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EVALUATION OF THE GOES I-M NORMALIZATION TECHNIQUE WITH THE VISIBLE IMAGES OF GOES-7

Washington, D.C.

April 1990

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CONTENTS

Abstract	-----1
1. Introduction	-----1
2. Background	-----2
3. The New Procedure	-----3
3.1 Evaluation	-----4
3.2 Operational Results	-----6
4. Summary	-----9
Acknowledgements	-----9
References	-----10

TABLES

1. Striping for three images of May 26, 198811
2. Partial histogram from the GOES 7 raw image of
March 15, 198912
3. Normalization table from the GOES 7 raw image of
March 15, 198913
4. Normalization table from the GOES 7 raw image of
March 15, 1989 with the noise deleted14

FIGURES

1. Residual striping from 3 images of Feb. 16, 198915
2. Residual striping from 3 images of March 3, 198916
3. Residual striping from 3 images of March 23, 198917
4. Maximum striping between April 19 and May 1, 198918
5. Average striping for the GOES 7 operational images
in 198919



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EVALUATION OF THE GOES I-M NORMALIZATION TECHNIQUE
WITH THE VISIBLE IMAGES OF GOES-7

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ABSTRACT. The visible images of the earth from the current and future NOAA geostationary satellites are produced from observations by eight separate detectors. Because the detectors have different responses to the reflected solar energy and are not calibrated in flight, the signals from seven of the detectors are normalized to that of the eighth detector to avoid banding or striping in the images. A technique employing matching of the channels' empirical distribution functions has been proposed for minimizing the striping in the images from the future GOES I-M spacecraft. This method has been evaluated in an operational setting with the data of GOES 7. The results from a series of comparisons between the images derived from the operational normalization technique and the new technique are discussed quantitatively. The new technique significantly reduces the level of striping in the visible images compared to that produced by the operational procedures. The new method improved the image quality to an extent that warranted its implementation for the GOES 7 operational images in June 1989.

1. INTRODUCTION

The first NOAA operational geosynchronous satellite was launched in 1974. That spacecraft, the Synchronous Meteorological Satellite (SMS-1), provided images of the earth on a routine basis. It was the first of a series of NOAA geosynchronous satellites that have provided day and night observations of the weather within the western hemisphere for 15 years. To date NOAA has flown 10 geostationary satellites, each with the capability of observing the earth and atmosphere in the visible spectral region during daylight and in the infrared region day

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and night.

The visible images from all the NOAA geosynchronous satellites have been constructed from measurements by instruments with a linear array of eight separate detectors. These detectors have approximately the same spectral and radiometric characteristics. As the satellite spins on its axis, the detectors view the earth in eight parallel adjacent paths. A stepping mirror advances with each spacecraft rotation so that the full earth disk is viewed in approximately 18 minutes. These measurements by the separate detectors are combined on the ground to create an image. When processed at full resolution, they provide visible images with a ground resolution of approximately 1 km at the nadir.

The processing corrects for differences in sensitivity among the eight detectors. At times there are residual effects of this correction process which are manifested as streaks or stripes in the image. The term 'striping' has been adopted to characterize the periodic light (dark) bands in an image created when one or more sensors have significantly higher (lower) sensitivity than the other sensors. This paper discusses the results of tests of a new procedure for reducing the striping in the images. The tests were performed in real time on the operational images from GOES 7. This new procedure will be used to reduce the striping in the images from the next series of NOAA geostationary satellites.

2. BACKGROUND

The NOAA geostationary satellites (SMS 1-3 and GOES 1-7) have used photomultipliers (Ensor, 1978) as detectors of the earth's reflected solar energy. Among the eight detectors on each of these satellites there exists at launch a range of sensitivities to the upwelling radiance from the earth and atmosphere. Furthermore, the output of each detector and its associated electronics (hereafter called a channel) may vary with age and with changes in spacecraft temperatures. Therefore the channels may produce dissimilar signals when they all view the same extended area of uniform brightness. Without an on-board calibration source to update each channel's calibration, the signals from the eight channels must be adjusted to generate an image of high quality.

On the spacecraft these signals are converted to digital counts and transmitted to the ground station. At the ground station an image is then generated by combining the observations of the eight detectors. If any photomultiplier's sensitivity actually differs significantly from the others, then striping will occur in the image unless the digital counts are adjusted prior to the image generation.

The process of adjusting the output of all channels so that the images appear as if they were constructed from the measurements of a single channel is called normalization. In the past the normalizing procedure was based on a determination of the

relative responses of the channels to scenes of uniform brightness in an image. Those scenes were selected by slicing an unnormalized image into small scenes and then testing for uniformity of signal within each scene. Only those scenes of uniform brightness were used to determine the relationship between one channel, chosen as a reference, and the other seven channels. The signals from each of the seven channels were then adjusted to match those of the reference channel through the seven relationships.

The normalization was accomplished by determining a function $f_j(x)$ such that the signals x from channel j were adjusted to approximate those of the reference channel x_r at all brightness levels.

$$f_j(x) = x_r \quad (1)$$

This function, restricted for operational reasons to a second or third order polynomial, was derived by a least squares technique for each of the channels. (For the reference channel, $x_r = x$).

