Experimental Evaluation of Ink Jet Interchannel Crosstalk Compensation

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Abstract

This study describes the experimental evaluation of a multiple-jet printhead concept in which the drop-charging process is controlled by utilization of an interchannel crosstalk compensation method. The crosstalk is first measured in a noncompensated setup with eight pairs of jets and electrodes. From these data the compensation is computed and implemented, and then its effect on the crosstalk is measured. Although the remaining drop-charge error does not quite meet the requirements, it is concluded that with a few improvements this should be possible.

Introduction

The development of relatively inexpensive powerful personal computers and high-resolution color monitors increases the demand for high-quality color hardcopy output. Continuous ink-jet technology contends successfully among the modern nonimpact printing technologies in terms of high-quality color output, but current implementations are ranked in the medium to low range in terms of print speed.

In the Hertz continuous ink-jet technology high-speed continuous jets are on–off controlled by electrical signals, as shown in Figure 1. The ink jet issues from a nozzle and breaks up into drops at its "point of drop formation," which is situated close to the control electrode C. When a signal voltage different from the ink-jet potential is applied to the control electrode, the formed drops become electrically charged. The charged drops will be deflected by the electrical field generated between the deflection electrodes *D* and caught by the knife edge *K* (off-state). Uncharged drops, which are generated by applying a signal voltage equal to the ink potential to the control electrode, will pass unaffected through the deflection field and reach the printing surface *R* (on-state).

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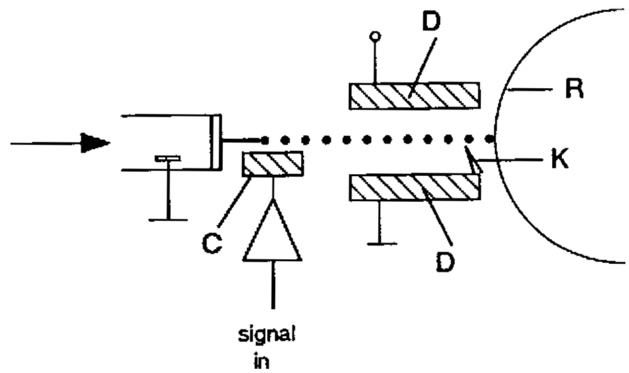

Figure 1. Electrode system for on-off modulation of continuous jets. The jet breaks up into drops near the charge electrode C. Charged drops are deflected by the electrodes D and intercepted by the catcher K. Uncharged drops pass the catcher and deposit on the drum surface R.

With one jet/color (magenta, yellow, cyan, and black) and jet speeds around 50 m/sec, a printer implementing the above described method needs about 2-3 min to print an A4 page. An increase of the jet speed to reduce the print time can give only a marginal improvement before it will lead to an unacceptable degradation of the print quality. To increase the print speed substantially without degradation of the print quality, it is necessary to design a printhead with multiple jets/color. A compact printhead with tight spacing between ink-jet channels raises the question of how to provide reliable control so that all the drops formed by the different jets are assigned correct drop charge.[2,3] The solution to this problem, used in the experiments presented in this study, is to use an open-face charge electrode structure that allows for interchannel crosstalk, combined with an electronic compensation circuit. This solution has been discussed theoretically in an earlier publication.[4] Figure 2 shows the model used to compute the lookup table implemented in the compensation circuit *EX*. The charge Q_X, which is induced on the jet J_X of the x-th channel, is equal to the sum of the products between the potential V_i of the charge electrode of the i-th channel and the capacitance C_i between said charge electrode and the jet J_X.

$$Q_x = \sum C_i V_i = C_x V_x + \sum_{i \neq X} C_i V_i \tag{1}$$

The charge induced on J_X from neighboring channels diminishes with the distance from channel X. This makes it possible to truncate Eq. 1 without considerably changing its outcome. A truncation to five channels, as shown in Figure 2, limits the computation of the compensation voltage $V_X(I)$ to the 32 states that the five binary inputs can generate.

