

**ESTIMATING POPULATION SIZE OF  
PYGOSCELID PENGUINS FROM TM DATA**

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**FINAL REPORT  
to the  
National Aeronautics and Space Administration  
under  
Contract NAS 5-28755**

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**August 1987**

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## ACKNOWLEDGEMENTS

The research described in this report was specifically concerned with developing satellite remote sensing methods to estimate the population size of Pygoscelid penguins on their nesting sites. This research was motivated in part by observations which found that penguins are one of the most sensitive elements in the complex of Southern Ocean ecosystems.

This final report summarizes work conducted with the support of the National Aeronautics and Space Administration's Announcement of Opportunity for Thematic Mapper Research, under contract NAS 5-28755. Additional support came from the National Science Foundation's Division of Polar Programs grant DPP-85-07483.

The following persons contributed to the research described in this report: William S. Benninghoff, David F. Parmalee, Kathy Wehnes, Zhenqui Ma, Zhiliang Zhu, Jerry Mullins, David G. Ainley, and Wayne Z. Trivelpiece. The conclusions drawn are, however, solely the responsibility of the authors.

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INTRODUCTION

The Southern Ocean ecosystem is one of the largest, most productive, and poorly understood natural systems on earth. Our lack of understanding of this ecosystem is, to a large extent, due to logistical difficulties of operating in this harsh and remote region. It is widely believed, however, that the isolation of the Southern Ocean ecosystem is being broken by commercial exploitation of Antarctica's renewable and non-renewable resources. The potentially harmful results of commercial activities led the 16 signatories of the Antarctic Treaty, plus a larger number of non-member nations, to express concern about Antarctica's future to United Nations Secretary General Javier Perez de Cueller. The United Nations is now preparing a "comprehensive, factual, and objective study on all aspects of Antarctica."

The unique observational capabilities of the Landsat Thematic Mapper (TM) can provide an important aid in Antarctic reconnaissance. We have focused our attention on the use of TM data for monitoring the dynamics of penguin populations in Antarctic and sub-Antarctic latitudes.

As a class, penguins are one of the most important biological components of Southern Ocean ecosystems. Penguins account for the vast majority of terrestrial vertebrate biomass in the Antarctic, and a single species--the Adelie penguin (Pygoscelis adeliae)--makes up approximately 90% of the Antarctic bird biomass (Croxall and Prince, 1979). To date, most studies have been confined to local surveys of the territorial and social behavior of these birds. There is, however, a growing interest in the study of the ecology and population dynamics of Antarctic seabirds on a regional basis.

Interest in investigating penguins over a larger territory is motivated, in part, by the observation that penguin populations, and especially Adelie populations, have been increasing (Conroy, 1975; Croxall and Kirkwood, 1977). It has been hypothesized that an increase in krill (Euphausia superba) is at least partially responsible for the rise in penguin numbers. Krill is the key species in the food web of the Southern Ocean; Euphausia

superba is the main prey of numerous species of whales, seals, squid, fish, and penguins. It has been suggested that the active whaling industry has diverted feeding biomass from whales to penguins, supporting an increase in penguin numbers (Sladen, 1962; Emison, 1968). A krill fishery, although still in its infancy, has begun to develop in the Southern Ocean. The apparent effects of the whaling industry on penguin populations and the strong interactions among all Southern Ocean species raise the possibility that commercial exploitation of krill will be at the expense of predators that feed in Antarctic and sub-Antarctic waters. Croxall and Prince (1979) have suggested that monitoring changes in the breeding numbers of krill-feeding seabirds, such as the Adelie penguin, may serve as an index of the distribution and availability of prey stocks. With the advent of a large scale krill fishery such an index may be particularly useful for setting realistic catch limits.

In accepting these views the Scientific Committee on Antarctic Research (SCAR) endorsed a large scale study of "Biological Investigations of Marine Antarctic Systems and Stocks" (BIOMASS). A SCAR working group proposed that programs be established to monitor Southern Ocean species including whales, seals, and sea birds (SCAR, 1979), because changes in the population density of these species may serve as sensitive indicators of the vitality of the Southern Ocean ecosystem.

Several of the Antarctic treaty nations, led by activities of the British Antarctic Survey, have been monitoring penguin populations in ground-based studies of rookeries on several areas bordering the Antarctic and sub-Antarctic waters. As a compliment to these conventional methods of measurement and reconnaissance, modern remote sensing techniques are expected to improve the power, scope, accuracy, and economy of data collection in the Antarctic.

#### OBJECTIVES

We began our study with four primary objectives:

1. To determine the most suitable spectral regions for detecting and monitoring penguin rookeries by studying the reflectance characteristics of the birds and their backgrounds.
2. To employ Thematic Mapper (TM) data as a means of detecting the size, location, and extent of Adelie penguin rookeries.
3. To estimate penguin population size at a rookery based on its areal extent and available data on penguin colony density.
4. To develop an inventory plan, based on TM data, for estimating the size of the total population of Adelie penguins.

## TECHNICAL BACKGROUND

Modern remote sensing methods have not been extensively or systematically employed in Antarctic ornithology and ecology. At the start of this study, only one investigation had been conducted to evaluate the utility of satellite data for identifying penguin rookeries (Ott, 1982). This study was based on data acquired with the Landsat-1 Multispectral Scanner (MSS) on February 16, 1973, a date after the end of the Austral summer breeding season when penguins are on the rookeries. No firm conclusions were reached regarding the value of satellite remote sensors for such work in the Antarctic. In the conclusions and recommendations Ott wrote:

"Of the products generated, it is our impression that the false color composite is most useful. However, persons more experienced with the Antarctic might reach other conclusions. In addition, different conclusions might well have been reached if a more optimal LANDSAT acquisition date were available."

"We recommend the LANDSAT-D data be special-ordered during the November-December time period. ...If Thematic Mapper data are available, the higher resolution (approximately 30m) could be quite helpful."

Prior to the ERIM study, all remote sensing investigations of penguin populations reported in the literature by Antarctic ecologists and ornithologists were based on aerial photographs (Bauer, 1964 & 1967; Stonehouse, 1969; Sladen and Leresche, 1970; Butler and Muller-Schwarze, 1977). These large scale photographs proved successful because individual birds or nests could be detected and counted. Such aerial photographic techniques are best suited to relatively local surveys, whereas satellite techniques offer particular advantages for inventories of extensive areas. To be useful, satellite remote sensing systems must be capable of recording something closely correlated with penguin numbers, for the resolution of available satellite sensors is insufficient to permit direct detection and counting of the birds. The Thematic Mapper (TM) carried by Landsat-4 and -5 appears to provide the needed capability.

Spectral reflectance measurements of plumage from a single Adelie penguin, a sample of three Adelie guano covered pebbles, and several other Antarctic --- materials (Figure 1) have been collected (Schwaller, et al., 1984). The reflectance of penguin plumage and guano are unlike reflectance from snow and rock, the two most common Antarctic terrestrial backgrounds. Experience has shown that objects with such differences in reflectance, at least at some wavelengths, can be differentiated from each other on the basis of remote sensor data. Relatively small reflectance differences can be amplified when data in two different spectral bands are ratioed. Ratios of the average reflectance of the materials in Figure 1, for the spectral bands of the Landsat TM are shown in Table 1. The TM Band 5 to TM Band 2 ratio for penguin plumage is several times greater than the reflectance ratios for the other materials. Other band to band ratios can be used to separate guano covered pebbles from basalt and snow. Ratios for penguin plumage and guano covered pebbles are almost always higher than the corresponding ratios for their basalt or snow backgrounds. Thus, a scene element containing all plumage, all guano covered pebbles, or a mixture of the two, should be readily distinguishable from scene elements consisting of basalt or snow, or a combination of these background materials.

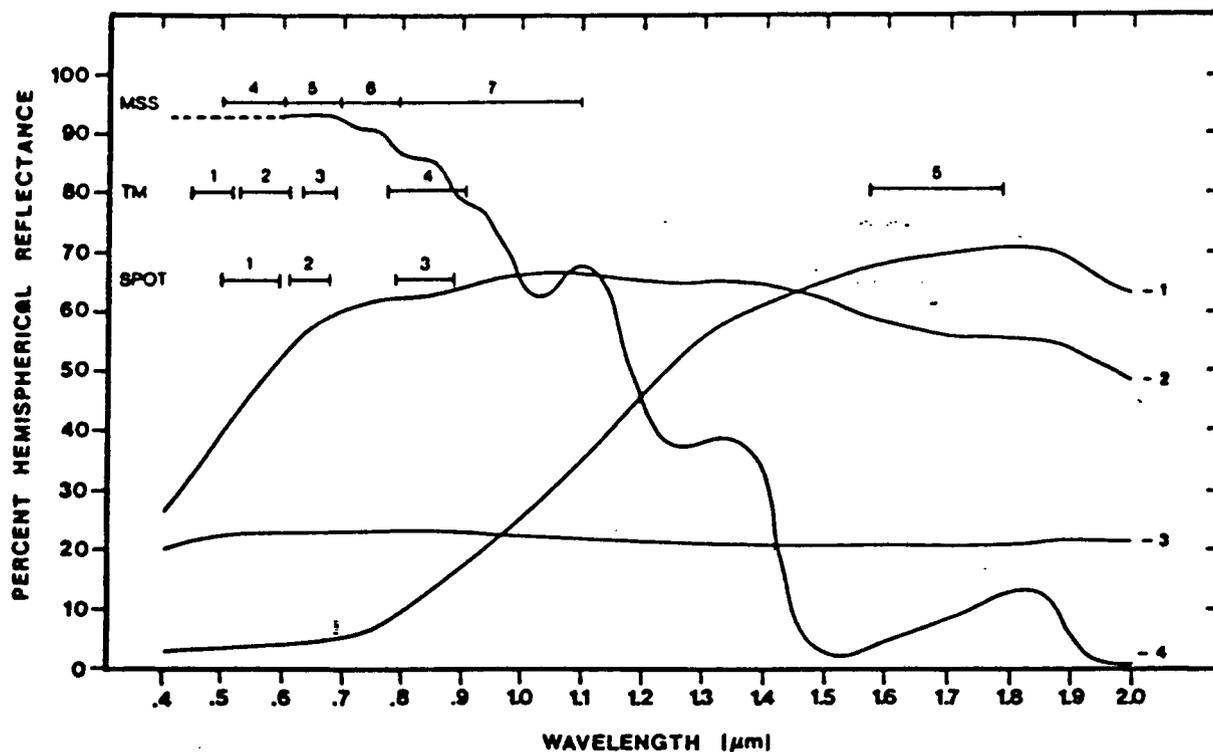


Figure 1. Spectral hemispherical reflectance, measured with a Beckman DK-2A spectrophotometer, of:

- 1- Adelie penguin plummage (Schwaller et al., 1984)
- 2- Adelie guano covered pebble
- 3- guano free pebble from Adelie rookery
- 4- new snow (Suits, 1978)

Spectral bandwidths for the Landsat MSS, Landsat TM, and SPOT sensors are indicated by horizontal bars in the upper left.

Table 1. Brightness ratios for various materials from the Antarctic environment. See Figure 1 for the spectral reflectance data and bandwidths of the various satellite channels.

Band Ratio	Environmental Material			
	Penguin Plumage	Guano Covered Pebble	Basalt Pebble	New Snow
Landsat 4 TM				
Band 5/Band 1	22.9	1.5	1.0	0.1*
Band 5/Band 2	22.9	1.2	0.9	0.1*
Band 5/Band 3	15.3	1.0	1.0	0.1
Band 5/Band 4	5.1	0.9	0.9	0.9
Band 4/Band 1	4.5	1.6	1.1	0.9*
Band 4/Band 2	4.5	1.3	1.0	0.9*
Band 4/Band 3	3.0	1.1	1.1	1.0
Band 3/Band 1	1.5	1.5	1.0	1.0*
Band 3/Band 2	1.5	1.2	1.0	1.0*
Band 2/Band 1	1.0	1.3	1.0	1.0*
Landsat MSS				
Band 7/Band 4	6.5	1.4	1.0	0.8*
Band 7/Band 5	4.9	1.1	1.0	0.8
Band 7/Band 6	3.1	1.1	1.0	0.8
Band 6/Band 4	2.1	1.1	1.0	0.8*
Band 6/Band 5	1.6	1.1	1.0	1.0
Band 5/Band 4	1.3	1.2	1.0	1.0*
SPOT				
Band 3/Band 1	4.1	1.4	1.0	0.9*
Band 3/Band 2	3.1	1.1	1.0	0.9
Band 2/Band 1	1.3	1.2	1.0	0.9*

\* Data below 0.6  $\mu\text{m}$  extrapolate from Suits (1978).

In addition to their spectral characteristics, the size of Adelie rookeries makes them appealing targets for remote sensing inventory. Although the spectrophotometric characteristics and sheer size of penguin rookeries suggest that they can be detected in TM imagery, it is necessary to consider the potential problems of remote sensing in the Antarctic. Low sun angles in the Antarctic can produce difficulties. At low sun angles, effects of "haze" due to atmospheric scattering of sunlight become more severe, particularly at shorter wavelengths. This can make TM Band 1 (0.45-0.52  $\mu\text{m}$ ) unusable. Low sun angles also increase absorption of solar radiation, particularly in TM Band 5 because of the significant optical density of the atmosphere in the wavelengths around 1.5  $\mu\text{m}$ , and because the solar flux is low at these wavelengths. There is also the question of the weather, which is notoriously cloudy along much of the Antarctic coast.

Assuming that the extent of the penguin rookeries can be discerned from TM data, this information could be used to conduct a census of the total Adelie population. Research has found that Adelie nests are spaced closely and regularly, with an average area per nest of 0.75 square meter (Penney, 1968). This regular spacing suggests that a penguin census can be based on a ratio estimation method employing TM data. Ratio estimation takes advantage of an auxiliary variable  $x_i$  (in this case the size of the rookery) to estimate the population total of a correlated variable of interest  $y_i$  (in this case penguin population). Ratio estimation has two advantages. One, the precision of the estimate is generally greater than with random sampling due to the correlation between  $x$  and  $y$ . Two, the ratio estimator is the best linear, unbiased estimator if the relation between the auxiliary variable  $x$  and the variable of interest  $y$  is a straight line through the origin, and if the variance of  $y_i$  about this line is proportional to  $x_i$  (Cochran, 1977, pp 158-159). We can safely assume that the relation between  $x$  and  $y$  passes through the origin, since if the rookery extent is zero the population size is also zero. Furthermore, the regular spacing of nests within a rookery argues for an approximately linear relationship between population size and rookery extent. The functional relationship between the variance of  $y_i$  and  $x_i$  is unknown, but adjustments can be made in the estimator if the variance of  $y_i$  is not strictly proportional to  $x_i$ .

In addition to the statistical advantages of a ratio estimator, there are also practical advantages to using this method for a penguin census. It is relatively cheap and easy to measure rookery size with remote sensing. Information on rookery extent plus a knowledge of the ratio of penguin numbers to rookery size can be used to estimate population size. This same estimate could, of course, be obtained by conventional means; however, directly counting birds in aerial or ground surveys becomes prohibitively expensive and increasingly unreliable as the scope of the census increases. Thus, estimating the size of the total penguin population with the help of TM data can yield more precise results than conventional methods, may do so more easily, quickly, and at less cost.

## METHODS

The experimental plan for this investigation was based on standard remote sensing techniques: data acquisition; data analysis, algorithm development and training from ground truth; and verification.

### Study Site

The principal study site was the large Adelie rookery on Cape Crozier, on the eastern shore of Ross Island, an area which borders the Ross Sea at approximately 77°30S' latitude and 169°15E' longitude. This is a well known and well studied rookery located about 100 kilometers from McMurdo Station, a major U.S. Antarctic research base. The aerial photograph in Figure 2 shows the extent of the rookery on Cape Crozier, covering from 2 to 3 square kilometers. This rookery has an Austral summer population of up to 350,000 birds (Penny and Lowry, 1967; Leresch and Sladen, 1970). Additional work was also done at rookeries on Cape Bird and Cape Royds.