The unnormalized signals from the channels are obtained operationally by acquiring a "calibration" image, i.e., an unnormalized image that contains the raw observations from the eight channels. An image of raw data is normally scheduled once per week and is used to derive $f_j(x)$, the normalization functions of Eq. 1. For the derived normalization function to be correct at all brightness levels, the raw image should contain observations over the full dynamic range of the detectors. The application of these functions to the operational images occurs in real time via a look-up table in the equipment at the ground station.

This operational technique has been used to normalize the visible channels of the NOAA geostationary satellites since the mid-1970s. Images normalized by this procedure have frequently exhibited some residual striping. On a typical image the maximum difference in signals from any two channels while viewing a uniform scene has been about 2-3 counts out of the 64 counts in the six-bit data stream, a level sufficient for an observer to detect striping in the image. We have observed that this operational normalization procedure eliminates striping at some brightness levels more effectively than at others. It is likely that the residual striping is a consequence of the inability of the low-order polynomials, which describe the relationship between each channel and the reference channel, to account for the non-linearities in the photomultipliers' responses.

3. THE NEW PROCEDURE

With the advent of the GOES I-M spacecraft, a new ground processing system is being designed. The data from the visible channels of the GOES I-M spacecraft are being increased from 6-bit words to 10-bit words. This change will increase the size of

the normalization table by a factor of 16 and allow for a more precise normalization of the visible images. A new technique utilizing empirical distribution functions, EDFs, (Horn and Woodham, 1979) was proposed as an improvement over the current operational method for normalizing the visible images. Preliminary feasibility of that method for GOES images was demonstrated by Weinreb et al., (1989a). We have undertaken a thorough study of that technique in an operational setting with the visible images from the current geostationary spacecraft (GOES 7) and report the results of that investigation here.

3.1 EVALUATION

Our evaluation of the EDF algorithm was initially undertaken on an interactive computer, the McIDAS (Suomi et al., 1983). Software was written to permit the McIDAS operator, in an interactive mode, to accumulate separately each channel's observations from numerous small areas of an image. Histograms and EDFs were constructed from the data of each of the eight channels. The method employed by the new technique adjusts the raw signals of each channel so that its EDF matches the EDF of the reference channel. A detailed discussion of the generation of a normalization table by the technique of matching the EDFs is presented in Weinreb et al., (1989a).

Additional McIDAS software was created to apply these tables to a sector of the raw image. This normalized sector was then displayed on the McIDAS monitor. Inspection of the first images normalized on the McIDAS by the new algorithm showed that the images were less striped than the operational images to which they were compared. Similar tests were conducted on a regular basis as new images of raw data became available. The new technique showed improvement over the operational normalization but the quality of the normalized image was dependent on the selection of data to generate the EDFs. A better image was produced by the normalization software when the operator built a histogram with nearly-equal samples from all brightness levels in the raw image. These were constructed more readily when areas of the image with variable brightness (scattered or multi-layered clouds) were selected rather than areas of uniform brightness (clear or overcast conditions). Construction of the data set entailed an iterative process of table creation, inspection of the data distribution through ancillary routines, and selection of additional data to fill any data voids. Clearly, this iterative process would not be suitable for an operational environment.

However, the results of the study on the McIDAS showed unambiguously that the new technique improved the quality of the GOES visible images and that further development of the technique for eventual operational application was worth pursuing. The algorithm was then coded for the NESDIS main-frame computer. This code permitted a much larger part of the image to be used

for the derivation of the new table and, more importantly, the new software processed the raw image data objectively. The normalization tables generated on the large computer were transferred to the McIDAS and then used to normalize a raw image. That image was displayed on the McIDAS monitor along with a routine operational image generated from the operational tables.

An evaluation of the level of residual striping in these two normalized images was undertaken. The striping was computed by analyzing the signals from approximately 10 areas of uniform brightness in each image, encompassing the full range of signals in the image. The measurements by each channel in each of these uniform areas were averaged separately; the differences in these averages is a measure of the magnitude of the residual striping in that area. The following discussion is based on these analyses performed on the McIDAS.

The first comparison of an operational image and an image normalized by a table created by the new technique on the main-frame computer was conducted on data acquired on May 26, 1988. Unnormalized data from a raw image acquired earlier (on May 18) had been used previously to produce a new table on the large computer. That table was transferred manually to the McIDAS and used to normalize the raw image acquired at 1849Z of May 26. The table derived by the operational normalization technique from the raw image of May 18 was also manually transferred to the McIDAS and used to normalize the same May 26 raw image. A third image, the operational image at 1901Z of May 26, was also acquired because it was generated by tables which had been transferred electronically to the ground station and were in operational use. The comparison of this additional operational image with the two images generated on the McIDAS was important because, under some circumstances, the procedures used to transfer the operational tables to the ground station were found to reduce the accuracy of the tables.

This operational procedure entails fitting the normalization table for each channel to a polynomial in counts whose coefficients are then transmitted from the site of the main-frame computer to the ground station. The coefficients are then used to recreate the full table at the ground station. A problem arises because the tables for some of the channels are non-linear. The system in use to transmit the coefficients to the ground station was limited, in practice, to transmitting the coefficients of a quadratic polynomial. A quadratic fit to the normalization table is often unable to represent the true normalization table of the more non-linear channels. Consequently, the tables recreated at the ground station from the coefficients are degraded. The third image is used here to assess the impact of these inaccuracies from the reconstructed table.