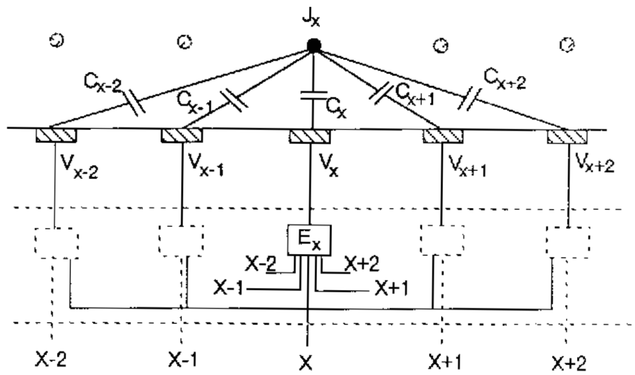

Figure 2. System model used to compute the compensation table implemented in the circuits E_x

$$V_x(I) = \begin{matrix} V(0) & V(1) & V(2) & V(3) \\ V(4) & V(5) & V(6) & V(7) \\ V(8) & V(9) & V(10) & V(11) \\ V(12) & V(13) & V(14) & V(15) \\ V(16) & V(17) & V(18) & V(19) \\ V(20) & V(21) & V(22) & V(23) \\ V(24) & V(25) & V(26) & V(27) \\ V(28) & V(29) & V(30) & V(31) \end{matrix} \tag{2}$$

The index I, which denotes the different states, is computed as

$$I = 2^4 Z_{X-2} + 2^3 Z_{X-1} + 2^2 Z_X + 2^1 Z_{X+1} + 2^0 Z_{X+2}, \tag{3}$$

where Z_i has the value 1 if channel i is in the off-state and the value 0 if channel i is in the on-state. An iterative method, implemented in a computer program, was used to compute the compensation table $Vx(I)$. Experiments have shown that the compensation table can be expressed as

$$V_X(I) = A \bullet Z_{X-2} - B \bullet Z_{X-1} + C \bullet Z_X - B \bullet Z_{X+1} + A \bullet Z_{X+2}, \tag{4}$$

where A, B. and C are positive constants depending on the capacitances resulting from the geometry of and the distances between jets and charge electrodes. At first glance one would expect that the nearest-neighbor terms ($X \pm 1$) and the second-nearest-neighbor terms ($X \pm 2$) in Eq. 4 both had negative signs and not opposite signs. The explanation of this could be found in that a transition of the second-nearest neighbor from its on-state to its off-state changes not only the voltage on the charge electrode of channel X, but also the voltage on the charge electrode of the nearest neighbor, and because the voltage applied to the charge electrode of the nearest neighbor is negative, the net result of the crosstalk from the nearest neighbor and the second-nearest neighbor is compensated by a positive voltage on channel X.[4]

Method

A nozzle fabricated by silicon micromachining methods[5] was used in the experiments. Figure 3 shows the nozzle geometry seen from the jet exit side. The nozzle contains eight orifices, each with a diameter of 12 µm, aligned with a 500-µm spacing. A fluid consisting of 80% water and 20% glycerine was forced through the orifices at a pressure of about 10 MPa, resulting in a jet velocity of about 25 m/sec. Figure 4 shows a photograph of the eight jets.

The charge electrodes are screen printed with a conductive paint onto an electrically isolated flat structure, to create strips 200 m wide and with a spacing of 500 µm (see Figure 5). A via connects the charge electrode to a contact pad on the opposite side.

To ensure correct compensation for channels at either end of the array without having to calculate special compensation tables for these channels, two dummy charge electrodes with active compensation are added to each side of the array (see Figure 6). These dummy channels do not have any jets, and their digital inputs are set to zero.

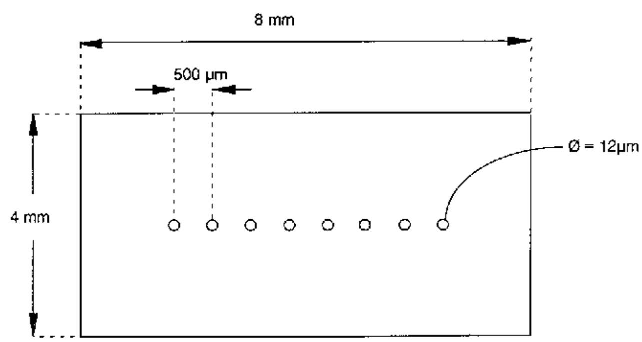

Figure 3. Simplified sketch giving the geometry of the silicon micromachined inkjet nozzle. Details of the conical shape of the jet outlets[5] are not shown.

