A Bi-Spectral Method for Cloud Parameter Determination

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1.0 INTRODUCTION

With the launch of the TIROS (1961-1965) and ESSA (1966-1969) series of satellites, interest arose in trying to determine cloud amount and cloud type (low, middle, high) from satellite data in an objective manner (Conover, 1962, 1963; Leese, 1964; Miller et al., 1970). After the launch of meteorological satellites such as Nimbus 2 and 3 carrying reliable infrared radiometers, multi-spectral techniques were developed to match data from different satellite sensors viewing the same cloud fields (Vonder Haar, 1970; Shenk and Holub, 1972). Beginning with ITOS-1 (1970) simultaneous high resolution visible and infrared data points from satellites were matched precisely in both space and time. Study of these combined data sets showed them to contain much more information than when both data channels were considered separately (Booth, 1973).

Figure 1 is an example of the simultaneous visible and IR data received from the scanning radiometer (SR) onboard the NOAA-2 spacecraft. As can be seen, the most striking difference between the two pictures is the cloudiness on the visible picture in southeast Colorado which disappears for the most part on the infrared picture of this area. In this case the clouds are bright and warm signifying the presence of low clouds, i.e., stratus. The clouds in the northern portion of Colorado show up bright in the visible and white (cold) in the IR signifying fairly deep, high clouds. The clouds over Washington, Oregon and Northern California appear very thin and gray on the visible image while on the infrared view these clouds cover a much larger area and are white (cold); thus probably indicating cirrus.

The bi-spectral technique of the present paper goes a step further than qualitative comparison of these combined data sets by analyzing both the visible and infrared data received at a single measurement point or
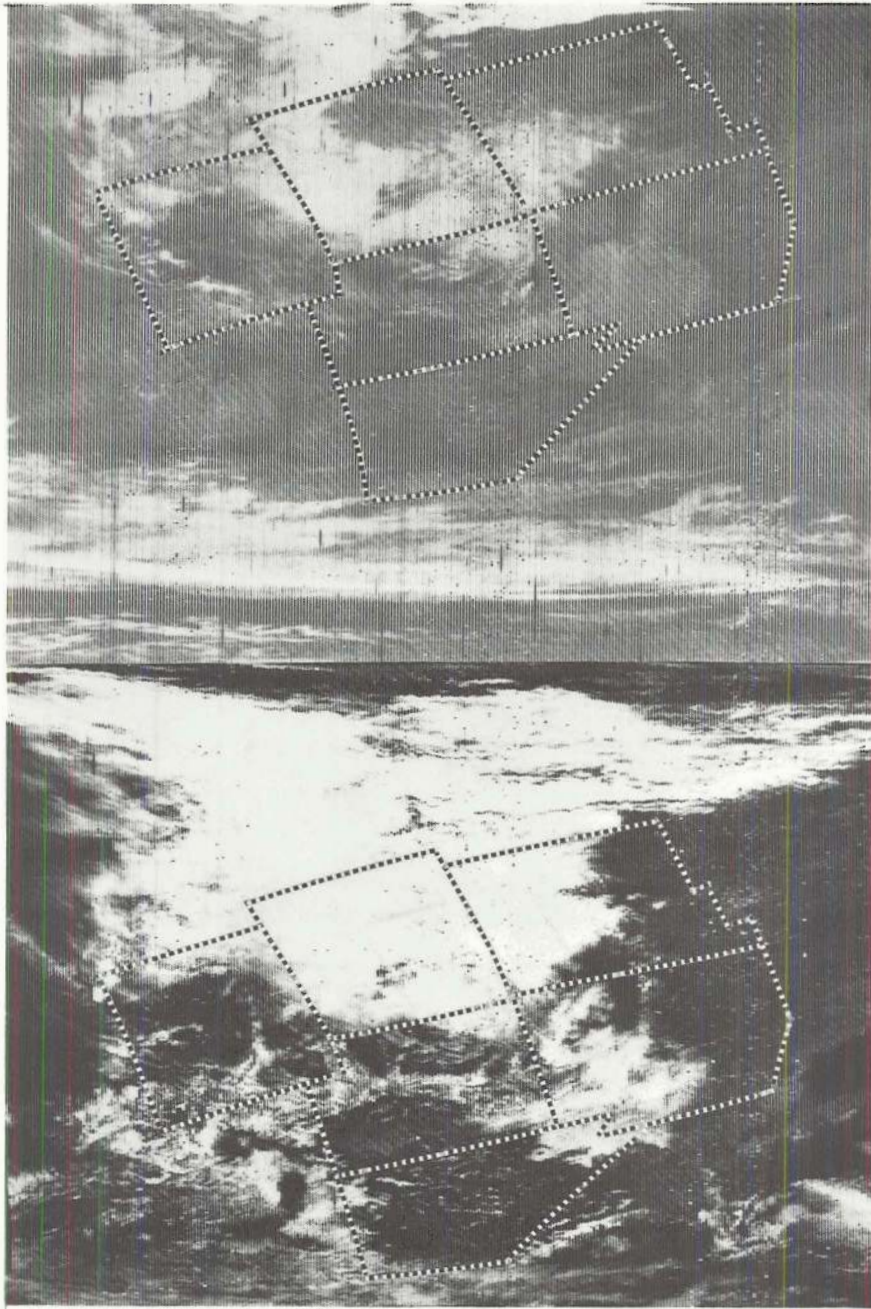
Figure 1. Hard copy print from the visible (left) and IR (right) channel of the Scanning Radiometer onboard NOAA-2 which is received directly at Colorado State University's APT station.

