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Covering the Period 15 January 1976 through 15 February 1977

APPLICATION OF THE SRI AUTOMATIC CLOUD-TRACKING SYSTEM TO SMS-GOES DATA

By: DANIEL E. WOLF, DAVID J. HALL, and ROY M. ENDLICH

Prepared for:

NAVAL ENVIRONMENTAL PREDICTION RESEARCH FACILITY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA 93940

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SRI Project ERU-4854

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The SRI automatic cloud-tracking system is being implemented at the present time on the SPADS minicomputer system of the Naval Environmental Prediction Research Facility at Monterey. This report gives background information concerning the system and describes recent improvements. The clustering process, which identifies groups potentially suitable for tracking, has been simplified and improved using a new algorithm for "touching groups." Also, the criteria have been made more accurate for pairing groups at two different times to determine cloud displacements. Some current tests of the method (carried out at SRI using a → next page

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Cont → CDC-6400 computer) are described. These tests used SMS-GOES data in both visible and infrared channels for several different types of clouds. In terms of the accuracy and number of cloud-motion vectors obtained, the results are considerably superior to any achieved previously using automatic methods. Our experience indicates that the system can process satellite data routinely to obtain cloud-motion vectors for input to numerical weather-prediction models.

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CONTENTS

ILLUSTRATIONS

PREFACE

Since 1970, research has been carried out at SRI to develop methods for automatically measuring the cloud motions shown in sequences of pictures from geosynchronous weather satellites. This work was begun under sponsorship of the U.S. Navy Project FAMOS and has been continued under contract to the Naval Environmental Prediction Research Facility. The intended application is to furnish input data for the numerical weather-forecasting models used at the Fleet Numerical Weather Center.

Under the present contract, a companion document to this report is also being prepared. It is entitled "User's Guide for Running the SATS Programs on SPADS." This user's guide documents the steps necessary to execute the SRI Automatic Tracking System (SATS) on the SATDAT Processing And Display System (SPADS) at Monterey, California. Practical steps are listed for operating the console and interactively modifying system parameters, as well as using and interpreting the results.

I INTRODUCTION

In an earlier paper, we described the formulation and preliminary testing of an automatic system for tracking clouds that are shown in sequences of pictures from geosynchronous weather satellites (Endlich et al., 1971). The system was based in part on the ISODATA computer program developed by Ball and Hall (1967). ISODATA is a general-purpose pattern recognition technique that subdivides data into groups or clusters (under the control of certain preselected parameters) and also locates group centers. By tracking the centers of brightness of cloud groups (as identified by ISODATA), cloud motions may be determined. Wolf et al. (1973) reported further tests of the method which included comparisons with human tracking performed using the SRI electronic cloud console (Serebreny et al., 1970). These comparisons showed that the automatic method performed rather satisfactorily for cases where only a single layer of clouds existed in the scene. A major difficulty was that the computer program produced a sizable proportion (approximately 15 to 20 percent) of spurious motions. These errors were caused mainly by the random changes in size, brightness, and shape associated with the dynamic nature of clouds. One of the main tasks of a human analyst in tracking clouds is to ignore this randomness and select representative tracers for tracking. Recent improvements to the programs have reduced the spurious vectors to a small proportion of the total number. This report describes the present programs with emphasis on the automatic tracking system, and shows results obtained using brightness data alone, IR data alone, and also a combination of brightness and IR data. The report is intended to aid NEPRF personnel in evaluating the programs using the SPADS computer system at Monterey.

The overall goal of this work is to develop an automatic cloud-tracking system that is accurate, applies to a wide variety of weather situations (including those having two or more cloud types in the scene), is fast and economical, makes use of the excellent quality of both visible and IR satellite data now being obtained on a routine basis, and requires little human control.

The SRI cloud-tracking system differs from those at the University of Wisconsin (Smith, 1975) and the Goddard Space Flight Center mainly in using automatic rather than human selection of trackable cloud groups, and in using a pairing program (described later) rather than cross-correlation guided by a human analyst to compute motion vectors. The NESS automatic tracking method (Leese et al., 1971; Green et al., 1975) uses a cross-correlation method of computation but does not use target selection. All these systems are under continuing development.

We do not expect that automatic methods are likely to replace human analysts where weather processes and cloud motions are most complex, or in detailed research studies of the type made by Fujita et al. (1968), Hubert and Whitney (1971), Smith and Hasler (1976), Bauer (1976), and others. The purpose of using objective methods is primarily to cope with the tremendous volume of satellite data in a routine fashion to obtain cloud motion vectors suitable for use in numerical prediction models.

II OUTLINE OF THE METHOD

A general theoretical overview of the method is given in the Appendix. Here we will describe the specific procedures followed. The first step in the process is to select a small portion of a cloud photograph at Time 1, and the corresponding area in the next photograph at Time 2. This is done after landmarks have been used to give a first-order (translational) correction to register the pictures. (Further corrections are introduced at a later stage.) The areas are typically a few hundred miles on a side. Next, on each picture the relatively bright portions of the data, as compared to the immediate surroundings, are saved and the remainder is discarded. To identify the tracers, the saved data of Picture 1 are subdivided into cloud groups or clusters. Each group is a potential tracer. Typically there will be 25 to 50 groups in the scene. For each group, several characteristics are computed including the location of its center, its size, average brightness, and average IR temperature (when available). Picture 2 is treated in the same way. In the remainder of the computer processing the original data are ignored, and only the information about the groups is retained. This represents a reduction of the original information to a very small amount. Next, the MOTION program uses the descriptors of groups at Times 1 and 2 to match the groups in pairs, thereby giving cloud-displacement vectors over the time interval between pictures. The matching is done in an iterative computation. A matched group is required to exhibit continuity in size, brightness, shape, and IR temperature. Moreover, each vector (defined by a matched pair) must conform within certain limits to the predominant motion (average of all those selected). Usually, less than half the centers will be matched. After one set of vectors has been identified, the remaining group centers can be reprocessed to compute a second set of vectors of a different speed or direction from the first set. A second set will exist if there are two distinct cloud layers in the scene. The final steps are to convert the motions from picture coordinates (rows and columns) to earth coordinates (latitude, longitude, cloud speed and direction), and to assign an altitude to them, depending on their brightness and IR temperature.

III PRESENT PROCEDURES

A. Landmark Matching

Landmarks are located on the pictures at the point of best fit using a correlation technique. The computation is similar to that used by the NESS and University of Wisconsin groups, with the difference that clouds are thresholded out of the computation by eliminating brightness values above an appropriate upper limit for land. In this approach, the fast Fourier transform, which is very efficient computationally, cannot be used. However, this loss is overcome to a large extent by using a search routine that avoids finding correlations at all points. In the search, a coarse scan jumps the landmark template over the search area to identify the best locations from which to start a fine scan, which then locates the final position of best match. Further details are given by Wolf et al. (1973).

B. Separation of Clouds from Background

Separating brightness values that belong to trackable cloud groups from background values is a major problem. The brightness values (points) that are retained must be well-clustered and trackable. By well-clustered, we mean that they should form tight groups in which points belonging to a group are close together and separated from other groups. By trackable, we mean that each group is unique (in size, shape, and brightness), and the unique group is recognizable over at least two frames. Also, these groups of brightness values should be distributed over the cloudy areas of the region being processed so that cloud-motion vectors will cover the area, insofar as possible. Finally, to minimize computation time we want to retain only enough points to adequately describe the clouds.

The CLOUDS program performs these functions. It normally works with an area (selected from data tapes) that is 120 horizontal units (columns) by 70 vertical units (rows). The size of a brightness element, in terms of original picture elements, is a variable that permits experimentation with various resolutions. Since the ATS-III data tapes (recorded in Rosman format) have 8192 columns along a line and 2400 lines per picture, for these data we use a ratio of 3 column elements to 1 line element in making up a brightness unit that covers roughly a square area. Thus typical unit sizes are 3 by 1, 6 by 2, 9 by 3, etc. (all column elements by row elements). Close to the subsatellite point, these units correspond roughly to a square 3 miles, 6 miles, or 9 miles on a side. Thus total coverage of the 120 by 70 area is approximately 360 by 210 miles, 720 by 420 miles, or 1080 by 630 miles. The smaller unit takes more repetitions of the cloud-motion computation subsystem in order to cover a given geographical region. Each repetition produces about the same number of cloud-motion vectors (typically 10-20 vectors per repetition), so the higher resolution data produce more closely spaced vectors. The price paid for higher resolution is simply more computer time.

The simplest method of separating trackable clouds from background is to select the brightest elements in the scene and discard the remainder. This can be accomplished easily by forming a cumulative count of the number of brightness values greater than or equal to a given gray-scale value. A threshold is picked from the cumulative count that gives a prespecified number of points. Several examples are given by Wolf et al. (1973) which show that selecting the brightest elements does well as long as clouds in different parts of the region have approximately equal brightness. However, if a very bright cloud is in one part of the region with dimmer clouds over the remainder, this procedure will select only the bright cloud. Hence cloud tracking will reflect the motion of the bright cloud only, and the motions of other clouds will be lost.

A method that overcomes this problem is to vary the threshold, depending on the relative brightness of a small area of the scene. Brightness values greater than the average of nearby values are retained, and other values are discarded. This is accomplished by using a 21-by-21-point areal average, centered on the point of interest, to smooth the picture. This smoothing operator is run over the scene; then positive deviations from the smoothed values are retained. These deviations are brighter than their surroundings and comprise the trackable targets. In addition, an absolute threshold is used to ensure that the deviations saved do not represent land or ocean background. These computations are made by the DEVIATION program. A minor disadvantage of this procedure is that a 10-point margin without deviations is left around the edge, reducing the scene from 120 by 70 to 100 by 50 points. To compensate for this, the 120 by 70 areas are overlapped to give complete regional coverage. The results have been found to be very satisfactory in isolating trackable targets in a variety of weather situations, including those with mixed cloud types.

Another procedure used to assure continuity between pictures is brightness normalization. This is done by a subroutine that computes cumulative brightness frequencies for Picture 1 and then for Picture 2. Then a brightness transformation is made so that the brightness frequencies of the second picture agree with those of the first as closely as possible. This gives a statistical correction for changes in illumination that occur during the day. Normalization is performed prior to use of the DEVIATION program.

C. Clustering to Identify Groups

The function of the clustering process is to subdivide the data into cloud groups (potential tracers), to count them, and to compute the location of their centers, their size, brightness, IR temperature, and shape. In earlier work (Endlich et al., 1971; Wolf et al., 1973), the ISODATA cluster-analysis algorithm was used to do this. The results were quite satisfactory; however, the computations were rather lengthy. Therefore the procedure has been simplified to give approximately equivalent results using a "touching group" algorithm: it is required that members of a group be touching at least one other member of the group. Touching is defined as being adjacent up or down, left or right, or along diagonals. Computation of touching groups is done by making several passes through the data from the DEVIATION program until the results are stable. The process is fast computationally. Also, a lower limit is set on group size (usually three) so that very small groups (having less than three points) are dropped. This eliminates many of the short-lived, random features from consideration.