The electronics implementing the compensation table are designed to provide for easy replacement of one compensation table by another, and also to allow for noncompensated tests. The compensation weights A, B, and C (see Eq. 4) are realized by resistors, as seen in Figure 7. A summing amplifier then adds the weights from the five digital inputs into the compensated signal that after amplification is applied to the charge electrode.

The nozzle is mounted onto a fixture that gives five degrees of freedom (translation in three dimensions; rotation in two planes) to facilitate correct alignment of the jets relative to the charge electrodes.

A fine wire mounted onto a micropositioner allows the selection of a single jet hitting the wire (see Figure 8). This wire is coupled to an electrometer, whose other lead is in electrical contact with the ink. Charged drops hitting the wire will cause the electrometer to register a current I_X, which can be transformed into drop charge by division with the drop frequency f_d.

$$Q_X = I_X/f_d \quad (5)$$

The crosstalk compensation experiment can be divided into three operations:

1. alignment of jets and charge electrodes, and measurement of the noncompensated drop charge,
2. calculation and implementation of the compensation table, and
3. measurement of the compensated drop charge.

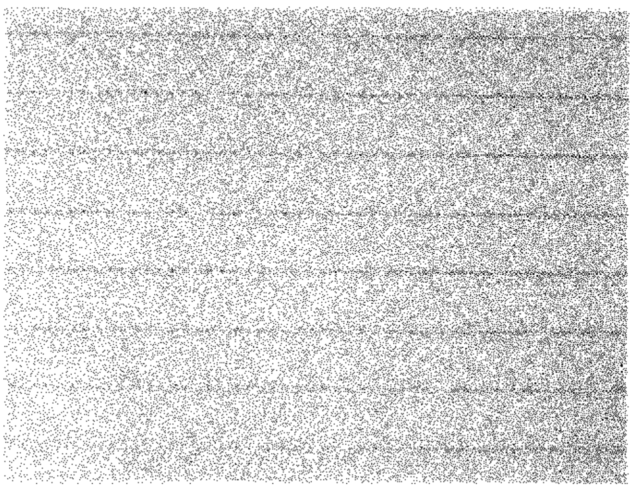

Figure 4. Photograph of the eight jets emerging from the silicon nozzle (to the left, not shown). The jet velocity is 35 m/sec, the drop frequency is 325 kHz, and the distance between the jets is 500 µm.

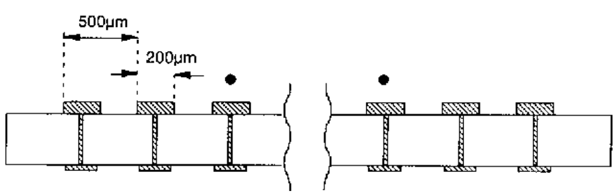

Figure 5. The charge electrode structure is screen printed with a conductive paint onto an electrically isolating material. The charge electrodes at the top are connected to contact pads at the bottom.

Operation

The electronics are set to the uncompensated mode, which makes it possible to set a single electrode to a potential different from zero while keeping all other electrodes at zero. This way the charge contribution from a single electrode to any of the jets can be measured. An acceptable alignment is reached when the charge contributions from the nearest charge electrodes on either side of a jet are equal, and when the charge contributions from neighboring charge electrodes measured at one side of the array are equal to what can be measured at the other end of the array. When an acceptable alignment is reached, the charge contributions Q_i from the five nearest electrodes to a jet are recorded with the electrometer. Because the input to the dummy charge electrodes is hardwired to zero, the contribution from these channels cannot be measured.

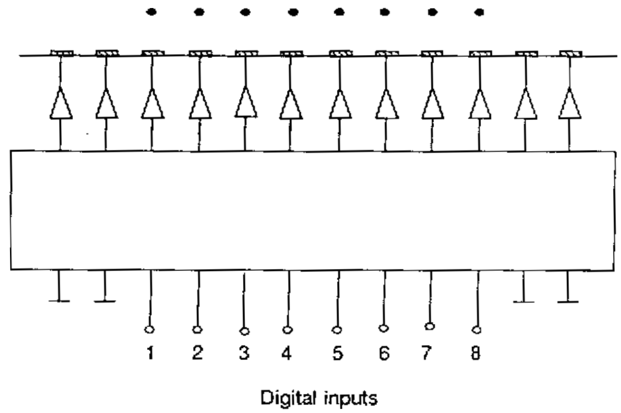

Figure 6. To enable the use of identical compensation tables for all channels, two dummy channels without corresponding jets and with their inputs set to zero are added at each end of the array.