contiguous array of scan spots in a quantitative manner. From these data
we derive the cloud amount (A_{CLD}) and the cloud top temperature $T_{CLD} =$
T_{CLD} (N_{CLD}); through an appropriate vertical temperature sounding we
derive cloud height. The technique is also designed to approach the prob-
lem of determining cloud amounts and heights for cloud sizes below the
size of the sensors geometric field of view. The present paper will pre-
sent the theory for the bi-spectral technique as well as the assumptions
that are made. An uncertainty analysis is used to show the required
measurement accuracy needed for the technique to be successful. Verifi-
cation of this technique is shown by using data obtained from the NOAA
polar orbiting satellites together with concurrect cloud estimates from
the ground. The bi-spectral techniques should prove valuable in the
analysis of SMS/GOES data as well as for several other satellite data
sets which have simultaneous visible and infrared capabilities.

2.0 GENERAL BI-SPECTRAL METHOD

Consider a single measurement spot:

4n mi at SSP
(Sub – Satellite Point
for NOAA 2 or 3)
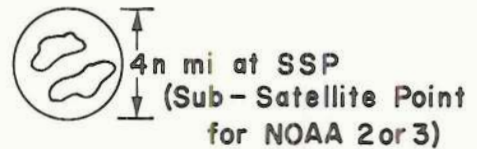
or a measurement array:
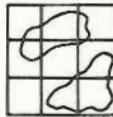
each containing a fraction of their total area covered with clouds $(A_{CLD}$,
in tenths) and the remaining fraction cloudfree (A_{CLR}). At each scan
spot and for each finite array we assume the availability of two spectral
radiance measurements from a satellite, M_S (i.e. $0.5 < \lambda < 0.8 \mu m$) and M_L (i.e.,
$10 < \lambda < 11 \mu m$). The magnitudes of the measured radiances may be assumed to
arise from:

$$M_S = (A_{CLR} \ a_{CLR} \ H_S + A_{CLD} \ a_{CLD} \ H_S) \tag{1}$$

with: a = albedo of the surface (cloud, land or ocean)

H_S = the solar irradiance (i.e., $0.5 < \lambda < 0.8 \mu m$)

reaching the surface; $H_S = N' \Omega_{SUN}$

N' = solar constant for the satellite

and assuming:

a) that bi-directional reflectance effects can be accounted for within "a"; for diffuse case, $a = \pi \rho$

b) that H_S is the same at all levels in the atmosphere,

and also

$$M_L = A_{CLR} N_{CLR} + A_{CLD} N_{CLD} \qquad (2)$$

with N_{CLR} and N_{CLD} the spectral infrared (i.e., $10 < \lambda < 11 \mu m$) radiance arising from the cloudfree and clear regions viewed respectively and assuming:

a) that the infrared emissivity of the (water) clouds and surface is .9.