After groups are identified, the following descriptors are computed: the size (S), the location of the center $(\bar{x},\bar{y})$, the average brightness $(\bar{B})$, the average IR temperature $(\bar{T})$, and two measures of shape (the RMS dispersion of the group along x and y axes). There is also a provision for limiting the size of very large groups (which are also bright groups) by eliminating some of the dimmest members. Thus the brightness and IR data in 120 by 70 arrays are reduced to a small set of summary descriptors. As mentioned earlier, in subsequent computations only these descriptors are used.

D. Computing Cloud-Motion Vectors

The MOTION program has the function of matching groups from two successive pictures in a manner that provides cloud-motion vectors that are logically and meteorologically acceptable. Hall et al. (1973) generated somewhat idealized Gaussian clouds with controlled displacements in computer simulations, and found that the MOTION program tracked them perfectly. At present, the program uses four iterations. In the first of these, a group center at Time 1 is matched with the nearest center at Time 2, provided that the distance between them is not larger than a certain preselected value, determined empirically by study of numerous cases. For all paired centers, the average motion (in row and column coordinates) is determined. This average is used as an estimate of the motion in the scene. In the second iteration, a new pairing is made in which the paired centers must give displacements that conform to the average displacement within the preselected limit. Then a new average displacement is computed. In the third iteration, pairing is done to obtain conformance to the improved average motion, and also to minimize changes in the size, brightness, IR temperature, and shape of groups. In other words, reasonable continuity of the groups is required in regard to these characteristics, which are also used intuitively in cloud tracking by humans. The computation of suitability of each potential vector is made using a "fit factor." The fit factor sums the influence of the several characteristics by giving each an appropriate weight, which has been determined empirically to give results that agree with human (eye) analysis of the same cases. As currently computed, a low value of the fit factor is desirable and means that the cloud has not changed appreciably in its size, brightness, etc., and that its motion conforms well to the areal average motion. Thus the fit factor is a measure of the reliability of each cloud-motion vector, and if it is larger than a preselected value, the continuity is poor and the motion vector is rejected. The fourth iteration repeats the computation as in the third, and ensures stable results.

The fit factor (F) is computed for each possible pair of groups. We use the notation Y1 for the row coordinate of the group center at Time 1 and Y2 at Time 2, X1 and X2 for the column coordinates, at the two times, B1 and B2 for brightness on a scale from 0 to 255, S1 and S2 for the size (number of points), T1 and T2 for IR temperature, SX1 and SX2 for the RMS distances of the group along the X axis, and SY1 and SY2 for the RMS distances along the Y axis. Also, the best estimate of the average cloud displacement in the scene along the two axes is represented by U and V. In the first iteration of MOTION, U and V are unknown so they are set equal to 0. If a reliable forecast were available, this could be used instead. For succeeding iterations, the average displacement computed from matched pairs is used for U and V.

The fit factor is defined as

$$F = (P1 + P2 + P3 + P4 + P5 + P6)^{1/2} + P7 \qquad (1)$$

where

$$P1 = 4.0\ (X2 - X1 - U)^2$$

$$P2 = 4.0\ (Y2 - Y1 - V)^2$$

$$P3 = 25.0\ \frac{|B2 - B1|^{3/2}}{B2 + B1}$$

$$P4 = 25.0\ \frac{|S2 - S1|^{3/2}}{S2 + S1}$$

$$P5 = 15.0 \frac{|T2 - T1|^{3/2}}{T2 + T1}$$

$$P6 = 2.5 \left[(SX2 - SX1)^2 + (SY2 - SY1)^2 \right]$$

$$P7 = -2.0 \frac{(\vec{V}a \cdot \vec{V})}{|\vec{V}a| + |\vec{V}|} \quad .$$

The multipliers (first terms on the right in each P) are weights that have been set to give results matching as well as possible those obtained by human analysts. A number of different sets of satellite data were used in setting the weights. The dot product in the term P7 makes the cloud-motion vector $\vec{V}$ (which is being tested for suitability) conform to the areal average $\vec{V}a$. To be acceptable in defining a cloud-motion vector, a pair must have a value of F less than 10.0.

One pass through the group centers in a scene identifies the predominant motion. The group centers not paired in this first pass represent a possible second set of motions (if a two-layered cloud system is present), plus random changes in the scene. A second set of motions (for example, that of cirrus clouds overlying stratocumulus) can sometimes be identified by making a second pass through the centers not matched in the first pass.

E. Registration and Transformation to Earth Coordinates

The CORRECT program performs final registration and transformation to earth coordinates. Using several landmarks, it computes the translation, rotation, X-stretching, and Y-stretching needed to map the second picture to the first picture. This allows an apparent earth motion to be computed at the location of each of the observed cloud motions. This apparent motion is subtracted from the observed cloud motion to give the true cloud motion, still in picture coordinates. Next, using landmark locations on an ideal picture, the CORRECT program determines the coefficients used in equations to map any point of the first picture onto the ideal picture. With these equations, the picture coordinates of the cloud-motion vectors are converted to the ideal picture. Then a subroutine is called to convert the vectors to speed and direction, latitude and longitude (further details are given in Wolf et al., 1973).

It should be noted that at present there is a visual step in this part of the system--namely, the selection of landmarks by inspection of pictures. It is assumed that the satellite will remain over a fixed sub-satellite point for extended periods so that landmarks once selected will be useful until the satellite is moved. The locations of the landmarks in terms of columns and rows (X,Y) are determined by reproducing pictures by facsimile with an X-Y grid superimposed or by using the CRT display system of the computer. Templates containing landmarks are roughly 60 miles on a side, i.e., 20 by 20 picture elements. By reference to a detailed atlas, the latitude and longitude of the central (or a corner) point in each template are determined. With the usual atlases, this can be done only with an accuracy of about 0.1° latitude; however, this is tolerable as it affects only the position of the cloud-motion vectors, not their magnitude or direction.

The cloud-motion vectors can be used by other programs, such as the Mancuso and Endlich (1973) objective (gridpoint) analysis, for input to a weather prediction model, or they can be used for kinematic studies, such as those made by Viezee et al. (1972).

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The cloud-motion vectors can be used by other programs, such as the Mancuso and Endlich (1973) objective (gridpoint) analysis, for input to a weather prediction model, or they can be used for kinematic studies, such as those made by Viezee et al. (1972).

IV EXAMPLES

A. Subtropical Atlantic Cumulus

These brightness data are from the ATS-III satellite on 23 August 1969, and consist of a sequence of five pictures. The data were read from tapes and displayed (for visual checking of the computations) on the CDC 280 CRT display system. The middle picture of the series is shown in Figure 1. These data have approximately 6-mile resolution so the area covered by the 120 by 70 data array is approximately 700 by 400 miles, located in the subtropics of the eastern N. Atlantic Ocean. Visual study of the sequence using the electronic cloud console indicates that

FIGURE 1 A PORTION OF AN ATS-3 GEOSYNCHRONOUS SATELLITE PICTURE FOR 23 AUGUST 1969 SHOWING SUBTROPICAL CUMULUS CLOUDS

The area covers approximately 700 by 400 miles.

the clouds are cumulus and stratocumulus moving generally from NE to SW. These data are among those discussed by Wolf et al. (1973). For this particular scene the motions obtained automatically at that time contained several spuriously large vectors; therefore the case was rerun with the present system and gives satisfactory results, as shown below.

As mentioned earlier, groups potentially suitable for tracking are the locally bright areas (compared to the immediate surroundings) that are organized into "touching groups." The centers of touching groups corresponding to Figure 1 are shown in Figure 2. With a little care, they can be related visually to the features of Figure 1. (No brightness centers are placed within 10 units from the edge for reasons discussed earlier.) According to the rules used in the MOTION program, only about half these centers have sufficient continuity in brightness, size, and shape to be

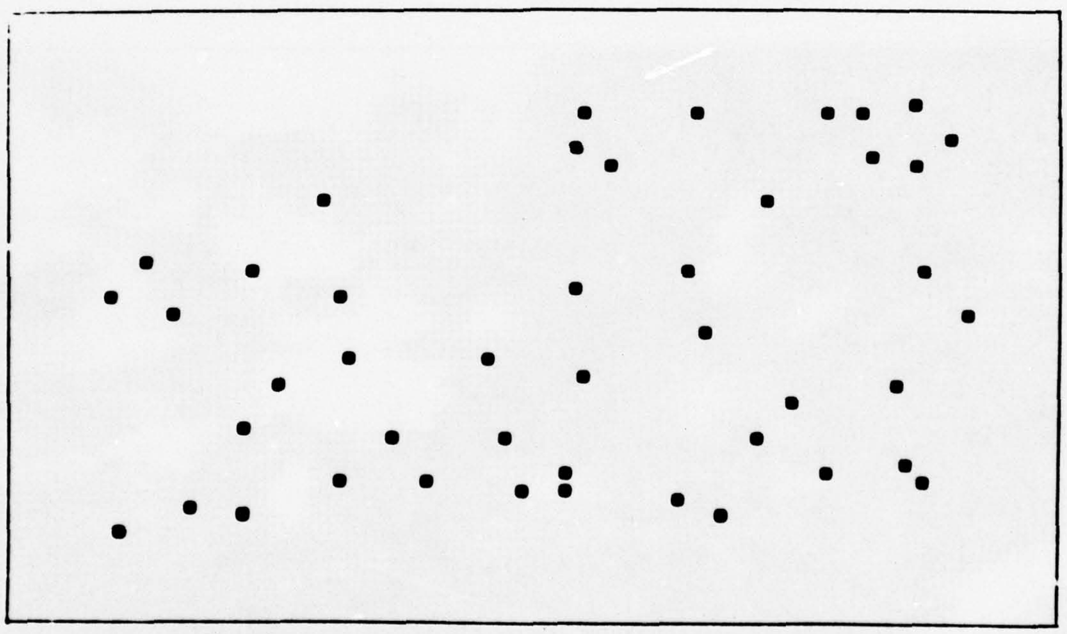


FIGURE 2 AUTOMATICALLY COMPUTED BRIGHTNESS CENTERS FOR THE VISIBLE DATA OF FIGURE 1

paired and give cloud-motion vectors. The cloud-motion vectors for the sequence of pictures are illustrated in Figure 3. Here each line segment

