Cloud Analysis from Bi-Spectral Satellite Data

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September, 1978

ABSTRACT

A horizontal differencing bi-spectral technique has been developed which includes an iteration scheme for reducing errors in computed cloud amount. The technique requires that cloud surfaces over the area of application be horizontally homogeneous, and as developed, assumes that the observed maximum and minimum brightness counts represent cloud and clear filled resolution points respectively. These values are then used to normalize the data in computing total cloud amount.

The computed results of the horizontal differencing bi-spectral method, as applied to real data sets, have been compared to the results obtained from a modified frequency distribution method and the general bi-spectral method. The results of this comparative analysis indicate that the computed cloud amounts of the horizontal differencing method are less variable than for the frequency distribution and general bi-spectral methods, and are thus better suited for objective analyses. The computed cloud temperatures of the horizontal differencing method were also shown to be more realistic than those computed by the general bi-spectral method.

As developed in this report, the horizontal differencing bi-spectral method uses observed visible spectral data to compute cloud amount, cloud radiance, and clear radiance. When applied to Synchronous Meteorological Satellite (SMS) data, the method allows the computed cloud and clear radiance values to be compared to observed infrared spectral values. The iteration technique uses this comparison of computed vs. observed radiance values to determine which observed spectral

values (visible or infrared) best represent cloud and clear surfaces. Once determined, these best values are used to recompute total cloud amount. The effectiveness of the iteration scheme has been examined using both objective and comparative type analyses. The results of these analyses show the iteration scheme to be a moderately effective method for reducing errors in the computed values of the horizontal differencing bi-spectral technique.

The opposing areal requirements of the two explicit assumptions in the horizontal differencing bi-spectral method (that cloud surfaces be horizontally homogeneous, and that the observed maximum and minimum brightness counts represent cloud and clear filled resolution points respectively), leads to the concept of an optimum area size: one that is small enough to be homogeneous, but also large enough to include cloud filled and cloud free resolution points. In defining this optimum area size for two tropical cloud regimes (convective and stratiform), several specific tests have been applied to real SMS data sets. The results of these tests show the optimum area size to be near 125 Km^2 for the convective regime and near 100 Km^2 for the stratiform regime.

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1.0 INTRODUCTION

The objective determination of cloud amount and cloud height is an important part of many meteorological studies using satellite data: radiation studies of the earth/atmosphere system make extensive use of cloud data; estimating winds from cloud tracers requires the precise knowledge of cloud height; and accurate cloud information is essential to very short range forecasting techniques. In one of the earliest attempts to determine cloud amount and cloud type from satellite photographs, Conover (1962, 1963) categorized cloud fields into structural patterns and gray shades, which could then be objectively analyzed. Other early attempts, designed for use with infrared as well as visible data, were developed by Rasool (1964), Wexler (1964), and Maykut (1964). These early methods suffered degradation both from the unknown radiative properties of clouds, and from the coarse ground spatial resolution of the contemporary satellites.

Fujita and Grandoso (1967) proposed a two-radiance model for determining cloud properties which anticipated the availability of matched high resolution visible and infrared satellite radiation data. Such bi-spectral or multi-spectral techniques involve the simultaneous viewing of a single cloud field in two or more radiation spectra. The two-radiance model of Fujita and Grandoso was designed to measure "equivalent" cloud properties rather than actual cloud properties: that is, a particular cloud field was found to have the reflective properties of an equivalent "whitebody" or isotropic reflector, or to have the emissive properties of an equivalent blackbody emitter. More sophisticated bi-spectral and multi-spectral techniques, designed to measure actual

cloud properties, have recently been developed by Vonder Haar (1970),
Reynolds and Vonder Haar (1977), Shenk and Holub (1972), and Mosher
(1974). The further development of these latter techniques is desir-
able because they offer an effective means of gathering cloud informa-
tion with a minimum amount of data processing.

Whereas in recent years observational meteorological satellites
have had ever improving ground spatial resolution, actual use of such
high resolution data has been limited because of the inordinate amount
of digital storage space and processing time it requires. This problem
of data assimilation has recently been demonstrated during the pro-
cessing of the Synchronous Meteorological Satellite (SMS) data for the
GARP Atlantic Tropical Experiment (GATE). In preparing the SMS data for
dissemination, full resolution infrared data (2 by 4 mile) were retain-
ed. However, the full resolution visible data (1/2 by 1/2 mile) were
reduced by averaging 4 by 4 sub arrays to produce 2 by 2 mile resolution
data. Even so, two thousand reels of tape (nine track, 2400 feet per
reel) were required to record the original 85 days of data. Determining
cloud amount over a square area 500 km on a side, for example, from a
frequency distribution of visible brightness counts taken from the
original recordings, would require the digital processing of approxi-
mately 2.0×10^6 data bits. In contrast to this, the bi-spectral tech-
nique proposed by Reynolds and Vonder Haar (1977) would require only
two averaged cloud radiance values (one for each spectral interval)
to determine cloud amount and cloud height over a given area. Once
perfected, such bi-spectral techniques could essentially eliminate the
need for mass data handling by both the original data collection
center and the operational user.

A basic assumption that all of the most recently developed bi-spectral and multi-spectral techniques have in common is that cloud surfaces across the area of application be horizontally homogeneous, and at approximately the same level. This assumption places areal limitations on the methods that have yet to be determined. The goal of the present study is to objectively define the areal limits over which such methods may be most effectively applied. A secondary objective is to test the effectiveness of a modified bi-spectral technique that includes an iterative scheme for computing cloud amounts.

2.0   THE HORIZONTAL DIFFERENCING METHOD

2.1   The general bi-spectral technique

The general bi-spectral method of objectively determining cloud amount and cloud height as given by Reynolds and Vonder Haar (1977) involves the use of simultaneous visible and infrared satellite measured radiance data.   Consider a single measurement array containing a fraction of its total area covered with clouds (NCLD in tenths) and the remaining fraction covered with clear area (NCLR in tenths).
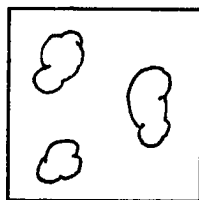
The magnitude of the shortwave (visible) measured radiance (M_s) for the total area may be assumed to arise from:

$$M_s = H_s \, (\text{NCLD ACLD} + \text{NCLR ACLR}) \tag{1}$$

where: M_s = measured shortwave spectral radiance of the total area

H_s = constant solar irradiance in the shortwave spectral interval

NCLD = fraction of the area covered by clouds

ACLD = albedo of the area covered by clouds

NCLR = fraction of the area which is cloud free

ACLR = albedo of the area which is cloud free.

Similarly, the magnitude of the longwave (infrared) spectral radiance (M_ℓ) for the total area may be assumed to arise from:

$$M_\ell = NCLD \ ICLD + NCLR \ ICLR \qquad (2)$$

where:
M_ℓ = measured longwave spectral radiance of the total area

NCLD = fraction of the area covered by clouds

ICLD = longwave spectral radiance of the area covered by clouds

NCLR = fraction of the area which is cloud free

ICLR = longwave spectral radiance of the area which is cloud free.

The implied relationship

$$NCLD + NCLR = 1.0 \qquad (3)$$

allows equations (2) and (3) to be solved for the desired unknowns, NCLD and ICLD.

$$NCLD = \frac{M_s - ACLR \ H_s}{H_s \ (ACLD - ACLR)} \qquad (4)$$

$$ICLD = \frac{M_\ell - ICLR}{NCLD} + ICLR. \qquad (5)$$

The cloud top temperature may then be computed from ICLD using the

Planck function and an assumed cloud emissivity, and the cloud height

can be determined from a knowledge of the vertical temperature profile.

Formally, the general bi-spectral method is a two equation set

with five unknowns. Thus, to solve the set for NCLD and ICLD as de-

rived above, values for the other unknowns, ACLD, ACLR, and ICLR, must

be assumed. The method also assumes that:

(1) H_s remains undepleted by any atmosphere above cloud top height

(2) all cloud surfaces in the array area are horizontally homogeneous.

Statement (2) above is used here to include the additional implicit

assumption that both cloud and clear areas have unit emissivity and

behave as perfect isotropic reflectors, and that cloud tops are all at

approximately the same level ($\pm$ 500 m).

Reynolds and Vonder Haar (1977) have shown that the general bi-

spectral technique is an effective method of objectively determining

cloud amount and cloud height for non-cirriform clouds. For cirriform

clouds the assumption of unit emissivity may break down leading to

erroneous results. A variation of the general bi-spectral method,

which takes into account the variability of cloud emissivity, has been

included in Reynolds and Vonder Haar (1977) and a second method has

been developed by Mosher (1974). In another variation of the technique,

Smith (1975 unpublished notes) used horizontally differenced variables

to compute surface temperatures.

2.2 The horizontal differencing (HD) bi-spectral technique

The idea of horizontal differences as proposed by Smith is easily

adapted to the general bi-spectral techniqe. Consider Equations (1)

and (2) applied over two horizontally adjacent array areas. Substitution from (3) and differentiating (1) while holding H_s, ACLD, and ACLR constant, yields:

$$\frac{dM_s}{dx} = \frac{dNCLD}{dx} (H_s \, ACLD - H_s \, ACLR). \qquad (6)$$

Similarly, differentiating (2) while holding ICLD and ICLR constant yields:

$$\frac{dM_\ell}{dx} = \frac{dNCLD}{dx} (ICLD - ICLR). \qquad (7)$$

Equations (6) and (7) may now be combined with (1) and (2) to solve for the desired unknowns NCLD, ICLD, and ICLR, yielding:

$$NCLD = (M_s - H_s \, ACLR) / (H_s \, ACLD - H_s \, ACLR) \qquad (8)$$

$$ICLD = M_\ell - (M_s - H_s \, ACLD) \frac{dM_\ell}{dM_s} \qquad (9)$$

$$ICLR = M_\ell - (M_s - H_s \, ACLR) \frac{dM_\ell}{dM_s}. \qquad (10)$$

Formally, the HD method introduces two new equations and one additional unknown $(\frac{dNCLD}{dx})$ to the general bi-spectral set of equations. There are now four equations with only six unknowns. Thus, to solve the set for NCLD, ICLD, and ICLR as derived above, values for only the two unknowns, ACLD and ACLR, need be assumed. In addition to the other general bi-spectral assumptions, the HD method also requires that the cloud and clear area radiative properties be constant across the area of application. This is simply an extension of the horizontal homogeneity assumption.

3.0 DATA

3.1 The bi-spectral method applied to SMS data

The initial bi-spectral method was developed using simplified radiation budget equations. Thus, the units of M_s and M_ℓ in equations (1) and (2) are watts/meter^2 steradian, and the equations are applicable only to satellite-measured radiance values. Fujita and Grandoso (1967) first applied their technique to TIROS satellite measurements. Reynolds and Vonder Haar (1977) first applied the method to NOAA-4 data, but later Smith and Vonder Haar (1976) also applied it to SMS data taken over the GARP Atlantic Tropical Experiment (GATE) area in 1974. Smith and Vonder Haar's initial results were promising and further improvement was expected with the final calibration of the visible sensors. Use of the high resolution SMS data is desirous in the present study because of the particular method used to determine initial cloud amount. The method assumes that at least one visible data resolution point over the area of application is filled by cloud (the maximum brightness count), and that at least one is filled by clear area (the minimum brightness count). These values are then used to normalize the total measured radiance and determine total cloud amount. The high resolution SMS data improves the accuracy of the method by enhancing the possibility that a single resolution point is indeed filled with cloud or clear area.

3.2 The data set

All of the data used in the present study were taken from a satellite data set prepared by Smith and Vonder Haar (1976) for the 1974 GARP Atlantic Tropical Experiment (GATE). The data set covers the time

period June 27 to September 20, 1974, and has been earth located. As discussed in Section 1.0, full resolution IR data, corresponding to a 2 by 4 mile resolution point, have been retained. However, the full resolution visible data were reduced (at the original data collection site) by averaging a 4 by 4 matrix of 1/2 by 1/2 mile resolution points into a single 2 by 2 mile resolution point. This averaging process does not preserve the original character of the data because it does not take into account the square root transformation function used to convert voltage response to raw SMS brightness counts (see below). The resulting errors range in magnitude from 0.3% to 1.3% and are considered negligible.

3.2.1 Conversion of infrared brightness counts to radiance values

The data set prepared by Smith and Vonder Haar (1976) uses a standard lookup table to convert IR brightness counts to equivalent blackbody temperatures. The conversion procedure assumes proper calibration of the IR data at the original data collection site before the raw counts were converted to the standard counts used in the data set. The conversion table used by Smith and Vonder Haar was produced using three linear equations relating temperature to brightness counts:

$$T = 329.80 - SBC/2 \quad \text{for } SBC \leq 143$$

$$T = 329.90 - SBC/2 \quad \text{for } 144 \leq SBC \leq 176$$

$$T = 417.90 - SBC \quad \text{for } SBC \geq 177$$

where $\quad T$ = equivalent blackbody temperature

$\quad SBC$ = standard IR brightness count.

The equivalent blackbody temperature may then be converted to a radiance value for use in the equations via the Planck function.

3.2.2 Conversion of visible brightness counts to radiance values

Relating the standard visible brightness counts of the data set to radiance values is a three step process (Smith and Vonder Haar, 1976):

(1) the standard 8 bit count (0-255) must be converted to a raw 6 bit count (0-63) through the linear equation

$$RBC = \frac{SBC}{4} \qquad (11)$$

where   RBC = raw 6 bit brightness count

SBC = standard 8 bit brightness count

(2) the raw 6 bit count is next related to the voltage response through the non-linear equation

$$V = [\frac{RBC}{28.1}]^2 \qquad (12)$$

where   V = voltage $(0 \le V \le 5)$

(3) the voltage response is then related to the incident energy (power) through the linear equation

$$P = G(V - 0) \qquad (13)$$

where   P = power (incident energy per second)

   G = sensor gain (watts/volt)

   O = voltage offset.

The measured satellite radiance value is simply this power value per unit area per steradian, and the albedo is defined as the ratio of the satellite measured radiance to the constant solar irradiance for the given spectral interval.

3.3 Use of visible brightness counts alone

Although the procedures relating standard brightness counts to radiance values are fairly simple, the counts must first be calibrated using known radiance values. At the time the data set used in this study was prepared, there was no calibration procedure available for the GATE SMS data. Fortunately, for calculations not explicitly requiring albedo values it can be shown that brightness counts alone may be used for determining cloud amounts. Solving equation (13) for "V" and substituting from (12), equation (1) may be written:

$$M_s = NCLD\ BCLD^2 + NCLR\ BCLR^2 \tag{14}$$

where M_s = averaged raw visible brightness count over the total
         area

   BCLD = raw visible brightness count of the cloud surface

   BCLR = raw visible brightness count of the cloud free surface.

Replacing equation (1) with equation (14) results in the following set of equations for the HD bi-spectral technique:

$$M_s = NCLD \ BCLD^2 + NCLR \ BCLR^2 \qquad (15)$$

$$M_\ell = NCLD \ ICLD + NCLR \ ICLR \qquad (16)$$

$$\frac{dM_s}{dx} = \frac{dNCLD}{dx} (BCLD^2 - BCLR^2) \qquad (17)$$

$$\frac{dM_\ell}{dx} = \frac{dNCLD}{dx} (ICLD - ICLR). \qquad (18)$$

Solving for NCLD, ICLD and ICLR yields:

$$NCLD = (M_s - BCLR^2) / (BCLD^2 - BCLR^2) \qquad (19)$$

$$ICLD = M_\ell - (M_s - BCLD^2) \ \frac{dM_\ell}{dM_s} \qquad (20)$$

$$ICLR = M_\ell - (M_s - BCLR^2) \ \frac{dM_\ell}{dM_s} . \qquad (21)$$

To solve the HD bi-spectral set as derived above only the values of BCLD and BCLR need be assumed. Additionally, the new set of equations has the advantage that calibration of the data is not required as long as an alternate method of verifying cloud amount is used. By assuming that at least one data resolution point is filled by cloud, and that at least one is filled by clear area, (the maximum and minimum

observed counts respectively) values of the assumed variables BCLD and

BCLR may be taken directly from the data. This leads to an important

cross-check verification scheme (Section 5.0) for determining an opti-

mum area size over which the HD bi-spectral method may be applied most

effectively, and for minimizing any errors in computed cloud amounts.

