," Stojan Radic, Nicholas George, and Govind P. Agrawal, Opt. Lett. **19**, 1789-1791 (1994).

"Nonlinear DFB phase-shifted structure: all-optical, low-intensity switching device," Stojan Radic, Nicholas George, and Govind P. Agrawal, LEOS '94 7th Annual Meeting, Conference Proceedings **2**, 61-62 (1994).

"Infrared target simulation environment for pattern recognition applications," Andreas E. Savakis and Nicholas George, paper presented at the Conference on Infrared Imaging Systems: Design, Analysis, Modeling, and Testing V, as part of SPIE's International Symposium on Optical Engineering and Photonics in Aerospace Sensing, 4-8 April 1994, Orlando, FL.

"Infrared target simulation and recognition," Andreas E. Savakis and Nicholas George, paper presented at the 1994 IEEE Dual Use Technologies and Applications Conference, 23-26 May 1994, SUNY Institute of Technology, Utica/Rome, NY.

PUBLICATIONS (CONTINUED)

"Prototype of an image recognition system," Alexander D. Mirzaoff and Nicholas George, paper presented at the 1994 IEEE Dual Use Technologies and Applications Conference, 23-26 May 1994, SUNY Institute of Technology, Utica/Rome, NY.

"l/4-shifted nonlinear periodic structure: theory of low-intensity switching," Stojan Radic, Nicholas George, and Govind P. Agrawal, paper presented at the International Symposium on Guided-Wave Optoelectronics, Weber Research Institute, 26-28 October 1994, New York City, NY.

"Theory of low-threshold optical switching in nonlinear phase-shifted periodic structures," Stojan Radic, Nicholas George, and Govind P. Agrawal, J. Opt. Soc. Am. B. **12**, 671-680 (1995).

"Analysis of nonuniform nonlinear distributed feedback structures: generalized transfer matrix method," S. Radic, N. George, and G. P. Agrawal, IEEE J. Quantum Electron. **31**, 1326-1336 (1995).

"Low-threshold optical switching in non-uniform nonlinear distributed feedback structues," Stojan Radic, Nicholas George, and Govind Agrawal, Optics & Photonics News **6**, 18-19 (1995).

"Generalized distributed feedback design: amplification, filtering, and switching," Stojan Radic, Nicholas George, and Govind P. Agrawal, in *Physics and Simulation of Optoelectronic Devices III*, Proc. SPIE **2399**, 37-48 (1995).

"Object recognition and image coding," Nicholas George, B. J. Stossel, and D. M. Berfanger, invited paper presented at Takayanagi Memorial Session, Asia Display '95, Hamamatsu, Japan, October 1995.

"Multiple point impulse responses: controlled blurring and recovery," Bryan J. Stossel and Nicholas George, Opt. Comm. **121**, 156-165 (1995). *Erratum*, Opt. Comm. **122**, 212 (1996).

PATENTS

"Halftone correction system," Shen-Ge Wang, U.S. Patent No. 5,469,267, November 21, 1995.

"Color calibration for halftone printing," Shen-Ge Wang, application in process.

"Tone correction for ordered-dithering screens," Shen-Ge Wang, application in process.

LISTING OF PARTICIPATING SCIENTIFIC PERSONNEL

Nicholas George, Director, Center for Opto-Electronic Systems Research, Wilson Professor of Electronic Imaging, Professor of Optics, and Professor of Electrical Engineering

Shen-Ge Wang, Scientist in Optics
(Dr. Wang is now a scientist in the Imaging Science Laboratory at Xerox Corporation, Webster, NY).

Donald J. Schertler, Scientist in the Center for Electronic Imaging Systems
Dr. Schertler received his Ph.D. in 1993. Thesis title: "Wavelength and roughness dependence of backscattering"

Bryan J. Stossel, Scientist in Optics
Dr. Stossel received his Ph.D. in 1994. Thesis title: "Image processing, coding, and compression with multiple-point impluse response functions"

(Dr. Stossel is now a scientist at the Research Laboratories, Eastman Kodak Company, Rochester, NY)

David Berfranger, Ph.D. Fellow. Anticipated date of Ph.D. is June 1997. Thesis title: "Automatic pattern recognition using an all digital ring-wedge detector."

UNIVERSITY OF ROCHESTER

CENTER FOR ADVANCED TECHNOLOGY
ELECTRONIC IMAGING SYSTEMS

PROJECT REVIEW

TUESDAY, 21 JUNE 1994

TOPOGRAPHIC ENGINEERING CENTER

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GORDON GRIFFIN
STEVE HOLLANDSWORTH

UNIVERSITY OF ROCHESTER

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SHEN-GE WANG
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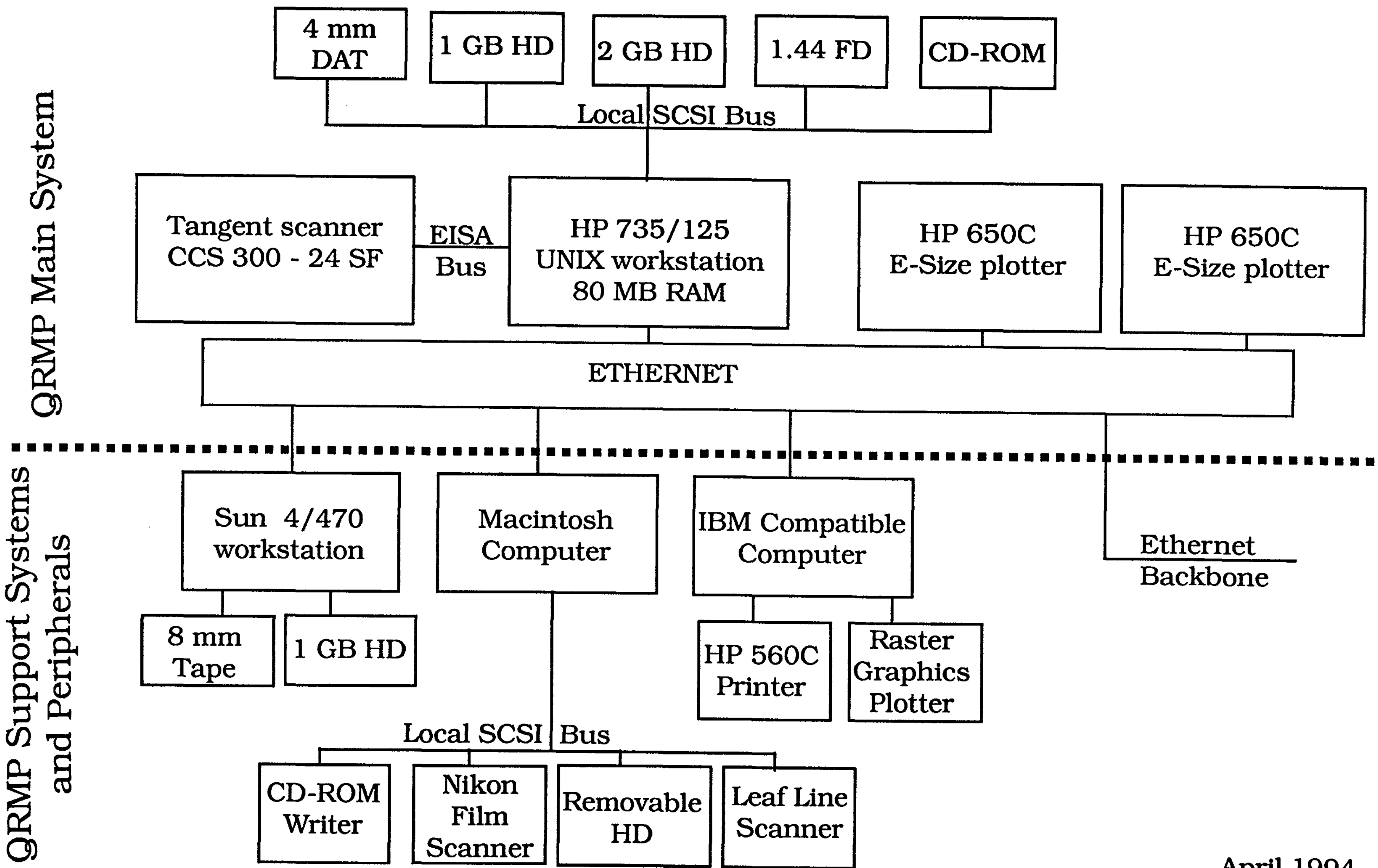
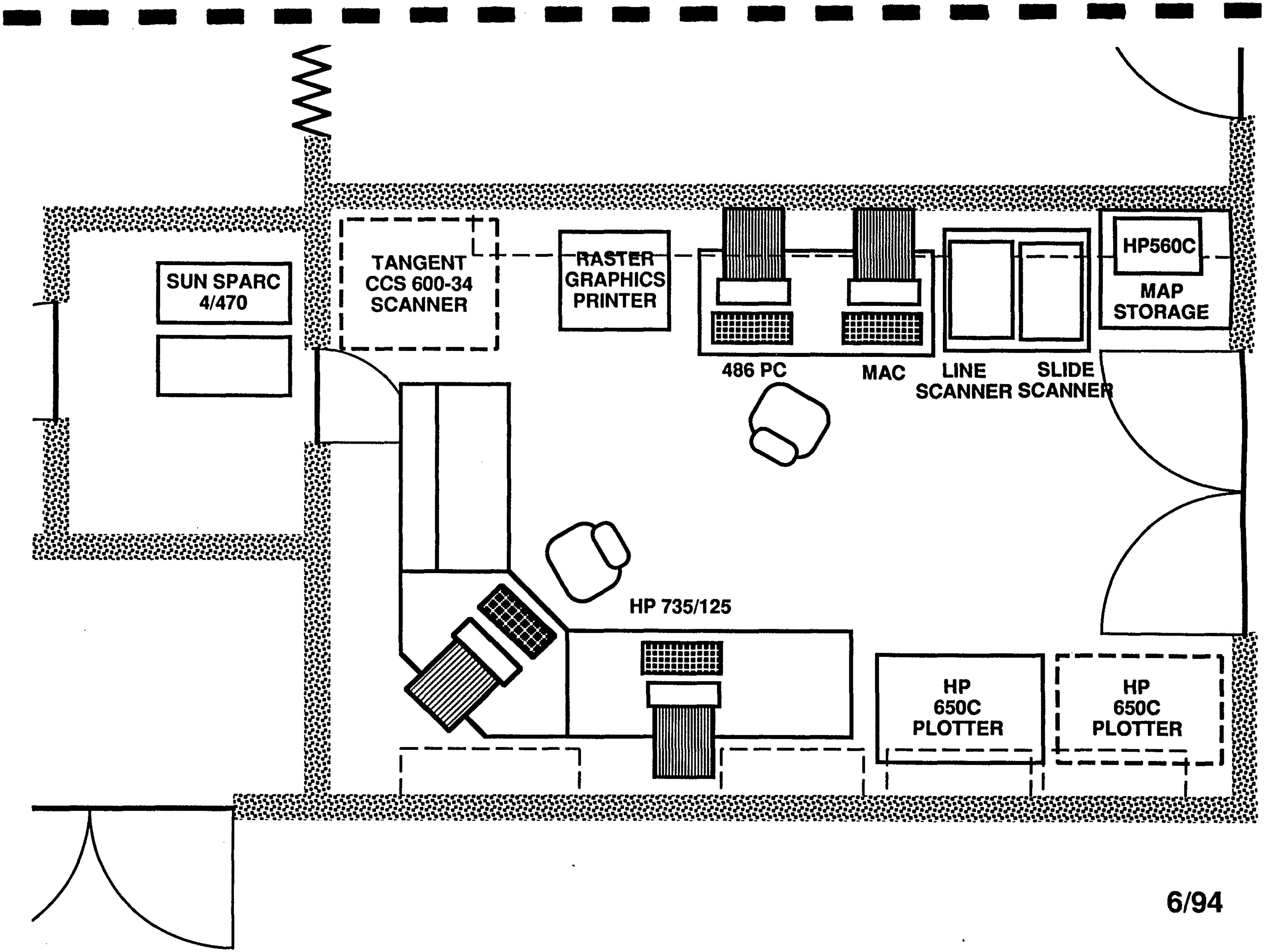
QRMP - UR Test Laboratory



