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Evaluation of Methods for Automatically Determining the Fitness of Currency

D. P. Stokesberry and I. Philmon

Microwave & Mechanical Instrumentation Section
Measurement Engineering Division
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Progress Report covering the period
July 1 – December 31, 1972

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Note
The results contained and the conclusions reached in this progress report are preliminary. Final results and conclusions will be presented in the final report.

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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EVALUATION OF METHODS FOR AUTOMATICALLY DETERMINING THE FITNESS OF CURRENCY

1. Summary

The work covered by this report has been mainly directed toward studying the feasibility of machine methods of verifying the denomination of a note. Progress has also been made on the methodology of detecting tape, tears, folds, and missing pieces. Hardware which demonstrates the utility of each detection method is now being devised.

The denomination of a bill is specified by the ink pattern on that bill, i.e., by the spatial relationship of the inked and non-inked areas. The ink pattern is low contrast; the inked areas are only partially covered by dark ink and the clear areas are covered by a background tint. Furthermore, the denomination is specified in a stylized font which does not optimize the differences between characters. The information contained in the ink pattern can be transformed into an electrical signal via optical reflectivity measurements. The resolution of the signal is determined by the size of the spot of light scanning the bill. A large spot will not adequately resolve that pattern. A very small spot size will resolve the fine detail of the printing, but this resolution is not necessary to determine the denomination of the bill. Many of the features of the ink pattern are independent of the denomination of a bill. Thus, much of the information in the electrical signal is not pertinent and only obscures the desired information.

Bills of different denominations have been scanned. We have demonstrated that the electrical signals contain the desired information by converting voltage levels to gray levels on a computer printout. The denomination of the bill is apparent by visual examination of the printout, which is a crude picture of the bill. A spot diameter in the range between 0.05 and 0.15 cm results in adequate resolution without overemphasizing the fine detail of the printing. The large amount of data generated can be somewhat reduced by restricting the examination of the note to specific areas of the bill. Methods of analyzing similar waveforms electronically have proven successful in the optical character recognition and pattern recognition fields. It is quite likely that the same techniques could be applied in the development of an automatic machine verification of denomination.

Both contacting and non-contacting methods of detecting the change in thickness of a bill due to the presence of tape have been investigated. We have found that it is possible to obtain adequate sensitivity and speed of response from a simple contacting, moving-arm device. The contact with the bill can be made in a way that will not interfere with many types of transports, because the device looks like a idler roller to the transport.

This method will work directly on either multiple-roller or spinning-cylinder transports, and it would be unobtrusive to a moving-belt transport. The measurement of thickness could be made through a moving belt, but the belting material may cause both a loss in sensitivity and an increase in noise. This approach looks more attractive than non-contacting thickness measurement by detection of the mass absorption of x-rays or beta particles. Commercially available detectors tend to be slow or fragile. The contacting method is cheaper, simpler, and more effective than this non-contacting method.

2. Verification of Denomination

The manual sorting process currently practiced in the Federal Reserve Banking System keeps an accurate account of the value of each packet of notes sorted by (1) counting the notes and (2) verifying that all the notes in a packet are the same denomination. This verification is done by visual inspection as each note is separated from the rest during the sorting. In an automatic currency-handling system, the notes will be separated only inside the transport, and there will be no opportunity to inspect each note separately. Therefore, the currency-handling system must include some method of verifying that the denomination of each note is what is expected. Notes of the wrong denomination should be separated from the rest of the bills. The machine need only recognize that the denomination of a bill is incorrect, but, since the currency-handling system will undoubtedly be capable of handling all denominations, each denomination must be uniquely identifiable.

The Federal Reserve Banking System is now considering proposals on various methods of determining the authenticity of a note. Some, but not all, of these proposed methods will also uniquely determine the denomination of the note. There is a need for a separate means of verifying the denomination during the interim period until these authentication methods are developed. We are currently studying methods of verifying the denomination of a note while it is in motion, as it would be in a currency-handling system.

The verification method is, in general, subject to two types of error: (1) it may incorrectly separate out bills of the correct denomination and (2) it may fail to separate out bills of the wrong denomination. Errors of the first type will cause an increase in activity for the operator and will reduce throughput and efficiency. If this type of error occurs very often, then almost all the bills sorted out will be false alarms. For example, if the machine verification method makes type-one errors one percent of the time and if less than one bill in a thousand is of the wrong denomination, then almost all the bills sorted out would be false alarms and a false alarm would occur on just about every strap of 100 bills. Type-two errors must also be minimized because these errors cause erroneous accounting. For example, if the machine verification method makes type-two errors one percent of the time and if about one bill in a thousand is of the wrong denomination, then an accounting error occurs on about one of a thousand straps. For a machine throughput rate of 50 000 bills per hour, this represents one error every two hours. This type of error may be unrecoverable since the verification method gives no indication of error. In a well designed machine, the suppression of one type of error will lead to an increase in the other type of error and it should be possible to change the ratio of the two types of errors by adjusting the machine.

Since the denomination of a note is specified by the pattern of the printing, optical sensing of the ink pattern is the most obvious approach, and it is the only method under study. The spatial pattern of the printing can be sensed by scanning the bill with a small spot of light and monitoring the light reflected from the bill with a photo-sensitive detector. The motion of the bill provides scanning in one direction; multiple spots of light can provide the effect of scanning in the other direction. The result is a time-varying signal at the output of the detectors. The denomination of a bill can be verified by comparing the signal with that expected for a bill of the correct denomination. If the signal does not compare adequately, the bill can be separated from the rest of the bills into a separate sort category. An automatic currency-handling system will probably require some type of operator procedure to keep the accounting correct whenever this occurs.

Our work on reflectivity measurements of currency, reported on previously,[1] indicates that adequate sensitivity can be obtained with a simple light source and photo-detector combination. Reflectivity profiles of a clean bill, Fig. 1(a), and a dirty bill, Fig. 1(b) show the output of a photo-detector as a 0.16 cm spot scans along a track parallel to the long dimension of the note and approximately equidistant from the top and bottom of the bill. The valleys in the waveforms occur as the spot scans across inked areas of the bill. These areas are readily discernible even on a dirty bill. This spot size is approximately equal to the dimensions of the printed denomination numbers on the note, and it is much larger than the fine detailed printing on the more heavily inked areas. Use of a smaller spot size would result in better definition of the ink pattern, but it would require more critical positioning for the scanning.

Entire notes have been scanned with a document scanner which moves a small spot of light over a stationary photographic negative of the document. The scan consists of horizontal sweeps across the document where the first sweep is across the top edge of the document and each succeeding sweep is moved down toward the bottom of the document. The results of these scans have been recorded in a form suitable for entry into a computer so that different comparison techniques can be analyzed. The results of these scans are two-dimensional arrays of numbers. One array coordinate represents distance along the long dimension of the bill and the other coordinate represents distance across the short dimension of the bill. Each number in the array represents the reflectance value found for the area of the bill defined by its coordinates. If shades of gray are substituted for the numerical values, the array becomes a crude picture of the bill. The resolution of the picture is determined by the number of points in the array. Hence, the scanning process has generated electrical signals which represent, in different form, the same information as a picture of the bill.