A search of the Landsat-1, -2, and -3 data archives was conducted to determine the availability of imagery for five coastal locations with large penguin populations: Ross Island, Cape Hallett, Anvers Island, Geologie Archipelago, and Hope Bay. In the preceding 10 years, 25 scenes potential Landsat scenes were identified. To ensure independence, 13 samples from the set of 25 were eliminated so that no scene was collected within 14 days of another. Of the 12 remaining samples, 3 had 10% or less cloud cover. This yielded an estimate that on a given trial there is a 75% chance ( $\pm 13\%$  error bound) that no suitable imagery will be obtained due to overcast conditions. If we use the mean of 75%, assuming that samples are independent, the binomial distribution can be used to predict that there is an approximately 50% chance that no suitable scenes will be imaged after a series of three trials. We can also predict that it is almost certain (>90% probability) that one or more acceptable scenes will be imaged in a series of eight trials.

Fortunately, the convergence of the Landsat-5 orbit near the poles frees the data acquisition schedule from the strict constraints of the equatorial 16-day repeat cycle of Landsat-4 or -5. Table 2 lists the coverage schedule for a ground station at 77°05'S latitude, comparable to the schedule expected at Cape Crozier and Cape Hallett. The ground station is in range of the TM scanner for 6 days of the 16 day cycle on the "day" orbit, 5 on the "night" orbit, and no coverage is obtainable for only 6 days of the 16 day cycle. Table 2 also lists the approximate solar elevation at Cape Crozier at the time of satellite overpass for the Austral summer months. Solar elevation is on the order of 23° to 28° during the months of November to January for the "day" orbits, and 8° to 13° for the "night" orbits. Given the relatively low sun angle for "night" orbits, it was decided to collect TM data during "day" orbits only.

Coverage of TM Path 53, Row 116 (Ross Island) was requested for the November 1985 to January 1986 Austral summer; the period coinciding with maximum rookery occupation (Penney, 1968). Plans for acquiring data for Cape Hallett (Path 63, Row 111) were cancelled when the 1985 price increase for Landsat data caused a cut-back in data availability.

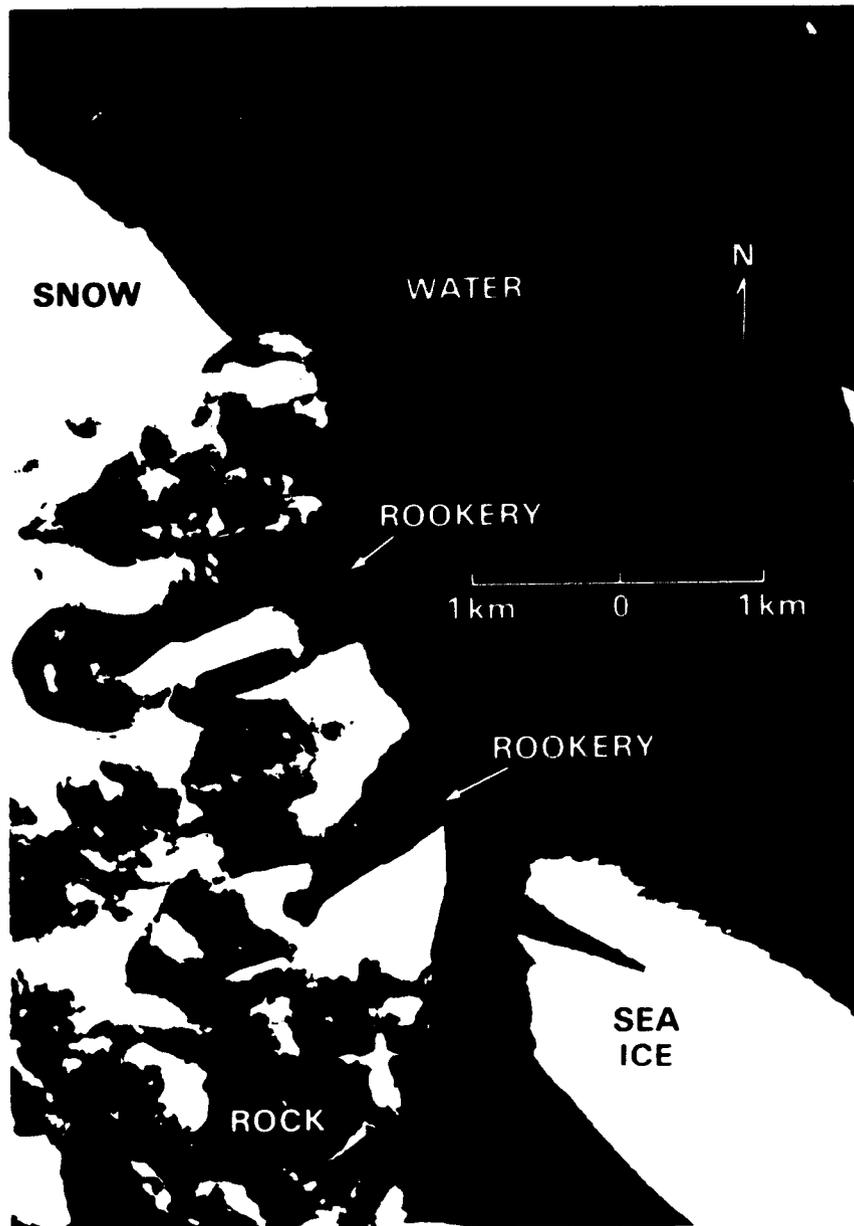


Figure 2. Vertical aerial photograph showing the size and location of the north and south nesting sites for Adelle penguins on Cape Crozier. The rookeries are readily distinguishable from snow, ice, water, and rock in this panchromatic image from the archives of the U.S. Geological Survey National Cartographic Information Center.

ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH

Table 2. Approximate TM coverage schedule and solar elevation angles for ground targets at high latitudes during the period of proposed TM data acquisition.

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Sixteen Day Coverage Schedule for October 1 to 16

<u>Days</u>	<u>Nights</u>	<u>Misses</u>
1st	4th	2nd
3rd	6th	7th
5th	8th	9th
8th	13th	11th
10th	15th	14th
12th		16th

Landsat-5 may pass within range of the ground area located at 77°05'S on the "day" orbit, the "night" orbit, or a miss may occur if the ground area is not within the field-of-view of the TM scanner on a given day. At this latitude, "day" or "night" coverage occurs approximately once every 48 hours.

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Mid-Month Solar Elevation Angles at Cape Crozier During the Austral Summer

For Day Orbits

	October	November*	December*	January*	February
Solar Elevation Angle	13°	23°	28°	23°	14°

For Night Orbits

	October	November*	December*	January*	February
Solar Elevation Angle		8°	13°	8°	

\* Months of maximum rookery occupation (Penney, 1968).

## Data Analysis

Image analysis was conducted on the Land Analysis System in the Laboratory for Terrestrial Physics at the NASA Goddard Space Flight Center. This work was based on our analysis of spectral reflectance measurements of guano, snow and three types of volcanic rock materials (tuff, andesite, and basalt) common in the area around penguin rookeries on Ross Island. These data included both laboratory measurements made with a Beckman DK-2A spectrophotometer and field measurements made with a three-band radiometer and halon reflectance standard designed by C. J. Tucker (Tucker et al., 1981) at NASA Goddard.

The reflectance measurements made with the Beckman DK-2A spectrophotometer included the spectral region from 0.38 to 2.6um. Spectral reflectance measurements were integrated over the wavelengths corresponding to the 6 reflective channels of the Thematic Mapper.

Ground level measurements made with the three band radiometer corresponded to TM bands 3,4, and 5. The measurements were made during January 1986 at Cape Crozier for four ground types: penguin colonies (n=61), exposed basalt (n=26), exposed tuffs (n=26), and snow (n=30).

Discriminant analysis, clustering, and graphical analysis were applied to the data to determine which channels contributed most to the separation of ground targets, and to assess the accuracy of separation.

## Derivation of Rookery Population Estimates

Starting with the observation that there is a relatively constant packing density of penguin nests within colonies (Penney, 1968), we developed linear models which describe the relationship between colony area and Adelie nesting population. The models were then re-defined into statistical estimators which, given the total colony area within a rookery, allows one to predict the total number of nests, and to place an upper and lower limit on the estimate.

## Developing a Regional and Continent-Wide Inventory

The long term objective is to develop a statistically sound design for a regional and continent-wide population survey of pygoscelid penguins in Antarctica. The number and cost of TM scenes needed to survey the entire Antarctic coastline is too large for a total practical survey based on TM data. We anticipate that a continent-wide survey will rely on a multi-stage design that incorporates ground-based information, high resolution aerial photographic and/or satellite imagery, plus low resolution satellite imagery such as NOAA AVHRR-LAC data. The low resolution AVHRR data would be used to identify snow-free/ice-free coastal areas which have potential as rookery sites. Higher resolution data would then be used to determine if a rookery is there; and, if so, how large it is.

## RESULTS

Bivariate scatter plots based on the laboratory reflectance data, the field radiometer data, and the TM brightness values for the Ross Island subscene are shown in Appendix A. In each case, the brightness of different terrain materials is shown for two TM spectral bands. The scatter plots derived from the TM data for bands 5 and 3, and bands 4 and 3, are also shown in Figure 3. In both of these two plots, snow and ice are clearly separable from all other materials, but the rookery mixes with tuff. Scatter plots derived from the TM data for bands 7 and 4, and bands 7 and 5, are shown in Figure 4. In the plot of bands 7 and 4, the snow and ice are clearly separable from all other materials, and the rookery stands out more clearly than in either plot of Figure 2. In the plot of bands 7 and 5, the snow and ice cannot be separated from other materials, but the rookery is clearly distinguishable from all other materials. Each of the spectral bands of the TM sensor provides information which helps distinguish between some of the terrain materials. Taken together, the TM spectral bands were found to be sufficient for identification of rookeries from their background materials. Data transformations, including two-band ratios, were not required.

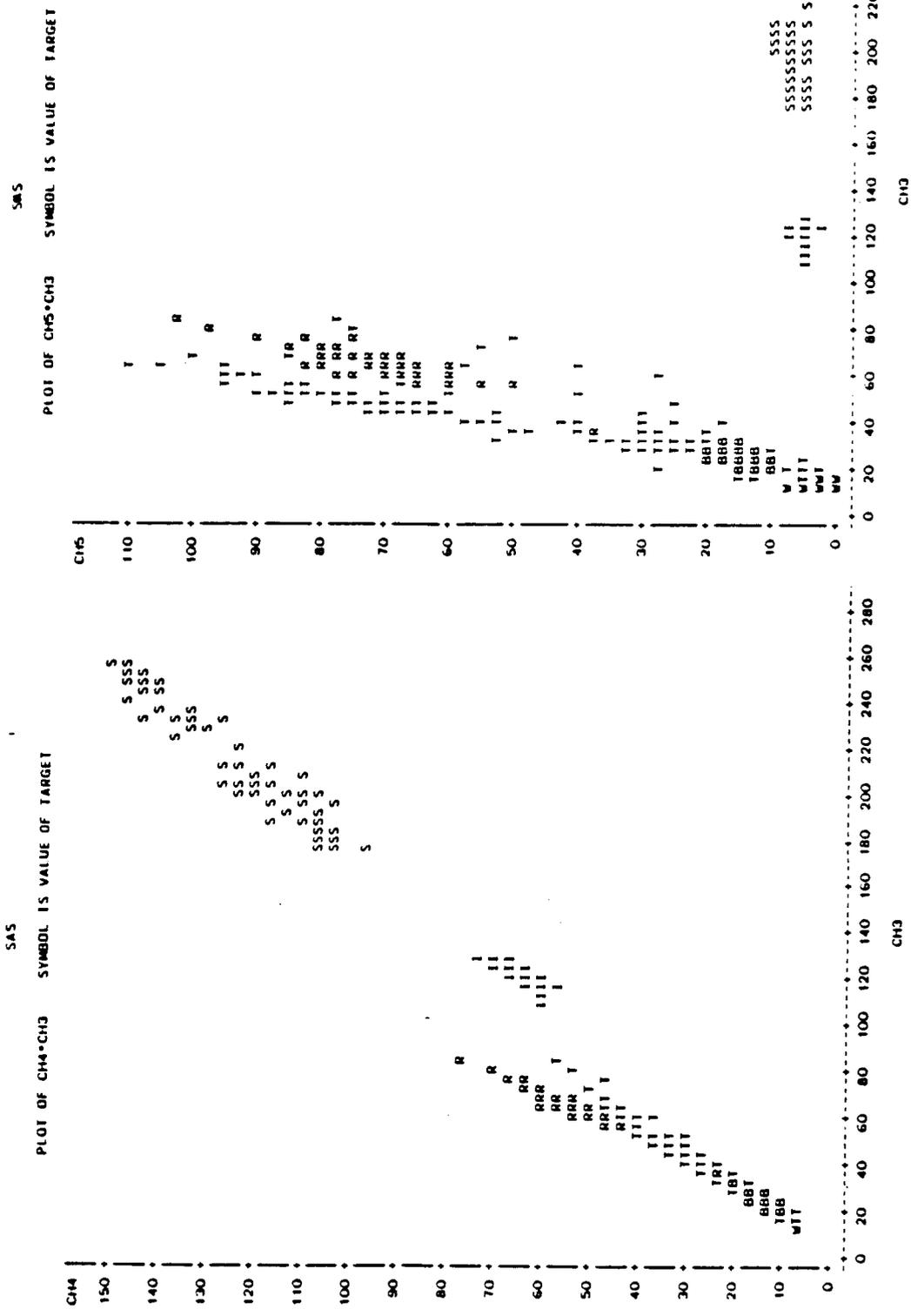
Results of these image analyses are summarized graphically in Figure 5, where black and white aerial photography of the Cape Crozier penguin rookery are compared with a classified TM image. In both cases the penguin rookeries are clearly evident, and the physical extent of the rookeries can be estimated from the TM data by counting pixels belonging to the rookery. The classified TM image was prepared by Earth Satellite Corporation using proprietary programs. Similar results were obtained at the University of Michigan using readily available programs and simple output devices (Figure 6). Preliminary results of our image analyses have been published in the Antarctic Journal of the U.S. (Appendix B).

Examination of Figure 5 suggested a relatively simple first order linear model should give a good fit to data relating colony area and nesting population. A series of hypothesis tests found that a weighted linear statistical model (where weight was proportional to colony area) provided an excellent fit to the data relating colony area,  $X$ , and the number of nests per colony,  $Y$ . The model can be described as follows:

$$\hat{Y}_i = X_i + w_i e_i \quad \text{where} \quad w_i = 1/x_i$$

Using this model, coefficients of determination ( $r^2$ ) of 0.90, 0.95, and 0.88 were obtained for regression of colony area and population when data were collected over the Cape Royds rookery, the Cape Bird rookery, and a pool of data from both rookeries, respectively. The results of this research phase are summarized in a report prepared for publication (Appendix C).

It is anticipated that the continent-wide estimate of penguin populations will be a complex survey. Assuming a multi-stage design, a considerable amount of flexibility is permitted when choosing the number of samples at each stage. An optimum design is one in which the precision is maximized for a given level of cost or effort. To obtain the optimum design it is necessary to estimate the cost and variance associated with each stage of the sample. Factors which need consideration include: the number of



NOTE: 663 OBS HIDDEN

NOTE: 602 OBS HIDDEN

Figure 3. Bivariate scatter plots of brightness in TM bands 4 and 3, and 5 and 3, for six terrain materials: basalt (B), sea ice (I), rookery (R), snow (S), tuff (T), and water (W). Data from TM scene for Path 53, Row 116 (Ross Island), acquired 26 January 1985.