Table 1 shows the striping from several brightness levels in these three images. Here striping is defined as the difference between the maximum signal and minimum signal of the eight channels. If the images were perfectly normalized, these differences would be zero except for the round-off errors accrued in

forming a table of integer values. The first row shows the striping for the operational images at 1901Z. That data reflects the cumulative inaccuracies of the quadratic fit and the re-creation of the tables at the ground station from the polynomial coefficients. Residual striping up to 4 counts is evident at the mid-range (30 counts) of signals. The second row of data shows the striping for the May 26 image from the operational table which was manually transferred to the McIDAS. This image shows a reduction in striping at the mid-range of brightness compared to the operational table. The striping is excessive only at the two highest brightness levels. Note that differences of 1 count may be caused by round-off. The third row contains the striping from the image normalized by the table generated by the new algorithm. The maximum striping in this image is reduced by a factor of nearly two relative to the other images. This demonstrates the improvement in image quality that the new algorithm can provide. Comparisons from images of other days (not shown) yielded comparable results.

3.2 OPERATIONAL RESULTS

After the successful test of the new technique on the McIDAS, the algorithm was next tested in the operational environment. A series of operational tests were performed in which a table, derived by the new algorithm from the weekly image of raw data, was inserted into the ground equipment and used as the operational table for one or two images. In this manner it was possible to evaluate the impact of the new tables in the operational setting where they would be used. The test was repeated on many days to uncover the variety of problems that arise when real data are processed. The most significant of these are discussed below.

Several of the these tests showed the extreme sensitivity of this new normalization algorithm to noise in the raw data from which the tables are derived. Table 2 shows a part of the histogram of the raw image from March 15, 1989. This table shows the number of data at each brightness level (index level) of each channel in the raw data image. Note that the data begin at different index levels for the individual channels. This variability is a consequence of the different sensitivities of the eight photomultipliers to the incoming radiance. In this sample from a raw data image there were no signals below 7 counts except in channel 7. A single datum of noise appears at index level 4 in channel 7. The new normalization algorithm interpreted that datum as the beginning of the channel 7 histogram and derived a table on that basis. Table 3 shows the top of the normalization table developed from that data. (An example of a complete normalization table is given in the appendix of Weinreb et al., 1989b.) The first table entries for all detectors are zero or one and have a progression of values, except channel 7 which begins at 4 (where the noise occurred). For that channel the

value of 8 is repeated for 6 entries whereas the values of the other channels index smoothly. Clearly, the noise datum severely affected the table for channel 7 at the lowest count levels. Single samples of noise were also observed in other data sets at high count levels, above the brightest scenes in the images. These values also produced an error in the table for the channel in which they occurred. We found that noise at count levels above and below the main body of the histogram can be excluded in the computation of the table by deleting an extremely small fraction of the data at the top and bottom of the empirical distribution function of each channel. That same fraction is entered in the software as an input variable for each channel and usually does not exceed 0.01% of the data.

Table 4 shows a part of the normalization table produced after deleting an even smaller fraction (0.001%) of the data from the empirical distribution function of the March 15 raw image. The same fraction of data from each channel was deleted prior to the computation of this normalization table. The table for channel 7 now appears similar to those of the other channels. The deletion of this small amount of data did not alter the tables generated for the other channels.

An additional problem uncovered in the analysis of images generated by the new tables involves the method used to extrapolate the tables to brightness levels that do not occur in the raw data image used to create the new table. When the observations by any channel do not include the full dynamic range (0-63 counts) of the digital system, it is necessary to extrapolate to produce a complete normalization table. Experimentation with several methods showed that the best tables were produced by simply indexing by one count at each level beyond the maximum and minimum values of the histogram. Thus the values at the lower levels in the normalization table are generated by indexing downward from the first entry provided by the normalization technique. As an example, in Table 2, no data appear in the histogram of channel 5 from index level 0 through level 10. Extrapolated values have been generated for index levels 10 and lower in the normalization table (Table 4). The other channels (except channel 2, the reference channel) show similar extrapolations. The levels above the last entry (not shown) are generated by indexing upward until the table is complete. If either zero or 63 counts is reached before the table has been completed, these extreme values are repeated until the table is complete. As an example, see channels 3, 5 and 7 in Table 4 which have values of zero for several index levels at the top of the table.

These improvements were incorporated in the software as the operational tests were proceeding. A typical test consisted of using a table generated by the new technique for one operational image. The striping from that image was compared with that from the operational images preceding and following the test images. Recall that the operational images were generated by tables that were recreated from the polynomial coefficients. Figures 1-3 show the results from the tests performed on February 16, March 2

and 23, 1989. The residual striping (maximum signal minus minimum signal from the array of eight detectors), derived from regions of uniform brightness in each image, is plotted in the figures. The abscissa is the brightness level (in counts) of the uniform areas. The solid squares show the striping from the test table made by the new algorithm; the open circles and open squares show the striping from the adjacent images generated from the operational normalization tables. With one exception these figures show that the residual striping is reduced in the images normalized by a table generated by the new technique. The exception is shown in Fig. 2 where the increased level of striping at 50 counts was caused by an inadequate extrapolation in the new normalization algorithm. Subsequent operational tests were conducted with tables generated with the improved extrapolation procedure discussed above.