The desired response from a comparison is a simple "yes" or "no" answer. The signal from the photo-detector, however, contains a great deal of information about the bill. Much of this information is not required to determine the denomination of a note and, indeed, it tends to mask the essential information. The problem, therefore, is to devise a system which will reliably determine whether or not the denomination of a note is correct in spite of expected signal variations. This system must operate on the essential information and it must be insensitive to the extraneous information gathered in the scanning process. This will require a comparison technique which will allow variations in the signals received from notes of the correct denomination but will recognize the difference between these signals and signals from bills of other denominations.

One method of distilling the information to a single value is to count the number of peaks in the waveform of a scan of the bill. If the number of peaks is particularly sensitive to the denomination of a note, this would constitute a simple and effective means of determining or verifying denomination. The number of peaks in longitudinal scans of bills of different denomination have been computed. (A longitudinal scan is one that parallels the long dimension of the note and extends over the entire length of the note.) The results are summarized graphically in Fig. 2 through Fig. 9. In these figures the horizontal axis is a scan number which indicates the position of the scan on the note. The first scan is across the top edge of the note, and increasing numbers indicate movement of the scan down the note. The last scan is across the bottom edge of the note. The vertical axis is the number of peaks in a scan.

Fig. 2, 3, 4, and 5 indicate the number of peaks in scans of one, five, ten, and twenty dollar notes respectively. Each scan was digitized into 160 points and 53 scans of the bill were recorded. This is equivalent to using a 0.1 cm diameter spot to scan the bills. The four figures are quite similar. The highest number of peaks occurs near the top and bottom edges of the bills. Scans of the middle sections of the four bills contain a lower number of peaks, and the number is relatively independent of denomination. This concurs with visual examination of the notes. The denomination of a note is most readily determined by the information in the top and bottom sections of the note. The middle section contains little information on the denomination except for the portraits, and a much finer spot would be required to resolve the portrait. The difference in number of peaks in either the top or bottom sections of the notes is not sufficient to identify denomination unequivocally under less than ideal conditions. If the notes are not in mint condition and if allowance is made for less than perfect alignment of the scan due to the transport or variability in the margins of the bill, there is a great deal of overlap between the number of peaks in the scan of notes of different denomination.

Higher resolution scans have also been recorded. Figures 6, 7, 8, and 9 indicate the number of peaks for selected scans of one, five, ten, and twenty dollar notes respectively. Each scan was digitized into 360 points, and the spacing between adjacent scans was approximately 0.05 cm. This is equivalent to using a 0.05 cm diameter spot to scan the bill. The first 24 scans are across the top section of the bill, starting at the top edge and proceeding down about 1.2 cm. The last 24 scans are across the bottom section of the bill, starting about 1.2 cm from the bottom edge and proceeding down to the bottom edge. These scans examine in greater detail those portions of the notes which explicitly specify their denomination. The number of peaks in a scan is increased as the spot size is reduced. The scans across the bottom section include the area of the bill which has the denomination of the bill spelled out on it. The number of peaks in this region varies from 27 to 45 for the one dollar note, 31 to 36 for the five dollar note, 31 to 40 for the ten dollar note and 36 to 47 for the twenty dollar note. All in all, although the number of peaks in a scan is affected by the denomination of a note, this method of analysis is not sufficient to determine denomination.

The identification of denomination by optical scanning is very similar in nature to optical character recognition and pattern recognition. Techniques which have been developed in these fields can be quite sophisticated. Further investigation should attempt to fit these techniques to the problem of denomination verification.

3. Tape Detection

Many different types of tape may be found on bills in circulation. These tapes are made of a variety of materials and they have a wide range of physical characteristics, but the presence of tape on a bill invariably causes a discernible increase in thickness. The thickness of a bill is approximately 0.004 inches. This value varies about 0.001 inches from point to point on the bill due to the engraving of the paper by the printing process and variations in thickness of the paper. The engraving is much less noticeable on worn currency. Commercially available tapes of the type found on bills are at least 0.002 inches thick. This additional thickness is not difficult to sense statically with simple instruments such as a micrometer. At low bill speeds, the additional thickness can be detected with a simple pivot arm and a microswitch. One end of the pivot arm is held in contact with the bill. The other end presses on the tripping mechanism of a small switch. The arm is designed so that a small change in thickness causes a proportionately longer change in the deflection of the end of the pivot arm. The position of the microswitch is adjusted so that at a predetermined deflection of the arm, the switch is tripped. This generates an electrical signal which indicates that the maximum acceptable thickness limit has been exceeded. This type of detector is common on low-speed currency-handling machinery to detect tape, folds or double feeds.

Both contacting and non-contacting methods of high-speed thickness detection have been investigated. Theoretically, non-contacting methods of detection are preferable because they do not interfere with the bill transport mechanism and they tend to be capable of more rapid response. One possible non-contacting method of detecting tape is a measurement of the absorption of either soft x-rays or beta particles. The absorption is proportional to the amount of material in the path of the radiation. Either one-sided or two-sided measurements are possible. In other words, the bill can either pass between the source and the detector, or the source and the detector can be on one side of the bill and the radiation can be reflected back with a suitable backing material. In either case, the position of the bill in the path is not critical. Thus, tight control of the bill by the transport is unnecessary. Experiment has shown that the presence of tape will cause a two-to-one change in detector output for 3 keV x-rays. The radiation detectors are of the ionization chamber type. The output of the detector is a pulse for each detected quantum of radiation. After each pulse the detector has a characteristic dead time before it is ready to sense another quantum of radiation. This dead time defines the speed of response of the system. The number of pulses per unit time is a measure of the intensity of the radiation. The accuracy of the measurement can be shown to be inversely proportional to the square root of the number of pulses counted in a time period. Hence, accuracy is obtained at the expense of speed of response. For bills moving at the rate of twenty bills per second the detection scheme must have a response time in the order of a few milliseconds in order to sense the presence of tape. A measurement accuracy of five percent requires that the detector output be about 400 counts in this time span. Thus the detector dead time must be less than 5μs. A Geiger-Mueller tube has a dead time of about 270μs. Proportional counters and scintillation tubes have fast enough response, but they tend to be fragile and have limited useful lifetimes for the measurement of soft x-rays. This method requires special high-voltage supplies and, in general, it is bulky and expensive. We do not feel that it is worthwhile to develop it at this time.

Contacting methods of tape detection require special care to obtain fast response and to avoid interference with the transport mechanism. The response time of a mechanical system depends upon the mass of the moving member and the spring constant which opposes the movement. If the movement is rotational the moment of inertia, rather than the mass, is used to characterize the system. Fast response is obtained by using a strong spring and a low mass. A strong spring implies that considerable force is required to deflect the moving member. This force must be applied through the paper in such a manner that the movement of the paper through the transport system is not impeded.

A laboratory model of a contacting thickness measuring device has been constructed. This device consists of a small narrow roller bearing mounted on a short shaft. The shaft is free to pivot in its mount. The roller bearing is spring loaded against a driving wheel of a mechanism which transports the bill. This device replaces one of the idler wheels of the transport mechanism and is unobtrusive to the type of transport that we are using. As a bill passes between the roller bearing and the drive wheel, the shaft must pivot to accommodate the thickness of the bill. Motion of the shaft is sensed optically. A flag attached to the shaft interrupts the beam of light between a light source and a photo-detector. Movement of the flag causes a difference in output from the photo-detector. Typical waveforms are shown in Fig. 10. Both waveforms are the response of the detector as a bill with tape on it moved through the device. The tape was 0.75 in. wide and it was placed on the portrait area of the bill. In Fig. 10(a), the bill was moving at the rate of two bills per second. The waveform is an accurate indication of the point-to-point thickness along the length of the bill. In Fig. 10(b), the bill was moving at the rate of twenty bills per second. The peaks in the waveform are due to the limited speed of response of the system and the waveform is not an accurate indication of the point-to-point thickness along the length of the bill. The presence of tape on the bill is, however, clearly indicated in both waveforms. This device is sensitive enough and fast enough to indicate the difference in thickness due to tape on bills moving at the rate of twenty bills per second.

