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FINAL REPORT

ACCURATE CLOUD COVER DETERMINATION AND ITS EFFECTS ON ALBEDO COMPUTATIONS

OCTOBER 1968

CONTRACT NO.: NAS 5-10478

Prepared by
Allied Research Associates, Inc.
Concord, Massachusetts

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GREENBELT, MARYLAND



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FOREWORD

The research described in this report was performed by the Geophysics and Aerospace Division of Allied Research Associates, Inc., for Goddard Space Flight Center of the National Aeronautics and Space Administration, under Contract No. NAS 5-10478.

The authors wish to acknowledge the technical assistance provided by Mr. Lewis J. Allison, of Goddard Space Flight Center, and the overall guidance given by Mr. Paul E. Sherr, of Allied Research, throughout the performance of the study. This report was prepared with the assistance of Mr. James Pike.

ABSTRACT

The effect of accurate cloud cover determination on computation of the earth's albedo is investigated through utilization of Nimbus II photographic and radiometric data. Satellite observed cloud cover, extracted primarily from APT (Automatic Picture Transmission) photography, is compared with standard surface observations for selected locations in the eastern United States. To determine whether cloud observations from viewed areas of limited size are applicable to albedo computation, a detailed analysis of cloud reflectance, obtained from MRIR (Medium Resolution Infrared) observations, is carried out for areas of uniform cloud cover.

The results of these investigations, for summer cloud cover conditions, indicate that satellite and surface cloud observations are in good agreement when the viewed areas are similar in size. Contrary to earlier results, there is no indication that the satellite significantly underestimates surface observed cloud amounts, except for cirrus cloud. These findings suggest that differences between measured and computed albedo values, particularly in tropical regions, can be attributed to the high albedo values traditionally assigned to cumuliform clouds, rather than to an overestimate of true "earth cover" by the ground observer.

Based on the technique used in this study for the identification of various clouds viewed by the satellite, it appears that unique cloud type signatures can be deduced from the MRIR data. The possible application of these signatures to objective cloud type analysis is discussed.

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1. INTRODUCTION

Until the advent of the meteorological satellite, computations of the earth's albedo were carried out almost solely on the basis of conventional cloud data. Now, the albedo can be measured directly from space, and satellite as well as surface observed cloudiness can be utilized. Suomi (1966), in a study comparing the meridional variation of albedo as measured by TIROS IV and as computed by London (1957), found, however, that the computed values appear too high, particularly for the tropics. While the difference, shown in Figure 1-1, is of the nature of 5%, it implies a difference in heat transport of about 40% between the latitudes of 20N and 20S.

Suomi also discussed further comparisons made between the computed and measured annual meridional variations of albedo. Although these values (Fig. 1-2) must be qualified because the computed albedo was based on annual climatological means and the satellite measurements did not cover a full year, the results are similar to those shown in Figure 1-1.

Similarly, in recent studies of the global radiation balance of the earth-atmosphere system obtained from Nimbus II data, Raschke and Pasternak (1967) found the global average of the albedo to be about 30%. They suggest that other authors who have found a value of about 35% from climatological data might have overestimated the cloudiness, especially in tropical latitudes.

Accurate cloud data are essential not only for albedo computations, but for input to general circulation models and for the development of long-range forecasting methods. Cloud observations from all parts of the earth are also required for various climatological and design studies. One important aspect is the effect of cloudiness on plans for experiments to be carried by manned orbiting research laboratories. In many studies of this type, as by Sherr et al (1968), both satellite and ground observed cloud data must be utilized. In such studies satellite data will be compared with conventionally acquired data to determine the representativeness of the sample, departures from normal, and climatic trends. Meaningful results will be obtained only if the satellite and surface observations form a homogeneous sample.

Several investigators, however, have found that satellite observed cloudiness is generally less than surface observed. In a study using early TIROS data, Clapp (1964) attributed the low TIROS values for small cloud cover to the limited resolving power of the television camera. Because of this, the satellite fails to "see" scattered

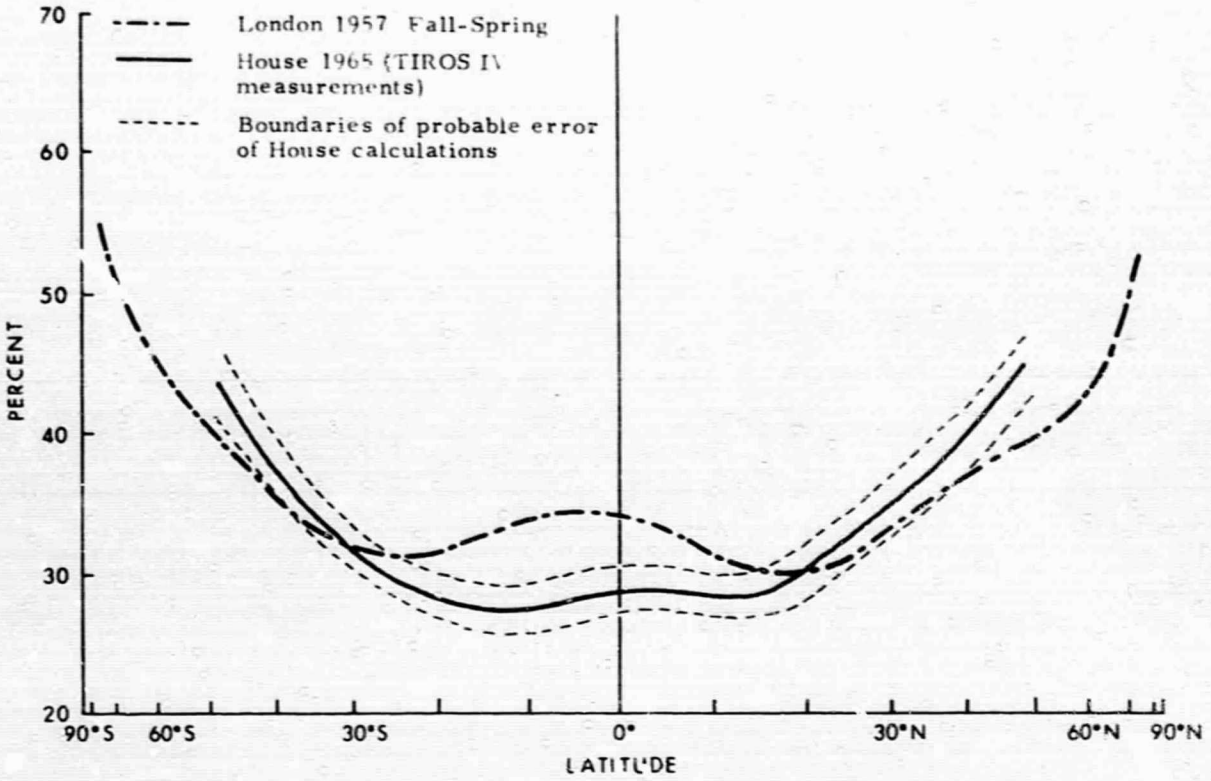


Figure 1-1 Comparison of the Meridional Variation of Albedo for March, April and May (After Suomi, 1966)

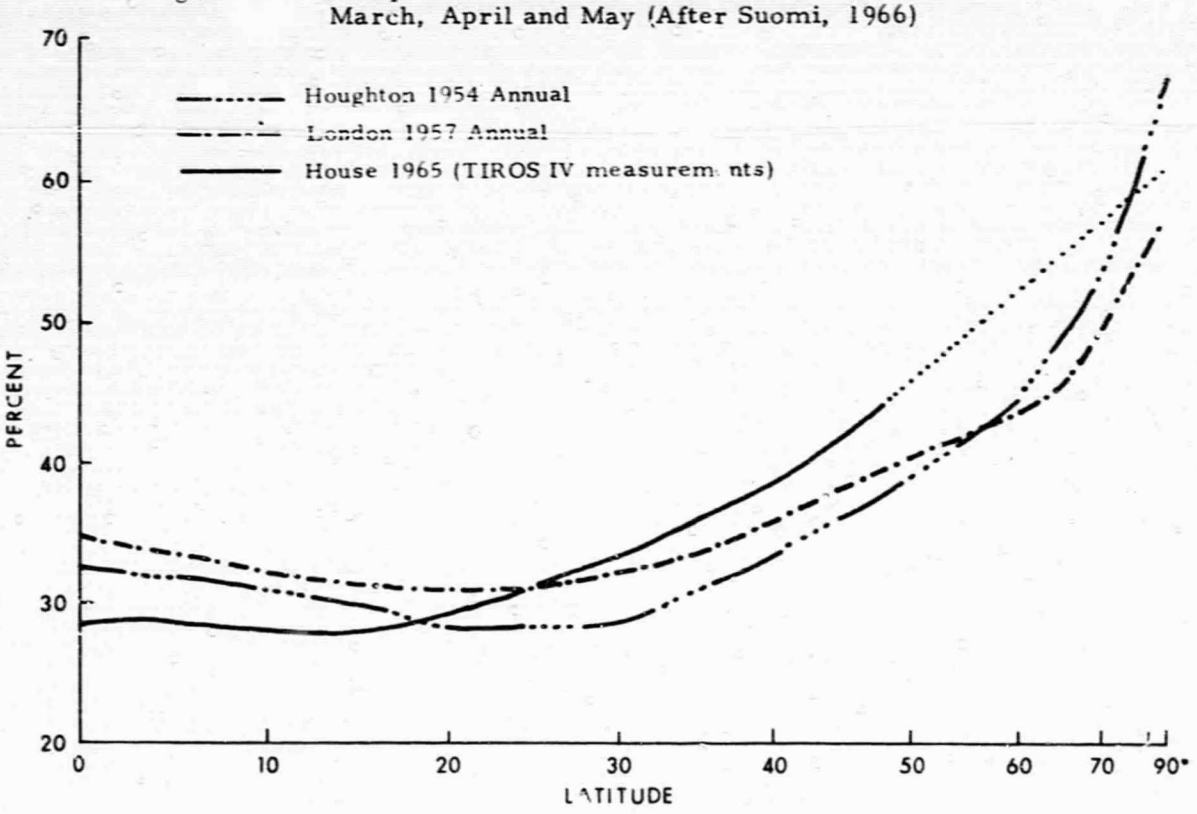


Figure 1-2 Comparison of the Annual Meridional Variation of Albedo (After Suomi, 1966)

clouds of small horizontal scale. Clapp suspected that a similar type of error, but with opposite sign, becomes important when the cloud amount approaches 100 percent, through the satellite's failure to resolve "holes" in the cloud deck.

Studies by Barnes (1966), Barnes et al (1967), and Cooley et al (1967) have found similar discrepancies between satellite and ground viewed cloud amounts. In the latter two studies, the observed differences were greater in areas of predominently cellular (convective) cloudiness.

Based on these studies, it appears that discrepancies between satellite and ground viewed cloudiness are due in part to the inability of the satellite camera systems to resolve small cellular clouds (i.e., satellite underestimate), and in part to the overestimation of cloudiness in surface observations. Clapp (1964), Appleman (1962), and McCabe (1965) have all found indications that ground observers may overestimate cloud cover. In a study to determine clear lines-of-sight through the atmosphere, McCabe stated that, since half the sky dome over which an observer integrates his total sky cover is less than 30° above the horizon, the observer's view is often blocked more by the sides of clouds than by their bases. Lund (1965) has computed the average "earth cover" for Tampa in August, based on a cloud model with typical cloud dimensions. His computed "earth cover" is as much as 40% less than the observed average cloud cover.

In addition to the problems of cloud cover there is the question of the compatibility of the specific albedo values used by London and satellite deduced values. Traditionally, specific values of albedo were obtained over limited areas of uniform cloud cover or surface material by devices on balloons or aircraft. However, the satellite measurements, such as those made by the scanning radiometer of TIROS, were obtained by narrow beam sensors which at any given instance can only measure the incident solar radiation reflected in a given direction. The ratio of this measured quantity to that which is incident on the surface has now come to be known as bidirectional reflectance. For a Lambertian surface, the bidirectional reflectance is independent of the angle of the incident solar radiation and of the angle of measurement. For such a surface, the albedo can be determined from a single measurement of bidirectional reflectance. For non-Lambertian surfaces, however, the bidirectional reflectance is a function of the geometry of illumination and of sensor orientation, and the albedo can only be computed if these functional dependences are known.

Subsequent to the initiation of this study, Sparkman and Cherrix (1967), Bartman (1967) and others have obtained bidirectional reflectance measurements from aircraft and balloon platforms, which demonstrate the anisotropic reflective properties of clouds. These measurements essentially confirm the theoretical calculations of Diermendjian (1964). At small scattering angles near the forward direction, which would correspond to conditions of low solar elevation angles, the bidirectional reflectance of clouds becomes highly anisotropic. These results show that the assumption of isotropy is not correct, and discrepancies between the satellite deduced albedos and the values computed by London should be expected. However, anisotropic effects cannot explain the systematic latitudinal dependence of this difference, which may be due to the improper application of albedo values obtained over individual and uniform cloud elements to the larger scale problem of planetary albedo.

Based on the results of these previous studies, which have indicated discrepancies between satellite and surface viewed cloudiness and between measured and computed albedo values, the general approach to the study discussed in this report consisted of: (1) an extensive comparison between satellite and surface cloud observations for selected locations corresponding to surface reporting stations, and (2) a detailed analysis of cloud reflectance by cloud type over selected areas of uniform cloud cover. Photographic and radiometric data from the Nimbus II meteorological satellite were utilized to carry out these investigations.

The objective of the single station cloud cover analysis was to determine whether significant differences do exist between cloudiness as viewed from space and from the ground, and if so, can these differences be attributed to cloud type or cloud amount. The objective of the cloud reflectance analysis was to investigate the reflective properties of the various types of cloud cover and surfaces at a scale commensurate with planetary albedo studies. The emphasis of these investigations, therefore, was nc. on individual cloud elements but on regions reporting uniform cloud cover.

2. SUMMARY OF RESULTS

2.1 Single Station Cloud Cover Analysis

The results of the analysis of satellite and surface observed cloudiness carried out for selected locations corresponding to reporting stations indicated that the overall agreement between cloud amounts as observed from space and from the ground is good when the viewed area sizes are similar. Contrary to earlier results, there was no indication that the satellite significantly underestimates surface observed cloudiness, except for thin cirrus cloud. It appears, therefore, that discrepancies between measured and computed albedo values in tropical regions cannot be attributed solely to the overestimation of cloud amounts by ground observers.

A total of 13 samples, stratified according to cloud type and cloud amount, were analyzed. Each sample contained at least 20 observations, with some containing more than a hundred. In all, some 50 separate tests were carried out. The procedures and results of these analyses, which are applicable to the summer season, are discussed in detail in Sections 4 and 5. Overall conclusion, based on these analyses and the reflectance analyses discussed below, are presented in Section 8.

2.1.1 Viewed Area Size and Type of Measurement

The correlation between satellite and surface observed cloud amount was highest when the satellite data were extracted from a circular area of 1/2 degree latitude diameter (30 n. mi.). Data extracted from a 1 degree area agreed better with the surface observations than that from a 1/2 degree area only for samples of cirrus cloud; when these high clouds exist, the field of view from the ground is larger. The correlations obtained when the satellite data were read from 2 and 3 degree area sizes were poor.

The satellite observed cloud amount was compared with the surface observed "total" cloud amount and with the surface observed "total opaque" cloud amount. The correlations obtained for the two comparisons were not significantly different.

2.1.2 Samples Stratified by Cloud Amount

A high correlation between satellite and surface viewed cloudiness (satellite data extracted from the 1/2 and 1 degree areas) was found for a sample consisting of "all observations with surface reported cloud amount less than four or greater than seven tenths sky cover." A low correlation was found for a similar sample except consisting of "all observations from four to seven tenths sky cover." Apparently, both the interpreter of the satellite photographs and the observer viewing cloudiness from the ground have difficulty in exactly estimating cloud amounts when the sky cover is near 50 percent. Because of the wide scatter of data points in the latter sample, which strongly influences the linear regression, the correlation coefficient may be the better measure of agreement between the two types of cloud observations.

2.1.3 Samples Stratified By Cloud Type

The cloud type sample for which the poorest overall agreement between satellite and surface observations was observed consisted of cirrus cloud. The results implied that cirrus seen from the ground is often not detected by the satellite.

The overall agreement for cumulus cloud was better than for cirrus. Although there was some indication that the satellite may not always "see" small amounts of cumulus, this effect was considerably less evident than with cirrus cloud. Furthermore, the correlations obtained for a sample of northern stations were only slightly greater than those obtained for a sample of southern stations, where a higher incidence of convectively produced (cumulus) cloud would be expected. Thus, cumulus cloud does not appear to produce as large a discrepancy between satellite and surface observations as does cirrus.

2.1.4 Subjectively Estimated Brightness

Samples of surface reported altocumulus and stratocumulus appeared brightest in the satellite photography. Cumulonimbus cells, although individually very bright, did not appear as bright overall, unless accompanied by altocumulus. Lower brightness values were estimated for samples of surface reported cumulus or cirrus. These brightness values are in good agreement with the values measured in the cloud reflectance analysis. As discussed below, the most significant factor in the observed differences between measured and computed albedos is probably the assignment of cloud reflectance values in the latter.

2.2 Cloud Reflectance Analysis

2.2.1 Cloud Type Identification

For the purpose of albedo evaluation, the identification of cloud type based on ground reports proved to be quite unsatisfactory. For example, in many instances in which stratus was reported, the MRIR (Medium Resolution Infrared) radiometric temperatures were much colder than could be accounted for by the existence of these clouds alone. On the other hand, thin cirrus reported by ground observers often was not obvious in the satellite data. The technique of using satellite, radiosonde and ground observed data was found to be very useful in providing consistent definition of the cloud field. Examples of this technique in "correcting" cloud reports are found in Section 7.

2.2.2 Variability of Cloud Reflectance

The results of the reflectance analyses indicated a high degree of variability in reflectance, and therefore in albedo, not only between different cloud types, but also for clouds of the same type. The degree of variability is the highest for clouds with vertical development such as cumulonimbus and altocumulus. The correspondingly large variations in effective "window" temperature measured by the MRIR Channel 2 (10-11μ) show that the spread in reflectance values is due primarily to variations in cloud thickness. Because of the variation in reflectance values, it is unrealistic to assign a single characteristic albedo to each cloud type.

2.2.3 Reflectances of Clouds

The results obtained in Section 7 show that cumulonimbus, as expected, has the highest reflectance values. High values were also found for stratocumulus and altocumulus. The existence of ice crystals in the upper layers of altocumulus does not substantially increase the reflectance. Furthermore, for thick clouds, such as Cb, Ac and Sc, the albedo of the underlying surface was found to have little or no influence on reflectance of the cloud.

Of the cloud types investigated, the least agreement between the results of this study and past measurements was found for cirrus. Based on analysis of reflectance data alone, it was not always possible to discriminate between cirrus

and clear areas. The results of the analyses for cumulus also indicate that traditional values of albedo for this cloud type appear to be too high. The effect of this discrepancy on albedo computations is discussed in Section 8.

2.2.4 The Use of the Water Vapor Channel in Cloud Discrimination

Data from the water vapor channel of the MRIR were found to provide a useful means of delineating the limits of cloud cover, even for thin tenuous cirrus. Effective temperatures of $< 240^{\circ}K$ were found almost inevitably to be associated with clouds. The possibility of automatic cloud type discrimination based on the analysis of data from this channel and from concurrent reflectance and window channel temperatures is discussed in Section 8.

3. DATA

3.1 Satellite Observations

Photographic and radiometric data from the Nimbus II meteorological satellite, launched on 15 May 1966, were utilized in the study. The Nimbus II AVCS camera system operated until 31 August 1966; the MRIR (Medium Resolution Infrared Radiometer) system operated only until 28 July, a period of slightly over two months. During that period, the MRIR coverage of the eastern United States, the region selected because of the higher density network of surface reporting stations, was more complete during the second month. Therefore, MRIR data were obtained for the periods 2-7 and 15-20 July; during these 12 days, the synoptic situation was sufficiently varied to allow an inclusive sampling of cloud amounts and types. Photographic data were obtained for all days with pictures available during the same periods.

3.1.1 Photographic Data

For initial analyses, AVCS photography was employed. These pictures have a maximum camera resolution of about 0.5 miles, and were available for every day of the selected period. Because of the rather poor picture quality, however, Nimbus II APT (Automatic Picture Transmission) photography was used for most analyses.

Examples of AVCS and APT photography of the eastern United States are presented in Figures 3-1 and 3-2. As can readily be seen, the APT picture quality is outstanding when compared with the AVCS. The vertical light-dark pattern on the AVCS, produced by electronic interference, is particularly troublesome when attempting to identify clouds. Even though the nominal camera resolution of the APT is only two miles, compared to the 1/2 mile resolution of the AVCS, the difference in picture quality is believed to result in similar "effective" resolutions. A comparative analysis of data extracted from the two types of photography is discussed in Section 5.2.

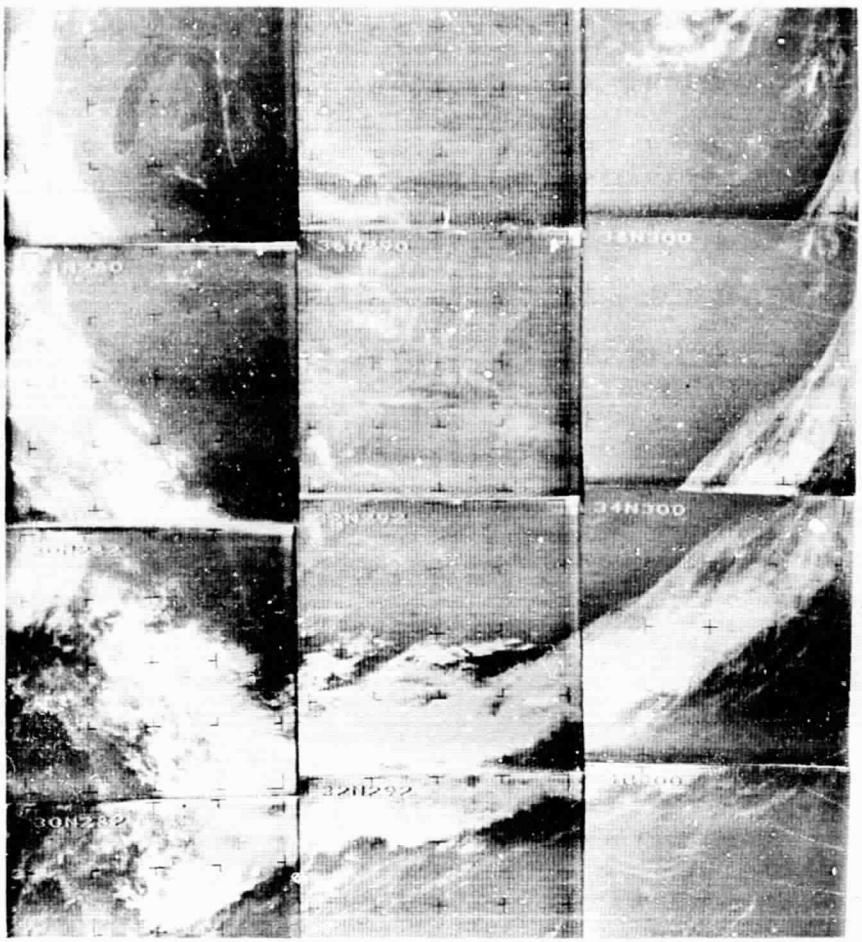


Figure 3-1 Nimbus II AVCS Photography of Northeastern United States; Orbit 830, 16 July 1966

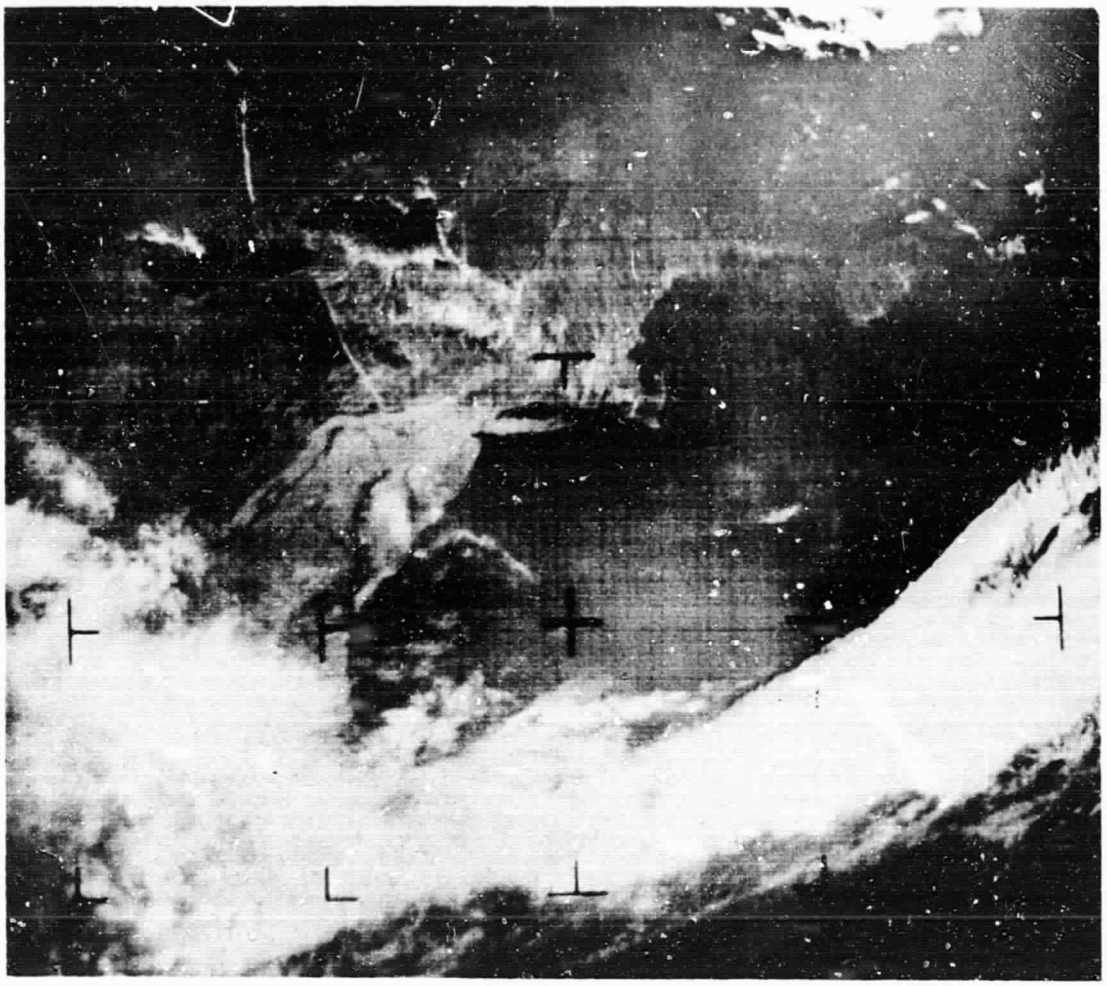


Figure 3-2 Nimbus II APT Photography of Northeastern United States; Orbit 830, 16 July 1966 (Received at Goddard Space Flight Center)

3.1.2 Radiometric Data

The five-channel MRIR radiometer made simultaneous measurements in the following spectral intervals:

Channel No.	Spectral Interval
1	6.4 - 6.9μ
2	10 - 11μ
3	14 - 16μ
4	5 - 30μ
5	0.2 - 4.0μ

All five channels operated through the same set of optics with an instantaneous angular field of view of 5 × 5 milliradians. At the satellite subpoint, corresponding to a zero degree sensor nadir angle, the spatial resolution on the surface of the earth is approximately 60 × 60 km for the nominal orbital altitude of Nimbus. The resolution degrades with increasing nadir angle with the degradation being most rapid at higher nadir angles.

