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A Study on the Stability and the Utility of Satellite Droplets for Classification of Ink Jet Printers

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The author investigated the stability of satellite droplets as either class or individual characteristics in the printouts from 40 types of Hewlett-Packard and Canon ink jets. Observation established that satellite droplets produced by one ink jet device might vary in appearance with different print modes, ink, media and other factors. Given their lack of repeatability, they are not considered to be characteristics that can be relied upon by FDEs for ink jet printer classification or identification. However, the forensic value of satellite droplets should not be totally ignored. Their structure can indicate the properties of the ink, and possibly the brand of printer. They are very useful for ascertaining certain characteristics for ink jet classification, including halftone dot, nozzle arrangement, and stepping of paper feed. They can also assist in determining print modes, without which no ink jet output can be produced. Therefore, satellites should be taken into consideration when FDEs are examining an ink jet -printed document.

Introduction

As forensic research on the examination of ink jet printouts progresses, some features of ink jet printed documents have been recognized as valuable. Among the several widely recognized features, satellite droplets, which are inevitably caused by current ink jet technologies, remain undefined in terms of the usefulness. The shape of an ejected main droplet and its satellites on a printout - regardless of the recording media's condition - are determined by a combination of factors including the designs of ink reservoir and heater, nozzle geometry, the volume and velocity of ejected droplets, the operating voltage of the electrical pulse, ink properties, and so forth. Printer to printer differences as to these factors cause satellites to vary with different printers. In order to employ satellites as a characteristic for classification or identification of printers, it is necessary to determine the repeatability of satellites.

In this study the goal was to investigate the stability of satellites and their forensic value. The printouts from thermal ink jets and bubble jets, represented by Hewlett-Packard (abbr. HP) and Canon respectively, were tested, along with a few printouts from Epson piezoelectric ink jets. According to recent research which has focused on the mechanism of droplet formation, physical properties of ink influence the tail length of an ejected droplet. Longer tail length increases the chances of the formation of satellite droplets. These ink properties include density, viscosity, viscoelasticity and surface tension. In addition, print head stepping determines the speed of print head movement in different print modes[1]. Based on the theories mentioned above, it was assumed that different factors lead to droplet tails landing at irregular distances or locations from primary drops. Therefore, in this study, experiments were designed to answer the following problems:

1. How do satellites appear in various parts of a single printout?
2. How do print modes influence the appearance of satellites in printouts?
3. How do ink properties influence the appear-

[1]An ink jet printer has at least two essential stepper motors: one is responsible for moving a print head assembly horizontally across the paper to spray ink drops; the other is for advancing a sheet of paper passing through a printer step by step in a decided increment. Both of these motors cooperate with each other to ensure normal printing. Only the step of a print head is difficult to perceive.

ance of satellites in printouts?

4. How do satellites morphologically vary with the paper variation?

Methods and Materials

Forty types of thermal ink jet and bubble jet printers were investigated experimentally, mainly focusing on Hewlett-Packard and Canon (see Table 1). Some Epson piezoelectric ink jet printers were also tested for comparison with thermal printers. The printing samples (A4) consisted of the same standard content with Microsoft Word, comprising text, graphics (including Chinese Characters) and images (see Figure1).

Among the aforesaid factors that influence the formation of satellites, the print head geometry and operating conditions were regarded as fixed if printers function normally. The variables in the experiments were print mode, ink property, and recording medium. The sampled ink jets were set up to print under the following selected conditions:

1. Print modes:
   - Fast/Draft
   - Fast Normal (only for HP ink jets)
   - Normal/Standard
   - Best

   Plain Paper and Photo Paper were used

   Print media:
   - Machine-glazed paper (30g, unknown brand)
   - Glossy paper(80g, produced by Siwei Industrial Corporation Limited, China)
   - Copier/printer paper (Gold Flagship Multi-purpose Paper 70g, Double A Copier Paper 80g)
   - Ink jet paper (Epson Photo Quality Ink Jet Paper)
   - Photo paper (Epson Economy Photo Paper)

2. Ink: OEM ink, compatible ink or third party ink. (OEM is the abbreviation of Original Equipment Manufacturer.)

Each tested printer was sampled at 20-30°C room temperature and 40%-70% Relative Humidity. After sampling, all printouts produced were subjected to scrutiny and photomicrographic comparison. To reduce interference, the ink dots and their satellites within print areas where malfunctions or defects occur were an eliminated in this study. The instruments used in the study were Olympus BX51 System microscope (the 5X objective lens was used to photograph all the illustrations in this paper) with a Media Cybernetics Evolution MP 5.0 mega-pixel camera and Image Pro Plus 5.1 software.