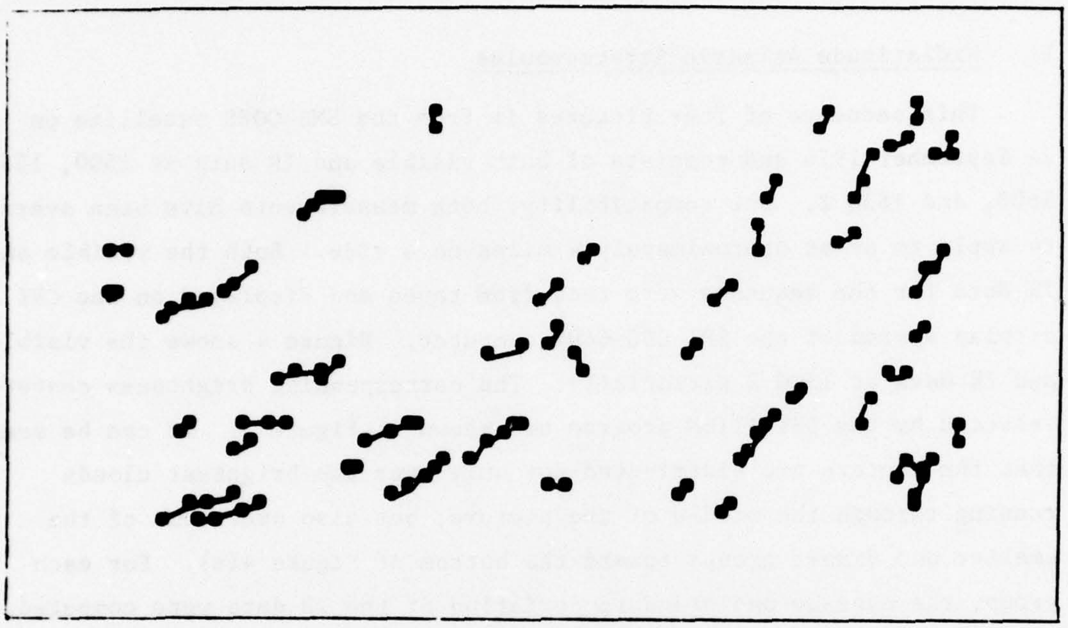


FIGURE 3 PLOT OF PAIRED BRIGHTNESS CENTERS FOR THE SEQUENCE OF PICTURES OF SUBTROPICAL CUMULUS CLOUDS

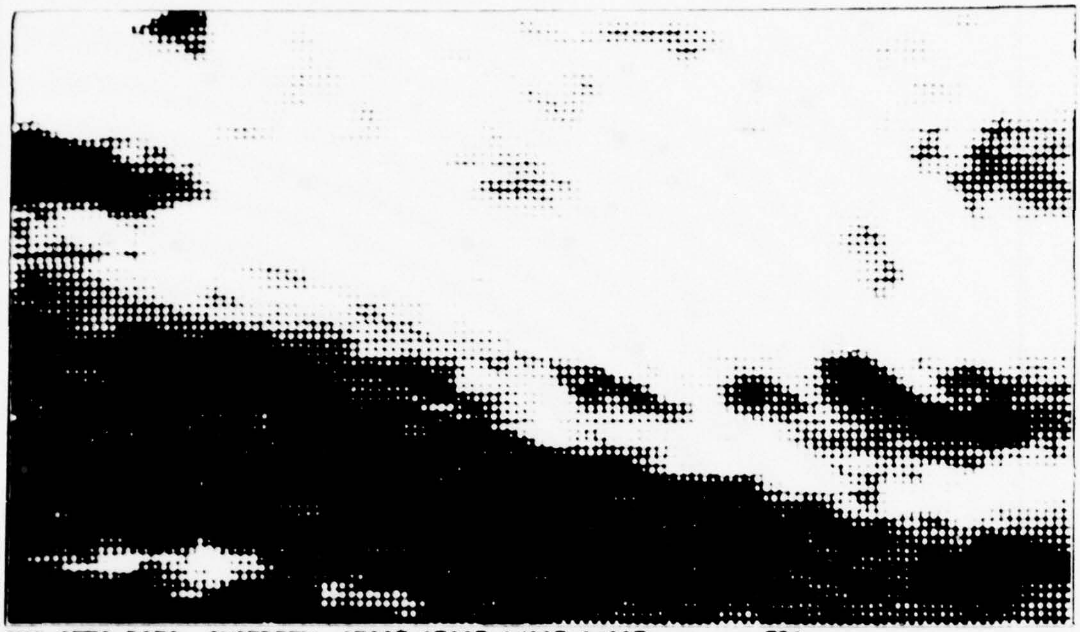
The lines joining brightness centers denote cloud displacements. All motion displacements computed for the sequence of five pictures are shown. Some brightness centers were tracked over the entire sequence; other are for single pairs of pictures only.

is a displacement vector between the adjacent centers. (However, plotting is not done with the full precision of the computations.) There are a few centers that persisted and were tracked for the entire sequence of five pictures. Other centers were tracked for only one, two, or three intervals. The average of the 73 cloud-motion vectors is 52° 11 m s^{-1}, and the variability can be seen by inspection. There are a few vectors produced by the program that appear doubtful since they differ in direction or speed from their neighbors. A relatively small number of uncertainties can be tolerated since an objective analysis program operating on all these vectors would either reject the most unusual ones or smooth them by weighting them with their neighbors. To appreciate the density of vectors for this case, one should note that in an area of this size over the United States, there are only about 4 or 5 radiosonde stations.

B. Midlatitude Atlantic Stratocumulus

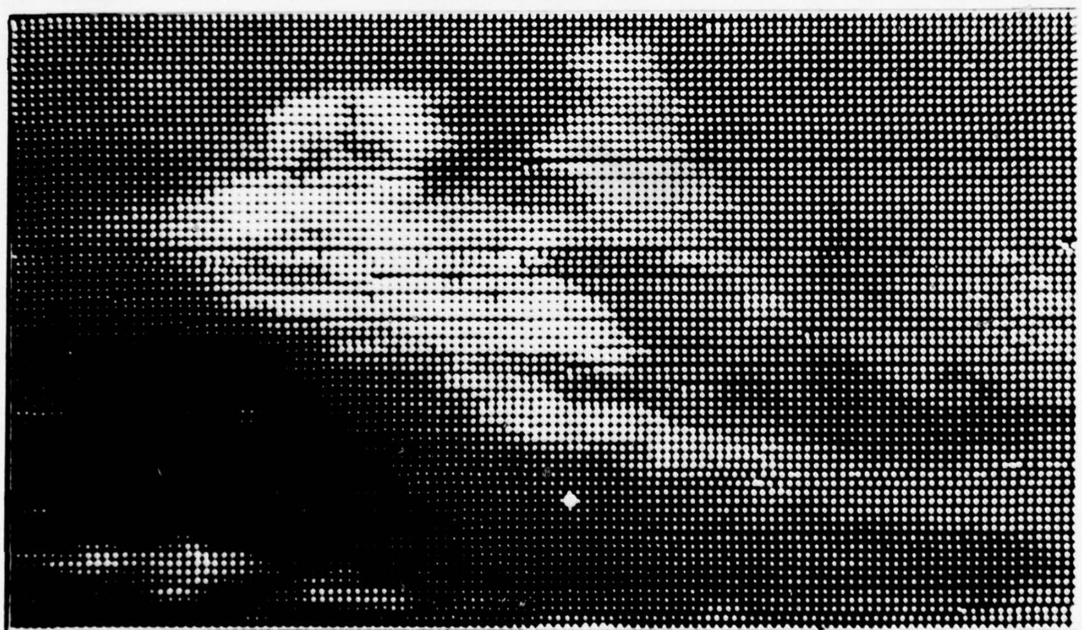
This sequence of four pictures is from the SMS-GOES satellite on 24 September 1974 and consists of both visible and IR data at 1500, 1530, 1600, and 1630 Z. For compatibility, both measurements have been averaged to apply to areas approximately 4 miles on a side. Both the visible and IR data for the sequence were read from tapes and displayed on the CRT display system of the SRI CDC-6400 computer. Figure 4 shows the visible and IR data at 1500 Z pictorially. The corresponding brightness centers selected by the DEVIATION program are shown in Figure 5. It can be seen that the centers are distributed not only over the brightest clouds running through the middle of the picture, but also over some of the smaller and dimmer groups toward the bottom of Figure 4(a). For each group, the average and standard deviation of the IR data were computed, as were all other group descriptions described earlier. The IR values are included in the pairing decisions made by the MOTION program. The motion vectors computed using Pictures 1 and 2 of the sequence are shown by the lines in Figure 6. (Centers without lines are also shown; these will be matched in the next computation using Pictures 2 and 3. They do not indicate zero motions.) The MOTION program gives a list of the vectors where X, Y, U, and V are in terms of rows and columns of the 120 by 70 array, and brightness and IR values are in terms of original measurements. Figure 7 shows the list pertaining to Pictures 1 and 2 of this sequence. Only the vectors indicated by a letter (far left) were accepted on the basis of the fit factor. This list is the input both for automatically plotting the vectors in row and column coordinates (as shown in Figure 6) and for transforming to earth coordinates (program CORRECT).

All cloud displacements for the sequence are shown in Figure 8. There are 52 motion vectors for the area, which is approximately 480 by 280 miles in dimension. The average cloud motion is 349° 21 m s^{-1}, and the variability can be seen in Figure 8. On a scale from 0 to 255, the



SMS GOES DATA 24SEPT74 1500Z 1530Z 1600Z 1630Z FB1
VISIBLE
1500Z

4(a)



SMS GOES DATA 24SEPT74 1500Z 1530Z 1600Z 1630Z FB1
INFRARED
1500Z

4(b)

FIGURE 4 A PORTION OF AN SMS-GOES PICTURE SHOWING MID-ATLANTIC STRATO-CUMULUS CLOUDS COVERING AN AREA OF APPROXIMATELY 480 by 280 MILES: (a) VISIBLE DATA, (b) IR DATA

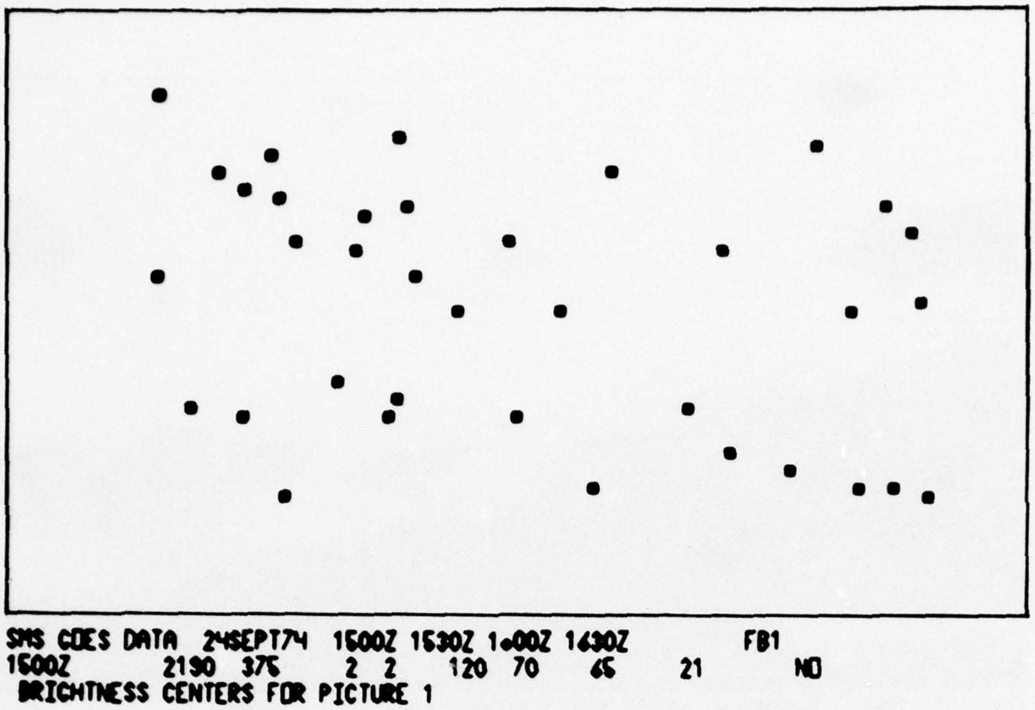


FIGURE 5 BRIGHTNESS CENTERS THAT CORRESPOND TO FIGURE 4(a)