4.0 ERROR ANALYSIS

4.1 Error sensitivity of the horizontal differencing method

Errors are generally considered to be of two main types: (1) non-controllable random or sampling errors, and (2) controllable or systematic errors. The most significant sampling errors in the GATE SMS data are introduced at the original data collection site through an averaging process that does not take into account the square root digitization process (Smith and Vonder Haar, 1976). Depending on the averaged values, these errors may range from 0.3% - 1.3% and may be considered negligible. The largest single cause of systematic errors in the data is the directional variability of reflected light from cloud surfaces. This variability, called anisotropy, is dependent upon several factors:

    (1)   the sun - target area - satellite geometry,

    (2)   the droplet size distribution of the cloud,

    (3)   the liquid water content of the cloud,

    (4)   the cloud thickness,

    (5)   the shape of the cloud.

Brennan and Bandeen (1970) showed that anisotropy may cause large errors in computed albedos (or in assumed cloud brightness counts) if not accounted for. These errors may range from 0 to 108% for different earth/atmosphere reflectors in the 0.55 - 0.85 μ bandwidth. Instrument errors are considered negligible in comparison.

Normalization procedures for correcting measured directional reflectance values have been developed by Sikula and Vonder Haar (1972). However, the method is based on empirical data which are scarce and

generally do not include variations of the reflectance pattern with respect to cloud microphysics. Other normalization methods, which attempt to overcome the limitations of the restrictive empirical data base, have been developed (Mosher, 1974), but the problem of anisotropy correction remains a difficult task at best.

By assuming that the area of application is radiatively homogeneous in the horizontal, the HD bi-spectral technique effectively eliminates the need to correct the data for anisotropy; since all values in a radiatively homogeneous field of view would have the same corrective factor, there would be no net correction. However, as a function of cloud microphysics, anisotropy may cause small differences in the directional reflectance pattern of the same cloud, or in clouds that appear visually similar and have the same geometric viewing conditions. The HD bi-spectral method is especially sensitive to this type of error since the values of the assumed variables, BCLD and BCLR, are actually the observed maximum and minimum visible brightness counts over the area of application, and since these values are used in all subsequent calculations.

To determine what effects errors in the values of BCLD and BCLR would have on the other computed variables, a simple error analysis was done using five different relationships of visible vs. IR brightness counts. The five categorical relationships were:

(1) cold convective clouds over a warm ocean,

(2) cold thin stratiform clouds over a warm ocean,

(3) cold convective clouds over the desert,

(4) cold thin stratiform clouds over the desert,

(5) warm thin stratiform clouds over the ocean.

4.2 Method of determining values used in the error analysis

True visible channel brightness counts for relationship (1) above were taken empirically from SMS data over the GATE area on 1 August 1974. A brightness count of 240 was assumed to correspond to a cumulonimbus cloud albedo of 0.90, and a brightness count of 62 was assumed to correspond to a sea surface albedo of 0.06. These figures were calculated using a pseudo solar constant of 4000, and the equations of Section 3.2.2, in the following manner:

$$(4000) \ (0.9) = 3600 = V \qquad\qquad (4000) \ (0.06) = 240 \ = V$$

$$(3600)^{\frac{1}{2}} = 60 \quad = (RBC) \ (28.1) \qquad (240)^{\frac{1}{2}} = 15.5 = (RBC) \ (28.1)$$

$$(60) \ (4) = 240 \ = SBC/28.1 \qquad (15.5) \ (4) = 62 \quad = SBC/28.1$$

True values corresponding to the other relationships above were computed using cloud and surface albedos that closely approximate those given by Sellers (Physical Climatology, 1965, p. 21) and those determined by Conover (1964) from TIROS Satellite Pictures. These values are summarized in Table 1.

True IR channel brightness counts for relationship (1) above were also adopted from actual SMS data over the GATE area on 1 August 1974. The values used correspond to blackbody temperatures of 220°K for the cold cumuliform and stratiform clouds, and 298°K for the ocean. Radiance values used for the other relationships above, i.e., the desert and the low warm stratiform clouds, correspond to blackbody temperatures of 313°K and 290°K respectively.

The values of BCLD and BCLR which were used in the error analysis were allowed to vary at the ± 5% and ± 10% level of uncertainty; the

	SELLERS (1965)	Conover (1964)	Value Used
Cumuliform	70 – 90	86 – 92	90
Cirrostratus	44 – 50	32 – 74	50
Altostratus	39 – 59	-------	50
Desert	25 – 30	27	30
Ocean	6 – 7	7 – 9	06
Stratus	59 – 84	42 – 64	50

Table 1. A comparison of cloud albedo values.

Brennan and Bandeen study indicates as much as a 35% difference in directional reflectance values for large viewing angles of strato-cumulus clouds over the Pacific, while a study by Martin and Suomi (1972) showed that the tops of cumulonimbus clouds behave as isotropic reflectors. Reynolds and Vonder Haar (1977) used an "optimistic" estimate of 10% uncertainty on measured visible channel reflectance values. This value appears more reasonable for the data used in the present study which were taken under conditions of small satellite viewing angles.

4.3   Results and discussion of the error analysis

Results of the error analysis show that:

A. the HD bi-spectral method may be a useful means of objectively determining cloud amounts over the oceans,

B. the effectiveness of the method in determining cloud amounts over a high albedo surface is marginal, and

C. the method as developed is not very effective in determining cloud temperatures and cloud heights.

The errors in computed cloud amount values for categorical rela-tionships (1) and (2) above (ocean cases) vary in absolute magnitude from 0.18 to 0.33, while for categorical relationships (3) and (4) above (desert cases) the error values vary in absolute magnitude from 0.23 to 2.44. The errors in computed cloud temperatures for all cases vary in value from 13°K to 65°K, while the errors in surface tempera-tures were more reasonably ranged from 0.5°K to 22°K.

4.3.1 Errors in computed cloud amount

Errors in computed cloud amount were found to vary linearly as a function of cloud amount, with the slope and offset being determined by the levels of error in BCLD and BCLR. Table 2 lists some of the more important equations governing the magnitude of error in computed cloud amount for each of the categorical relationships described above. These equations were used to prepare Figures 1 through 4, which graphically illustrate the possible range of error in computed cloud amount, for each relationship, given a $\pm$ 0.10 error level in BCLD and BCLR. The significant features show that:

[1] in all cases, the absolute magnitude of error in computed cloud amount is smaller where the error in BCLD is positive,

[2] in all cases, the absolute magnitude of error in computed cloud amount is minimized where the errors in BCLD and BCLR are in the same direction,

[3] for constant levels of uncertainty in BCLD or BCLR, errors in computed cloud amount increase as the magnitude of BCLD decreases and BCLR remains constant, or as the magnitude of BCLR increases and BCLD remains constant,

[4] from [3] above, the minimum errors in cloud amount occur in categorical relationship (1), bright cloud over dark ocean, where BCLD is relatively large and BCLR is relatively small,

[5] from [3] above the maximum errors in computed cloud amount occur in categorical relationship (4), dark cloud over a bright surface, where BCLD is relatively small and BCLR is relatively large. The errors in computed cloud amount for the ocean cases (1) and (2) do not exceed an absolute value of 0.35 for even the most

CATEGORICAL RELATIONSHIP	BCLD ERROR %	BCLR ERROR %	GOVERNING EQUATION y = absolute error in cloud amount x = fractional cloud amount
1 - cold convective clouds over a warm ocean	-0.10	-0.10	y = + 0.033 + 0.23 x
	-0.10	+0.10	y = - 0.035 + 0.32 x
	+0.10	-0.10	y = + 0.018 - 0.20 x
	+0.10	+0.10	y = - 0.022 - 0.17 x
2 - cold stratiform clouds over a warm ocean	-0.10	-0.10	y = + 0.057 + 0.24 x
	-0.10	+0.10	y = - 0.072 + 0.40 x
	+0.10	-0.10	y = + 0.035 - 0.23 x
	+0.10	+0.10	y = - 0.043 - 0.17 x
3 - cold convective clouds over a desert	-0.10	-0.10	y = + 0.120 + 0.24 x
	-0.10	+0.10	y = - 0.180 + 0.66 x
	+0.10	-0.10	y = + 0.070 - 0.30 x
	+0.10	+0.10	y = - 0.090 - 0.17 x
4 - cold stratiform clouds over a desert	-0.10	-0.10	y = + 0.360 + 0.23 x
	-0.10	+0.10	y = - 1.628 + 4.06 x
	+0.10	-0.10	y = + 0.161 - 0.46 x
	+0.10	+0.10	y = - 0.266 - 0.17 x