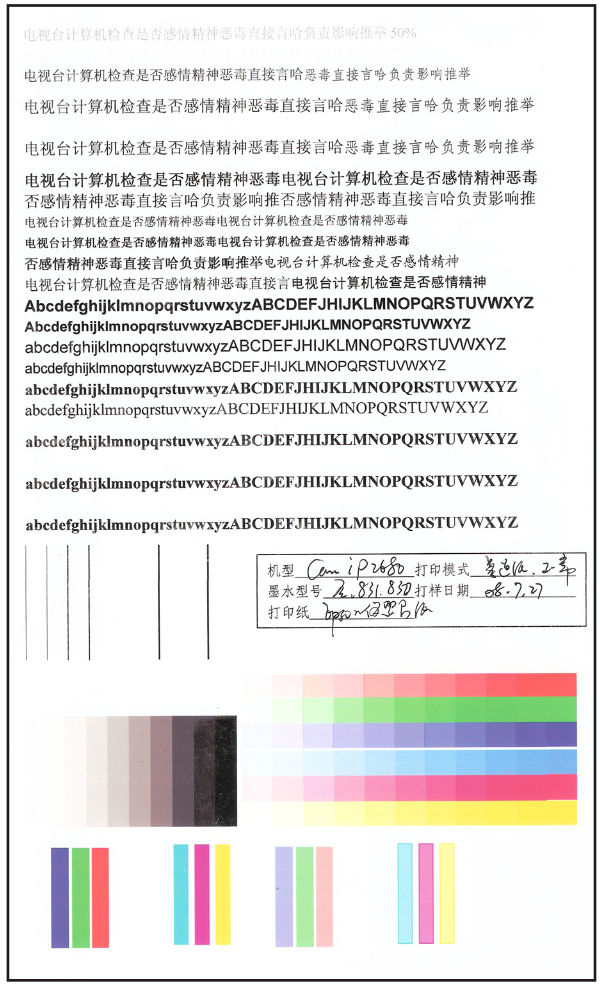


Figure 1 A page of standard sample in the study

Results

The microscopic scrutiny was focused on some parts of each printed sample, mainly in black and gray text, lightest parts of halftone images, and other parts where satellites were distinguishable. The satellites of both black and color ink drops were investigated.

1. Satellite Appearance in Various Parts of a Single Printout

It was observed that a unit of typical Canon satellites consisted of a dot smaller than the main drop followed by a tiny dot, which was farther away from the main dot (see Figure 2). A main ink

Canon	bjc-210sp/ bjc-255sp/ bjc-265sp/ bjc-1000sp/ bjc-4310sp/ bjc-4650/ i6100/ S6300/s900/ s200sp/ i950/ i255/ i320 /i455/ i70/iP1000/ iP1200/iP1600/ iP2200/iP1880/iP1980/ iP2680/ iX4000/ MP 338
Hewlett-Packard	Deskjet 656c/840c/1120c/1125c/1180c/1280/930c/920c/3820/3325/ 3658/3748/3938/9808/9868/D4168/ psc2110/psc6110 Officjet4255/5510/5608, Photosmart 7550

Table 1 The list of 40 types of tested ink jet printers in the study.

Note: 46 models included. Some models are duplicates in terms of the hardware and the software they are equipped with for printing.

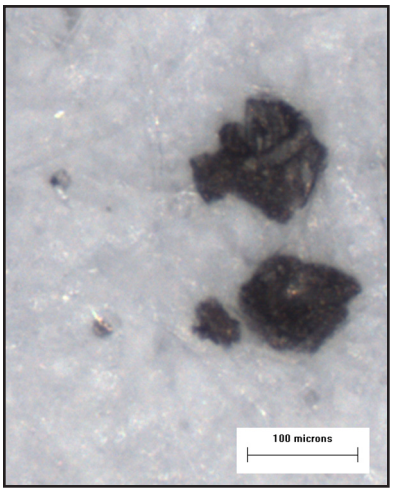


Figure 2a

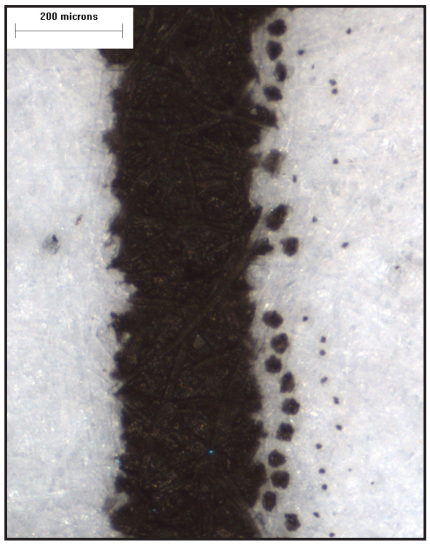


Figure 2b

Figure 2c

Figure 2 Depiction of the satellites generated by three Canon devices. 2a (more magnified than 2b and 2c) shows individual main drops with their satellites; 2b shows the bigger and tiny satellites both visible beside a line; 2c shows only tiny satellites visible along with a line.

dot from an HP printer was normally followed by several small dots with a bigger one at the end of a satellite tail (see Figure 3a, 3b).

However, on a sample page without apparent defects, there is variation in the satellites at different locations. With the Canon model, sometimes the bigger satellite droplets were merged into the edge of a character (see Figure 2c); sometimes the tiny dots did not appear. Their distances from the primary ink dots were variable, though within a certain range. There was a similar situation with satellite tail length and droplet size on HP samples.