Data from the MRIR are available in a number of formats including a grey scale pictorial presentation in which the data from the five channels are displayed side by side. This format is useful for such qualitative applications as case selection and determination of gross cloud features. More appropriate to detailed analyses are the digital formats, in which grid print maps and data listings are available. For this study, both grid print maps and data listings for the selected orbits were used. The data listings proved to be the most convenient format for the technique of cloud reflectance analysis ultimately adopted. In this format the data from each of the channels are separately listed, together with the sensor nadir angle, latitudinal and longitudinal location of the subsatellite point corresponding to the scan line, and the angular position of the scan.

Analysis of the MRIR data were limited to Channels 1, 2 and 5. The use of Channel 5 is obvious since it provides the reflectance data. Channels 1 and 2 were used in conjunction with ground observations to assist in defining the cloud field.

3.2 Surface Observations

Surface cloud observations as reported at First Order Weather Bureau Stations in the eastern United States were extracted from WBAN 10B forms. On these forms both "total" sky cover and "total opaque" sky cover are reported hourly; a complete cloud observation, including types and heights, is given every three hours.

Since Nimbus passage time was usually between 1100 and 1200 LST, complete cloud data were extracted for 1000 and 1300 EST in eastern sections, and for 0900 and 1200 CST in central sections; cloud amounts were extracted for the hours just before and just after satellite passage. Thus, a cloud amount observation was always available within one-half hour of the satellite observation, and a cloud type observation within one and one-half hours. By considering the surface reports both prior to and after the satellite passage, rapidly changing cloud conditions could be detected.

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4. SINGLE STATION CLOUD COVER ANALYSIS

4.1 Data Extraction Procedures

Cloud data were obtained from satellite photographs for 15 locations corresponding to surface reporting stations. The locations and station call numbers are shown in Figure 4-1. The sample contains northern, southern, coastal, and inland stations.

In the initial analyses, using AVCS photography, data were extracted for circular areas of 1/2, 1, 2, and 3 degree latitude diameter, centered on the station location. These distances correspond to 30, 60, 120, and 180 nautical miles. In the more extensive analyses, using APT photography, data were extracted for only the 1/2 and 1 degree areas. Due to the difference in picture scale on the hard copy prints, a 1 degree circle for the APT was slightly larger than for the AVCS (1 degree on the AVCS ~ 1/4 inch; 1 degree on the APT ~ 3/8 inch). To reduce bias, cloud information for different sized areas was read at different times.

For each location and area size, cloud amount, cloud type, and brightness were recorded for each observation. In addition, information such as picture quality, location confidence, and cloud distribution were noted. Cloud amount was estimated in tenths of the circular area, and brightness was reported in three levels: very bright, moderate or low. Although the cloud cover to the nearest tenth was at times difficult to determine because of the small area sizes, these units were selected to conform with those used in surface observations.

Cloud type definition as detailed as that reported by ground observers is not possible from satellite photographs. In his study of the atmospheric heat balance, London (1957) classified the cloud types into six major groups: (1) Ci (cirrus, cirrostratus, cirrocumulus), (2) As (altostratus, altocumulus), (3) St (stratus, stratocumulus, fractocumulus), (4) Ns (nimbostratus), (5) Cu (cumulus), and (6) Cb (cumulonimbus). To relate as closely as possible to the scheme of London's study, five satellite observed cloud types, as shown in Table 4-1, were defined. Under Category 5, the particular cloud type was noted in the Remarks Column.

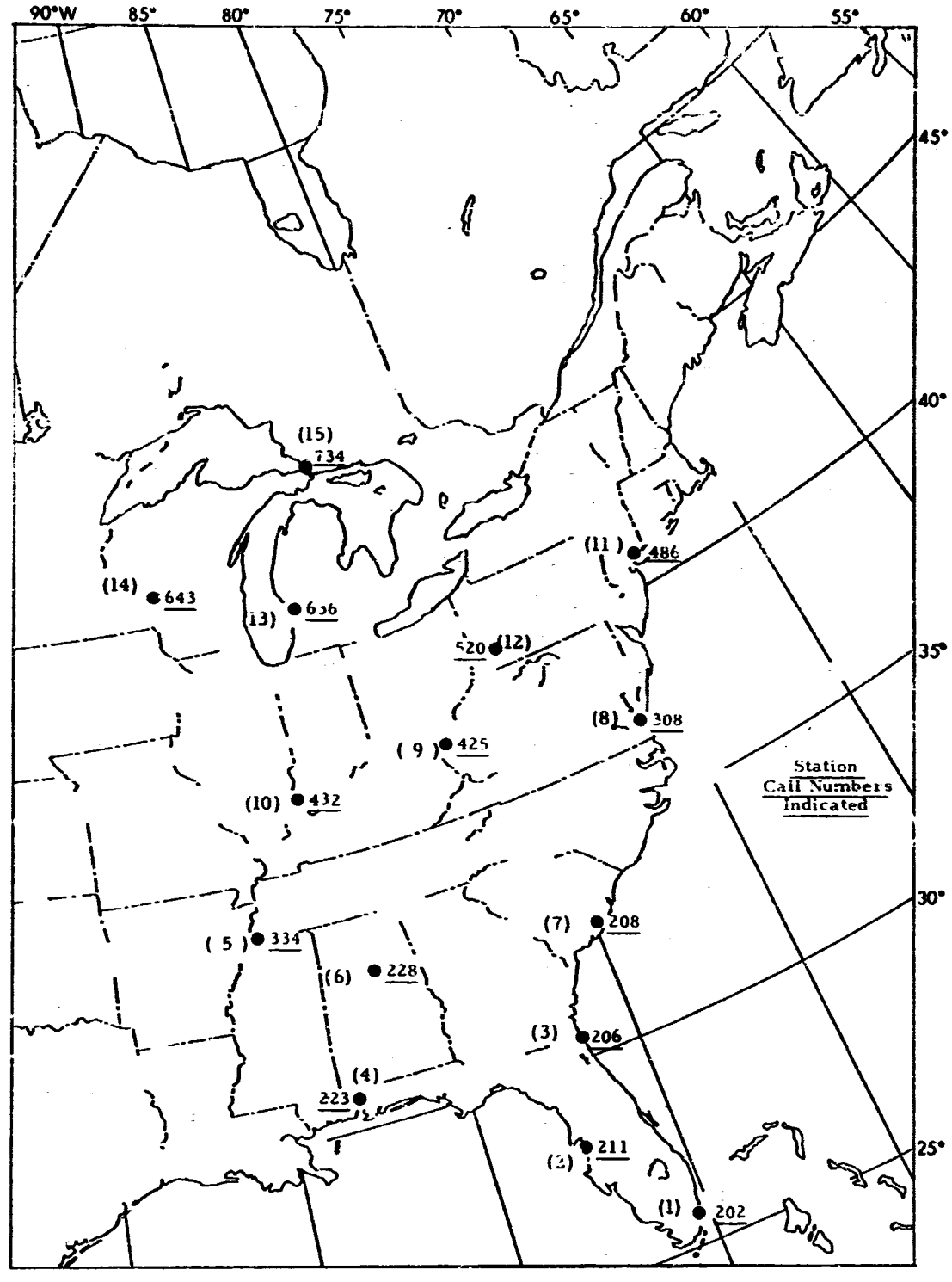


Figure 4-1 Locations For Single Station Cloud Cover Analysis

Table 4-1 Satellite Observed Cloud Types

Code Number	Cloud Type	General Brightness	Predominant Characteristics	Probability Surface Reported Cloud Type	Probable London Cloud Group *
0	No Cloud	-	-	Clear	0
1	Cellular-Small	Low-Moderate	Small cells, or area may have an overall gray tone	Cumulus	5
2	Cellular-Large	Bright	Large cells; may have Cirrus Plumes	Large Cumulus or Cumulonimbus	6
3	Non-Cellular (A)	Moderate	Smooth texture	Cirrostratus, or Thin Altocumulus, Altostratus Stratocumulus, Stratus	1, 2, or 3
4	Non-Cellular (B)	Bright	May have lumpy texture	Nimbostratus, or thick Altocumulus, Altostratus, Stratocumulus, Stratus	2, 3, or 4
5	Other	Variable	Fibrous, or other distinct characteristic	Thin Cirrus, Stratus, or Fog	1 or 3

* From London (1957)

4.2 Data Sample

The AVCS data sample, for which initial analyses comparing satellite viewed and surface viewed cloud cover were carried out, consisted of 12 days of observations for the 15 locations. Because of higher picture quality, however, APT data were used for the bulk of the single station cloud cover analyses. APT coverage in the photographically reproduced format was available on eight days of the 12-day period originally selected for analysis (facsimile reproductions were available for the other days, but were considered not usable for these purposes). To increase the sample size, photographs were collected for an additional 14 days. Thus the complete data sample consisted of cloud observations from photographs taken on 22 days; 21 days of the sample period were in July 1966, and one was in June. Since complete coverage of all stations was not available on every day, the total number of observations was approximately 250.

4.3 Statistical Analyses

4.3.1 AVCS Data Sample

For the AVCS data sample, mean cloud amounts and cloud amount frequency distributions were computed for each area size for the entire sample of 15 stations, and for samples of seven stations in the southern part of the country and five stations in the north. Mean cloud amounts and frequency distributions were also computed for both "total cloud amount" and "total opaque cloud amount" reported in the surface observations. The distributions are compared in Section 5.1.

Before embarking on more detailed analysis of the entire sample, a subsample was selected to test the observer variability in extracting cloud data from the satellite photographs. A day was selected at random for each viewed area size, and the data were extracted by two additional experienced observers. Scatter diagrams were plotted for the cloud amounts estimated by each pair of observers and for these cloud amounts vs. surface reports. Correlation coefficients were computed.

Because of the rather large observer variability and poor correlation between satellite and surface observations, similar computations were carried out with an APT data sample. Based on the results of these computations, discussed in Section 5.2, it was decided to use APT photography for the remaining analyses.

4.3.2 APT Data Sample

Computations of cloud amount frequency distributions and mean cloud amounts provide an overall comparison between satellite and surface cloud observations, but may mask out significant differences for individual observations. Therefore, the data were stratified according to cloud type and cloud amount, and for each sample the correlation coefficient and linear regression were computed. In the regression computations, the surface observed cloud amount was held as the independent (x) variable, and the satellite cloud amount as the dependent (y). The standard error of estimate and significance of the correlation and regression coefficients were also computed.

The satellite observed cloud amounts, extracted for 1/2 and 1 degree latitude (diameter) circular areas, were compared with both the "total cloud amount" and "total opaque cloud amount" reported in the surface observations. Comparisons were made between the following: (1) the satellite viewed cloudiness within the $1/2^{o}$ area and the surface observed total cloud amount; (2) the $1/2^{o}$ area and total opaque cloud amount; (3) the 1^{o} area and total cloud amount; and (4) the 1^{o} area and total opaque cloud amount.

The data were stratified geographically, into a sample consisting of four stations in the southern part of the country and a sample of five northern stations. The southern stations would be expected to have a larger percentage of convectively produced cloudiness (cumulus) and the northern stations synoptic scale cloudiness.

The data were also stratified into eight samples; consisting of all observations with the surface reported cloud types or cloud amounts shown in Table 4-2.

Table 4-2 Stratification by Surface Reported Cloud Type or Amount

1. Cirrus or cirrostratus alone
2. Cumulus, Stratocumulus, or cumulonimbus alone
3. Cumulonimbus, alone or with other clouds
4. Cirrus or cirrostratus, with cumulus, stratocumulus, or cumulonimbus
5. Cumulus alone
6. Total opaque cloud amount ≤ 3 or ≥ 8 tenths sky cover
7. Total opaque cloud amount = 4-7 tenths sky cover
8. Total cloud amount 4 tenths or more greater than total opaque cloud amount.

Additional samples consisted of all observations with the satellite reported cloud type cirrus (Type 5 in Table 4-I), with satellite cloud type-cumulus (Type 1), and with satellite brightness - very bright. Cirrus and cumulus were selected since these clouds were suspected as being more difficult to detect in satellite photography.

For comparisons between the subjective brightness as determined from the satellite photograph and the reflectance as measured by the MRIR, samples of surface reported altocumulus and stratocumulus were also extracted. The results of all analyses are discussed in the following section.

5. RESULTS OF SINGLE STATION CLOUD COVER ANALYSES

5.1 Mean Cloud Amount and Cloud Amount Frequency Distribution

Mean cloud amounts were computed for the samples discussed in Section 4.3.1. The results, shown in Table 5-1a, indicate a tendency for the mean cloud amount to increase as the area size increases, with the mean amount at 3 degrees being about a tenth of sky cover more than at 1/2 degree. For all stations combined the mean satellite observed cloud amount is in better agreement with the mean opaque amount than the total cloud amount. For the southern stations, the satellite observed cloud amount is considerably less than the surface observed; for the northern stations the mean amount for all area sizes except the 3 degree is less than the surface mean total amount but greater than the mean opaque amount.

For the above samples, cloud amount frequency distributions were computed (Tables 5-1b, 5-2a and 5-2b). As the viewed area size increases, the frequency distribution becomes distinctly bell-shaped. A similar result was observed in a recent study of cloud input for space flight simulation (Sherr et al, 1968), where the problem is discussed in considerable detail. The difference in distribution is particularly noticeable in the sample of northern stations (Table 5-2b), where there is a dramatic change from U-shaped at the 1/2 degree area size to bell-shaped at 3 degrees.

In the surface observations, the frequency distribution for the northern stations tends more toward U-shaped. The distributions for total opaque cloud amount are skewed toward lesser amounts in all three samples. It should be remembered that these distributions are from data taken during July; therefore, these and all other results of the study are representative of summer cloud cover conditions.

The agreement between the satellite observed and surface observed distributions is better for the 1/2 and 1 degree area sizes, with the best agreement occurring between the one degree and the total opaque distributions. The 2 and 3 degree circles are apparently covering larger areas than are seen by the surface observer. Since cloud elements are in general fairly small, with respect to the larger area sizes, the overall cloudiness tends toward middle cloud amounts as the viewed area size increases. The number of clear and overcast observations accordingly decreases.

Table 5-1 Comparison Between Mean Cloud Amounts and Cloud Amount Frequency Distributions for Satellite and Surface Observations; AVCS Data Sample

(a) Mean Cloud Amounts

Sample	Mean Cloud Amount in Tenths					
	Surface Observed		Satellite Observed for Area Size			
	Total Cloud Cover	Total Opaque Cloud Cover	1/2°	1°	2°	3°
All Stations	6.1	5.0	4.5	5.0	5.1	5.6
Stations 1-7 (Southern United States)	7.0	6.1	4.6	5.1	5.0	5.7
Stations 11-15 (Northern United States)	4.8	3.6	4.0	4.4	4.6	5.0

(b) Cloud Amount Frequency Distributions: All Stations

Cloud Amount in Tenths	Percentage Cloud Cover					
	Surface Observed		Satellite Observed for Area Size			
	Total Cloud Amount	Total Opaque Cloud Amount	1/2°	1°	2°	3°
0	14	14	22	15	8	2
1-3	15	24	13	17	26	19
4-6	23	29	33	36	33	38
7-9	24	17	15	18	25	35
10	24	16	17	14	8	6

Table 5-2 Comparison Between Satellite and Surface Observed Cloud Amount Frequency Distributions; AVCS Data Sample

(a) Stations 1-7 (Southern United States)

Cloud Amount in Tenths	Percentage Cloud Cover					
	Surface Observed		Satellite Observed for Area Size			
	Total Cloud Amount	Total Opaque Cloud Amount	1/2°	1°	2°	3°
0	3	3	17	9	3	0
1-3	13	19	18	19	28	22
4-6	25	38	37	42	39	40
7-9	32	20	16	19	26	32
10	27	20	12	11	4	6

(b) Stations 11-15 (Northern United States)

Cloud Amount in Tenths	Percentage Cloud Cover					
	Surface Observed		Satellite Observed for Area Size			
	Total Cloud Amount	Total Opaque Cloud Amount	1/2°	1°	2°	3°
0	28	28	30	26	21	8
1-3	18	28	10	15	21	8
4-6	18	17	27	26	24	30
7-9	14	15	12	19	24	34
10	22	12	21	14	10	8

5.2 Comparative Analyses Between AVCS and APT Data Samples

In the AVCS sample the observer variability test revealed low correlations between observers for the 1/2 and 2 degree area sizes, with the highest correlation at 3 degrees. The mean correlation coefficients for the three pairs of observers were: $\bar{r} = 0.57$ for $1/2^{\circ}$, $\bar{r} = 0.71$ for 1°, $\bar{r} = 0.59$ for 2°, and $\bar{r} = 0.79$ for 3°. From the cloud amount frequency distributions, the observer variability would be expected to be less at the 2 and 3 degree area sizes, since the estimates from each observer tend toward middle cloud amounts.

In the comparison between satellite and surface observations, the highest mean correlation for the three samples was found for the 1 degree area size; a low correlation was evident at the 1/2 and 3 degree sizes. Mean correlation coefficients were less than 0.4 for 1/2 and 3 degrees, near 0.5 for 2 degrees, and greater than 0.8 for the 1 degree area size.

Both the cloud amount frequency distributions and the results of the observer variability test demonstrate that the 2 and 3 degree satellite viewed area sizes do not correspond to the area viewed by the ground observer. Because of this, the later analyses were carried out for only the 1/2 and 1 degree areas.

Since the 1/2 degree area should approximate the ground viewed area, a higher correlation for this comparison would be expected. The rather large degree of observer variability for all area sizes is also disturbing. The discrepancies at the 1/2 degree area size may be due, in part, to difficulties in exactly locating the stations in the satellite photographs; since the area size is small, slight differences in location could give large differences in cloud amount. The problem was believed to be due in part, however, to the relatively poor quality of the AVCS pictures.

Similar data as obtained from the AVCS photographs were extracted from an eight day APT sample, for the 1/2 and 1 degree viewed area sizes. Two observers extracted an initial sample, consisting of all observations for five stations. Although the APT coverage did not extend to each station on each day, most of the eastern United States was observed on all eight days.

For the sample of about 30 observations, the correlation coefficient between the cloud amounts estimated by the two observers was 0.78 for the 1/2 degree and 0.82 for the 1 degree area size. Thus, the observer variability is slightly less for the 1 degree, and greatly less for the 1/2 degree, area than was observed for the AVCS sample. A tabulation of the differences, in tenths of sky cover, between the two observers showed an overall mean difference (disregarding sign) of 1.4 tenths

for the 1 degree area. This is in good agreement with the results of an observer variability test carried out by Barnes et al (1967), using Nimbus I AVCS pictures, and is within the range that would intuitively be expected when considering the "human factor" involved. Correlation coefficients also indicated considerably better agreement between the satellite and surface observed cloud amounts than was found in the AVCS data sample.

5.3 Linear Regression and Correlation

5.3.1 Data Samples

As discussed in Section 4.3.2, the data were stratified into 13 samples. For 12 of these samples, four separate tests were performed; for one sample, data were not extracted for the 1/2 degree area size. Thus, a total of 50 tests were carried out, with each consisting of at least 20 pairs of observations.

The correlation coefficient for the relationship between satellite observed and surface observed cloud amount was significant at the 99 percent level in 88 percent of the tests. The correlation coefficient exceeded a value of 0.50 in 82 percent of the tests, and a value of 0.80 in 44 percent.

Two samples stratified according to cloud type (Samples 1 and 5 in Table 4-2) were further broken down by cloud amount. In most of these cases, the correlation coefficients were not significant at the 99 percent level, probably due to a small number of observations.

5.3.2 Correlation for Total and Total Opaque Cloud Amounts

The correlation coefficients obtained when comparing satellite observed cloud amounts with surface observed total cloud amounts and with surface observed total opaque cloud amounts were not significantly different. The differences in the two correlations varied more from sample to sample when the computations were carried out for the 1 degree satellite viewed area size than for the 1/2 degree, but the number of samples in which r (total) was greater than or less than r (opaque) were about equal. The largest differences were for the samples stratified by cloud amount; however, these correlations are low, and in one sample r (total) exceeded r (opaque) while in another r (opaque) exceeded r (total).

These results do not bear out those of the mean cloud amount tabulations, using AVCS pictures, which implied a closer agreement between satellite viewed cloudiness and surface viewed total opaque cloudiness.

5.3.3 Correlation for 1/2 and 1 Degree Area Sizes

Similar tests revealed significantly higher correlations between satellite and surface observed cloud amounts when the satellite data were extracted from a 1/2 degree area than from a 1 degree area.

In 10 of 12 samples, where the satellite data were compared with surface reported total cloud amount, and in 8 of 12 samples when compared with total opaque cloud amount, r (1/2) exceeded r (1). This implies that the 1/2 degree area corresponds more closely with the ground observers field of view than does the 1 degree area. The poor correlations obtained with the AVCS sample were apparently due to the poor picture quality and less accurate gridding than was the case for the APT data.

For the samples stratified according to surface observed cloud type, r (1) exceeded r (1/2) in only one sample - cirrus (when compared with total opaque cloud). For the samples stratified according to satellite observed cloud type, r (1/2) exceeded r(1) for cumulus and r (1) exceeded r (1/2) for cirrus. There is an indication, therefore, that the cloud amount extracted from the 1 degree area in the satellite data is in better agreement with the surface observation when cirrus is reported, and the cloud amount from the 1/2 degree area is in better agreement when lower clouds are reported. Since the ground observer's field of view ranges from a diameter of less than ten miles for low clouds to more than 60 miles for cirrus at 60,000 feet (Blackmer and Alder, 1965), such a result would be expected.