b) that clouds in view have all tops at nearly the same level (i.e., ±500 m)

Equations (1) and (2) may be joined by the relation implied above:

$$A_{CLD} + A_{CLR} = 1.00 \qquad (3)$$

and the set solved for the two desired unknowns:

A_{CLD} and N_{CLD}

(where N_{CLD} yields T_{eff} of clouds, from Planck's Law).

provided we assume "a priori" knowledge of:

a_{CLR} = the albedo of the cloudfree region (i.e., .10 for ocean, .20 for land, both include atmospheric term)

a_{CLD} = the albedo of the cloud (i.e., 0.50)

and N_{CLR} = the infrared radiance from the cloud-free surface (i.e., $N_{CLR} = F(T_S)$)

All of this "a priori" information can be acquired in practice from the actual array of satellite measurements, using suitable methods such as "minimum albedo" (Vonder Haar et.al., 1973); "clear column radiance" (Smith, 1974), etc. A complete description of these methods is beyond the scope of this paper. However, an uncertainty analysis to test the effect of these assumptions used in the bi-spectral method will be included in the next section.

The solutions for (1), (2) and (3) for cloud amount and cloud radiance are:

$$A_{CLD} = \frac{M_S - \rho_{CLR} H_S}{H_S(\rho_{CLD} - \rho_{CLR})} \tag{4}$$

and:

$$N_{CLD} = \frac{M_L - N_{CLR}}{A_{CLD}} + N_{CLR} \tag{5}$$

3.0 UNCERTAINTY ANALYSIS

The general approach contains several assumptions. Since there are many methods to infer the required "a priori" data, as well as possibilities for iterative solutions, the practical application of the bi-spectral method to determine cloud parameters to meet the need of air operations, temperature soundings, wind sets from SMS, etc. will depend first of all on uncertainties in the measured radiances M_S and M_L. To test the method we have thus proceeded through the development in reverse order.

Differentiating Equation (4) implicitly:

$$\Delta A_{CLD} = \frac{\Delta M_S}{M_S} \left[\frac{M_S}{H_S(\rho_{CLD} - \rho_{CLR})} \right] \qquad \text{(continued next page)}$$

$$+ \frac{\Delta\rho_{CLR}}{\rho_{CLR}} \left[\frac{\rho_{CLR}(M_S - H_S \ \rho_{CLD})}{H_S(\rho_{CLD} - \rho_{CLR})^2} \right]$$

$$+ \frac{\Delta\rho_{CLD}}{\rho_{CLD}} \left[\frac{-\rho_{CLD}(M_S - \rho_{CLR} \ H_S)}{H_S(\rho_{CLD} - \rho_{CLR})^2} \right] \tag{6}$$

$$+ \frac{\Delta H_S}{H_S} \left[\frac{-M_S}{H_S(\rho_{CLD} - \rho_{CLR})} \right]$$

This shows that the uncertainty in cloud amount (ΔA_{CLD}) depends on the magnitude and uncertianty of the incident solar irradiance on the cloud, H_S; the reflected solar radiance measured at the satellite, M_S; and the assumed bi-directional reflectance of the cloud and cloudfree regions, ρ_{CLD} and ρ_{CLR}, respectively. Note that in most cases ΔH_S and $\Delta\rho_{CLR}$ will be less than 10% of their magnitudes, ΔM_S can be within 5% and $\Delta\rho_{CLD}$ can be deduced by direct measurement.

Differentiating (5) we have:

$$\Delta N_{CLD} = \frac{\Delta M_L}{M_L} \left[\frac{M_L}{A_{CLD}} \right] + \frac{\Delta A_{CLD}}{A_{CLD}} \left[\frac{N_{CLR} - M_L}{A_{CLD}} \right]$$

$$+ \frac{\Delta N_{CLR}}{N_{CLR}} \left[\frac{N_{CLR}(A_{CLD} - 1.0)}{A_{CLD}} \right] \tag{7}$$