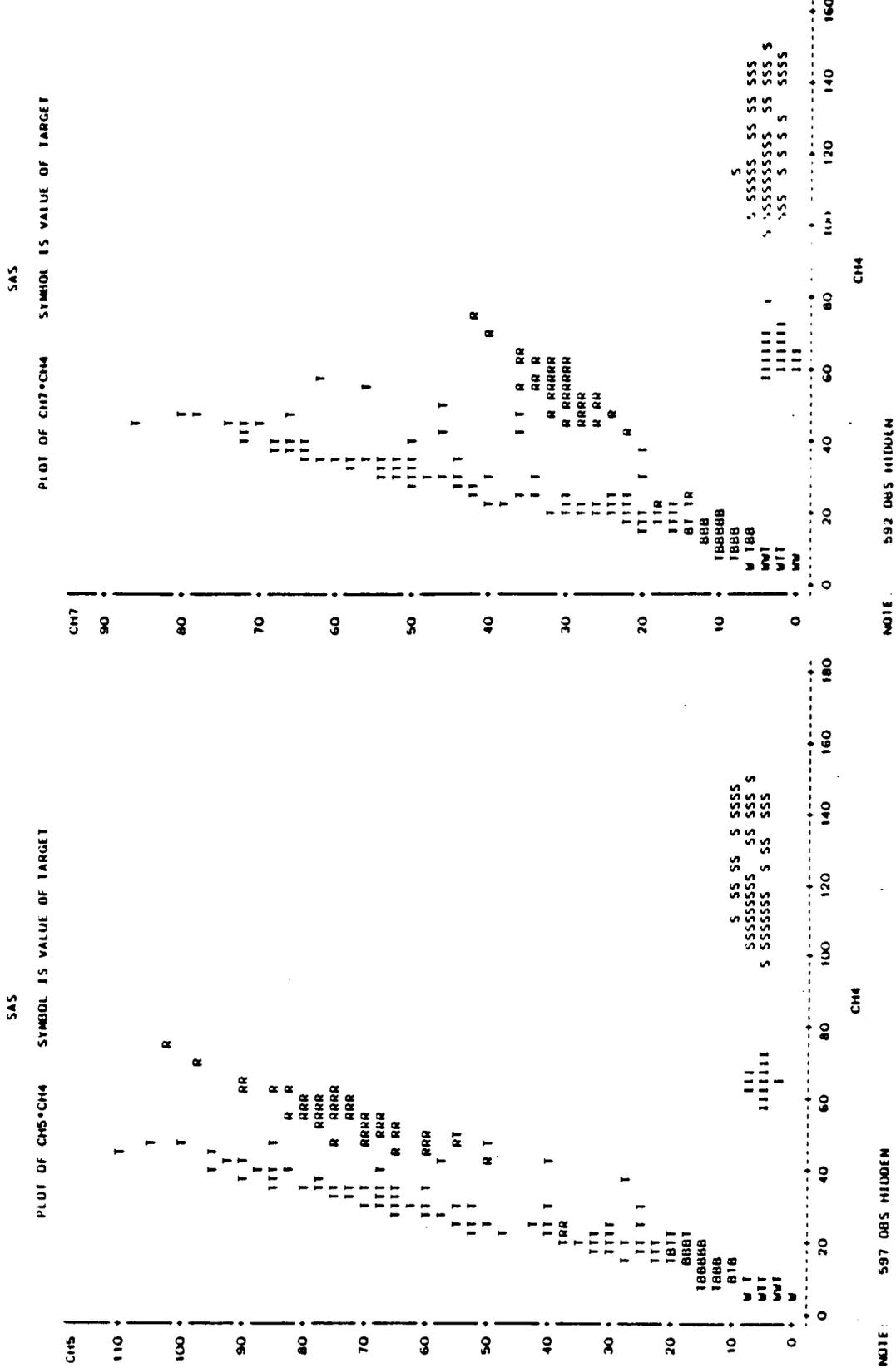


Figure 4. Bivariate scatter plots of brightness in TM bands 5 and 4, and 7 and 4, for six terrain materials: basalt (B), sea ice (I), rookery (R), snow (S), tuff (T), and water (W). Data from TM scene for Path 53, Row 116 (Ross Island), acquired 26 January 1985.

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COLOR PHOTOGRAPH

SCAR ARCHIVE  
AERIAL PHOTOGRAPH

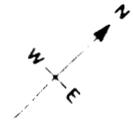


1km 0 1km

LANDSAT THEMATIC MAPPER  
COMPOSITE OF BANDS 3, 4 & 5



1km 0 1km



LEGEND

- C = CLOUD
- F = SNOW FIELD
- P = PENGUIN ROOKERY
- R = ROCK
- S = SEA ICE
- W = WATER



M SCHWALLER

Figure 5. Comparison of a panchromatic aerial photograph from the SCAR archives with a computer classified image of the Adelie penguin rookery at Cape Crozier. The computer classified image is a composite of TM bands 3, 4, and 5, and was prepared by M. R. Schwaller at the NASA Goddard Space Flight Facility, Greenbelt, Maryland, from the data for Path 53, Row 116 (Ross Island) acquired 26 January 1985.

ORIGINAL PAGE IS  
OF POOR QUALITY

PROCESSED BY ZHENKUI MA USING 7 CHANNELS

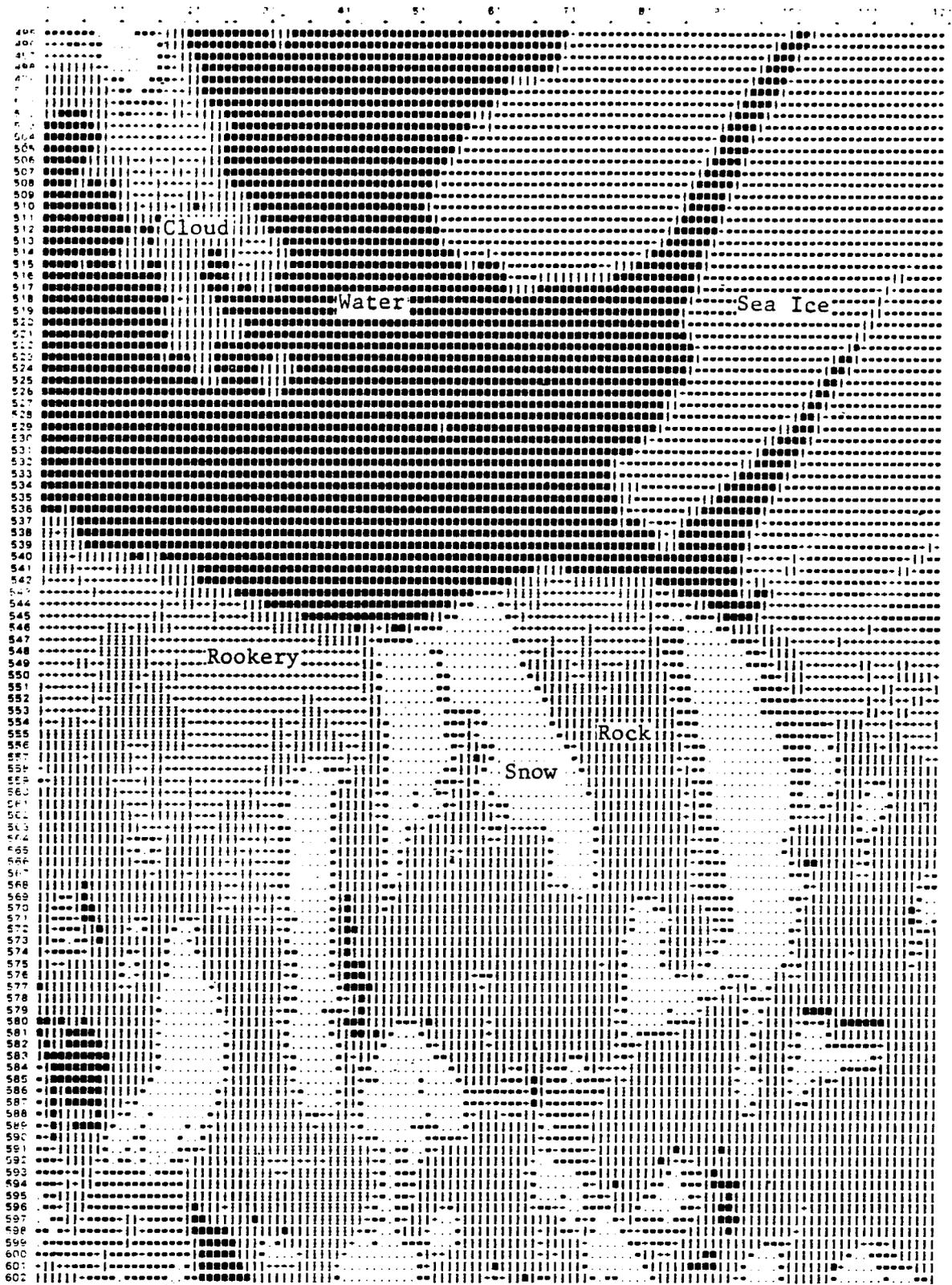


Figure 6. Computer classified gray-map of the Adelie penguin rookery at Cape Crozier prepared by Z. K. Ma at the University of Michigan using all seven channels of the TM data for Path 53, Row 116 (Ross Island) acquired 26 January 1985.

satellite images and the cost of locating rookeries on these images, the number of rookeries to sample for estimation of total rookery size, the number of rookeries to sample with ground and aerial photographic reconnaissance, which rookeries to sample, and the cost. All of these factors can be quantitatively estimated to obtain the optimum sampling design and to estimate precision for a given level of cost. We now believe a three year period. We do not believe it is appropriate to undertake a continent-wide survey without first testing the design concept on an area larger than a simple landsat scene.

#### DISCUSSION

This study represents an important first step toward a continent-wide estimate of penguin populations. The results of this study indicate that TM data can be used to identify penguin rookeries due to the unique reflectance properties of guano. Furthermore, strong correlations exist between nesting populations and rookery area occupied by the birds. These correlations allow estimation of the number of nesting pairs in colonies. The success of remote sensing and biometric analyses lead us to believe that a continent-wide estimate of penguin populations is possible based on a timely sample employing ground-based and remote sensing techniques.

It is interesting to note that differences in tone are apparent in the classified TM image (Figure 5). These differences may possibly be attributed to variations in nesting density within the rookery. If this association can be quantified, it could be developed into an excellent estimator of rookery population

Gray-maps, like that in Figure 6, can be prepared without the sophisticated computer used to prepare the color composite in Figure 5. The software used to prepare Figure 6 is being adapted for stand-alone use on a personal computer comparable to an IBM-AT, and could be used to provide a meaningful image analysis capability in Antarctica.

Several technical problems remain before a continent-wide population survey is feasible.

1. Establishment of the relationship between penguin rookery density and radiometric response observed in satellite imagery.
2. Development of multi-stage sampling methods which employ coarse resolution remote sensing data such as AVHRR-LAC.
3. Solution of the logistic problems of ground-based and remote sensing data collection.

that a timely and cost efficient estimate of pygoscelid penguin populations for the entire continent of Antarctica can be developed and implemented in Several important scientific questions, posed in the literature, await

accurate estimation of penguin populations on continent-wide and large regional scales. These questions include:

1. Location of previously undiscovered rookeries that have been hypothesized based on observations of penguins at sea, especially along the coastline of Marie Byrd Land (Siple and Lindsey 1937; Ainley et al. 1984).
2. Use of penguin population estimates as an index of the Southern Ocean ecosystem vitality (Croxall and Prince 1979).
3. Test of hypotheses that size and distribution of neighboring rookeries are related to competition for food resources (Firnness and Birkhead 1984).
4. Test of hypothesis that species composition of penguin rookeries is a function of physical factors, especially pack ice distribution (Ainley et al. 1983; Trivelpiece et al. in press).

In summary, the results of this research can be integrated into survey methods for estimating penguin populations on a continent-wide basis. Using the techniques that we envision, meridional as well as total penguin populations estimates may also be possible. In addition, satellite remote sensing along the coastline may well locate previously undiscovered penguin nesting sites, or locate rookeries which have been assumed to exist for over half a century--but which have never been located. Proposals are being developed for submittal to NASA and NSF to support the research necessary to conduct a continent-wide survey. The results of a continent-wide survey of penguin populations will contribute to an understanding of the influence of the physical environment on rookery choice and breeding success, the patterns of penguin migration, and population fluctuation.

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APPENDIX A. BIVARIATE SCATTER PLOTS FOR LABORATORY, GROUND, AND  
SATELLITE MEASUREMENTS OF TERRAIN REFLECTANCE

Laboratory Reflectance Data from a Beckman DK-2A

Percent Reflectance and 95 percent confidence ellipses for four materials - TM4 over TM3 . . . .	21
Percent Reflectance and 95 percent confidence ellipses for four materials - TM5 over TM3 . . . .	22
Percent Reflectance and 95 percent confidence ellipses for four materials - TM5 over TM4 . . . .	23

Ground Reflectance Data from a Tucker 3-band Radiometer

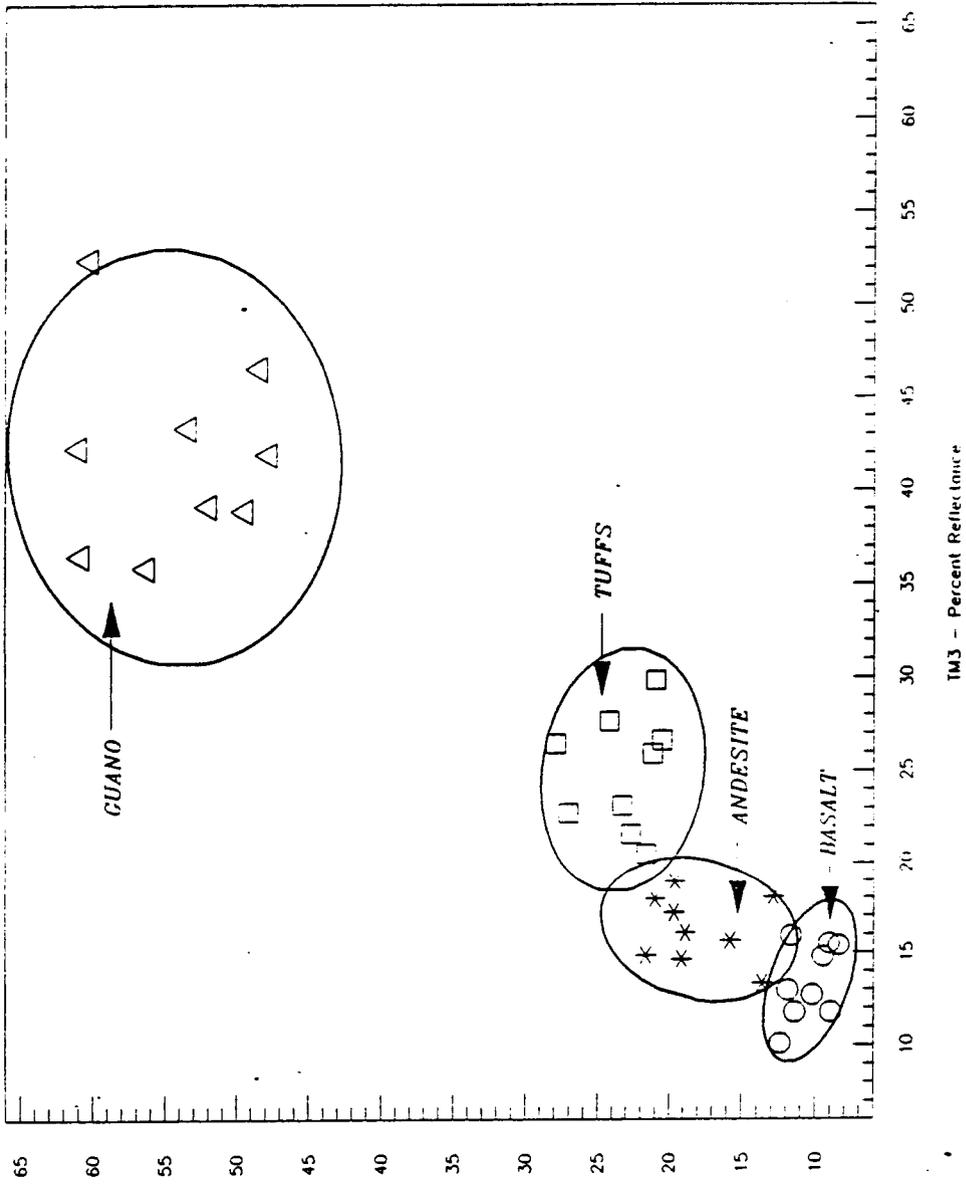
95 percent confidence ellipses for four materials measured at Cape Crozier - TM4 over TM3 . . . .	24
95 percent confidence ellipses for four materials measured at Cape Crozier - TM5 over TM3 . . . .	25
95 percent confidence ellipses for four materials measured at Cape Crozier - TM5 over TM4 . . . .	26