5.3.4 Mean Values of Correlation Coefficients

5.3.4.1 Stratification By Cloud Type

Mean values of the correlation coefficients for 1/2 and 1 degree areas, and for total and total opaque cloud amounts, are given in Table 5-3 for the samples stratified by cloud type. The mean correlations for the columns reflect the results discussed in the previous sections, that no significant difference exists between the total and total opaque cloud amount tests, but that the correlations for 1/2 degree

Table 5-3 Mean Correlation Coefficients (r) For Satellite vs. Surface Observed Cloud Amounts; Samples Stratified By Cloud Type

Sample All Observations With:	Number of Observations	Mean Value of (r) for 1/2 and 1° Area Sizes		Mean Value of (r) for Total and Opaque Cloud Amounts		Overall Mean Value of (r)
		Total Cloud	Opaque Cloud	1/2° Area	1° Area	
Surface Reported Cloud Type						
a) Ci or Cs Alone	27	0.72	0.79	0.76	0.75	0.76
b) Cu, Sc, or Cb Alone	44	0.87	0.85	0.88	0.84	0.86
c) Cb, Alone or with Other Types	22	0.77	0.80	0.93	0.65	0.79
d) Ci or Cs with Cu, Sc, or Cb	47	0.63	0.52	0.64	0.52	0.58
e) Cu Alone	35	0.83	0.80	0.87	0.76	0.81
Satellite Reported Cloud Type						
f) Cirrus	39	0.81	0.80	0.78	0.82	0.80
g) Small Cellular (Cumulus)	105	0.71	0.70	0.77	0.64	0.70
Mean Value of (r) for All Samples	-	0.76	0.75	0.80	0.71	0.76

"1/2°" and "1°" refer to area sizes for which satellite data were extracted

"Total" and "Opaque" refer to surface observed Total Cloud Amount and Total Opaque Cloud Amount

are significantly greater than for 1 degree. The mean values for the different cloud types show the overall correlation for the sample "Cu, Sc, or Cb alone" to be the highest and for the sample "Ci or Cs, with Cu, Sc, or Cb" to be the lowest.

The mean correlations for the various cloud types do not differ greatly from the overall mean value, r = 0.76. There are no obvious differences, such as the correlation for one cloud type being near zero and for another being near 1.0. It is of interest that the mean value for "surface reported cirrus" is less than that for "surface reported cumulus"; in the satellite reported cirrus and cumulus samples, the opposite is true. The difference is reasonable in the case of the cirrus; the satellite camera may not detect cirrus when it is reported from the ground (see Section 5.4), but when the cirrus is thick enough to be seen in the satellite picture, it is also reported by the ground observer. The case of the cumulus cloud is more difficult to explain but may be due in part to the existence of other cloud types, as well as the small cellular, in Sample "g" (Table 5-3).

5.3.4.2 Stratification By Cloud Amount

In the results shown in Table 5-4, where the samples are stratified according to cloud amount, a large variation exists in the mean correlations for the different samples. The sample consisting of all observations with the total opaque cloud amount "≤ 3 or ≥ 8 tenths sky cover" has a high mean correlation between the satellite and surface observed cloud amounts. For the other two samples, particularly for the total opaque cloud amount "4-7 tenths sky cover," the mean correlations are very low.

These results appear to indicate that both ground observers and observers interpreting satellite pictures estimate cloud amounts more accurately when the sky is nearly clear or nearly overcast. In a comparison between surface observations and observer interpreted all-sky photographs, Merritt (1966) found a good agreement, but did not break the sample down by cloud amount. Other investigators, such as Galligan (1953), have found considerable variability between surface observers, particularly for middle (4-7 tenths) cloud amounts. Similarly, in a test of the variability among observers estimating cloud amounts from satellite photographs (Barnes et al, 1967), the greatest range in estimates (for area sizes similar to those used in this study) was for cloud amounts of near 5 tenths.

Table 5-4 Mean Correlation Coefficients (r) For Satellite vs. Surface Observed Cloud Amounts; Samples Stratified by Cloud Amount

Sample All Observations With:	Number of Observations	Mean Value of (r) for 1/2 and 1° Area Sizes		Mean Value of (r) for Total and Opaque Cloud Amounts		Overall Mean Value of (r)
		Total Cloud	Opaque Cloud	1/2° Area	1° Area	
a) Surface Reported Total Opaque Cloud Amount ≤ 3 or ≥ 8 Tenths Sky Cover	182	0.90	0.91	0.92	0.89	0.91
b) Surface Reported Total Opaque Cloud Amount = 4-7 Tenths Sky Cover	70	0.35	0.04	0.19	0.20	0.19
c) Surface Reported Total Cloud Amount 4 Tenths or More Greater Than Total Opaque Cloud Amount	24	0.21	0.42	0.32	0.31	0.31
Mean Value of (r) for All Samples	-	0.49	0.46	0.48	0.47	0.47

"1/2° and "1°" refer to area sizes for which satellite data were extracted

"Total" and "Opaque" refer to surface observed Total Cloud Amount and Total Opaque Amount

Although the correlation in the sample "Total - Total Opaque Cloud Amount ≥ 4 Tenths" is greater for the opaque, both values are low. Observations with a large difference between total and total opaque sky cover indicate thin cloudiness, which is difficult to detect in satellite photography. This may account for the low correlations.

5.3.4.3 Stratification By Cloud Type and Cloud Amount

Two samples, "Surface Reported Ci or Cs" and "Surface Reported Cu," were further stratified into samples consisting of 4-7, 0-5, and 6-10 tenths cloud amount. The mean correlation coefficients are given in Table 5-5. The correlations for the cumulus sample are in general higher than those for the cirrus sample. In both samples, the correlation is significantly higher in the "0-5 tenths" subsample; the lowest correlations, which are negative for the cirrus sample, are for the "4-7 tenths" subsample.

The higher correlations are undoubtedly due in part to the greater number of observations in the 0-5 tenths range. However, in the cumulus sample, the "4-7 tenths" subsample has more observations than "6-10 tenths", and yet has a much lower correlation. These tests demonstrate that when cloud types are broken down by cloud amount, the resulting correlations are similar to those obtained when the overall sample is stratified by cloud amount (Table 5-4).

5.3.5 Linear Regression and Correlation for Samples of Northern and Southern Stations

In order to determine whether geographic location has a significant effect on the correlation between satellite viewed and surface viewed cloudiness, samples of observations from the southern and northern parts of the country were tested. In southern areas a greater percentage of the overall cloudiness would be expected to be convective in origin, in contrast to a larger amount of synoptic scale cloudiness in the north. The southern sample consisted of all observations from Stations 1-4 and the northern sample from Stations 11-15 (Fig. 4-1).

Table 5-5 Mean Correlation Coefficients (r) For Satellite vs. Surface Observed Cloud Amounts; Samples Stratified By Cloud Type and Amount

Sample All Observations With:	Number of Observations	Mean Value of (r) for 1/2 and 1° Area Sizes		Mean Value of (r) for Total and Opaque Cloud Amounts		Overall Mean Value of (r)
		Total Cloud	Opaque Cloud	1/2° Area	1° Area	
Surface Reported Cloud Type and Total Cloud Amount	Note 1					
Ci or Cs, 4-7 Tenths	5/4	-0.25	-0.44	-0.28	-0.41	-0.35
Ci or Cs, 0-5 Tenths	17/25	0.39	0.69	0.56	0.53	0.54
Ci or Cs, 6-10 Tenths	10/2	(0.34)	Note 2	Note 2	Note 2	Note 2
Cu, 4-7 Tenths	10/8	0.07	0.48	0.23	0.32	0.27
Cu, 0-5 Tenths	30/30	0.76	0.69	0.78	0.67	0.72
Cu, 6-10 Tenths	5/5	0.50	0.50	0.46	0.54	0.50
Mean Value of (r) for All Samples	-	0.29	0.38	0.48	0.33	0.34

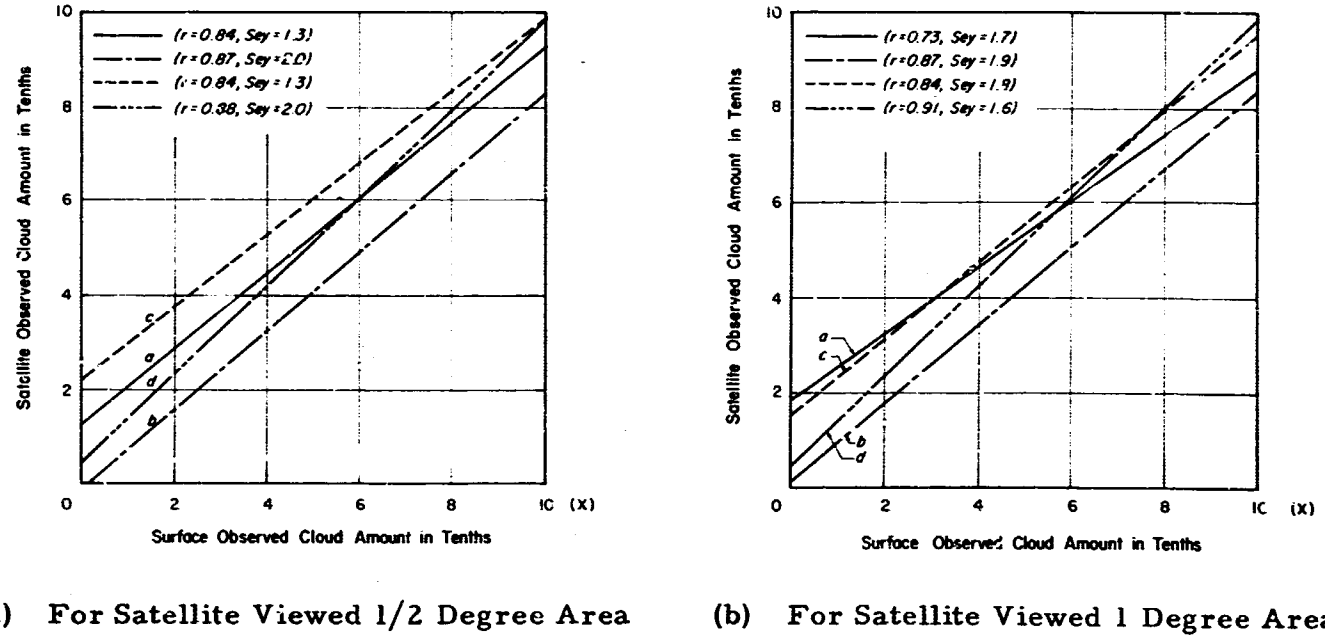
[1] First Number is for Total Cloud Amount; Second is for Total Opaque Cloud Amount

[2] Insufficient Number of Observations

"1/2°" and "1°" refer to area sizes for which satellite data were extracted

"Total" and "Opaque" refer to surface observed Total Cloud Amount and Total Opaque Amount

The linear regression curves and correlation coefficients are given in Figure 5-1. In all four tests, the correlation for stations 11-15 (North) is greater than for Stations 1-4 (South). The greatest difference is r = 0.14 for the 1 degree



(a) For Satellite Viewed 1/2 Degree Area (b) For Satellite Viewed 1 Degree Area

Figure 5-1 Linear Regression (y on x) For Southern (Stations 1-4) and Northern (Stations 11-15) Samples. Tests are a) South - Total, b) North - Total, c) South - Opaque, d) North - Opaque (Total = Comparison with Surface Reported Total Sky Cover; Opaque = Comparison with Surface Reported Total Opaque Sky Cover; r = Correlation Coefficient; Sey = Error of Estimate)

area vs. total cloud amount. The regression curves are not significantly different, although there is some indication that the satellite overestimates small cloud amounts in the "Stations 1-4" sample, and underestimates large cloud amounts in the "Stations 11-15" sample. For the 1/2 degree area size, the standard error of estimate is considerably greater for the northern stations.

Although these results do indicate a higher correlation for the sample with the greater amount of synoptic scale cloudiness, the differences do not appear as large as might be expected.

5.3.6 Linear Regression for Samples Stratified by Cloud Type and Cloud Amount

5.3.6.1 Stratification By Surface Reported Cloud Type

Mean regression curves for cloud type samples with the standard errors of estimate, are shown in Figure 5-2. The curves in Figure 5-2, which are mean values for the two satellite viewed area sizes, are not significantly different except for the sample "Ci or Cs alone." Excluding that sample, the curves indicate that the satellite overestimates small cloud amounts, in comparison with the surface observation, and very slightly underestimates large amounts.

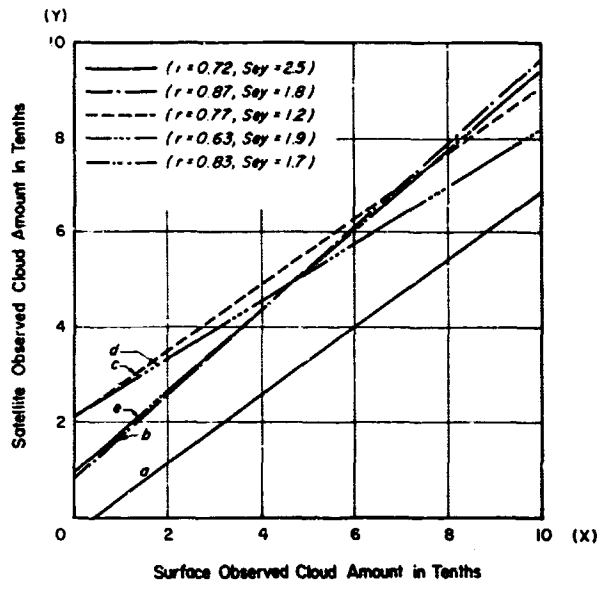
For the sample consisting of cirrus observations, the satellite underestimates the cloud amount, particularly for large values, when compared with the total cloudiness. When compared with the total opaque cloudiness, however, the satellite overestimates the cloud amount, particularly for large values. Thus, the cirrus sample appears significantly different from the other cloud types, most likely because the satellite does not detect thin cirrus.

In Figures 5-2c and d, the mean regression curves for the 1/2 degree area size are closer to the 45° curve. At the 1 degree area size, curves for two samples, "Cb" and "Ci or Cs with Cu, Sc, or Cb," indicate a significant overestimation by the satellite for small cloud amounts. In all tests carried out, the standard error of estimate is greatest for the sample of cirrus observations.

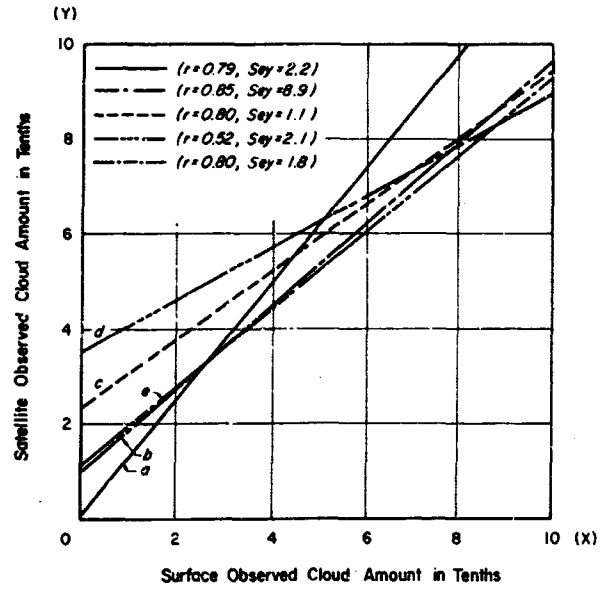
5.3.6.2 Stratification By Satellite Reported Cloud Type

Mean regression curves for samples stratified according to satellite reported cirrus and cumulus are given in Figure 5-3. For comparison, the curves for similar surface reported cloud types are repeated. In Figures 5-3a and b, the curves for the two "cumulus" samples are similar in both graphs; the curves for the two "cirrus" samples are, however, quite different. In Figures 5-3c and d, there are no outstanding differences between the curves for either sample.

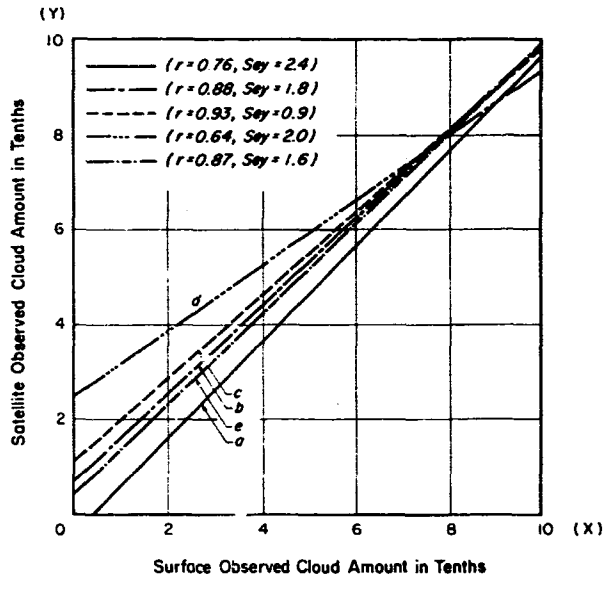
As was observed when considering mean correlation coefficients (Section 5.3.4.1), only a small difference is apparent whether the cumulus sample is stratified according to the satellite or surface cloud type. With cirrus, differences are observed because of the difficulty in detecting thin clouds in the satellite photographs.



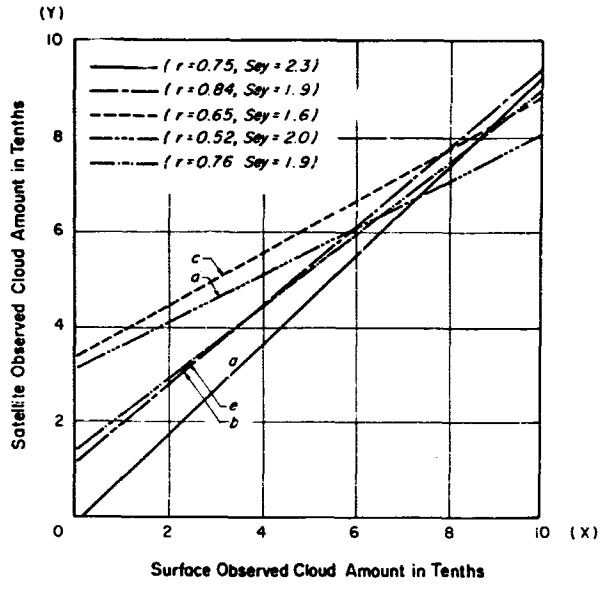
(a) Mean Curves For Total (1/2 + 1)



(b) Mean Curves For Opaque (1/2 + 1)

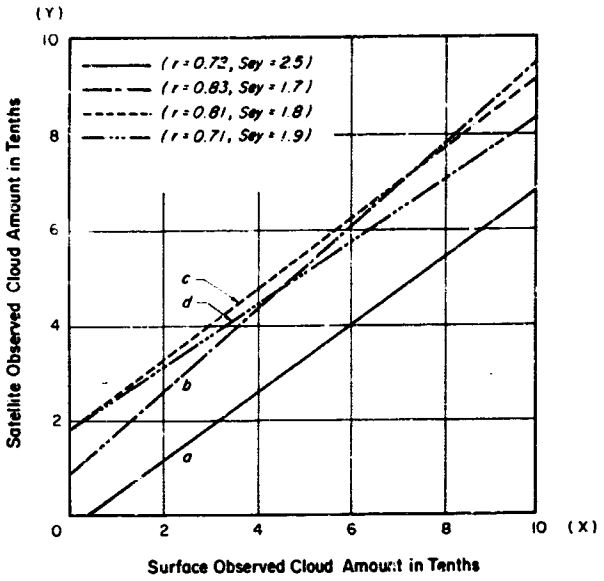


(c) Mean Curves For 1/2 (Total + Opaque)

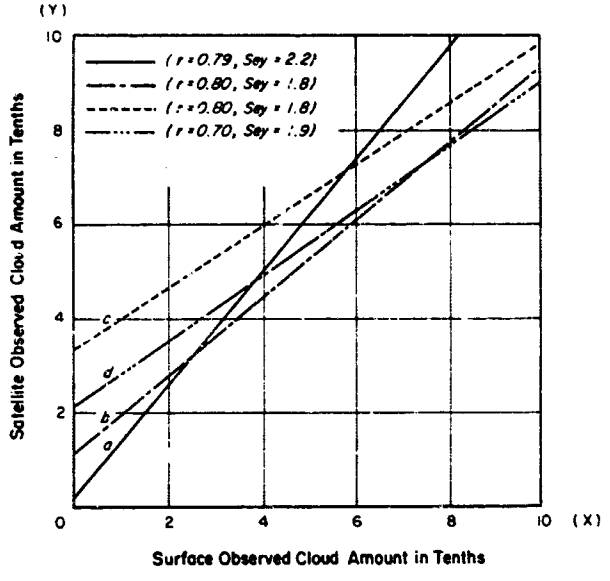


(d) Mean Curves For 1 (Total + Opaque)

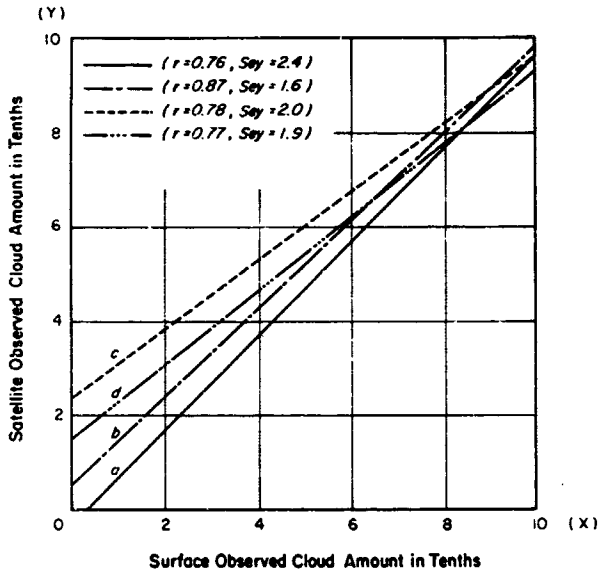
Figure 5-2 Linear Regression (y on x) For Surface Reported Cloud Type Samples: a) Ci or Cs Alone; b) Cu, Sc, or Cb; c) Cb Alone or With Other Types; d) Ci or Cs with Cu, Sc, or Cb; e) Cu Alone. (1/2 = Satellite Viewed 1/2 Degree Area; 1 = Satellite Viewed 1 Degree Area; Total = Comparison With Surface Reported Total Sky Cover; Opaque = Comparison With Surface Reported Total Opaque Sky Cover; r = Correlation Coefficient; Sey = Error of Estimate)



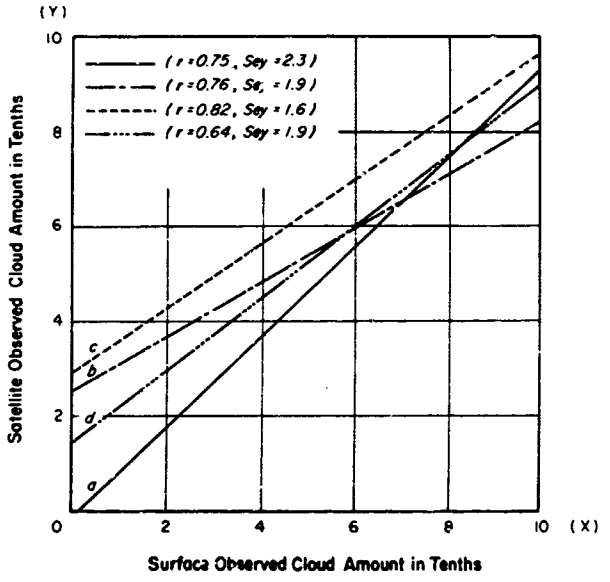
(a) Mean Curves for Total (1/2 + 1)



(b) Mean Curves For Opaque (1/2 + 1)



(c) Mean Curves for 1/2 (Total + Opaque)



(d) Mean Curves For 1 (Total + Opaque)

Figure 5-3 Linear Regression (y on x) for Cirrus and Cumulus Samples: a) Surface Reported Ci or Cs; b) Surface Reported Cu; c) Satellite Reported Cirrus; d) Satellite Reported Cumulus (1/2, 1, Total, Opaque, r, Sey are explained in Fig. 5-2)

5.3.6.3 Stratification By Cloud Amount

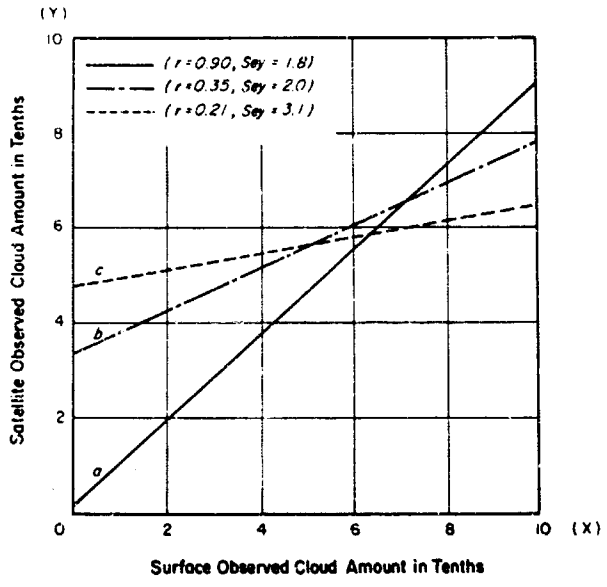
The regression curves for the sample "total opaque cloud amount ≤ 3 or ≥ 8 tenths" have a near 45° slope, indicating good agreement between satellite and surface cloud observations (Fig. 5-4). The regression curves for the other two samples, "Opaque Amount = 4-7 tenths" and "Total-Opaque Amount ≥ 4 tenths," indicate a very poor agreement. In fact, the scatter of the points in these samples is so great, that no meaningful information can be derived from the regression curves.