4. Other Work

Tears and missing pieces can be detected optically, and folds can be detected by a combination of an optical measurement of bill size and a thickness measurement. Tears with a folded edge and missing pieces are relatively easy to detect optically, but tears where the edges tend to stay together are difficult to sense.

Optical methods of detecting torn bills require some type of mechanical deflection of the bill to separate the edges of the tear. We have found that light transmission measurements are quite sensitive to cuts in the paper because the edges do not tend to overlap. A tear, however, does not have sharp, straight edges, so there is no light path directly through the bill. Even if the edge of the bill is deflected perpendicularly to the plane of the bill, the overlap at the edges of the tear still tends to mask the transmission of light through the bill. Best results are obtained by looking for light transmission along a path parallel to the edges of the tear instead of perpendicular to the plane of the bill. This would imply that two transmission paths are needed because the optimum path may be slanted either to the left or the right, depending upon the direction of overlap of the tear. This method will not be sensitive to tears parallel to the direction of motion of the bill, since separation of the edges of a tear along the leading edge is difficult to implement. Unobtrusive methods of deflecting the bill are highly dependent upon the characteristics of the transport. Therefore, an optical tear detector with mechanical or pneumatic means to "open" the tear must be specifically designed to fit on a particular type of transport.

5. Plans For Future Work

1. Construct a measurement device which demonstrates the contacting thickness measurement proposed for tape detection and investigate any promising new methods for the detection of tape or tears.

2. Design optical sensing methods which are sensitive to tears, folds and missing pieces.

3. Determine whether well established techniques of optical character recognition and pattern recognition are directly applicable to the verification of the denomination of a bill.

6. Bibliography

[1] Stokesberry, D. P. and Philmon, I., Evaluation of Methods of Automatically Determining the Fitness of Currency, NBS Report 10 602, July 15, 1971.