April 1994


SUN SPARC 4/470
TANGENT CCS 600-34 SCANNER
RASTER GRAPHICS PRINTER
486 PC
MAC
LINE SCANNER
SLIDE SCANNER
HP560C
MAP STORAGE
HP 735/125
HP 650C PLOTTER
HP 650C PLOTTER

6/94

TEC QRMP EQUIPMENT PURCHASES

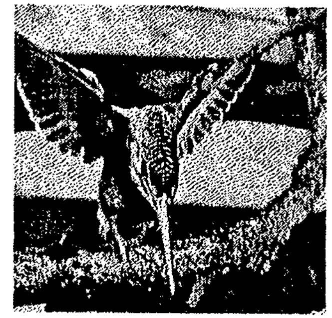
5-23780

		Status	Date
Hardware:			
1 *	HP735/125 Workstation (new product, 125 MHz CPU)	P.O. Placed Delivery expected	6/14/94 8/94
2 *	Tangent CCS 600-24SF	P.O. Placed Delivery expected	6/14/94 8/94
3 *	HP 650C Plotter	One received 2nd ordered	5/94 9/94
4	Nikon LS-3510 Film Scanner	Received	5/94
5	HP 560C A-Size Color Printer	Received	5/94
6	Leaf Line Scanner	Received	6/94
7	Pinnacle CD-Writer	P.O. Placed Delivery expected	6/15/94 6/94
8	Sun SPARC 470 Workstation, PC, MAC	Existing systems	
9	Raster Graphics Color Printer Electro Static	Received	4/94
10	Zoom Microscope	P.O. Placed	6/94
Software:			
1 *	HP-UX Operating System	Delivered with HP735	8/94
2 *	Tangent Color Document copying software (Scanner & Printer drivers)	Delivered with CCS 600	8/94
3	SUN OS, MS Windows, MAC OS	Existing	
4	Khoros I (Executable & Source) (Khoros II expected)	Existing (9/94)	
5	MAE (MAC Applications Environ.)	Demo. Disk	
6	Soft PC		

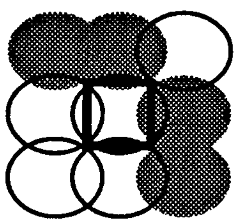
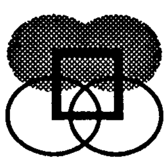
* QRMP prototype required

Dot-Overlapping Correction in Halftoning

Error Diffusion Without Correction

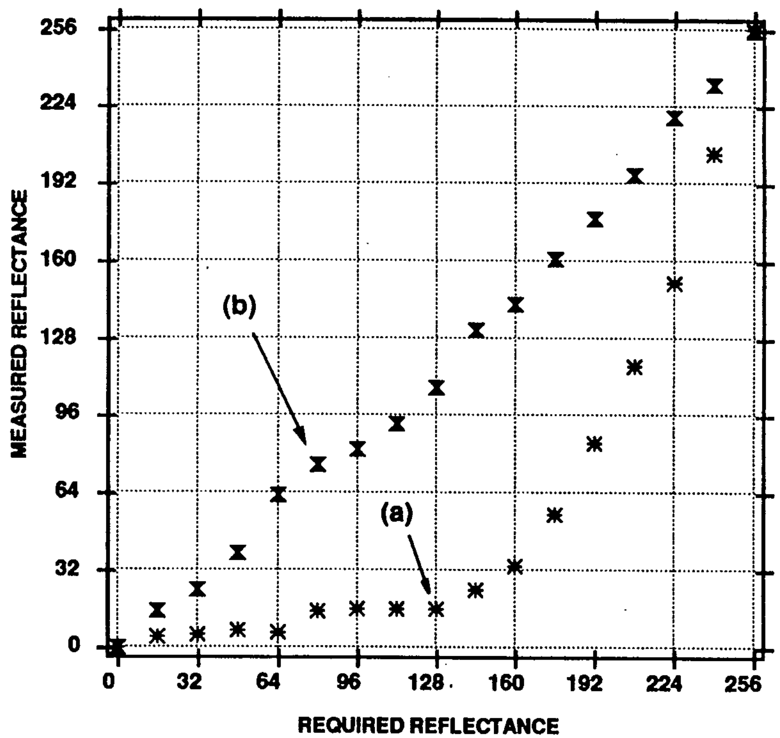


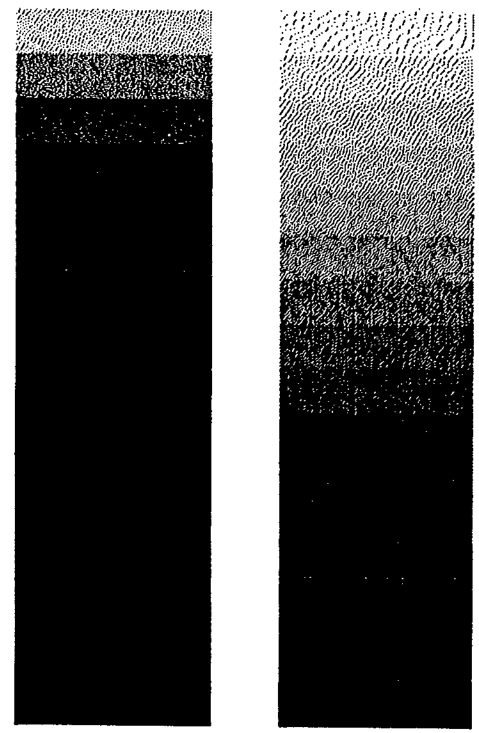
Centering Concept Applied

	Model-Based Correction	Test Patterns Needed	Overlapping Determination	Applied to Error Diffusion
	Current Approach *	200	Least-Square Optimization	5 Iterations
	TEC - Rochester New Centering Concept †	7	Direct	1 Run

* Pappas, Dong & Nuehoff (1993)
† S. Wang (Pat. Applied for 1994)

DOT-OVERLAPPING CORRECTION IN HALFTONING





(a) (b)