Multiple specimens of the same models of printer were also experimented upon to produce consistent, repeatable results. For example: printed samples from the HP 920c 5 devices, HP Officejet 5608 2 devices, with their respective OEM ink cartridges, and printed samples from Canon iP1000 with the same OEM ink cartridge printed at the interval of months. The outcomes were similar: the satellites from the same model or same cartridge had the same patterns, but with variations in quantity, length, and location of satellite droplets. Therefore, after a vain attempt at quantitative analysis, the author concludes that a mathematical measurement is not applicable here.

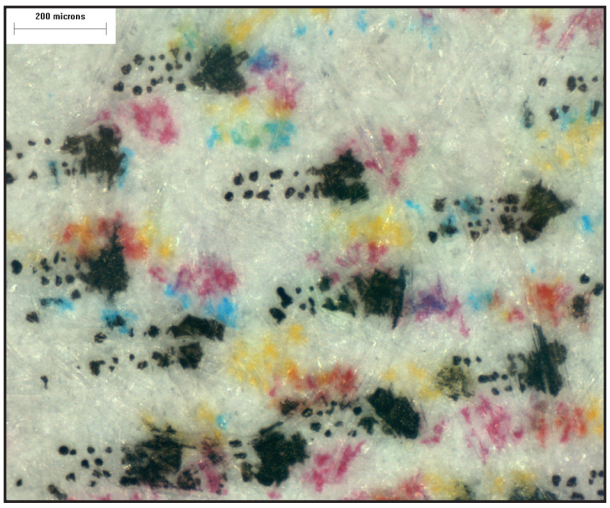


Figure 3a

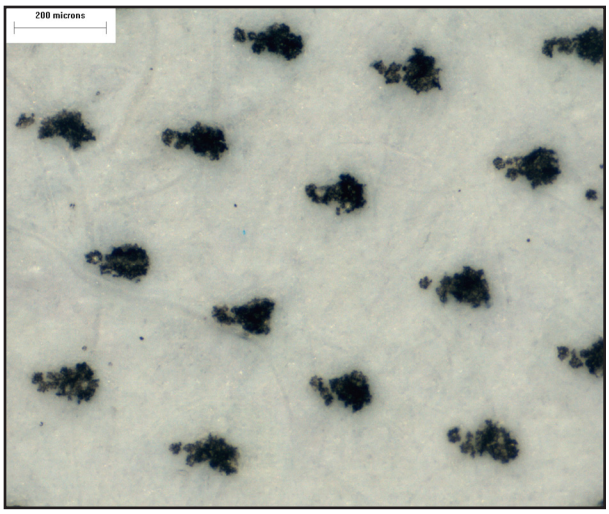


Figure 3b

Figure 3 The comparison of black dots and their satellites produced by HP D4168 in Fast mode (Figure 3a) and Normal mode (Figure 3b).