Table 2. Equations governing the magnitude of absolute error in computed cloud amount for each categorical relationship described in the text. Note: The governing equations for relationship 5 were the same as for relationship 2.
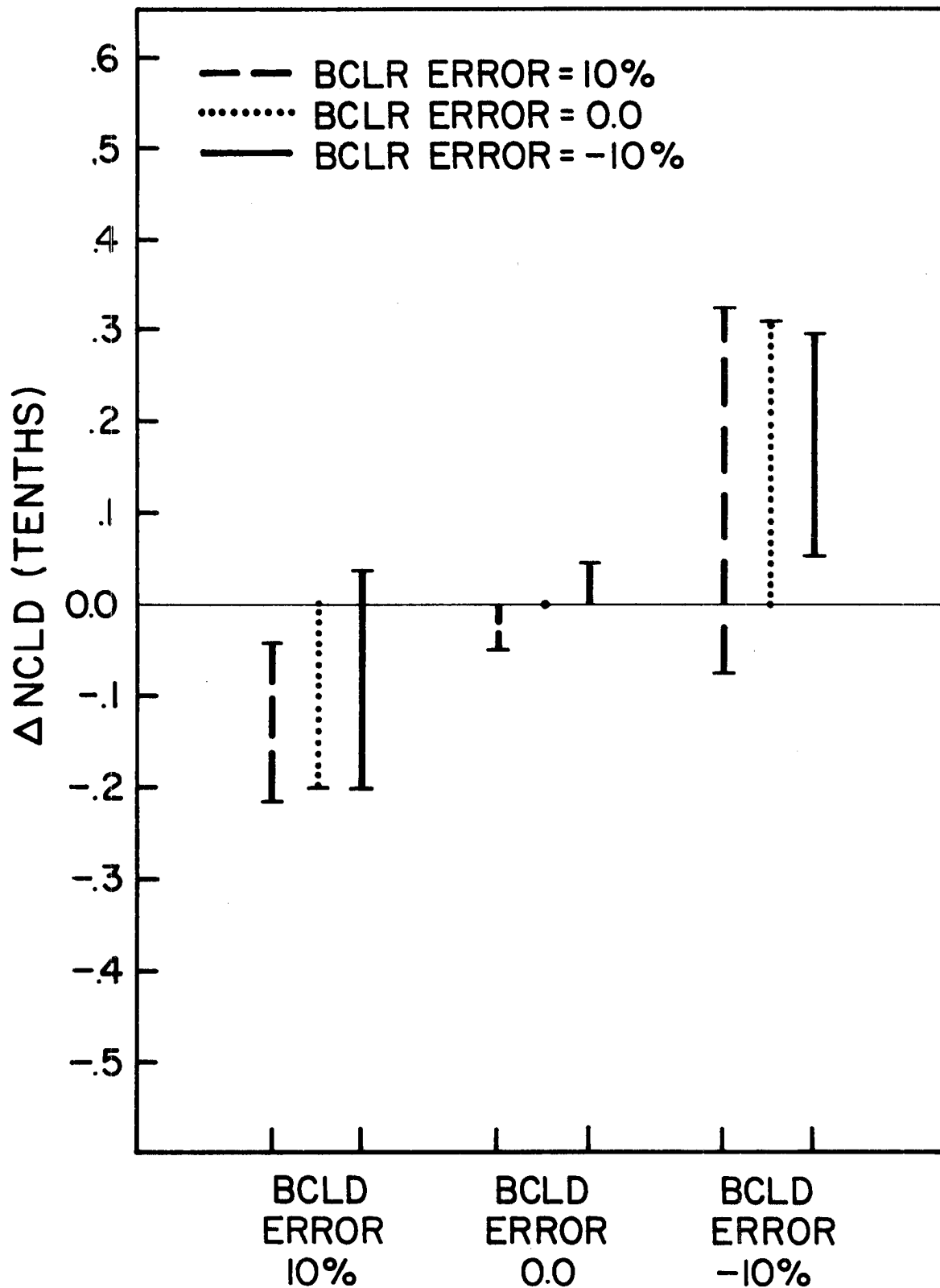
Figure 1. The possible range of error in computed cloud amount for various levels of error in BCLD and BCLR (categorical relationship 1 - see text).
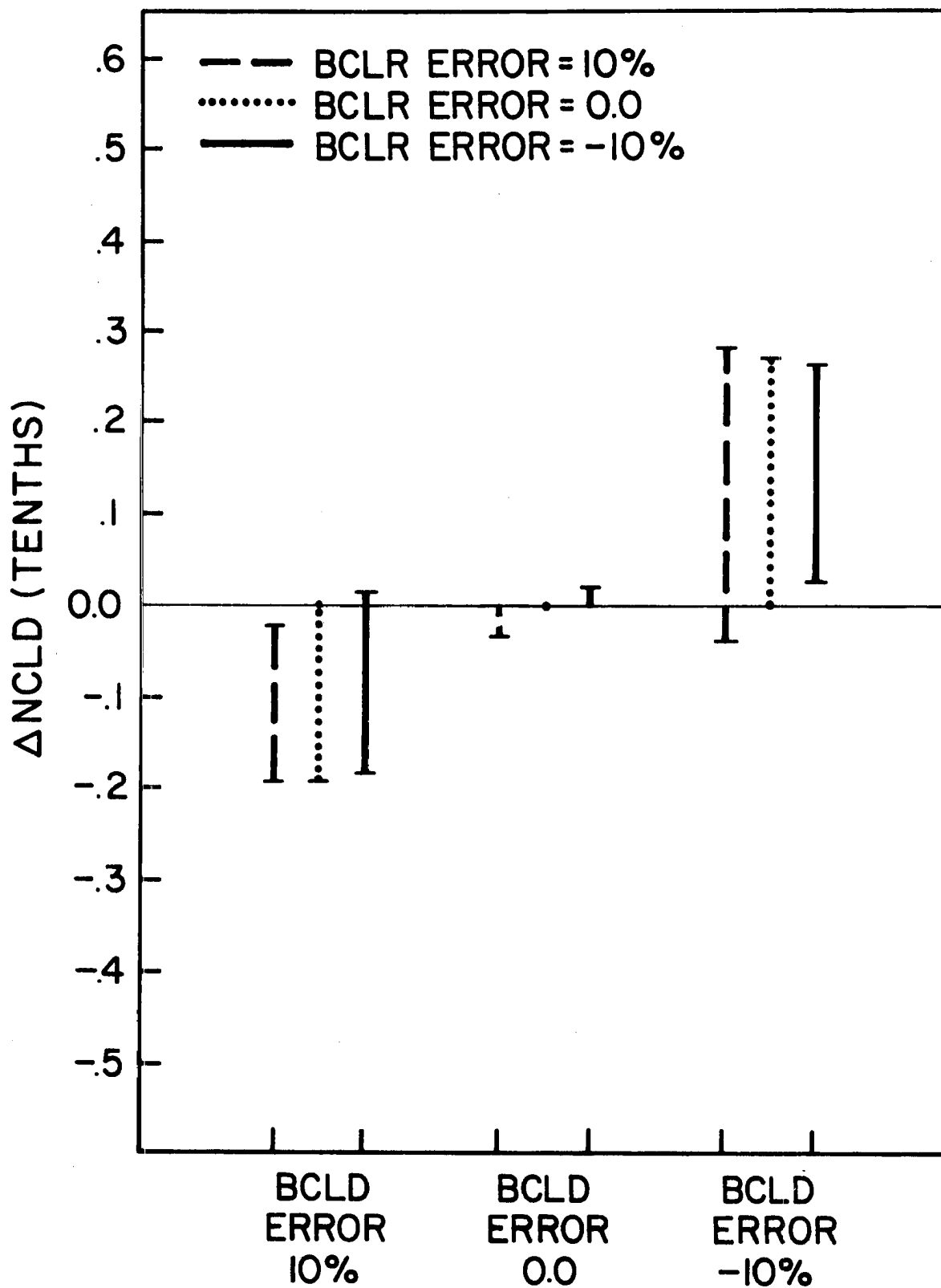
Figure 2. The possible range of error in computed cloud amount for various levels of error in BCLD and BCLR (categorical relationship 2 - see text).
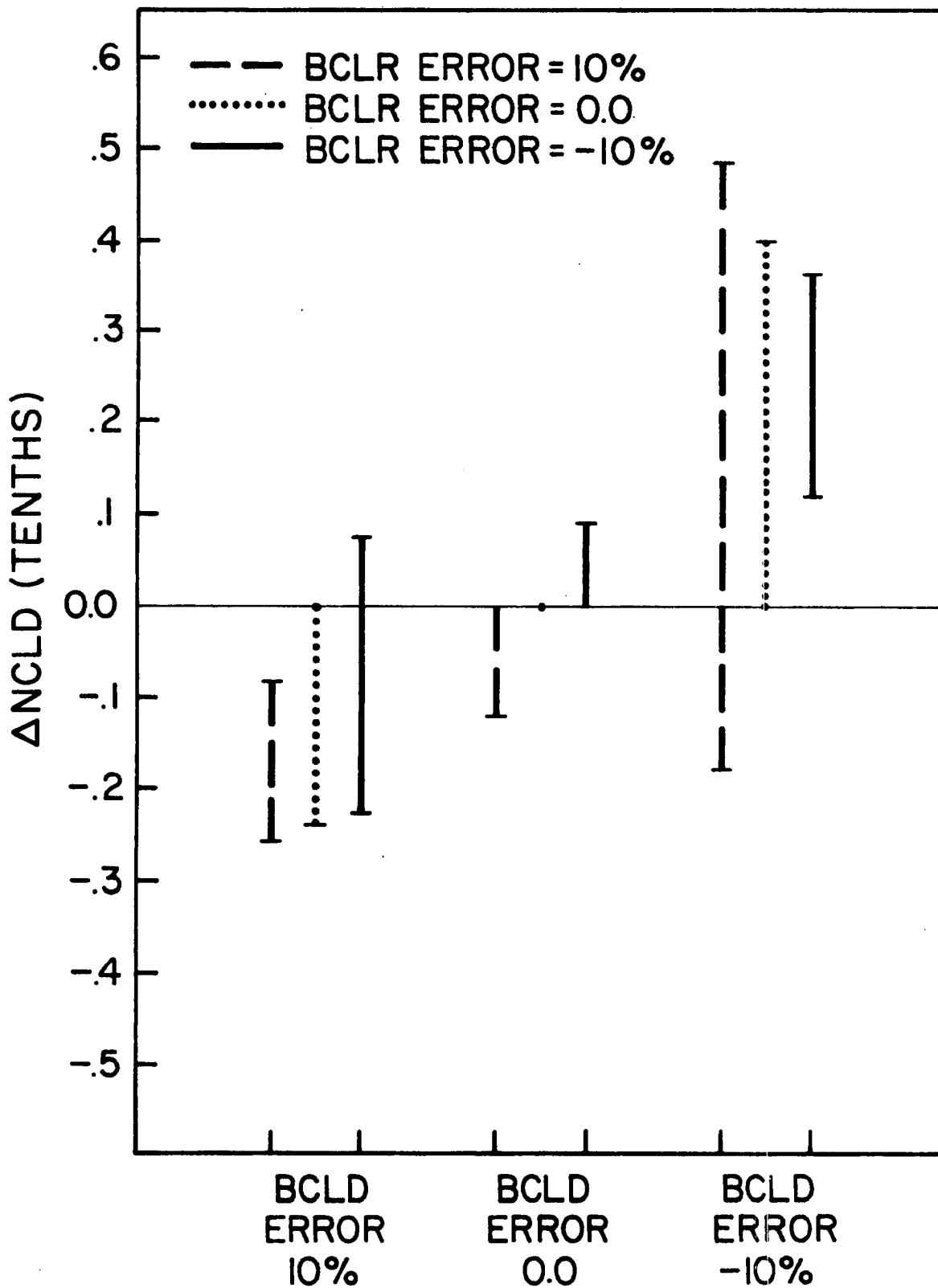
Figure 3. The possible range of error in computed cloud amount for various levels of error in BCLD and BCLR (categorical relationship 3 - see text).
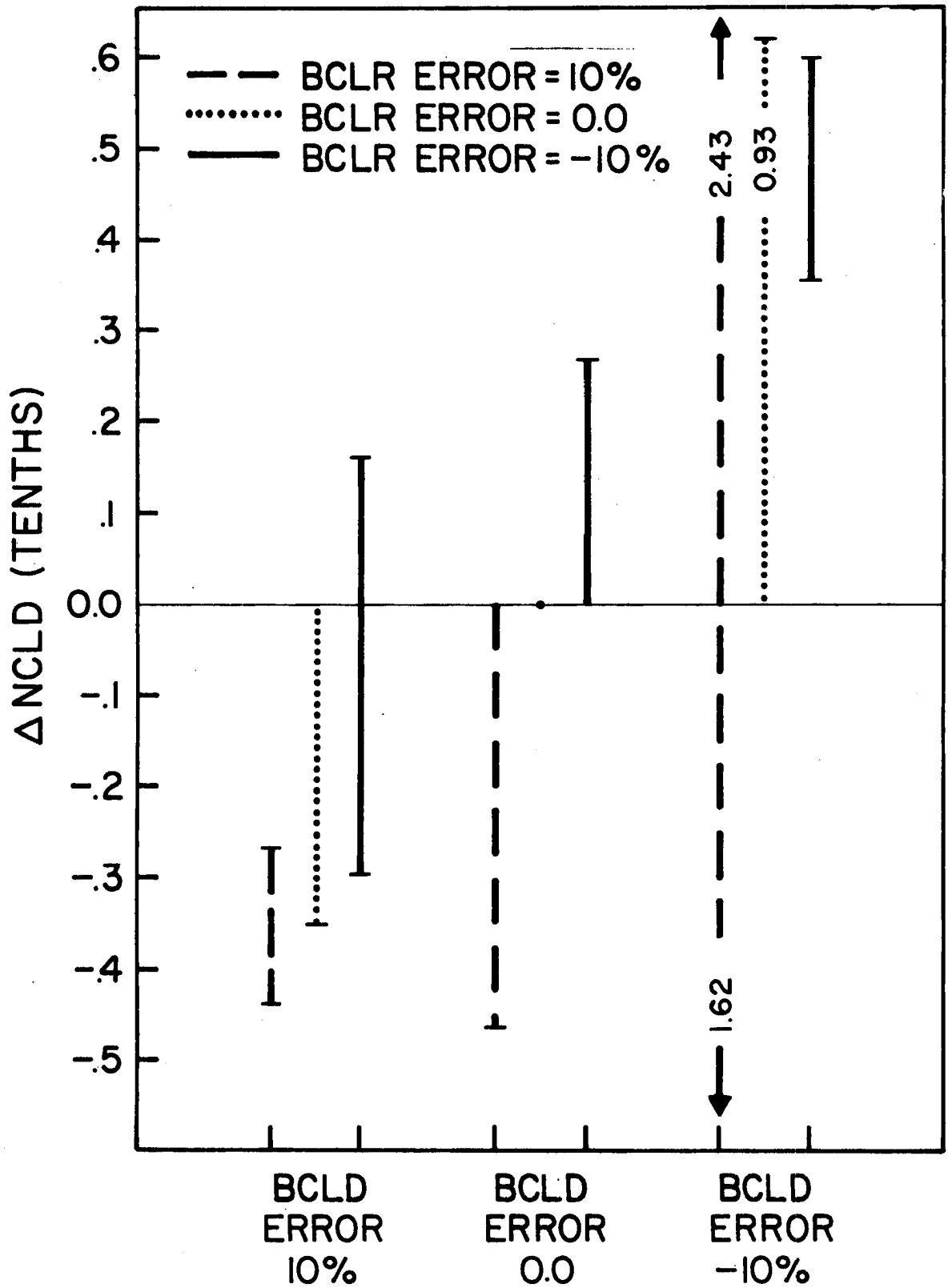
Figure 4. The possible range of error in computed cloud amount for various levels of error in BCLD and BCLR (categorical relationship 4 - see text).

pessimistic errors in BCLD and BCLR. This result suggests that the method may be used effectively over the ocean. However, the errors in computed cloud amount for the desert or snow cases (3) and (4) become prohibitive for certain combinations of error in BCLD and BCLR (see [2] above). This result indicates that the method may be only marginally effective over a high albedo surface.

4.3.2 Errors in computed cloud and surface temperatures

Equations (20) and (21) show that for a given set of total radiance values, the computed cloud and clear radiance values, and thus equivalent blackbody temperatures, are functions only of assumed cloud and clear brightness counts respectively. Tables 3 and 4 summarize the results of the errors found in cloud and surface temperatures for the different levels of error in BCLD and BCLR. Note the inverse relationship between computed temperatures (radiance values) and errors in BCLD/BCLR. This is a direct result of the fact that $\frac{dM_\ell}{dM_s} < 0$ in equations (20) and (21). The tables show that computed cloud top temperatures are not acceptable for use in exact analyses even at the $\pm$ 5% error level and assuming unit emissivity. The computed surface temperatures are more conservative, but also represent a much less desirable unknown in terms of satellite inferred information, than do cloud top temperatures. Thus, the method, as developed, is considered useful only in grossly estimating cloud heights from computed cloud top temperatures. More sophisticated bi-spectral techniques, for computing cloud top temperatures and cloud height, applicable to SMS data, have recently been developed by Vonder Haar, Reynolds and Smith (1976).

CATEGORICAL RELATIONSHIP	TRUE CLOUD Temp. °K	BCLD ERROR - 10%	BCLD ERROR - 5%	BCLD ERROR + 5%	BCLD ERROR + 10%
Cb Ocean	220.0	+24.0	+13.0	-18.0	-52.0
As/Cs Ocean	220.0	+26.0	+14.5	-20.5	-67.5
Cb Desert	220.0	+37.0	+21.5	-38.0	Neg. Rad.
As/Cs Desert	220.0	+55.0	+33.0	Neg. Rad.	Neg. Rad.
St Ocean	290.0	+2.0	+1.0	-1.5	-2.0

Table 3. Computed cloud temperature differences for various levels of error in BCLD.

CATEGORICAL RELATIONSHIP	TRUE SFC Temp. °K	BCLR ERROR - 10%	BCLR ERROR - 5%	BCLR ERROR + 5%	BCLR ERROR + 10%
Cb Ocean	298.0	+1.5	+0.5	-0.5	-1.5
As/Cs Ocean	298.0	+2.5	+1.5	-1.5	-2.5
Cb Desert	313.0	+6.0	+3.0	-3.5	-7.0
As/Cs Desert	313.0	+17.0	+9.0	-10.5	-22.0
St Ocean	298.0	+0.5	+0.0	+0.0	-0.5

Table 4. Computed surface temperature differences for various levels of error in BCLR.

5.0 TESTING FOR AN EFFECTIVE HORIZONTAL AREA

5.1 The optimum area concept

The assumption of horizontal homogeneity necessary for the application of the HD bi-spectral method (Section 2.0) requires that cloud surfaces be horizontally homogeneous, and at approximately the same level. This assumption becomes increasingly more difficult to justify as the area over which it is applied becomes larger. The reason for this is that larger areas may include different cloud regimes with different radiative properties. In conflict with this requirement for a small horizontal area, is the assumption necessary for determining initial cloud amounts in the present bi-spectral technique: that the maximum and minimum observed brightness counts over the area of application represent cloud and clear filled resolution points respectively (Section 3.0). This assumption becomes increasingly more difficult to justify as the area over which it is applied becomes smaller. The reason for this is that for small areas the array elements may be only partly cloud filled and none need be totally filled. The contradiction of these two assumptions, the one requiring a small area to be effective, and the other requiring a large area to be effective, suggests that some optimum area exists where both requirements may be met with a maximum degree of confidence. In the present study, several tests were devised for the specific purpose of defining this most effective area size.

5.2 The sampled cloud regimes

The present study focuses on two specific tropical cloud regimes: a deep convective (cumulonimbus) regime, and a stratiform

(stratocumulus) regime. Both regimes were readily identifiable from satellite photographs and, although coexistent, were geographically separated enough to be independent cloud systems. Both regimes were large in extent and long lived: covering approximately 500 Km^2 and lasting on the order of six to ten hours for the convective regime and twenty-four or more hours for the stratiform regime.

The sample size of the convective regime consisted of ten days and two time periods per day; a total of twenty samples. The sample size of the stratiform regime was identical, except that one time period was not available yielding a total sample size of nineteen. Time periods for both regimes were early to mid-afternoon depending primarily on the avoidance of sunglint. Geographically, both sample regimes were found in the so-called GATE Sector; 5°S to 22°N latitude, and 5°W to 50°W longitude. Figures 5 and 6 illustrate a typical sample element, and Table 5 lists the days, time periods, and exact geographical locations of the sample regimes. It is important to emphasize that all of the tests used in the present study are statistical in nature and, therefore, any conclusions drawn from the results of these tests must be confined to the sampled cloud regimes and not generalized to include other cloud regimes.