TM Brightness (DN) Values on 26 January 1985

TM2 over TM1 and TM3 over TM1 . . . . .	27
TM4 over TM1 and TM5 over TM1 . . . . .	28
TM6 over TM1 and TM7 over TM1 . . . . .	29
TM3 over TM2 and TM4 over TM2 . . . . .	30
TM5 over TM2 and TM6 over TM2 . . . . .	31
TM7 over TM2 . . . . .	32
TM4 over TM3 and TM5 over TM3 . . . . .	33
TM6 over TM3 and TM7 over TM3 . . . . .	34
TM5 over TM4 and TM6 over TM4 . . . . .	35
TM7 over TM4 . . . . .	36
TM6 over TM5 and TM7 over TM5 . . . . .	37
TM7 over TM6 . . . . .	38

LABORATORY REFLECTANCE DATA  
PLOT OF TM4•TM3

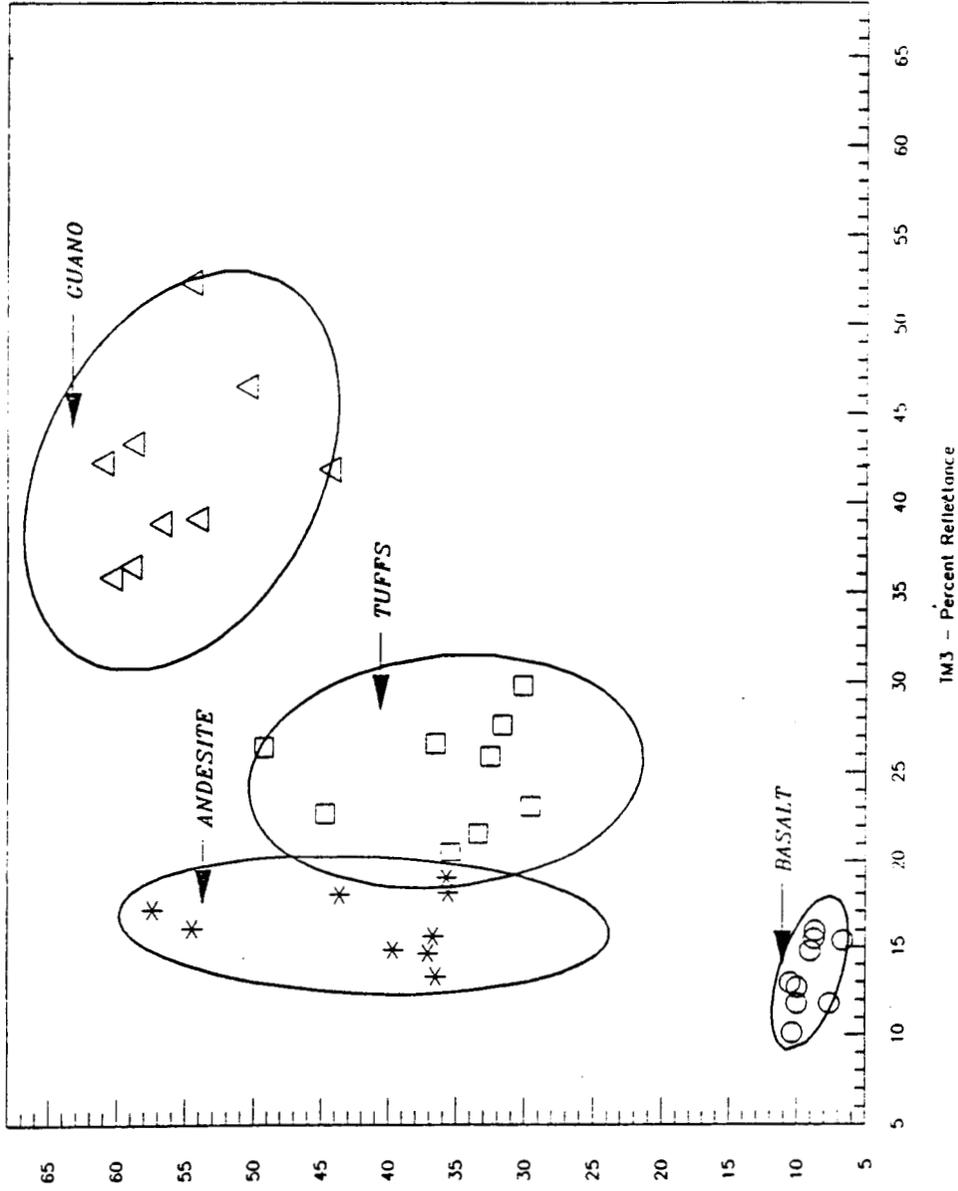
TM4 - Percent Reflectance



Prepared by M. R. Schwaller at NASA Goddard Space Flight Center

LABORATORY REFLECTANCE DATA  
PLOT OF IM5\*IM3

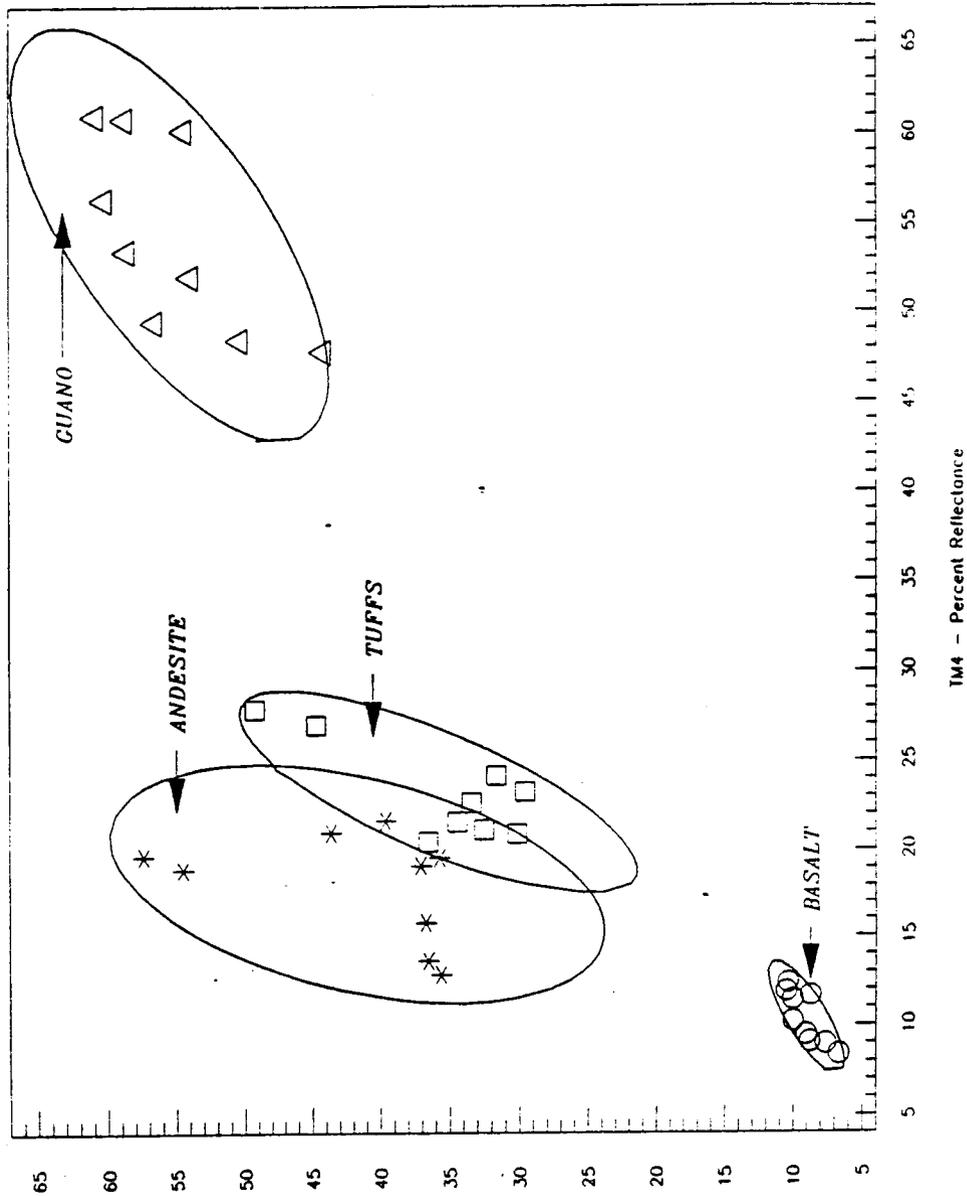
IM5 - Percent Reflectance



Prepared by M. R. Schwaller at NASA Goddard Space Flight Center

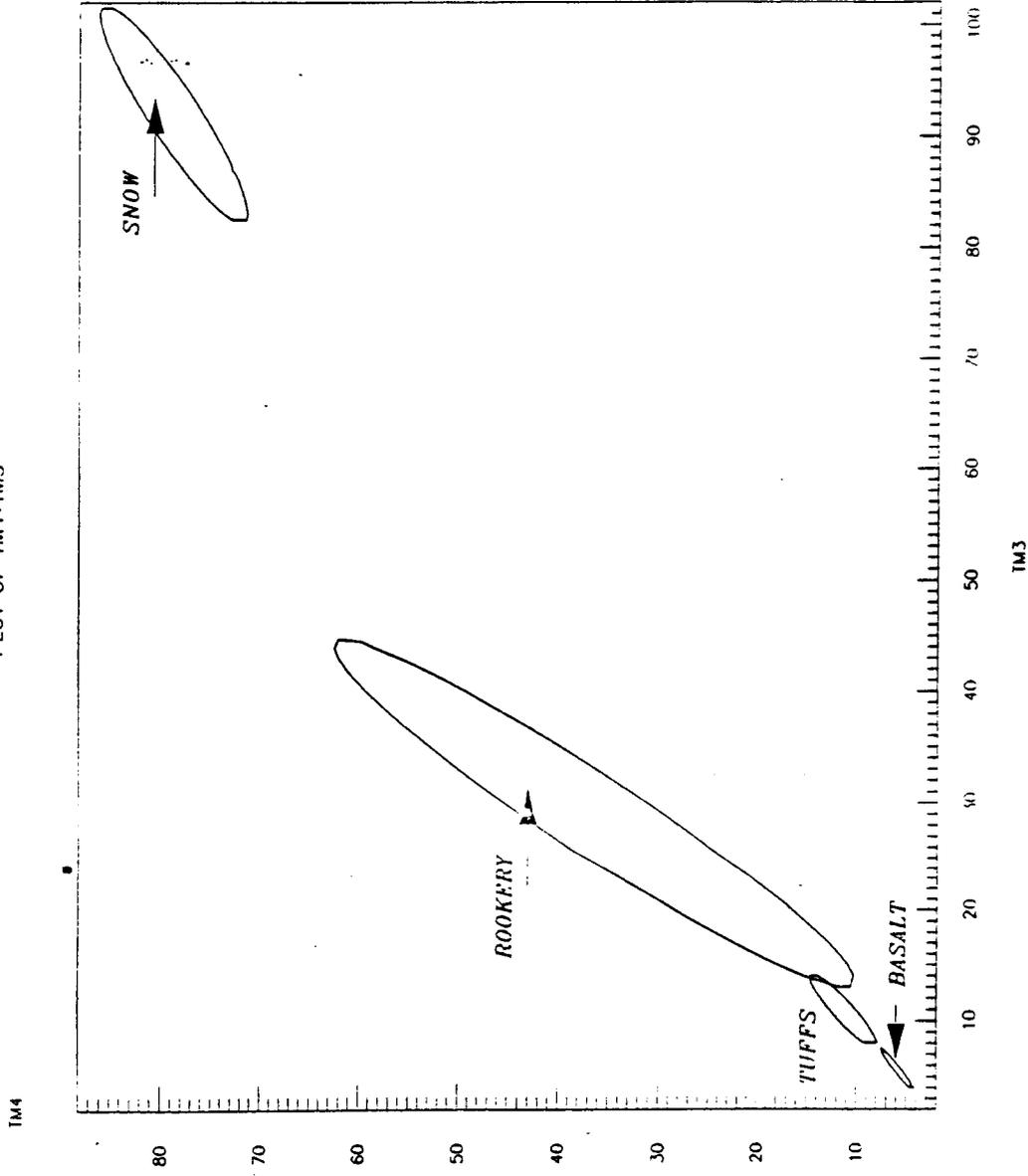
LABORATORY REFLECTANCE DATA  
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TMS - Percent Reflectance



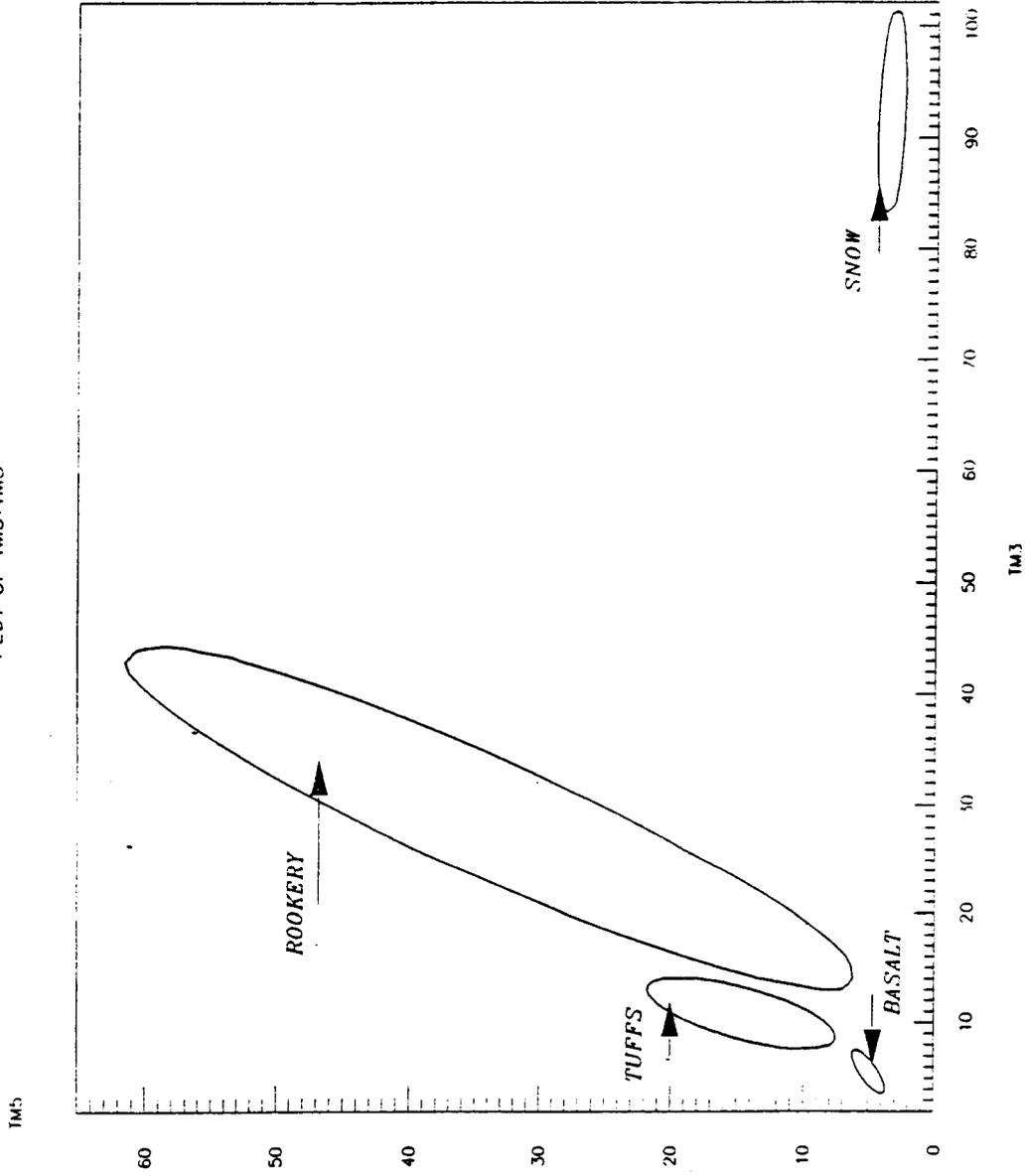
Prepared by M. R. Schwaller at NASA Goddard Space Flight Center