A final test prior to initiating full-time use of the new table was performed from April 24 through April 28, 1989. Over this four-day period all operational images were normalized by a table generated by the new technique. The regular operational table was used on the days preceding and following the test period. Both the test table and the operational table had been generated from the same raw image. Figure 4 shows the striping measured on those days. The ordinate is the maximum residual striping observed in any of approximately 10 areas of uniform brightness evaluated in each image; the abscissa is the date. The solid squares depict the values from the images with the new table; the open squares, those from the images normalized by the operational normalization tables. This figure shows clearly the reduced levels of residual striping in the images normalized by the new table.

Every comparison of the images generated by the two techniques showed that operational images would contain less striping if they were generated by the new algorithm. The improvement in image quality was sufficient to proceed with implementation of tables from the new algorithm even though an improved communication system to transfer the tables to the ground station hardware by computer was not in place. On June 7, 1989 the table generated by the new algorithm from the May 18, 1989 raw image was keyed into the hardware at the ground station for full-time operational use. This same table remained in operational use until December 5, 1989 when the table was updated because striping had become evident in the GOES 7 images.

Fig. 5 shows the mean striping computed from operational images for January 9 through December 31, 1989. The striping in this figure is an average of the striping at nine brightness levels over the 10-50 count range. Striping from the very brightest scenes has not been included because above 52 counts the signal level from 2 of the detectors saturates and can not be corrected by either normalization technique. The striping in the images generated by the new normalization technique are shown as solid squares and that in images by the old technique are shown as open squares. Note the reduction in striping from April 24 to

April 28 when the 4-day test of a table generated by the new algorithm was conducted and after June 7 when a table from the new algorithm was placed in continuous operational use. The plus signs appearing at the top of the figure identify the days when changes were made in the operational tables. Note that the frequency of table changes was dramatically reduced with the implementation of a table from the new algorithm. The table implemented on June 7 (generated by the new algorithm) was used for about six months before it was updated on Dec. 5, 1989. The minor increase in the level of striping around day 250 coincides with the eclipse period when the GOES 7 spacecraft passed through the earth's shadow every day. A similar increase in striping appears around day 80, the time of the spring eclipse. These increases in striping are most likely a consequence of the changing spacecraft temperature on the output of one or more of the channels.

Figure 5 demonstrates the improvements that can be achieved with the new algorithm. As operational experience is gained with this technique, the levels of residual striping in the GOES images should be held to 1 count or lower. Experience with this new algorithm indicates that the images from the next series of geostationary satellites, which will be normalized by the same algorithm, will contain a lower level of striping than that observed previously in images from the geostationary satellites.

4. SUMMARY

A new technique using empirical distribution functions to normalize the visible images from GOES 7 was evaluated. A series of comparisons were made between the operational images and images normalized by the new method. In every instance the new method produced images with less striping. Quantitative studies showed that the striping was reduced, on the average, from about 2 counts to 1 count (out of 64 counts). Operational use of the tables from the improved method began June 7, 1989 on the GOES 7 visible images and continues to demonstrate the higher quality of the images produced by the new algorithm.

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TABLE 1

STRIPING (IN COUNTS) FOR THREE IMAGES OF MAY 26, 1988

BRIGHTNESS LEVEL (counts)	12	20	25	30	40	45
------------------------------	----	----	----	----	----	----

TABLE

OPERATIONAL (from polynomial fit)	1.2	2.8	4.1	4.0	2.5	1.8
OPERATIONAL	1.7	1.2	1.2	1.8	3.0	3.8
NEW ALGORITHM	1.5	1.5	1.0	1.5	1.5	2.0

TABLE 2

PARTIAL HISTOGRAM FROM THE GOES 7 RAW IMAGE OF MARCH 15, 1989

INDEX	CHANNEL							
	1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	1	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	273	0	0
9	929	41	0	4163	0	29165	5	2953
10	24794	9154	0	80596	0	86692	1909	66832
11	67866	64330	58	58725	8	39004	38757	64568
12	41677	53966	2325	20650	596	14334	63185	24142
13	20091	25472	18529	12664	7951	10499	37968	13530
14	12050	13641	45656	9648	30095	8816	17982	9253
15	10118	11107	49821	8447	48456	8602	12118	7917

TABLE 3

NORMALIZATION TABLES FROM THE GOES 7 RAW IMAGE OF MARCH 15, 1989

INDEX	CHANNEL							
	1	2	3	4	5	6	7	8
0	0	0	0	0	0	1	4	0
1	1	1	0	1	0	2	5	1
2	2	2	0	2	0	3	6	2
3	3	3	1	3	0	4	7	3
4	4	4	2	4	1	5	8	4
5	5	5	3	5	2	6	8	5
6	6	6	4	6	3	7	8	6
7	7	7	5	7	4	8	8	7
8	8	8	6	8	5	9	8	8
9	9	9	7	9	6	10	8	9
10	10	10	8	11	7	12	9	11
11	11	11	9	13	8	13	10	12
12	12	12	9	14	9	14	12	13
13	13	13	10	15	10	15	13	14
14	14	14	11	16	10	16	14	15
15	15	15	12	17	11	17	14	16