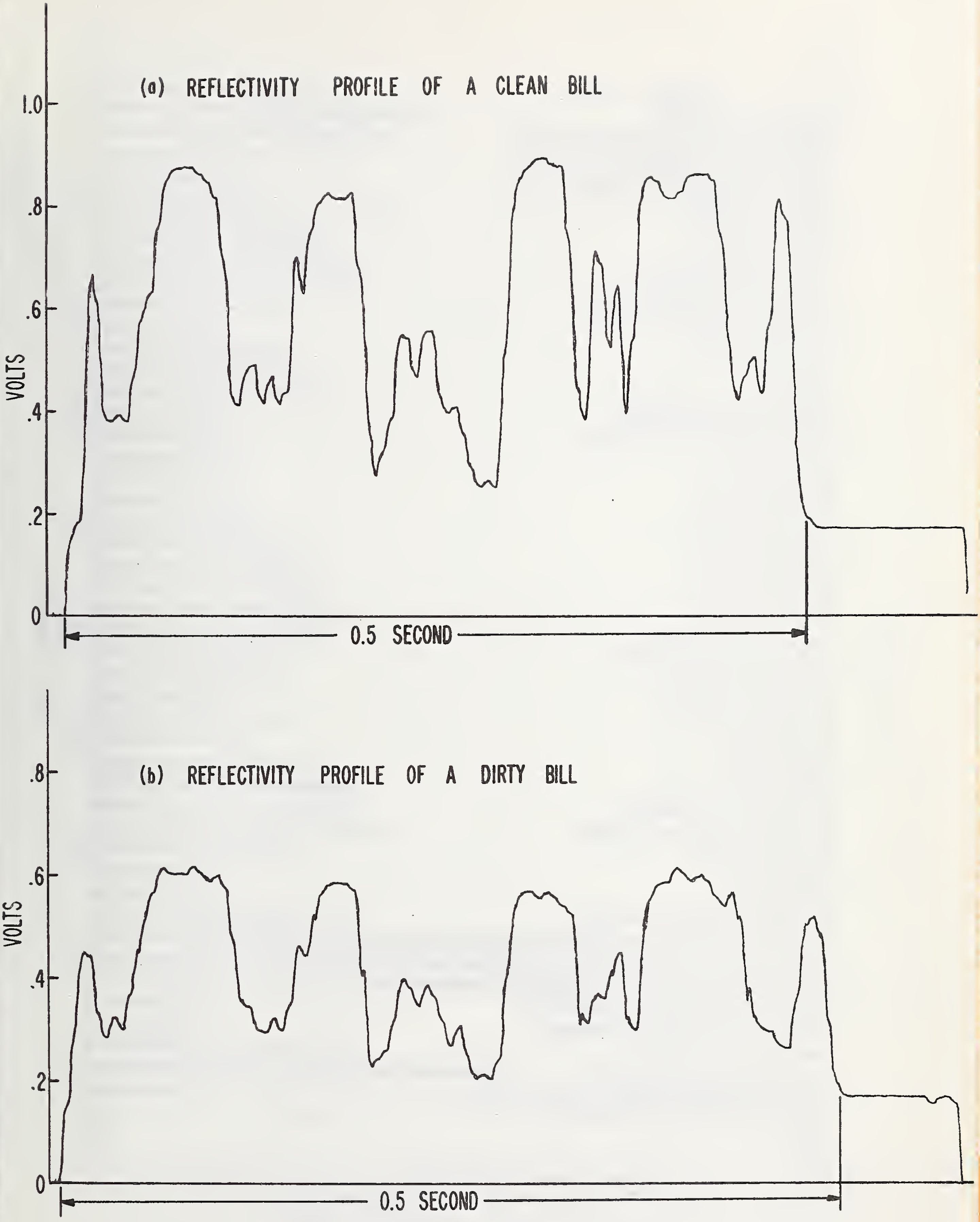


Figure 1. Reflectivity profile of a clean and a dirty bill

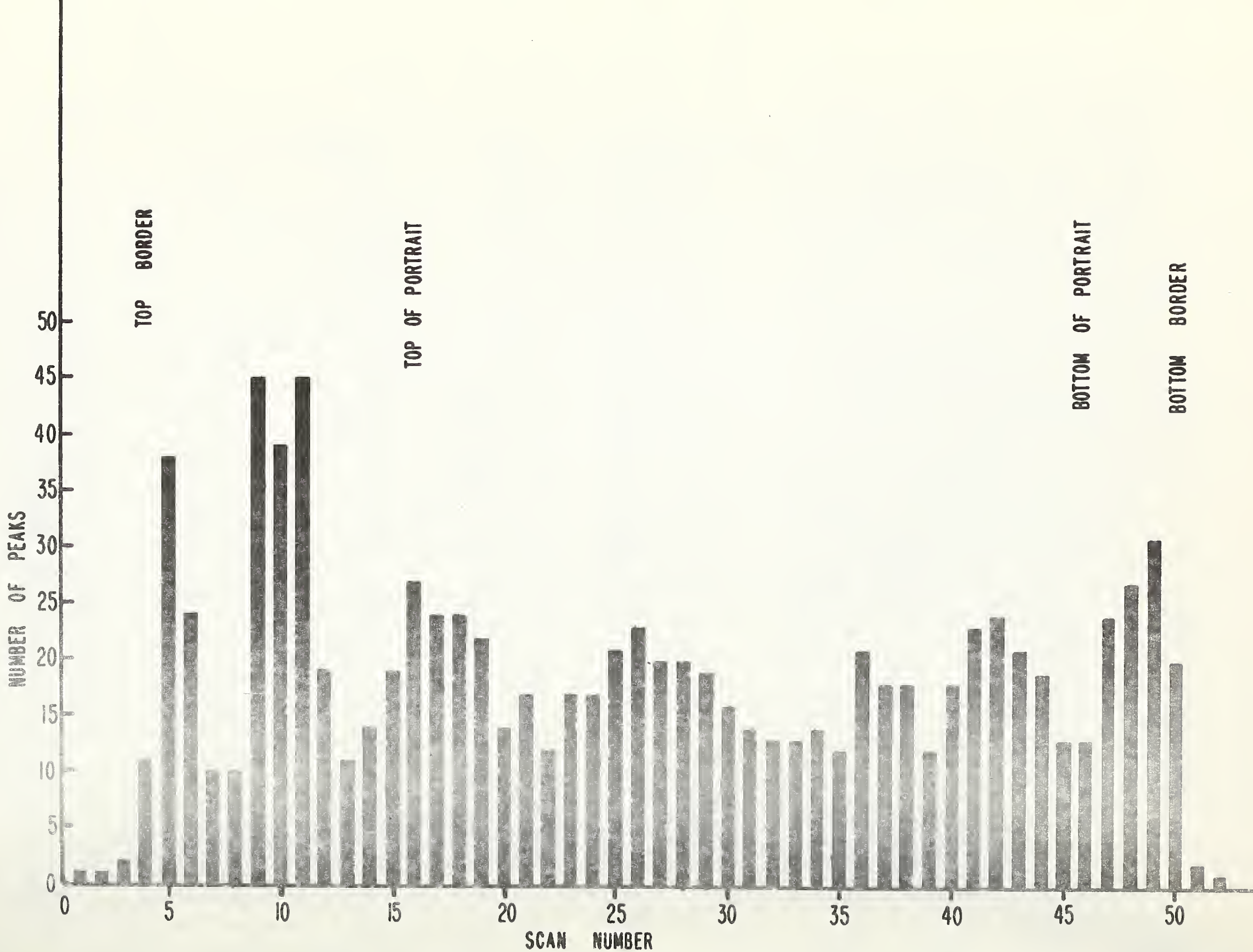


Figure 2. Number of peaks in scans of a one dollar bill.

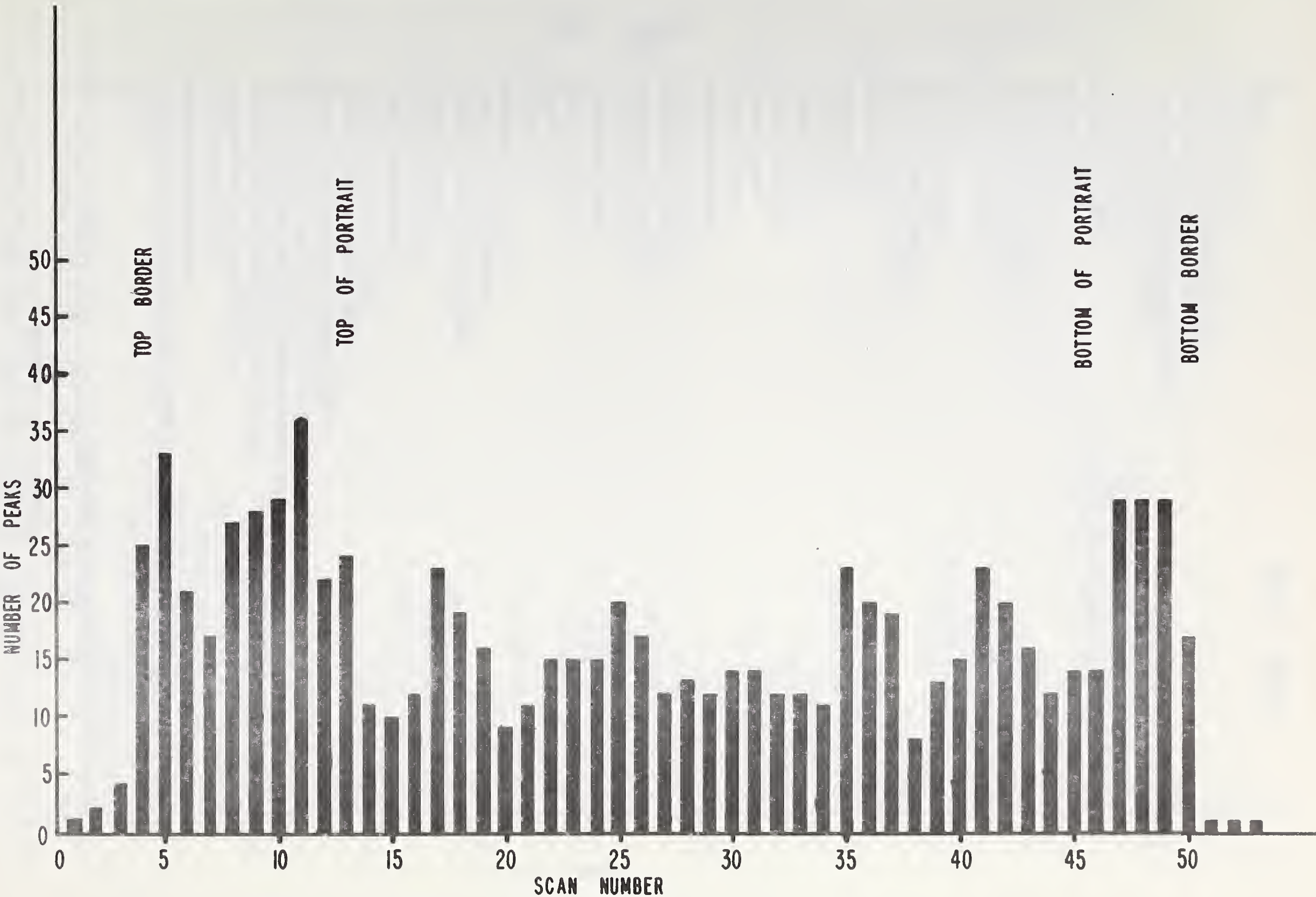


Figure 3. Number of peaks in scans of a five dollar bill.