GROUND REFLECTANCE SAMPLES  
PLOT OF TM4+TM3



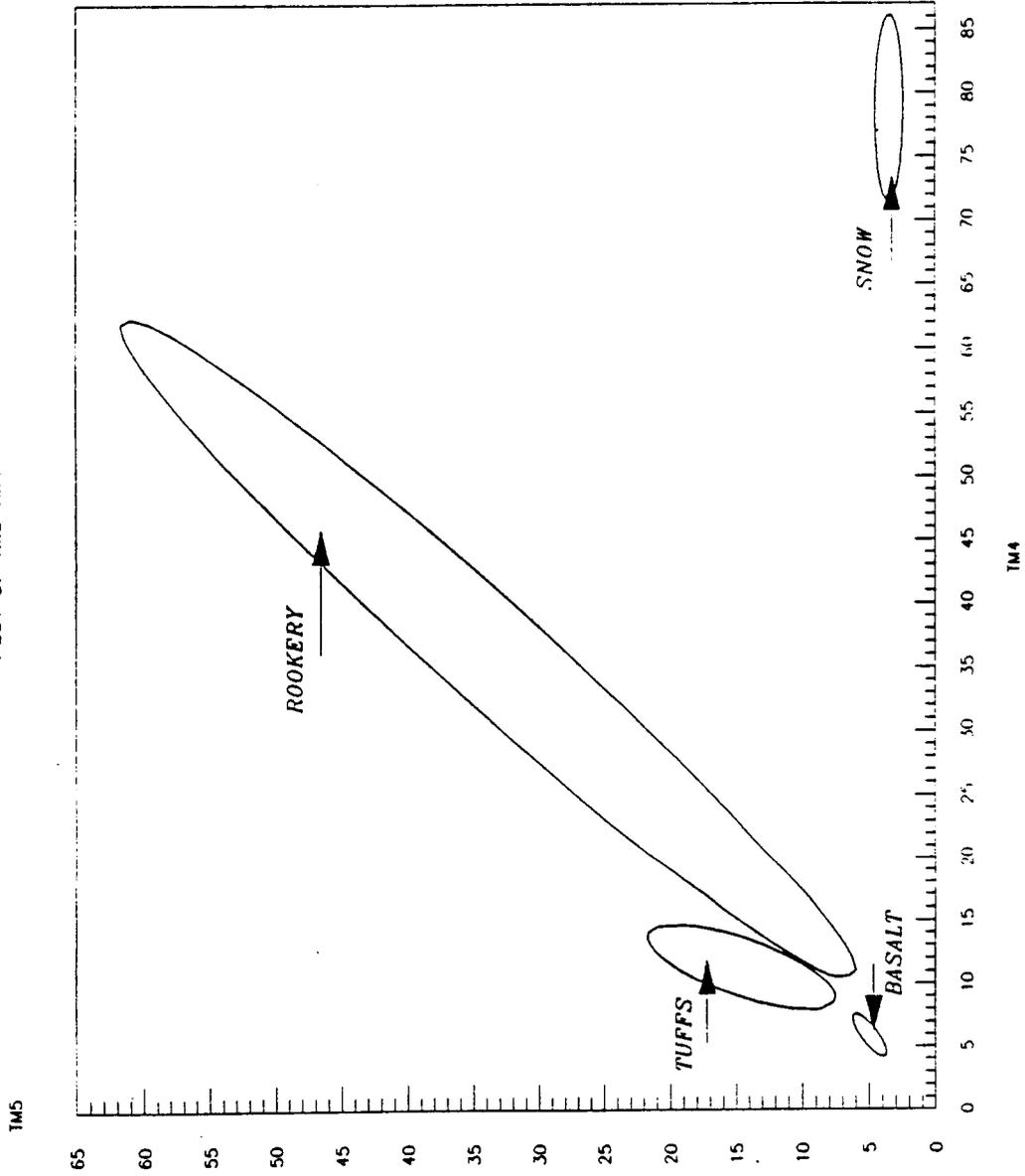
Prepared by M. R. Schwaller at NASA Goddard Space Flight Center

GROUND REFLECTANCE SAMPLES  
PLOT OF TM5•TM3



Prepared by M. R. Schwaller at NASA Goddard Space Flight Center

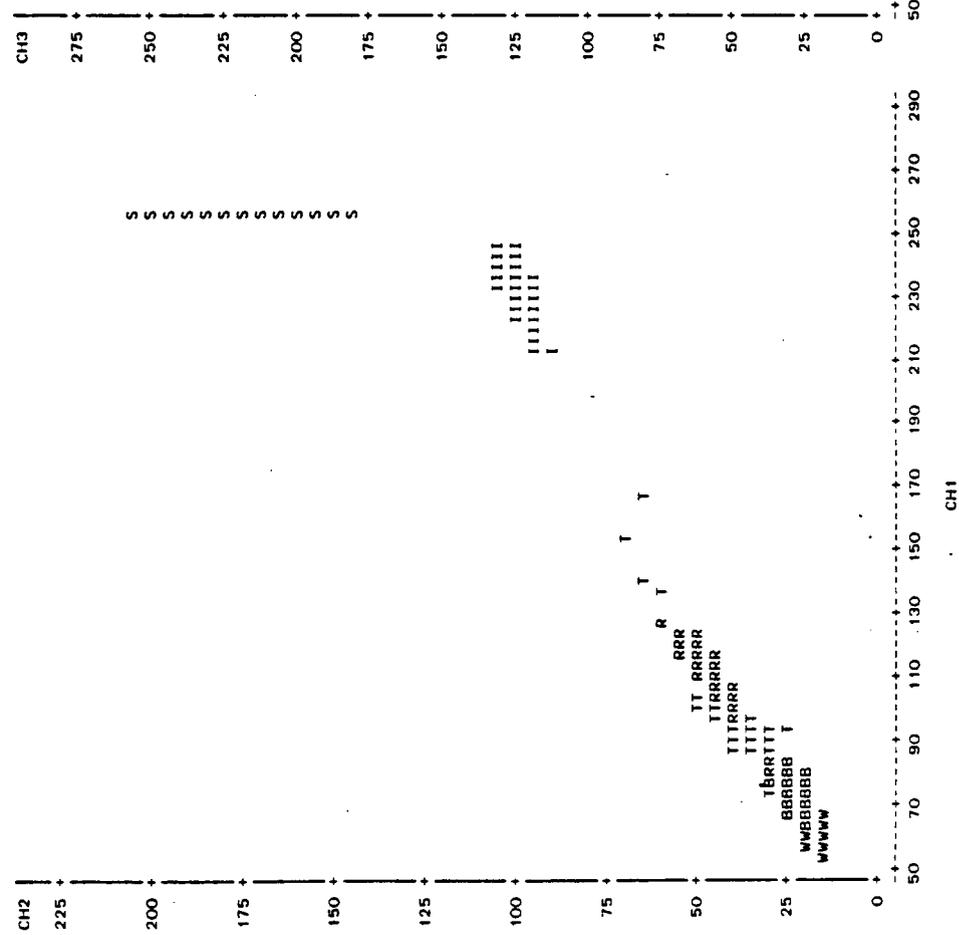
GROUND REFLECTANCE SAMPLES  
PLOT OF TM5\*TM4



Prepared by M. R. Schwaller at NASA Goddard Space Flight Center

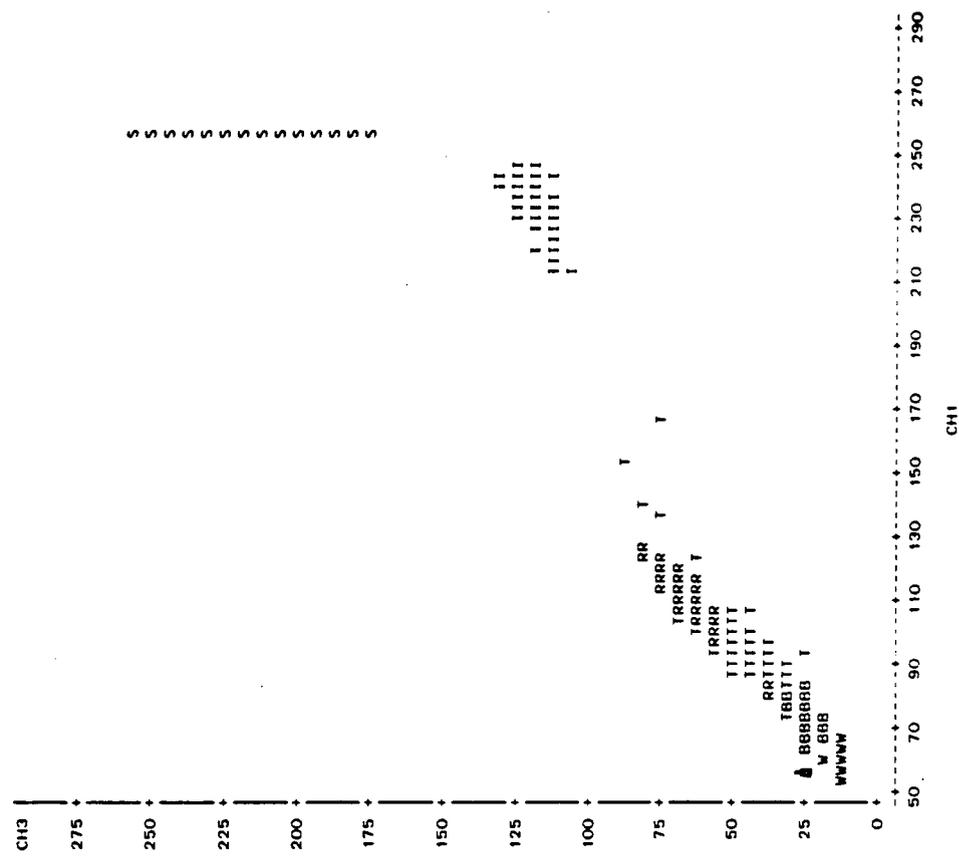
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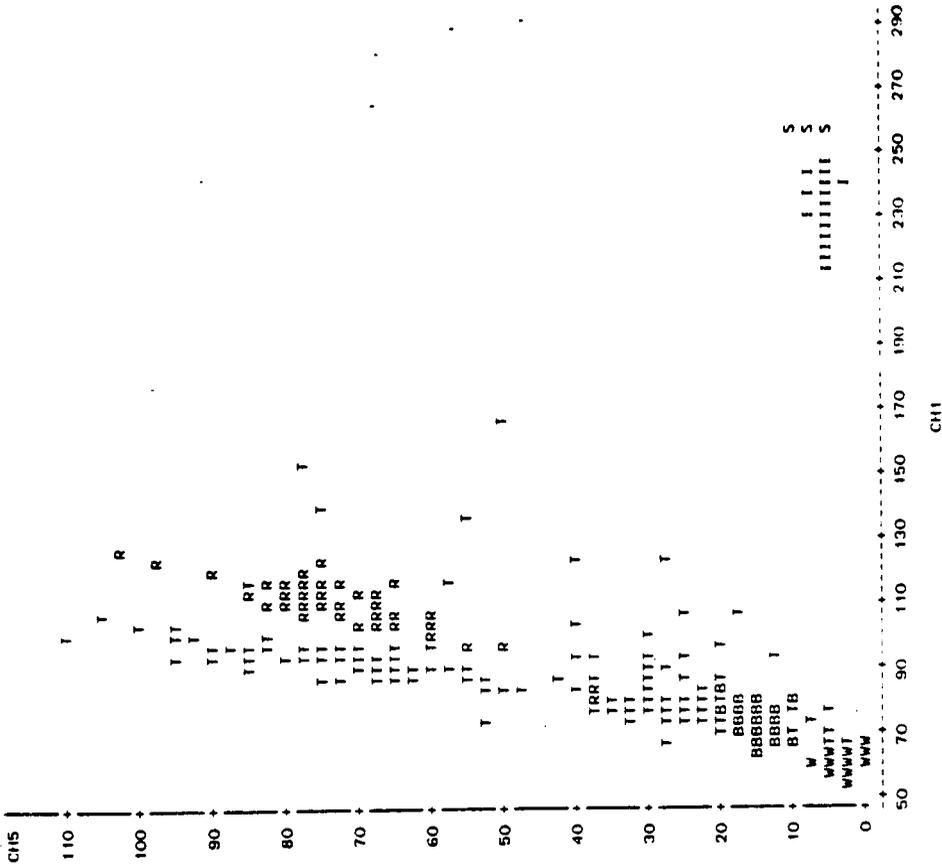
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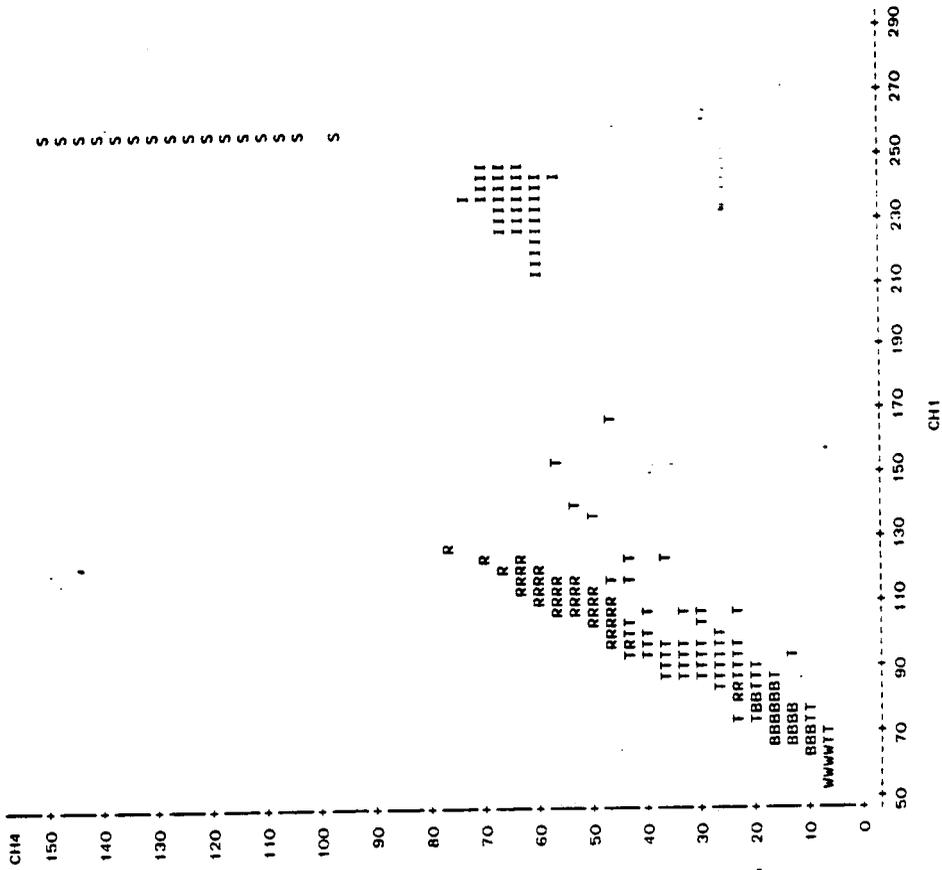
Prepared by Z. K. Ma at the University of Michigan