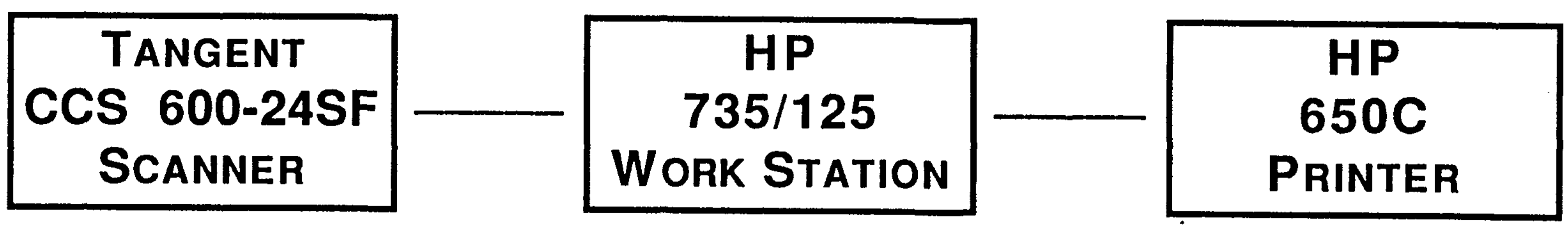
Distortion Self-Test
Illustrative Experiment

Error Budget:
1. Scanner
2. Printer
3. System Total: 0.1% (900 mm) 1mm/D Size

Printer Only:
a) Polyester Film (Stable)
b) HP Printer Paper

Differential Calibration Error ~0.4 mm

Next Stage:
Scanner, Printer Combined
Plan Careful Length Comparison



Color Management

1. Calibration of QRMP

   - Color Standard ANSI — Printer: IT 8.7/3 SCID; Scanner: Agfa IT8.7/1/2

   - Geometric Measurement

     - HP Plotter Calibration, Scanner Calibration, System Calibration — Distortion, MTF (Resolution), Color Registration

   - Design of test data base for QRMP

*2. Color Optimization for QRMP

   - Adaptive
   - System Approach (Scan + Print)
   - Highlight vs Background
   - Choice of Halftone Method
   - Choice of Compression

3. Interaction with TEC

   - Format
   - Specification
   - Test, Evaluation

*Planned Work

6/20/94

Halftoning Algorithm Development

Black-White Halftoning:

- Novel Centering Concept for Overlapping Correction
  - Paper / Transparency
    - (Patent Applied 5/94)
- Applications
  - To Error Diffusion
  - To Dithering
    - (IS&T Annual Meeting 5/94)
  - To Blue-Noise Mask
  - To Cluster & Void Mask
    - (OSA Annual Meeting 10/94)

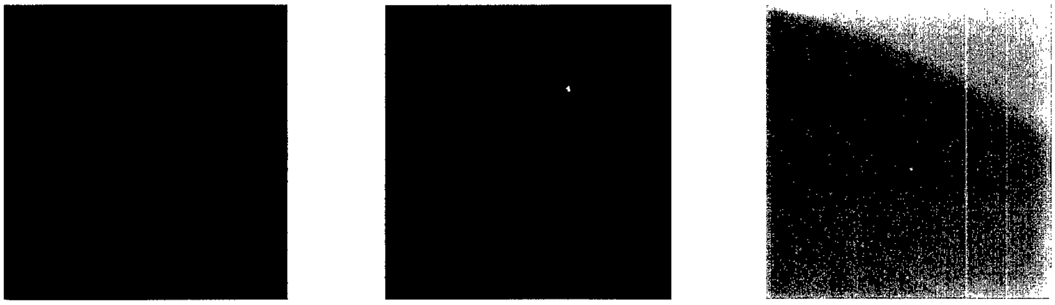
Planned Work on B&W Halftoning

- Edge Enhancement
- New Approach to Stochastic Screen
- Human-Vision Dependence
- Object-Dependent Halftoning

Color Halftoning:

RGB
CMYK
Color Compression
Stochastic Screens
Overlapping & Color Registration

Color Matching



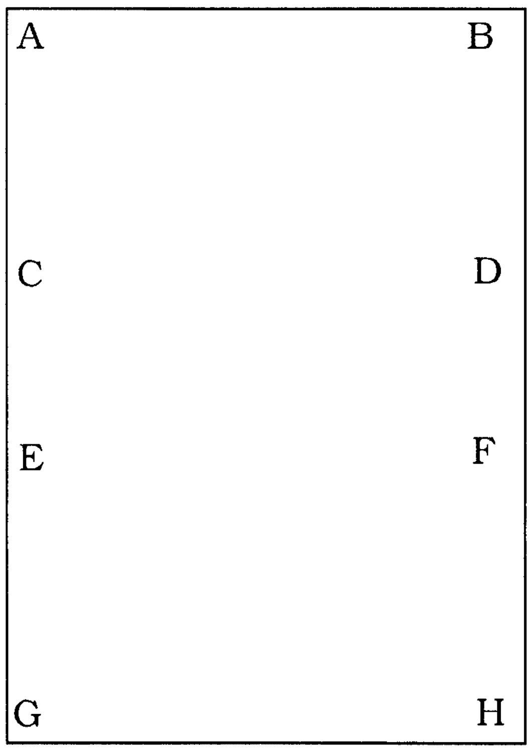
C_1 C_2 C_3

ΔE := Just-Noticeable-Difference

$\Delta E_{12} \approx 5$ $\Delta E_{23} \approx 50$

Printer Inconsistencies:

Print identical RGB color patches in two locations on page
(see following page)



Red: $\Delta E_{AB} \approx 5.8$

Yellow #1: $\Delta E_{CD} \approx 6.3$

Yellow #2: $\Delta E_{EF} \approx 3.8$

Green: $\Delta E_{GH} \approx 4.3$

Technical Progress Report No. 2 — September 1994

UNIVERSITY OF
ROCHESTER

CENTER FOR ADVANCED TECHNOLOGY
ELECTRONIC IMAGING SYSTEMS

Nicholas George
Director

September 15, 1994

MEMORANDUM

TO: B. D. Guenther

FROM: Nicholas George

SUBJECT: **Technology Transfer Report (September 1994)**

GRANT NUMBER: DAAH04-94-G-0062

GRANTEE NAME AND ADDRESS: Center for Electronic Imaging Systems (CEIS)
University of Rochester
The Institute of Optics
Rochester, NY 14627-0140

PRINCIPAL INVESTIGATOR: Dr. Nicholas George

RESEARCH TITLE: Halftoning Algorithms and Systems

ARO SCIENTIFIC OFFICER: Dr. B. D. Guenther

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Industry Principal
Xerox Corporation
Keith Knox
L. Dale Green
Charles Hains

Summary

We report on an important advancement in error diffusion algorithms for printing color maps. A patent has been applied for by Dr. Shen-Ge Wang of the University of Rochester. Significant technology transfer has been made directly to the Topographic Engineering Center (TEC) of the U.S. Army Corps of Engineers. This research has been leveraged by close interaction between the CEIS of the University of Rochester, the Xerox Corporation, TEC, and ARO. The details are described below.

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Relevance to the Electronic Imaging Industry

After the introduction of xerographic copiers, there was a long period in which many believed that printing high quality images using digital methods was impossible because the basic process of the xerographic copier is printing dark and light in a binary fashion. During the seventies many investigators recognized that the solution of the printing problem depends upon ingenious applications of sampling theory, or more broadly, communications theory. One very important analogy is worth mentioning. In printing images using films with a silver-bromide base, it is well-known that the development of silver on the film is also with a binary medium. Hence, many notions of fidelity and noise can be carried over from this older field. Topographic maps and maps of all types are important both to the civilian and the military sectors. The U.S. Army has established a long-term strategic plan for producing high-quality maps in the field with a system requirement designated: Quick Response Multicolor Printing (QRMP).

Plan of Approach

First, we have discovered a new sampling method, i.e., a new centering concept, for computing the overlapping correction in digital halftoning. This novel concept will greatly reduce the complexity in making the measurement-based overlapping correction. We are investigating corresponding halftoning algorithms and built-in-printer hardware for real-time monitoring and calibration in order to maintain the optimum performance of hard-copy devices [1]. Secondly, we plan to extend the new centering concept to multicolor halftoning studies. Modified halftoning algorithms will be examined in terms of color gamut and color reproduction. Multicolor test patterns will be designed for measurement-based overlapping correction. In this research we will find suitable color halftoning methods that will produce high quality, device independent, multicolor printouts while maintaining high data through-put. For the third topic we propose to conduct system research for multiplexed output devices. The research will be focused on architectures which provide support for a multi-output system. This program of research is heavily leveraged by participation from the ARO-URI Center for Opto-Electronic Systems Research, the new Center for Advanced Technology in Electronic Imaging Systems, and the industrial sponsors including several U.S. corporations who are leaders in imaging.

1. "Novel Centering Method for Overlapping Correction in Halftoning," Shen-Ge Wang, K. T. Knox, and Nicholas George, IS&T's 47th Annual Conference. The Physics and Chemistry of Imaging Systems, 15-20 May 1994.

UNIVERSITY OF ROCHESTER

CENTER FOR ELECTRONIC IMAGING SYSTEMS

HALFTONING ALGORITHMS AND SYSTEMS

COLOR MEASUREMENT REPORT

PREPARED FOR THE

U.S. ARMY TOPOGRAPHIC ENGINEERING CENTER

31 MAY 1995

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SHEN-GE WANG
BRYAN STOSSEL

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Overview

This report contains results obtained by the Optoelectronics Group of The Institute of Optics at the University of Rochester for the comparison of inks and media for the purpose of color ink jet printing. Particular attention is placed on topics of primary concern to TEC.