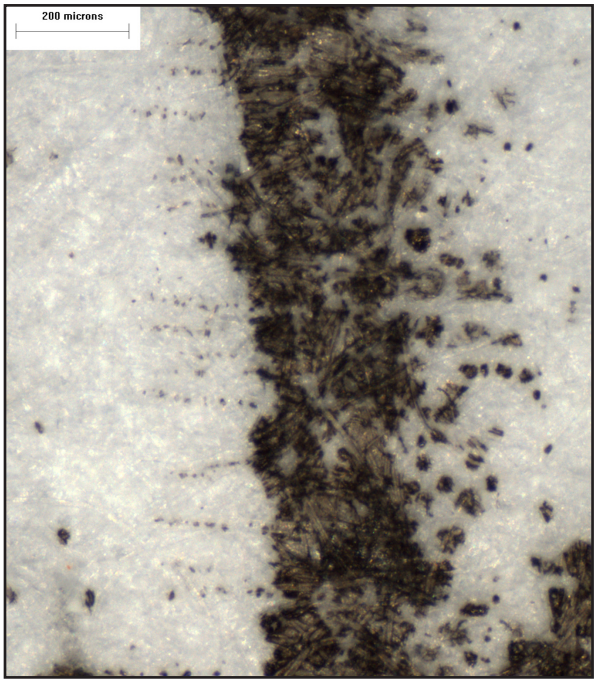


Figure 4a

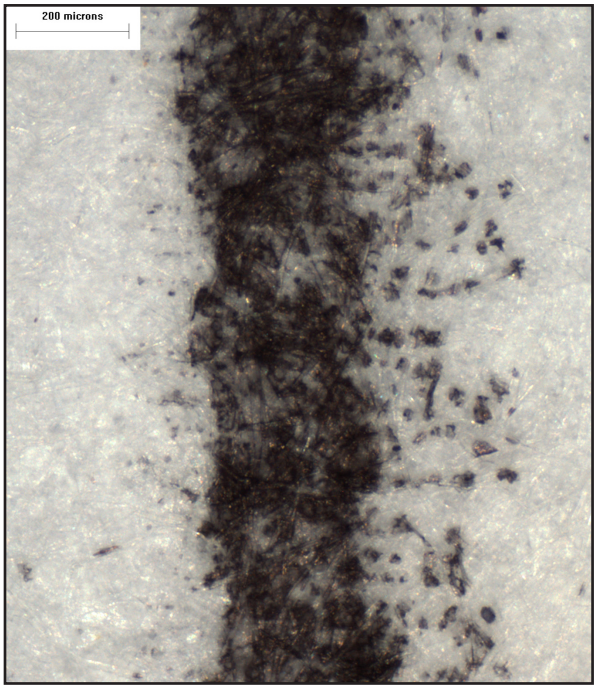


Figure 4b

Figure 4 The comparison of the parts of characters printed by a same device of HP Officejet 5608 in Fast mode with OEM ink (Figure 4a) and third-party ink (Figure 4b). To the right of the lines are the satellites; to the left are unidentified ink marks which will be discussed later in this article.

2. Print Modes and Satellites

Observation and comparison showed that satellites of black droplets produced by all tested Canon devices and some older HP devices, such as HP Deskjet 656c/840c/1125c/930c/920c, kept their basic form and structure in Fast and Standard print modes. It is worth pointing out that the satellites produced by other HP models (most of them are newer models) vary for different modes in terms of the quantity of droplets and the length of the tail (see Figure 3). This might be due to the fact that these HP ink jets were

Figure 5a

Figure 5b

Figure 5c

Figure 5 The comparison of satellites produced by the same Canon iP1000 in same print mode but with OEM ink (Figure 5a),and two kinds of third-party ink (Figure 5b, Figure 5c)

configured with different stepping for their print heads to advance the paper at different speeds. Subsequently longer tails are formed in Fast mode and shorter tails in higher quality modes. Color drops had similar appearances compared with black ones, but are, in some cases, indistinguishable e on a plain paper due to the lower contrast and the effect of absorption and penetration between ink and paper.

3. Ink Properties and Variation of Satellites

Generally, ink jet printers are equipped with dye ink or pigment ink by OEMs. The satellites of pigment ink droplets are apparent and farther from the main droplet. The satellites produced by ink jet printers with dye inks are normally smaller and closer to the primary dot. Due to the osmosis effect, they have irregular shapes or are difficult to find. For instance, Canon S900 and Canon i950, which are primarily used to produce photos, are equipped with dye ink both in black and color cartridges. Likewise, because older models of Canon (Bubble Jet Color series) are equipped with dye ink in their color cartridges, the satellites produced are often not discernable. Apart from the above examples, most of the ink jets tested are equipped with pigment ink in both black and color cartridges by the OEMs.

Each printer was tested with OEM ink and third-party ink respectively, keeping the other printing conditions the same. The satellites from the same devices vary to a certain extent depending on the differences in density, viscosity, and surface tension between the OEM ink and the third-party ink. Figure 4 and Figure 5 show two examples of the relatively small variation. If the pigment OEM ink is displaced by third-party dye ink, the features of satellites will change dramatically.

4. Paper Variable and its Effect on Satellites

With other printing conditions constant, the experiments of recording media show that the different effects of absorption and penetration of paper do not influence the distribution and structure of satellite droplets; however, the shape and the size were somewhat affected (see Figure 6).

If both the ink and the medium are changed, the combination causes so tremendous a change to the satellites that no valid conclusions can be reached (see Figure 7).

Discussion

There are many factors which influence the formation of satellite droplets. Due to their lack of repeatability, satellite droplets should not be considered as reliable characteristics for identifying printing devices or types of devices.

However, there is some forensic value of satellites, which was unexpected at the beginning of this study. During the course of the study on the stability of satellites, along with studies on other characteristics, such as halftone dot, nozzle arrangement, and the stepping of paper feed, the author realized the significant roles of satellites