5.3 The minimum area test

Determining a minimum area over which a maximum/minimum brightness count actually represents a cloud/clear filled resolution point is best done statistically. One method is to take a specific area with a given maximum brightness count and plot the frequency that a higher count is found in a larger area. For example, given the maximum brightness
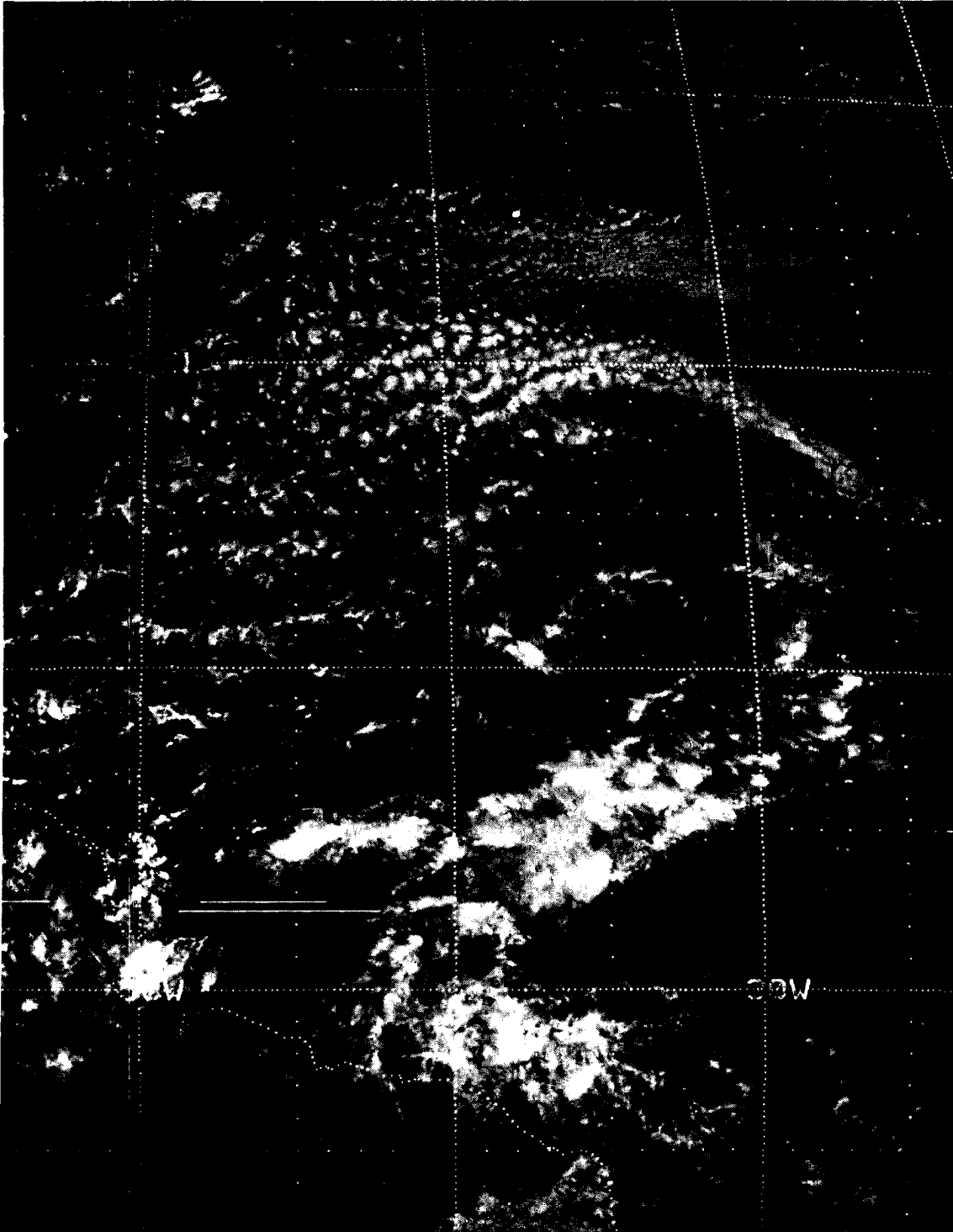
Figure 5. SMS visible photograph taken on 25 July 1974, at 1200:00
GMT. The sampled cloud regimes are located at 02-07°N
latitude, 34-39°W longitude (convective) and 17-22°N
latitude, 38-43°W longitude (stratiform).
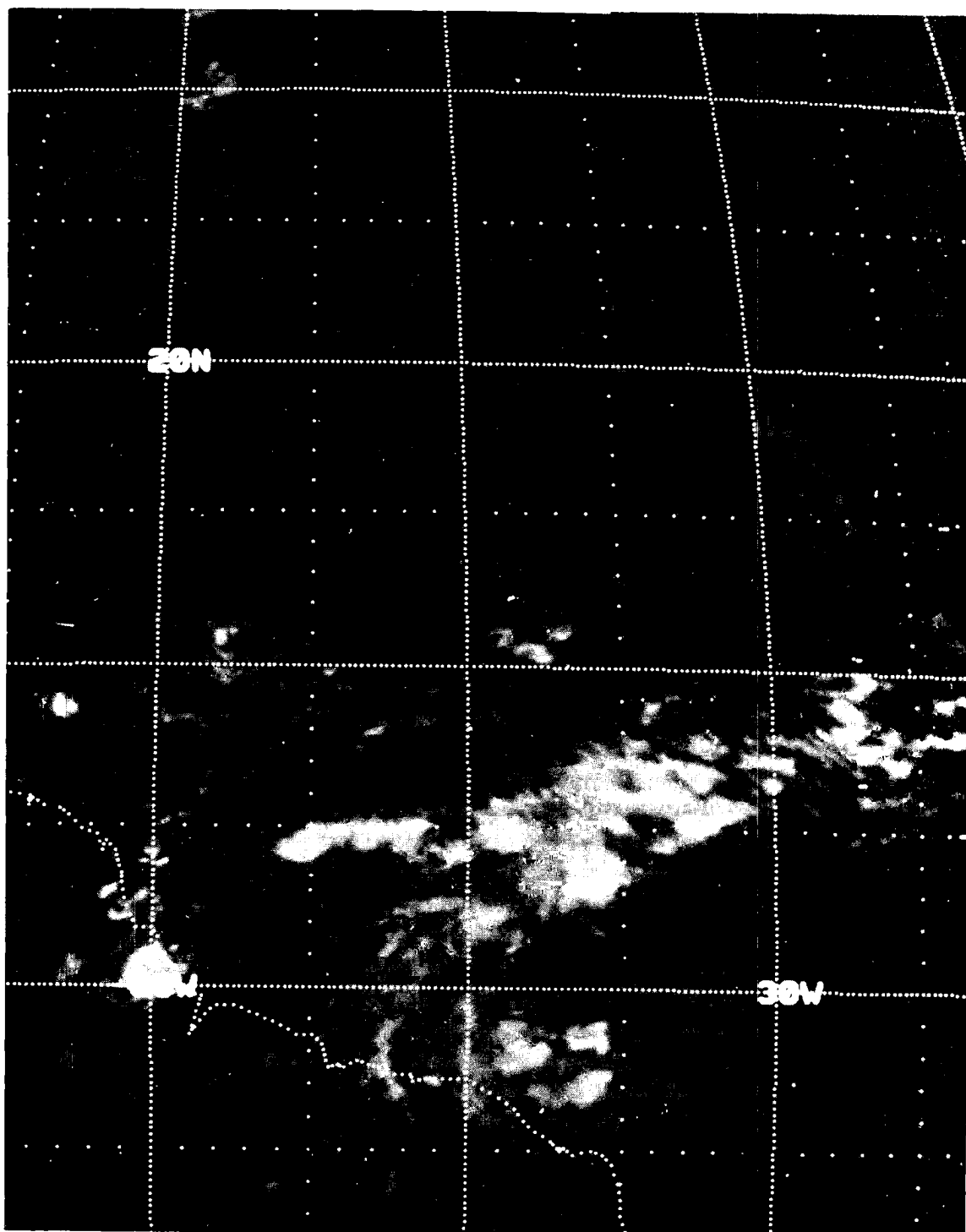
Figure 6. SMS infrared photograph taken on 25 July 1974, at 1200:00
GMT. The sampled cloud regimes are located at 02-07°N
latitude, 34-39°W longitude (convective) and 17-22°N
latitude, 38-43°W longitude (stratiform).

JULIAN DATE	GMT	CONVECTIVE REGIME		STRATIFORM REGIME	
		LATITUDE	LONGITUDE	LATITUDE	LONGITUDE
74180	1000	03-08N	17-22W	11-16N	35-40W
	1500	05-10N	19-24W	11-16N	35-40W
74188	1300	06-11N	17-22W	16-21N	27-32W
	1600	07-12N	18-23W	16-21N	28-33W
74189	1000	05-10N	18-23W	15-20N	30-35W
	1400	05-10N	20-25W	15-20N	35-40W
74201	1400	07-12N	27-32W	16-21N	27-32W
	1600	06-11N	27-32W	16-21N	27-32W
74206	1000	02-07N	33-38W	Not Available	
	1200	02-07N	34-39W	17-22N	38-43W
74220	1100	05-10N	35-40W	16-21N	37-42W
	1300	05-10N	40-45W	16-21N	37-42W
74221	1000	05-10N	40-45W	16-21N	35-40W
	1200	05-10N	40-45W	16-21N	35-40W
74226	1100	06-11N	37-42W	16-21N	44-49W
	1300	05-10N	36-41W	16-21N	44-49W
74231	1200	06-11N	18-23W	14-19N	27-32W
	1400	07-12N	18-23W	14-19N	25-30W
74232	1000	06-11N	20-25W	15-20N	31-36W
	1500	06-11N	21-26W	16-21N	30-35W

Table 5. The sampled cloud regimes.

count in a very small specified area, a higher count will be found in a larger area very frequently. Whereas given a very large specified area, a higher count will be found in a larger area only infrequently. A plot of these frequency values vs. area size should indicate some minimum area size where the maximum brightness count may reasonably be assumed to represent a cloud filled resolution point.

5.3.1 Application of the minimum area test

Although the maximum and minimum infrared observed brightness counts are not explicitly used in the general bi-spectral method, the iteration technique of the present study (Section 6.0) and the specific test used to determine an overall effective area for bi-spectral application, require that the computed radiance values be compared to the observed radiance values. For this reason the infrared data were included in the minimum area test. Additionally, because the sample cloud regimes were by necessity mostly cloudy, the chances that a single resolution point would be clear filled was far less than the chance that one would be cloud filled. Therefore, the minimum area test was only applied to the case of maximum value, or cloud filled, resolution points.

5.3.2 Results of the minimum area test

The plotted results of the minimum area test as applied in the present study are illustrated in Figures 7 through 10. Figures 7 and 8 are the visible and infrared data plots for the convective cloud regime respectively. Both figures clearly show that higher maximum value brightness counts than those found in area sizes of 125 Km^2 are found only infrequently (10% to 25% of the time). For the stratiform
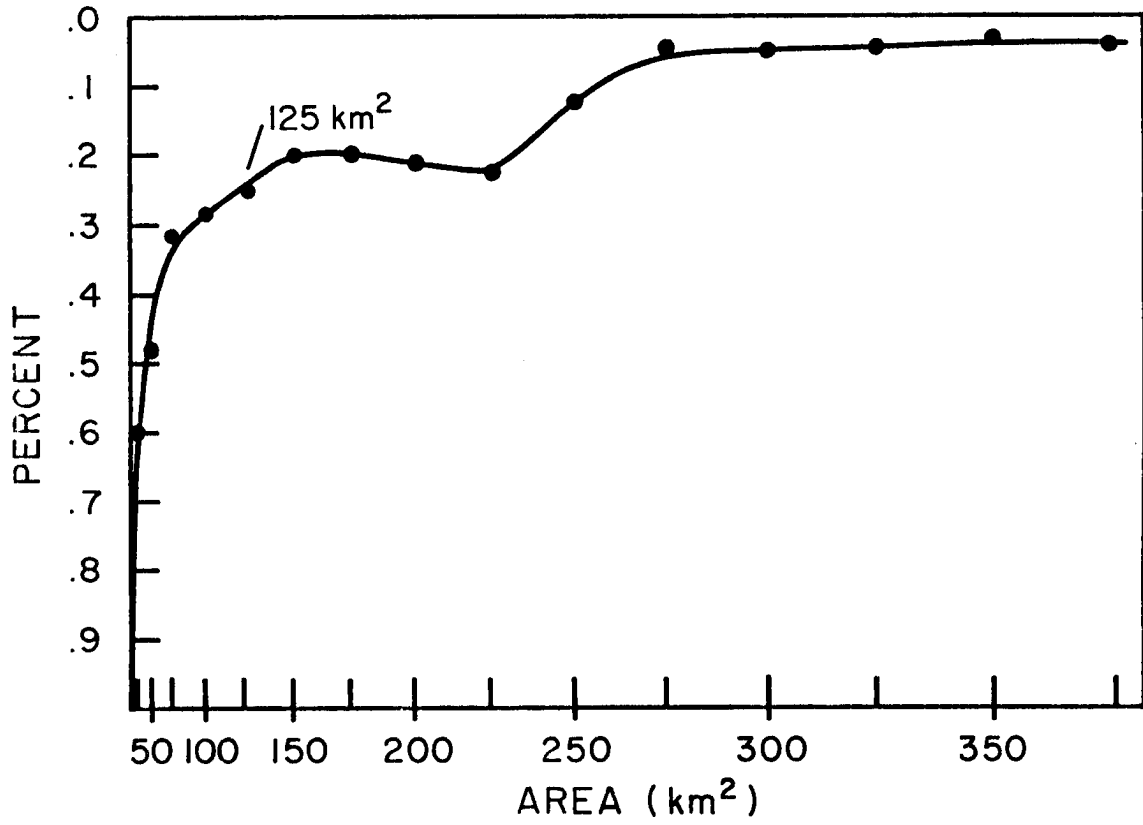
Figure 7. The frequency that a higher brightness count was found
in a larger area (convective cloud regime - visible
data).
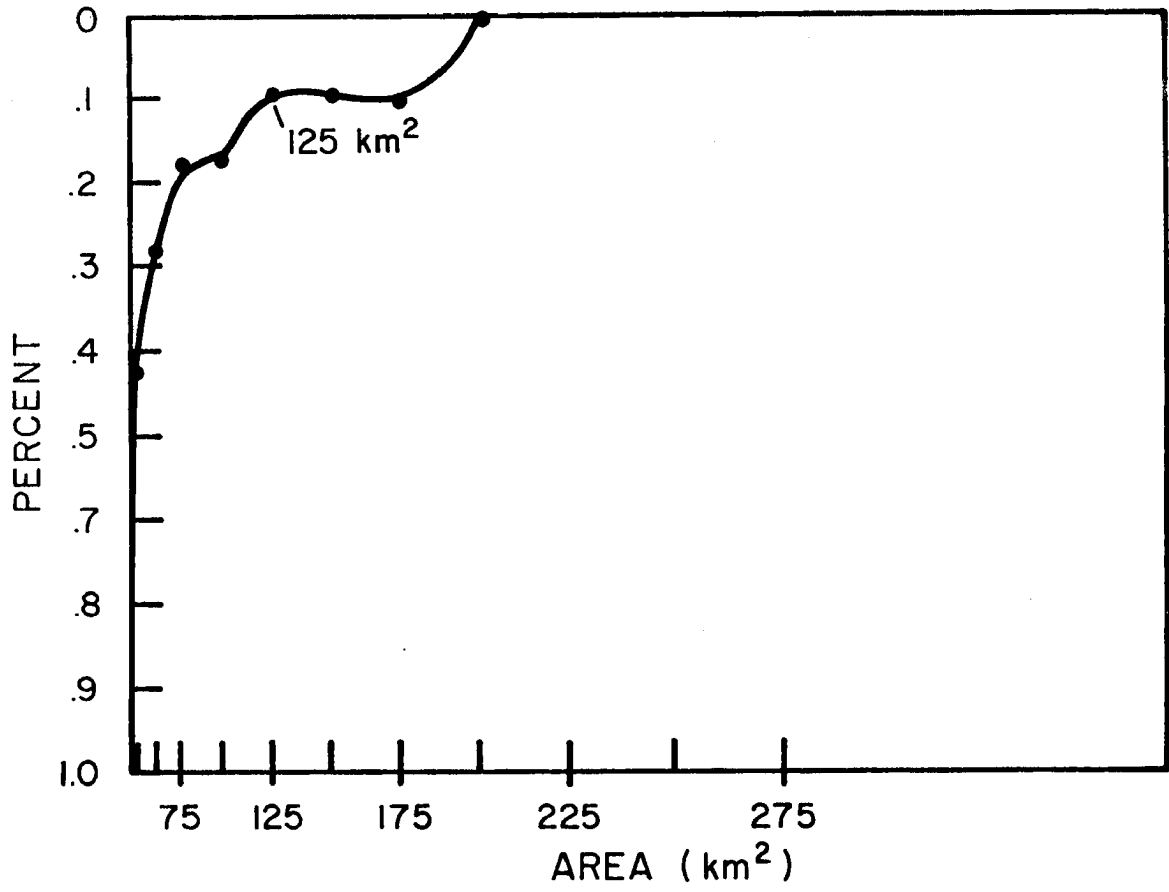
Figure 8. The frequency that a higher brightness count was found in a larger area (convective cloud regime - infrared data).
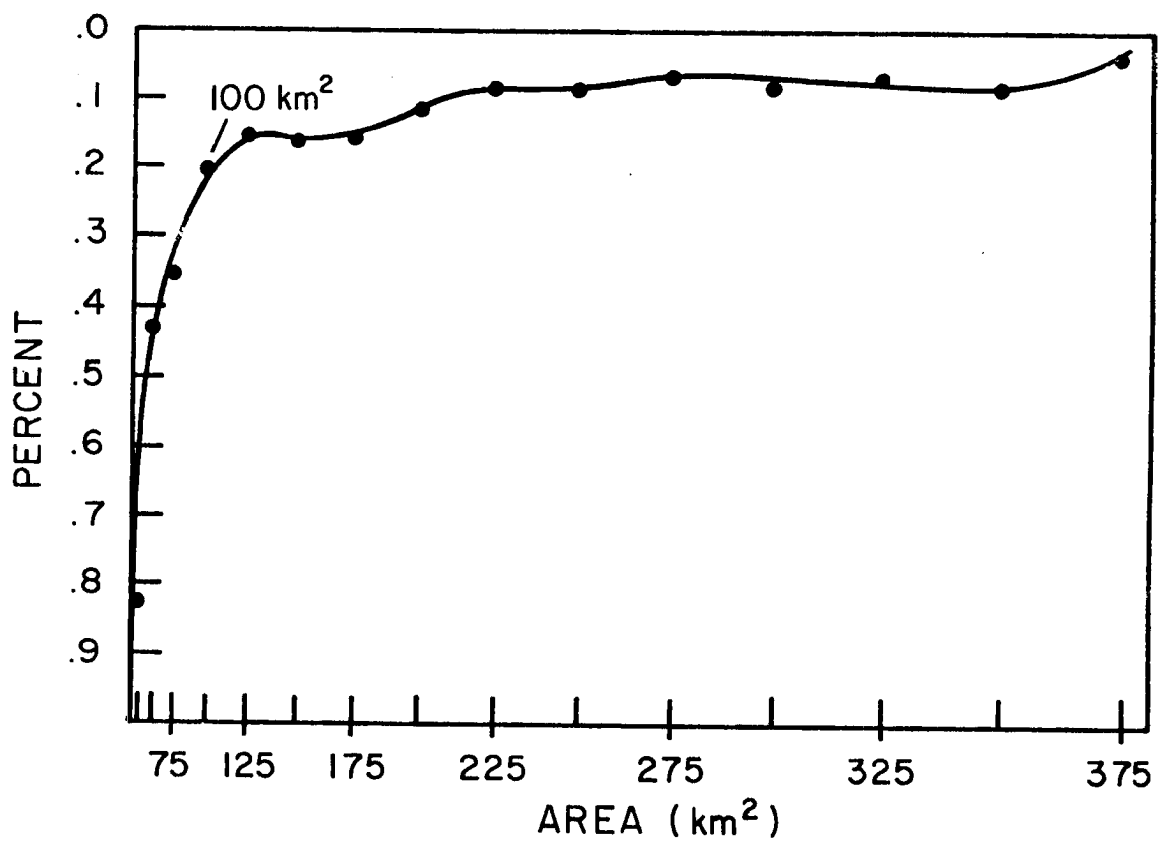
Figure 9. The frequency that a higher brightness count was found in a larger area (stratiform cloud regime - visible data).
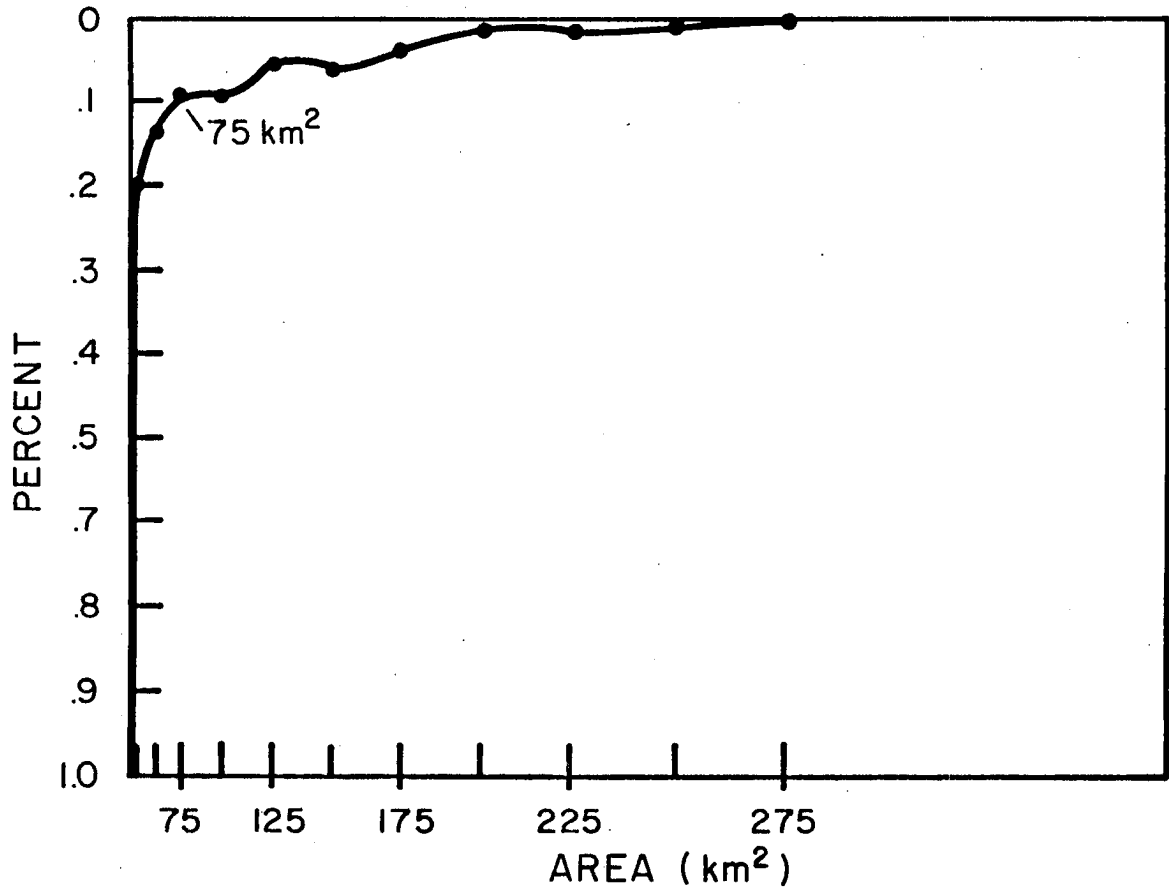
Figure 10.   The frequency that a higher brightness count was found
in a larger area (stratiform cloud regime - infrared
data).