Three different combinations of inks and media are tested:

1) standard HP inks and HP special paper for the Hewlett Packard HP650C printer/plotter,
2) inks from American Ink Jet Corp. (AIJ) printed on media A supplied by AIJ, and
3) inks from AIJ printed on media B supplied by AIJ.

The first part of this report consists of data, both numerical and graphical, on the extent of the color gamut for the different ink and media combinations.

In addition to the gamut measurement data, example printouts for a pictorial scene as well as a typical ONC map are presented for comparison of the results obtained by the various inks and media.

Primary Color Printouts

The first data presented are printouts for the seven primary colors obtainable on the ink jet printer. Figure 1 contains the primary colors for the standard inks from Hewlett Packard using HP special paper. Figures 2 and 3 are the corresponding printouts using inks obtained from American Ink Jet Corp. as of 24 May 1995 using media supplied by AIJ, designated as media A and media B respectively.

A comparison of Figs. 1-3 show that the HP inks produce more saturated colors than the AIJ inks. We have also noticed that the upgraded AIJ inks represent a significant improvement in the amount of saturation from the previous AIJ ink samples which we tested. There are also several color hue shifts between the HP and AIJ inks, most notably in magenta which also effects the hue of red and blue.

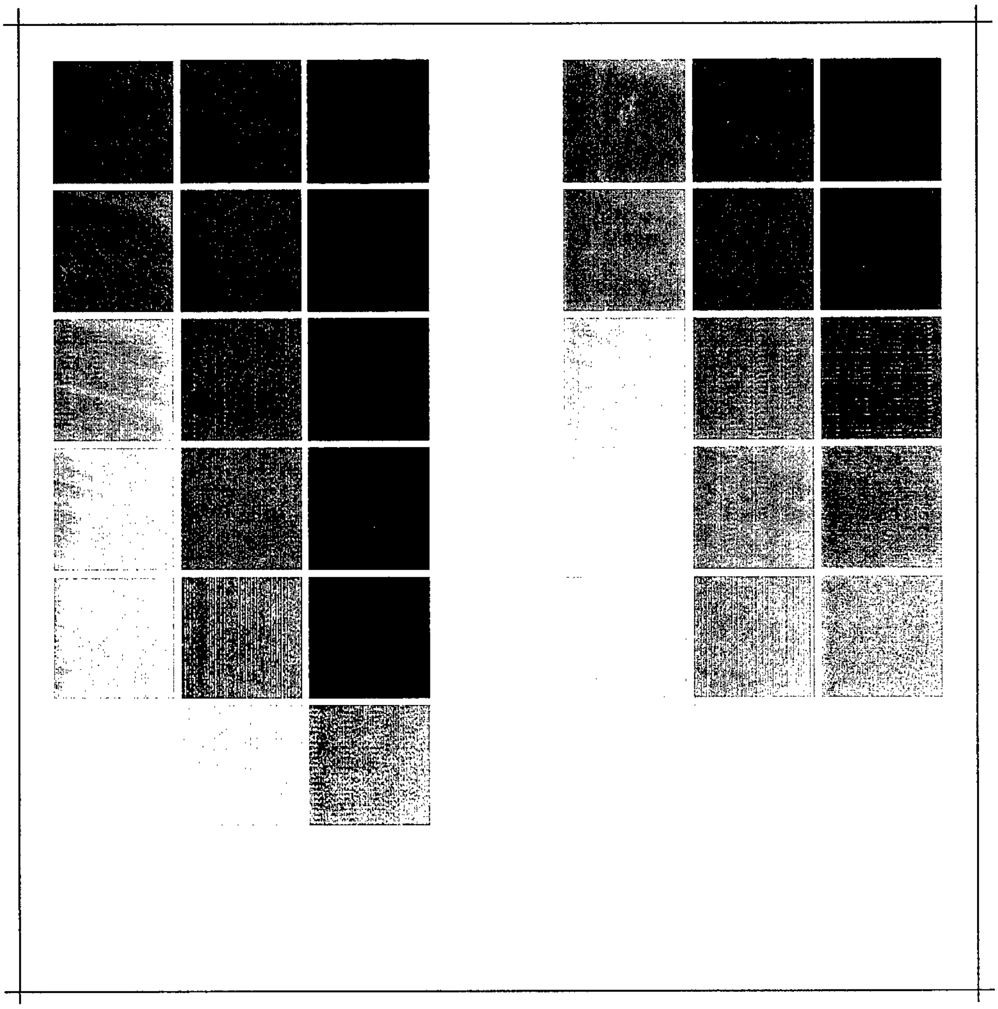


Fig. 1

HP ink - HP paper

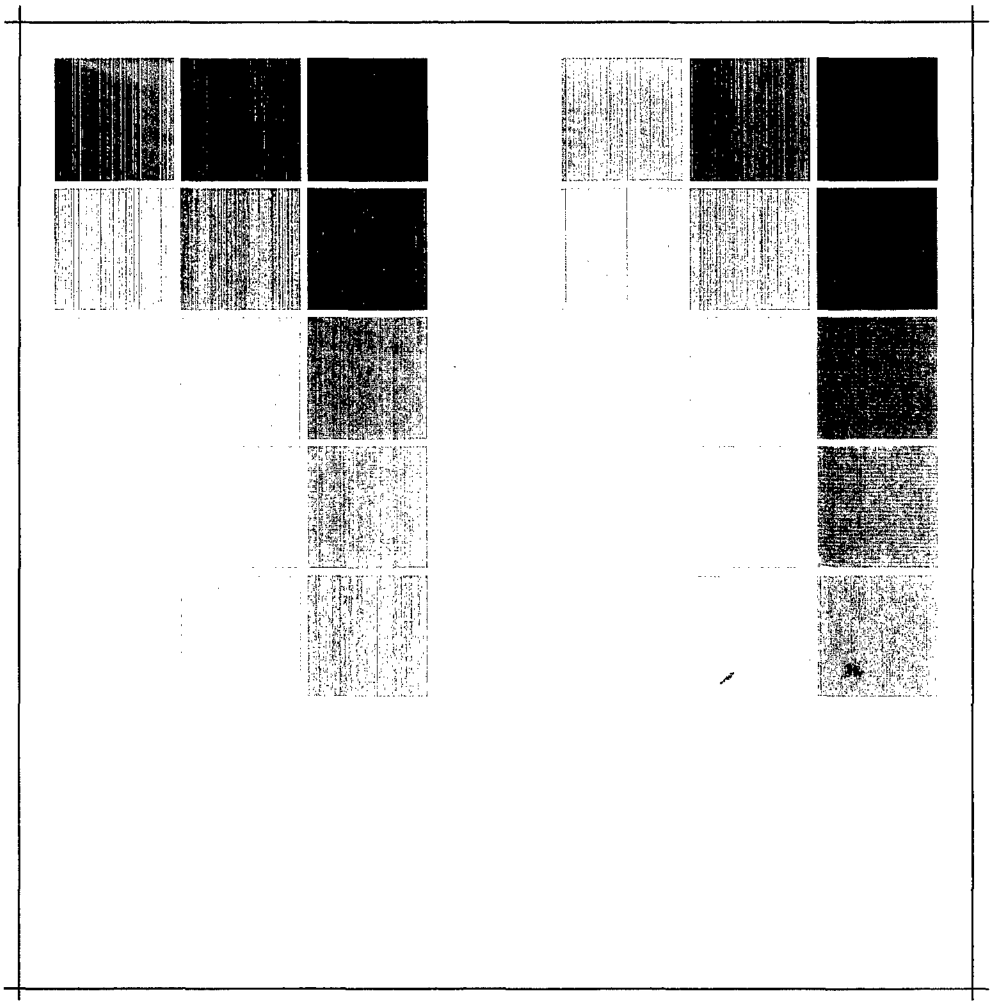


Fig. 2

AIJ - media A

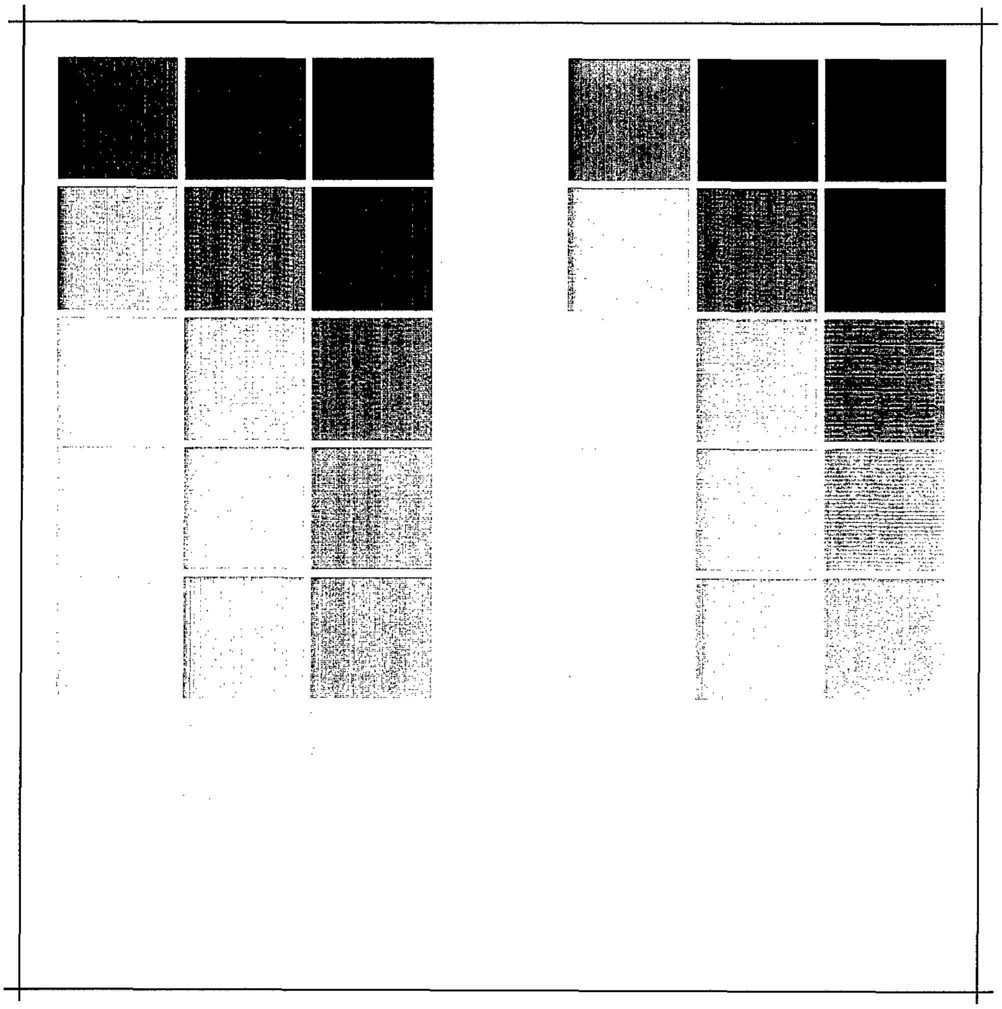


Fig. 3

AIJ - media B

Measurements of Primary Colors and Gamut Plot

Data regarding the color gamut of the ink/media combinations were obtained using a Gretag SPM100 spectrometer. These data are represented by the x-y-Y values of the CIE color standard and tabulated in Tables 1-3. These data correspond to the HP inks on HP paper, AIJ inks on media A, and AIJ inks on media B respectively. Included in each data set is a plot of the color gamut for the particular ink/media combination. This color gamut plot shows the extent of the printable colors limited by the x-y values of the six saturated primary colors. Beginning at the far right data point and continuing counterclockwise the data points correspond to red, yellow, green, cyan, blue, and magenta.

The plot in Figure 4 facilitates the comparison of the gamuts between each of the ink/media combinations. The data points connected by the yellow lines are for the HP inks on HP paper. The data for the AIJ inks on media A are connected by the red lines and the AIJ inks on media B are connected with red-orange lines. This plot confirms the visual observation made regarding Figs. 1-3. First both of the AIJ curves lie within the HP curve thus signifying that the HP inks remain more saturated than the AIJ inks. Secondly, the shifts of the red hues of the AIJ inks toward the orange and the magenta hues toward the red are clearly evident in this plot.

Also noticed in this plot is that the choice of media A or media B does not yield a significant difference between the printable gamuts of the AIJ inks. This result is verified visually by the color patches in Figs. 2 and 3.