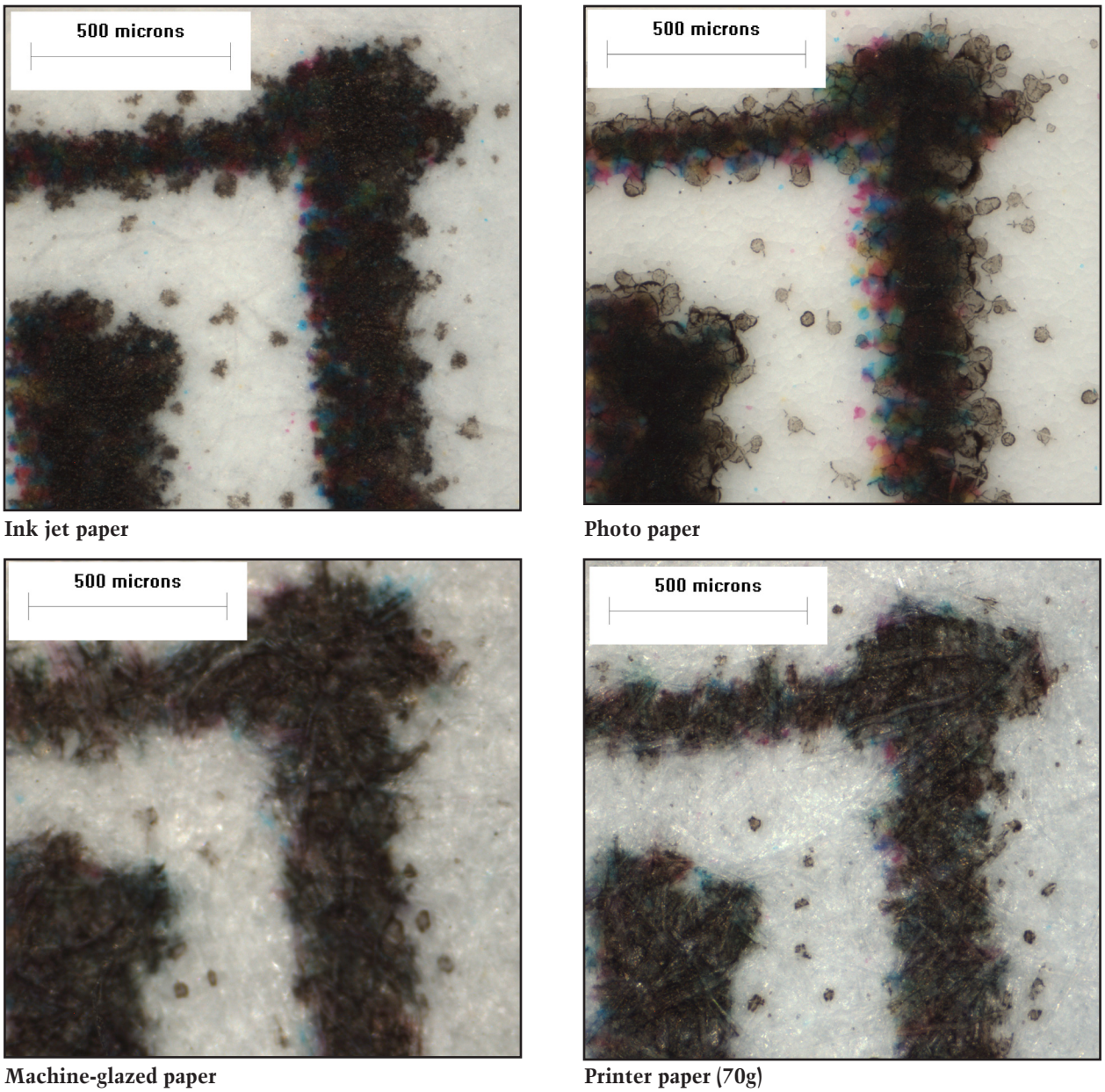


Figure 6 The comparison of satellites produced by the same HP Deskjet 930c printer but on four different papers.

for ink jet classification.

1. Typical Satellites as an Indication of Ink jet Brand

Most tested Canon devices produce similar satellites which comprise a bigger ink dot and a tiny dot (see Table 2). The tiny dot, which might be produced due to the ink splatter, is farther away from the main dot and the bigger satellite droplet. This remains to be proved by more sophisticated experiments. The author has studied printed samples from more than 70 models from HP, Epson, Lexmark, and Lenovo manufacturers. None of HP and Epson devices were found to possess this kind of satellite. However, some devices of Lenovo and Lexmark generated similar forms of satellites. One must be cautious when analyzing these kinds of satellites.

There are two phenomena which exclusively belong to HP ink jets. Firstly, accompanied by satellites, a trail of tiny drops always occurs on the opposite side and pointing to the opposite direction of a satellite tail. These whip-like ink marks might be generated due to impact splatter.

Figure 7a

Figure 7b

Figure 7 Comparing the same lines printed, in the same print mode, by the same Canon iP1000 printer, on machine-glazed paper(Figure 7a) and printer paper (Figure 7b) respectively.

Satellite droplet	bjc-210	bjc- 265	bjc-1000	bjc-4310/4650	S6300 /i6100	s200	i255	i320	i455
Bigger one	√	√	√	√	√	√	√	√	√
Tiny one	√	×	√	√	√	√	√	√	√
Satellite droplet	iP1000	iP1980	iP 2200 /iP1600	iP2680	4000	0	MP 338	s900	i950
Bigger one	√	√	√	√	×	√	√	×	×
Tiny one	√	√	√	√	√	√	√	×	×