regime, Figures 9 and 10 indicate that 100 Km^2 is a minimum area size. Thus, for tropical convective and tropical stratiform cloud regimes, the results of the minimum area test show that the maximum brightness count observed over areas larger than 125 Km^2 may reasonably be assumed to represent a cloud filled resolution point.

5.4 The homogeneous area tests

The present study uses two similar methods to test for the area over which the assumption of horizontal homogeneity is valid. In both tests the total sample population of brightness counts is partitioned into areas of equal size and the observed maximum brightness count over each area is found. A second sample population of these maximum brightness counts is constructed and assumed to represent the elements of a continuous cloud field. The area size over which the maximum counts are taken is then varied as the tests for horizontal homogeneity are applied, and the results of the tests are analyzed for those area sizes which produce the most homogeneous fields.

The first test method is the application of a simple statistical analysis, where the standard deviation of the sample population is of particular interest. As a measure of the average magnitude of any given element's deviation from the sample mean value, the standard deviation may also be assumed to be a measure of the population homogeneity; i.e., the smaller the standard deviation, the more homogeneous the population. With this premise in mind, each standard deviation value may be plotted as a function of the area size over which the elements of the second sample population were taken. A graph of these

plots should yield an indication of which area sizes produce the most homogeneous maximum (cloud) value populations.

The second test method is the objective analysis technique proposed by Gandin (1963), which defines homogeneity in terms of statistical properties. The primary mathematical expression used in the analysis is the auto-correlation function, or more simply the correlation function, which is defined as the mean product of all equidistant pairs of elements within a population field. In equation form:

$$M_f(\rho) = \overline{[f(\vec{r}_1) \cdot f(\vec{r}_2)]} \tag{22}$$

where, $\quad \rho$ = some scalar distance $(\vec{r}_2 - \vec{r}_1)$

$f(\vec{r}_1)$ = value of the property f at distance $\vec{r}_1$

$f(\vec{r}_2)$ = value of the property f at distance $\vec{r}_2$

and where the bar denotes an average.

The correlation function may be determined for populations of actual element values, or for populations of deviant values from the population mean. The correlation function of deviations is defined as:

$$m_f(\rho) = \overline{[f'(\vec{r}_1) \cdot f'(\vec{r}_2)]} \tag{23}$$

where the prime denotes a deviation from the population mean. The final expression defines the normalized correlation function; the correlation function divided by the population variance.

$$\mu_f(\rho) = \frac{m_f(\rho)}{m_f(0)} \tag{24}$$

where

$$m_f(0) = \overline{[f'(\vec{r}_1) \cdot f'(\vec{r}_1)]}.$$

Operationally, the normalized correlation function of deviations is preferred because it is more conservative than the simple correlation function, and for this reason it was used in the present study.

From equation (24) it is obvious that for the perfectly homogeneous population (a binary population) $\mu_f(\rho) = 1$ for all values of ρ. In practice, however, $\mu_f(\rho)$ will normally be near unity for small ρ and drop off non-linearly for increasing ρ. The value of the function at any given distance indicates how closely the average product of the points at that distance resembles the total population variance; or how similar/homogeneous these equidistant points are. In the present study, it is only necessary to analyze the normalized correlation function of deviations with respect to the next adjacent area, or smallest ρ value for a given population of assumed cloud brightness values. The reason for this is that the HD bi-spectral method is only applied across two adjacent areas of a cloud field for any calculation.

As in the standard deviation test, the value of the normalized correlation function may be plotted as a function of the area size over which the elements of the second sample population were taken; and a graph of these plots should yield an indication of which area sizes produce populations with the most homogeneous adjacent elements.

5.4.1 Application of the homogeneous area tests

The requirement for horizontal homogeneity of the present HD bi-spectral technique applies to both the visible and infrared data fields. However, the resolution area of the infrared data is coarser than that of the visible data (Section 3.2). This mismatch of resolution areas means that there is less chance in the infrared case for a single re-solution point to be cloud or clear filled. Consequently, the area sizes that produce the most homogeneous populations of maximum bright-ness counts may not be the same for both data sets. For this reason the homogeneous area tests were applied to both the visible and infra-red data.

5.4.2 Results of the homogeneous area tests

Figures 11 and 12 illustrate the results of the standard deviation and correlation function tests as applied respectively to the visible and infrared data of the convective cloud regime. In the case of the visible data, the standard deviation plots fall off rather rapidly up to the 100 Km^2 area size, and then level off before dropping again to a minimum value. The relative maximum standard deviation values for area sizes smaller than 100 Km^2 may be explained as the effects of largely deviant (dark) non-filled resolution points (as found in the minimum area test). As for area sizes larger than 150 Km^2, an explana-tion may be found by considering the physical properties of a convec-tive cloud field: in an unstable environment the individual buoyancy of each cloud element is strongly dependent upon local dynamics. A few elements may be strongly buoyant while others may be less buoyant, and only a very few of the strongest, most buoyant elements ever become

Figure 11. The homogeneous area tests as applied to the visible data of the convective cloud regime: the standard deviation in units of volts X 28.1 (thin line) and pseudo albedo (thin dashed line) — see Section 4.2 of the text; and the normalized correlation function of adjacent areas (heavy line).

Figure 12. The homogeneous area tests as applied to the infrared data of the convective cloud regime: the standard deviation in units of radiance (thin line) and Kelvin degrees from the population mean (thin dashed line); and the normalized correlation function of adjacent areas (heavy line).

(very bright) super cells. The continual fall in the standard deviation plots for area sizes larger than 150 Km^2 may thus be explained by the fact that for larger areas the population of maximum brightness counts becomes saturated with these very bright super cells. In which case each super cell may be only slightly deviant from the population mean, contributing to a small standard deviation, but have no correlation with adjacent elements.

The standard deviation plots for area sizes 100 Km^2 to 150 Km^2, however, are of greatest interest. It is here that the effects of the anomalously bright super cells become maximized, and the effects of the non-filled, anomalously dark, resolution points become minimized. The net result of these cross purpose effects is a flattening out of the standard deviation plots as evidenced in Figure 11.

The plot of the normalized correlation function also supports the super cell line of reasoning. The population of maximum counts taken over very small areas naturally shows the highest correlation of adjacent elements, while for very large areas the populations of highly deviant super cells actually show negative correlation of adjacent elements. As in the standard deviation plots, the normalized correlation function shows greatest stability for area sizes 100 Km^2 to 150 Km^2.

For the infrared data, the plots of the standard deviation and normalized correlation function show the same general features as the visible data plots. In the infrared case, however, non-filled resolution points represent largely deviant warm elements rather than dark elements, while super cells represent largely deviant cold elements rather than bright elements. As could be expected, the standard

deviation plots are less conservative in terms of temperature than in terms of reflectivity. In all other respects, the plots are similar including the plot of the normalized correlation function, which shows greatest stability for area sizes 100 Km^2 to 150 Km^2. Thus, for tropical convective cloud regimes, the most homogeneous populations of cloud fields, with the best correlation of adjacent elements, are produced from maximum brightness counts taken over area sizes near 125 Km^2.

For the stratiform cloud regime, Figures 13 and 14 illustrate the results of the homogeneous area tests as applied to the visible and infrared data respectively. In the case of the visible data, the standard deviation plots again show the effects of the largely deviant non-filled (dark) resolution points for area sizes smaller than 100 Km^2. The effects of the anomalously bright cloud elements are coincidentally maximized again near 150 Km^2. The plot of the normalized correlation function shows maximum stability for area sizes 75 Km^2 to 150 Km^2, and indicates negative correlation of adjacent elements for area sizes larger than 175 Km^2.