TABLE 4

NORMALIZATION TABLE FROM THE GOES 7 RAW IMAGE OF MARCH 15, 1989
WITH THE NOISE DELETED

	CHANNEL							
	1	2	3	4	5	6	7	8
INDEX								
0	0	0	0	0	0	1	0	0
1	1	1	0	1	0	2	0	1
2	2	2	0	2	0	3	1	2
3	3	3	1	3	0	4	2	3
4	4	4	2	4	1	5	3	4
5	5	5	3	5	2	6	4	5
6	6	6	4	6	3	7	5	6
7	7	7	5	7	4	8	6	7
8	8	8	6	8	5	9	7	8
9	9	9	7	9	6	10	8	9
10	10	10	8	11	7	12	9	11
11	11	11	9	13	8	13	10	12
12	12	12	9	14	9	14	12	13
13	13	13	10	15	10	15	13	14
14	14	14	11	16	10	16	14	15
15	15	15	12	17	11	17	14	16

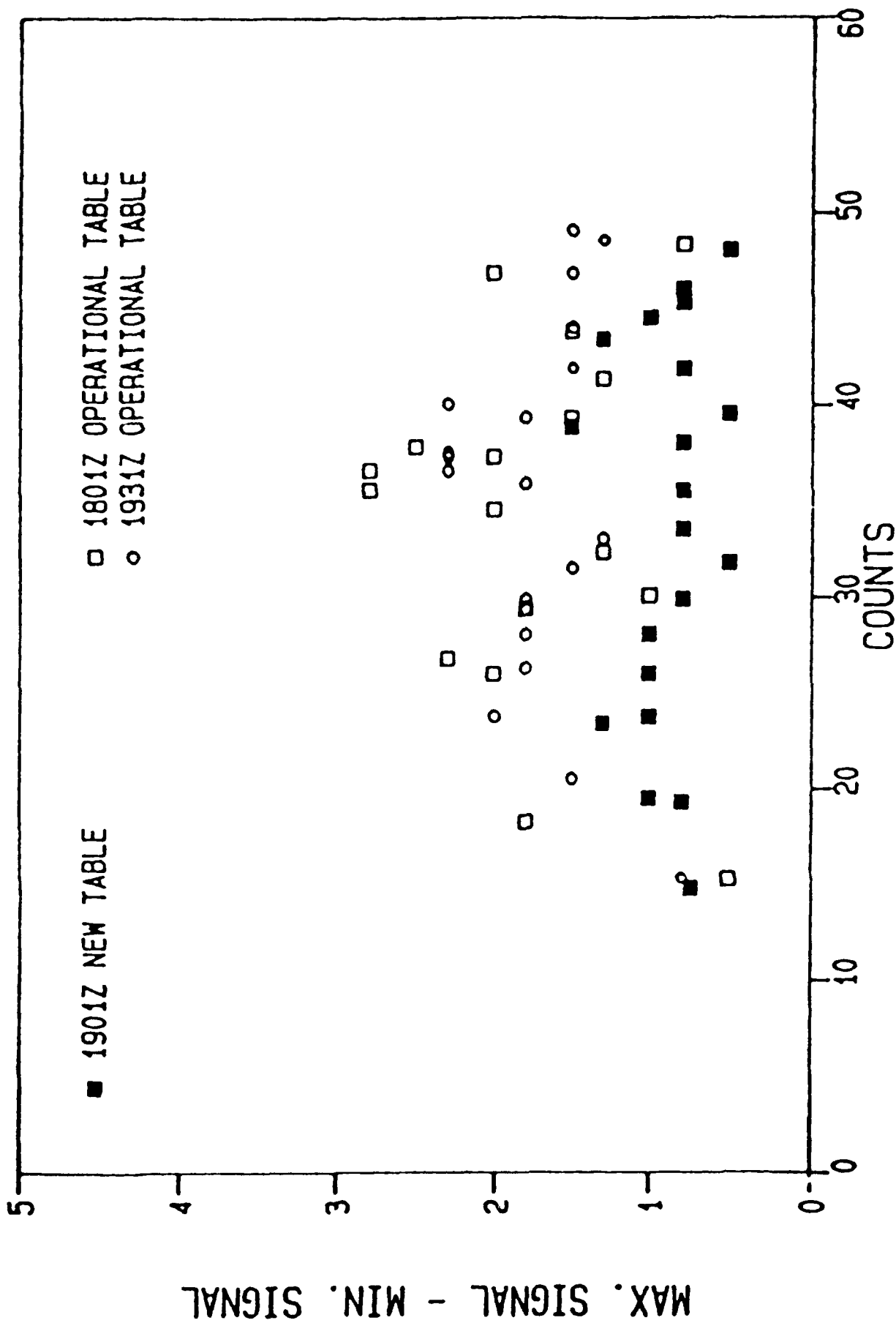


Figure 1. Residual striping from 3 images of February 16, 1989. The open symbols represent data from the operational algorithm, the solid are from the new algorithm.