Equation (6) and (7) were evaluated systematically using these typical mid-latitude values:

$$H_S = 305 \ W \cdot m^{-2} \ (\text{for } \cos \zeta_{SUN} = 0.82)$$

$$M_S = 22. \ W \cdot m^{-2} \cdot sr^{-1}$$

$$M_L = 7. \ W \cdot m^{-2} \cdot sr^{-1}$$

$$N_{CLR} = 8.5 \ W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$$

$$N_{CLD} = 4.0 \ W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$$

$$A_{CLR} = 0.50$$
$$A_{CLD} = 0.50$$
$$a_{CLR} = 0.12$$
$$a_{CLD} = 0.50$$

(the N_{CLR} and N_{CLD} radiances correspond to effective surface temperatures of $290^{\circ}K$ and $250^{\circ}K$, respectively)

Using the values above we evaluated Equation (5) and (6) for uncertainties of 5%, 10% and 20% and Equation (7) for values of A_{CLD} ranging from 0.3 to 0.7.

4.0 RESULTS AND DISCUSSION OF UNCERTAINTY ANALYSES

Results of the uncertainty analysis for cloud amount (A_{CLD}) shows that as the cloud amount varies, the relative uncertainty in cloud amount determination remains about 15 to 20%. The absolute uncertainty thus remains in the 0.05 to 0.10 range for total cloud amounts less than 0.50 and when measurements and assumptions have 5% uncertainty. For example, with all uncertainty at the 5% level:

If:

A_{CLD}	A_{CLR}	Then ΔA_{CLD}
0.7	0.3	0.12
0.5	0.5	0.09
0.3	0.7	0.05

Results of the uncertainty analysis for determining cloud top temperature

showed that with measurement uncertainties of 5% and A_{CLD} assumed to be ± .05 then:

A_{CLD}	A_{CLR}	ΔT_{eff}	ΔZ
0.7	0.3	$5^{\circ}K$	0.6 km*
0.5	0.5	$10^{\circ}K$	1.5 km
0.3	0.7	$19^{\circ}K$	3.0 km

As can be noted, we have the fortunate situation wherein the determination of cloud height is most difficult for scenes of low cloud amount but that the uncertainty in obtaining cloud amount is minimized for these scenes.

Overall, the uncertainty analysis indicates that useful data from the bi-spectral technique is highly probable. Thus a simultaneous test of the method against ground observations was performed. (Simultaneously, satellite radiance measurements were tested for accuracy and stability (see Appendix 1).

5.0   RESULTS FROM THE BI-SPEC PROGRAM

In order to test the bi-spectral program, it was necessary to choose an area that corresponded to a location where cloud observations and upper air data were available. The first obvious location was WSMR since it took cloud observations during the time of the satellite pass and took frequent upper level soundings. Two other locations which were usually in good view by the satellite were chosen, Denver, Colorado and Oklahoma City, Oklahoma. We applied the bi-spectral model for a $2^{\circ} \times 2^{\circ}$

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*to obtain this value it will be necessary to refine our measurements for A_{CLD} since we found that A_{CLD} could not be determined to ± .05 for cloud amounts greater than 0.5.

latitude-longitude box centered on the location of interest. The problem arose of the size of an area to choose to correspond best with the ground observer's measurement of cloud amount. The method chosen was to assume a 40 mi. radial visibility in terms of sky cover measurements for the ground observer and to use data ± 40 miles from the location of the site to compute an average cloud amount and cloud top temperature from the model output.