The standard deviation plots of the infrared data for the stratiform cloud regime are particularly interesting. Whereas for the cold convective regime, non-filled (warm) resolution points represent largely deviant elements, for the warm stratiform regime, non-filled (warm) resolution points are non-deviant. Thus, for the infrared data of the stratiform regime, the standard deviation plots are minimized for area sizes smaller than 100 Km^2 where the effects of non-filled resolution points are predominant. The infrared plots are strikingly consistent with the visible plots, however, in that they also illustrate the increasing effects of the anomalously bright (cold) elements
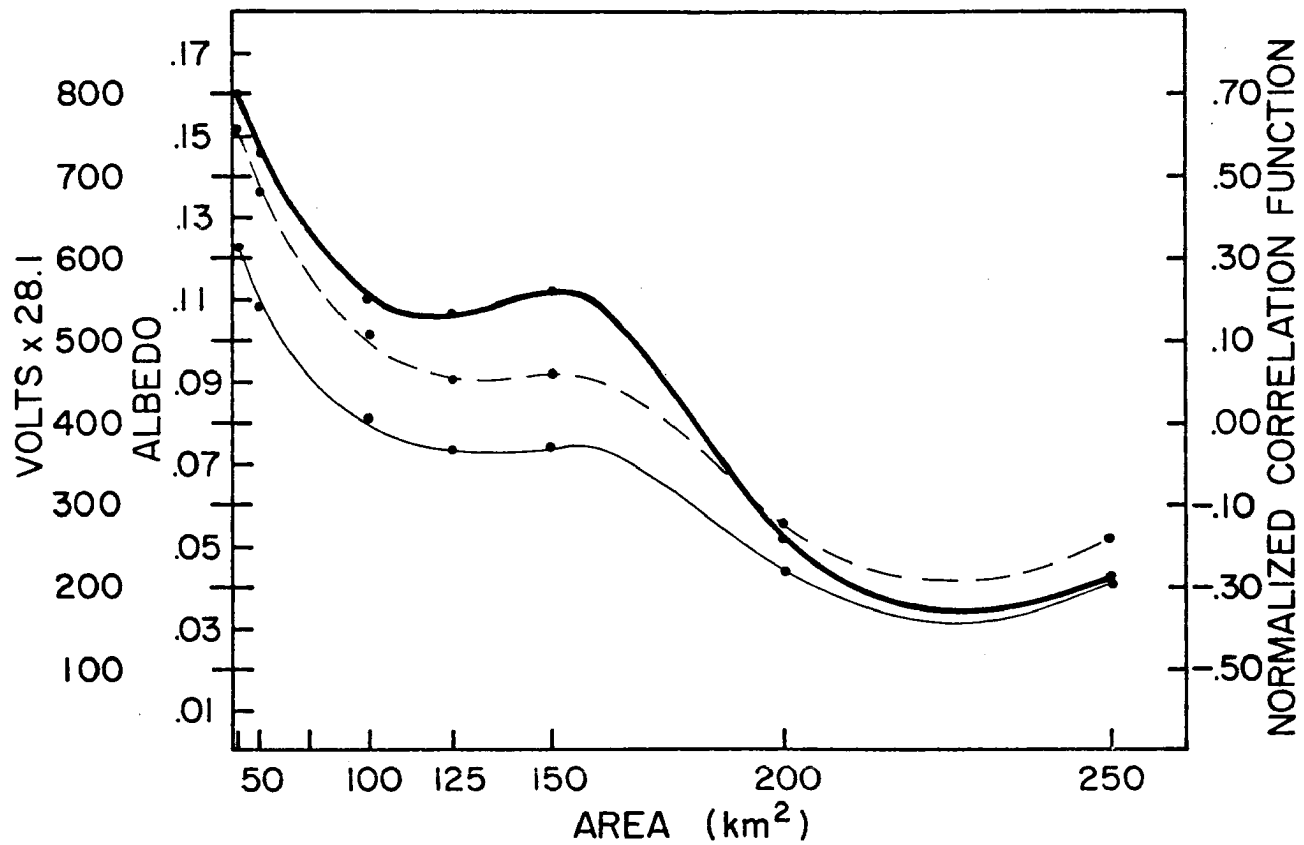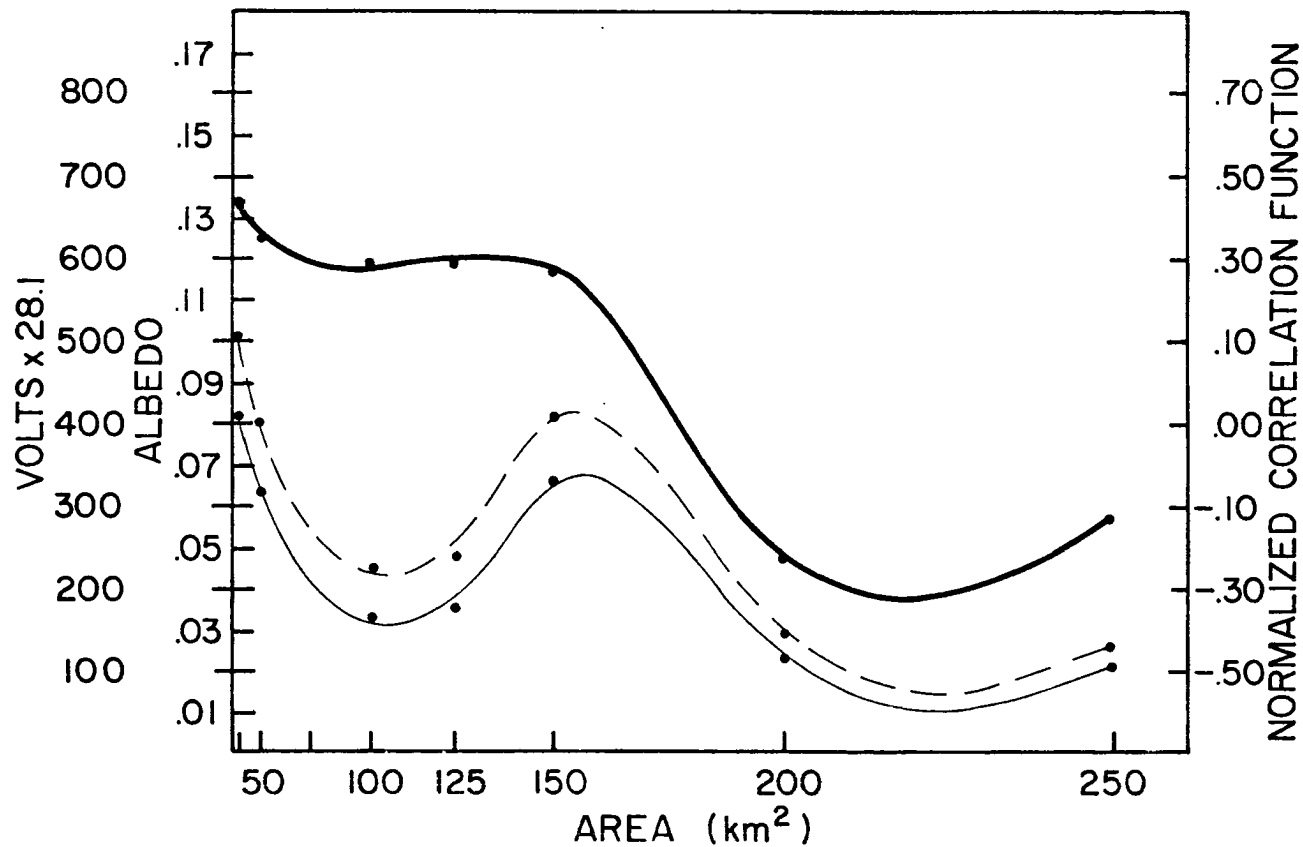
Figure 13. The homogeneous area tests as applied to the visible data of the stratiform cloud regime: the standard deviation in units of volts X 28.1 (thin line) and pseudo albedo (thin dashed line) - see Section 4.2 of the text; and the normalized correlation function of adjacent areas (heavy line).
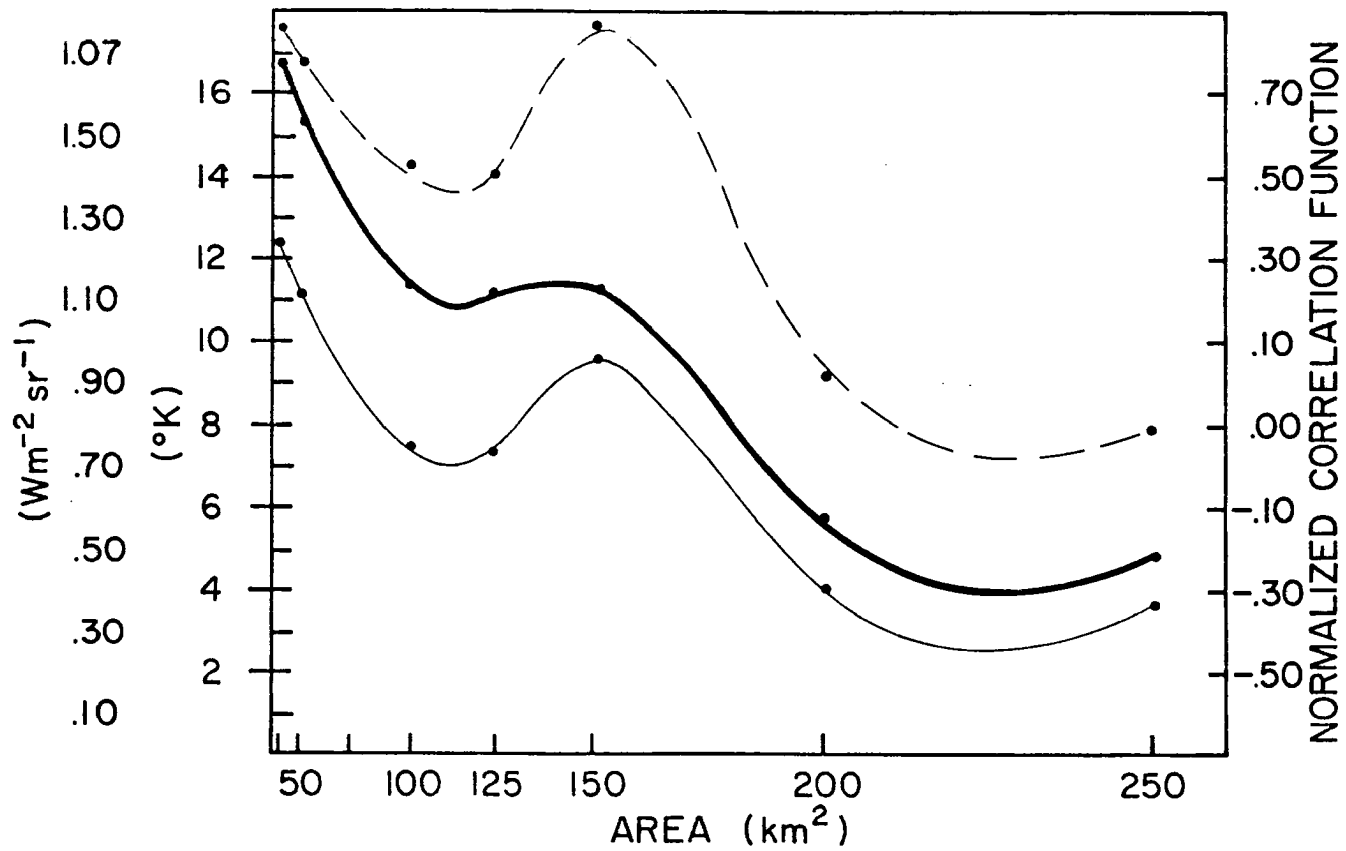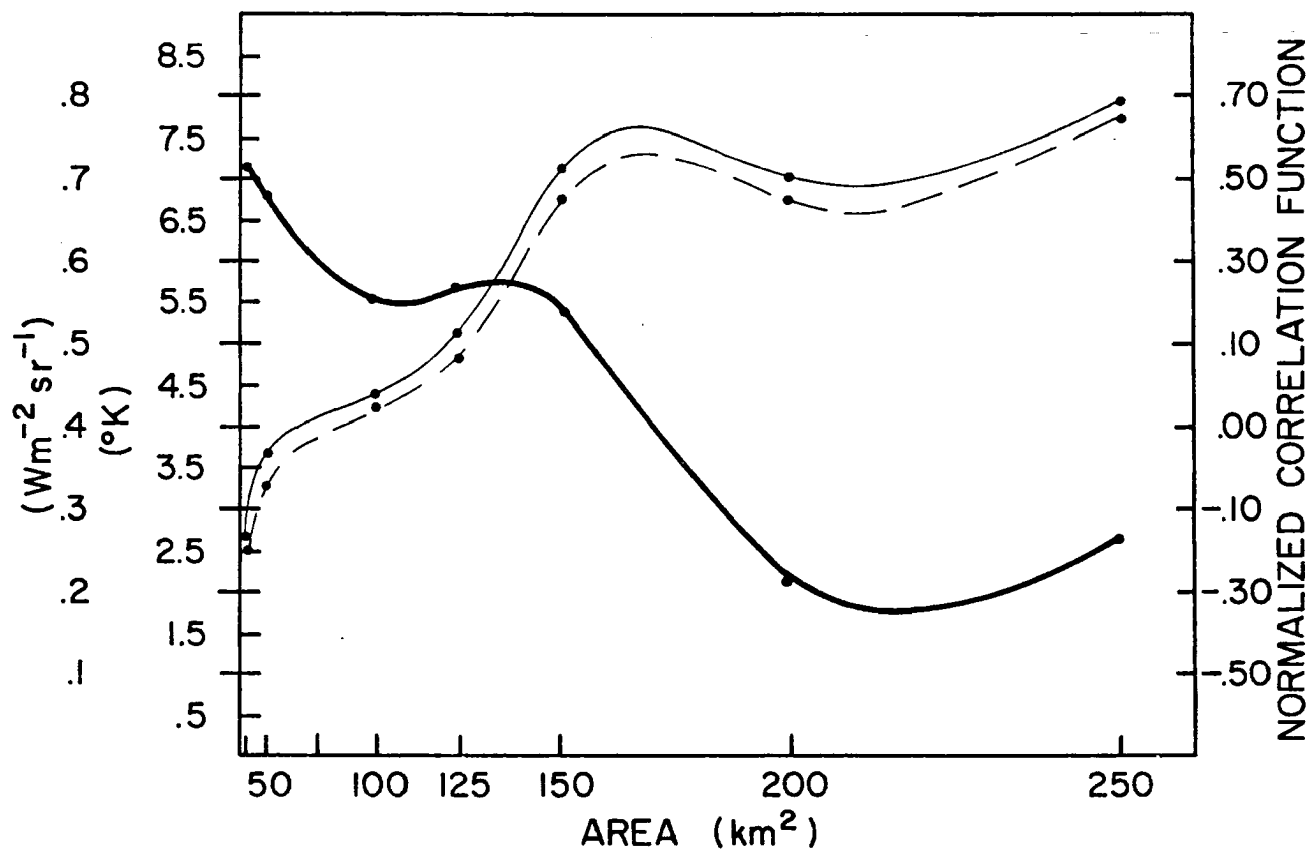
Figure 14. The homogeneous area tests as applied to the infrared data of the
stratiform cloud regime: the standard deviation in units of radiance
(thin line) and Kelvin degrees from the population mean (thin dashed
line); and the normalized correlation function of adjacent areas
(heavy line).

between 100 Km^2 and 150 Km^2, and the maximization of these effects near 150 Km^2. The plot of the normalized correlation function for the infrared data shows maximum stability for area sizes between 100 Km^2 and 150 Km^2 and also indicates negative correlation of adjacent elements for area sizes larger than 175 Km^2. Thus, for tropical stratiform cloud regimes, the most homogeneous populations of cloud fields, with the best correlation of adjacent elements, are produced from maximum value brightness counts taken over area sizes near 100 Km^2.

5.5 The optimum area test

An important practical result of applying the HD bi-spectral equations of Section 3.0 to observed visible and infrared SMS brightness counts is that the computed infrared cloud and surface radiance values may be compared to those corresponding to observed infrared brightness counts. Obviously, given correct visible brightness counts for BCLD and BCLR, and the conditions that all of the explicit and implicit assumptions are satisfied, the HD bi-spectral equations will yield correct values of cloud amount (NCLD), cloud radiance (ICLD), and surface radiance (ICLR). When this occurs during actual application, the computed values of ICLD and ICLR will perfectly match those taken from the observed maximum and minimum infrared brightness counts. In this way the overall validity of the HD bi-spectral method may be observationally verified.

Although this verification scheme does not specifically test the validity of any one HD bi-spectral assumption, it may be used to determine an effective area over which the technique may be applied. The procedure involves the comparison of computed cloud radiance values

to observed cloud radiance values, as the HD bi-spectral method is applied over areas of different size. The difference in computed and observed values is then plotted as a function of the variable area size, and the graphical plot is analyzed for areas that produce a minimum difference in the two values.

5.5.1 Application of the optimum area test

As noted in the test for a minimum area size, the fact that the sample cloud regimes were mostly cloudy, limited the possibility that a clear filled resolution point would be found over small areas. For this reason, during the optimum area test, which requires the actual application of the HD bi-spectral technique, the minimum brightness count over the entire cloud regime area was used for the clear area brightness value in each spectra. Such a procedure may be used for the HD bi-spectral method, or as in the application of earlier bi-spectral methods, representative cloud and clear values may be determined a priori and assumed to be constant.