5.3.7 Discussion of Regression Curves

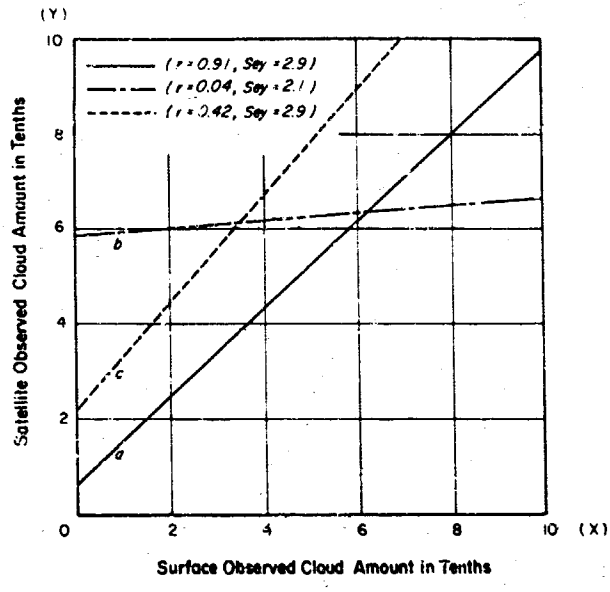
The linear regression curves discussed in the previous sections were computed for "y on x;" with the surface observed cloud amount being held as the independent variable, x. The surface observation was selected as the independent variable since the objective of the study was to compare satellite observed with surface observed cloud amounts, particularly with respect to albedo determination. Previous albedo computations and nearly all climatological studies have utilized surface cloud observations.

The majority of the regression curves shown in Figures 5-1 through 5-4 have a regression coefficient of less than 1.0, with a positive y intercept, and a y value of less than 10 at $x = 10$. Hence, these curves imply that in comparison to surface observations the satellite overestimates small cloud amounts and underestimates large cloud amounts. Previous studies, as discussed in Section 1, have generally found the opposite to be true; in particular, the satellite has been found to significantly underestimate small cloud amounts.

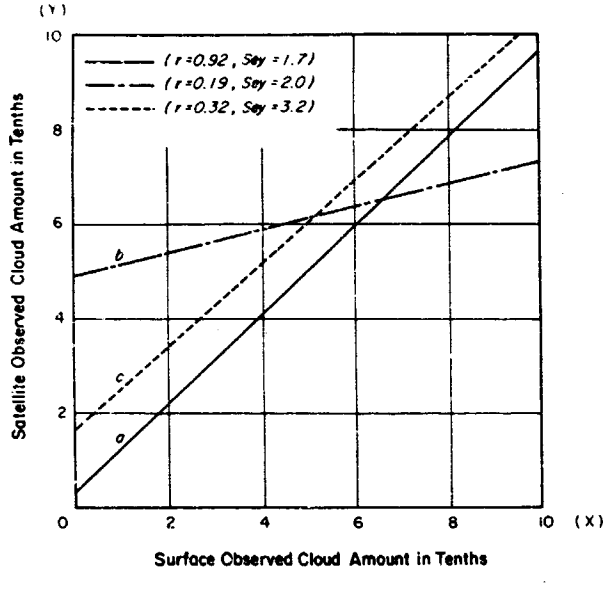
For comparison with the "y on x" regression curves, the "x on y" regression (satellite observation held as independent variable) was computed for two samples. In one sample, the correlation between satellite and surface observed cloudiness was high ($r \approx 0.9$, for "all observations, surface reported total opaque sky cover ≤ 3 or ≥ 8 tenths"), and in the other, low ($r \approx 0.3$ and < 0.1, for "all observations, surface reported total opaque sky cover 4-7 tenths"). The two regression curves for two tests on each sample are given in Figure 5-5.



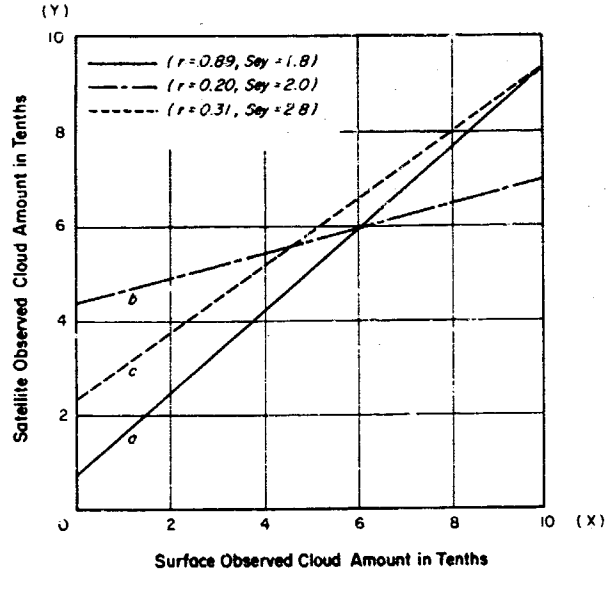
(a) Mean Curves For Total (1/2 + 1)



(b) Mean Curves For Opaque (1/2 + 1)

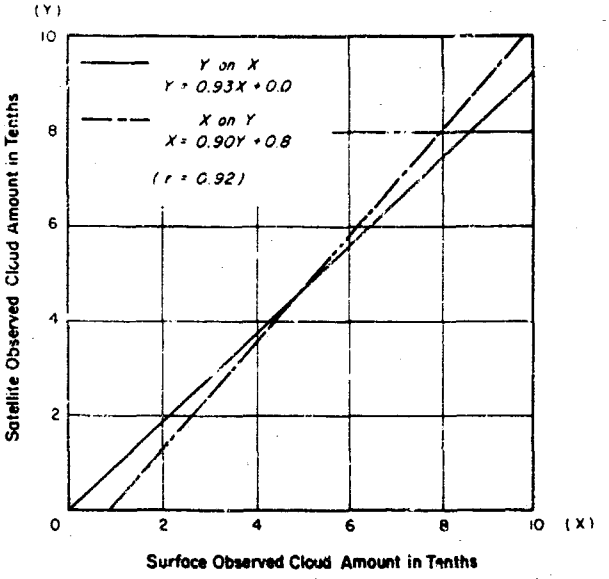


(c) Mean Curves For 1/2 (Total + Opaque)

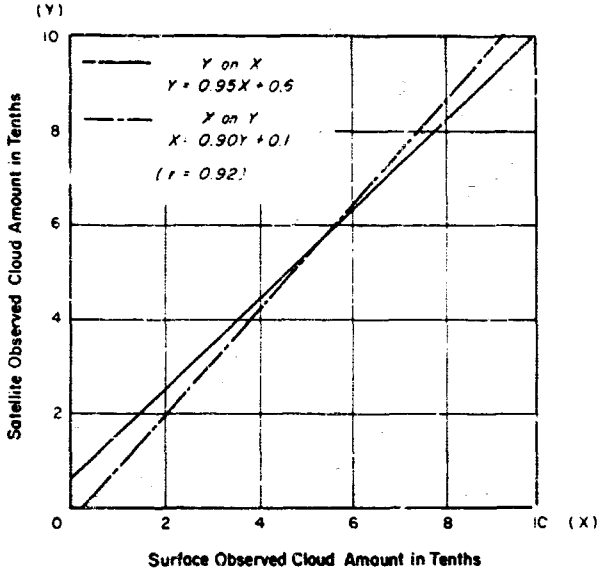


(d) Mean Curves For 1 (Total + Opaque)

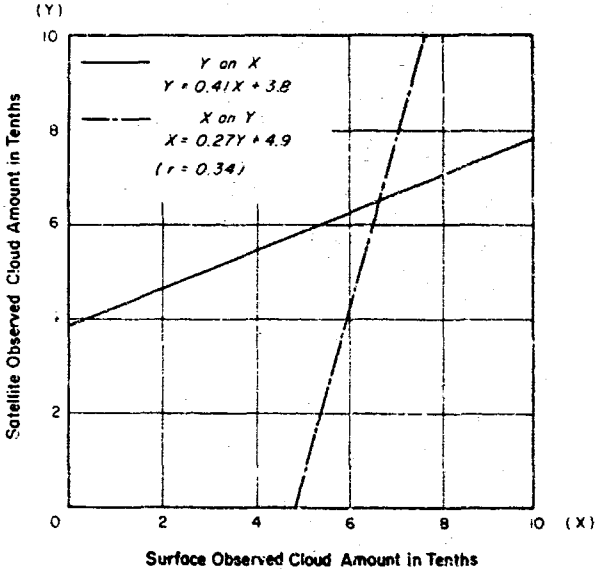
Figure 5-4 Linear Regression (y on x) for Surface Reported Cloud Amount Samples: a) Opaque ≤ 3 or ≥ 8 Tenths Sky Cover; b) Opaque = 4-7 Tenths; c) Total-Opaque ≥ 4 Tenths (1/2, 1, Total, Opaque, r, Sey are explained in Fig. 5-2)



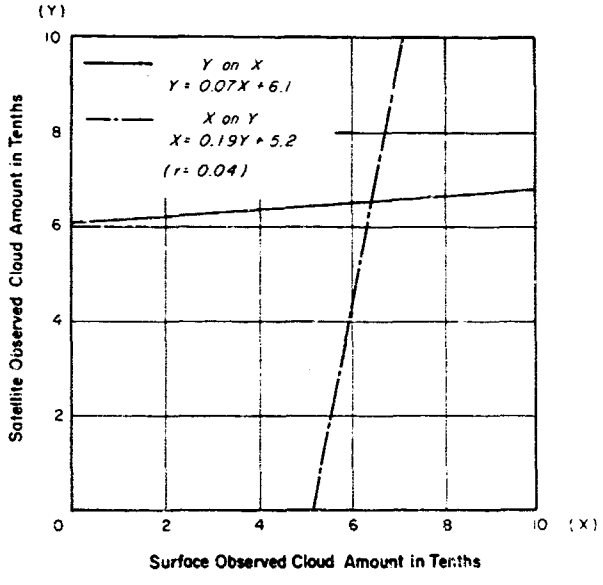
(a) Sample: Opaque $\leq$ 3 or $\geq$ 8 Tenths
Test: 1/2 vs. Total



(b) Sample: Opaque $\leq$ 3 or $\geq$ 8 Tenths
Test: 1/2 vs Opaque



(c) Sample: Opaque = 4-7 Tenths
Test: 1/2 vs Total



(d) Sample: Opaque = 4-7 Tenths
Test: 1/2 vs Opaque

Figure 5-5 Comparison Between Linear Regressions Computed for "y on x" and for "x on y" (1/2, 1, Total, Opaque, and r are explained in Fig. 5-2)

In the sample with a high correlation, the "y on x" and "x on y" regression curves are only slightly different; in the samples with a low correlation, however, the curves are completely different, being nearly 90° to each other in one test. This large difference, depending on which variable is held as the independent, can be attributed to the large scatter of the data points. Also, the regression may be nonlinear, although the scatter diagrams give no obvious indication of any nonlinearity.

These results indicate that the regression curves discussed in Section 5.3.6 may not be a true measure of the agreement between satellite and surface viewed cloudiness. The apparent over and under estimation by the satellite may not be real, at least to the degree implied, because of the strong influence of the scatter of data points in the 4-7 tenths sky cover range. If an over-or underestimation does exist, at either small or large cloud amounts, the sample in which it should be the most obvious is the sample of "cloud amount ≤ 3 or ≥ 8 tenths." In Figure 5-5, however, there is no indication of a significant overestimation or underestimation of the surface observed cloudiness by the satellite for either cloud amounts near zero sky cover or near 10 tenths sky cover.

Because of the differences between regression curves, depending on the variable held constant, the correlation coefficient may be the better measure of the agreement between satellite and surface observed cloudiness.

5.4 Comparison Between Satellite and Surface Reported Cloud Types and Brightness Values

In Tables 5-6 and 5-7, satellite and surface reported cloud types are compared for various samples. Brightness values, as estimated subjectively from the satellite photographs, are given for each cloud type in Table 5-8.

In Table 5-6a, cirrus cloud as reported from the ground and from space is compared. In only 26% of the observations in which the ground observer reported cirrus, was cirrus also reported from the satellite photographs. Furthermore, of the total observations, 41% were indicated as being "clear" in the satellite data, an indication that cirrus often is not detected in satellite photography. The agreement is better in the other direction, with cirrus being reported by the ground observer in about two-thirds of the observations in which it was reported from the satellite data; in most of these cases, however, cirrus was reported with another cloud type. It

Table 5-6 Cloud Type Comparisons for Cirrus and Cumulus Cloud Samples

(a) Cirrus

All Observations with Surface Reported Cloud Type - Cirrus or Cirrostratus	% of Observations (Total = 27)	All Observations with Satellite Reported Cloud Type - Cirrus	Cirrus Alone % of Observations (Total = 5)	Cirrus Alone or with Other Cloud Types % of Observations (Total = 39)
Satellite Reported Cloud Type (see Table 4-1)		Surface Reported Cloud Type		
Cirrus Alone	7	Ci or Cs Alone	20	10
Cirrus, Alone or with Other Cloud Types	26	Ci or Cs, Alone or with Other Cloud Types	60	67
Other Than Cirrus, Including Clear	74			
Clear (No Cloud Type Reported)	41	Other Than Ci or Cs (Including Clear)	40	33

(b) Cumulus

All Observations with Surface Reported Cloud Type - Cumulus	% of Observations (Total = 35)	All Observations with Satellite Reported Cloud Type - Cumulus (Cellular-Small)	Cumulus Alone % of Observations (Total = 61)	Cumulus Alone or with Other Cloud Types % of Observations (Total = 106)
Satellite Reported Cloud Type (see Table 4-1)		Surface Reported Cloud Type		
Cumulus (Cellular - Small) Alone	54	Cumulus Alone	30	24
Cumulus, Alone or with Other Cloud Types	69	Cumulus, Alone or with Other Cloud Types	76	75
Other Than Cumulus (Including Clear)	31			
Clear (No Cloud Type)	23	Other Than Cumulus (Including Clear)	24	25

Table 5-7 Cloud Type Comparisons for Cumulonimbus, Altocumulus, and Stratocumulus Cloud Samples

(a) Cumulonimbus

All Observations with Surface Reported Cloud Type - Cumulonimbus	% of Observations (Total = 23)	All Observations with Satellite Reported Cloud Type - Cumulonimbus (Large-Cellular)	Cumulonimbus Alone % of Observations (Total = 9)	Cumulonimbus Alone or with Other Types % of Observations (Total = 37)
Satellite Reported Cloud Type (see Table 4-1)		Surface Reported Cloud Type		
Cumulonimbus (Large Cellular) Alone	13	Cumulonimbus (Cb) Alone	0	0
Cumulonimbus, Alone or with Other Types	39	Cb, Alone or with Other Types	44	27
Other Than Cumulonimbus	61	Other Than Cb	56	73
Non-Cellular - Bright	35	Ac, Alone or with Other Types	78	59

(b) Altocumulus, Stratocumulus

All Observations with Surface Reported Cloud Type - Altocumulus, (Amount ≥ 6/10)	% of Observations (Total = 21)	All Observations with Surface Reported Cloud Type - Stratocumulus (Amount ≥ 6/10)	% of Observations (Total = 14)
Satellite Reported Cloud Type (see Table 4-1)		Satellite Reported Cloud Type (see Table 4-1)	
Non-Cellular (Type 4), Alone	43	Non-Cellular (Type 3) Alone or with Others	21
Non-Cellular (Type 4), Alone or with Other Types	57	Non-Cellular - Bright (Type 4), Alone or with Others	58
Non-Cellular (Type 3), Alone or with Others (Excluding Type 4)	28	Other Than Non-Cellular (Type 3 or 4)	21
Other Than Type 3 or 4	15		

Table 5-8 Analysis of Subjectively Estimated Cloud Brightness

(a) All Observations With Satellite Reported Brightness - Very Bright

Observations With	Subsample A		Subsample B	
	Number of Observations	Percentage of Total	Number of Observations	Percentage of Total
Satellite Reported Cloud Type:				
Cumulus (cellular-small), alone or with other cloud types	0	0	13	18
Cumulonimbus (cellular-large), alone or with other cloud types	14	30	29	41
Non-Cellular, alone	33	70	34	48
Non-Cellular, alone or with other cloud types	34	72	42	59
Surface Reported Cloud Type				
Cirrus, alone or with other types	16	34	32	45
Cumulus, alone or with other types	13	28	23	32
Altocumulus, alone or with other types	32	68	44	62
Cumulonimbus, alone or with other types	6	17	12	17

A Total Observations - Brightness "1" (Very Bright) Alone = 47

B. Total Observations - Brightness "1", alone or with other values = 71

(b) Satellite Reported Brightness for Surface Reported Cloud Type Samples

Surface Reported Cloud Type Sample	Number of Observations	Percentage of Observations With Satellite Reported Brightness Value			
		Very Bright	Moderate	Low	None
(1) Cirrus or Cirrostratus Alone	27	4	11	44	41
(2) Cumulus Alone	35	0	37	40	23
(3) Cumulonimbus, Alone or With Other Types	23	65	31	4	0
(3a) Cumulonimbus, With Altocumulus	11	82	18	0	0
(3b) Cumulonimbus, Without Altocumulus	12	50	42	8	0
(4) Altocumulus (≥ 6 Tenths Sky Cover)	21	47	28	5	0
(5) Stratocumulus (≥ 6 Tenths Sky Cover	14	64	29	7	0

* Either Very Bright or Very Bright-Variable With Another Value

was also found that a large percentage of the surface observations were in the 0-5 tenths cloud amount range, as compared with the satellite distribution, implying further that small amounts of cirrus are often undetected by the satellite.

In Table 5-6b, the agreement between satellite and surface reported cumulus is better than that for cirrus, with a large percentage of the surface observations with this cloud type also being reported as cumulus in the satellite data. Even in this sample, however, 23% of the surface observations were reported as clear in the satellite picture; this indicates that the satellite, although not to the degree as with cirrus, may not always detect small amounts of cumulus.

Similar tabulations are given for cumulonimbus, altocumulus, and stratocumulus in Table 5-7. The percentage of the cumulonimbus observations in the 6-10 tenths sky cover range was 87%; thus, this sample is compatible with the altocumulus and stratocumulus samples, both of which consisted of all observations $\geq$ 6 tenths. These samples were selected primarily to determine their brightness values, which are discussed below.

The surface reported cloud types for the observations that were indicated as being "very bright" in the satellite pictures are given in Table 5-8a; the satellite reported brightness values for the cloud types given in the previous tables are summarized in Table 5-8b.

Altocumulus is most often reported when the satellite brightness value is "very bright." While this is largely due to a greater number of observations with altocumulus, the results of Table 5-8b substantiate that this cloud appears extremely bright in the satellite picture. For example, cumulonimbus also appears bright; however, samples 3, 3a and 3b indicate that a significant part of this "brightness" is due to the existence of altocumulus with the cumulonimbus. Stratocumulus also has a large percentage of "very bright" observations, but both cirrus and cumulus appear significantly less bright in the satellite observations than do these other cloud types (stratus was not tested because of a lack of observations). Objectively measured reflectances for similar cloud types are discussed in the following sections.

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6. ANALYSIS OF REFLECTANCE

6.1 Cloud Type Identification and Case Selection

Identification of specific cloud types and extent of cloud cover was based on analysis of ground reports entered in WBAN-10 forms, radiosonde data of temperature and dewpoint, data from the MRIR, and concurrent APT and AVCS photographs. Inclusion of all these available data was found to provide a more consistent definition of the cloud field.

In this study, use was made of only three channels of the MRIR. (Characteristics of the MRIR system, including the spectral ranges of the different channels, are discussed in Section 3.1.2.) Channel 5 provided the basic information on the reflective properties of the earth's surfaces and of clouds as seen from outside the earth's atmosphere. The Channel 2 data were used to supplement ground observations in a more exact identification of cloud height, and therefore of cloud type. The primary purpose of Channel 1, measuring in the water vapor absorption band, is to measure the distribution of atmospheric water vapor. This channel is also sensitive to clouds, however, and, in a study by Beran et al (1968), it was found to be an excellent detector of cirrus clouds sufficiently tenuous as not to be apparent in the concurrent Channel 2 data. Because of this unique characteristic, the data from this channel were also included in the analysis.

The actual Channel 5 values used are defined by

$$R = \frac{\pi \overline{N}}{\overline{H}^{*} \cos \xi}$$

where $\overline{N}$ = effective radiance, measured by Channel 5

$\overline{H}^{*}$ = effective solar irradiance as measured through the filtering system of the sensor

ξ = solar zenith angle

The value of R differs from the defined value of bidirectional reflectance by the factor π. For this reason and because the assumption was made of isotropy within the limited geometry, the more general term "reflectance" is used in this report to denote the quantity defined above.

As in the study of percentage cloud cover, the analysis of the radiometric

data was restricted to the eastern United States to take full advantage of the availability of supporting ground-based data. Satellite passage at these latitudes occurred between 1600 GMT and 1800 GMT, corresponding to solar elevation angles of about 20 degrees. These restrictions, together with the choice of data from sensor nadir angles less than 40°, limited scattering angles away from the forward direction. However, as the measurements of Sparkman and Cherrix show, the bidirectional reflectance in this region is nearly independent of angle. Based on these considerations, the restricted radiometric data were treated as being independent of angle, and variations in measured values were attributed solely to variations in the properties of the cloud field, such as cloud type and cloud thickness.

The MRIR data are available in both analog grey scale picture format and in digital printouts. For the analyses performed in this study, only the digitized data were used. Since the final analysis technique adopted was the accumulation of statistics of the three channel values over large areas, the data listings were found to be the most convenient format to use.

Initial case selection was based on plotted reports of ground-observed cloud cover, which were within two hours of the time of the satellite data. Even within this period, however, large changes in both cloud cover and cloud type may have taken place. As a check on the temporal stability of the cloud field, the hourly percentage sky cover reports prior and subsequent to the 1800 GMT reports were examined. Cases of rapid clearing or build-up were eliminated from further analysis.

The second consideration in case selection was uniformity in cloud cover over a fairly large area - on the order of 2° by 2°. The plotted WBAN data were checked to identify areas reporting cloud cover of the same type or predominantly of the same type. This latter criterion was found to be more realistic in application.

In addition to cases of cloud cover, clear area cases were also selected for further analysis. These included cases of clear skies over the oceans. The lack of systematic reports of sky cover over the oceans made selection difficult. Analysis had to be restricted to the coastal regions where it was possible to extrapolate the extent of cloud cover to these regions based on reports at coastal stations and with the help of APT photographs.

As a further check on the identification and delineation of areas of cloud cover, the AVCS and APT photographs, when available, were compared with the coverage depicted in the plotted surface observations. These photographs were used primarily as a check on the spatial extent and uniformity of coverage. No attempt was made to

redefine the cloud types based on interpretation of the depicted cloud field.