			Color Gamut Measurements for Hp inks					
				using Hp Special paper				
				5/24/95				
Gretag settings:		Meas	Abs	D65	10	D65		
	x	y	Y					
White	0.3113	0.3284	91.52					
k-1	0.322	0.3379	3.88					
k-2	0.3196	0.3349	7.04					
k-3	0.3178	0.3331	11.29					
k-4	0.3171	0.3327	13.52					
k-5	0.3141	0.3301	16.4					
k-6	0.313	0.3293	34.57					
r-1	0.5348	0.3252	15.07					
r-2	0.5162	0.3281	16.81					
r-3	0.4728	0.3345	21.38					
r-4	0.4732	0.336	22.36					
r-5	0.465	0.3324	22.33					
r-6	0.385	0.3407	40.87					
g-1	0.2734	0.5204	20.33					
g-2	0.2855	0.5186	25.1					
g-3	0.2946	0.4889	33.97					
g-4	0.2952	0.494	33.68					
g-5	0.2936	0.4847	34.22					
g-6	0.3104	0.4105	54.33					
y-1	0.482	0.4649	63.33		c-1	0.1657	0.2725	33.87
y-2	0.4667	0.463	66.45		c-2	0.1812	0.2847	40.09
y-3	0.4354	0.448	72.26		c-3	0.2038	0.2958	48.08
y-4	0.4312	0.4438	72.58		c-4	0.2087	0.2972	49.01
y-5	0.419	0.4311	73.58		c-5	0.2132	0.2982	49.88
y-6	0.3705	0.3907	81.29		c-6	0.2523	0.3129	64.43
b-1	0.1605	0.1278	7.92		white	0.3106	0.3276	90.62
b-2	0.1631	0.1358	9.78		black	0.3217	0.3377	3.96
b-3	0.1758	0.1606	14.51		red	0.5344	0.3259	15.07
b-4	0.1748	0.1579	14.05		yellow	0.4821	0.4654	63.34
b-5	0.1791	0.1671	15.42		green	0.272	0.5201	20.53
b-6	0.2249	0.2323	32.28		cyan	0.1657	0.2727	34.08
					blue	0.1594	0.1277	7.98
m-1	0.3143	0.1716	17.8		magenta	0.3158	0.1716	17.73
m-2	0.3073	0.1788	21.02		red	0.5355	0.3255	15.12
m-3	0.2993	0.1977	27.51					
m-4	0.3008	0.2063	29.65					
m-5	0.3019	0.2174	32.33					
m-6	0.301	0.2599	49.87					

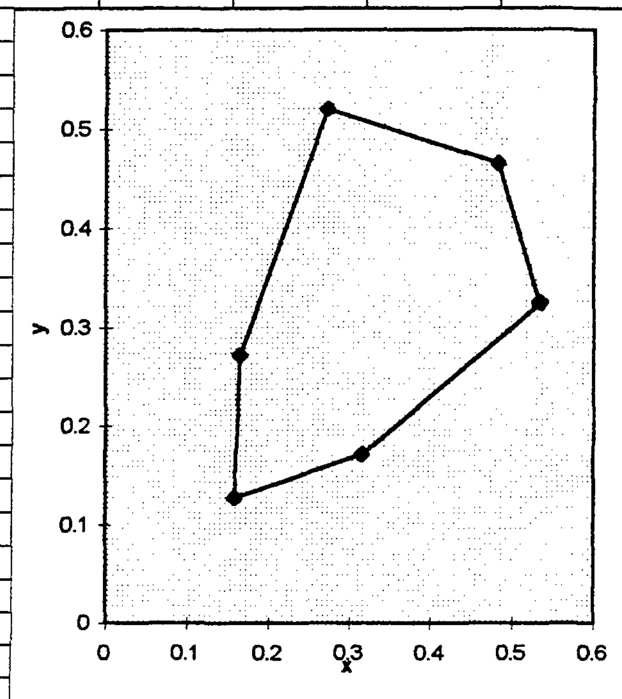


Table 1

			Color Gamut measurements for American InkJet inks					
				using AIJ A-paper				
					5/24/95			
Gretag settings:		Meas	Abs	D65	10	D65		
	x	y	Y			Color Gamut Plot		
White	0.3004	0.3168	85.39					
k-1	0.2916	0.3234	4.09					
k-2	0.293	0.3242	6.5					
k-3	0.2975	0.3247	12.85					
k-4	0.2988	0.3241	15.65					
k-5	0.2994	0.3239	17.29					
k-6	0.3013	0.3213	37.46					
r-1	0.5134	0.3485	22.26					
r-2	0.477	0.3571	28.33					
r-3	0.4301	0.3582	37.02					
r-4	0.4272	0.3622	39.25					
r-5	0.4005	0.3503	42.19					
r-6	0.3571	0.3396	55.92					
g-1	0.2939	0.5008	28.62					
g-2	0.3009	0.4626	35.55					
g-3	0.3054	0.4203	45.09					
g-4	0.3066	0.4116	46.67					
g-5	0.3078	0.4153	46.48					
g-6	0.3058	0.361	61.52					
					c-1	0.1898	0.2714	41.06
y-1	0.433	0.4623	68.74		c-2	0.2142	0.2835	48.26
y-2	0.4075	0.4385	71.48		c-3	0.2366	0.2943	56.88
y-3	0.3831	0.4163	74.22		c-4	0.2389	0.2945	57.31
y-4	0.3783	0.4097	73.45		c-5	0.2434	0.2962	57.5
y-5	0.3726	0.4019	74.59		c-6	0.2698	0.3064	69.01
y-6	0.3402	0.3656	78.18					
					white	0.3005	0.3164	85.16
b-1	0.2114	0.1874	11.6		black	0.2915	0.3235	4.16
b-2	0.2231	0.2129	17.57		red	0.5135	0.3464	22.05
b-3	0.2428	0.24	26.65		yellow	0.4326	0.4621	68.71
b-4	0.2451	0.2479	28.9		green	0.2931	0.5005	28.67
b-5	0.2497	0.2511	30.23		cyan	0.1916	0.2729	41.48
b-6	0.2761	0.2855	50.31		blue	0.2119	0.1897	11.83
					magenta	0.3706	0.2401	26.29
m-1	0.3697	0.2402	26.55		red	0.5135	0.3464	22.05
m-2	0.3504	0.2544	33.65					
m-3	0.3329	0.2671	42.83					
m-4	0.3296	0.2737	45.09					
m-5	0.3272	0.2788	47.77					
m-6	0.3141	0.2943	61.32					