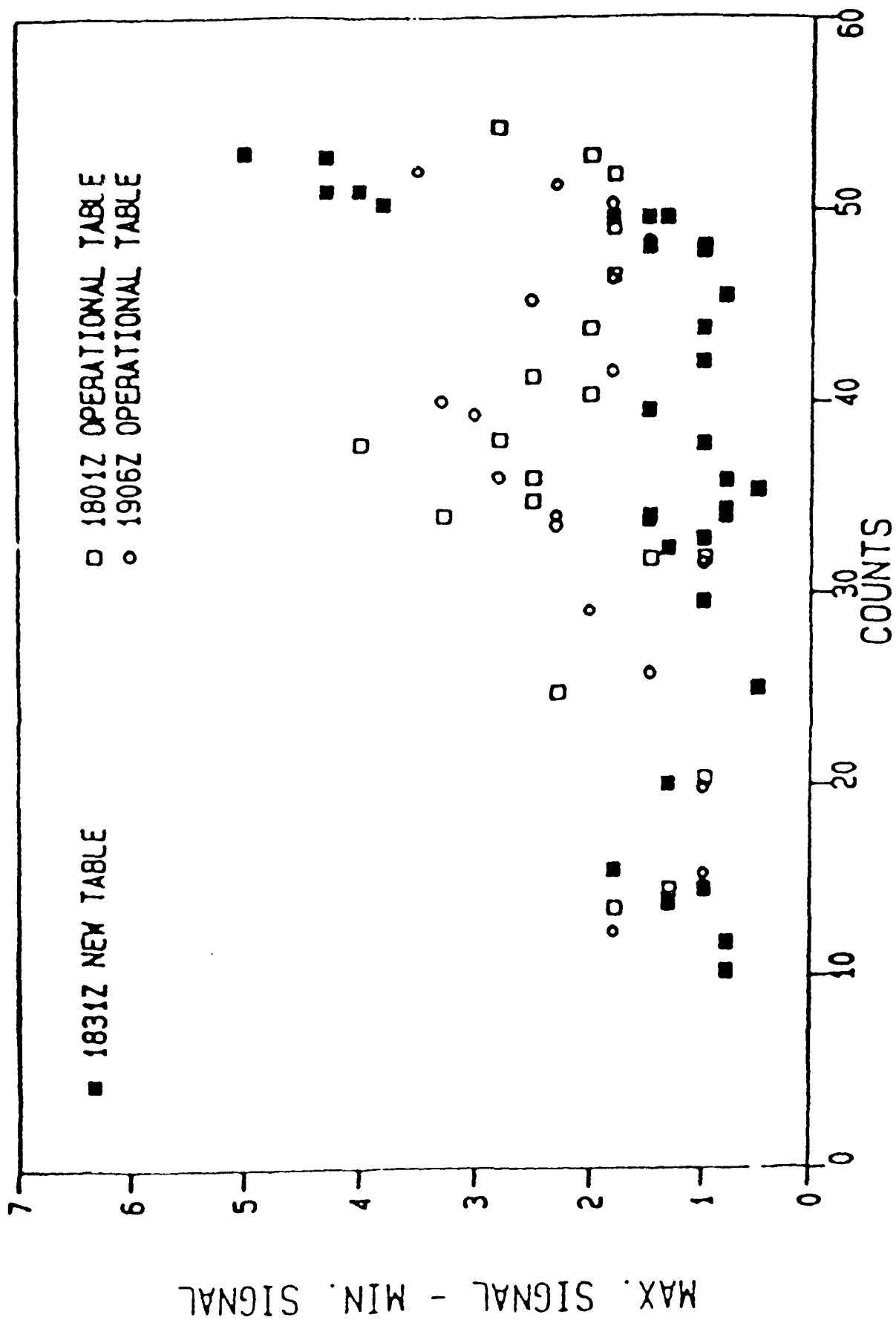


Figure 2. As in Figure 1 but from images of March 3.