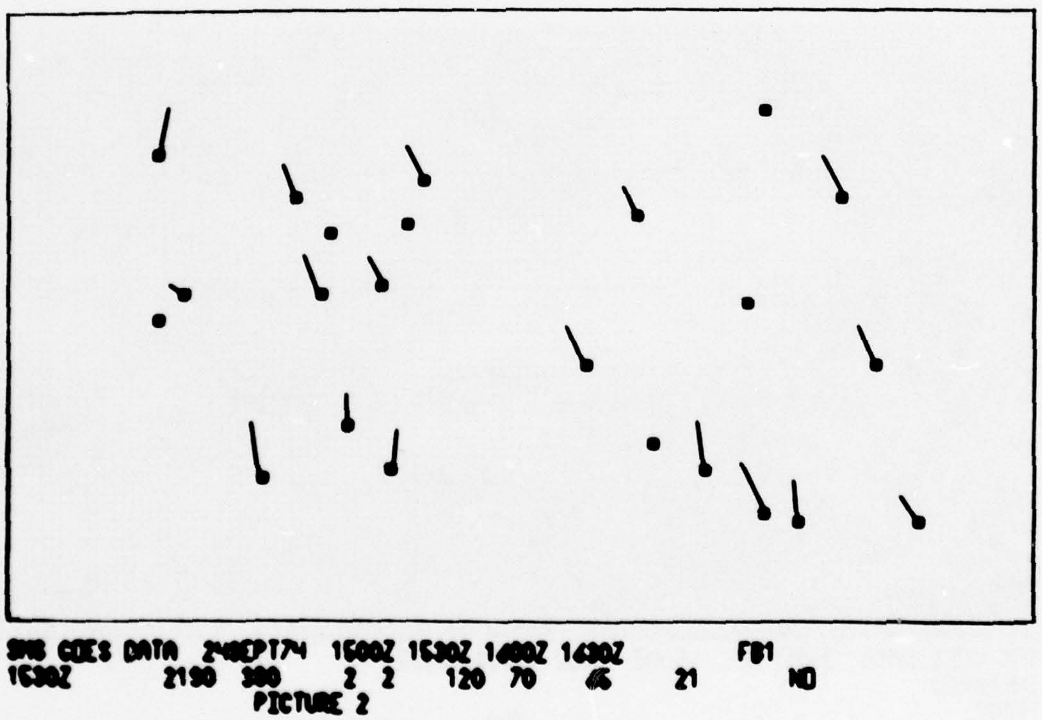


FIGURE 6 BRIGHTNESS CENTERS ON PICTURE 2 THAT WERE SELECTED BY THE MOTION PROGRAM TO REPRESENT CLOUD DISPLACEMENTS

The lines denote displacements from Picture 1 to Picture 2. (Centers without lines are matched between Pictures 2 and 3.)

CRITICAL VALUE = 10.0 NUMBER OF PAIRS MATCHED = 17

	CENTER1	CENT2	U	V	X	Y	B	IR	BRTNESS CHANGE	NUMBER POINTS	DIFF POINTS	FIT	DIFFERENCES SGX	SGY	SGB	SGIR
A	5 12	11 19	1.6	4.2	33.2	19.9	157.5	76.2	-1.4	5.0	0.0	-1.48	.160	.160	2.360	-1.000
B	3 10	12 22	1.9	4.1	73.4	22.4	154.2	77.9	-4.8	25.5	-3.0	.08	.290	-.750	-.110	.100
C	34 94	38 90	2.0	3.0	106.0	57.5	146.3	73.7	-4.7	3.0	0.0	.93	0.000	0.000	-1.480	-.580
D	15 37	22 44	1.9	4.5	35.7	30.5	154.8	78.5	-3.6	6.0	-2.0	1.85	-1.250	.350	.220	-.240
E	25 69	34 80	.8	5.7	81.6	50.1	148.7	73.6	-3.6	9.0	-2.0	1.99	-.350	-.300	1.290	.080
F	2 6	9 15	2.3	4.1	48.0	18.0	149.2	78.5	-4.5	10.0	-4.0	2.26	.060	-.480	-1.340	-.660
G	28 72	33 78	-.4	4.9	45.6	50.7	70.9	68.9	-3.1	7.0	0.0	2.90	.370	-.070	-2.370	-.200
H	23 63	31 70	.1	4.1	39.8	46.3	73.9	68.4	-1.4	10.5	3.0	2.94	.270	.210	-1.940	-.360
I	1 1	7 13	-1.0	5.7	18.5	14.2	143.8	72.5	-3.7	3.0	0.0	3.69	0.000	-.580	.420	0.000
J	31 88	37 89	.5	5.2	92.7	56.7	148.7	74.7	-6.2	4.5	-3.0	3.82	-.050	-.170	.540	-.170
K	27 71	35 82	1.2	6.8	29.1	50.9	77.8	65.4	-2.3	3.5	-1.0	4.06	0.000	0.000	-2.910	0.000
L	21 55	30 61	2.1	5.0	101.1	38.9	157.3	73.9	-.6	8.5	-7.0	5.44	-1.140	-.120	-1.120	-.450
M	17 42	23 47	2.0	1.3	20.0	32.3	144.7	72.0	-2.0	3.0	0.0	6.25	0.000	-.580	.950	.950
N	20 50	28 57	2.1	4.5	66.7	38.7	162.0	78.0	-.9	35.5	-21.0	6.37	-1.460	-.290	-1.670	.180
O	4 11	10 18	2.7	4.7	97.1	19.5	154.0	74.2	-4.9	13.0	10.0	6.72	1.130	.610	.780	-.220
P	16 39	18 37	2.2	3.5	43.3	30.4	155.8	79.5	-2.7	15.5	15.0	8.09	.710	.790	1.100	-.600
Q	30 81	36 86	2.6	5.3	87.7	54.9	149.1	75.5	-3.2	9.0	-10.0	9.66	-2.080	-.120	.440	-.820
	12 27	14 27	3.6	.4	45.2	25.0	155.1	78.2	-6.2	5.0	0.0	10.17	-.430	.390	-1.460	1.070
	22 56	27 55	5.8	3.0	56.9	37.5	148.6	80.1	3.2	4.5	3.0	11.38	.170	.890	-.560	.750
	13 31	19 39	1.6	2.5	60.9	29.4	150.8	78.3	-1.0	10.0	-14.0	12.13	-.980	-.640	-2.390	-.170
	19 48	26 54	1.7	2.3	108.5	35.8	153.2	76.0	-6.3	9.5	-13.0	12.35	-.570	-.960	-1.140	-.440
	9 18	16 33	1.8	4.2	85.8	31.6	158.1	75.3	-1.7	92.5	-79.0	12.53	-1.180	-2.460	-.690	-.250
	7 15	17 35	-5.0	10.3	23.2	25.5	154.0	77.7	-2.0	3.0	0.0	14.96	0.000	0.000	1.000	-.420
	18 43	20 41	1.8	0.0	49.4	32.0	150.3	78.4	2.0	6.5	-7.0	16.75	-.850	.330	-1.730	-.600
	6 14	13 24	4.8	2.7	35.6	24.8	161.7	79.1	1.2	45.0	-44.0	20.24	-3.190	-.940	-2.130	-.270
	29 73	32 73	15.2	1.5	68.4	48.8	146.1	75.9	-1.3	4.0	0.0	27.16	.320	-.240	.650	.080
	14 33	15 31	-8.3	-1.0	102.4	26.7	149.6	75.0	4.4	4.5	-1.0	28.04	.410	-.340	-.080	0.000
	10 19	2 3	-1.6	-9.4	27.7	16.8	150.7	76.3	-16.2	5.5	3.0	40.28	.110	.630	.100	.240
	8 16	21 43	19.7	8.0	57.9	27.6	150.8	77.5	-16.1	12.5	-15.0	45.86	-1.250	-1.970	-.880	-.150
	26 70	25 50	-5.2	-11.4	20.4	41.3	107.4	67.2	73.5	4.0	2.0	53.55	-.160	.550	.060	.550
	11 21	4 5	-14.4	-12.2	96.5	18.1	148.7	74.1	.3	19.5	-3.0	57.82	.970	-1.300	.950	.180
	33 93	24 49	5.1	-21.6	72.8	45.5	104.7	71.8	73.9	3.5	-1.0	71.09	-.380	.080	-.920	1.030
	32 92	29 59	-17.0	-14.5	92.3	49.1	151.4	74.5	4.1	17.5	25.0	77.30	3.880	.150	-1.060	.030
	24 66	3 4	16.3	-34.2	55.3	28.4	111.6	73.4	38.1	10.5	-1.0	102.49	-.990	-.560	-11.720	1.050
	35 95	8 14	-27.0	-36.2	95.2	37.4	146.0	73.5	-5.5	4.0	0.0	111.99	0.000	-.080	-.880	0.000
	36 97	6 12	-21.9	-40.0	22.7	37.4	107.4	68.0	76.0	7.0	-4.0	121.94	-.740	.020	.470	.020

AVERAGE U	AVERAGE V	NO.VECTORS
1.45	4.50	17

FIGURE 7 COMPUTER PRINTOUT GIVING A LIST OF THE CLOUD-MOTION VECTORS SHOWN IN FIGURE 6

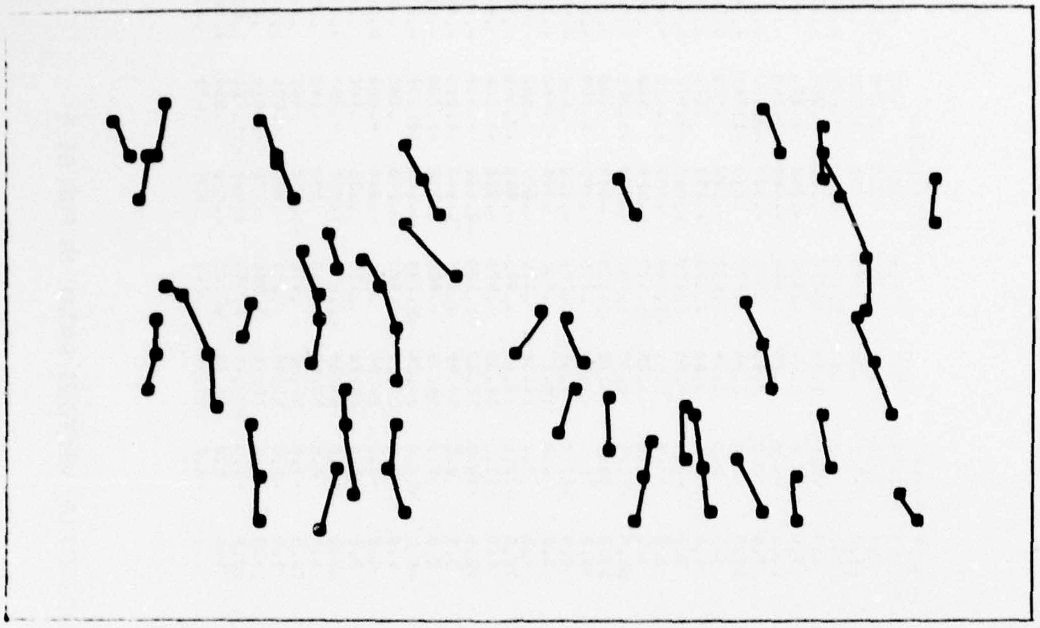


FIGURE 8 PLOT OF PAIRED BRIGHTNESS CENTERS FOR THE SEQUENCE OF PICTURES OF STRATOCUMULUS CLOUDS

The lines joining brightness centers show all cloud-motion displacements for the sequence of four pictures, computed using both visible and IR data.

average IR measurements for groups varied only from 65 to 80, indicating that clouds are at low levels. Brightness values for groups varied from 69 to 162.