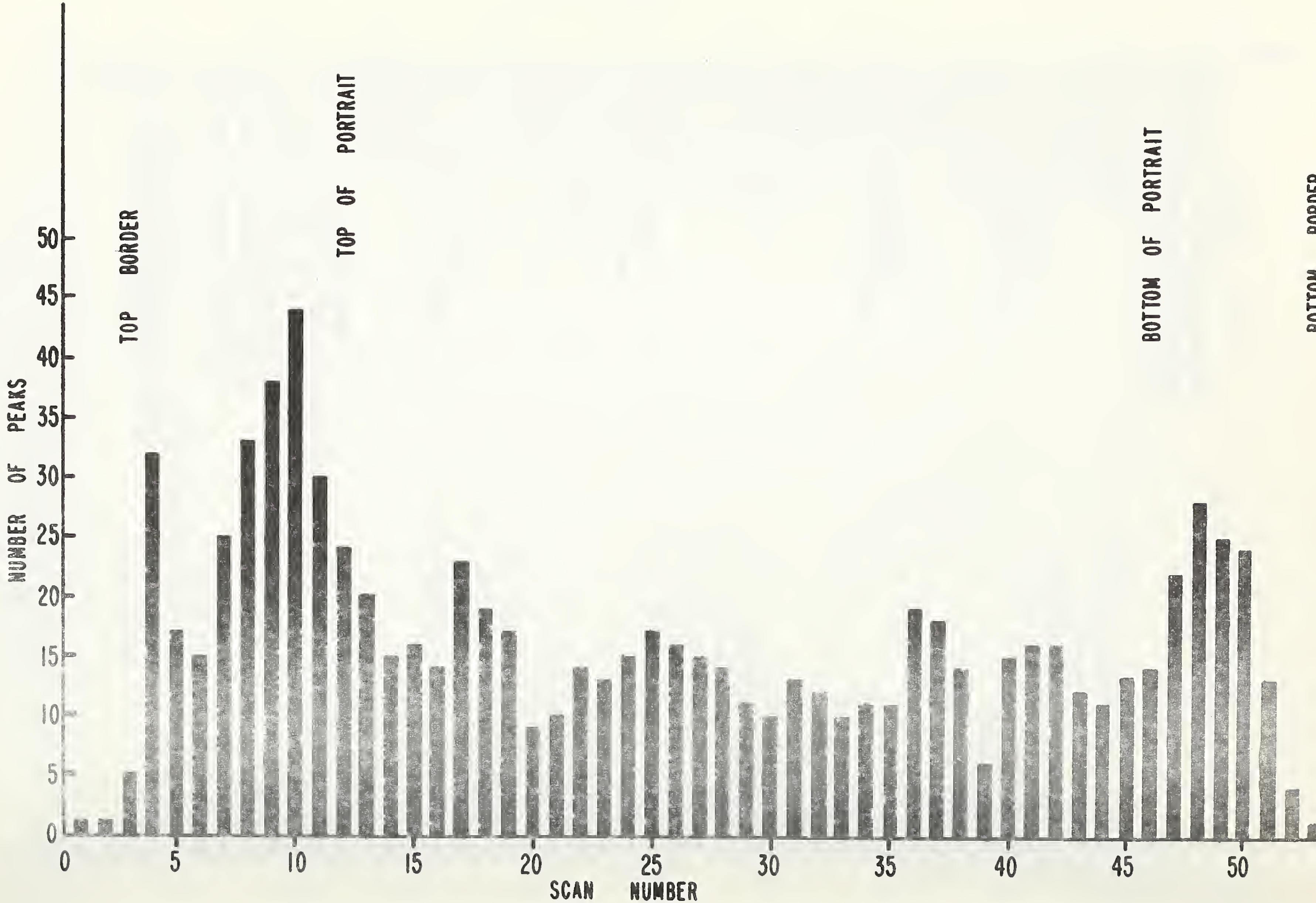


Figure 4. Number of peaks in scans of a ten dollar bill.

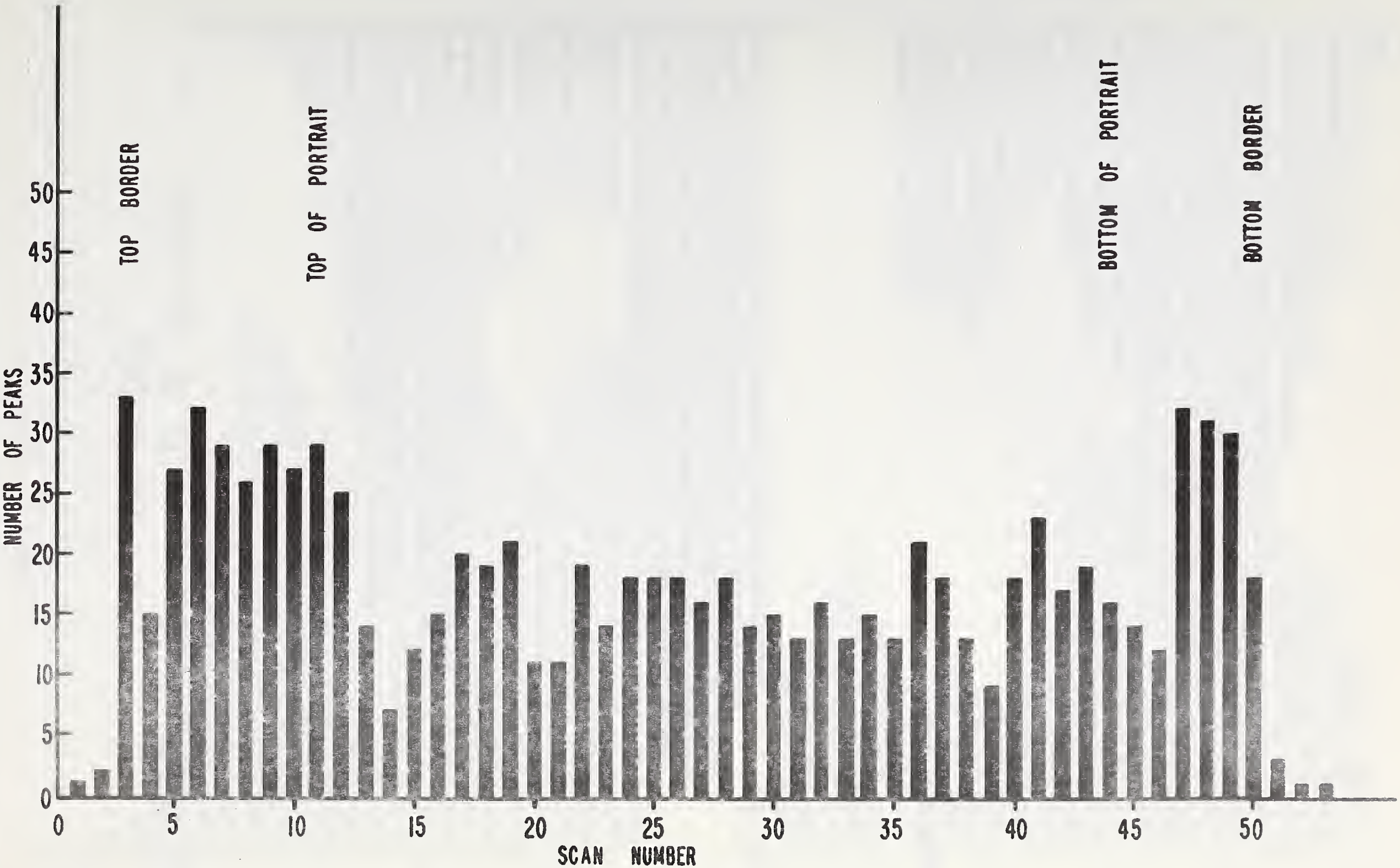


Figure 5. Number of peaks in scans of a twenty dollar bill.