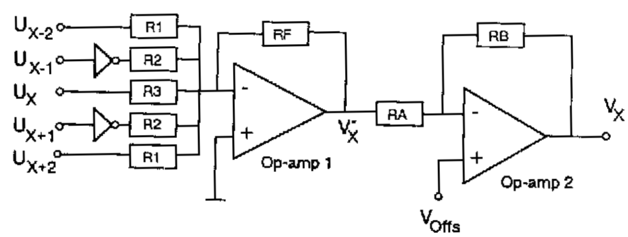

Figure 7. Circuit implementing the compensation table. Op-amp 1 sums the contributions from the surrounding channels, and Op-amp 2 adjusts the offset.

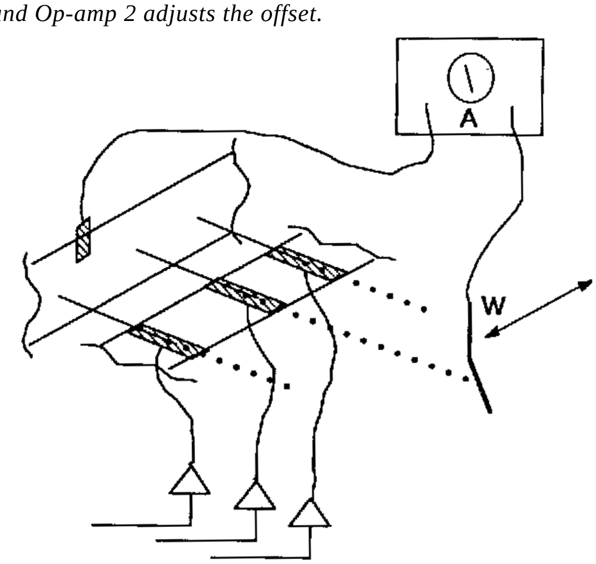

Figure 8. The drop charge for a specific jet is measured by positioning the wire (W) so that it is hit by the jet, thereby creating a closed current path through the electrometer (A).

Table I. Standardized Capacitances Computed From Current Data Measured in Noncompensated Mode*

	Current (nA)					Standardized capacitances				
	$X-2$	$X-1$	X	$X+1$	$X+2$	C_{X-2}	C_{X-1}	C_X	C_{X+1}	C_{X+2}
Jet $X = 1$	—	—	1.87	0.60	0.03	—	—	1.000	0.321	0.016
Jet $X = 2$	—	0.57	1.77	0.57	0.06	—	0.322	1.000	0.322	0.034
Jet $X = 3$	0.06	0.57	1.91	0.62	0.04	0.031	0.298	1.000	0.325	0.021
Jet $X = 4$	0.05	0.58	2.05	0.56	0.06	0.024	0.283	1.000	0.273	0.029
Jet $X = 5$	0.06	0.65	1.94	0.63	0.04	0.031	0.335	1.000	0.325	0.021
Jet $X = 6$	0.07	0.58	1.94	0.55	0.07	0.036	0.299	1.000	0.284	0.036
Jet $X = 7$	0.08	0.64	1.87	0.68	—	0.043	0.342	1.000	0.364	—
Jet $X = 8$	0.06	0.50	1.94	—	—	0.031	0.258	1.000	—	—

*The left part of the table shows the current measured in the setup shown in Figure 8, with the electronics set in noncompensation mode so that the potential V_{ref}, (30 V) can be applied to a single charge electrode at a time. To the right the standardized capacitances computed from these current measurements are shown.

Operation 2

The compensation table is calculated by a computer program that takes the standardized capacitance values as input. These values are defined as

$$Ç_i = C_i/C_X \ (X - 2 \leq i \leq X + 2) \qquad (6)$$

The charge contributions Q_i from the five electrodes surrounding a jet, measured in Operation 1 above, can be expressed as C_iV_{ref} (see Eq. 1), where V_{ref} is the constant potential applied to the charge electrodes in Operation 1. This makes it possible to compute the standardized capacitances $Ç_i$ as

$$Çi = C_i/C_X = C_iV_{ref}/C_XV_{ref} = Q_i/Q_X \quad (X - 2 \leq i \leq X + 2) \qquad (7)$$

from the data Q_i registered by the electrometer in Operation 1.