√: found in the samples

×: not found in the samples

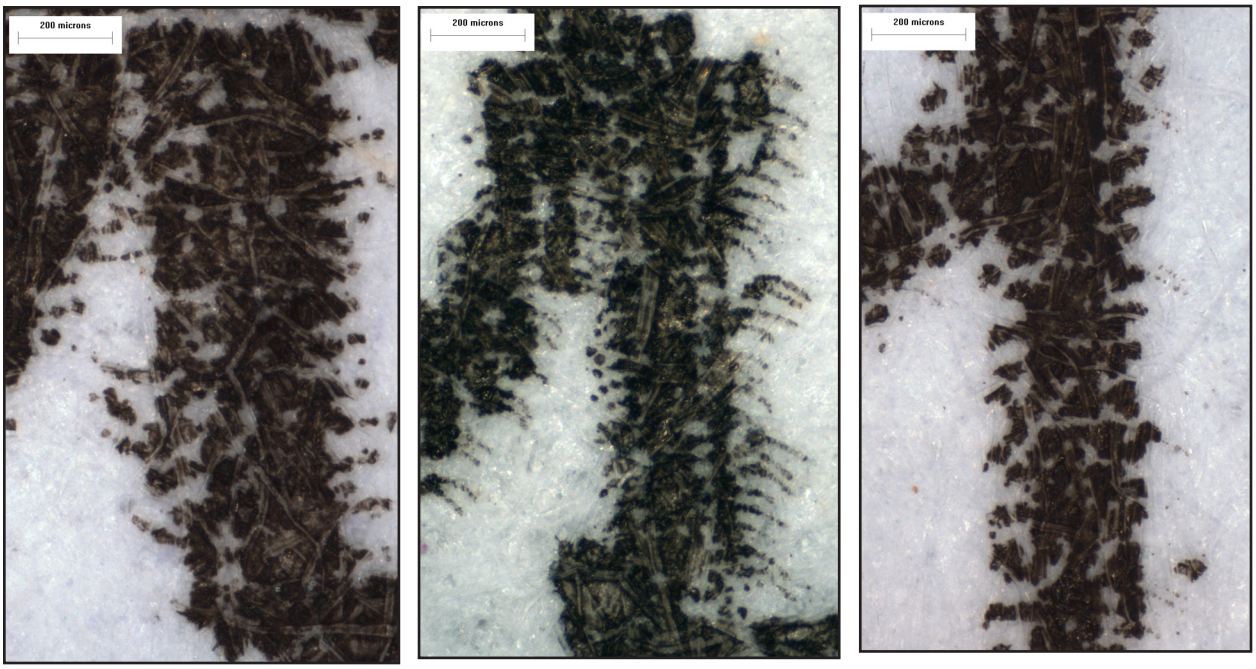
Table 2 An observation of satellite form produced by Canon OEM black ink.

The pictures in Figure 4 and Figure 8 show these seeming spatters produced by HP models. The phenomenon was found in many samples printed by HP printers (see Table 3). Based on A K Sen, J Darabi's and others' studies about droplet ejection performance, the author of this study tried to interpret the phenomenon. A hypothesis is that HP ink jets are not only set up with larger stepping of the print pen, but also with certain parameters, such as higher thermal energy, to increase the droplet velocity in Fast, Fast Normal and Normal modes. Consequently, a droplet strikes the paper at a sufficient intensity to splatter. This remains to be proved experimentally.

The other phenomenon exclusive to HP ink jets in Fast Normal and Normal modes is technology that hides the satellites in the center of printed lines. The tested HP ink jets, except for older models: HP Deskjet 656c/840c/920c/930c/1120c/1125c/3820/3325, employ a patented technology which aims at effectively hiding satellites into the center of characters to improve print quality. To achieve this, each individual character is divided into left portion and right portion, which are printed respectively in two passes of the print head, locating the primary drops at the left portion first on the right-directional pass and then the right portion the left-directional. As a result, satellite tails are deposited in the center of a character, as shown in Figure 9 and Figure 10.

2. Usage of Satellites in Ascertaining Certain Class Characteristics

Satellites are unstable in their morphologic aspects; however, their frequent appearance makes utilizing other class characteristics possible. One of these characteristics is the halftone dot, which can be easily analyzed in printed



HP Dj 1125c **HP Dj 3938** **HP Officejet 6110**

Figure 8 Unidentified whip-like marks occur on the opposite side of satellites produced by HP ink jets.

Model	Fast	Fast Normal	Normal	Model	Fast	Fast Normal	Normal
Deskjet 656c	×	-	×	Deskjet 3748	√	√	√
Deskjet 840c	×	-	√	Deskjet 3938	√	√	√
Deskjet 1120c /1125c	√	-	×	Deskjet 9808 / 9868	√	√	√
Deskjet 1180c	×	-	×	Deskjet D4168	√	√	√
Deskjet 1280	×	-	×	officjet 5608,	√	√	√
Deskjet 930c	×	-	×	officjet 4255	√	-	×
Deskjet 920c	×	-	×	officjet 5510	√	√	√
Deskjet 3820	×	-	√	photosmart 7550	√	-	√
Deskjet 3325	×	-	×	Psc 2110	×	√	√
Deskjet 3658	√	√	√	Psc 6110	√	-	×

√: found in the samples.

×: not found in the samples.

- : the printer does not have this print mode or no sample was collected in this print mode.