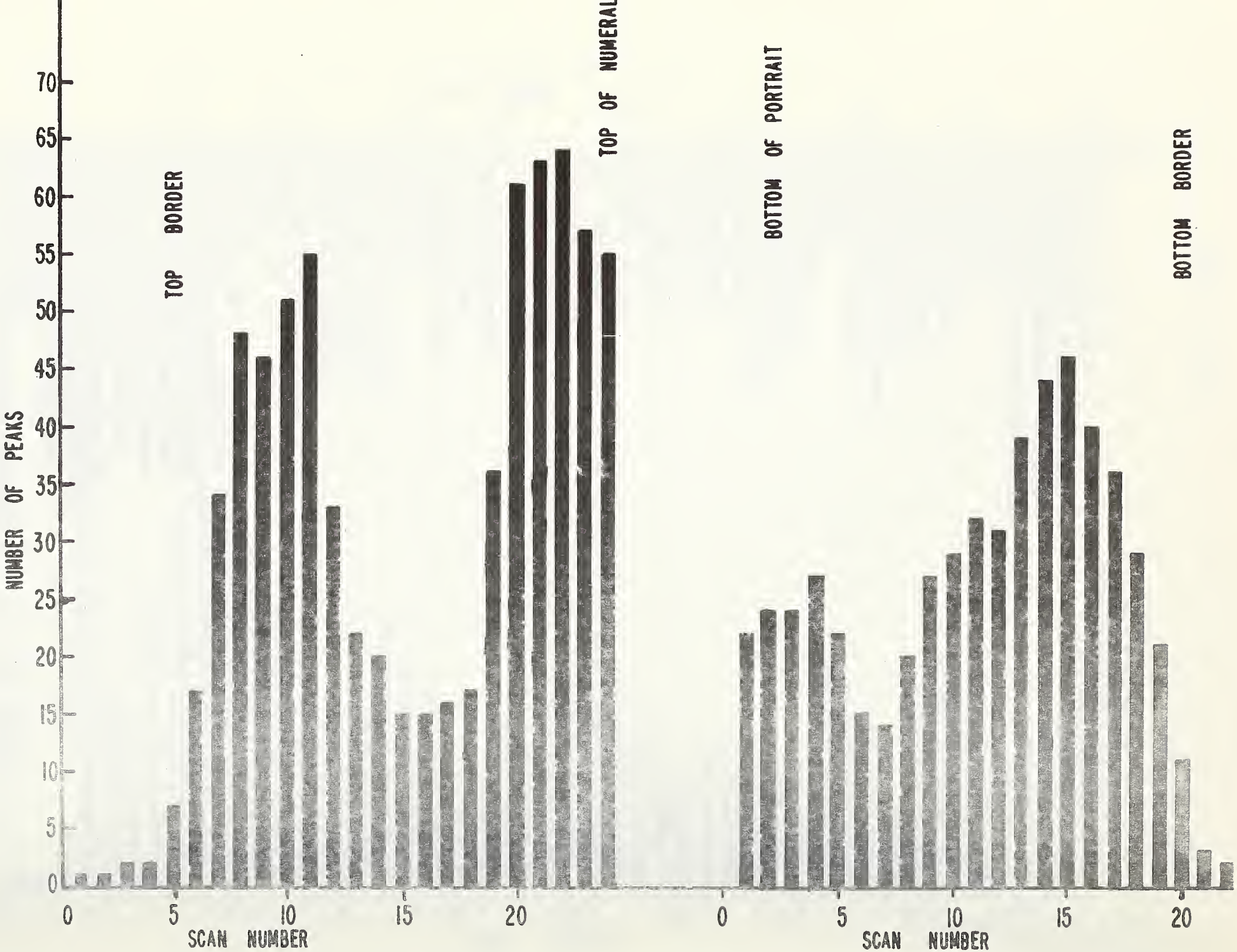


Figure 6. Number of peaks in scans at the top and bottom portions of a one dollar bill.

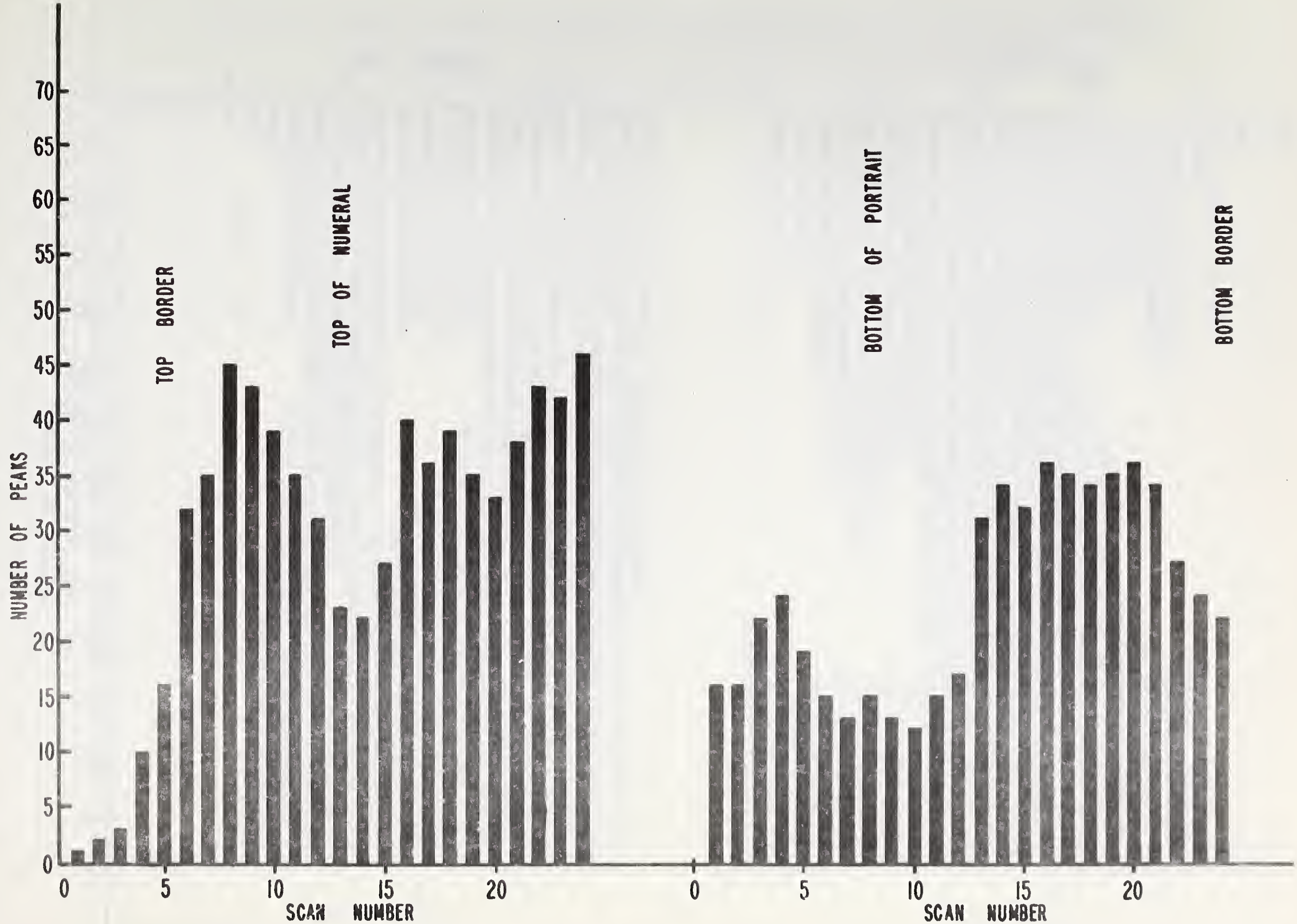


Figure 7. Number of peaks in scans at the top and bottom portions of a five dollar bill.