Figure 2 is a comparison of ground observed and satellite determined cloud amount and cloud height where standard meteorological symbols are used for amount for the WSMR area. Since these data correspond to the data set used for calibration, (See Table 1 in Appendix 1), it tends towards mostly clear cases. Thus, the bi-spectral technique handles this well as should be expected. In several cases shown here, the bi-spectral technique does pick out small scale fields of cumulus and towering cumulus building up over the White Sands region (Figure 3). For middle and higher type cloudiness the technique shows some discrepancies. Unfortunately, no estimate was made of the total opaque cloud amount in the surface observations made at White Sands as was done for Denver and Oklahoma City. Since our assumption of an emissivity of .9 is made of all emitting surfaces, we will obviously determine too warm a cloud-top temperature for surfaces less than this. In some instances when very thin cirrus is observed, the visible channel measurements are off as well since it views the underlying surface as well as the cloud. In some instances, as seen on November 13, 1974, we completely miss the clouds. This problem will appear in the two other locations and will be discussed in further detail in the next section. Table 2 gives the actual percentage amounts and heights of clouds observed as determined
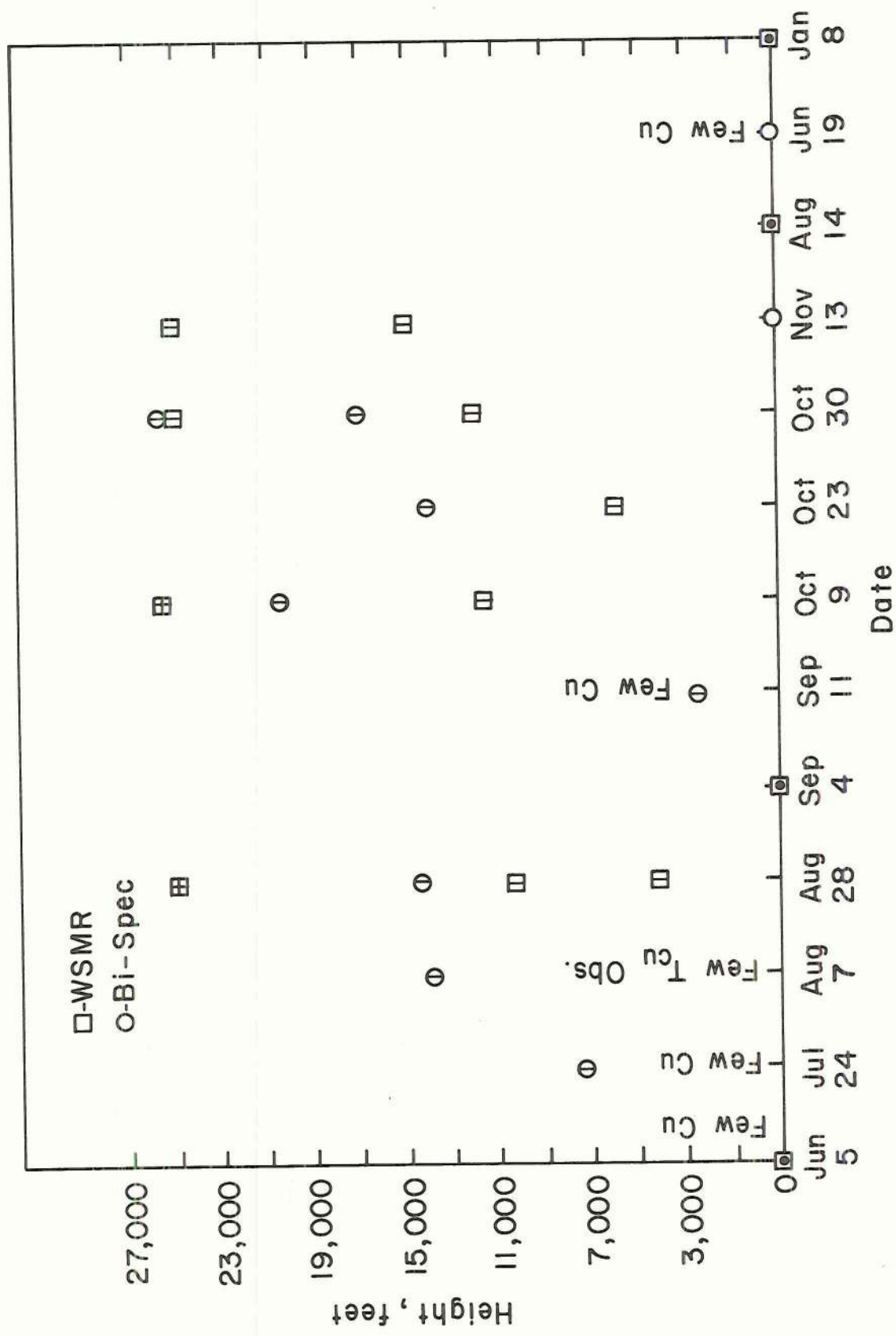
Figure 2. Results from the Bi-Spectral program for a 40n.mi. x 40n.mi. area over WSMR