5.5.2 Results of the optimum area test

Figures 15 and 16 illustrate the results of the optimum area test as applied to the convective and stratiform cloud regimes respectively. The plot of the convective regime (Figure 15) clearly indicates a relative minimum difference in computed vs. observed radiance values where the HD bi-spectral technique was applied across adjacent areas of 100 Km^2 - 125 Km^2. This is in good agreement with the results of the other effective area tests. But there is also another relative minimum value indicated near 25 Km^2. This is most probably the result of the extremely high correlation of adjacent cloud elements found
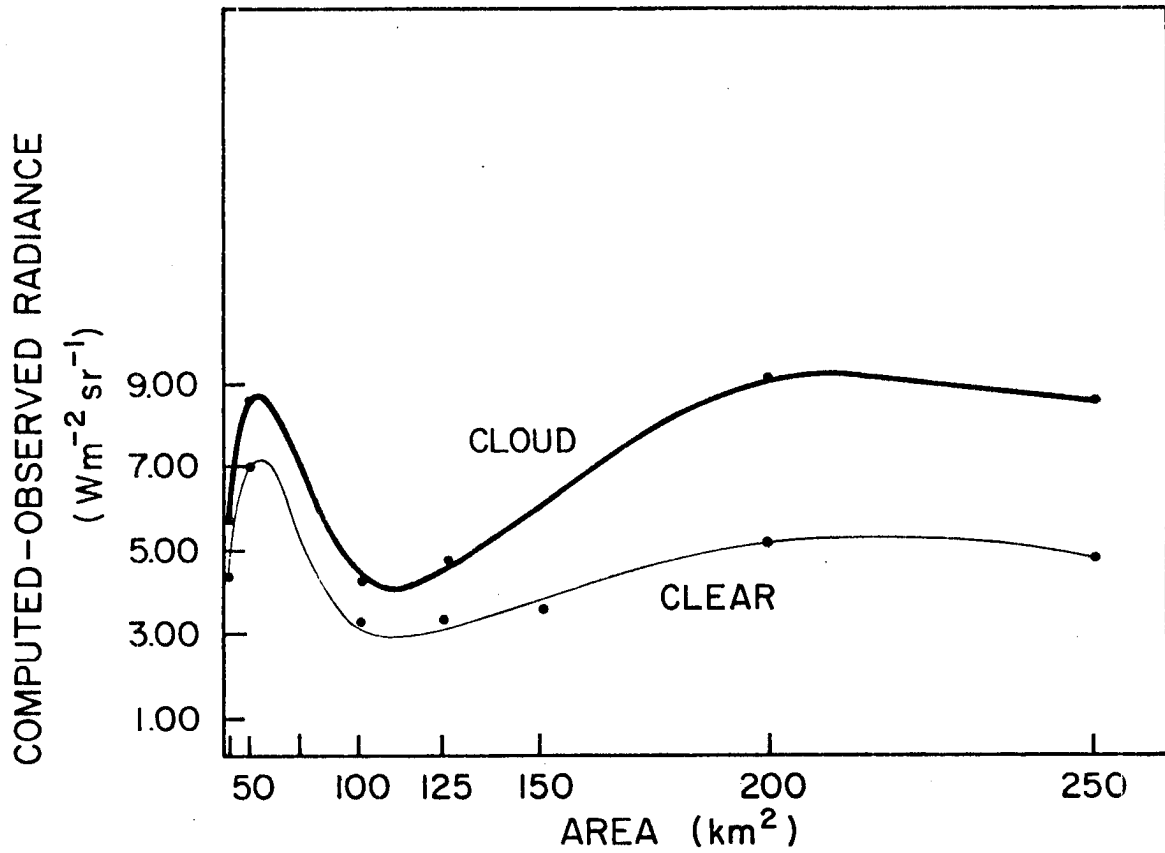
Figure 15. The difference in computed vs. observed cloud (heavy line)
and clear (thin line) radiance values, as the HD bi-
spectral method was applied across adjacent area sizes of
the convective cloud regime.
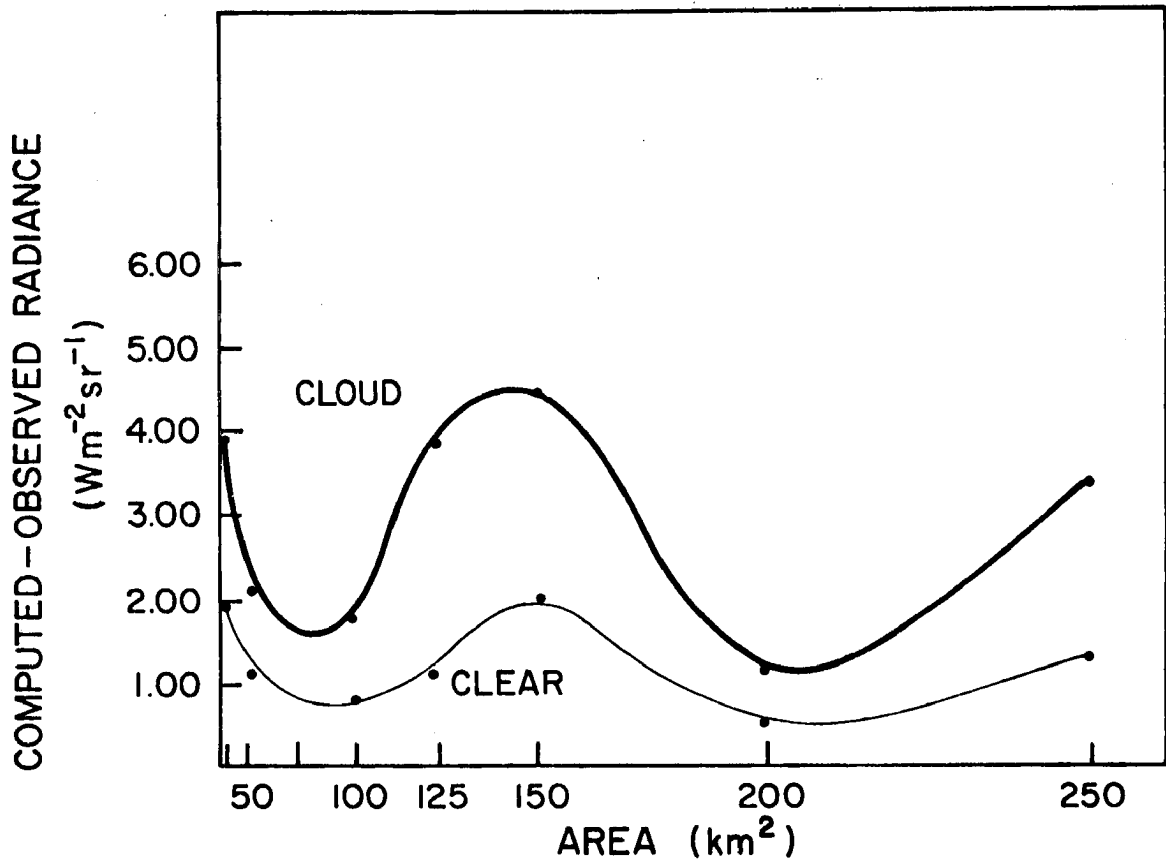
Figure 16. The difference in computed vs. observed cloud (heavy line) and clear (thin line) radiance values, as the HD bi-spectral method was applied across adjacent area sizes of the stratiform cloud regime.

here, for both the infrared and visible data sets (see homogeneous area tests). The difference in computed vs. observed radiance values is really a measure of how well the infrared and visible data sets are "matched" with respect to maximum, minimum, and mean values. Over very small areas, the data sets are apparently well matched for the convective regime, but cloud amount values computed over these small areas will be in error because the maximum brightness counts which are used to normalize the data cannot reasonably be assumed to represent a cloud filled resolution point over such small areas (see minimum area test). Thus, for the convective cloud regime, the logical optimum area size for the application of the HD bi-spectral technique is 100 Km^2 – 125 Km^2.

The results of the optimum area test as applied to the stratiform cloud regime (Figure 16) also show two relative minima in the difference of computed vs. observed radiance values: one near 75 Km^2 – 100 Km^2, and one near 200 Km^2. The minimum value near 200 Km^2 is neither compatible with the standard deviation nor the correlation function test. Apparently the infrared and visible data sets are well matched over these large areas, even though the individual cloud elements are largely non-homogeneous; and here again, any cloud amounts computed over these large areas will be in error because the maximum brightness counts actually represent deviant cloud elements (see homogeneous area tests). Thus, for the stratiform cloud regime, the logical optimum area size for the application of the HD bi-spectral technique is 75 Km^2 – 100 Km^2.

5.6 Summary of the effective area test results

Figure 17 illustrates the combined results of the effective area tests: for the convective cloud regime, the minimum area test indicates that the HD bi-spectral technique should not be applied to area sizes smaller than 125 Km^2 if the assumption that a maximum brightness count represents a cloud filled resolution point is to remain valid; the standard deviation and normalized correlation function tests indicate that the assumption of horizontal homogeneity is most valid where cloud elements are taken from areas of 100 Km^2 to 150 Km^2; and the optimum area test indicates that the infrared and visible data fields are best matched for area sizes 100 Km^2 - 125 Km^2. Thus, for the convective cloud regime, the HD bi-spectral technique should yield best results when applied across adjacent areas of 125 Km^2.

For the stratiform cloud regime: the results of the minimum area test indicate that an area no smaller than 100 Km^2 is necessary for satisfying the assumption that the maximum brightness count represents a cloud filled resolution point; the standard deviation and normalized correlation function tests indicate that the assumption of horizontal homogeneity is most valid where cloud elements are taken from areas of 100 Km^2 - 125 Km^2; and the optimum area test indicates that the infrared and visible data sets are best matched for area sizes 75 Km^2 to 100 Km^2. Thus, for the stratiform cloud regime, the HD bi-spectral technique should yield best results when applied across adjacent areas of 100 Km^2.

CONVECTIVE CLOUD REGIME

APPLIED TEST	75 Km^2	100 Km^2	125 Km^2	150 Km^2
MIN. AREA			*	
STD. DEV.		*	*	*
COR. FUN.		*	*	*
OPT. AREA		*	*	

STRATIFORM CLOUD REGIME

APPLIED TEST	75 Km^2	100 Km^2	125 Km^2	150 Km^2
MIN. AREA		*		
STD. DEV.		*	*	
COR. FUN.		*	*	
OPT. AREA	*	*		

Figure 17. A summary of the effective area tests. An asterisk denotes most effective area as found in the tests.

6.0 AN ITERATIVE APPROACH

6.1 Computed vs. observed values (a verification scheme)

As discussed in section 5.5, the present HD bi-spectral application allows the computed values of cloud radiance (ICLD) and surface radiance (ICLR) to be compared to corresponding radiance values taken from the observed maximum and minimum infrared brightness counts. The difference in these values may be assumed to be a measure of the technique's over-all effectiveness, although it does not, by itself, indicate which assumed values or assumptions are in error. However, the assumption of the present study that the maximum/minimum observed visible brightness counts over a given area represent a cloud/clear filled resolution point, imposes important physical constraints that allow for a more definitive analysis of computed vs. observed radiance value differences.

Consider the physical characteristics of the visible channel SMS brightness counts. The maximum observed brightness count over any given area is simply a measure of the most reflective or "brightest" feature in that area (assuming isotropic surfaces). Over the tropical ocean, where surface albedo may always be assumed to be less than cloud albedo, this value should never be an overestimate of cloud brightness (BCLD) because the brightest resolution point in any field of view will always be cloud-related. The maximum observed brightness count may, however, be an underestimate of cloud brightness if it represents a resolution point that is only partially filled by opaque cloud, or one that is filled by an optically thin cloud. Similarly, the minimum observed brightness count of the visible channel is simply a measure of the least reflective feature in a given area. Again, over the tropical

ocean, this value should never be an underestimate of surface brightness because it will always be ocean (surface) related. It may, however, be an overestimate of surface brightness if it represents a resolution point that is partially filled by (a higher reflective) cloud.

In the infrared channel, the maximum observed brightness count over any given area is simply a measure of the coldest feature in that area. Since the coldest point in any field of view will always be cloud re-lated (assuming a positive tropospheric lapse rate) the maximum observed infrared brightness count should never yield a corresponding cloud radi-ance value that is too small (underestimate). Note the inverse rela-tionship between observed infrared brightness count and radiance value (Section 3.2.1); the higher the brightness count the lower the corres-ponding radiance value. Thus, the maximum observed infrared brightness count should never yield a corresponding cloud radiance value that is too low (underestimate). It may, however, yield a cloud radiance value that is too high (overestimate), if it represents a resolution point that is only partially filled by cloud of unit emissivity, or one that is filled by an optically thin cloud. Similarly, the minimum observed infrared brightness count can only be surface related, and should never yield a corresponding surface radiance value that is too high (overestimate). It may, however, yield a surface radiance value that is too low (underestimate) if it is partially filled by (a colder) cloud.

6.2 Minimizing computed cloud amount errors

Equations (20) and (21) show that for a given set of measured visible and infrared brightness counts, the computed cloud and surface

radiance values (ICLD and ICLR) vary only as a function of the visible channel cloud and clear brightness counts respectively. Furthermore, the results of the error analysis (Section 4.3.3) show that the relationship between the visible brightness values BCLD and BCLR, and the computed radiance values ICLD and ICLR, are inverse; that is if the assumed BCLD/BCLR visible brightness value is less than the true value, then the computed radiance value, ICLD/ICLR will be larger than the true radiance value. This may also be seen from equations (20) and (21) where dM_ℓ/dM_s is a negative value. The consequence of these results, when combined with the physical characteristics of the SMS data as discussed above, leads to a unique set of possible assumed value errors that may be used to minimize the error in computed cloud amounts.

Consider the case where the computed cloud radiance value is greater than the value corresponding to the observed infrared maximum brightness count. Two possibilities exist: (1) the corresponding observed cloud radiance value is too low, or (2) from the error analysis, the assumed cloud brightness value (BCLD) is an underestimate of the true value. The physical possibilities discussed above, however, show that the maximum observed infrared brightness count will always represent the coldest point over a given area so that the corresponding observed cloud radiance value should never be too low. Possibility (1) above can, therefore, be dismissed. On the other hand, it is physically possible for the maximum observed visible brightness count to be an underestimate of cloud brightness (BCLD) if the resolution point is "contaminated" by a lower reflecting clear area within it, or by an optically thin cloud. Thus, in this instance, the obvious value to adjust is the assumed cloud brightness value (BCLD). (Note that equal channel

reliability is assumed here.) Similar and symmetric analyses may be made for the other computed vs. observed values of cloud radiance (ICLD) and surface radiance (ICLR) which lead to the unique set of possible value errors listed below:

ICLD observed < ICLD computed

    (1)   ICLD observed too low   - not possible (true value)

    (2)   BCLD assumed too low   - possible (clear area contam)

ICLD observed > ICLD computed

    (1)   ICLD observed too high - possible (warm area contam)

    (2)   BCLD assumed too high - not possible (true value)

ICLR observed < ICLR computed

    (1)   ICLR observed too low   - possible (cold area contam)

    (2)   BCLR assumed too low   - not possible (true value)

ICLR observed > ICLR computed

    (1)   ICLR observed too high - not possible (true value)

    (2)   BCLR assumed too high - possible (cloud area contam).

Thus, for any possible combination of observed vs. computed values, only one possible assumed variable may be in error, and the direction and magnitude of the error is clearly indicated. By adjusting the value in error, through this iterative, cross verification scheme, any error in computed cloud amount will be minimized.

6.3 Evaluating the iteration technique

Two separate schemes were devised to evaluate the iteration technique. The first scheme was an objective analysis which involved applying the HD bi-spectral method without the iteration technique to

predetermined visible and infrared data sets having a known noise level
and cloud amount. The computed results of this application could then
be compared to the results obtained by applying the method, with the
iteration technique, to the same data sets.

The second evaluation scheme was a subjective comparative analysis,
i.e., the results of the HD bi-spectral method, both with and without
the iteration technique, were compared to the results obtained from
the general bi-spectral method (Section 2.1), and from a modified fre-
quency distribution method of determining cloud amount. This second
evaluation of the technique was accomplished using the same sample data
sets that were used in the effective area tests (twenty samples of
tropical convective cloud regime data and nineteen samples of tropical
stratiform cloud regime data). By comparing the results of several
different methods, an indication of the relative effectiveness of each
method should be provided.