The compensation table is realized with the circuit shown in Figure 7. The output V_x'' of Op-amp 1 can be expressed as

$$V_x'' = -RF(U_{X-2}/R1 + U'_{x-1}/R2 + U_X/R3 + U'_{x+1}/R2 + U_{X+2}/R1) \qquad (8)$$

where the input voltages U_i are binary and can attain either the value 0 or the value U. By rewriting U_i by the following rules

$$U_i = U \bullet Z_i;\ Z_i = [0,1];\ Z' = 1 - Z, \qquad (9)$$

Eq. 8 can be stated as

$$V_x'' = -RF \bullet U(Z_{X-2}/R1 - Z_{X-1}/R2 + Z_X/R3 - Z_{X+1}/R2 + Z_{X+2}/R1 + 2/R2). \qquad (10)$$

Identification between Eqs. 4 and 10 gives

$A = -RF \bullet U/R1,$
$B = -RF \bullet U/R2,$
$C = -RF \bullet U/R3.$

Equation 4 evaluated for the indices 1, 2, and 4 gives

$V_X(1) = A,$
$V_X(2) = -B,$
$V_X(4) = C.$

With $R3$ set to a given value, $R1$ and $R2$ can be solved from the equations above.

$$R1 = V_X(4)/V_X(1) \bullet R3 \qquad (11)$$

$$R2 = V_X(4)/V_X(2) \bullet R3 \qquad (12)$$

By taking the values for $V_X(I)$ from the computer program output and applying to Op-amp 2 an offset voltage V_{offs} that balances out the constant term in Eq. 10, the output of the circuit in Figure 7 can, after amplification, represent the compensation table and be applied to a charge electrode.

Operation 3

When the resistors representing the compensation table are installed in the electronics it is possible to measure the effectiveness of the interchannel crosstalk compensation. This is done by measuring the drop charge for each jet while going through the 32 input states that the five binary input signals of the channel can attain.

Results

The left part of Table I shows the current measured with the electrometer when a signal was applied to one at a time of the five charge electrodes nearest to each jet, after alignment of charge electrodes and jets. The voltages applied to the charge electrodes were either 0 V (same as ink potential) or 30 V, the distance between jets and their corresponding charge electrodes was 300 µm the ink pressure was 12 atm, and the signal applied to the piezo crystal controlling the drop formation had a frequency of 325 kHz. The data in the left part of Table I were used to calculate the standardized capacitances shown in the right part. From these data the standardized capacitances used as input to the computer program that calculates the compensation were derived

$$[Ç_{X-2}, Ç_{X-1}, Ç_X, Ç_{X+1}, Ç_{X+2}] = [0.031, 0.310, 1.000, 0.310, 0.031]. \qquad (13)$$

Table II is the compensation table resulting from this input. The resistors needed to implement this compensation table were derived by setting $R3 = 10$ kΩ, and by using Eqs. 11 and 12 to calculate $R2 = 31$ kΩ, and $R1 =$

146 kΩ. Because the resistor values of $R1$ and $R2$ were not available, the values installed in the electronics were

$$[R1, R2, R3, R2, R1] = [130\text{k}\Omega, 30\text{k}\Omega, 10\text{k}\Omega, 30\text{k}\Omega, 130\text{k}\Omega]. \quad (14)$$

Table III shows the current measured with the electrometer in the 32 different states for the jets 3, 4, 5, and 6 of the array (1-8).

Table II. Compensation Table Resulting from the Computer Calculations Using the Capacitance Values in Eq. 13 as Input*

	0.000	0.088	-0.412	-0.324
	1.281	1.369	0.869	0.957
	-0.412	- 0.324	- 0.823	- 0.736
V_X=	0.869	0.957	0.458	0.545
	0.088	0.176	-0.324	-0.236
	1.369	1.457	0.957	1.045
	- 0.324	- 0.236	- 0.736	- 0.648
	0.957	1.045	0.545	0.633

*The format of the table is defined in Eqs. 2 and 3.