In spite of the care taken in the delineation of cloud types, discrepancies between the reported and the actual cloud type can be expected. London (1957) pointed out the difficulty involved in properly identifying all types of clouds which might be simultaneously present over a station. A ground based observer is not a to see higher level clouds if they are obstructed by opaque lower cloud decks. Therefore a refinement in cloud type identification was made based on analysis of the Channel 2 effective temperatures.

While clouds cannot in general be considered radiationally black, the effective temperatures measured by Channel 2 should give some indication of cloud top height. As an example consider the scan line from Orbit 857 (18 July) shown in Figure 6-1. The scan intersected a station reporting 10/10 stratocumulus with upper layers unknown (see arrow near scan spot 35). The Channel 2 temperatures were relatively high - on the order of 280°K to 290°K. This would place the cloud top at approximately 1 or 2 km, which is quite realistic for stratocumulus clouds. While it is not possible to discuss unambiguously the presence of upper level clouds, if such clouds were present, they must necessarily be optically thin. Their contribution to the overall reflectance would be small.

A total of some 40 cases were selected for analysis. Included in these cases were examples of all the cloud categories used by London with the exception of altostratus and nimbostratus.

6.2 Analysis Technique

A preliminary examination of the distribution of Channel 2 T_{bb} values was made for each of the cases selected. Over clear sky regions the spread of the Channel 2 values was found to be less than 10°K. In the presence of reported cloud cover, however, substantially larger temperature spreads were found. The degree of spread in the Channel 2 values was also reflected in the large range in concurrent temperatures measured by the other two channels. One factor contributing to the spread is the presence of mixed clouds at different levels. A case in point is the scan line shown in Figure 6-2. The data were taken from Orbit 817 with the scan line located in a region reporting predominantly cumulonimbus. However, scattered to broken altocumulus clouds were also reported. The Channel 2 T_{bb} values, ranging from 226°K to 280°K reflect the presence of mixed cloud types, with the lower altocumulus being clearly delineated by the warmer, > 260°K, temperatures. In this instance, the Channel 2 T_{bb} values should fall into two more

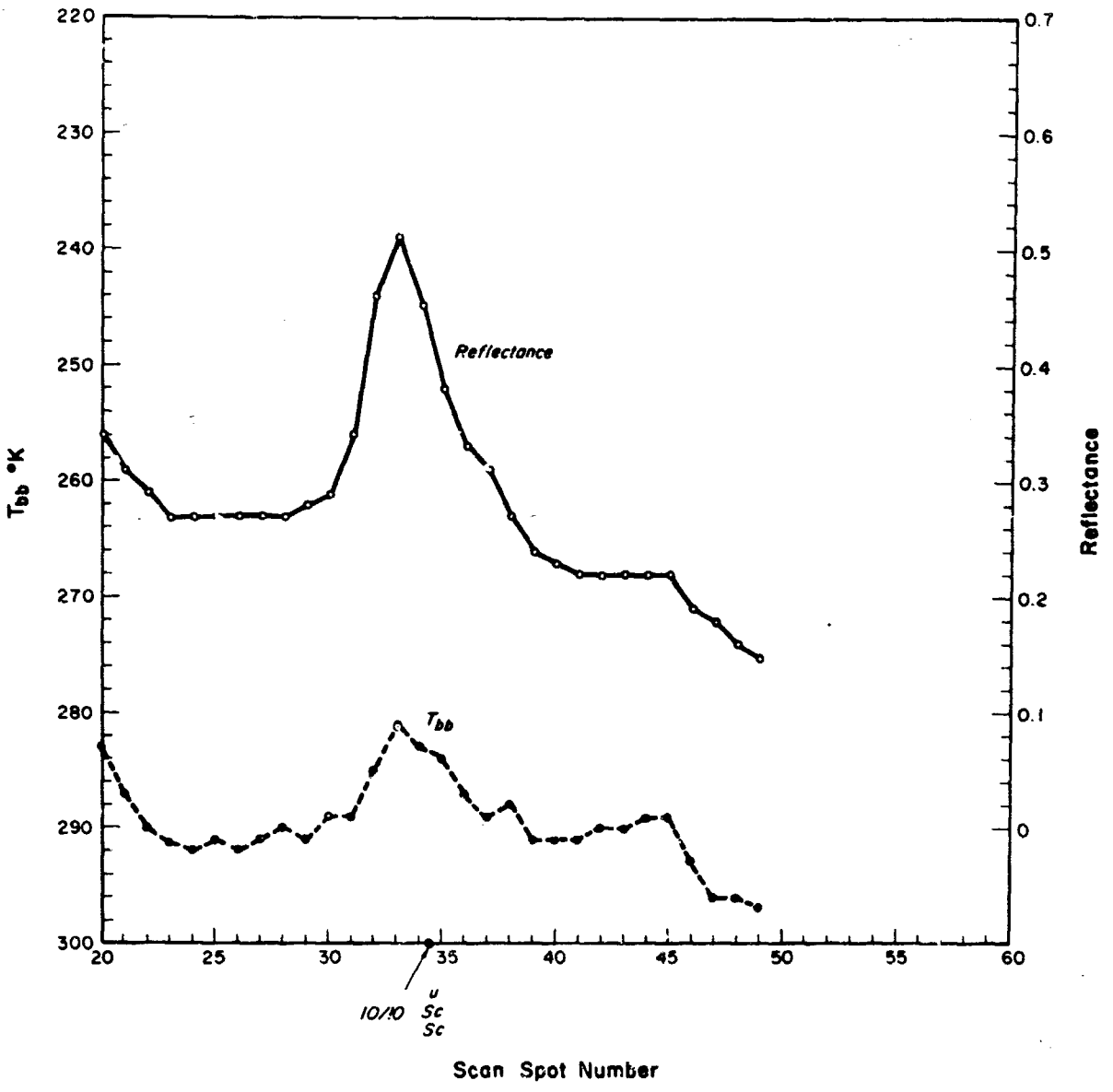


Figure 6-1 Reflectance and Channel 2 T_{bb} Analysis; Orbit 857 (18 July 1966) at Approximately 37°N, 82° W

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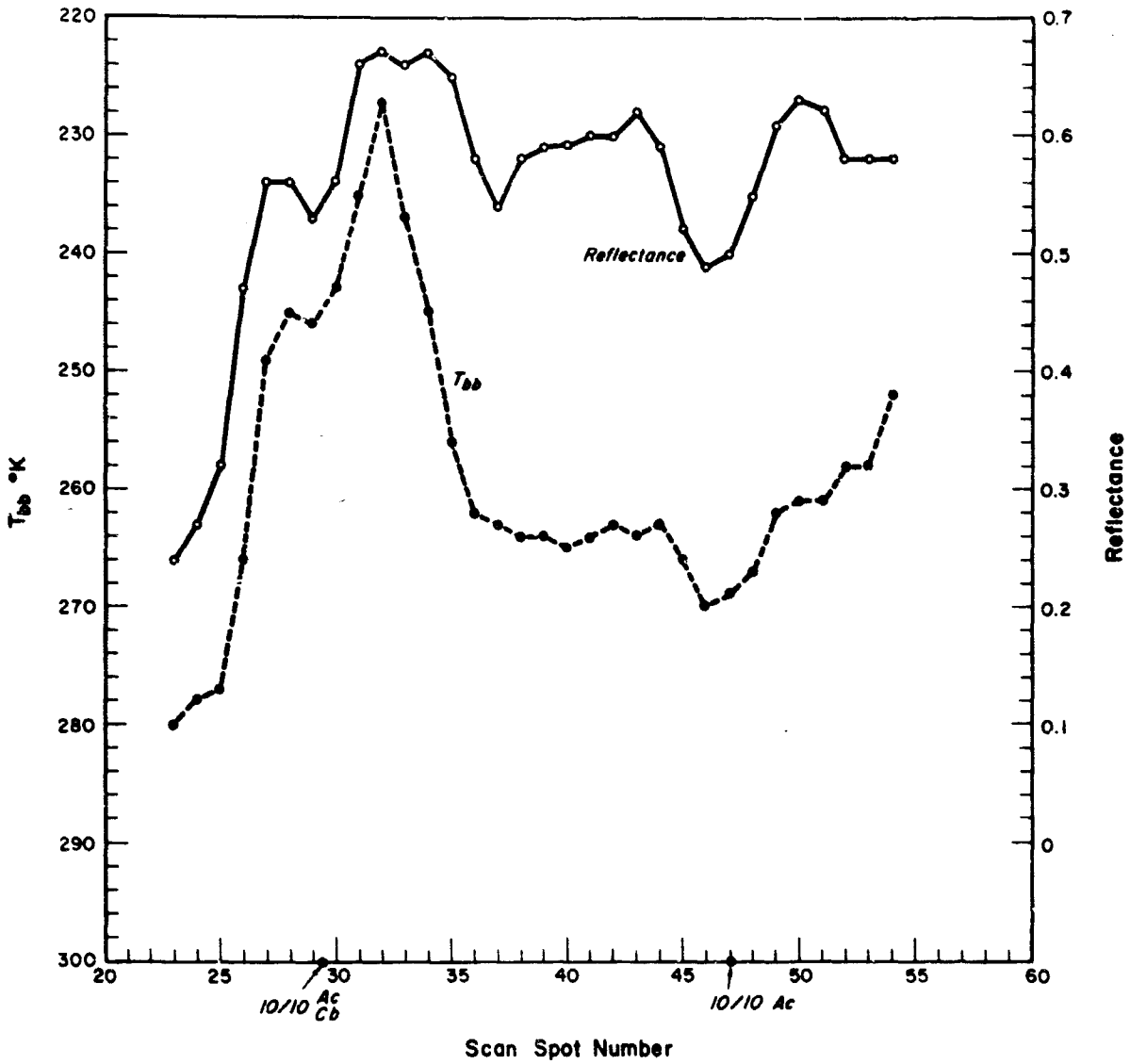


Figure 6-2 Reflectance and Channel 2 T_{bb} Analysis; Orbit 817 (15 July 1966) at Approximately 30°N, 80°W

or less distinct regimes corresponding to the two types of clouds.

A second factor contributing to the spread in the radiometric temperature is the large variability in optical thickness which is found for clouds belonging to the same class. In a case of cirrostratus, discussed in detail in Section 7, the Channel 2 T_{bb} values ranged from 240°K to 290°K. Over the selected region, surface stations all reported 10/10 cover. Examination of the concurrent APT photograph shows that while cirrostratus could be identified over the region, the apparent brightness was not uniform. A large variety of grey scale values could be detected. The distribution of Channel 2 T_{bb} values merely reflected the non-uniform optical thickness of the cloud field.

The optical thickness of a cloud element is a complex function of many factors, including the geometric thickness, the drop size distribution and number thickness, and the wavelength of the measurement. In addition, the optical properties of the droplets themselves, such as the index of refraction and shape, are significant parameters. While it would be highly desirable to relate the optical thickness, computed on the basis of these factors, to the measured reflectance, the lack of actual in-cloud measurements of droplet distribution characteristics, and a practical computational technique, make this approach impossible. On the other hand, the availability of the concurrent Channel 2 T_{bb} values, apparently quite sensitive to the optical thickness, can provide a rough estimate of these properties. This is especially true when radiosonde data are also used to define the probable extent of the moist or cloud layer.

In view of the high degree of variability in characteristics for clouds belonging to the same class, the value of reflectance measured over a single cloud element cannot be treated as being representative of the class. The only logical approach to reflectance analysis, it would seem, must be statistical in nature. The technique adopted was to treat the distribution of cloud properties for each of the selected cases as being statistically representative of the cloud type and cloud cover situation as reported. This is a gross assumption which must ultimately be refined by more analysis. However, it does provide a convenient starting point.

For each of the cases, distributions of Channels 5, 2 and 1 values were accumulated in the form of histograms. Characteristics of the distributions were noted and compared. Relative "brightness" between regions reporting different cloud types and coverage was investigated.

7 RESULTS OF REFLECTANCE ANALYSIS

7.1 Clear Areas

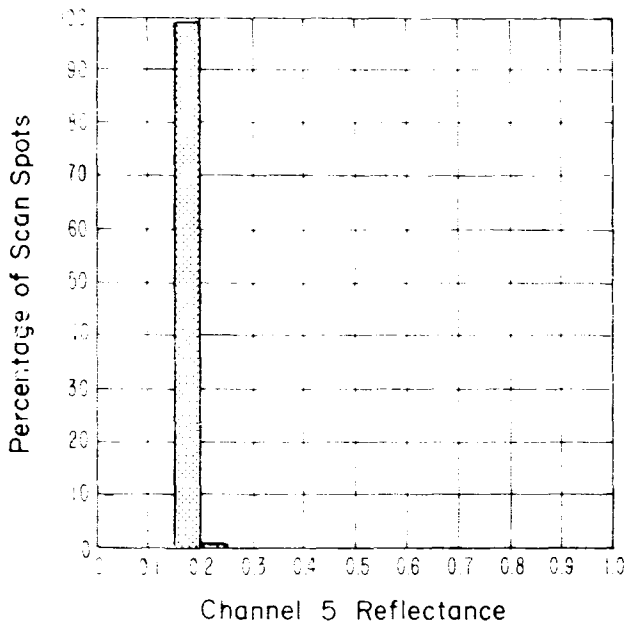
Analysis of the plotted ground-observed cloud covered data showed that cases of clear skies of any significant horizontal extent were rare for the orbits selected. Many of the areas which appeared clear in the AVCS photographs turned out to be partially covered (1/10 - 2/10) by cirrus. On 7 July, however, Orbit 711 passed over Central United States at approximately 1700 GMT. A large clear region was apparently evident in the APT photograph (1711:55 GMT) covering the states of Kansas and Nebraska. Both the Platte River in Nebraska and the Arkansas River in Kansas and eastern Colorado were clearly evident in the APT photograph. All of the stations in Nebraska reported clear skies from 1700 GMT to at least 1900 GMT. Of the five stations in Kansas, three - Dodge City (DDC), Topeka (TOP) and Wichita - reported partial cloud cover up to 5/10. The reports at 1800 GMT showed that the cloud types over these stations were predominantly cirrus and cumulus.

Based on these reports of cloud cover, the area enclosed by latitudes 38°N and 41°N, and longitudes 96°W and 100°W was selected for analysis. This area should be representative of wheat and cornfields.

The total number of scan spots included in the analysis was in excess of 100. The percentage distribution of the scan spots in each of the three channels is shown in Figure 7-1. Over 93% of the Channel 2 T_{bb} values were found to be greater than 295°K, evidence that the area was predominantly clear. The distribution of Channel 5 reflectance shows that the reflectance over the surface was below 0.2. No value of reflectance in this data sample was found below 0.15. The distribution of the Channel 1 T_{bb} values is quite typical of clear regions. Over 97% of the scan spots had a Channel 1 T_{bb} greater than 240°K.

For comparison, a case of reflectance over an ocean surface was selected for presentation. The absence of systematic shipboard observations of cloud cover makes identification of clear areas over the oceans more difficult, and probably more ambiguous. The selection of this particular case was based on analysis of the Channel 2 T_{bb} values and a concurrent APT photograph.

Orbit 857 on 18 July, passed over the east coast of the United States. The APT photograph taken at 1624 GMT (Fig. 7-2) shows the sharply outlined coast of the United States, extending from New York to Florida. North of the Cape Hatteras region, the ocean surface appears black contrasted with the lighter greyish tones of the land surfaces. South of Hatteras, however, sunglint is quite evident over the



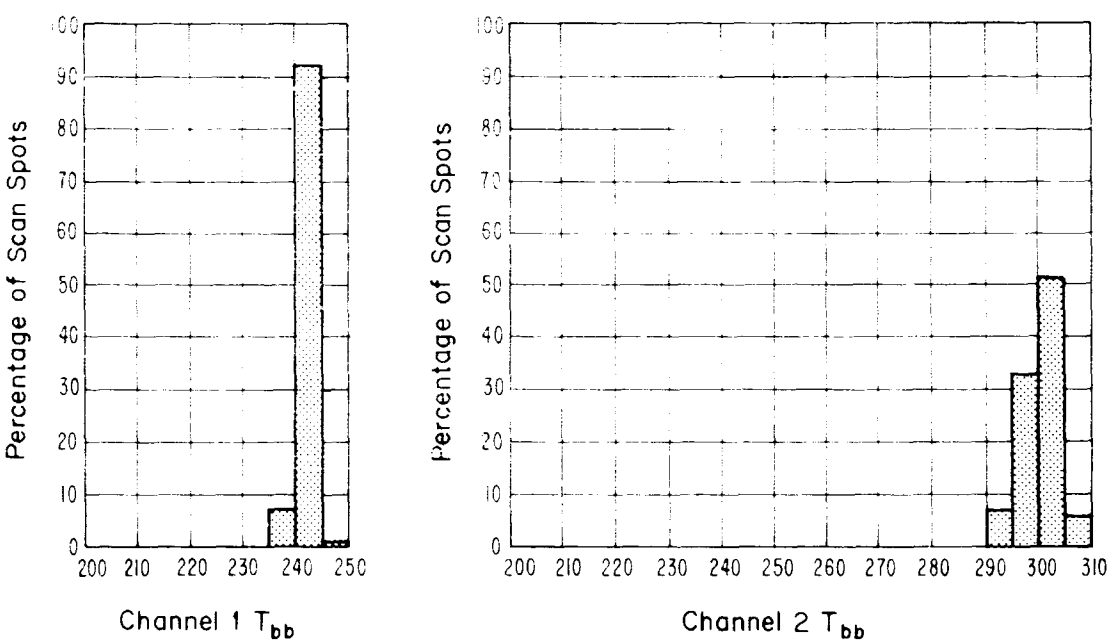


Figure 7-1 Distributions of Radiometric Data from Orbit 711 (7 July) Over Nebraska. Clear Skies were Reported Over the Region. Note the Large Percentage of Scan Spots having Channel 2 T_{bb} Values $>300^{\circ}K$ and Reflectance < 0.2. Also, Over 90% of the Scan Spots had Channel 1 T_{bb} Values $>240^{\circ}K$.

oceans. The coastal areas of the Carolinas appear much darker than the off-shore waters. Over Southern New York and extending into Virginia, cirrus is evident in the APT photograph. This cirrus, originating from a storm complex in eastern Canada, apparently did not extend over the ocean. Coastal stations from southern New Jersey, Delaware, Maryland and Virginia were all reporting clear skies at 1600 GMT. It was therefore assumed that over the coastal waters of the Mid-Atlantic States, the skies were also clear. From the same APT photograph, it was evident that the eastern extent of this clear region was limited by a broad cloud band which intersected latitude $40^{\circ}N$ at longitude $70^{\circ}W$ and latitude $36^{\circ}N$ at longitude $73^{\circ}W$. The area chosen for analysis was therefore limited north and south by latitudes $40^{\circ}N$ and $36^{\circ}N$ respectively, and west and east by the coast line and the edge of the cloud band. The southern limit of the area is sufficiently far north to avoid "contamination" by sunglint.

The results of the analysis of the data listings for the three channels are shown in Figure 7-3. The distribution of Channel 2 T_{bb} values, with some 75% greater than $290^{\circ}K$, reflects the July climatological value of sea surface temperature of $\sim 20^{\circ}C$ in this region, providing further evidence that the skies were indeed clear at the time of satellite passage. The Channel 5 data show that the reflectance over the ocean surface is indeed lower than that found over the farmlands of Nebraska. Close to 50% of the values were found to be under 0.05. Again, note the distribution of Channel 1 T_{bb} values with over 87% warmer than $240^{\circ}K$.

The results of the two cases presented in this section are typical of other clear area cases investigated. The reflectance of the earth's land surface is characteristically lower than 0.15. Over water, the reflectance is significantly lower. More interesting is the distribution of Channel 1 T_{bb} values, which are predominantly greater than $240^{\circ}K$.

7.2 Cirrus and Cirrostratus

The APT photograph at 1624 GMT of 18 July, given in Figure 7-2, shows good examples of visible cirrus and cirrostratus covering the north eastern states and extending to the Great Lakes region. The 1700 GMT and 1800 GMT surface reports indicate that over Michigan, Illinois, Indiana and Ohio, the predominant cloud type observed was cirrostratus with 10/10 sky cover generally reported. To the southeast, in the area of Maryland, Virginia and West Virginia, fractional cover, ranging from 2/10 - 9/10, by cirrus was reported. These two areas were separately analyzed.

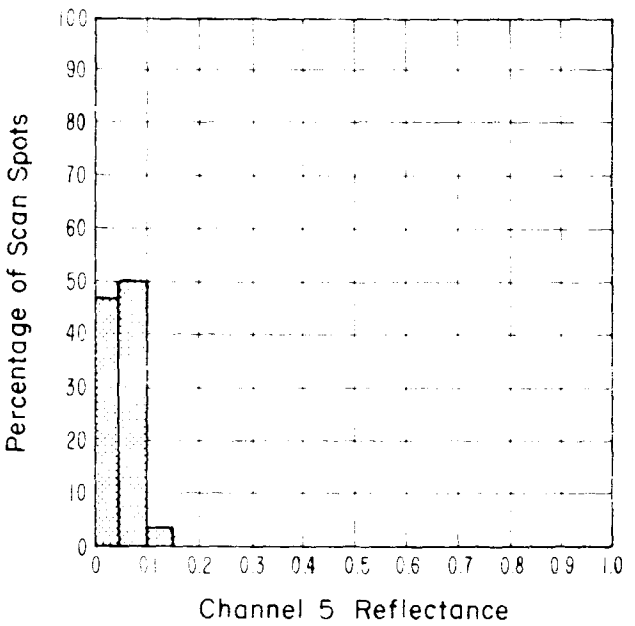
oceans. The coastal areas of the Carolinas appear much darker than the off-shore waters. Over Southern New York and extending into Virginia, cirrus is evident in the APT photograph. This cirrus, originating from a storm complex in eastern Canada, apparently did not extend over the ocean. Coastal stations from southern New Jersey, Delaware, Maryland and Virginia were all reporting clear skies at 1600 GMT. It was therefore assumed that over the coastal waters of the Mid-Atlantic States, the skies were also clear. From the same APT photograph, it was evident that the eastern extent of this clear region was limited by a broad cloud band which intersected latitude $40^{\circ}N$ at longitude $70^{\circ}W$ and latitude $36^{\circ}N$ at longitude $73^{\circ}W$. The area chosen for analysis was therefore limited north and south by latitudes $40^{\circ}N$ and $36^{\circ}N$ respectively, and west and east by the coast line and the edge of the cloud band. The southern limit of the area is sufficiently far north to avoid "contamination" by sunglint.

The results of the analysis of the data listings for the three channels are shown in Figure 7-3. The distribution of Channel 2 T_{bb} values, with some 75% greater than $290^{\circ}K$, reflects the July climatological value of sea surface temperature of $\sim 20^{\circ}C$ in this region, providing further evidence that the skies were indeed clear at the time of satellite passage. The Channel 5 data show that the reflectance over the ocean surface is indeed lower than that found over the farmlands of Nebraska. Close to 50% of the values were found to be under 0.05. Again, note the distribution of Channel 1 T_{bb} values with over 87% warmer than $240^{\circ}K$.

The results of the two cases presented in this section are typical of other clear area cases investigated. The reflectance of the earth's land surface is characteristically lower than 0.15. Over water, the reflectance is significantly lower. More interesting is the distribution of Channel 1 T_{bb} values, which are predominantly greater than $240^{\circ}K$.