6.3.1 The evaluation procedures

Actual implementation of the first evaluation scheme involved
forming a complete data array of predetermined visible and infrared
brightness counts to produce a known cloud amount. A random error was
then added to these predetermined values, where the random error was
taken from a population of elements with normal distribution and having
a standard deviation equal to 3% of the true brightness count values.
In this way, a complete set of data points with a known noise level was
simulated. This evaluation method was different from the error analysis
test of Section 4.0 in that the error analysis test was applied holding
the averaged values M_s and M_ℓ constant (see Section 2.0) while the BCLD

and BCLR values were allowed to vary. In evaluating the iteration technique, the values of M_s and M_ℓ were allowed to vary as determined by the variations in the individual visible and infrared brightness counts. Additionally, the present evaluation was less general because only one set of unique brightness counts was used, and the method was evaluated using only one true cloud amount value. Although the test conditions were specifically selected to represent average conditions (see below), the reader is cautioned not to generalize the results. The error analysis of Section 4.0 (see Table 2, and Equation 19) shows that errors in computed cloud amount vary as a function of M_s as well as BCLD and BCLR. This preliminary evaluation, however, was kept as general as possible: cloud amounts across the area of application were chosen at 0.500 and 0.667 respectively; the surface temperature and albedo were chosen at 299°K and 0.06 respectively; and cloud temperature and albedo were chosen at 238°K and 0.60 respectively. These conditions may be considered representative of scattered to broken middle clouds of unit emissivity over a tropical ocean.

Because the comparative analysis of the iteration technique involved the use of real data sets, a completely objective evaluation such as that applied to the random error analysis was not possible. Instead, each particular method of computing cloud amount and/or cloud radiance was applied to the same data arrays, and the results were listed in tabular form. In this way, an "objective" comparison of the results from each method could be made.

In the case of the frequency distribution method, some cutoff brightness count is usually assumed, above which all elements represent cloud filled resolution points. The computed cloud amount is then the

ratio of cloud filled elements to total elements. The difficulty with this method is in determining a valid cutoff value; small differences in the cutoff value where large frequency values occur may mean large differences in resultant computed cloud amounts. This inherent variability makes it difficult to compare the frequency distribution method with the other bi-spectral methods. However, a slight modification of the method is sufficiently analogous to make an objective comparison possible. In this "hybrid" technique, a maximum brightness count is assumed, above which all elements represent cloud, and a minimum brightness count is assumed, below which all elements represent clear area. All in between brightness counts are then normalized using these base values. This technique differs from the traditional frequency distribution method, in that the traditional method assumes the maximum and minimum cutoff values to be equal, thus eliminating the normalization procedure. The "hybrid" frequency distribution method differs from the general bi-spectral method only in the manner that it handles the brightness counts above and below the cutoff values: in the general bi-spectral method, any brightness count representative of an albedo higher than the assumed cloud albedo, is normalized to a cloud amount greater than unity, and any brightness count representative of an albedo lower than the assumed clear albedo is normalized to a cloud amount less than zero. The "hybrid" method eliminates these possibilities by only normalizing brightness counts that are in between the maximum and minimum values; all values above or below the cutoff values are set to unity or zero respectively. The "hybrid" method becomes completely analogous to the general bi-spectral technique when identical albedo values are assumed in each case. In the present analysis,

several albedo values were assumed for each method and for each differ-
ent cloud regime so that a more complete perspective of the different
methods would be provided.

6.3.2   Results of the objective evaluation

The results of the objective analysis evaluation of the iteration
scheme are presented in Table 6 which indicates that the iteration
scheme may be a valid, but conservative, method for reducing errors in
computed cloud amount. The scheme reduced the error in computed cloud
amount by more than 14% for the data conditions used in the evaluation.
However, the reader is again cautioned that the results are not general.
Different values or levels of error in BCLD and BCLR, as well as changes
in total cloud amount, will vary the amount of improvement.

Nevertheless, there are other interesting aspects of the results.
For example, in recomputing the cloud amount value, the iteration scheme
assumed the computed ICLD value to be true, but also assumed the
observed ICLR value to be true. This is not evident from equations (20)
and (21) as might be expected. Equation (20) indicates that an over-
estimate of BCLD (as occurs when random errors are introduced) will re-
sult in an underestimate of computed ICLD, which satisfies the reason-
ing for the iteration scheme to assume the ICLD computed value to be
true. However, equation (21) indicates that an underestimate of BCLR
(as also occurs when random errors are introduced) will result in an
overestimate of computed ICLR, which would require the iteration scheme
to assume the computed ICLR value to be true. This would be the case,
except that the observed ICLR value (taken from the data set) was even
larger than the computed value. This indicates that the direct effect

	True Value (Noiseless)	Observed Value (With Noise)	(1) No Iteration	(2) Iteration	(3) Difference (2) − (1)
NCLD	0.583	−	0.493	0.506	+ 0.013
ICLD ($Wm^{-2}sr^{-1}$)	3.08	2.20	1.82	1.82	$\pm$ 0.00
ICLR ($Wm^{-2}sr^{-1}$)	9.22	9.54	9.31	9.54	+ 0.23
TCLD (°K)	238	223	216	216	$\pm$ 0.00
TCLR (°K)	299	302	300	302	+ 2

Table 6. A comparison of variables from the objective evaluation of the iteration technique. Cloud and surface temperature were prespecified as indicated; cloud and surface albedos were prespecified as 0.60 and 0.06 respectively. For a further discussion see the text.

of random errors on the minimum observed infrared brightness count may be larger than the indirect effect on the minimum observed visible brightness count. This result may have important implications with respect to the effectiveness of the iteration scheme in low (warm) cloud situations, which should be further investigated.

6.3.3 Results of the comparative evaluation

The results of the comparative analysis as applied to the data sets of the convective and stratiform cloud regimes are presented in Tables 7 and 8 respectively. In general, the comparative analysis shows that:

A. For a given assumed cloud albedo, the modified frequency distribution method yields more conservative cloud amount values than the general bi-spectral method.

B. Both the modified frequency distribution and the general bi-spectral method may yield highly variable cloud amounts and (in the case of the general bi-spectral method) cloud temperatures, depending upon the values of the assumed variables.

C. For similar values of the assumed variables, the HD bi-spectral method yields more realistic cloud temperatures than the general bi-spectral method.

D. Computed values of the HD bi-spectral method are only minimally affected by addition of the iteration technique.

For the convective cloud regime (Table 7), the frequency distribution method produced cloud amounts that were more conservative than those of the general bi-spectral method, especially for values of low assumed cloud albedo; for low cloud albedos, the general bi-spectral

CONVECTIVE REGIME

MODIFIED FREQ. DIST.			NCLD
CLD ALB = 0.40			.657
CLD ALB = 0.60			.503
CLD ALB = 0.80			.384

GEN BI-SPEC	ASSUMED SFC TEMP (°K)	TCLD (°K)	NCLD
CLD ALB = 0.40	[290] < 270 >	[NEG RAD] < 245 >	.840
CLD ALB = 0.60	[290] < 270 >	[NEG RAD] < 241 >	.529
CLD ALB = 0.80	[290] < 270 >	[NEG RAD] < 236 >	.386

HD BI-SPEC	TCLD (°K)	TCLD (°K)	NCLD
W/O ITER	(274)	(203)	.426
W/ ITER	(276)	(200)	.442

Table 7. A comparison of results obtained by applying the indicated methods
to the data sets of the convective cloud regime. Abbreviations are:
CLD ALB = assumed cloud albedo; NCLD = computed cloud amount; TCLD =
computed cloud temperature; TCLR = computed clear temperature. The
surface albedo was assumed to be 0.06 for the frequency distribution
and general bi-spectral methods. For a further discussion, see the text.

STRATIFORM REGIME

MODIFIED FREQ. DIST.				NCLD
CLD ALB = 0.30				.566
CLD ALB = 0.50				.355
CLD ALB = 0.70				.247

GEN BI-SPEC	ASSUMED SFC TEMP (°K)	TCLD (°K)		NCLD
CLD ALB = 0.30	[298] < 280 >	[263]	< 291 >	.622
CLD ALB = 0.50	[298] < 280 >	[218]	< 298 >	.361
CLD ALB = 0.70	[298] < 280 >	[NEG RAD]	< 304 >	.248

HD BI-SPEC	TCLR (°K)	TCLD (°K)	NCLD
W/O ITER	(283)	(283)	.360
W/ ITER	(284)	(283)	.393

Table 8. A comparison of results obtained by applying the indicated methods to the data sets of the stratiform cloud regime. Abbreviations are: CLD ALB = assumed cloud albedo; NCLD = computed cloud amount; TCLD = computed cloud temperature; TCLR = computed clear temperature. The surface albedo was assumed to be 0.06 for the frequency distribution and general bi-spectral methods. For a further discussion, see the text.

method normalizes more brightness counts to a cloud amount greater than unity, thus increasing the final computed value. For the stratiform cloud regime (Table 8), the respective computed cloud amounts of the frequency distribution and general bi-spectral methods show this same general relationship. Both tables also indicate that the frequency distribution method may produce highly variable results depending upon the values of the assumed cloud albedo.

The results of the general bi-spectral method as applied to the convective cloud regime indicate a high degree of variability in both the computed cloud amounts and computed cloud temperatures. Specifically, where the assumed variables appear to be realistic (cloud albedo = 0.80, surface temperature = 290°K), the method yields negative radiance values. (NOTE: The bracketed cloud temperature values in Tables 7 and 8 correspond to the bracketed assumed surface temperatures, etc). Where the assumed surface temperature is approximated by the values computed from the HD bi-spectral method (270°K), the computed cloud temperatures of the general bi-spectral method become positive, but are still too warm to realistically represent a convective cloud regime. The least desirable aspect of the general bi-spectral method appears to be the large range in computed values for the given changes in the assumed variables. This would seem to indicate that even with empirical guidance, the assumed variables must be highly accurate for the method to produce reasonable results.

The results of the general bi-spectral method as applied to the stratiform cloud regime also show significant variability in computed values. As in the case of the convective regime, where the assumed surface temperature appears to be realistic (298°K), the computed cloud

temperature is too cold to be representative of a stratocumulus cloud regime; and where the assumed surface temperature approximates the temperature computed in the HD bi-spectral technique (280°K), the computed cloud temperature of the general bi-spectral method is higher than the surface temperature. These inconsistencies again indicate that empirical guidance is desirable, but that even then the assumed variables must be highly accurate for the general bi-spectral method to produce reasonable results.

In contrast to the variability of the other methods, the computed values of the HD bi-spectral technique appear to be comparatively conservative. For the convective cloud regime, the computed cloud temperatures appear realistic, both with and without the iteration technique; but the computed surface temperatures are too low to be representative of a tropical ocean, even with the iteration technique applied (which assumes the highest of the computed vs. observed clear radiance values to be true). This bias toward colder temperatures, which may be as great as 10-12°C in the tropics, is due to the inability of the SMS infrared sensor to "see through" the heavy amount of water vapor over a tropical ocean. The computed cloud amount was only minimally adjusted by addition of the iteration technique.

For the stratiform cloud regime, the computed cloud temperatures are slightly colder than may be representative of a tropical stratocumulus cloud regime, and surface temperatures are again unrealistically cold. The computed surface temperatures for the stratiform regime are warmer than those computed for the convective regime, because there is less water vapor above the stratiform regime, which is under the influence of large scale subsidence. This allows the SMS

infrared sensor to "see deeper into the atmosphere" producing a warmer integrated radiance value. As in the case of the convective regime, the computed cloud amount was only marginally adjusted by adding the iteration technique.

The HD bi-spectral technique has one advantage over the other methods in that no calibration procedures or empirical guidance is required to apply the method effectively. Empirical considerations may improve the results, but the comparative analysis shows that the technique is already more effective in producing realistic cloud temperatures, than the general bi-spectral method. In comparing the results of the computed cloud amount, an objective analysis is not possible because there is no known true cloud amount value for comparison. In general, however, the frequency distribution and general bi-spectral methods, as applied, appear to produce cloud amounts that are too variable for use in objective analyses.

Additional commentary concerning the iteration technique is necessary: the technique basically forces the maximum observed visible and infrared brightness counts to match each other at the brightest or coldest value, and the minimum observed visible and infrared brightness counts to match each other at the darkest or warmest value. These values are then used in recomputing total cloud amount (Section 6.2). The effects of this procedure are minimized in the comparative analysis evaluation because for each cloud regime the methods were applied over the most effective area for bi-spectral application, as defined by the effective area tests. Over these areas, the visible and infrared data sets are well matched (see Section 5.4), and therefore, require only minimal adjustment by the iteration technique. This reconfirms the

conclusion that the effectiveness of the HD bi-spectral technique is
maximized when applied over these areas for each cloud regime.

7.0 CONCLUSIONS

The horizontal differencing bi-spectral technique, as developed in this report, has been shown to be a more effective method of determining cloud parameters than either the general bi-spectral technique or the frequency distribution method. It has been shown that, as applied to real data sets, the general bi-spectral and frequency distribution methods may yield highly variable and unrealistic results, depending upon the values of the assumed variables. The magnitude of variability indicates that assumed values must be highly accurate if these methods are to yield realistic results. When applied to the same data sets, the horizontal differencing method has been shown to yield comparatively stable and realistic results.

The iteration technique has been shown to be moderately effective in improving the computed results of the horizontal differencing bi-spectral method. In the objective analysis evaluation, the iteration scheme improved the computed cloud amount values by more than fourteen percent. In the comparative analysis evaluation, the iteration scheme had only minimal effects on the computed values. These results should not be generalized, however, because the amount of improvement realized by the iteration scheme has been shown to be dependent upon the magnitude and error level of several different variables.

The most effective area for application of methods such as the horizontal differencing bi-spectral technique has been defined for tropical convective and tropical stratiform cloud regimes. Several specific tests have been applied to real data sets in defining these areas. The results of these tests have shown the optimum area size to

be near 125 Km^2 for tropical convective cloud regimes and near 100 Km^2

for tropical stratiform cloud regimes.

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BIBLIOGRAPHIC DATA SHEET	1. Report No. CSU-ATS-295	2.	3. Recipient's Accession No.

4. Title and Subtitle		5. Report Date September, 1978
CLOUD ANALYSIS FROM BI-SPECTRAL SATELLITE DATA		6.

7. Author(s) Christopher Mendola and Stephen K. Cox	8. Performing Organization Rept. No. CSU-ATS-295

9. Performing Organization Name and Address	10. Project/Task/Work Unit No.
Department of Atmospheric Science Colorado State University Fort Collins, Colorado 80523	11. Contract/Grant No. NSF ATM-77-15369 NSF OCD-74-21678

12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered
National Science Foundation NOAA GARP GATE Project Office 1800 G. Street, N.W. 6010 Executive Blvd. Washington, D.C. 20550 Rockville, Maryland 20852	14.

15. Supplementary Notes

16. Abstracts A horizontal differencing bi-spectral technique has been developed to infer cloud information from satellite data; the technique includes an iteration scheme for reducing errors in computed cloud amount. The technique requires that cloud surfaces over the area of application be horizontally homogeneous, and as developed, assumes that the observed maximum and minimum brightness counts represent cloud and clear filled resolution points respectively. These values are then used to normalize the data in computing total cloud amount. The computed results of the horizontal differencing bi-spectral method, as applied to real data sets, have been compared to the results obtained from a modified frequency distribution method and the general bi-spectral method. The results of this comparative analysis indicate that the computed cloud amounts of the horizontal differencing method are less variable than for the frequency distribution and general bi-spectral methods. The computed cloud temperatures of the horizontal differencing method were also shown to be more realistic than those computed by the general bi-spectral method. The horizontal differencing bi-spectral method uses observed visible spectral data to compute cloud amount, cloud radiance, and clear radiance. When applied to Synchronous Meteorological Satellite (SMS) data, the method allows the computed cloud and clear radiance values to be compared to observed infrared spectral values. The iteration technique uses this comparison of computed vs. observed radiance values to determine which observed spectral values (visible or infrared) best represent cloud and clear surfaces. Once determined, these best values are used to recompute total cloud amount.

17. Key Words and Document Analysis. 17a. Descriptors

SMS-1 Satellite
GATE
Radiation
Cloud Cover
Cloudiness

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 75
	20. Security Class (This Page) UNCLASSIFIED	22. Price