SAS  
 PLOT OF CH5\*CHI SYMBOL IS VALUE OF TARGET



NOTE: 600 OBS HIDDEN

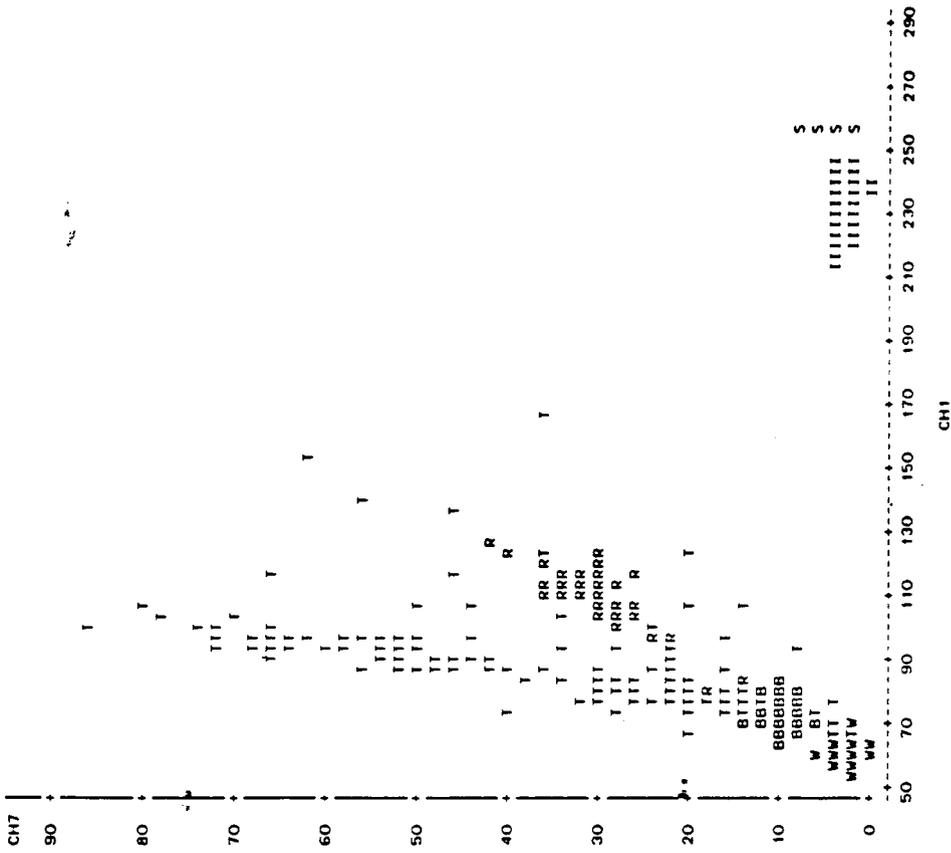
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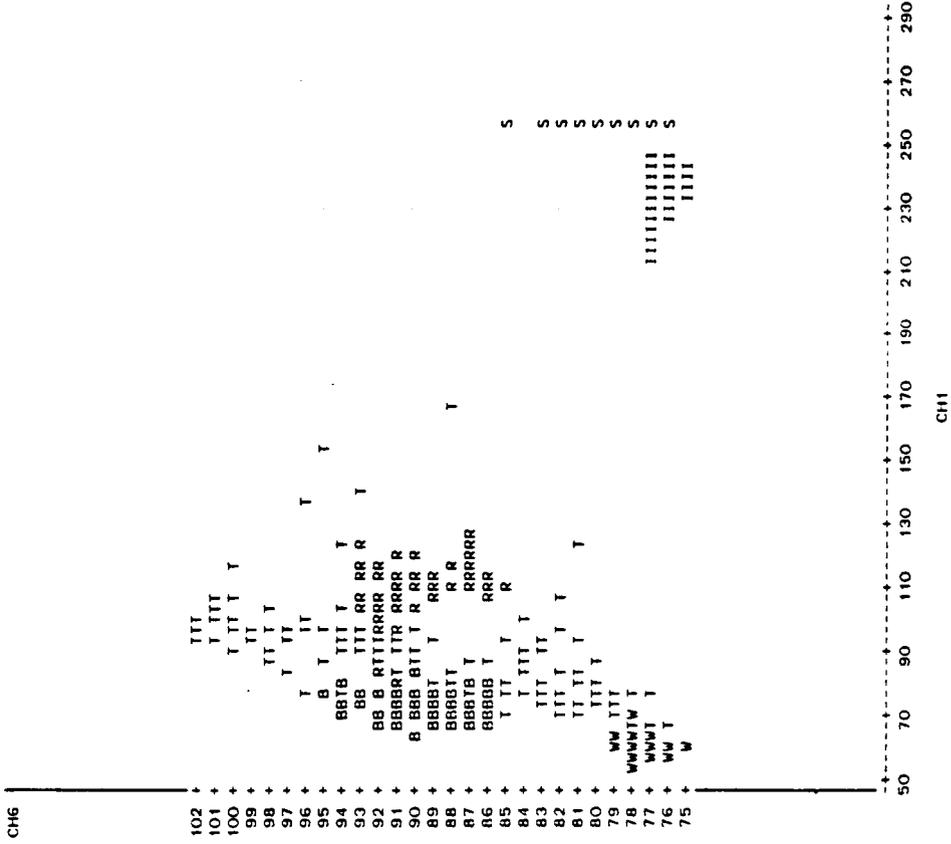
NOTE: 638 OBS HIDDEN

Prepared by Z. K. Ma at the University of Michigan

SAS  
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SAS  
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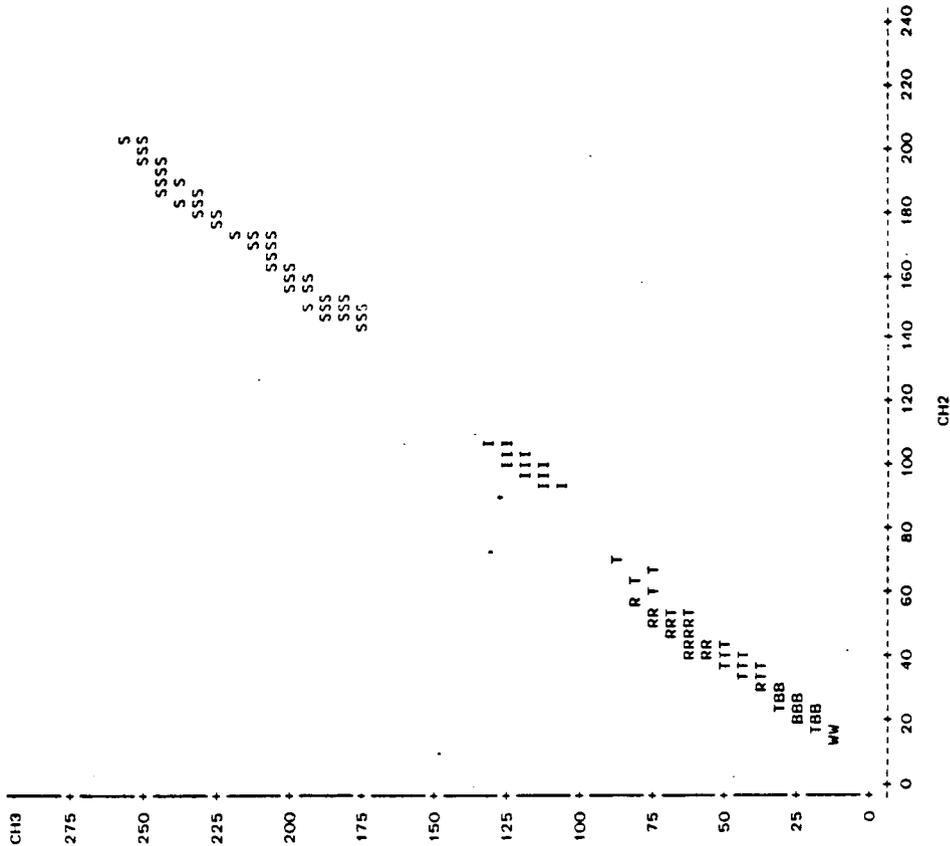
NOTE: 602 OBS HIDDEN

NOTE: 576 OBS HIDDEN

Prepared by Z. K. Ma at the University of Michigan

SAS

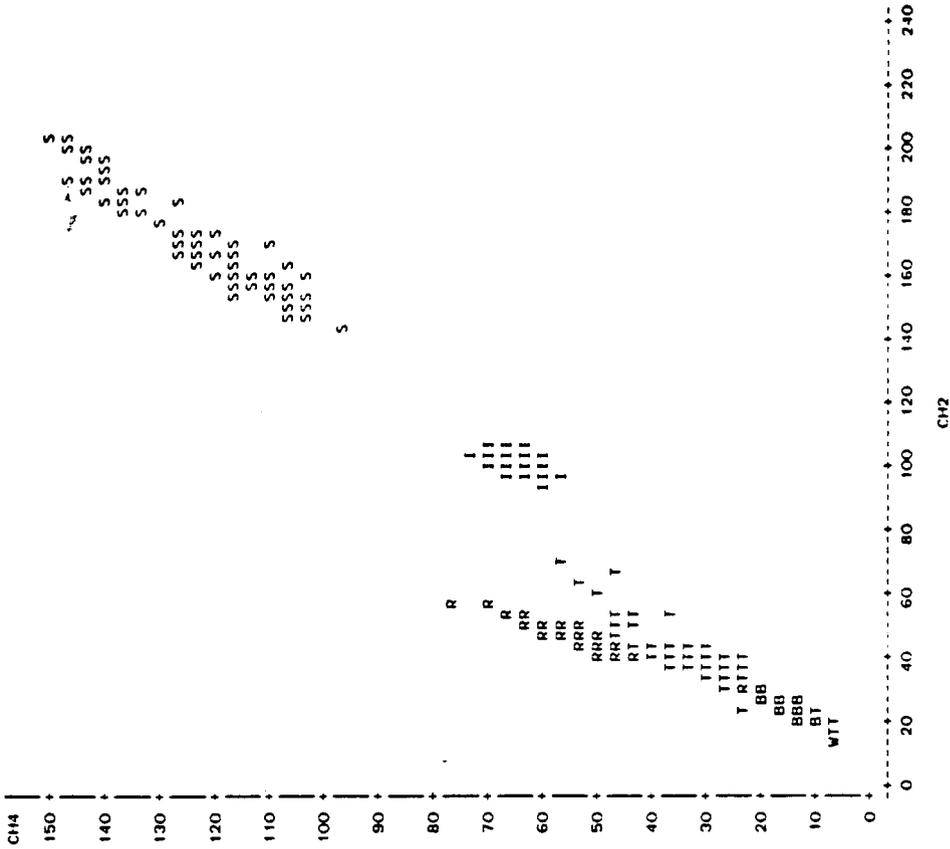
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NOTE: 701 OBS HIDDEN

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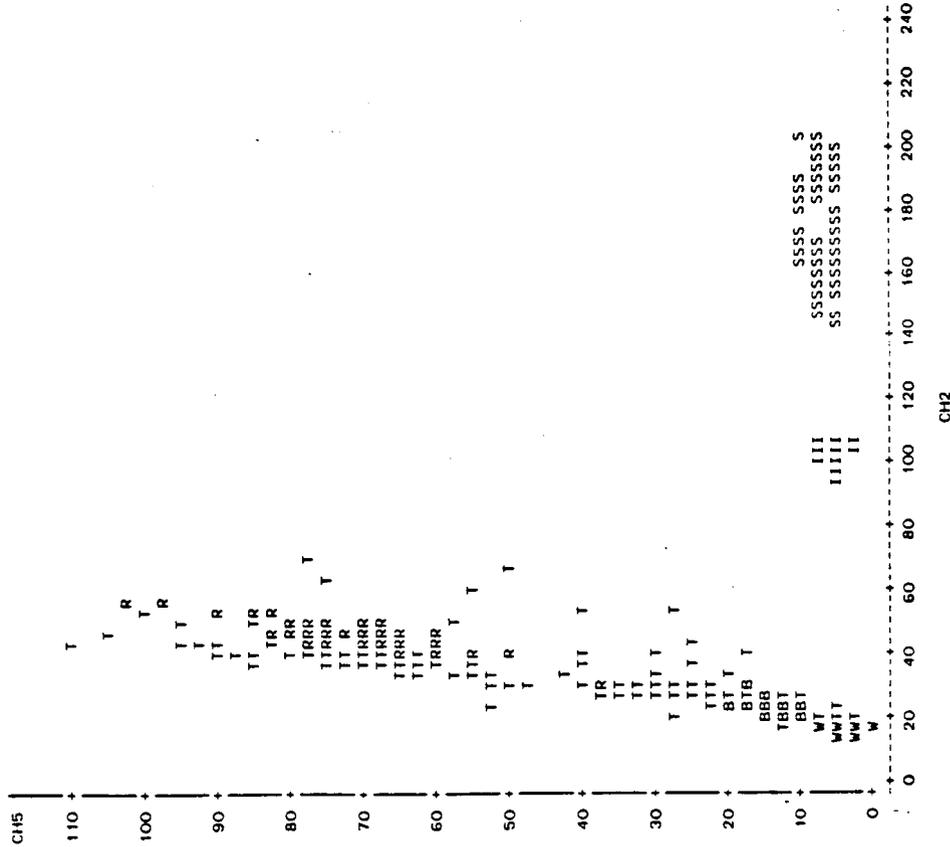
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NOTE: 656 OBS HIDDEN