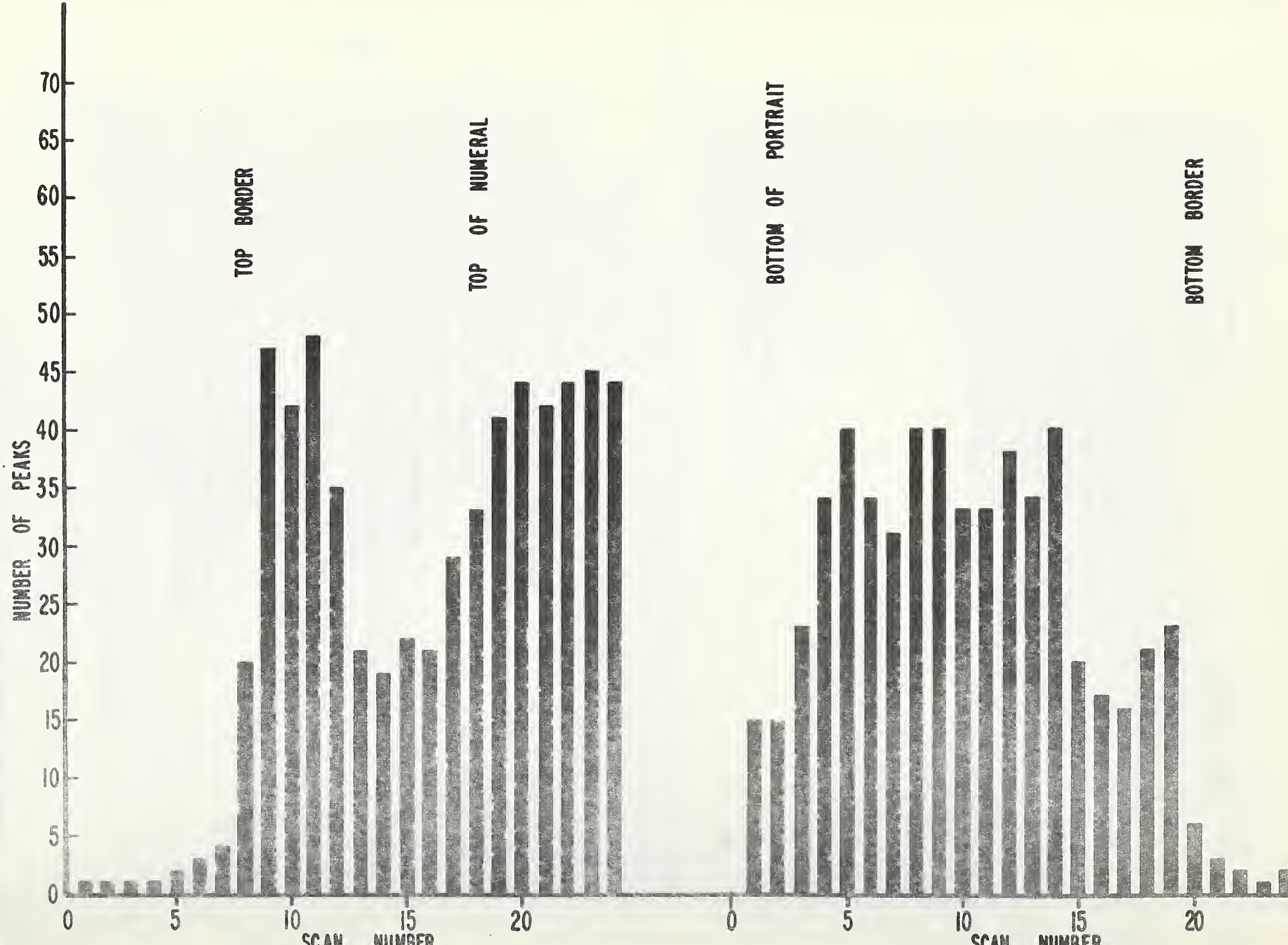


Figure 2. Number of peaks in scans at the top and bottom portions of a ten dollar bill.