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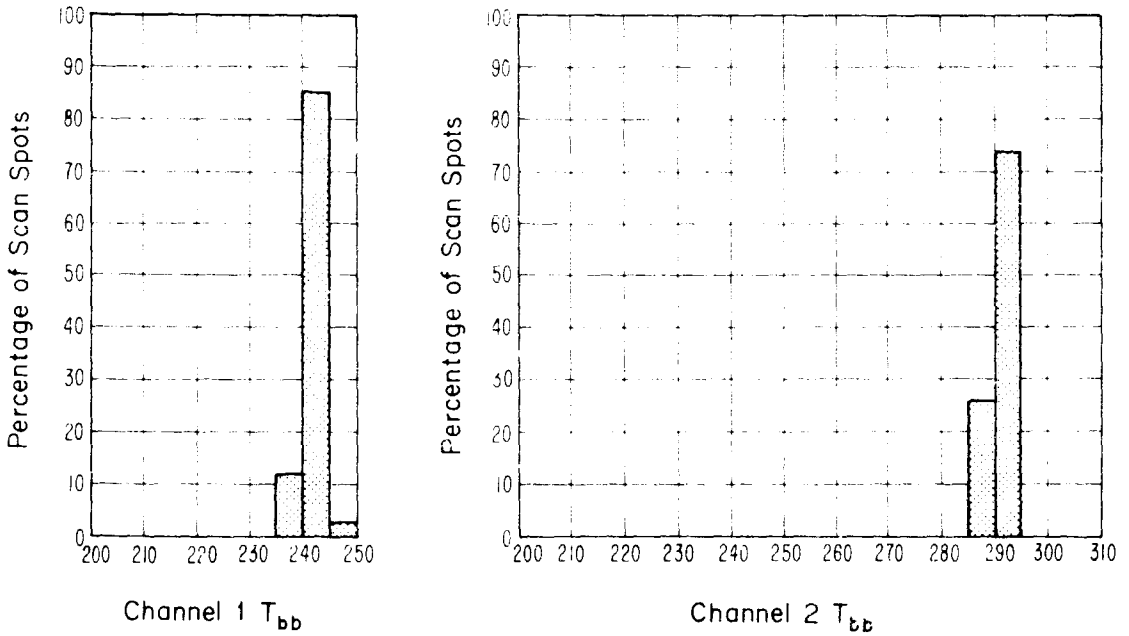


Figure 7-3 Distributions of Radiometric Data from Orbit 857 (18 July) Over the Coastal Waters of the Mid-Atlantic States. Coastal Stations Reported Clear Skies. The Clear Sky Conditions are Reflected in the Distribution of Channel 2 T_{bb} Values. The Reflectance Values for this Case are Lower than Those Over the Farmlands of Nebraska (Fig. 7-1). Note Also the Large Percentage of Data Points having Channel 1 T_{bb} Values $>240^{o}K$, Which is Typical of Clear Sky Cases

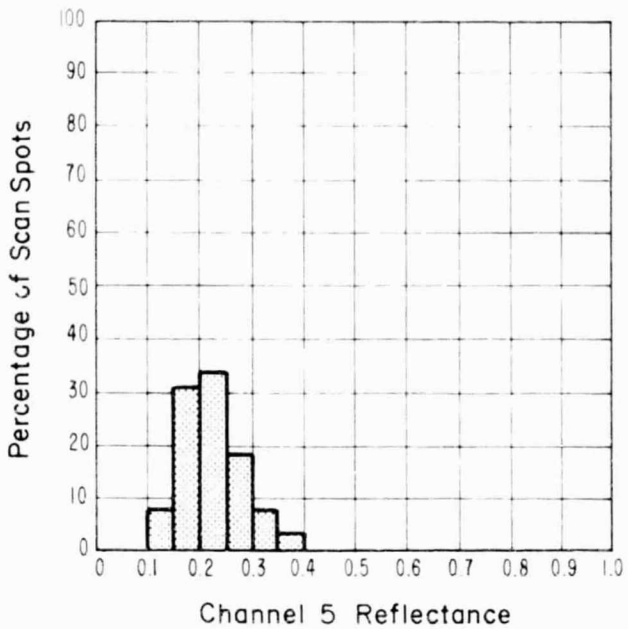
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In the 1200 GMT radiosonde data, all stations in the Great Lakes region reported relative humidities in excess of 40% at the top of the moisture sounding at 300 mb. At these altitudes (~9.0 km), the resulting dew point spread of ~4 or 5°C is highly indicative of ice crystal clouds. Furthermore, with the tropopause reported at 12 - 13 km, the tops of the clouds are most likely located above 300 mb. Since the 300 mb temperatures were reported to be of the order of -34°C (or 239°K), the cloud top temperature would probably be colder than this value.

The surface cloud observations indicate a latitudinal variation in the thickness of the upper level moist layer. To the south, Dayton, Ohio, was reporting 10/10 Cs with only 6/10 being opaque. At Flint, Michigan, the report was 10/10 Cs, but with 10/10 being opaque. Farther north, the clouds thicken to include Ac and Sc at International Falls. This variability in the thickness of the cloud layer is substantiated by the 1200 GMT radiosonde data. At this time, four hours before satellite passage, Dayton reported an "incipient" cloud layer between 350 and 265 mb with relative humidities in the low 30's. At Flint, however, the dew point spread at 322 mb was less than 7°C. The relative humidity dropped sharply to 27% at 350 mb. At International Falls, the depth of the moist layer reached the surface with the atmosphere at near saturation point throughout.

The three-channel analysis of the cirrostratus case, shown in Figure 7-4, certainly manifests the variability in optical thickness. This is especially true for the Channel 2 T_{bb} data. The relatively large percentage of data points in the 285 - 295°K range, and the low reflectance values of less than 0.2, suggest partial coverage by thinner cirrus, or possibly even "holes" in the cloud cover. These holes or thinner cirrus are apparent in the APT photograph shown in Figure 7-2. The fact that the surface stations reported 10/10 cover, and for the most part 10/10 opaque sky cover, over the same region, points out one of the difficulties of using ground observed sky cover in estimating the actual cloud cover over large areas.

The coldest Channel 2 T_{bb} values found over this region were in the range of 240 - 245°K. Only 2% of the data points attained these low values. Since the cloud top temperatures deduced from radiosonde data were at least as cold, and probably much colder, than 240°K, it may be seen that the cirrostratus was for the most part optically thin. The energy received by the MRIR in the 10 - 11 μ interval originated at various levels below cloud top. This situation is reflected in the data for the reflectance channel. While the distribution of the reflectance values is



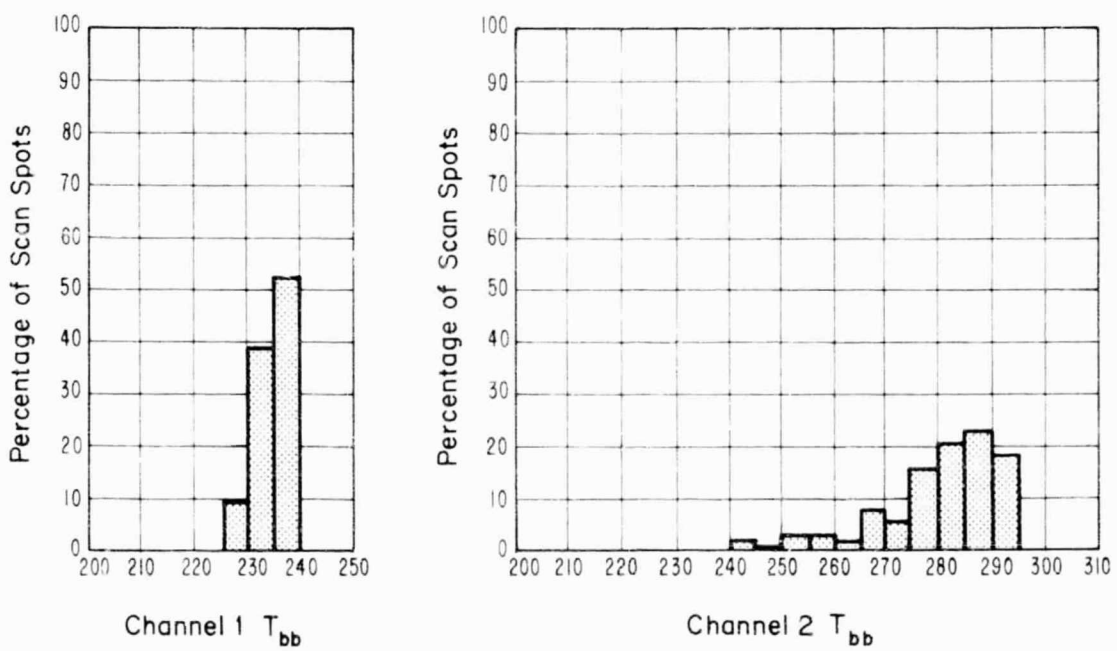


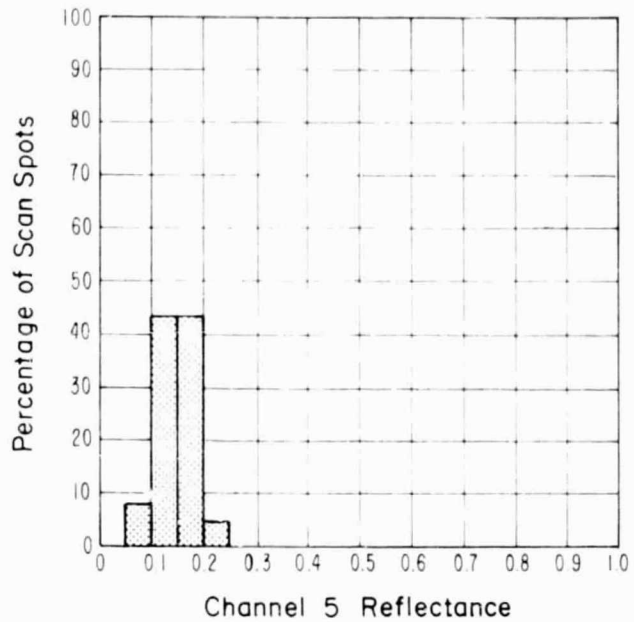
Figure 7-4 Distribution of Radiometric Data from Orbit 857 (18 July) Over Michigan Cirrostratus Overcast, Ranging from 10/10 to 6/10 Opaque, were Reported. The Nonuniform Optical Thickness of the Cloud Cover is Reflected in the Spread of the Channel 2 and Channel 5 Values. In Contrast to the Clear Sky Cases (Figs. 7-1 and 7-3), no Channel 1 Value of >240°K were Measured.

characteristically different from the clear sky cases shown previously, the weight of the values has been shifted only to the .2 - .3 range. It is seen, therefore, that cirrostratus by itself does not constitute a class of bright clouds.

The distribution of the Channel 1 T_{bb} values shown in Figure 7-4 is interesting when compared to that in Figures 7-3 and 7-1 for the clear sky cases. For the cirrostratus case, no value of Channel 1 T_{bb} was found warmer than 240°K. For the clear sky cases, over 90% of the Channel 1 values were warmer than 240°K. The apparent dichotomy of Channel 1 T_{bb} values for clear sky and cloud cover situations is valid for even thin cirrus as is evident in the following case.

The area over Maryland, Virginia and West Virginia for Orbit 857 reported fractional cover by cirrus. The three-channel analysis for this region is shown in Figure 7-5. The distribution of Channel 2 T_{bb} values, with some 76% greater than 290°K, does not indicate significant cloud attenuation in the 10 - 11 μ region. This, however, is not an unexpected result for cirrus. What is more surprising, perhaps, is the distribution of reflectance values, with over 90% falling below 0.2. Furthermore, the overall reflectance of this region is less than that for the clear sky case over Nebraska (Fig. 7-1). It is possible that the difference in scattering angle can account for the higher reflectance values over Nebraska. In any event, the data indicate no significant difference between the reflectance of wheat fields and partial cirrus cover, in spite of the face that the cirrus was quite apparent in the APT photograph.

The association of Channel 1 T_{bb} values $< 240°K$ with cloud contamination was found to be true even for thin cirrus not clearly identifiable in concurrent APT photographs, but which were reported by ground observers. Since Channel 1, besides being sensitive to clouds, is affected by both the water vapor and temperature distribution in the atmosphere, the question is raised as to whether the differences in Channel 1 T_{bb} distribution between the clear sky cases and the cirrus cases were due simply to the differences in these atmospheric parameters. A comparison was therefore made between the radiosonde data for the case of clear skies over Nebraska and of the thin cirrus over Washington. Figure 7-6 shows the plotted radiosonde data for Omaha, Nebraska and for Washington, D. C. Unless substantial changes in upper and middle level moisture and temperature took place between the 1200 GMT soundings and satellite passage (1700 GMT), one is led to the conclusion that the presence of even tenuous cirrus is sufficient to alter the distribution of Channel 1 T_{bb} values.



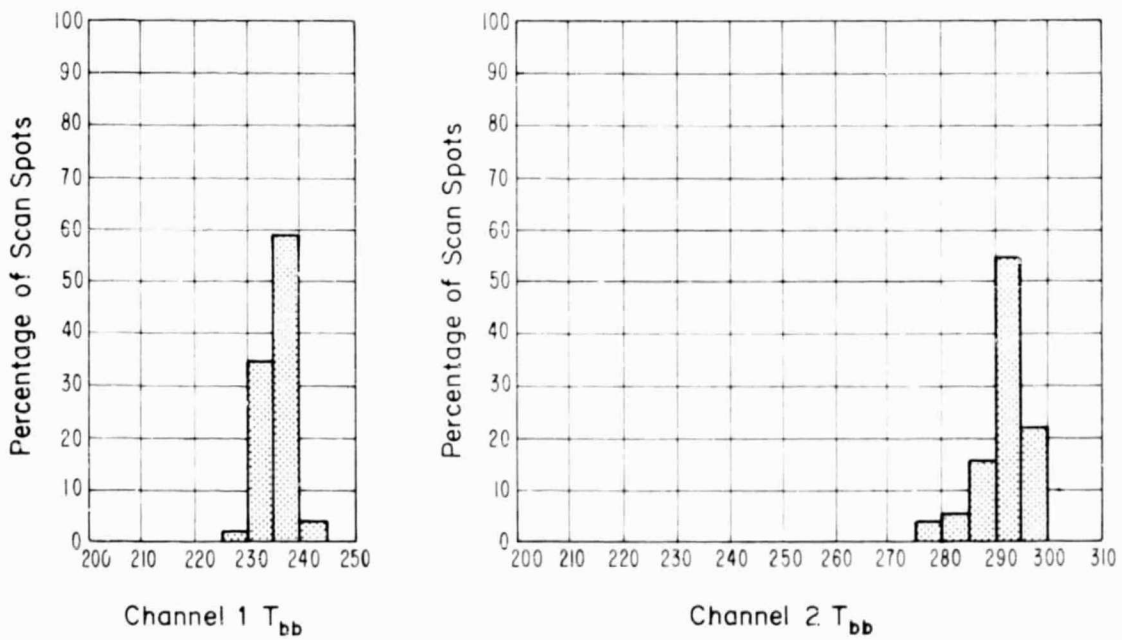
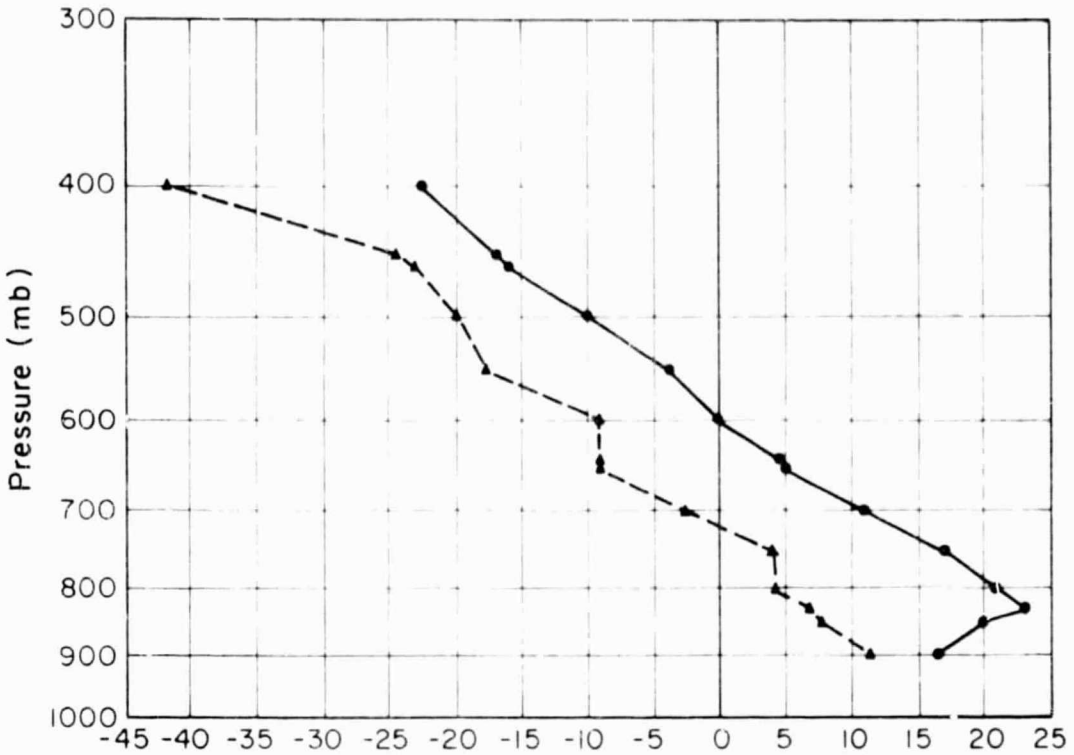
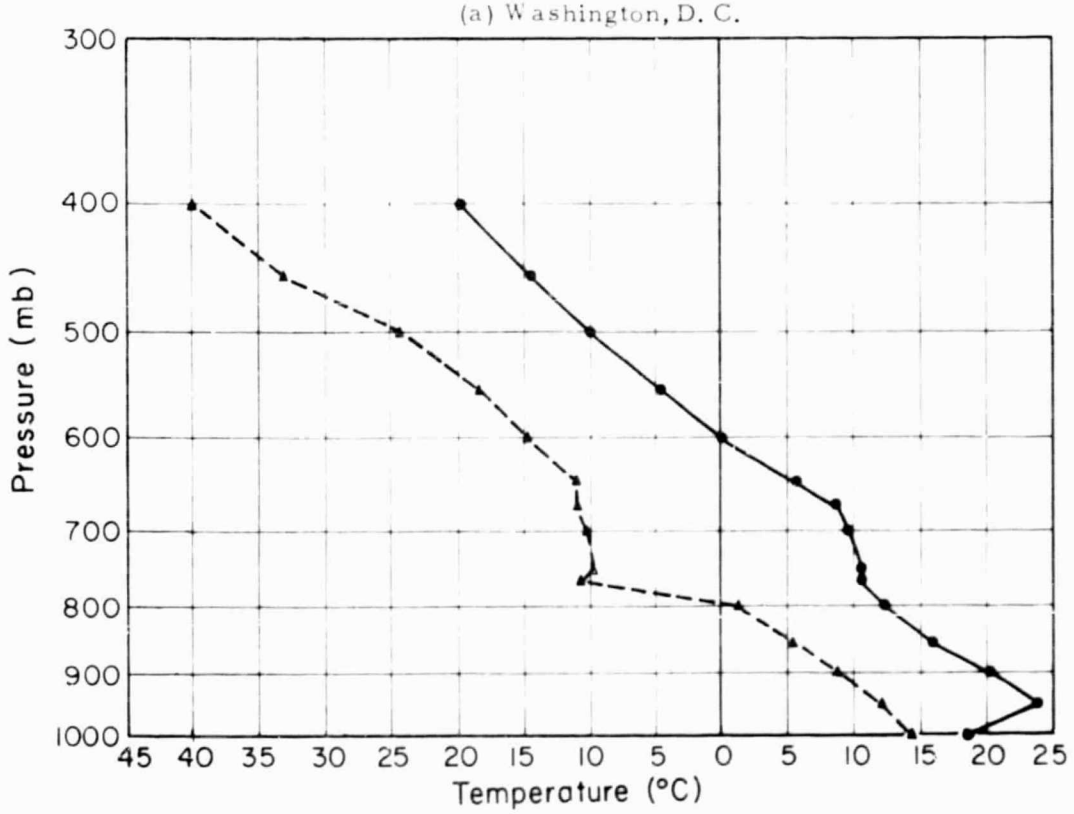


Figure 7-5 Distributions of Radiometric Data from Orbit 857 (18 July) Over the Mid-Atlantic States. Ground Stations Reported Partial Cirrus Coverage. Note the Low Reflectance and Warm Channel 2 T_{bb} Values, Which are Almost Comparable to the Clear Sky Cases (Figs. 7-1 and 7-3). The Channel 1 T_{bb} Values are However Quite Different with Less Than 5% Being Warmer 240°K.



(a) Washington, D. C.



(b) Omaha, Nebraska

Figure 7-6 1200 GMT Radiosonde Data for (a) Washington, D.C. (18 July), and (b) Omaha, Nebraska (7 July)

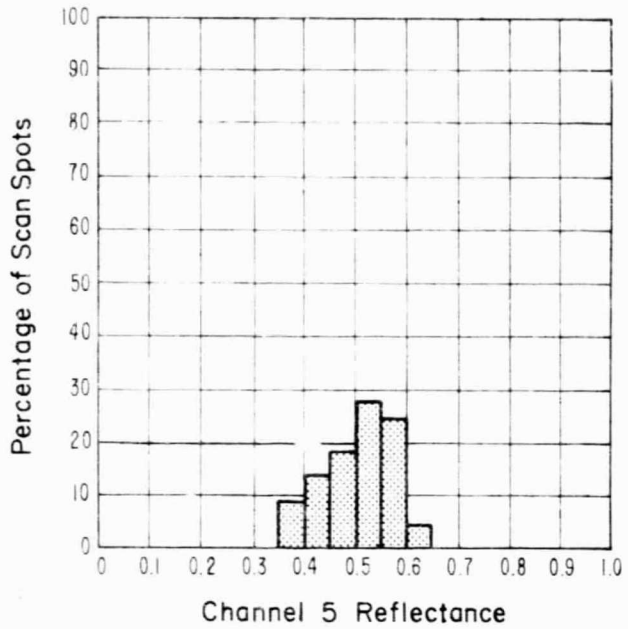
7.3 Stratocumulus and Altocumulus

The predominant cloud types reported during the selected period were various forms of stratus clouds, including stratocumulus, stratus, and altocumulus. In many of the cases in which only stratus or stratocumulus were reported, the distribution of Channel 2 T_{bb} values showed a dominance by higher level altocumulus clouds. Indeed, of the cases investigated (summer), no clear cut case of low stratiform clouds was found over any extended region without the presence of some altocumulus.

A good example of this mixed cloud type occurred over the north eastern states on 6 July. Stations in the southern New England states of New Hampshire, Vermont, Massachusetts, Rhode Island and Connecticut reported 10/10 opaque covered by stratus, stratocumulus, fractostratus and fog, with stratocumulus being reported by stations in the western part of the region. Further west, in New York and the eastern Great Lakes region, altocumulus were reported with some occurrence of stratocumulus. From the surface reports alone, it would appear that this cloud coverage, from the New England coast to the Great Lakes region, should provide a good case for studying the difference in reflectance between low stratus and higher alsocumulus. It would be most interesting, for instance, to note the effects of glaciation in the altocumulus.

Two areas were selected for analysis. The first was over the New England states which reported low clouds. The second area, further west between longitudes 79^{o} and 83^{o} was selected as being representative of altocumulus. The statistical distributions of the radiometric data for the case of reported stratus is shown in Figure 7-7, while those for the case of altocumulus are shown in Figure 7-8.

Consider first the case of the reported stratus. The 1200 GMT (2 hours prior to satellite passage) radiosonde data for Nantucket, shown in Figure 7-9, with saturation from surface to ~950 mb certainly indicate the presence of stratus and fog. The near saturation at 526 mb with a dewpoint spread of only $3^{o}C$, is highly indicative however of the presence of an upper cloud layer probably altocumulus with a thickness of between 10 to 20 thousand feet. The temperature at the top of the second moist layer is approximately $-10^{o}C$ or $263^{o}K$. The distribution of Channel 2 T_{bb} values shown in Figure 7-7 shows that some 44% of the scan spots recorded values between $260^{o}K$ and $265^{o}K$ corresponding to the top of the upper moist or cloud layer. While some values are as warm as $280^{o}K$, the high proportion of colder temperatures indicate that the situation investigated is one of middle clouds over a low cloud overcast and the distribution of the reflectance values shown should be treated accordingly.