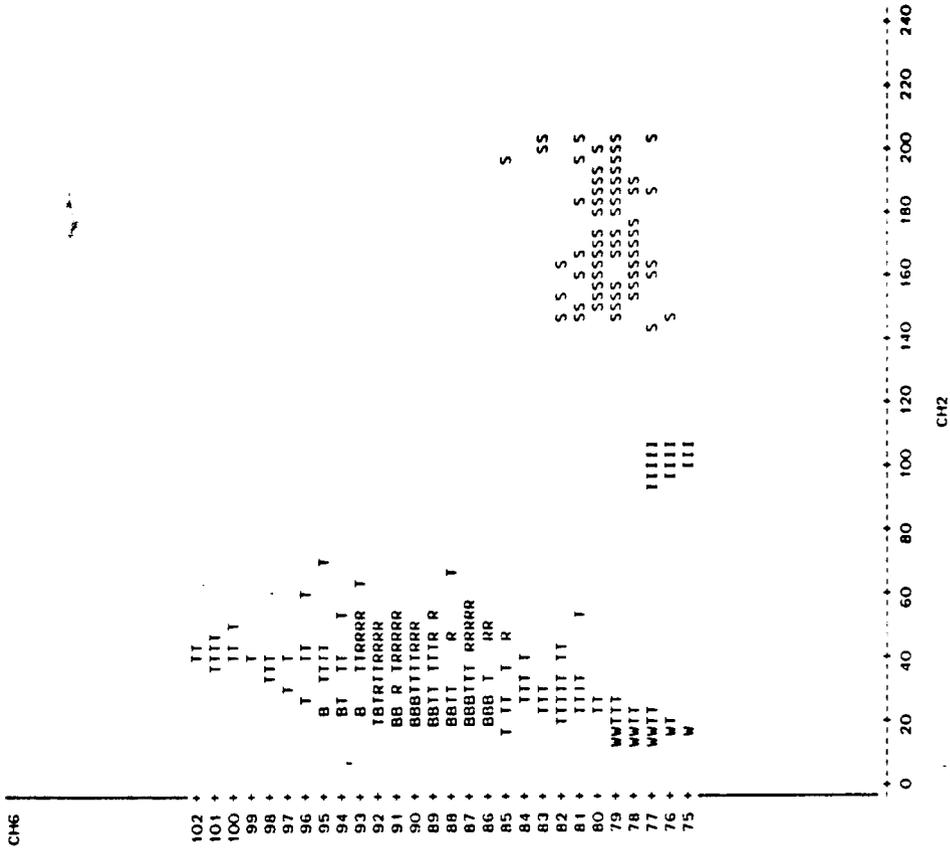
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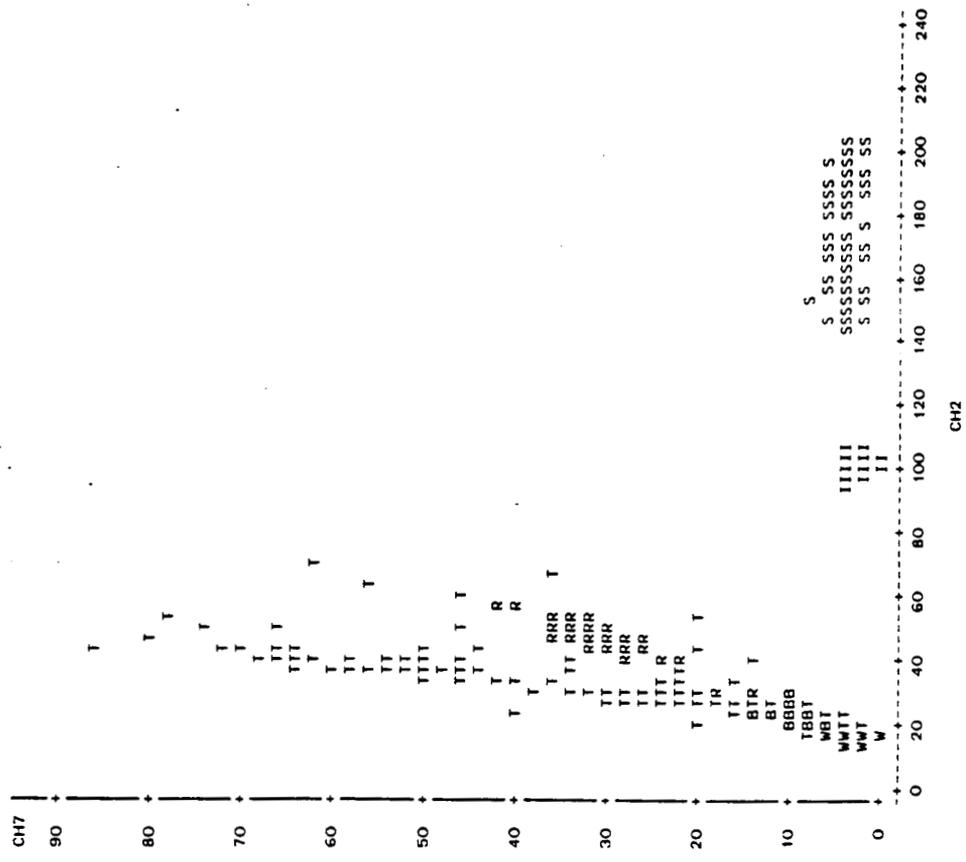


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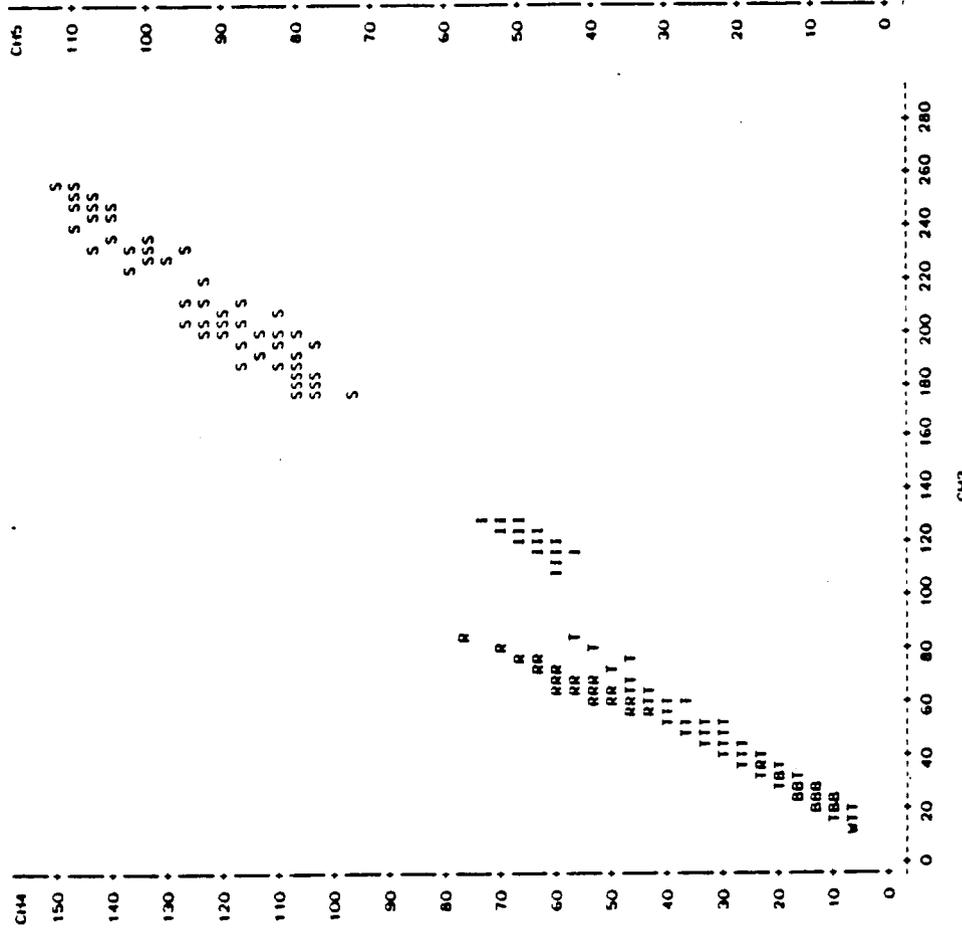
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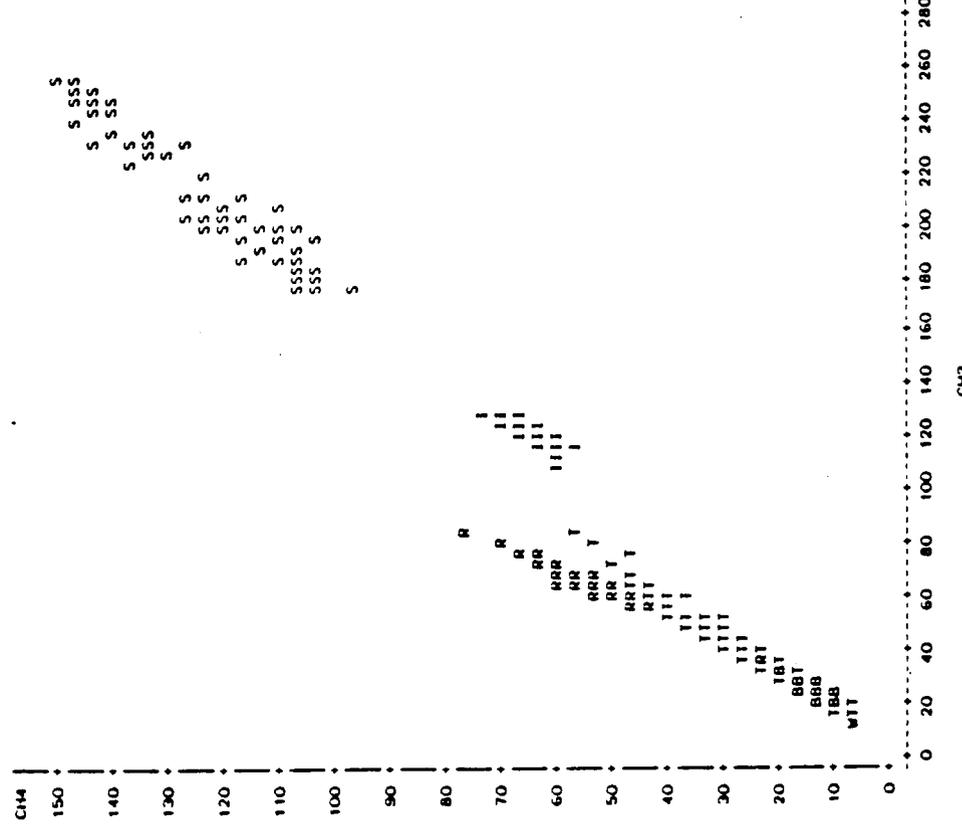
NOTE: 618 OBS HIDDEN

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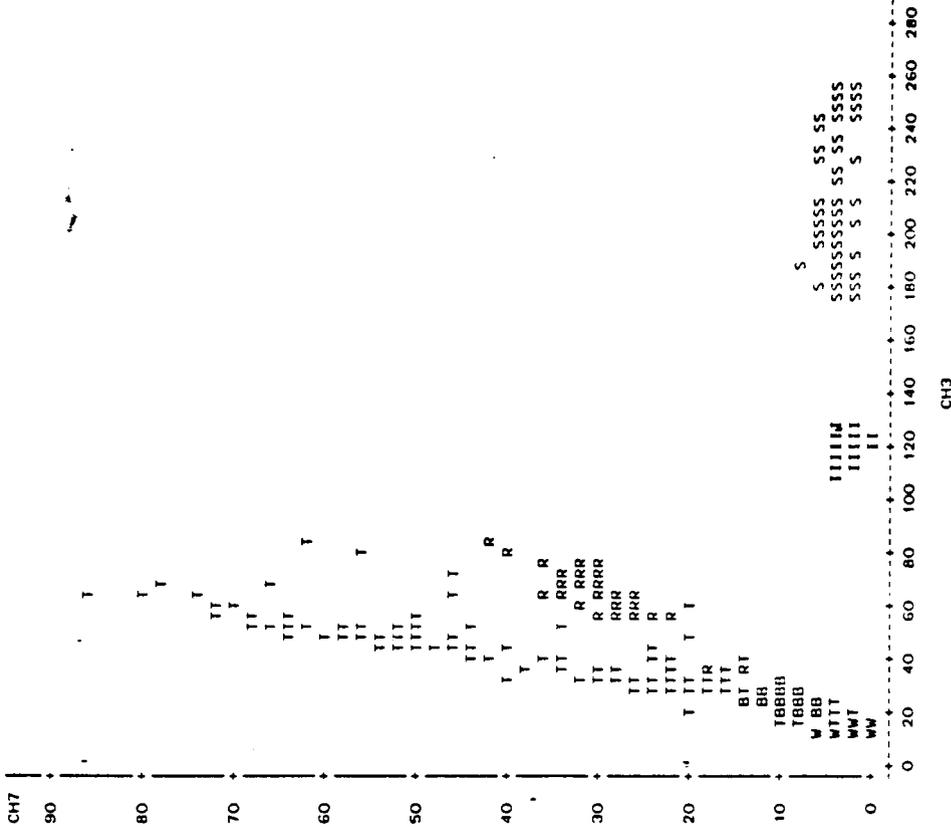


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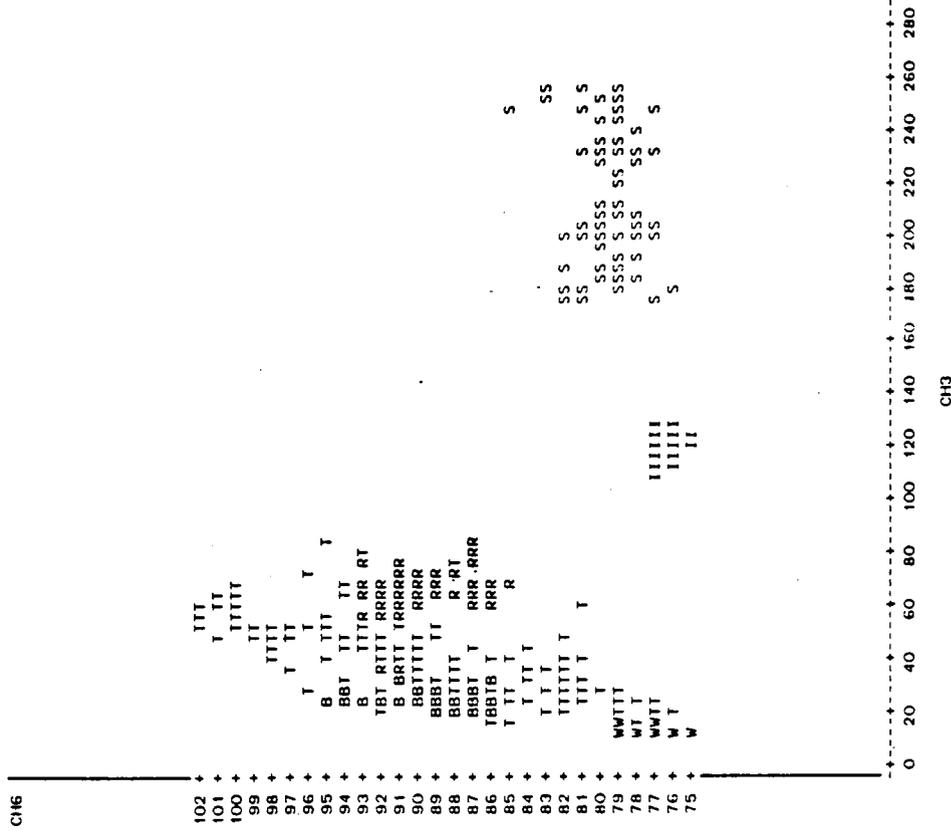