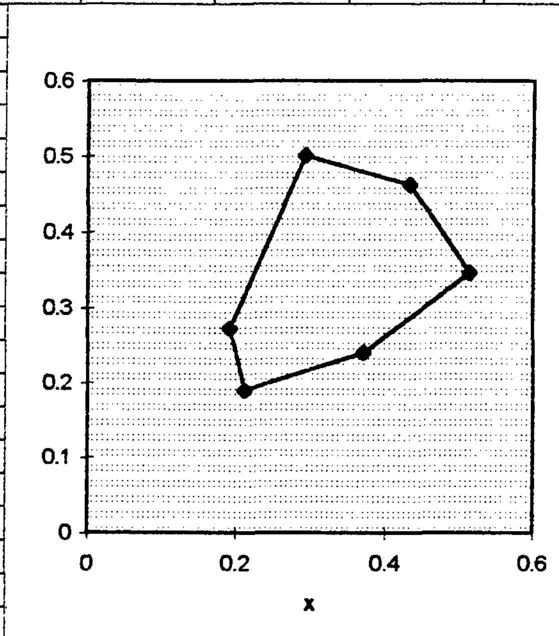


Table 2

			Color Gamut Measurements for American InkJet inks					
				using AIJ B-paper				
.				5/24/95				
	Gretag settings:		Meas	Abs	D65	10	D65	
	x	y	Y		Color Gamut Plot			
White	0.3046	0.3202	84.9					
k-1	0.2889	0.3231	4.03					
k-2	0.2957	0.3237	9.39					
k-3	0.2991	0.3246	16.36					
k-4	0.3006	0.3242	20.15					
k-5	0.3012	0.3235	22.87					
k-6	0.303	0.3222	41.99					
r-1	0.5094	0.3486	23.28					
r-2	0.4656	0.355	30.13					
r-3	0.4198	0.3559	39.82					
r-4	0.4166	0.3593	41.52					
r-5	0.3855	0.3404	44.06					
r-6	0.3505	0.3386	59.66					
g-1	0.2929	0.4855	30.4					
g-2	0.3023	0.442	38.64					
g-3	0.3082	0.4055	49.46					
g-4	0.3098	0.3999	50.28					
g-5	0.3078	0.3922	51.14					
g-6	0.3074	0.3547	65.66					
y-1	0.4249	0.4543	70.04		c-1	0.1993	0.2761	43.29
y-2	0.4002	0.4301	72.61		c-2	0.2209	0.2868	50.22
y-3	0.375	0.4051	75.71		c-3	0.2446	0.298	58.6
y-4	0.371	0.3997	76.04		c-4	0.2472	0.2987	59.45
y-5	0.3672	0.3944	76.06		c-5	0.2498	0.2993	60.05
y-6	0.3384	0.362	79.98		c-6	0.275	0.31	70.71
b-1	0.2116	0.19	12.11		white	0.3048	0.3203	84.74
b-2	0.2354	0.2221	19		black	0.289	0.3232	4.07
b-3	0.254	0.2508	29.71		red	0.5075	0.347	23.28
b-4	0.26	0.262	33.3		yellow	0.4268	0.4563	70.06
b-5	0.2637	0.2653	34.78		green	0.2939	0.482	30.85
b-6	0.2828	0.291	52.66		cyan	0.2013	0.2766	43.65
					blue	0.2111	0.1893	11.99
m-1	0.3682	0.2448	27.43		magenta	0.3693	0.2441	27.04
m-2	0.3485	0.2606	35.48		red	0.5075	0.347	23.28
m-3	0.332	0.2753	45.58					
m-4	0.3302	0.2791	47.32					
m-5	0.3279	0.2839	49.8					
m-6	0.3167	0.2987	62.9					

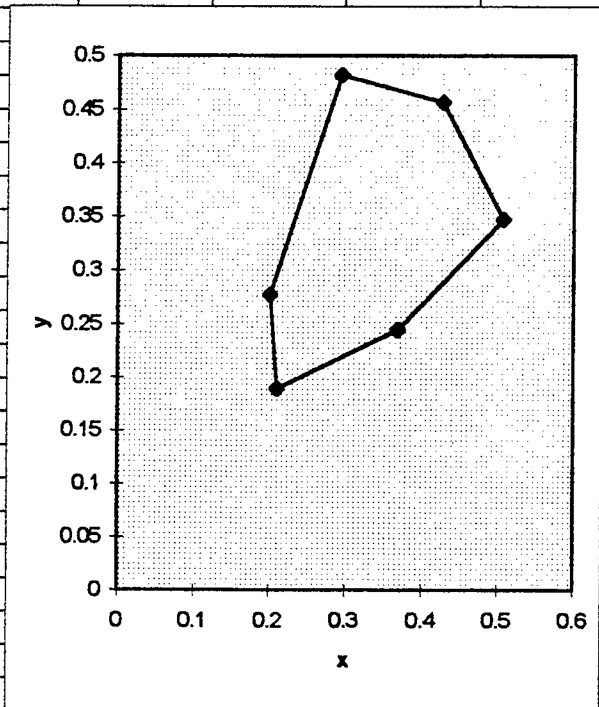
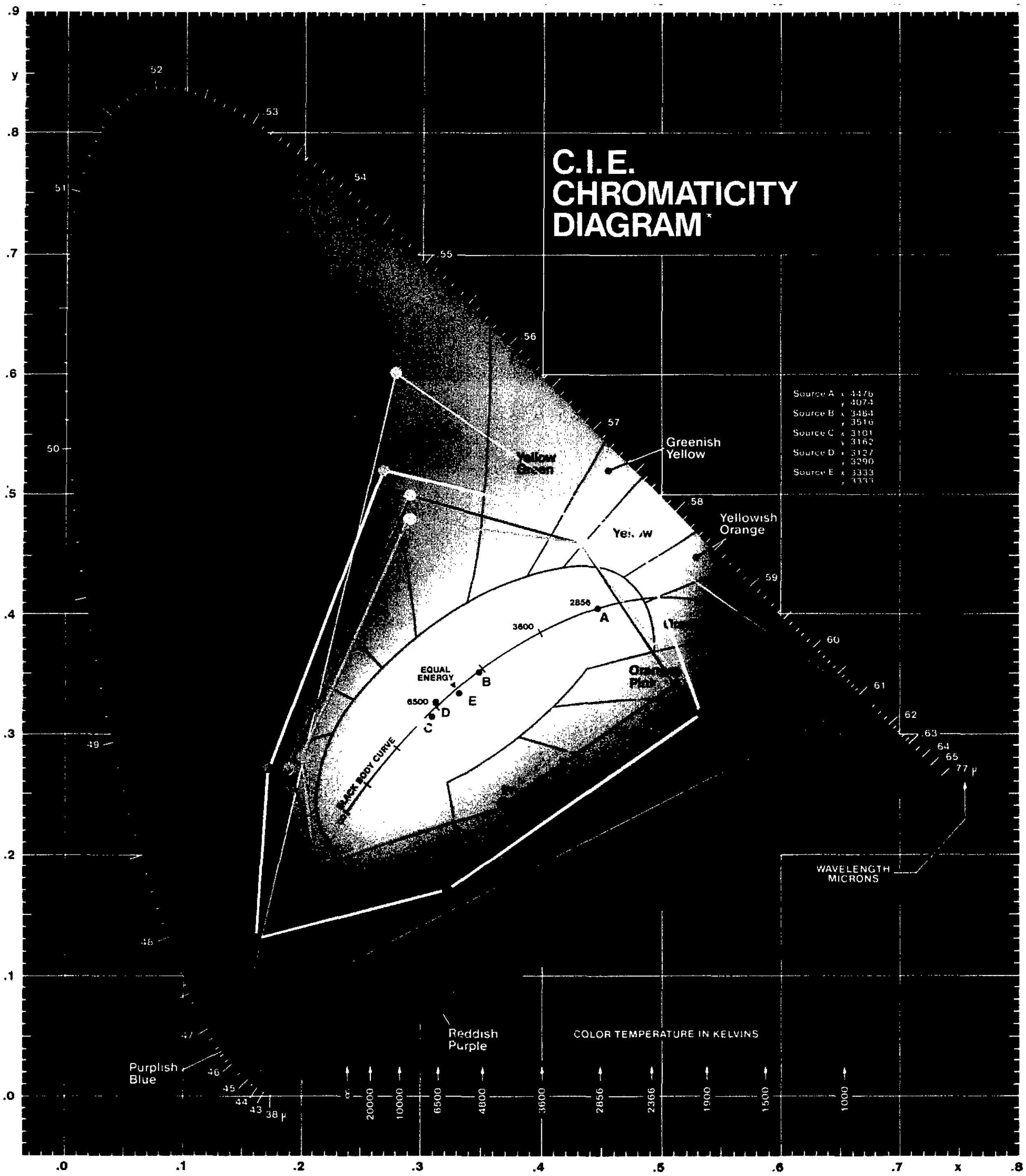


Table 3



Courtesy RCA Solid State Division, Electro Optics & Devices Courtesy Hoffman Engineering Corp. * CIE 1931 2° Standard Observer

Fig 4

Pictorial Images

Figures 5-7 show the results obtained when the same data are printed using the different ink/media combinations without the use of any color calibration procedures. In this case identical data were sent to the printer, the only difference being the inks and media. Figure 5 corresponds to the HP inks on HP paper. The amount of saturation obtained from the HP inks is clearly noticeable in this figure.