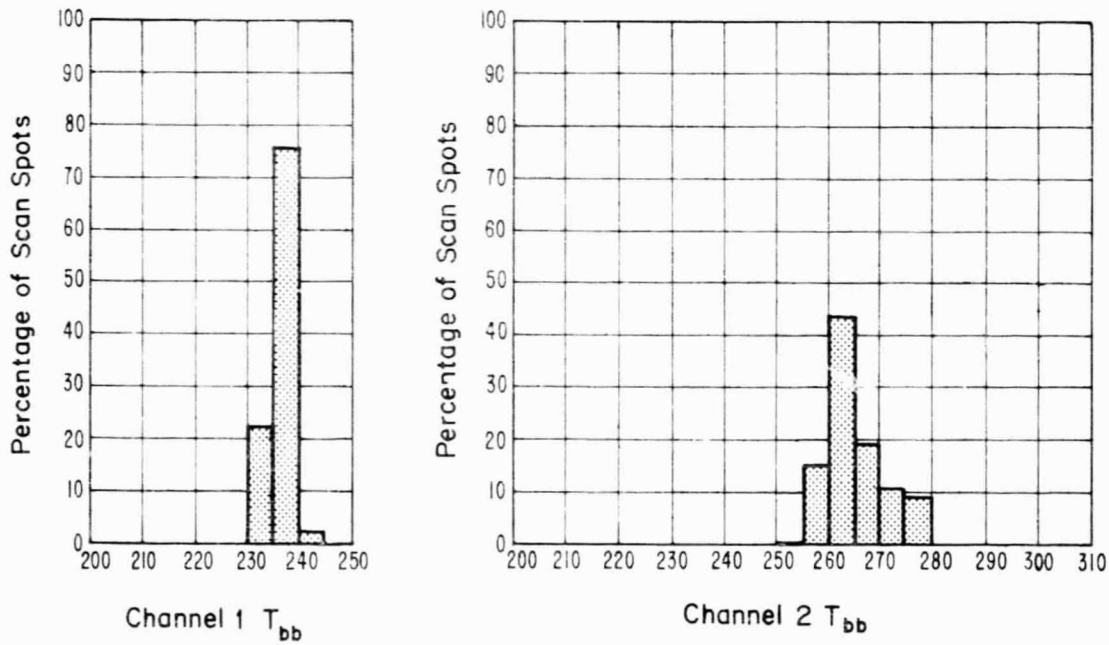
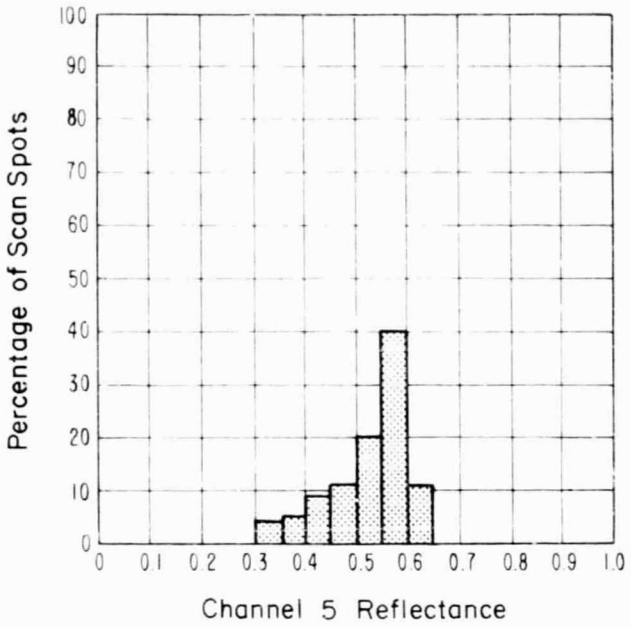


Figure 7-7 Distributions of Radiometric Data from Orbit 697 (6 July) Over the New England States. Surface Reports Indicate 10/10 Coverage by Stratiform Clouds and Fog. The Channel 2 Data, However, Indicate the Presence of Middle Clouds, Probably Altocumulus.



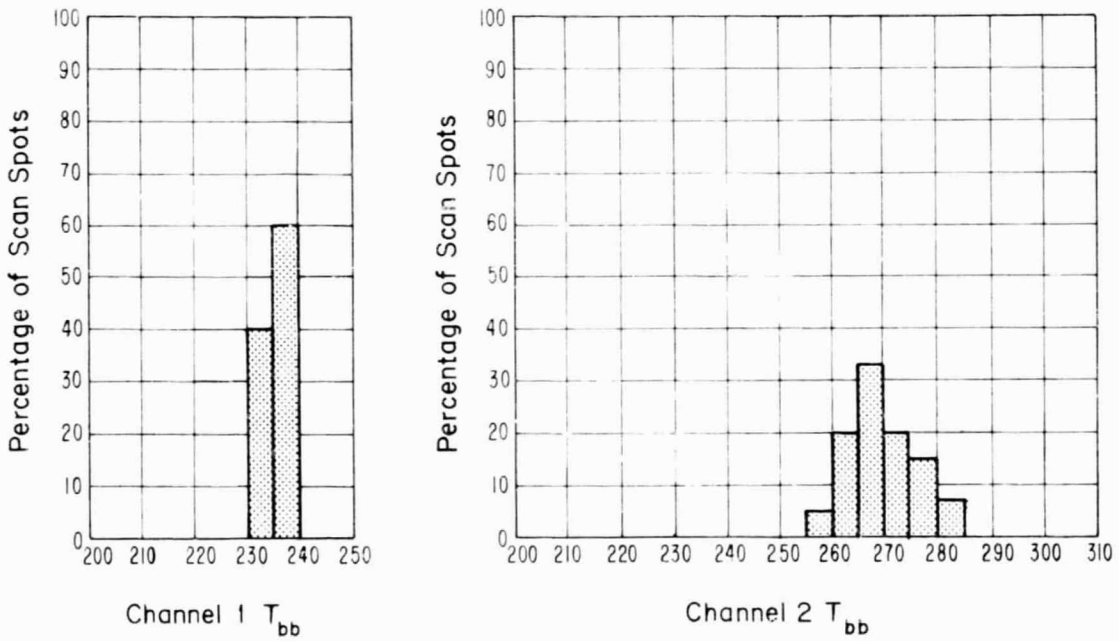


Figure 7-8 Distribution of Radiometric Data from Orbit 697 (6 July) Over the Eastern Great Lakes Region. 10/10 Altocumulus were Reported. This is confirmed by the Channel 2 Data. The Spread in the Reflectance Data is Quite Large. The Large Percentage of the Data Points with Values > 0.5 shows that the Clouds are Relatively Bright.

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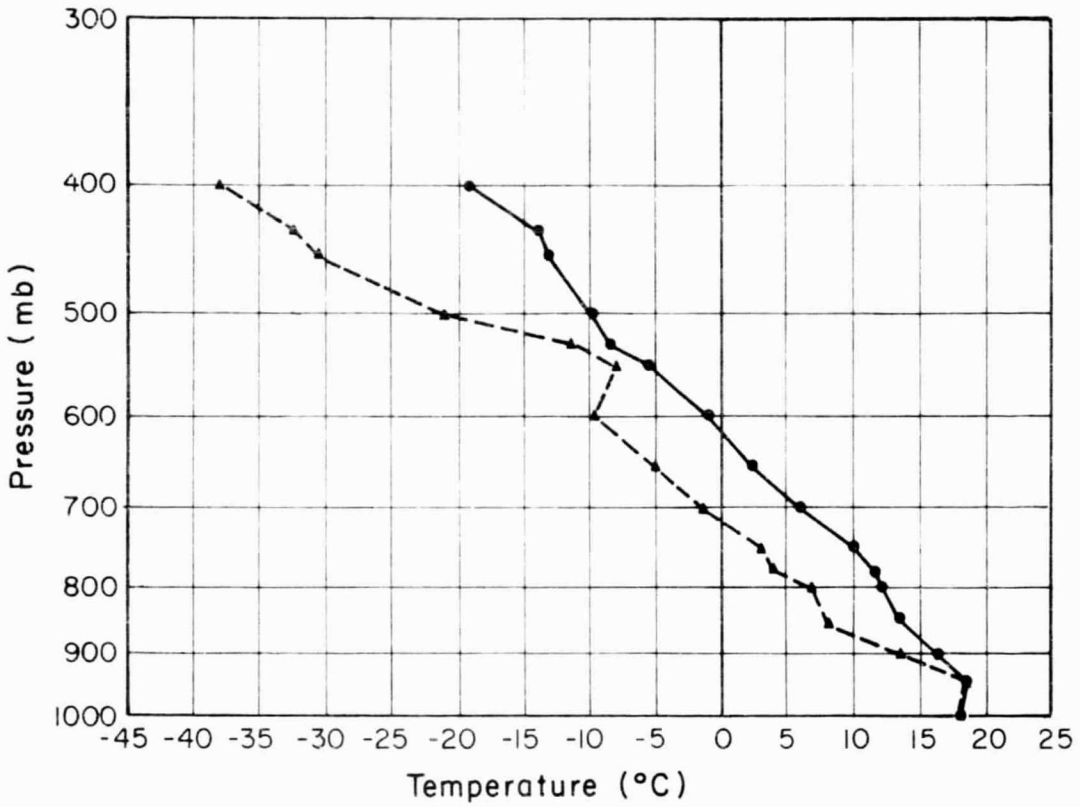


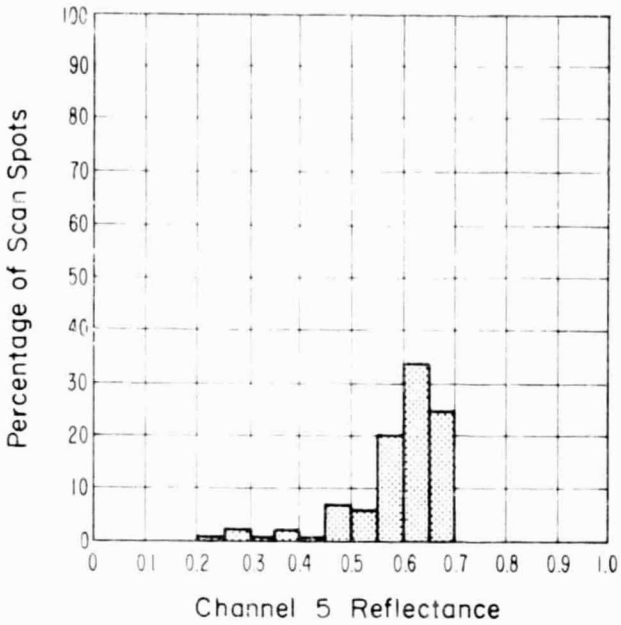
Figure 7-9 Nantucket Radiosonde Data for 6 July 1966 at 1200 GMT

To the west of the New England states, 1200 GMT radiosonde data at Dayton, Ohio, and Pittsburg, Pa., did not show a saturated or stratus layer at the surface. A middle tropospheric moist layer with tops at ~ 6 km were reported, however. The concurrent cloud reports, as stated previously, showed that only altocumulus was present at the time of satellite passage. The distribution of radiometric measurements over this area, shown in Figure 7 8, are not characteristically different from that shown for the New England case. Apparently the albedo of the underlying surface has little or no influence on the reflectance of the upper clouds.

On 15 July, 10/10 opaque sky cover formed by multilayers of low clouds was reported in the Ohio Valley region of Kentucky, West Virginia and northern Tennessee. The upper layer was predominantly stratocumulus. The distributions of radiometric measurements corresponding to this case are shown in Figure 7-10. When these values are compared with those in Figure 7-8 and 7-7, two things are immediately apparent. The reflectance of the clouds over the Ohio Valley was decidedly greater and the Channel 2 T_{bb} values were warmer. While the presence of some middle clouds cannot be discounted because of values of Channel 2 T_{bb} less than 270°K, it cannot be denied that a large percentage of the region was indeed covered by low clouds, with stratocumulus being the most probable upper layer.

The apparent increase in reflectance of the stratocumulus case over that for altocumulus was further compared with a case of altocumulus in which there were glaciated cloud tops. The case selected for comparison occurred on 16 July over the southern United States between longitude 96°W and 92°N. The cloud reports were of 10/10 cover of altocumulus with some cirrostratus. Analysis of the radiometric data for this case are shown in Figure 7-11. The distribution of Channel 2 T_{bb} values, which are significantly colder than those for the previous altocumulus cases, certainly reflects the presence of the reported ice crystal cirrostratus clouds. The distribution of reflectance values, however, shows that these clouds, in spite of the presence of the overlying cirrostratus, are not as bright as the stratocumulus of 15 July. Indeed no characteristic difference in reflectance can be found between this case and the other lower altocumulus cases shown previously.

From the analyses presented so far, it may be concluded that of all the stratiform clouds, low stratus apparently has the higher values of reflectance. Furthermore, for sufficiently thick clouds, such as altocumulus, the albedo of underlying surfaces or overlying thin clouds exerts little or no influence on their reflectance.



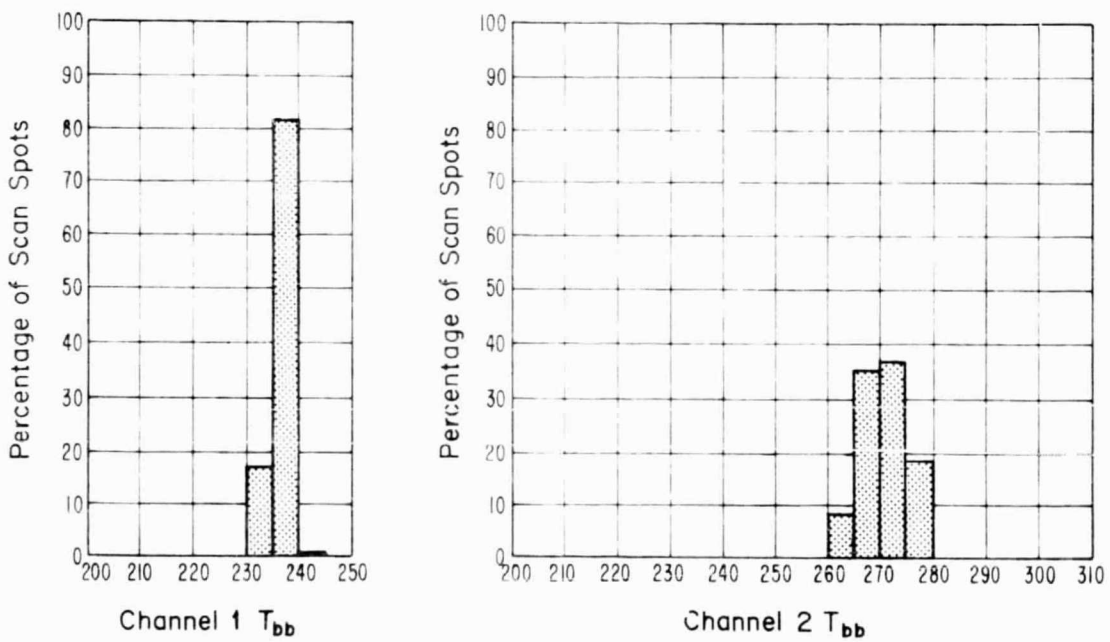
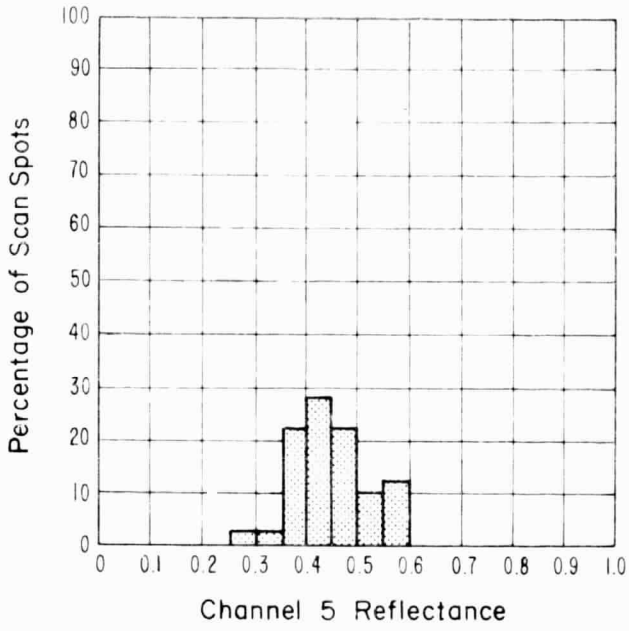


Figure 7-10 Distributions of Radiometric Data from Orbit 817 (15 July) Over the Ohio River Valley. Surface Observations Indicate 10/10 Coverage By Low Clouds, Predominantly Stratocumulus. Note the Possible Presence of Altocumulus Clouds Reflected in Values of Channel 2 T_{bb} Colder than 265°K. The Distribution of the Reflectance Values Show that These Clouds are Slightly More Reflective Than the Ac Shown in Figure 7-9.



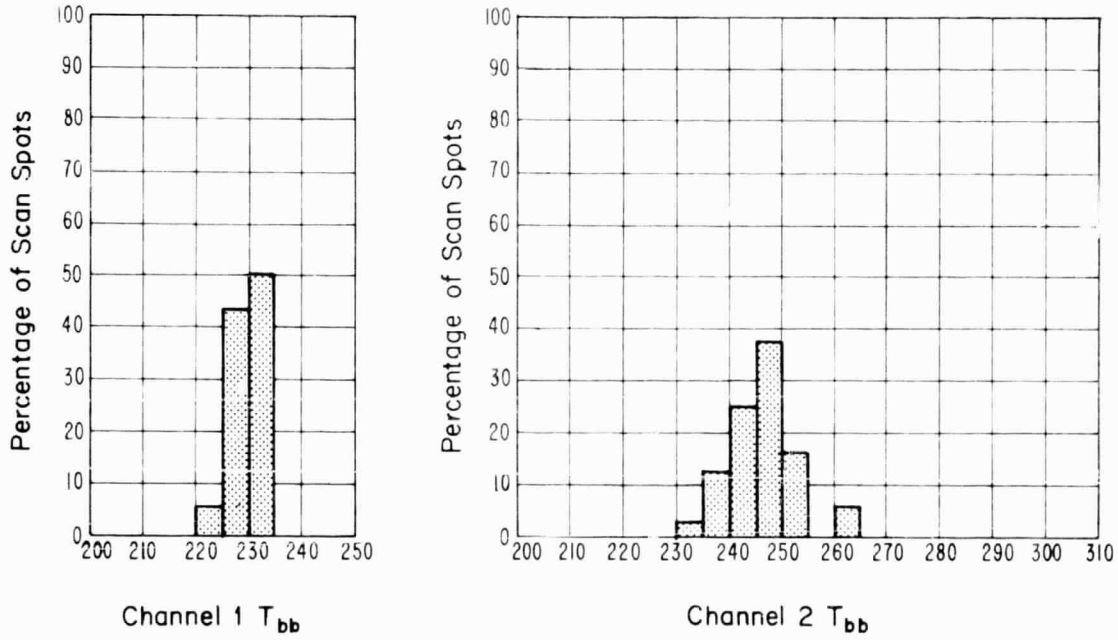


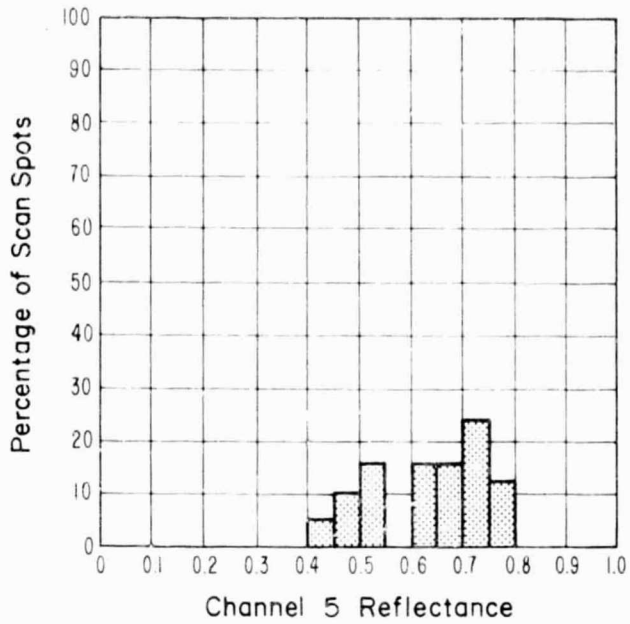
Figure 7-11 Distributions of Radiometric Data from Orbit 831 (16 July) Over Louisiana. The Distribution of Channel 2 T_{bb} Values Shows the Presence of Cirrostratus Over the Reported Altocumulus or at Least Glaciation of the Altocumulus Tops Compared to the Data in Figures 7-10 and 7-9, the Presence of Substantial Layer Ice Crystals has Apparently no Significant Influence on Cloud Reflectance.

7.4 Cumuliform Clouds

The analysis of cumulus and cumulonimbus clouds using the technique adopted in this study is basically more difficult than that of the stratiform clouds. Clear cut cases of cumulus with no other type of attendant clouds usually only occur as fair weather cumulus. Under these conditions, the sky coverage is low, probably 5/10 or less, and the spatial distribution of coverage is likely to be variable. The lateral extent of individual cumulus elements are sufficiently small so that the question of sensor resolution relative to target size becomes significant. With the resolution of the MRIR at 60 km and the average extent of a cumulus element on the order of 1 km, the probability of clouds filling the total field of view of the sensor is extremely low even for high percentages of sky cover. Cumulonimbus complexes are larger in extent than cumulus elements. However, in terms of total sky coverage, they are generally isolated phenomena penetrating above a deck of lower clouds such as altocumulus. Because of the large gradients in cloud top altitude and thickness at the edges of these cumulonimbus complexes, a variety of optical characteristics can be expected.

An example of the large gradients in cloud top heights found over cumulonimbus can be seen in the data presented previously in Figure 6-2. In this instance, as in all cases studied, the cumulonimbus complex was embedded in a field of altocumulus. The sharp gradients in both the Channel 2 T_{bb} and reflectance result from the combined effects of sensor resolution and target element size. On a larger scale, these problems of cloud size and distribution are manifested in large spreads in the radiometric values as evident in Figure 7-12. The data shown in this figure were taken from Orbit 884 (20 July) over central Alabama. The concurrent APT photograph showed a large bright complex of clouds in this region which were confirmed to be cumulonimbus and altocumulus by ground station reports. It was not possible to properly delineate the region for analysis based on the ground reports alone due to the poor station density and isolated nature of the cloud complex. Use had to be made of the APT photograph in conjunction with the ground reports. Because of the limited area of obvious cumulonimbus coverage, the total number of data points available for analysis - only 49 - was significantly lower than those generally available for the stratiform clouds.

The distributions of radiometric measurements in Figure 7-12 show large spreads in the data for all channels as expected. What perhaps is surprising is the obvious break in the distributions of reflectance and Channel 2 values into two



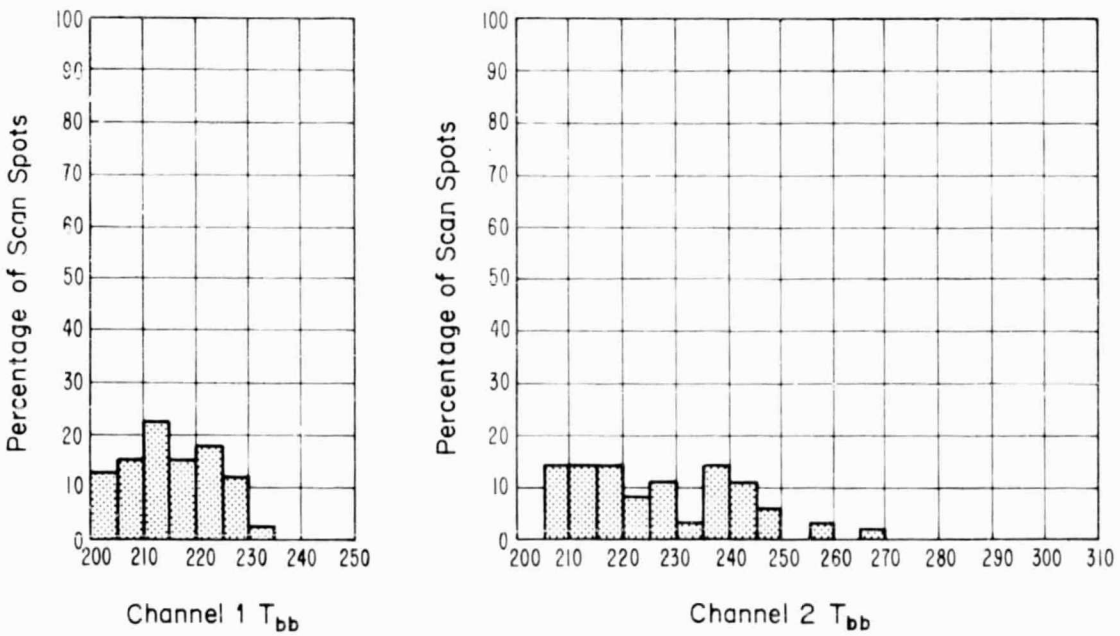


Figure 7-12 Distributions of Radiometric Data from Orbit 884 (20 July) Over Alabama. 10/10 Coverage by Cumulonimbus and Altocumulus were Reported. Note the Large Spread of the Data in All Channels and the Separations into Two Distinct Distributions in the Data from Channels 2 and 5. The Warmer Channel 2 Values are Probably Associated with the Reported Ac.

separate distributions. In the Channel 2 values, the break occurs between 230°K and 235°K, while the break in the reflectance data is between 0.55 and 0.60. The warmer temperatures, > 235°K, and the associated lower reflectance, < .055, are characteristic of altocumulus and reflect the presence of this cloud type in which the cumulonimbus was embedded. Undoubtedly, higher reflectance values and colder temperatures correspond to the cumulonimbus themselves. The reflectance of the cumulonimbi are expectedly high, much higher than any of the stratiform clouds discussed previously

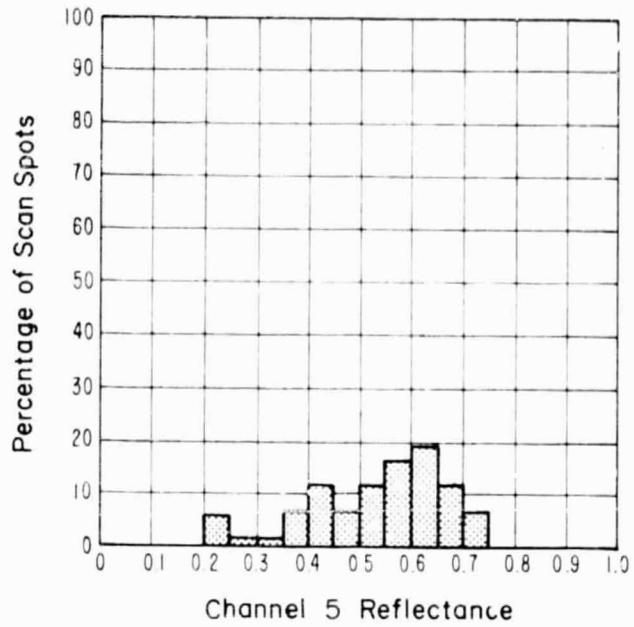
A second region, over the Florida Panhandle, also reported cumulonimbus. From the APT photograph, it was evident that the clouds extended southward into the Gulf of Mexico and the area for analysis was selected accordingly. Again, the number of data points included in the analysis was of the order of 50. The results are shown in Figure 7-13.