C. Intertropical Convergence Zone

This sequence is from the same data tapes discussed in Section IV-B. The area is at approximately 3°N in the Atlantic west of Africa, along the southern edge of the intertropical convergence zone. The active convection and complex motions expected here are in marked contrast to the primarily translational flow of the previous case. The visible and IR data at the beginning of the sequence are shown pictorially in Figure 9. The brightness centers, selected for groups identified as being brighter than their nearby surroundings, are numerous, as shown in Figure 10. There is a large range in the average brightness values (from 74 to 187) and IR values (from 62 to 180) for the different groups. Also, there

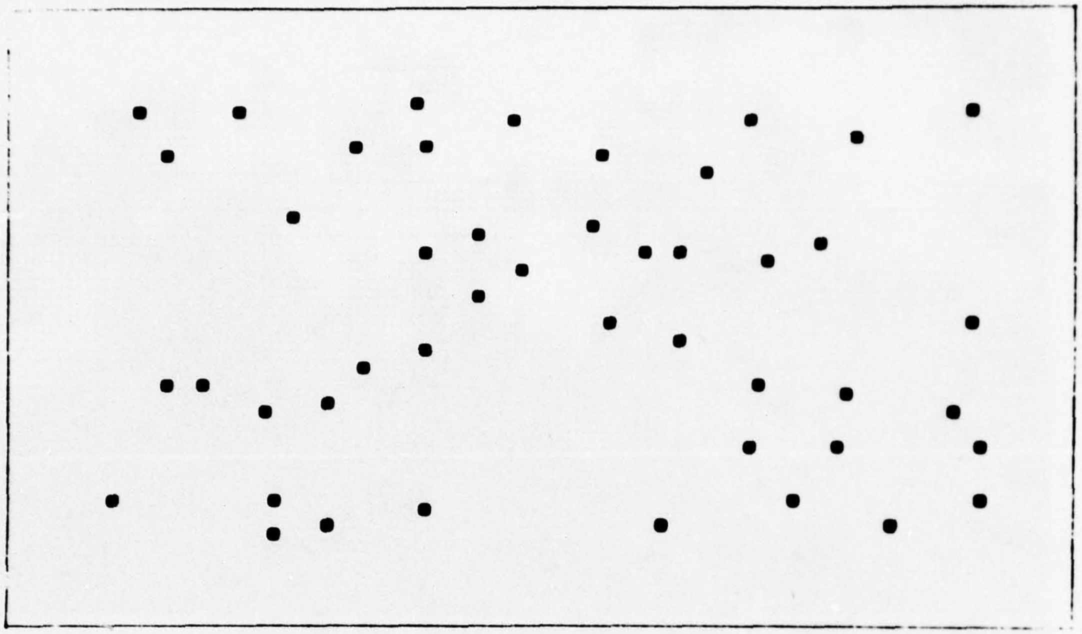
SMS GOES DATA 24SEPT74 1500Z 1530Z 1600Z 1630Z CZ2 INT CONV
VISIBLE
1500Z

9(a)

SMS GOES DATA 24SEPT74 1500Z 1530Z 1600Z 1630Z CZ2 INT CONV
INFRARED
1500Z

9(b)

FIGURE 9 A PORTION OF AN SMS-GOES PICTURE SHOWING PART OF THE INTERTROPICAL CONVERGENCE ZONE: (a) VISIBLE DATA, (b) IR DATA



SMS GOES DATA 24SEPT74 1500Z 1530Z 1600Z 1630Z CZ2 INT CONV
1500Z 2600 1500 2 2 120 70 65 21 NO
BRIGHTNESS CENTERS FOR PICTURE 1

FIGURE 10 BRIGHTNESS CENTERS THAT CORRESPOND TO FIGURE 9(a)

are considerable changes in the brightness and IR values with time, and according to the rules of the MOTION program, only about one-fourth of the centers are paired. As shown in Figure 11, no center was tracked on all four pictures, and most pairs were matched for single time intervals only. However, the cloud displacements show a generally consistent motion from the northeast, with a few essentially zero displacements. Viewed in animation on the electronic cloud console, the computed vectors agree well with human visual judgment; however, a human, given sufficient time, could track centers rejected by the automatic system. There are 30 vectors in the approximately 480-by-280-mile area of Figure 11, with an average value of 22° 8 m s^{-1}.

Since IR data are always available, whereas visible data are available only in daylight, this case was rerun using only the IR data. In this mode the deviations and touching groups are found for the IR data,

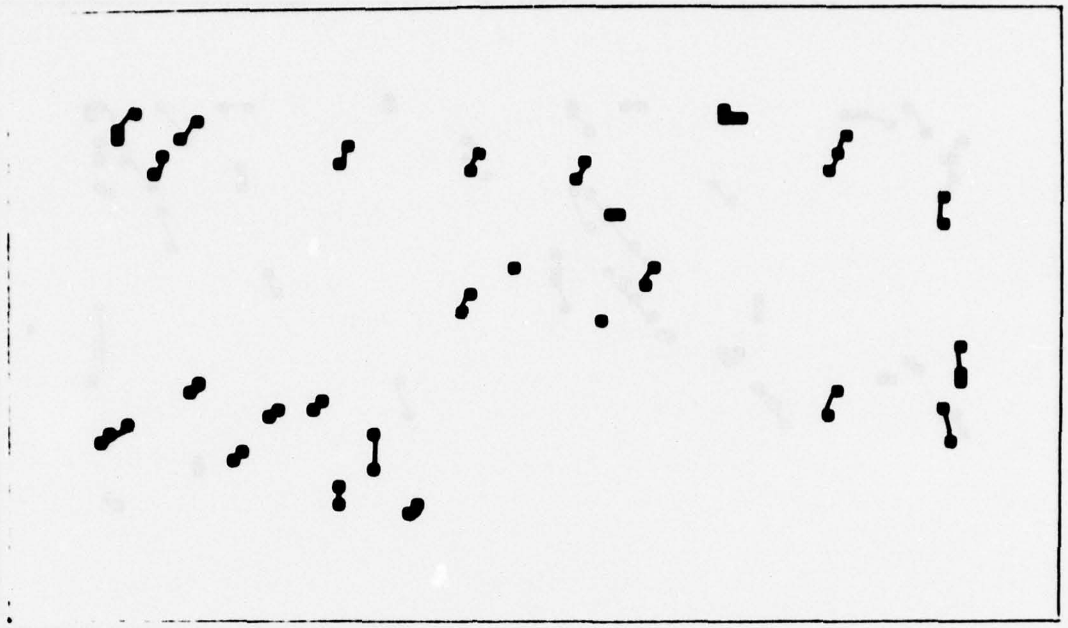


FIGURE 11 PLOT OF PAIRED BRIGHTNESS CENTERS FOR THE SEQUENCE OF PICTURES OF THE INTERTROPICAL CONVERGENCE ZONE

The lines joining brightness centers show all cloud-motion displacements for the sequence of four pictures, computed using both visible and IR data.

and the group centers are IR centers rather than brightness centers. As one would expect from the different appearance of Figure 9(a) and (b), the IR centers that pertain to Figure 9(b) are not identical to the brightness centers of Figure 10 [which pertain to figure 9(a)]. In particular, in the lower left-hand portion of Figure 9 the clouds are easily seen in the visible data but not in the IR, as they are evidently not much colder than the ocean background. In this region, only a few IR centers were positioned by the system. The cloud displacements obtained from the IR data alone are shown in Figure 12. Comparison with Figure 11 shows good agreement. There is a significant increase in the number of vectors computed using the IR data, namely from 30 in Figure 11 to 53 in Figure 12. There are however, no apparent differences in overall accuracy between Figures 11 and 12 when the vectors are evaluated visually on the cloud console.