Figures 6 and 7 correspond to the same data printed using AIJ inks on media A and media B respectively. Again these images represent a significant improvement over printouts using previously obtained AIJ inks and yield more acceptable results. The increased amount of saturation is clearly evident in these prints.

A comparison of Figs. 6 and 7 with Fig. 5 again reveals the differences between the two inks. First the shift in hues obtained, most notably in the red of the apple and peppers, is clearly seen in these prints as the fruit appears more orange in the cases of the AIJ inks. Secondly both the blue in the napkin and the red of the fruit are not as saturated for the AIJ inks as the HP inks, thus yielding a less 'rich' image.

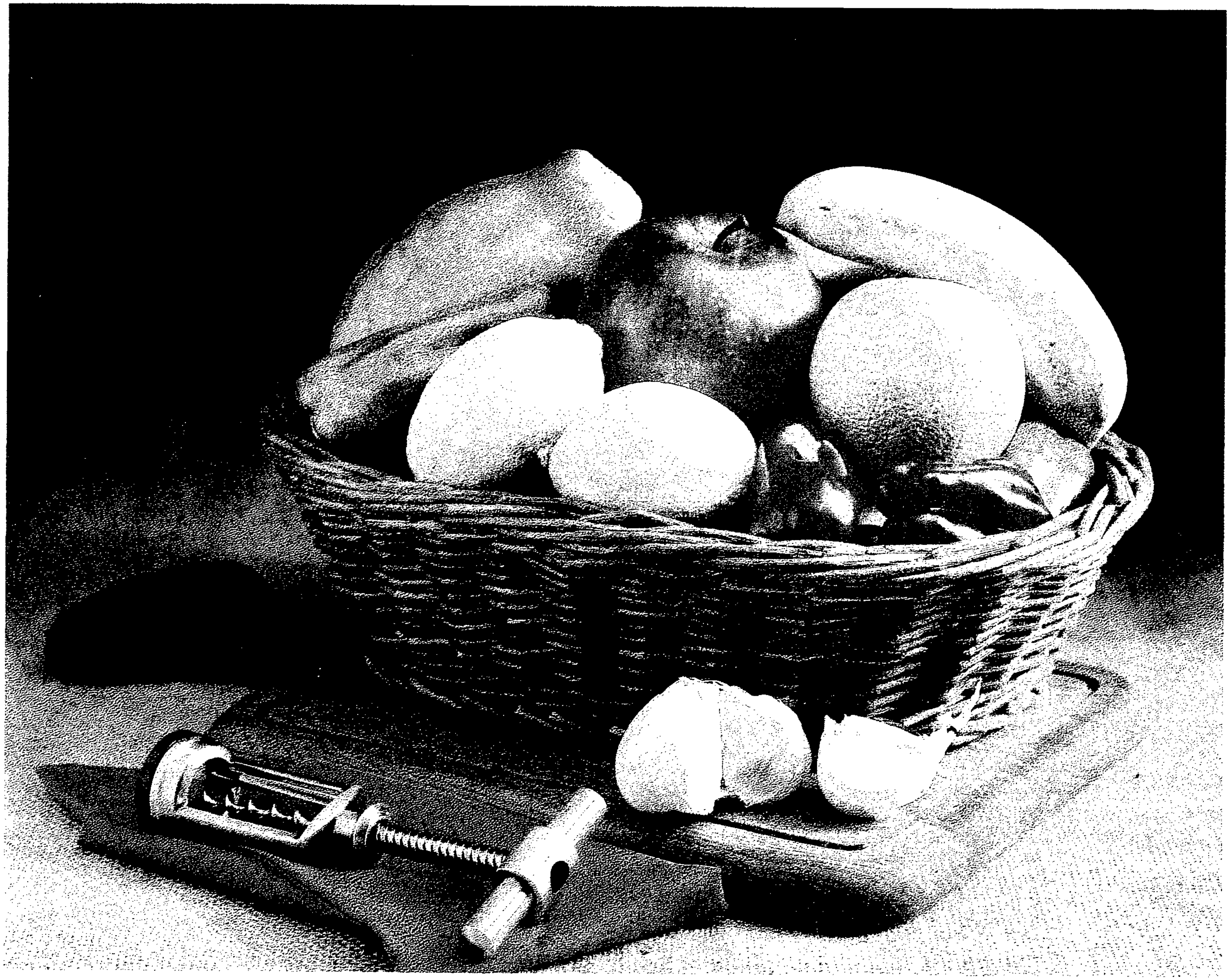


Fig. 5

Fig. 6
AIJ - media A

Fig. 7
AIJ - media B

Color Map Printing Using Color Calibration

Whereas the pictorial image did not involve any color calibration, the ONC maps shown in Figures 8-10 were obtained using the various ink/media combinations along with the color calibration procedures developed at the University of Rochester. The aim of these examples is to create visually similar prints using each of the inks and media.

Data obtained from the primary color measurements of Figs. 1-3 and tabulated in Tables 1-3 were used in the color calibration procedure to adapt the color halftoning algorithm to each of the ink/media combinations.

Figure 8 corresponds to the case of HP inks and HP paper, while Figs. 9 and 10 correspond to AIJ inks printed on media A and media B respectively. There is a slight, but noticeable, difference in the color appearance of these maps, but overall there is very good color matching obtained using the color calibration procedures with each of the ink/media combinations.