Cumulus Field

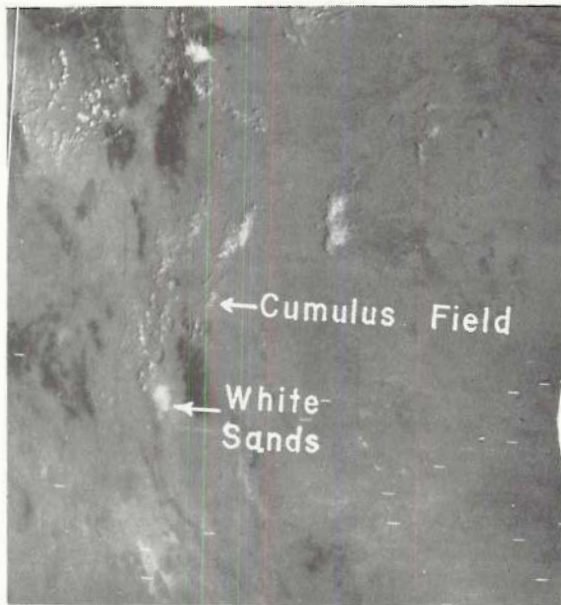White Sands

Figure 3.   a.) NOAA-2 VHRR (Very High Resolution Radiometer) 1 Km
                 visible image for 9/11/74 showing small cumulus just
                 to the north of White Sands.
            b.) NOAA-2 SR 4 Km visible image for 9/11/74 corresponding
                 to a.) above.

TABLE 1

WSMR MEASURED AND BI-SPEC HIGH RESOLUTION COMPARISON

Date	Time	High Res. Calc. (^{o}K)	WSMR Meas. (^{o}K)	Radian V Results
3/13/74	1545Z	287	275	±0
6/19/74	1547Z	308	310	-3°C
6/26/74	1617Z	310	308	±0
8/14/74	1718Z	309	311	-4
10/9/74	1657Z	288	312	Cloud Contamination 250 -3°C
10/30/74	1702Z	278	282	±0°C
11/13/74	1630Z	275	280	250 ±0°C
1/8/75	1650Z	275	275	±0°C

WSMR MEASURED AND BI-SPEC CAL. TEMP. COMPARISON

Date	Time	Bi-Spec Calc. (^{o}K)	WSMR Meas. (^{o}K)	Radian V Results
6/5/74	1647Z	319	323	-1°C Attenuation .23" Precip. Water
7/24/74	1708Z	305	307	-2°C Attenuation .54" Precip. Water
8/7/74	1637Z	298	302	-4°C due to Attenuation .5" Precip. Water
8/28/74	1642Z	290	297	Possible Cloud Contamination -2.5^{o}C Attenuation .57" Precip. Water
9/4/74	1533Z	294	298	-2°C Attenuation .43" Precip. Water
9/11/74	1607Z	293	301	-2°C Attenuation .45" Precip. Water
10/23/74	1624Z	288	288	-2°C due to Attenuation .4" Precip. Water

TABLE 2

		WSMR CLOUD OBS.						SATELLITE CLOUD OBS.					
		LAYER 1		LAYER 2		LAYER 3		LAYER 1		LAYER 2		LAYER 3	
DATE	TOTAL OPAQUE CLOUD	AMT	HGT*	AMT	HGT	AMT	HGT	AMT	HGT	AMT	HGT	AMT	HGT
6/05/74		few Cu						clear					
6/19/74		few Cu						clear					
6/26/74			15.0					clear					
7/24/74		few Cu						.2	7.0				
8/07/74		few TCu						.5	14.0				
8/14/74		few Cu						clear					
8/28/74			250					.10	14.0				
9/04/74		clear						clear					
9/11/74		clear						clear					
10/09/74			11.0		250			.4	19.5				
10/23/74		few Cu						.1	2.5				
10/30/74			120		250			.14	17.0	.6	25.5		
11/13/74			150		250			clear					
1/08/75		clear		1" snow				.07	sfc.	snow			