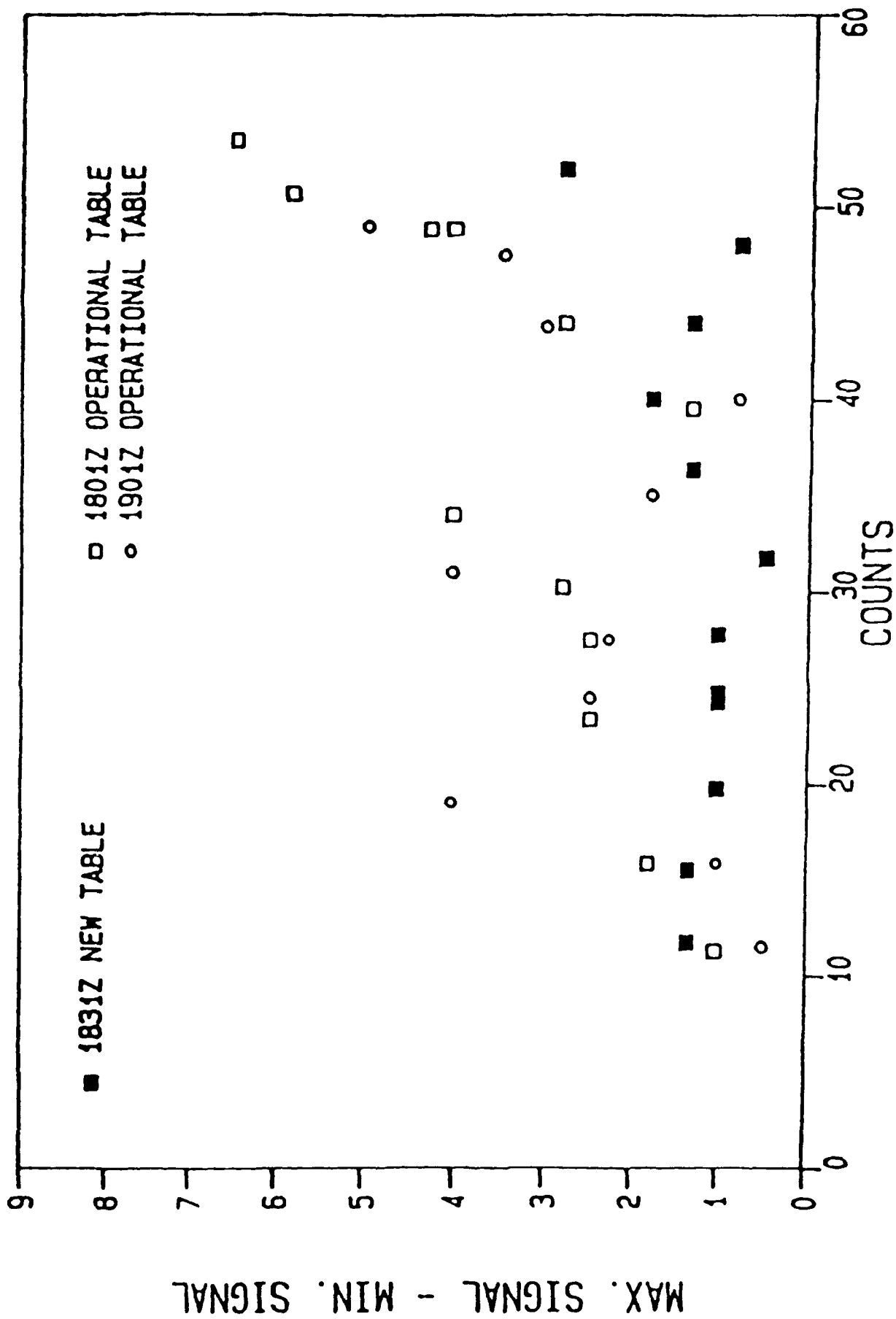


Figure 3. As in Figure 1 but from images of March 23.