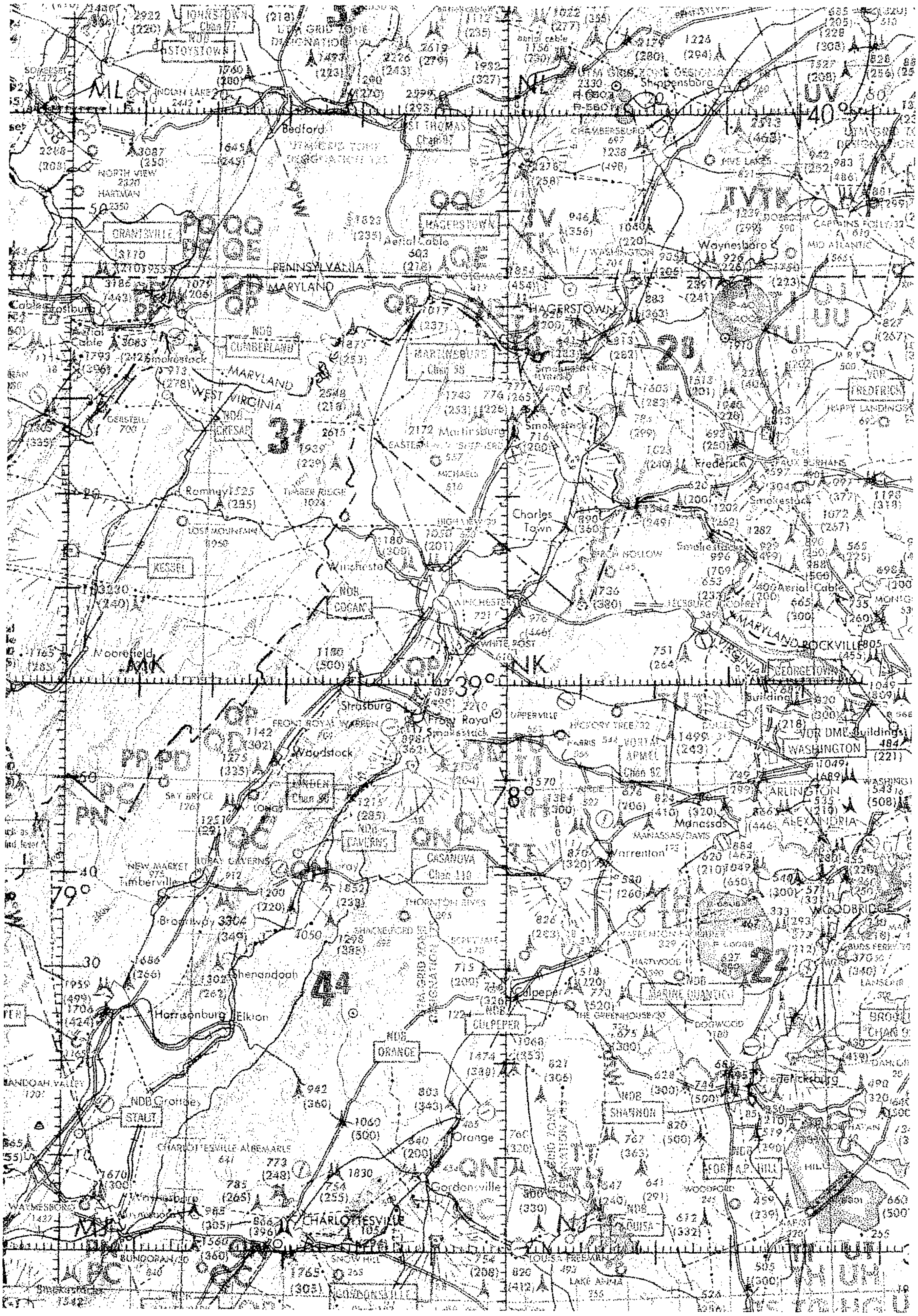


Fig. 8
HP paper - HP ink

-30 -30 -30 30

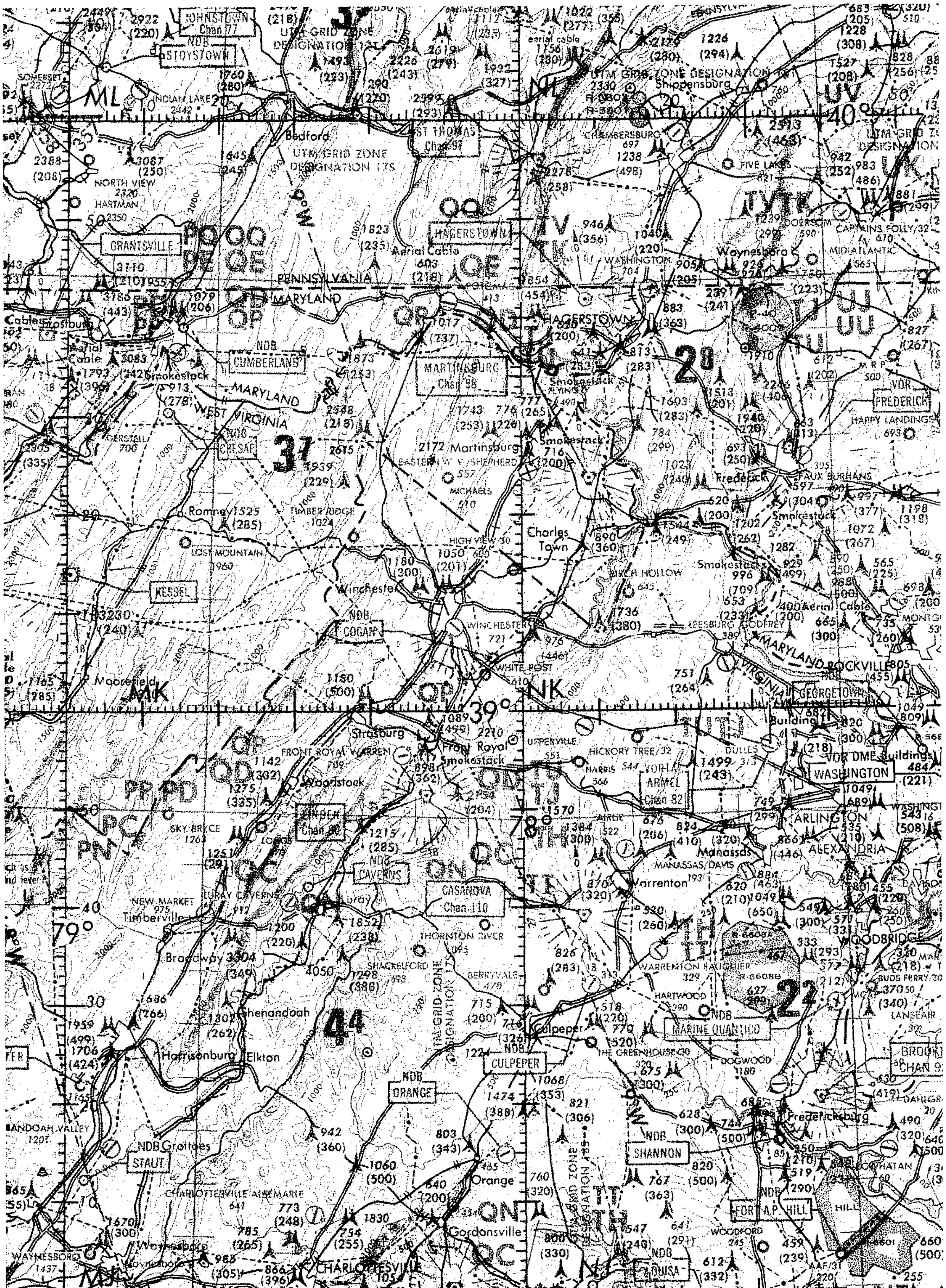


Fig. 9

AIJ - media A

0 0 0 30

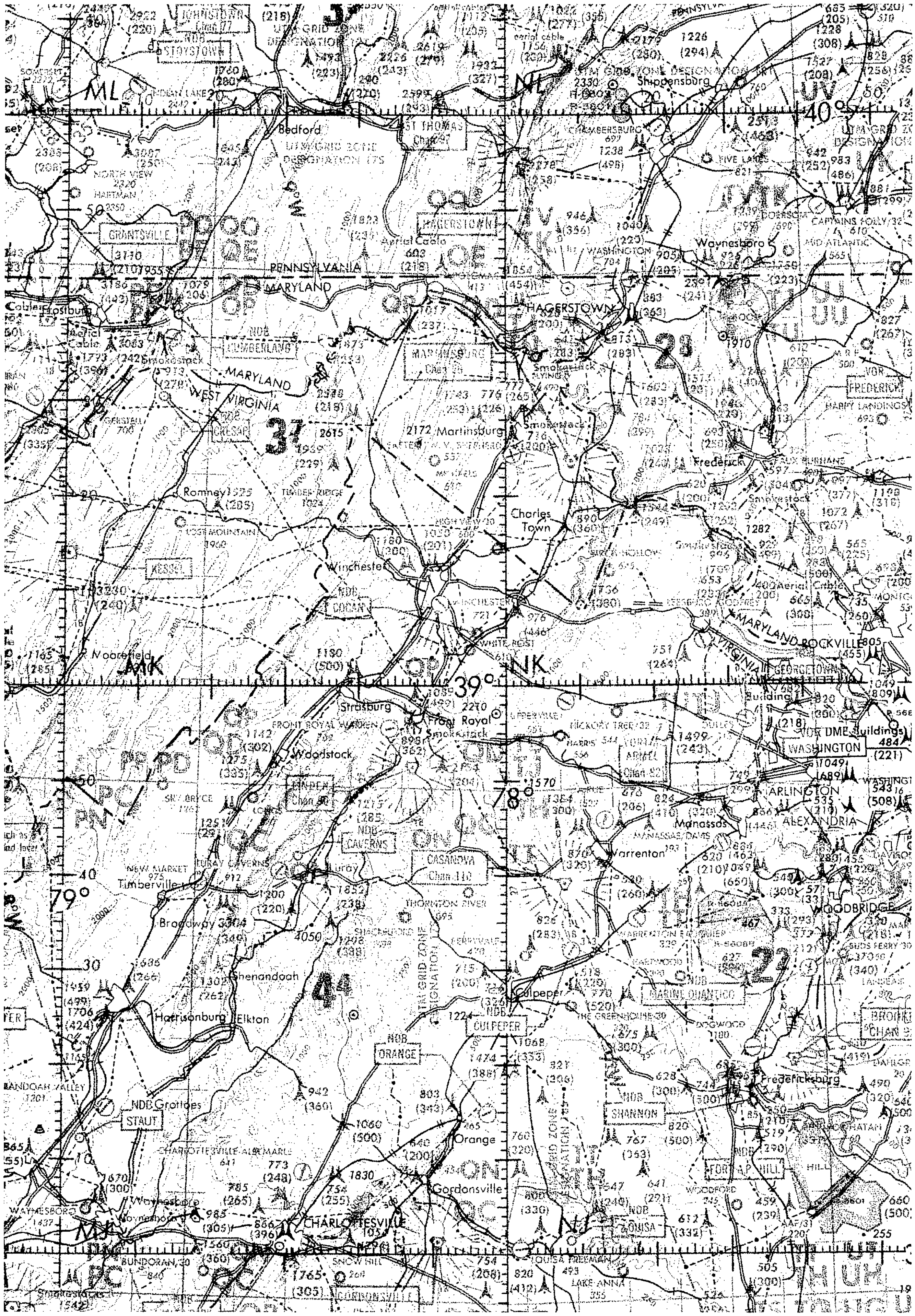


Fig 10

AIJ - media B

Concluding Remarks

The results presented here do not represent a comprehensive test. From these rudimentary tests we offer the following concluding remarks. The color printouts using the inks and media received in May 1995 from American Ink Jet Corp. have a significant improvement over previous trials. Although all primary colors from AIJ inks are less saturated than HP inks, there is a marked increase in the amount of saturation with the new AIJ inks. Compared with HP inks and HP paper there is a noticeable hue shift in the magenta as can be seen from Fig. 4, and this shift also effects the hues for both the red and blue. The amount of color saturation and hue shift may be objectionable for certain images. Using the color calibration procedure developed by the University of Rochester and incorporated into the software to be delivered to TEC, very good color matching between the printouts using the AIJ inks and the HP inks is obtained. For the majority of maps it does not appear to be an objectionable difference between the AIJ ink prints and those for the HP inks.

Other color tests may be performed by the University of Rochester in the future. Also a more extensive collection of example printouts can be prepared as needed. From past experience with other inks and media, it is suggested that color fastness be investigated for different inks and media, especially as pertaining to color fading.