* in thousands of feet

from satellites. In the Denver comparisons (Figure 4, Table 3), there were more cloudy cases, and the results seem quite good for all but the thin cirrus cases. On March 13, 1974, the technique was able to determine two layers of cloud which were observed, while on November 13, the satellite was able to determine the tops of the clouds while the observer reported sky obscured at 500 ft. Cases such as August 28 and October 23 point out the problem with cirrus and how the visible channel sees through them partially and underestimates amount while the IR determines too warm a temperature giving them too low a height. However the technique appears to do a good job at a fairly high resolution for the most part. You will note on this curve, the total opaque cloud amount as estimated by the observer is plotted. This number is more closely related to what the satellite sees than is the total cloud amount since the opaque cloud would have a higher optical depth and would have been seen by the satellite. Its emissivity would be closer to 1 allowing the proper temperature to be measured. The satellite is very close to both amount and height, in all but two instances, August 28 and October 23, when the opaque cloud amount is greater than .8. In the cases where the bi-spectral program measures a higher cloud height, it would obviously mean the satellite perceives the cloud-top while the observer sees cloud base. On the two cases mentioned above, the satellite determined close to the amount observed but measured too high a temperature. This shows that even with an apparent opaque cloud, the emissivity may not be 1, thus allowing the satellite to measure too warm a temperature and consequently too low a height. There does not appear to be any correlation between errors in height and amount due to large satellite viewing angles.
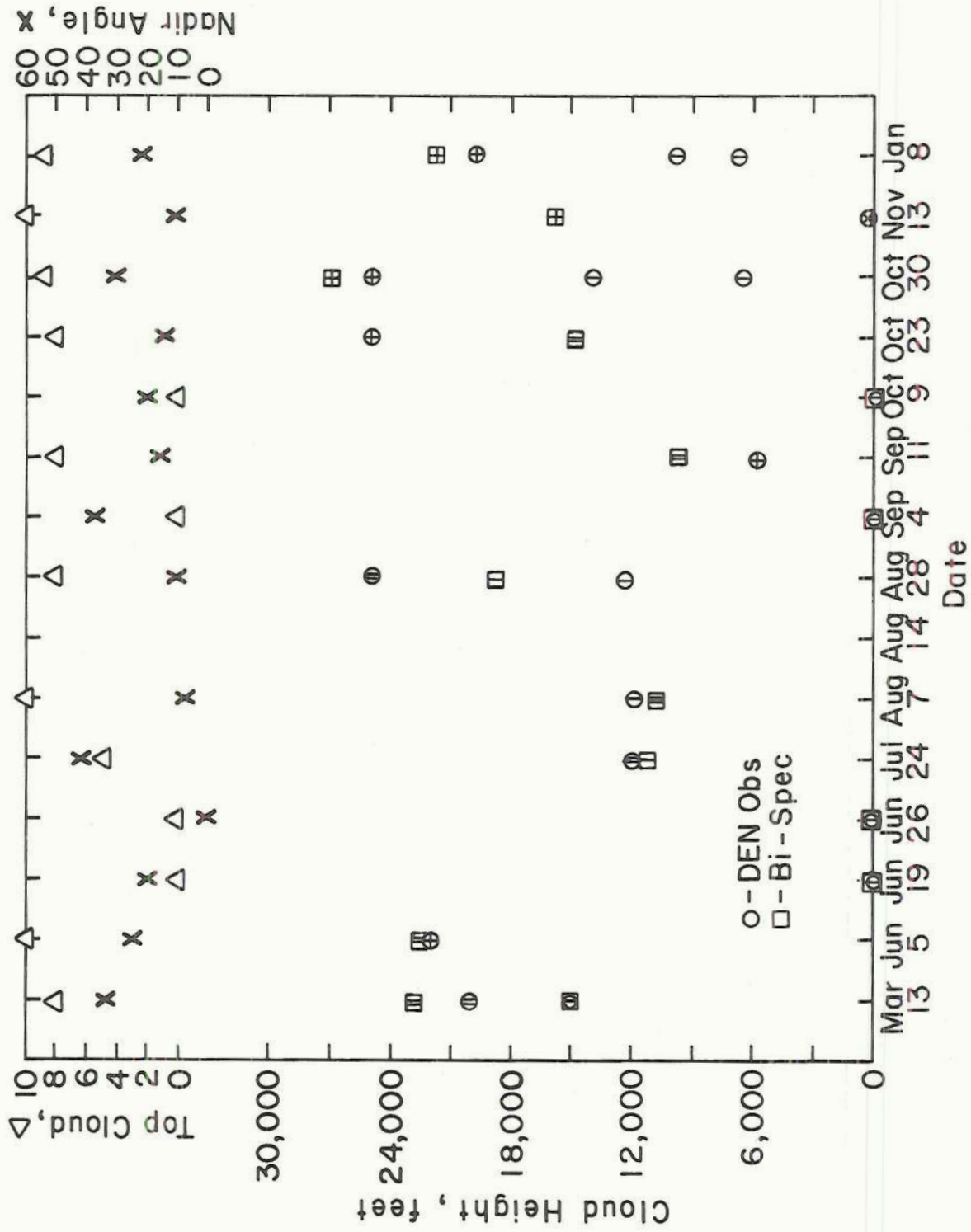
Figure 4 Results from the Bi-Spectral program for a 40 n.mi. x 40 n.mi. area over Denver, CO. (Top) above stands for total opaque cloud amount.