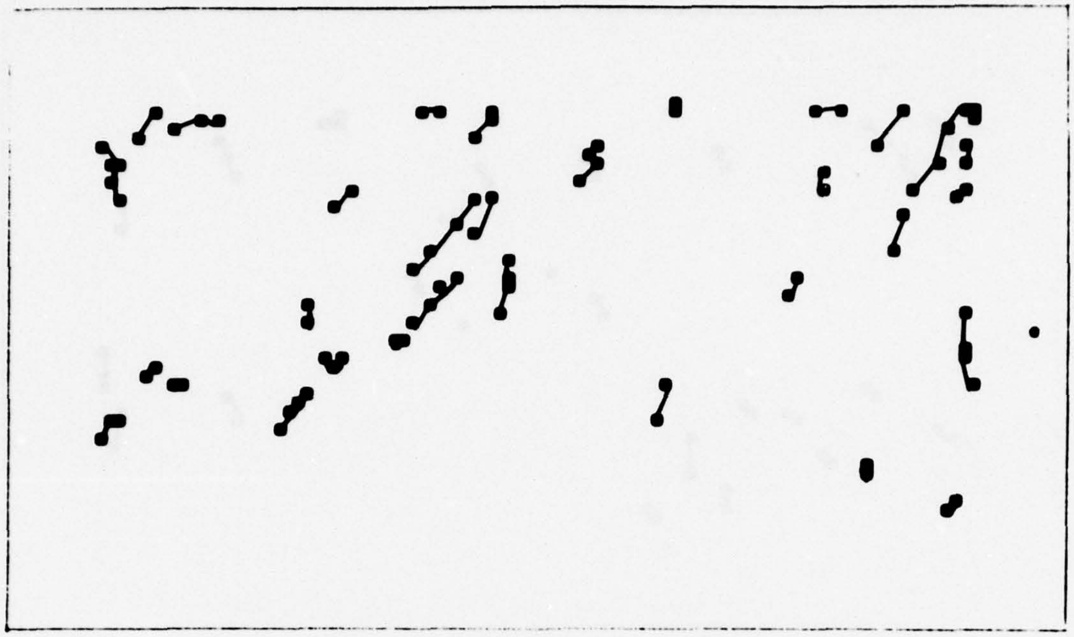


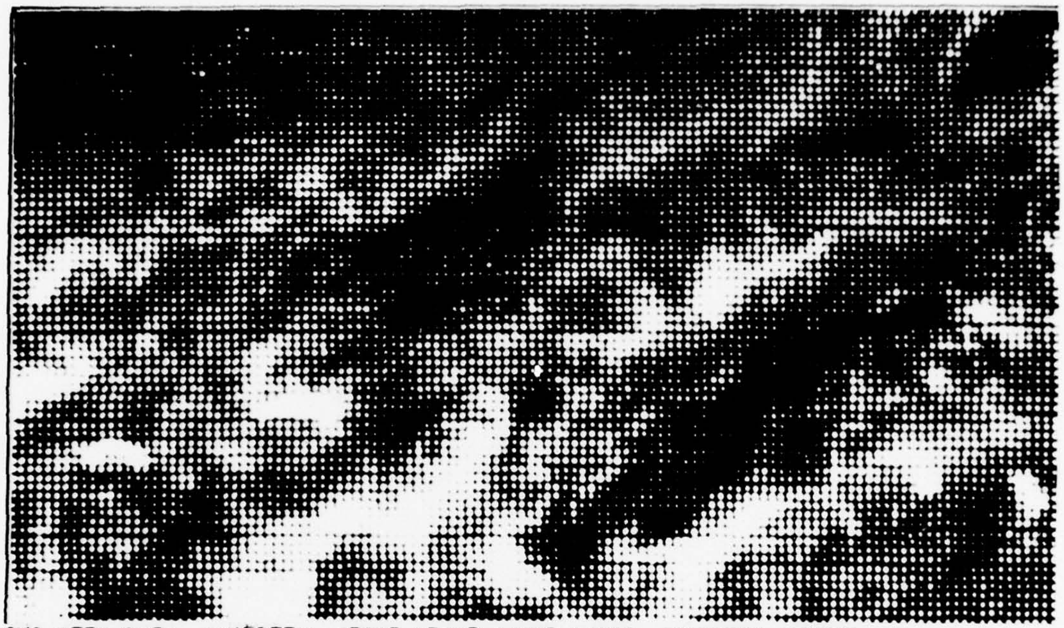
FIGURE 12 PLOT OF PAIRED IR CENTERS FOR THE SEQUENCE OF PICTURES OF THE INTERTROPICAL CONVERGENCE ZONE

The lines joing IR centers show all cloud-motion displacements for the sequence of four pictures, computed using IR data only.

D. Atlantic Cirrus

This sequence is for subtropical clouds located near 20^{o}N 43^{o}W, from the same tapes discussed in Section IV-B and C. As before, the data have approximately 4-mile resolution and the array covers an area approximately 480 by 280 miles in extent. Inspection of visible and IR pictures produced on the computer display system indicates that the clouds are predominantly cirrus. The patterns at the outset are shown in Figure 13. Cirrus clouds are difficult to track automatically (and often even by eye) due to the complexity of the patterns and their relatively rapid motions. The numerous brightness centers corresponding to Figure 13(a) are shown in Figure 14; similar numbers were found on subsequent pictures.

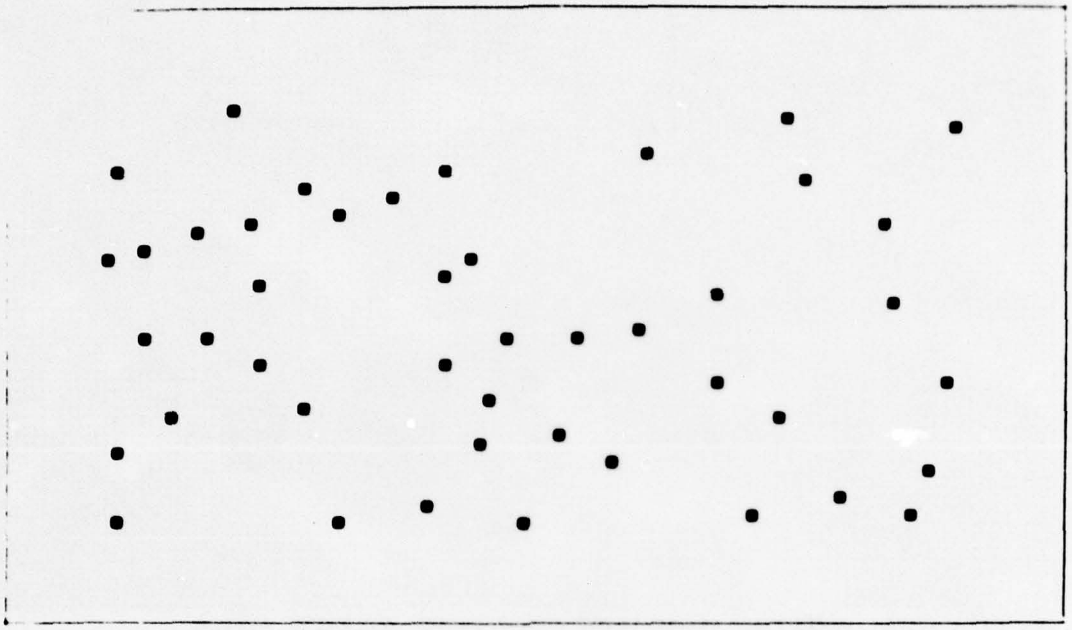
In the first experiment, pairing by the MOTION program was done in the usual way, using U = V = 0 as a first guess of the expected motions.



13(a)

13(b)

FIGURE 13 A PORTION OF AN SMS-GOES PICTURE SHOWING SUBTROPICAL CIRRUS CLOUDS: (a) VISIBLE DATA, (b) IR DATA



SMS GOES DATA 24SEPT74 1500Z 1530Z 1600Z 1630Z ATLANTIC CIRRUS
1500Z 1970 890 2 2 120 70 65 21 YES
BRIGHTNESS CENTERS FOR PICTURE 1

FIGURE 14 BRIGHTNESS CENTERS THAT CORRESPOND TO FIGURE 13(a)

Because the motions are fairly rapid, satisfactory results were not obtained. Then it was assumed that in an operational environment, a better first guess would be available from previous history, or from a numerical forecast. In lieu of this, we made a visual inspection of the static pictures. This indicated that the true motion was probably from the west, so the initial guesses were set to U = 3.0, V = 0.0 (in column and row coordinates). In this case, correct results were obtained, and for the first picture pair, the average U and V were found to be 4.2 units and -2.1 units, respectively.

For the sequence of four pictures, the cloud-group displacements are shown in Figure 15. A few brightness centers were tracked on all four pictures; however, apparent indications of longer connected sequences of points are due to accidental intersections of the plotted trajectories.

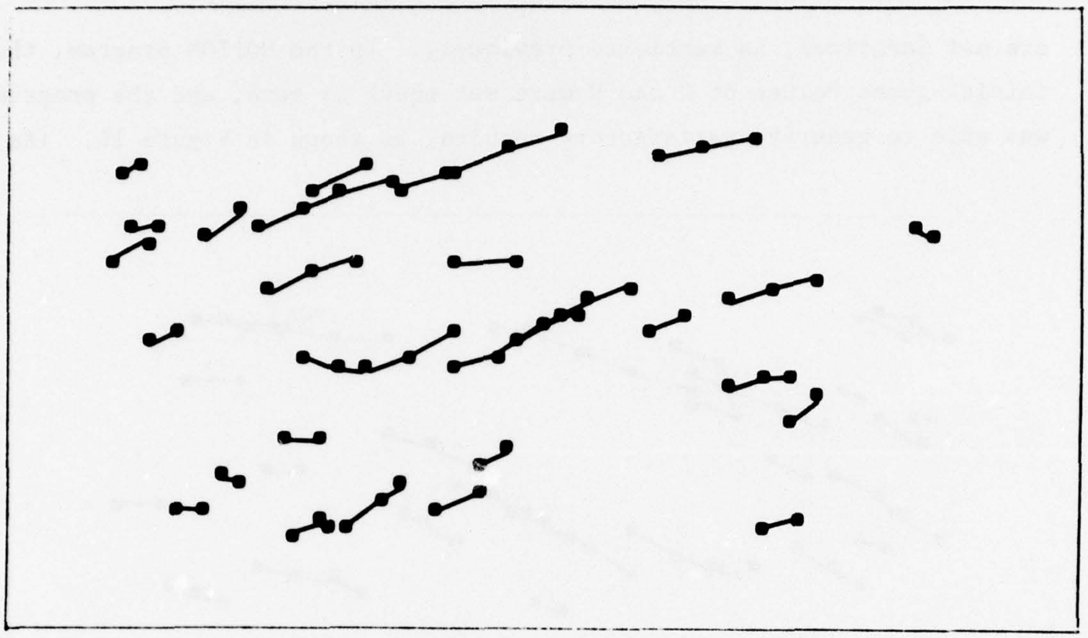


FIGURE 15 PLOT OF PAIRED BRIGHTNESS CENTERS FOR THE SEQUENCE OF PICTURES OF SUBTROPICAL CIRRUS CLOUDS

The lines joining brightness centers show all cloud-motion displacements for the sequence of four pictures, computed using both visible and IR data.

(This apparent confusion does not exist in the output file of motions.) Visual verification of these motions obtained by including the visible data in animation on the electronic cloud console shows that they are quite accurate in representing the motions of the cirrus. However, the animation shows that in the lower right portion of the scene there were also low clouds moving at moderate speed from the east. Since this motion is opposite to the predominant cirrus motion, the low-level vectors were eliminated by the dot product term in Equation (1). For the vectors of Figure 15, brightness values range from 73 to 157, and IR values from 61 to 187. For the sequence, the average cloud-motion vector is from 251^{0} at 18 m s^{-1}.

As in the previous case, this case was rerun using only the IR data. For these cirrus clouds, the IR data give an excellent picture, as seen in Figure 13(b). The IR centers fit Figure 13(b) in exactly the same way that Figure 14 fits Figure 13(a); however, the two sets of centers are not identical, as mentioned previously. In the MOTION program, the initial-guess values of U and V were set equal to zero, and the program was able to generate satisfactory results, as shown in Figure 16. (As

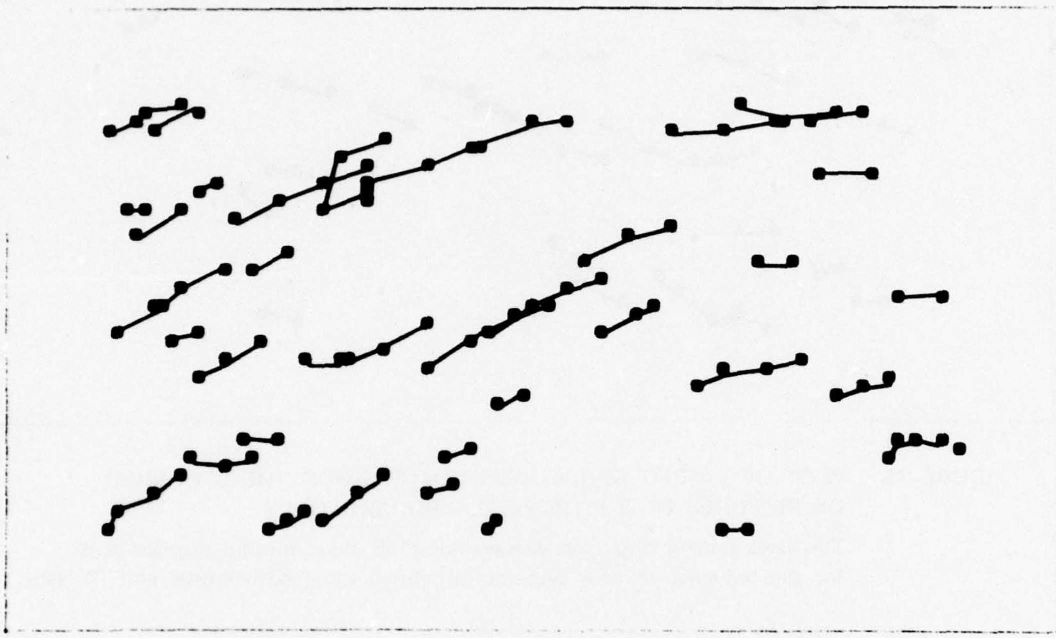


FIGURE 16 PLOT OF PAIRED IR CENTERS FOR THE SEQUENCE OF PICTURES OF SUBTROPICAL CIRRUS CLOUDS

The lines joining IR centers show all cloud-motion displacements for the sequence of four pictures, computed using IR data.

discussed earlier, for this case a better first guess than zero was needed when the touching groups were based on visible data. (This difference in performance of the automatic system for visible and IR data may be accidental.) One cloud-motion vector in the upper left portion of Figure 16, indicating motion from the south (approximately), is in error. Otherwise the motions appear accurate when viewed in animation with the IR data as background. It is interesting that the low clouds referred to earlier cannot be seen in the IR animation, evidently because their temperature is close to the ocean temperature. In Figure 16 there are 69 cloud-displacement vectors, compared with only 44 in Figure 15. This case of cirrus clouds appears to indicate that IR data are as good or better than visible data in tracking them, as noted previously by others.