Compared to the distributions for the Alabama case, the separation into the two different cloud types, cumulonimbus and altocumulus, is just as evident in the Channel 2 data with the separation again occurring at 240°K. In the reflectance channel, the separation, though less obvious, can still be detected between 0.45 and 0.50.

London, in his study of the albedo of the earth, assigned the same high albedo value of 70% for both cumulonimbus and cumulus. Over individual cumulonimbus complexes, the albedo can undoubtedly reach such high values. It is difficult to see, however, how cumulus with its lower water content can attain the 70% albedo specified by London.

A typical case of cumulus occurred over Florida on 18 July. The surface reports indicated coverage of greater than 5/10. The concurrent APT photograph showed that the cumulus field extended into the Gulf of Mexico. By dividing the area of cumulus coverage into two separate cases, one over the Florida Peninsula, and the other over the waters of the Gulf, it was possible to investigate the reflectance of cumulus and the effect of the albedo of the underlying surface on reflectance.

The radiometric data analyses for the case over Florida are shown in Figure 7-14. The distribution of Channel 2 T_{bb} values shows that the reported cumulus did not extend very high into the atmosphere and is quite typical of fair weather cumulus. The reflectance over the whole region was not high with maximum values of individual scan spots being 0.3. These relatively low values undoubtedly are due in part to the size of the cells relative to the resolution of the sensor. The data for the case over the Gulf is shown in Figure 7-15. Again the reflectance is low. Compared to the data shown in Figure 7-14, there is a greater percentage of



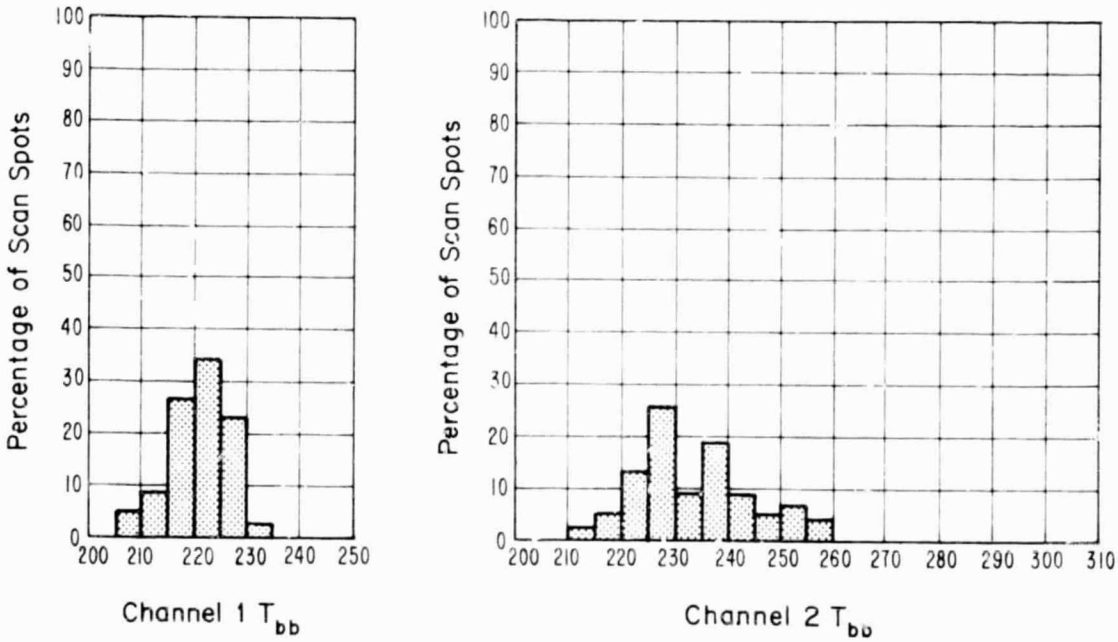


Figure 7-13 Distributions of Radiometric Data from Orbit 884 (20 July) Over Florida. 10/10 Cumulonimbus and Altocumulus were Reported. Again, Note the High Values of Reflectance and the Distinct Breaks in the Distributions of Channel 2 and Channel 5 Data.

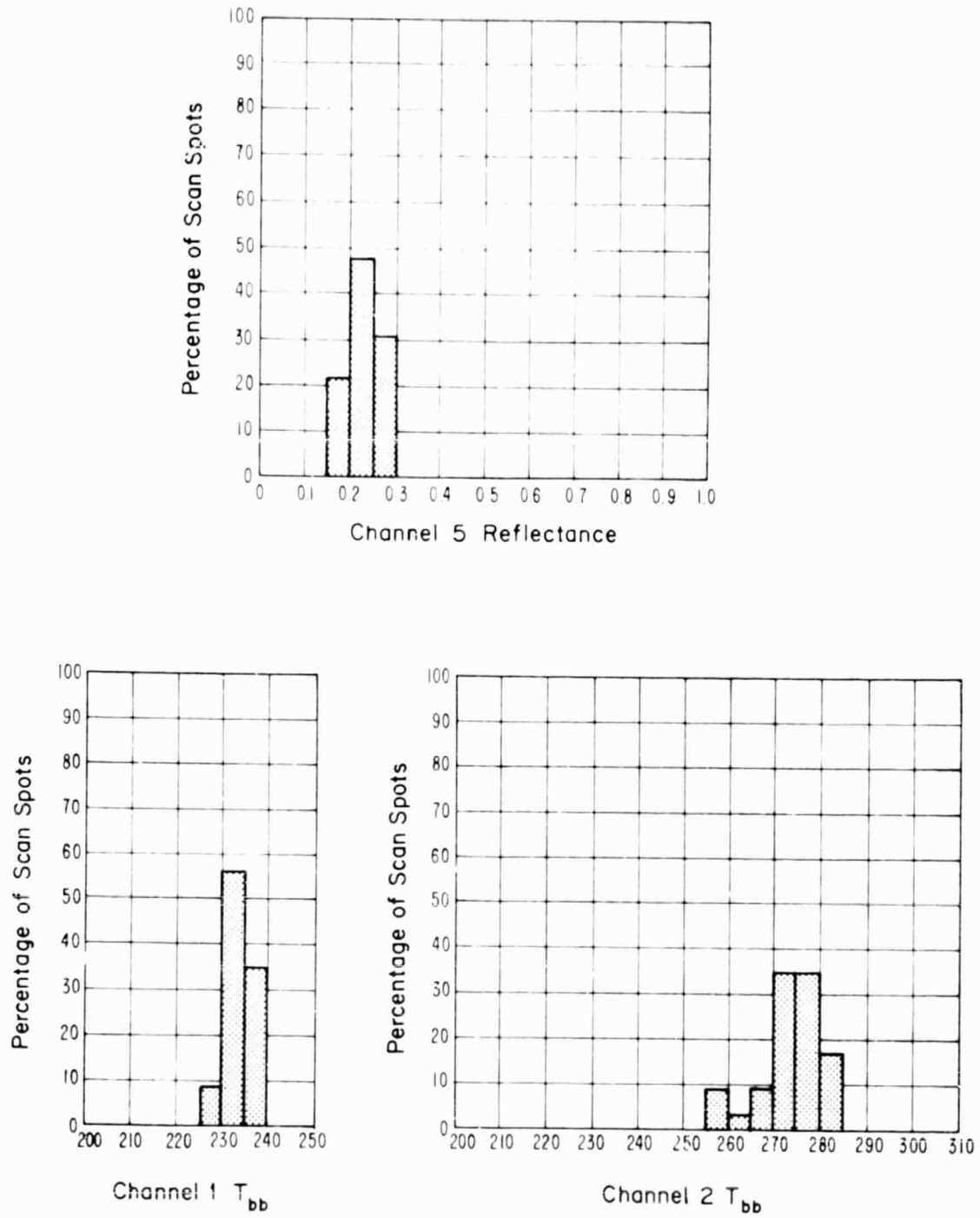
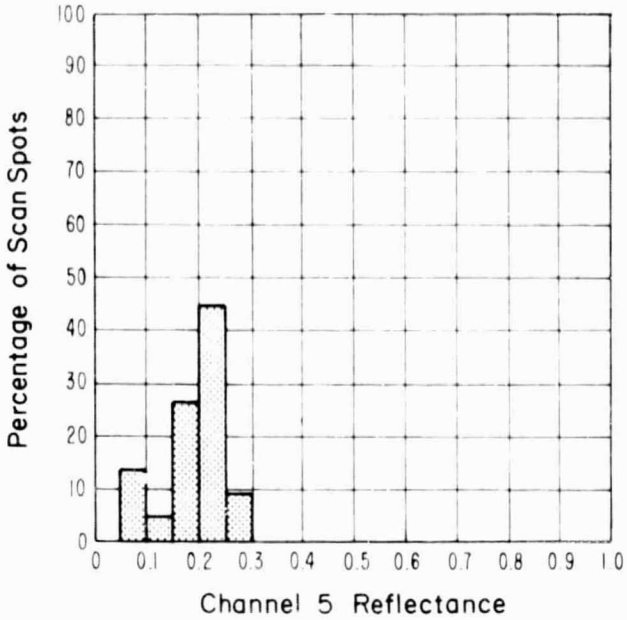


Figure 7-14 Distributions of Radiometric Data from Orbit 857 (18 July) Over Florida. Surface Reports Indicate >5/10 Coverage by Cumulus. Note the Low Reflectance Values Measured Over the Area.



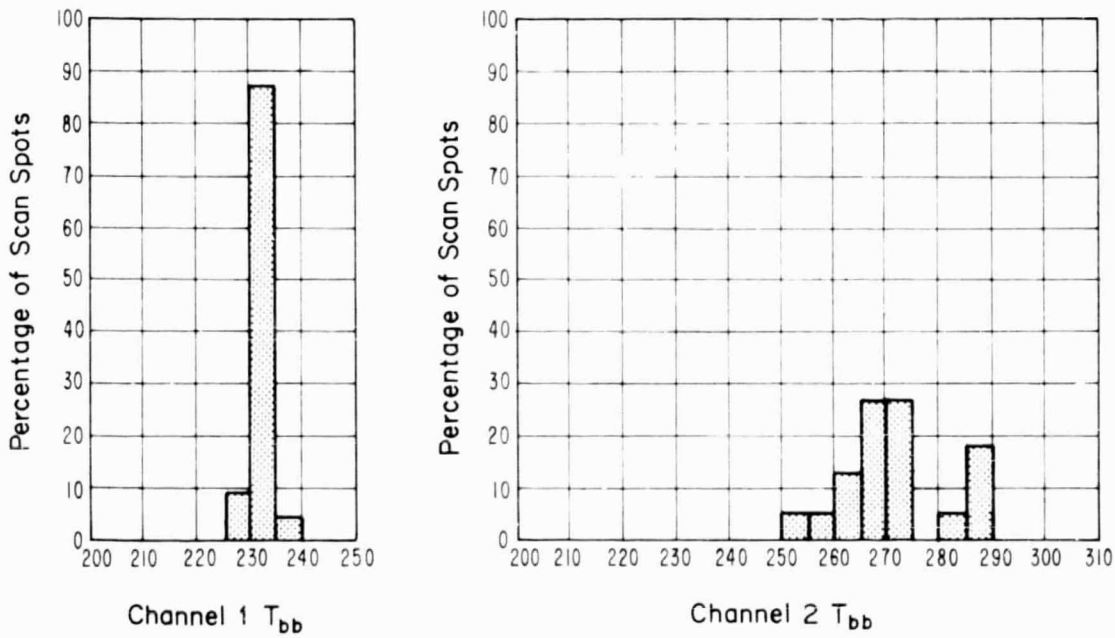


Figure 7-15 Distributions of Radiometric Data from Orbit 857 (18 July) Over the Water of the Gulf Adjacent to Florida. Concurrent APT Photograph Shows that the Cumulus Reported Over Florida Extended into this Region of the Gulf. Again, the Reflectance Values are Low. Compared to the Data in Figure 7-14 the Larger Percentage of Data Points having Reflectance Less Than 0.2 Over tnis Region is Probably Associated with the Lower Percentage of Cloud Cover as Reflected in the Channel 2 Data.

data points with reflectance lower than 0.2. At first glance, this may be attributed to the lower albedo of the underlying ocean surface. However, the surprisingly large number of data points with Channel 2 T_{bb} values in excess of 285°K suggests that the lower reflectance may also be due to the larger breaks in the cloud field. Note, however, that in spite of the large number of points having warm Channel 2 T_{bb} values, no Channel 1 T_{bb} value warmer than 240°K was found.

7.5 Discussion of Results

The results of the reflectance analyses are summarized in Figure 7-16, in which the probable spread in reflectance for each of the cloud types analyzed is separately plotted. For a relative comparison, London's (1957) albedo values are shown in the following table.

Table 7-1

Cloud Albedos (London, 1957)

Cloud Type	Albedo Min	Albedo Max	Cloud Type	Albedo Min	Albedo Max
St	56	65	Cb	70	70
Ns	70	73	As	48	52
Cu	70	70	Ci	16	23

The brightest class of clouds, as expected, is cumulonimbus. It also has one of the largest spreads in reflectance values. It was noted previously that this spread resulted from the large variations in cloud thickness. Similarly, altocumulus with its "lumpy" surface has an equally large spread in reflectance. The spread in the case of cirrostratus is probably due not so much to variations in geometric thickness, as to variations in ice crystal content and size distribution.

The data presented in Figure 7-16 cannot be directly compared to measurements made by hemispherical devices. However, narrow beam MRIR type measurements have been made recently. Cherrix and Sparkman (1967) obtained bidirectional reflectance measurements of stratus from aircraft with an MRIR device having the same spectral response function as that used in Nimbus II. The range of reflectance values for stratus shown in Figure 7-16 compares well with their bidirectional

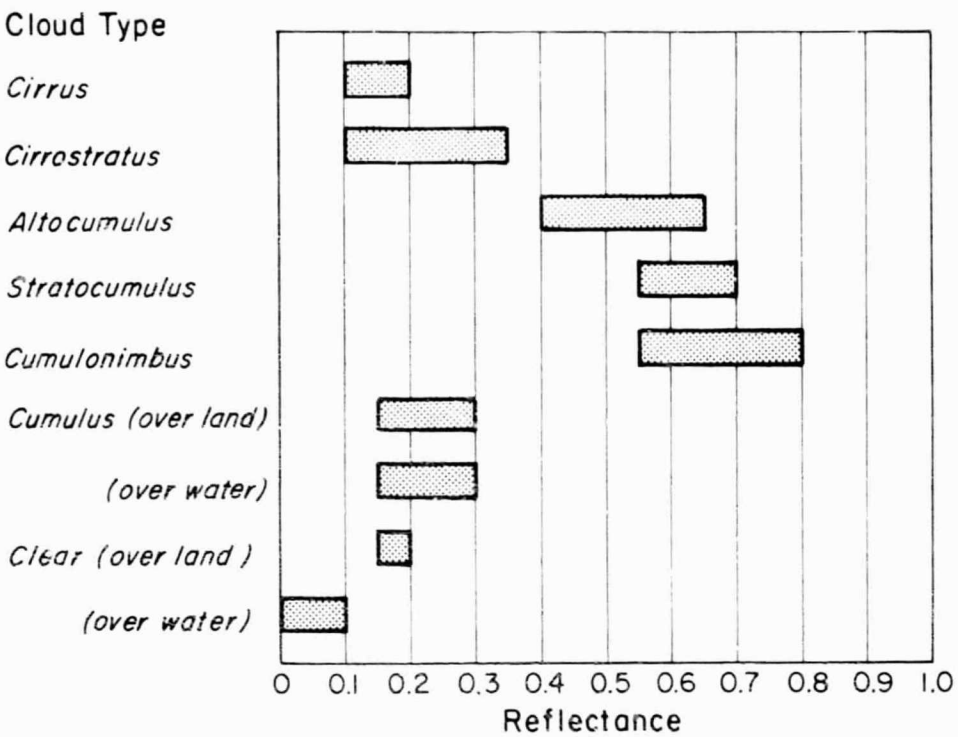


Figure 7-16 Summary of the Probable Spread of Reflectance for Each of the Cloud Types Analyzed

reflectance values for the range of aircraft sensor nadir angles restricted to near zero degrees. Systematic bidirectional reflectance measurements for other cloud types are not, however, available. In an earlier study of the TIROS television camera data, Conover (1965) deduced bidirectional reflectance values for various cloud types. With the exception of cases involving cirrus and cumulonimbus, the results of this study compare well with his values. For cirrus over land, he arrived at a value of 36% which is high, higher than the value he derived for cirrostratus. His value of 92% for cumulonimbus is somewhat higher than those derived in this study.

8. EVALUATION AND CONCLUSIONS

The results of the single station cloud cover analysis, applicable to the summer season, indicate an overall good agreement between satellite and surface observed cloud amounts when the viewed area sizes are similar. Although the mean cloud amounts derived from the AVCS data sample implied an underestimation by the satellite, particularly when compared with the surface reported total cloud amount, no such indication was evident from the more extensive analyses carried out using the higher quality APT photography.

In particular, the high correlation between satellite and surface observed cloud amounts for the sample consisting of less than four or greater than seven tenths sky cover did not reveal either an underestimation or overestimation by the satellite. The wide scatter of data points when the surface amount was near 50% sky cover can probably be attributed to a difficulty in accurately determining these cloud amounts by both the person viewing cloud from the ground and the person interpreting the satellite photograph.

The analyses of various cloud types did not indicate a significant discrepancy when scattered cumulus clouds are viewed from space or from the ground. Although there was some evidence that small amounts of cumulus may not be "seen" by the satellite, the greatest overall differences between satellite and surface observations were found for cirrus cloud. Cirrus reported by the ground observer is often not detected from space. A similar conclusion, with regard to cirrus cloud, can be drawn from the results of the reflectance analyses.

Thus, for climatological purposes, satellite cloud amounts extracted for circular areas of about 1/2 degree latitude diameter (30 n mi) can be considered to form a sample compatible with surface observations. In problems applicable to determining the probability of seeing the earth's surface from space, the low correlation for middle cloud amounts would not be significant, since the prime interest is not in these cloud amounts, but rather in the occurrence of nearly clear or nearly overcast conditions. The results of previous studies, indicating an underestimation of cloud cover in satellite data when compared with surface observations, may be due to the use of nephanalyses in which cloudiness is integrated over larger areas, satellite observations taken at different times than the surface observations, or satellite pictures of lower quality than the Nimbus II APT. The problems caused by picture noise when extracting cloud data are evident in the results of the analyses based on Nimbus II AVCS photography.

Based on the results of this study, it does not appear that the ground observer significantly overestimates cloud amounts, in comparison with the true "earth cover" as observed from space, when scattered cumulus clouds exist. For the area which he views, the observer probably estimates the cloudiness fairly accurately. The observed difference between the albedo value as measured by satellite and as computed from ground viewed cloud data cannot, therefore, be attributed solely to an overestimation of cloud amount in tropical regions.

It should be pointed out, however, that the results of the cloud cover analyses were based on comparisons between reported and depicted cloud cover over a very limited area. With the ground observed data, spatial continuity of cloud observations are not available except possibly over the dense station network in northeastern United States. This lack of continuous, or at least contiguous, observations was found to introduce ambiguities in estimates of cloud cover over a larger region.

In the presence of stratiform clouds, the extrapolation of cloud cover amounts into areas of no data can in general be made with some confidence based on reports from scattered ground observation stations. The highly localized nature of cumulonimbus, on the other hand, makes it difficult to perform any reasonable extrapolation based on ground reports alone. Initial attempts to specify the cloud coverage by cloud type over regions reporting cumulonimbus overestimated the areal coverage by this cloud type when the concurrent Channel 2 and Channel 5 radiometric data were analyzed. An overestimation of the cumulonimbus cloud field would result in a higher estimate of the albedo. Because of the high values of reflectance and albedo associated with this cloud type, small differences in cloud cover estimates can result in large differences in albedo. Since cumulonimbus clouds occur most frequently in lower latitudes, the latitudinal dependence of the discrepancy between albedo computed by London and those derived from satellite data may be attributed, at least in part, to this effect.

The low reflectance values found in areas reporting cumulus cloud, both in the subjective estimates and objective measurements, also appear to be a contributing factor. London assigned a value of 70% to the albedo of cumulus. For an area reporting 50% cumulus coverage, a mean albedo of 0.43 (including contributions from the surface) would be obtained using London's values. For the same type of cumulus coverage, the results of this study show that the highest reflectance measured was 0.30. It is doubtful that the large difference can be attributed to anisotropic effects alone. An overestimation of the albedo of cumulus by London is more likely the cause.

Thus, the discrepancy in albedo values noted at low latitudes is concluded to be

more the result of an overestimation of reflectance than of cloud amount. The reflectance integrated over an area, particularly for cellular cloudiness (cumulus and cumulonimbus), is significantly less than that derived by London, based on values assigned to individual cloud types (Table 7-1) In accordance with London's average cloud distributions for the summer season, this effect would be most pronounced from 0^{o} to about 30^{o} latitude; in that region the largest percentage of cumulus and cumulonimbus cloud is observed.

An interesting result from the analyses presented in Section 7 is the possibility of developing techniques for cloud type discrimination. It is well-known that for sufficiently thick clouds, the temperature measured by Channel 2 approximates that of the cloud top. For these clouds the Channel 2 T_{bb} values provide a means of classification into height regimes. However, it has been pointed out that thin cirrus and scattered cumulus are often not readily apparent in the Channel 2 data. Identification of low stratus with cloud top temperatures not much colder than the surface is also difficult if Channel 2 T_{bb} values alone are used. Channel 2 T_{bb} values alone, therefore, cannot provide unambiguous definitions of the cloud field.

It appears from the radiometric data analyses presented in Section 7, that the use of the data from Channels 1 and 5 would be advantageous in minimizing ambiguities inherent in the Channel 2 data. Over cloud covered regions, the Channel 1 T_{bb} values were almost invariably colder than $240^{o}K$. This was found to be true even for cases of low percentage of sky cover by thin cirrus and scattered cumulus. Stratus, on the other hand, has a high reflectance value, almost as high as cumulonimbus. Analysis of data from Channels 2 and 5 would provide a means of detecting the presence of stratus and also of delineating it from the higher and colder cumulonimbus.

A unique three-channel signature, therefore, is associated with each of the cloud types, giving rise to the speculation that these signatures can be used in cloud type identification. At this time, however, it is not certain whether or not the uniqueness in the signatures is due simply to the rather restrictive conditions placed on the selection of cases. A related question, not investigated in detail, is the applicability of the signatures to complex mixed cloud covered situations. In this regard, the results obtained for the cases of cumulonimbus embedded in altocumulus are encouraging.

It is recommended that identification of cloud types by their three-channel signatures be pursued further, through additional studies. The development of an objective cloud type identification technique would greatly advance satellite data application in meteorology

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