Discussion

In an ideal system the drop charge should be either zero for undeflected "print" drops, or at a sufficiently high value to deflect drops properly. A charge different from zero on "print" drops will lead to a misplacement of the drop on the receiving medium or to the drop being deflected enough to be caught by the knife edge. In a standard printhead configuration the maximum acceptable drop misplacement on the receiving medium gives a requirement on drop charge for "print" drops less than ± 2.5% of the charge on properly deflected drops.[4] Table IV shows the average and maximum charge error of the 16 "print" states from the data in Table III, expressed as a percentage of the minimum charge among the 16 deflected states.

One reason for the charge error not being able to meet the requirement of ± 2.5% for all states is the variation on the standardized capacitances for the different channels, as shown in Table I, which are all represented by the values shown in Eq. 14. This variation is due to facts like geometrical irregularities in the charge electrode structure, imperfection in the alignment of jets and charge electrodes, and offset and amplification variations in the amplifiers of the different channels.

Another reason for not meeting the requirement is the selection of resistor values for the compensation table implementation, which had available resistor values from only one (1%) resistor value series. Table V shows the standardized drop charge Q_X that would result from an implementation with the resistor values in Eq. 14 in an ideal system having the standardized capacitance values in Eq. 13. The average error on "print" drops is 1.0%, and the maximum error is 2.5%, expressed as a percentage of the minimum charge among the 16 deflected states.

Several of the reasons given above to explain why the requirements on drop charge were not met in the experiments can be overcome. The design of a complete prototype printhead where the problems discussed above will be corrected is currently under way.[6]

Table III. Current Measured with the Compensation Table Installed*

	0.04	0.09	-0.05	- 0.02
	1.63	1.64	1.52	1.54
	-0.01	0.04	-0.11	-0.08
I_3 =	1.59	1.60	1.51	1.53
	0.03	0.10	-0.02	-0.00
	1.62	1.65	1.52	1.55
	0.01	0.05	-0.09	-0.06
	1.56	1.61	1.52	1.56
	0.10	0.11	0.07	0.06
	1.69	1.64	1.63	1.62
	0.11	0.11	0.07	-0.07
I_4 =	1.69	1.65	1.67	1.67
	0.07	0.09	0.06	0.06
	1.62	1.62	1.60	1.60
	0.09	0.09	0.06	0.06
	1.67	1.64	1.67	1.67
	0.07	0.13	-0.04	-0.01
	1.80	1.79	1.67	1.67
	-0.01	0.04	-0.13	-0.09
I_5 =	1.71	1.73	1.60	1.64
	0.09	0.14	-0.01	0.02
	1.78	1.82	1.66	1.69
	0.00	0.05	-0.11	-0.07
	1.72	1.74	1.62	1.68
	0.05	0.06	0.02	0.01
	1.58	1.55	1.57	1.55
	-0.02	-0.01	-0.04	-0.05
I_6 =	1.53	1.52	1.56	1.57
	0.05	0.04	0.05	0.04
	1.61	1.54	1.57	1.56
	-0.01	0.00	-0.03	-0.04
	1.54	1.50	1.58	1.58

*The four tables show in nanoamperes the current in the 32 different states for each of the jets 3, 4, 5, and 6.

Table IV. Average and Maximum Charge Error of the 16 "Print" States from the Data in Table III, Expressed as a Percentage of the Minimum Charge among the 16 Deflected States

	Channel			
	$X = 3$	$X = 4$	$X = 5$	$X = 6$
Avg error (%)	3.5	5.0	4.3	2.4
Max error (%)	7.3	6.9	8.7	4.0

Acknowledgments

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Table V. Standardized Drop Charge °x that Would Result from an Implementation with the Resistor Values in Eq. 14 in an Ideal System Having the Standardized Capacitance Values in Eq. 13

	0.000	0.006	-0.012	-0.007
	1.015	1.020	1.002	1.008
	-0.012	-0.007	-0.025	-0.019
	1.002	1.008	0.990	0.995
Q_x =	0.006	0.012	-0.007	-0.001
	1.020	1.026	1.008	1.014
	-0.007	-0.001	-0.019	-0.013
	1.008	1.014	0.995	1.001

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