V DISCUSSION

The method described herein normally operates without any advance information about the expected cloud-motion vectors in the region being treated, i.e., the initial values of U and V in Equation (1) are taken to be zero. Also, the initial pairing is done only within a preselected search radius around each initial center. This search radius is defined in terms of elements in the 120 by 70 data array. This means that if the motions are unusually large, the method may not be able to determine them.

Several procedures can mitigate this limitation. The first is to use a first guess that is a reasonable approximation to the expected cloud motion. If this is done, the search radius would encompass the desired pairs, and a match would be made. The first guess could come from the wind prediction of a numerical forecast model if our system were used in an operational mode. A second procedure would be to have available more frequent satellite data so that cloud displacements would be relatively small in the time-interval between pictures. Of course, data frequency is ordinarily outside the control of an automatic analysis system. The third procedure would be to reduce the resolution of the data by averaging prior to using the automatic method. For example, one could go from 4-mile to 8-mile resolution. In this case, the search radius used in initial pairing would be twice as large as before (in terms of earth distances), and cloud motions twice as fast could be handled. The price of doing this would be a reduction in the number of cloud-motion vectors obtained in a given geographical area, and probably also a slight loss of accuracy. The values of U and V from low-resolution data could then be used initially in a recomputation based on high-resolution data from which final results would be obtained. Some preliminary computations using different resolution have been made and indicate that this last approach is feasible.

The results of automatic tracking shown here are typical of those obtained in testing other representative cases. It is true, of course, that a human analyst, aided by complex electronic display devices and given sufficient time, could obtain a larger number of cloud-motion vectors, and could also concentrate on those that are representative, in effect eliminating the few questionable vectors that are obtained automatically. We believe that the advantages of automatic computation in terms of speed outweigh this manual advantage and are of paramount importance in the long run, since objective wind-analysis methods can be used to smooth the effects of a few doubtful cloud-motion vectors (e.g., Thomasell, 1976). Also, the reliability indicator (fit factor) described earlier could be used as a weighting factor in objective analysis.

A question outside the scope of this study and not discussed heretofore in this report concerns the relation of cloud-motion vectors to "real" atmospheric winds as they have traditionally been measured. We remark only that even though a particular cloud group may not move exactly with the local winds, it seems clear that a wind analysis based on a number of cloud-motion vectors will be reasonably representative, if they are positioned at the correct altitude. This subject is of course under continuing investigation at SRI and elsewhere (e.g., Fujita et al., 1975; Bauer, 1976; Davis, 1976; Hasler et al., 1976; Hubert, 1976; Smith and Hasler, 1976).

VI SUMMARY

The system for cloud tracking described in this report (SATS) has the following characteristics:

- It is automatic.
- It gives a high density of vectors in cloudy regions with the average spacing between them controlled by the resolution of the data.
- It can cope with variable motions in the scene.
- When both visible and IR data are available, it makes cloud-motion decisions using both of them. Alternatively, it can operate separately with either visible or IR data.

The results shown here indicate that this system for measuring cloud-motion vectors is a major improvement over previously existing objective methods, both in terms of the accuracy and number of cloud-motion vectors obtained and in terms of computational efficiency. The values of brightness and/or IR temperature found for each cloud-motion vector are useful in assigning heights to them. Recently, the system has been implemented on the SPADS minicomputer system at NEPRF. It is expected that an operator will be able to use this system to select SMS-GOES data as desired, to obtain the automatically computed motions, and to monitor their accuracy. We recommend that the system be studied for its usefulness in providing cloud-motion vectors for operational input to Fleet Numerical Weather Center prediction models, and for monitoring weather conditions in limited areas of special interest to Naval activities.

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Appendix

AN ADAPTIVE PROCESS FOR TRACKING CLOUDS FROM SATELLITE IMAGES

by

David J. Hall

A revised version of a paper presented at the Symposium on Image Science Mathematics, November 10-12, 1976, Monterey, California. Published in Image Science Mathematics, C. O. Wilde and E. Barrett, eds. (Western Periodicals Co., 13000 Raymer Street, N. Hollywood, California 91605, 1977).
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I MATHEMATICAL STATEMENT OF THE PROBLEM AND ITS SOLUTION

The automatic tracking of multilayered clouds from satellite images is one of the most difficult problems in image science. "Automatic" implies the use of a computer, and programming it to process images "intelligently" implies we understand and can formulate human vision[1,2] and the perception of motion. Therefore there are many mathematical problems in this field (sometimes known as pattern recognition).[3] The main problem we cover mathematically here is how to condense and transform the vast quantities of data from successive satellite images to produce accurate cloud motion vectors within a short delay after the images are received. This delay must not be long if the results are to be useful for practical weather prediction. Mathematically, we can represent this overall problem in the form of an equation that formulates the solution:

$$V = P\{I\}$$

where

- P symbolizes the computer <u>programs(s)</u> (FORMULATION)
- I symbolizes the satellite <u>image(s)</u> (DATA)
- V symbolizes the list(s) of <u>vector(s)</u> (SOLUTION)

The computer program is the objective or automatic process, P_o, for finding motion vectors, and these vectors must be validated by comparison with the subjective results produced by a person or persons, P_s. (Subscript "s" denotes subjective and subscript "o" denotes objective.) As aids to the subjective judgment, we allow the inclusion of any other measurements of the atmosphere, including radiosondes and weather radar.

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A. Simplifying Assumptions

We can simplify or factor the program, P, into two separate sections or phases. A motion vector is defined only with respect to (at least) two successive images:

$$I_{T_i} \quad \text{and} \quad I_{T_{i+1}}$$

These refer to the times: T_i and T_{i+1}. For each of these times, clouds must be identified and located precisely in the image. This function is performed by the clustering process, C. After this, the two images must be operated on together (symbolized by the operator $*$) to produce the motion vectors. We represent this factorization mathematically by:

$$P\{I\} = M\left[C\left\{I_{T_i}\right\} * C\left\{I_{T_{i+1}}\right\}\right]$$

where the matching or pairing operation, M, connects corresponding clusters to provide motions.

The images we deal with on the computer consist of picture elements produced by a high-resolution telescope on the spin-scan satellite. The size of the resolution element we deal with represents approximately 2 miles on the earth. Resolution depends on the satellite design and this governs the lowest bound on element size that we need consider. Our problem then is to aggregate or collect mathematically these picture elements (pixels) of clouds in a meaningful fashion, C_o, so that the results we get with our mathematical process for aggregating pixels into larger units (i.e., clouds) agree with expert human meteorological[4] observers, C_s. We call this aggregation process clustering. Any one image is a static, fixed view of the world, and we must also consider how to enhance the process to dynamically take account of <u>time</u> and motion, as well as the fixed distribution in <u>space</u>. The name for this adaptive process using successive static views is dynamic clustering.

B. Static Clustering

We next define the static clustering process, C, as operating on an image to transform it into a data list, L, containing several items including the locations of the cluster centers, indexed from $j = 1,k$:

$$C\{I\} = \underset{j=1,k}{L} \left\{k, \left(\overline{x}_j, \overline{y}_j\right)\left(\sigma_{\overline{x}_j}, \sigma_{\overline{y}_j}\right), S\right\}$$

where k is the number of cluster centers (clouds), $(\overline{x}_j, \overline{y}_j)$ is the image coordinate of the jth cloud center, and

$$\left(\sigma_{\overline{x}_j}, \sigma_{\overline{y}_j}\right)$$

is the standard deviation of the pixels of the cluster and measures the cloud size. S represents miscellaneous summary statistics such as all pairs of intercluster distances and the number of pixels, n, contributing to each cloud, etc.

The ISODATA clustering process, C (ISODATA is a particular clustering algorithm whose development was begun in 1965 at SRI), is iterative, but it may be "instructed" to settle to a static condition by the "settling process," in which transmigration of pixels from one cluster to another is eventually ended. This usually occurs after about three iterations of the image data through the ISODATA process on the computer, provided no control parameters of the program are externally disturbed. The program parameters are the means by which the user guides the computational process to adapt to his needs.

The static part of the clustering is locating or identifying the clouds, and since these are usually the brightest features in the image, brightness of the elementary pixels is the prime variable identifying a cloud.

Since we are interested in tracking clouds, we must first apply some function of this brightness (or radiance, in the case of an infrared image) to eliminate background pixels. If n_t is the total number of pixels in the original (total) image, including background, then the total number of pixels retained in the reduced or partial image is n_r, where $n_r < n_t$. See Figure 1.

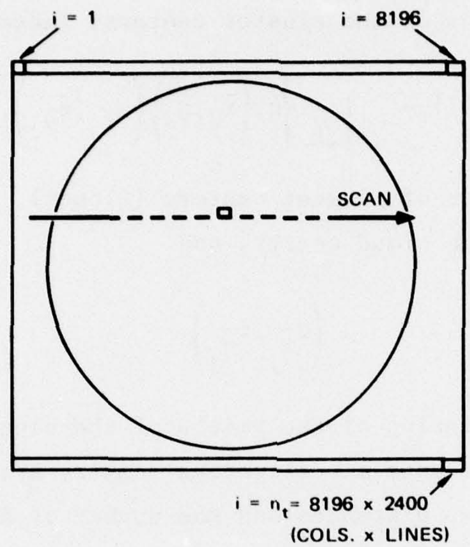

FIGURE 1 DIAGRAM OF WHOLE IMAGE, SHOWING SPECIFIC RESOLUTION DETAILS FOR ATS-3 SATELLITE

Several separating algorithms, A, have been evaluated, to include or exclude each pixel, i. The simplest algorithm uses a fixed brightness threshold. It is convenient to define a binary variable, b_i, for each pixel, as:

$$b_i = \begin{matrix} 1 \\ \dashv \\ 0 \end{matrix} A\{I\}$$

Then

$$n_r = \sum_{i=1}^{n_t} b_i$$

The simple fixed-threshold (Θ) algorithm is represented mathematically by $B_i \geq \Theta$, where B_i is the brightness at the ith pixel.