Table 3 An observation of the occurrence of the whip-like mark produced by HP devices.

areas of the lightest gray-scale halftone images. Generally, ink jets are configured to eject bigger halftone dots at lower resolutions to improve printing speed while smaller halftone dots at higher resolutions to improve printing quality. Epson's Variable-Sized Dot Technology enables ejection of several volumes of drops from a single printer. Normally Epson ink jet printers use drops of larger volumes in Fast mode, and smaller drops in high quality modes. The tested printers cannot modulate the volumes of ink drop as Epson's piezoelectric technology can; they are configured to modulate the drop quantity at each halftone cell to achieve variable resolutions in different modes. Different models have different configuration for their halftone dot structures: with Error Diffusion Halftone, normally either 4 drops or 2 drops for Fast mode and 1 drop for higher quality modes; with Regular Dithering Halftone, quantity of dots changes according to the corresponding gray scale. In addition, newer Canon ink jets employ another strategy of selecting smaller nozzles from their multi-nozzle print heads to eject second-level drops for photo quality modes. Being fixed in a print driver and therefore not varying with ink or media, halftone dot struc-

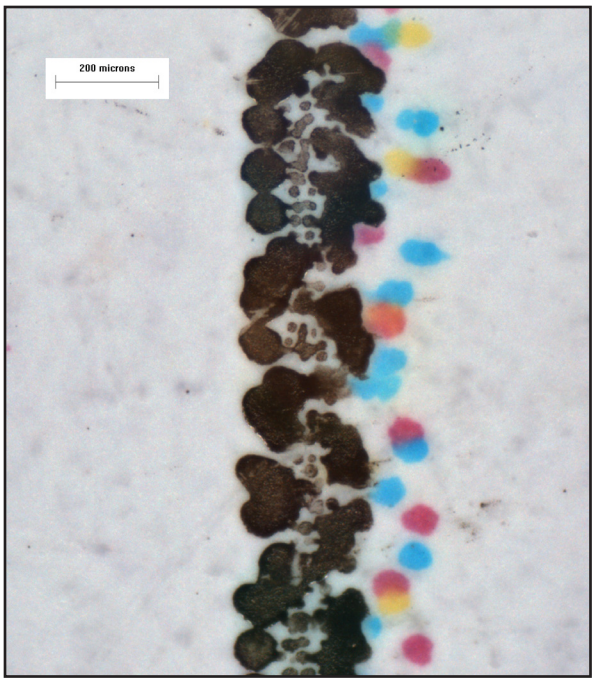


Figure 9 An obvious satellite-hiding example of the patented HP technology

ture can be a piece of evidence for determining the print mode and the model of the printer used. However, if there are no satellites, halftone dots cannot be analyzed because of ink drops overlapping or merging. 4-drop and 2-drop halftone cells depicted respectively in Figure 3a and Figure 3b can be discerned with the assistance of satellite analysis. Figure 11 also shows that satellites play an essential role in distinguishing the drop quantity of a halftone dot.

Print head nozzle arrangement also can be inferred by analyzing satellites (see Figure 12). Different types of print heads have their own forms of nozzle array. Nozzle arrangement which can be revealed by satellites includes two aspects: the shape of nozzle array and the space between adjacent nozzles. Without satellites, these two features are concealed in printed text in Normal mode and can hardly be analyzed.

Another valuable class characteristic embodies paper feed stepping which is configured into the hardware and software of a printer. It can be observed and measured via bandings and other