Prepared by Z. K. Ma at the University of Michigan

SAS  
PLOT OF CH7\*CH3 SYMBOL IS VALUE OF TARGET

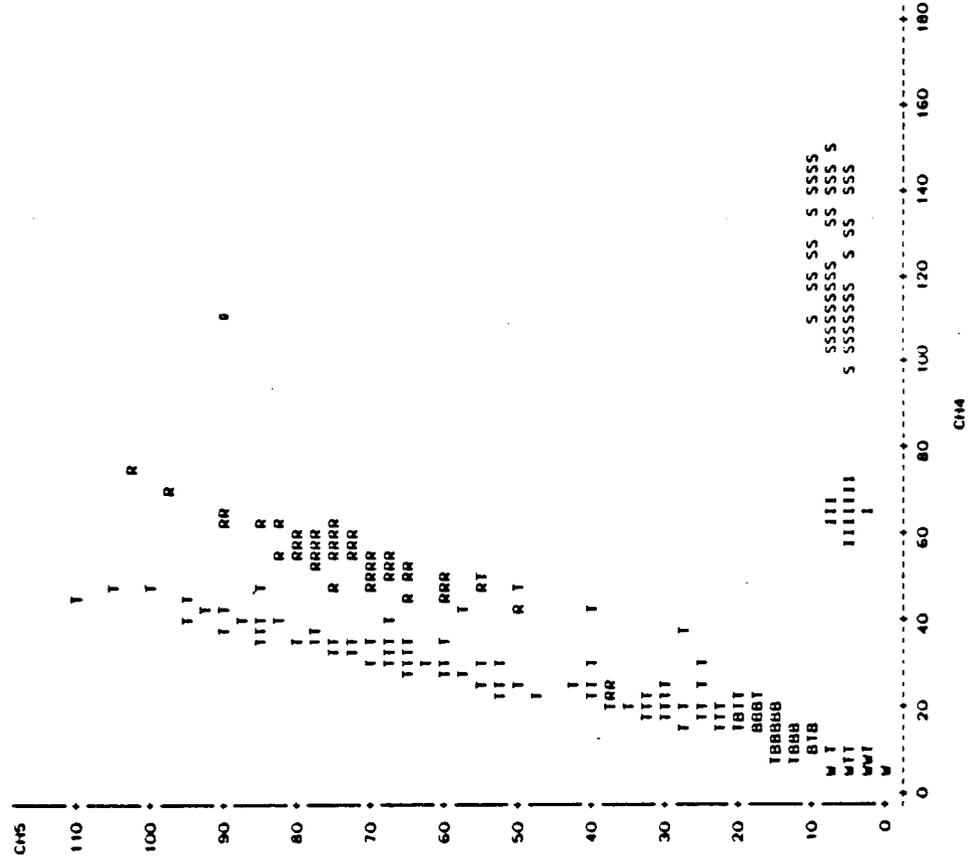


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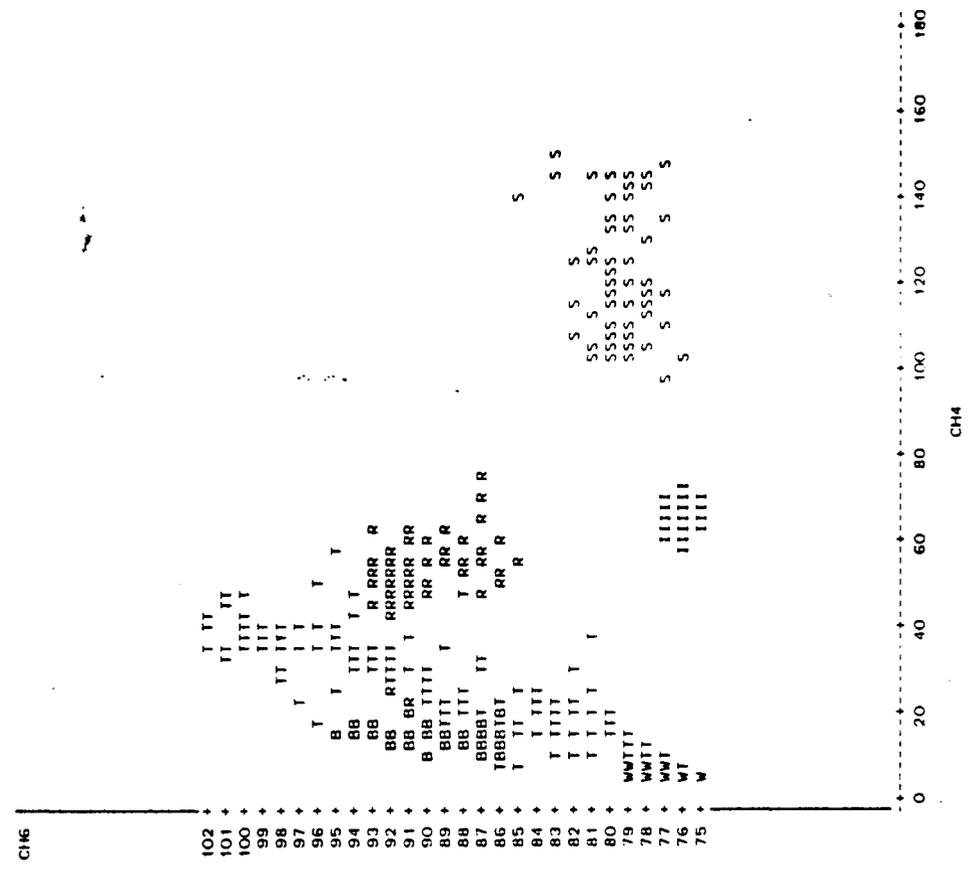
Prepared by Z. K. Ma at the University of Michigan

SMS  
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NOTE: 597 OBS HIDDEN

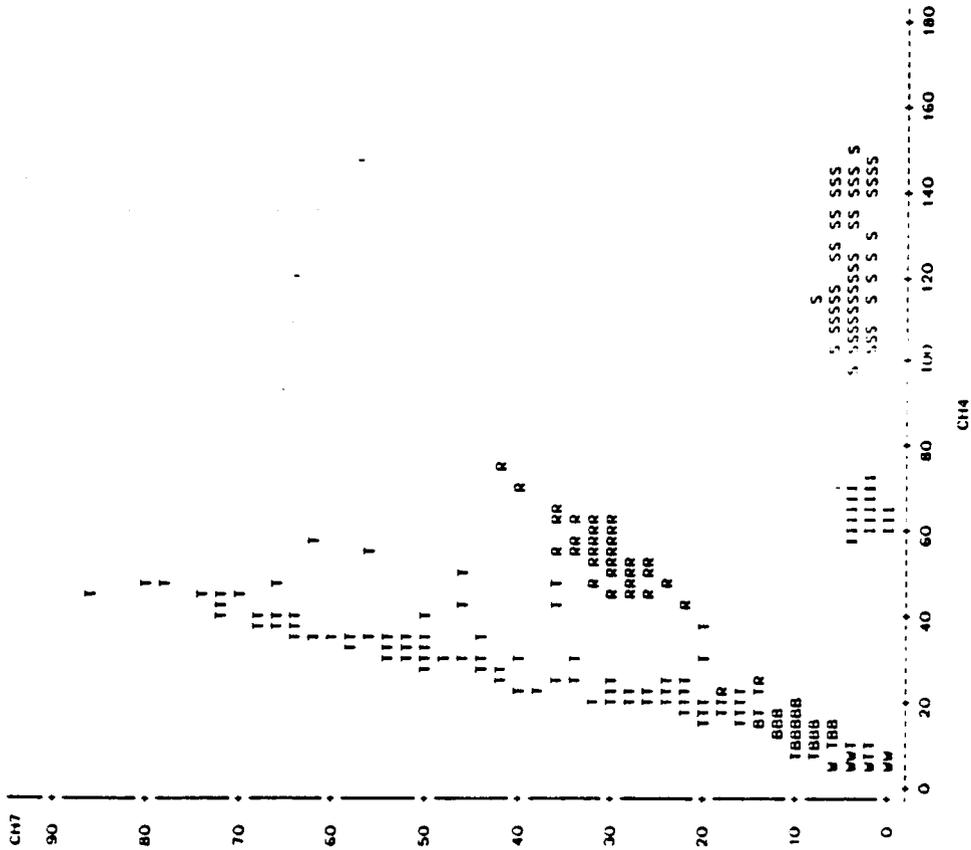
SMS  
 PLOT OF CH6\*CH4 SYMBOL IS VALUE OF TARGET



NOTE: 548 OBS HIDDEN

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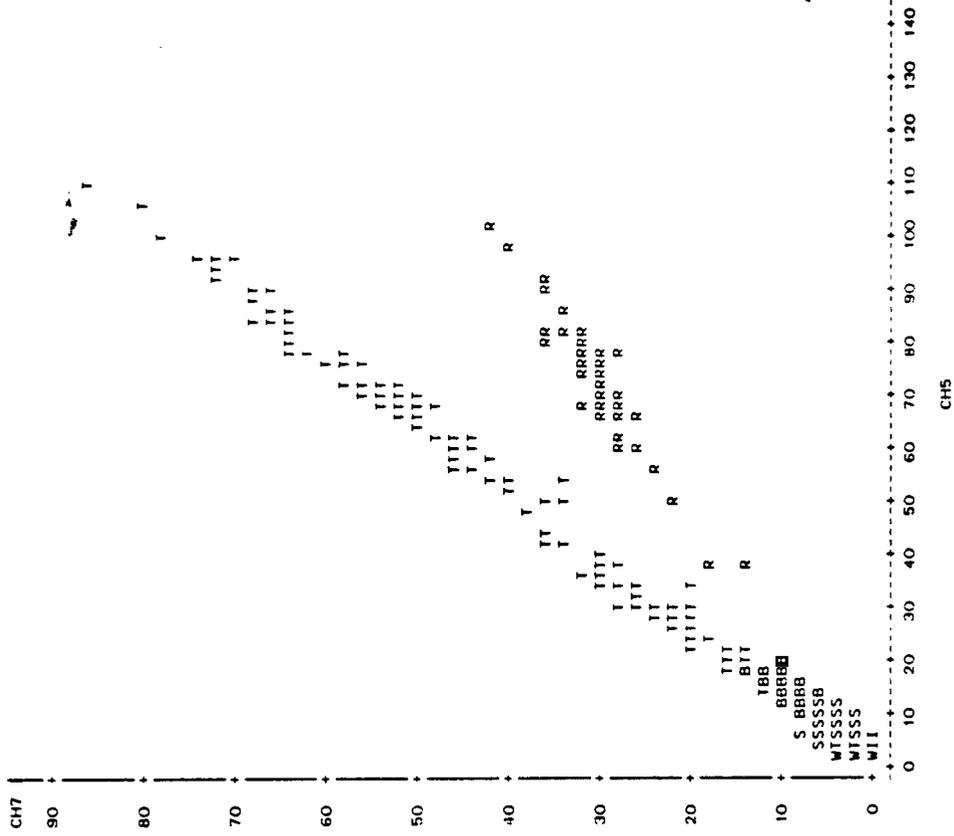
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NOTE: 592 OBS HIDDEN

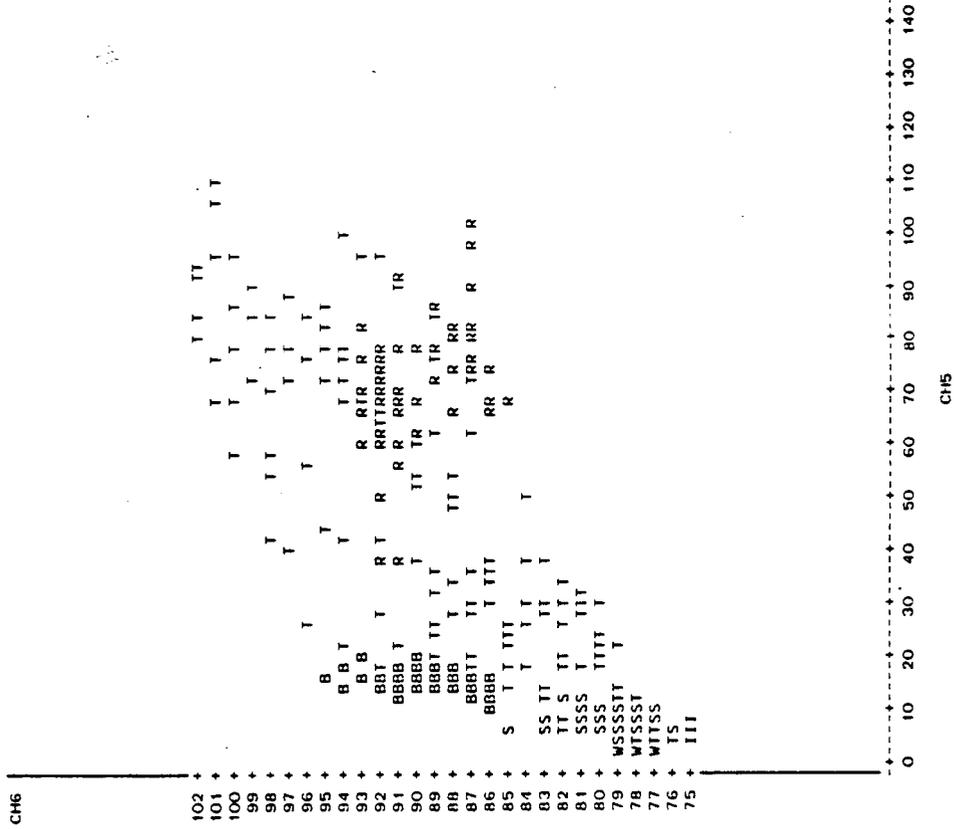
Prepared by Z. K. Ma at the University of Michigan

SAS  
 PLOT OF CH7\*CH5 SYMBOL IS VALUE OF TARGET



NOTE: 633 OBS HIDDEN

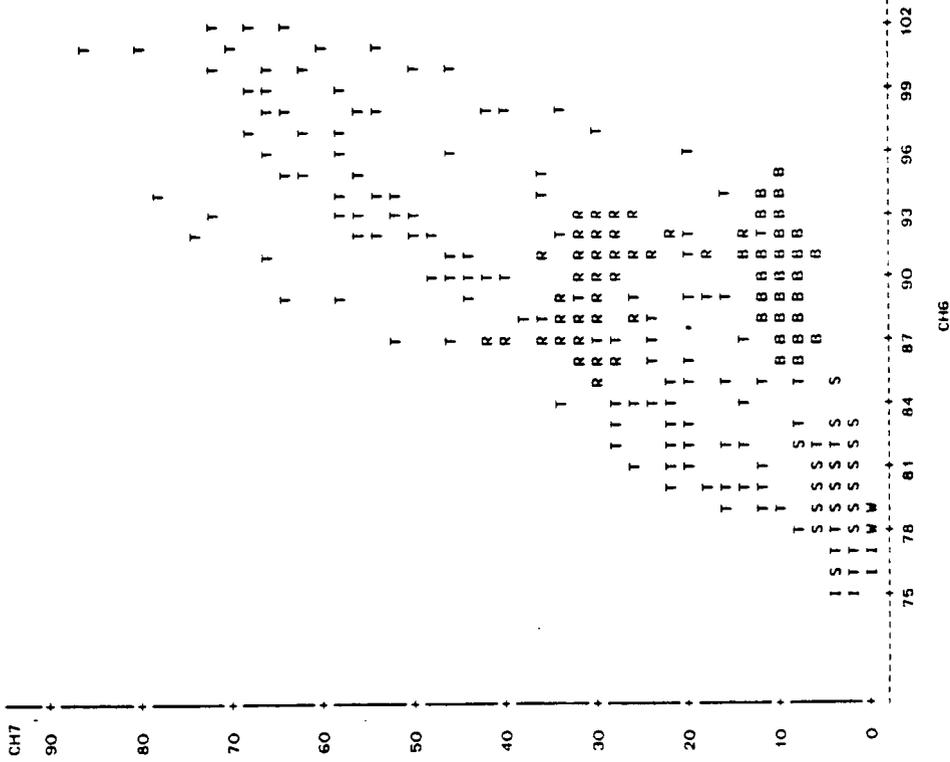
SAS  
 PLOT OF CH6\*CH5 SYMBOL IS VALUE OF TARGET



NOTE: 567 OBS HIDDEN

Prepared by Z. K. Ma at the University of Michigan

SAS  
 PLOT OF CH7\*CH6 SYMBOL IS VALUE OF TARGET



NOTE: 582 OBS HIDDEN

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APPENDIX C. DRAFT COPY OF PAPER SUBMITTED FOR PUBLICATION IN  
THE AUK

"Ratio Estimation of Occupied Nests on Adelie  
Penguin Rookeries"

by

Mathew R. Schwaller

Paul A. Dahmer

Charles E. Olson, Jr.

SAIC

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University of Michigan