Obviously, not every bright pixel is a separate cloud, so we aggregate, average, or cluster the pixels into cluster centers. Assume that there is one cloud or cluster in the image; its location is defined by our process to be at $(\overline{x},\overline{y})$ image coordinates, where

$$\overline{x} = \frac{1}{n_r}\sum_{i=1}^{n_t} b_i x_i \qquad \overline{y} = \frac{1}{n_r}\sum_{i=1}^{n_t} b_i y_i$$

and i counts only the pixels in the selected image. The spread is measured by

$$\sigma_{\overline{x}}^2 = \frac{1}{n_r - 1}\sum_{i=1}^{n_t} b_i\left(x_i - \overline{x}\right)^2$$

and similarly for $\sigma_{\overline{y}}^2$.

However, it is not realistic to assume only one cloud in the image, and because of the large variations encountered in practice, both as to shape and extent of cloud coverage, the adaptive process searches for and finds the locations of an appropriate number, $\hat{k}$, of clouds (approximately 15 or 20 per image, determined by reasonable use of computer time) to represent any image. Thus, the prime function of the static clustering process is counting and locating the centers of significant clouds.

The adaptive search process of ISODATA, and the parameters used to guide it, will not be discussed in detail here, as there have been a number of publications describing them.[5,6] At SRI, Dan Wolf has recently been using a special-purpose "touching" algorithm that finds suitable centers and also reduces computation time compared with the full clustering algorithm.

C. Dynamic Clustering

The motion program, M, produces a ranking, R, of vectors from the clustering results. (For conceptual simplicity and concise description, we shall continue to use I as the selected image as well as the original image, ignoring the background.) Thus

$$M\left[C\left\{I_{T_1}\right\} * C\left\{I_{T_2}\right\}\right] = \underset{j=1,k}{R} \left\{V_j, F_j\right\}$$

assuming, for simplicity of this formulation, that k is the same number of clusters found at times 1 and 2. F is a fit factor computed for each vector, j, and defined heuristically as the following combination of statistical descriptors (derived from the clustering, and implied by the previously defined quantity, S):

$$F = \left[w_x \Delta x^2 + w_y \Delta y^2 + w_B \Delta B^2 + w_R \Delta R^2 + w_n\left(\frac{\Delta n^2}{n_1 + n_2}\right) + w_\sigma\left(\Delta\sigma_x^2 + \Delta\sigma_y^2 + \Delta\sigma_B^2 + \Delta\sigma_R^2\right)\right]$$

where

w is the weight for the respective factors

Δ stands for the difference in the respective statistical descriptors of a pair of cluster centers

x is the measurement in image units in the east-west direction (as before)

y is the measurement in image units in the north-south direction (as before)

B is the average brightness of a cluster (0 to 255)

R is the average infrared temperature of a cluster (160 to 330 degrees Kelvin)

n is the number of points in a cluster (in particular, n_1 is the number of points in the cluster at time 1 and n_2 is the number of points in the cluster at time 2)

σ is the standard deviation of the various quantities (σ_x is the standard deviation in the east-west direction, σ_y is the standard deviation in the north-south direction, and so forth)

II COMPUTATIONAL EXPERIMENTS

The data image consists of a global view of the whole earth, with sea, land, and air.[7] This is real data for our experiments, because it is the ultimate application for which the program is intended. Our task is to match a program to this data, to give useful meteorological results. However, it may be more natural for the program to process other data, obtained hypothetically from a mathematical model or concept. We have artificially generated such data for our experiments, to simulate clouds. The benefit of artificial data is that its basic characteristics of motion are perfectly known, by construction. See Figure 2.

A. Experimental Method

The method of conducting our experiments has been to generate artificial data (representing clouds) and then to process these data using the dynamic clustering program to see if the computer can recover the same motion information from the data that we used to generate it. This method is sound because it is complete, having a closed-loop form. Discrepancies that arise between the two sources of information, at the input and output of the closed loop, denote errors in the dynamic clustering program. If the errors are statistically significant, modifications to the program are necessary. Sometimes the errors are of a gross kind, but often the search for a remedy requires introspection concerning the nature of the human visual tracking process and how to describe this within the practical limitations of the computer system. The commands implemented in the data-generating language are not discussed here, but have been published.[3] A high-performance CRT display connected to a PDP 11, and line-printer plots from a CDC 6400 computer, have been used for this work.

B. Tracking More Complex Artificial "Clouds"

We have reported tracking 39 clouds simulating the Intertropical Convergence Zone.[8] These "clouds" were tracked by the computer program and by human observers on the SRI cloud console. Agreement between man

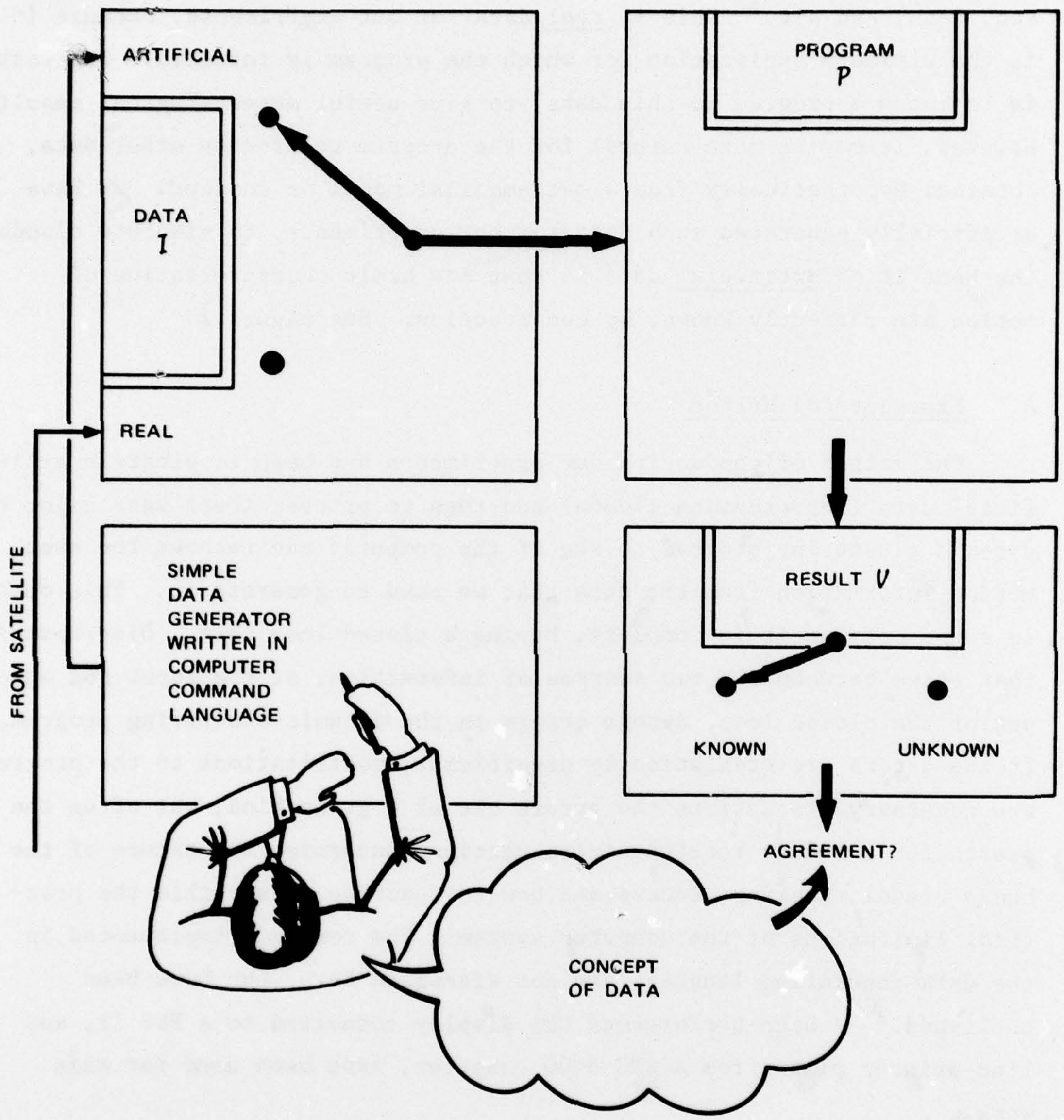

FIGURE 2 DIAGRAM OF EXPERIMENTAL METHOD FOR ADAPTING THE PROGRAM TO REAL AND ARTIFICIAL IMAGES

and machine was very good for motion vectors. We have also reported tracking simulated infrared imagery.[9] These results, although of great interest, are not easy to display graphically in this paper. It is necessary to inspect the printout (or the report containing extracts of printout) to appreciate the finer points of these more complex experiments.

C. Tracking ATS III Images

On a related project we have carried out a detailed comparison of the cloud vectors produced by humans. An area off the west coast of Africa was selected for these comparisons, using five frames of real satellite data taken on 23 August 1969. There were 66 clouds, clusters, or tracers, identified and tracked, using both objective program P_o and the average of four subjective human trackers P_s. Although the result[10] showed that objective tracking by computer was quite good, some recent improvements have resulted in even better performance. The first improvement was gained by an adjustment of the weights, w (given earlier in the equation for the fitting factor F). This improvement was made by Roy Endlich, based on his meteorological observations using the cloud console and his familiarity with the inner workings of the program. The second improvement was due to the introduction of a "touching" method for finding centers. These improvements are summarized in the following tabulation, for 199 possible vectors:

	Correct	Incorrect	Rejected
Results, 1973	147(74%)	34(17%)	18(9%)
Results, 1976	168(84%)	3(1.5%)	28(14%)

III DEVELOPMENT OF NEW ADAPTIVE SYSTEM (SPADS), FOR TRACKING, AT MONTEREY, CALIFORNIA

The adaptive process we have been describing in this paper is being "installed" on a dual-processor minicomputer system at the Naval

Environmental Prediction Research Facility, in Monterey, California. The system is presently operating on the CDC 6400 at SRI, and extensive plans[11] have been laid, including dual-site (SRI/NEPRF) capability and smooth transfer to an interactive-display facility, supported by two NOVA-800 computers. This system is called SPADS (SATDAT Processing And Display System). Fortunately, both computers have FORTRAN compilers, but incompatibility between CDC's FORTRAN-extended" and Data General's Fortran IV has required many special modifications. These incompatibilities have been minimized by means of a conversion program, developed and operational at SRI.

IV CONCLUSIONS

The author feels that this adaptive process is the most effective operational algorithm existing today for tracking cloud motions. Another interesting and useful system is being implemented by the Space Science and Engineering Center at the University of Wisconsin, but their emphasis is more on human guidance for cloud tracking, and is thus not an automatic or objective system. There is no automatic clustering process in the Wisconsin system: "Only candidate clouds identifiable by the scientist throughout the picture sequence were tracked...."[12] The correlation method being used by the National Environmental Satellite Service seems to be less accurate, because fixed background is not separated from moving clouds. With the increasing use of satellite weather pictures, it is appropriate that the most promising methods of tracking should be thoroughly investigated. Furthermore, the study of the navigation of clouds is most appropriately a naval function.

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