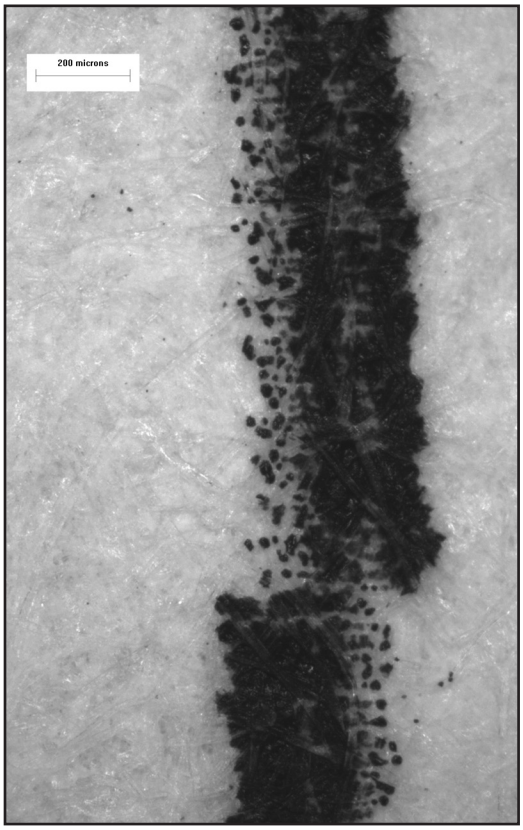


Figure 10a

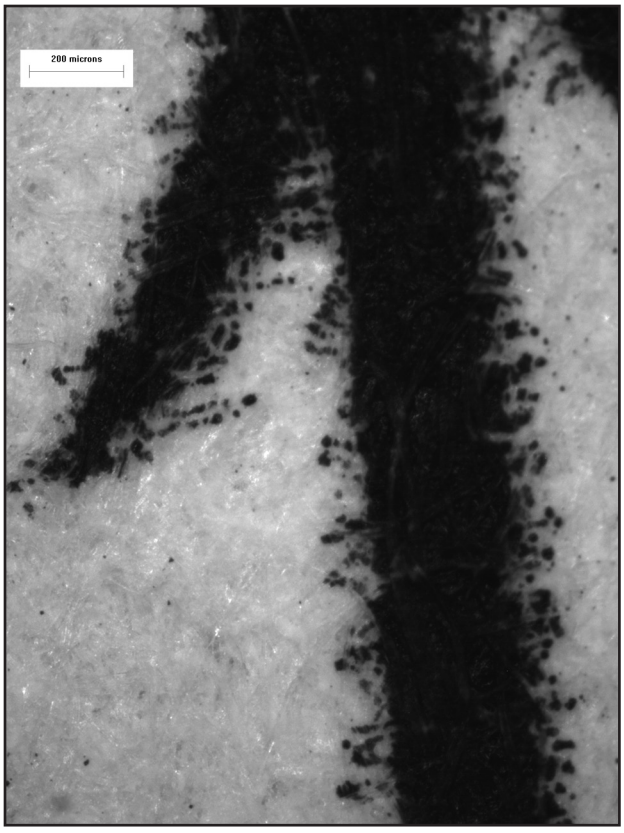


Figure 10b

Figure 10 The distribution of satellites in text produced by HP Deskjet D4168 in different modes: Fast mode (Figure 10a), Normal mode (Figure 10b). The evidence of employing the patented technology in Normal mode is apparent.

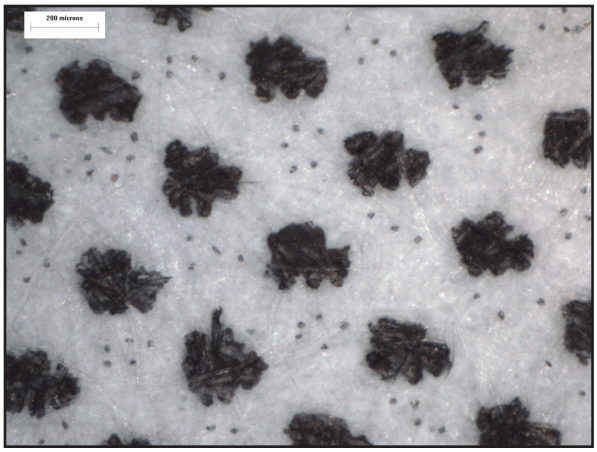


Figure 11 An example of Regular Dithering Halftone dots and their satellites revealing the quantity of drops printed by Canon bjc 255sp in Normal mode.

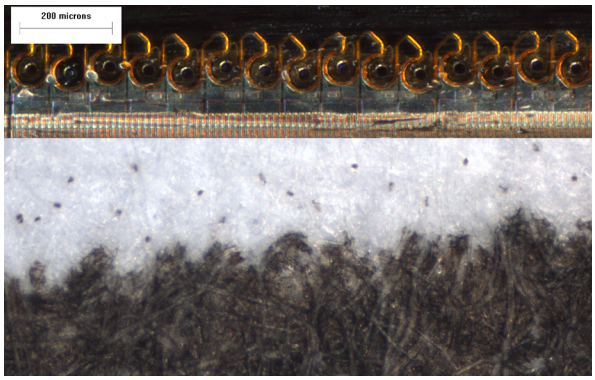


Figure 12 Nozzle arrangement (the upper) and Canon iX4000 and its satellites distribution (the lower) in Fast mode.

kinds of repeated defects in printouts. However, in a flawless text-only page printed in 1-pass mode, checking the turning points of satellites distribution is the only way to measure the step of paper feed.

3. Usage of Satellites in Determining Print Modes.

Every printout has an inextricable relationship with a print mode, that is, without a print mode no ink jet output can be produced, except for a Printer Test Pages. Consequently, every printed material carries the features of a print mode, which often reflects the characteristics of the type of printer. In the author's point of view, the first step in examining a printed document should be ascertaining the print mode.

Bidirectional printers produce, in a swath of printed area, satellites pointing in same direction in Fast mode, whereas satellites pointing in both left and right directions in higher mode. These can be easily found in a light-colored image under a microscope. Some older unidirectional ink jets generate satellites located on only one side of the primary dots throughout the whole printed area. Newer ink jets in their photo modes also employ unidirectional printing, as a result, the same phenomenon was observed.

With regard to documents which only consist of text, the distribution of satellite droplets indicates the mode used. As Figure 10 shows, satellite droplets deposited on both sides of a line indicate the print mode is multi-pass mode. However, ascertaining 1-pass mode of bidirectional printing has to be verified by finding the shifting points of satellites.

The combination of these features - the length of satellite tails, the structure of halftone dot, paper feed stepping, locations of satellite droplets and so forth - via the analysis of satellites, constitutes a complete examination.

In summary, satellites are not a stable characteristic for classification or identification of ink jet printers. However, the analysis of satellites is essential in the examination of an ink jet-printed document and should be taken into consideration accordingly.

Acknowledgments

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