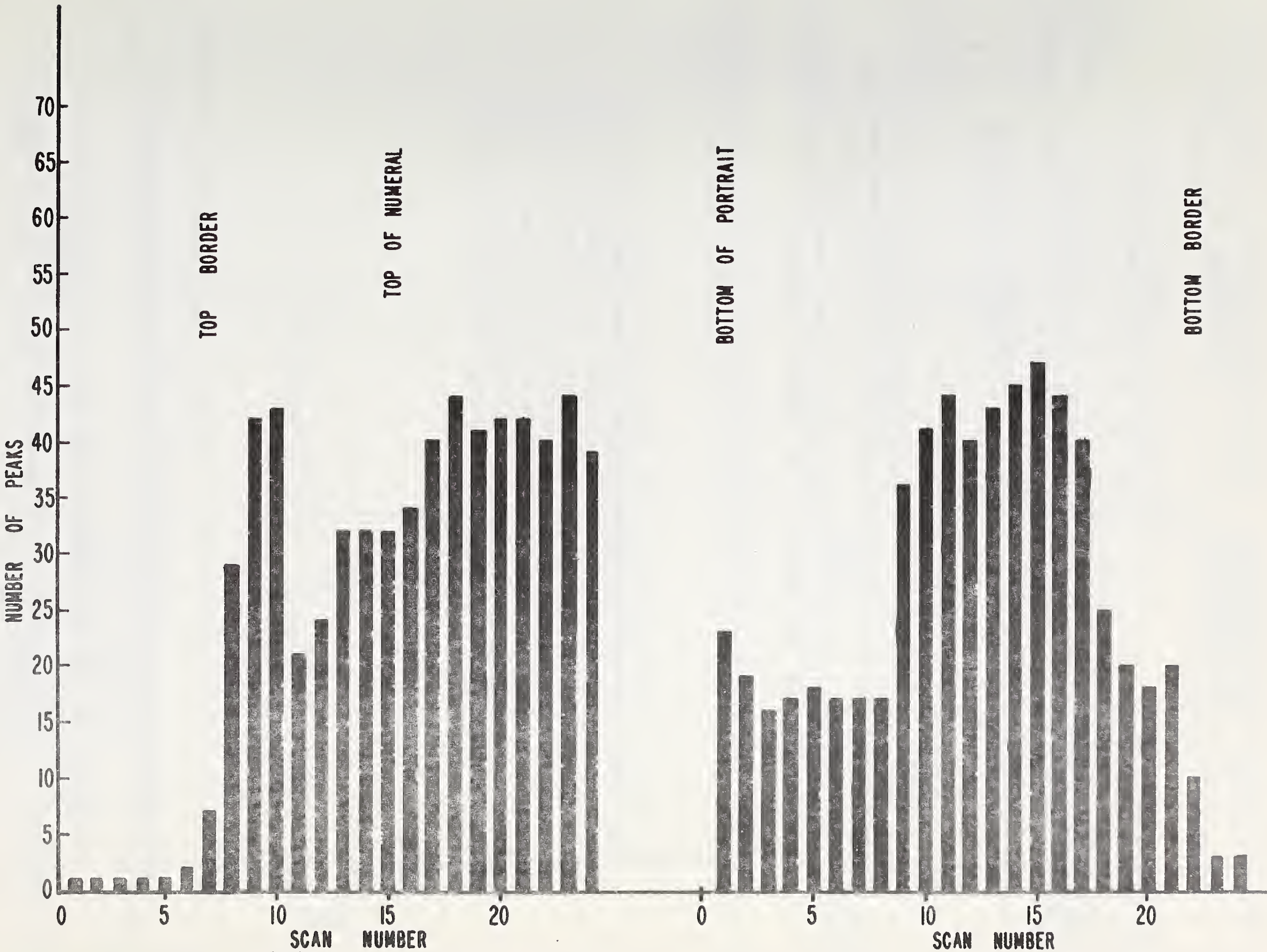
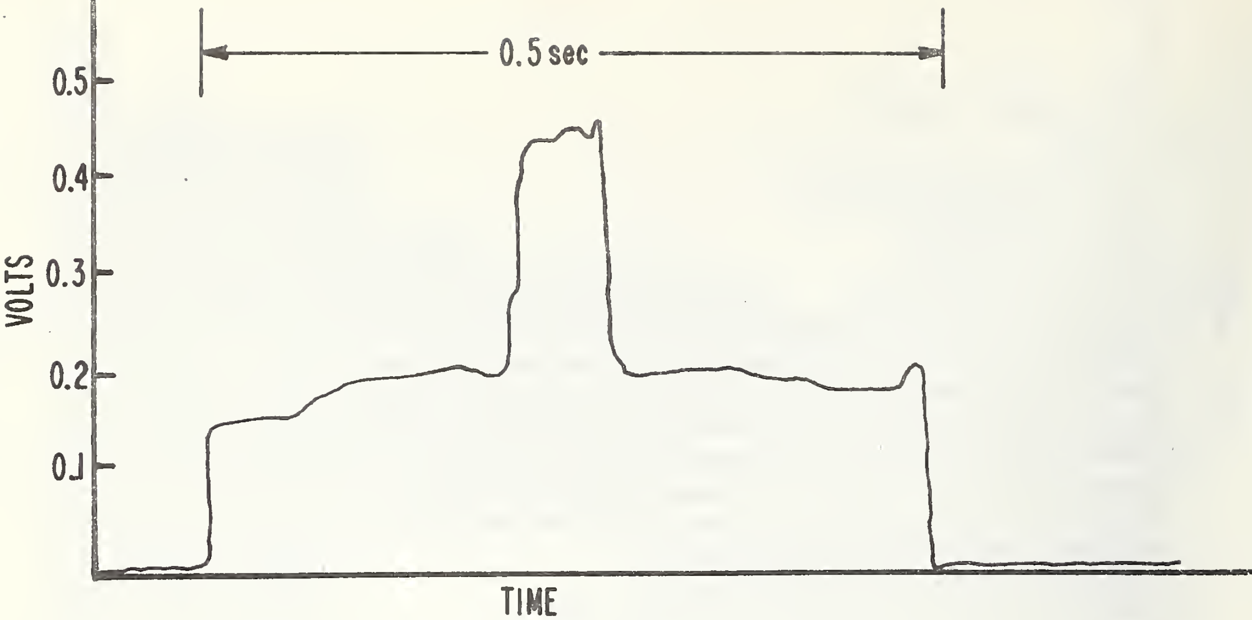
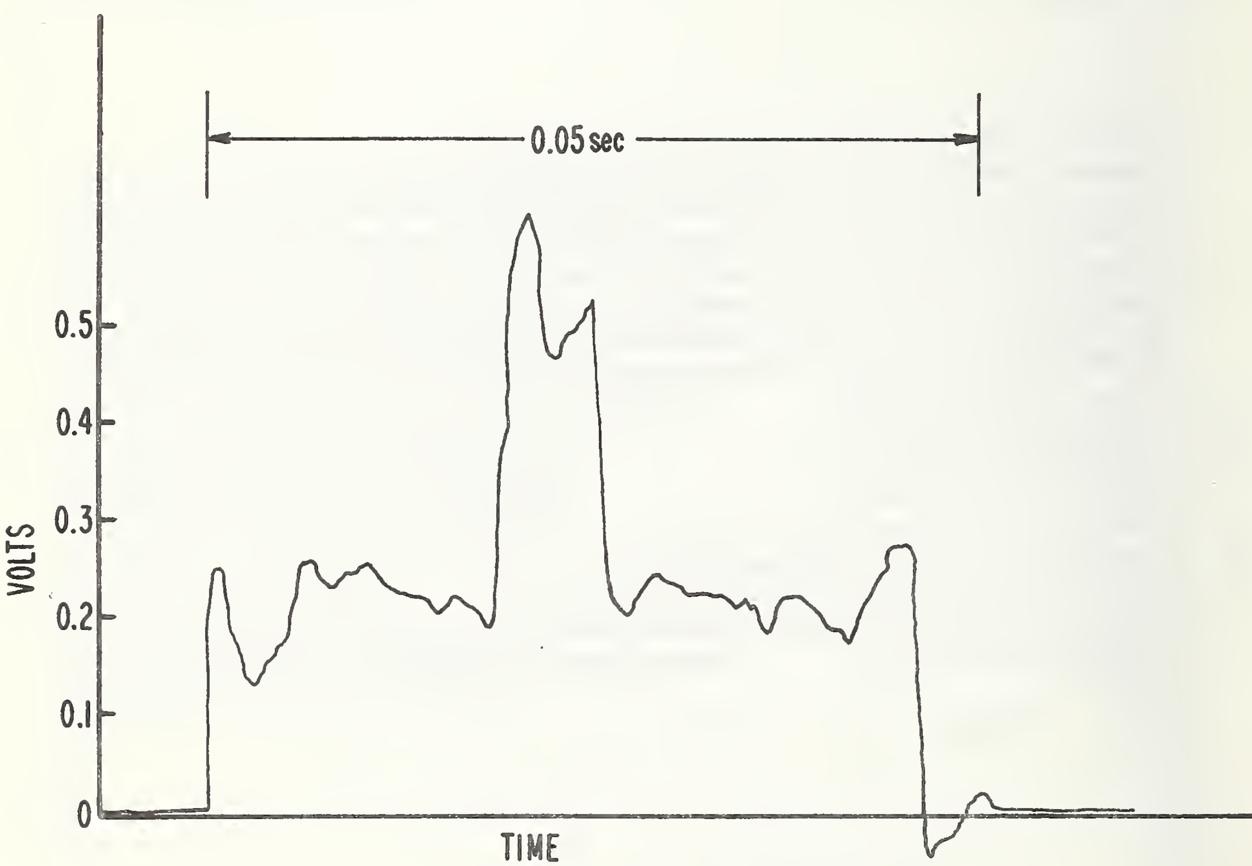


Figure 9. Number of peaks in scans at the top and bottom portions of a twenty dollar bill.



(a) OUTPUT FOR THE BILL MOVING AT THE RATE OF 2 BILLS/SEC



(b) OUTPUT FOR THE BILL MOVING AT THE RATE OF 20 BILLS/SEC

Figure 10. Thickness detector output as a bill with tape on it passes through the detector.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This report summarizes the progress on developing fitness measurement methods necessary for the automatic handling of currency. This work shows the feasibility of determining the denomination of a bill by making measurements of the optical reflectivity of the portrait side of the bill. It also describes a method of measuring the thickness of a bill while it is in motion. This method has adequate sensitivity and speed of response to detect the presence of tape on a bill which is moving through the detector at the rate of twenty bills per second.

17. KEY WORDS (Alphabetical order, separated by semicolons)

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