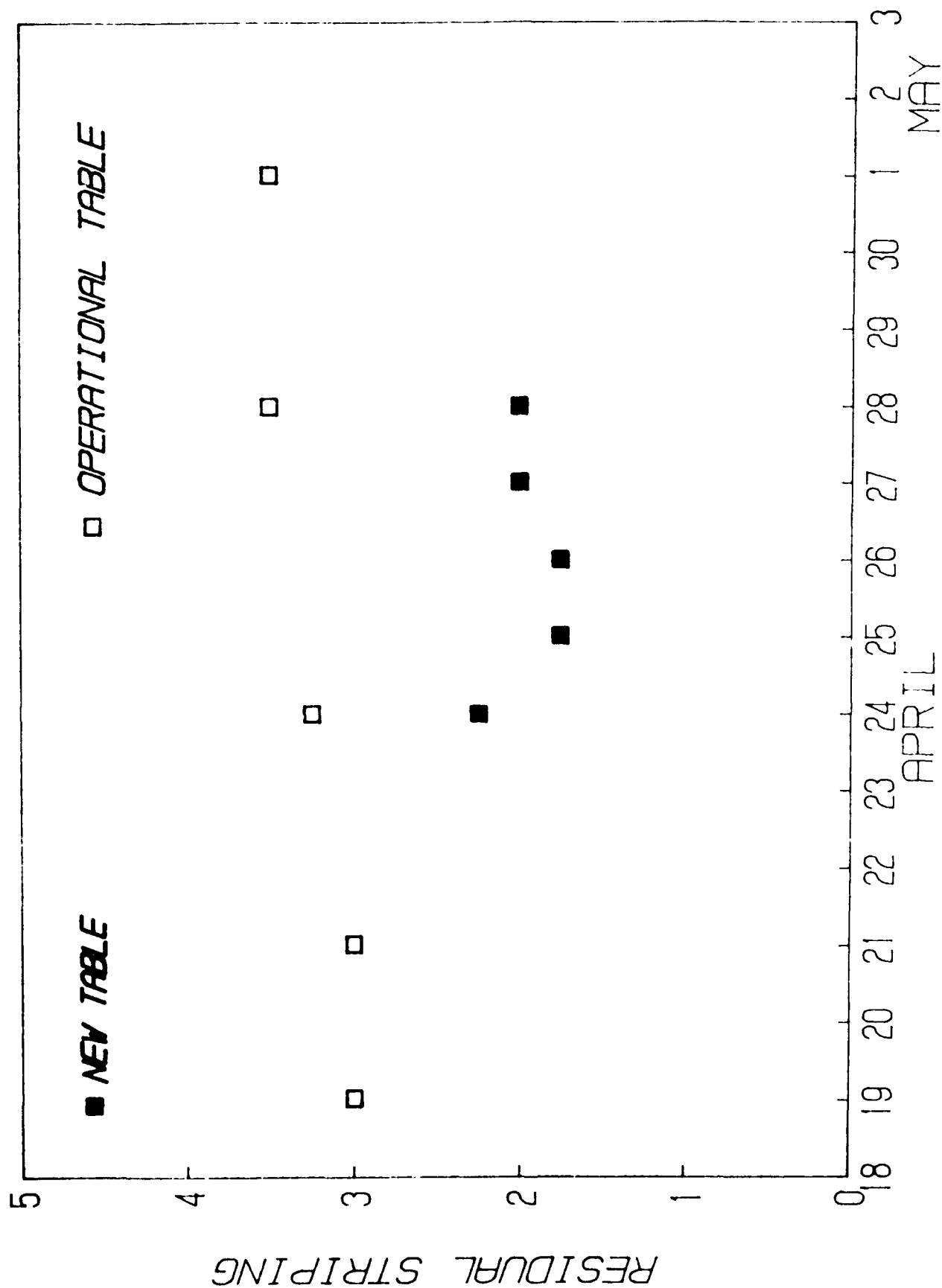


Figure 4. The maximum residual striping from images between April 19, and May 1, 1989. Tables from the new algorithm were used operationally from April 24 to April 28.

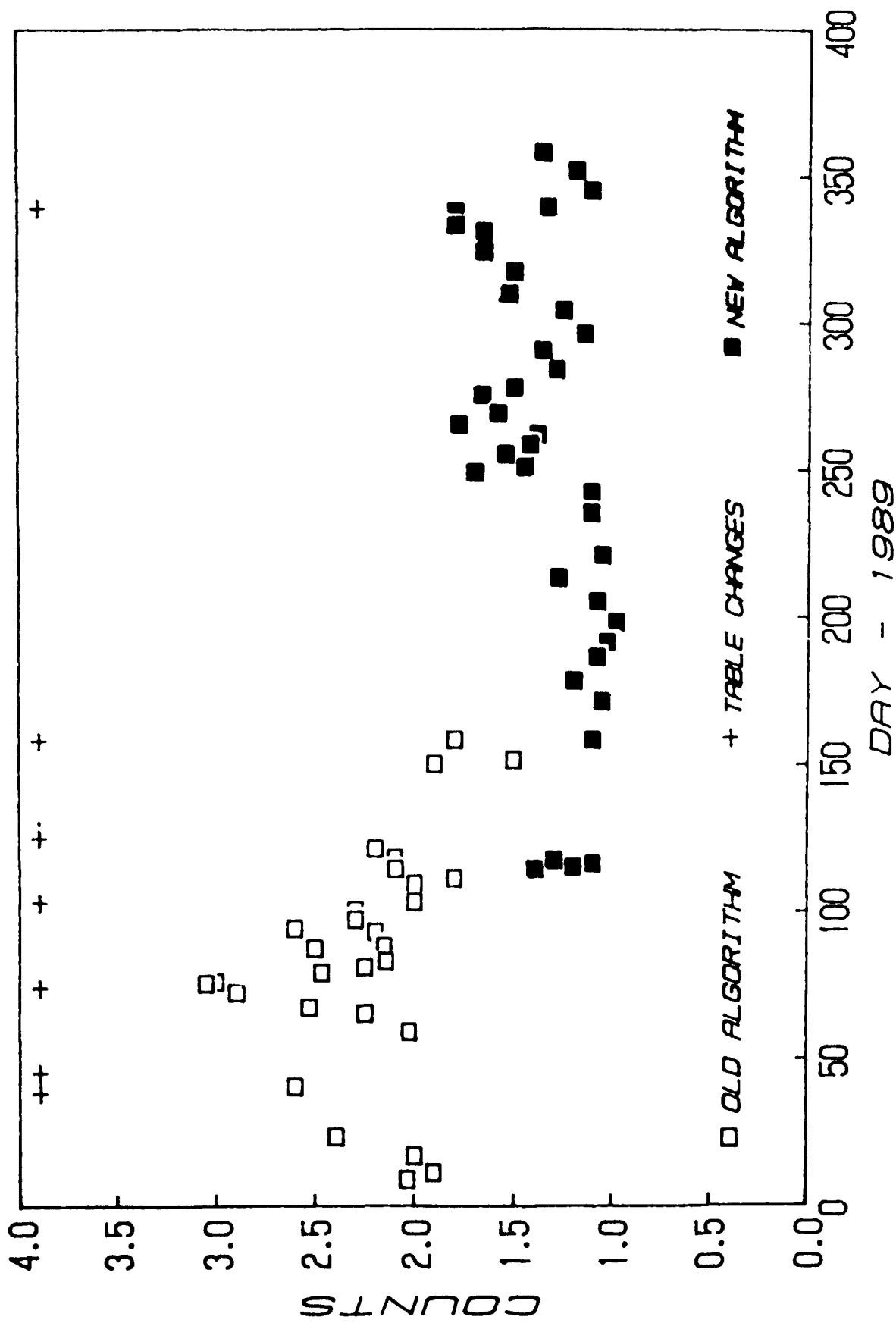


Figure 5. The average striping for the GOES 7 operational images of 1989. The solid squares depict the striping in the images generated by the new algorithm. The dates of table updates are marked by (+) at the top of the figure.

(Continued from inside front cover)

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