The third location chosen was Oklahoma City. As can be seen in
Figure 5 and Table 4, there was a high percentage of thin cirrus and
large viewing angles by the satellite. The thin cirrus problem is quite
evident for the October 9 and November 13 cases. Here the observer re-
ported 8/10 cloudiness for both days but only 0/10 and 1/10 total
opaque cloudiness, respectively. Therefore, on these days the satellite
was not able to detect any cloudiness over OKC. In other instances, the
satellite is able to determine multi-layered clouds when the observer
was socked in by low clouds, such as 3/13. On October 30, the satellite
seemed to be measuring the top of the thunderstorm over OKC while the
observer could only see the base of the clouds. In most other cases where
large errors occur, it is due to the assumption of a emissivity of .9,
although the clouds observed definitely had an emissivity of less than
this. Again, there doesn't seem to be any real error induced by low
viewing angles, most of the error is due to the emissivity and optical
depth problem.

6.0 SPECIAL APPROACH FOR THE CASE OF CIRRUS

As has been shown by the previous results, cirrus clouds point out
a special problem in the present technique for determining cloud amount
and height. There are two approaches that can by used to try and deter-
mine the proper emissivity of these clouds. The first method is to
correlate visible brightness to emissivity and correct the IR data by
the emissivity determined by the visible channel. The second method is
to use multispectral data available from the same NOAA satellite (VTPR -
Vertical Temperature Profile Radiometer data) and correlate the radiances
of each spectral band to each other until a proper level is determined

TABLE 4

			OKC CLOUD OBS.						SATELLITE CLOUD OBS.					
			LAYER 1		LAYER 2		LAYER 3		LAYER 1		LAYER 2		LAYER 3	
NADIR ANGLE	DATE	TOTAL OPAQUE CLOUD	AMT	HGT*	AMT	HGT*	AMT	HGT*	AMT	HGT*	AMT	HGT*	AMT	HGT*
9°	3/13/74	1.0	1.0	1.3					.55	7.0	.30	17.5	.15	26.5
45°	6/05/74	.6	.1	3.0	.7	250			.5	9.4				
9°	6/19/74	0	clear						clear					
29°	6/26/74	0	clear						clear					
48°	7/24/74	.1	.4	30.0					.5	21.0				
35°	8/07/74	.2	.2	5.0					.1	7.0				
55°	8/14/74	.1	.4	25.0					.5	18.0				
36°	8/28/74	1.0	1.0	1.3					.75	21.4				
14°	9/11/74		clear						clear					
43°	10/09/74	0	.8	25.0					clear					
32°	10/23/74	.5	.5	8.0					.4	7.3				
46°	10/30/74	1.0	1.0	1.3	R reported				1.0	33.0				
13°	11/13/74	.1	.8	25.0					clear					

*in thousands of feet

for the cloud.

To account for the cirrus problem equation (2) must be modified as follows:

$$M_L = A_{CLR} \; N_{CLR} + (1.0-E) \; A_{CLD} \; N_{CLR} + E \; A_{CLD} \; N_{CLD} \qquad (2')$$

where:

E = emissivity

One method to obtain (E) would be to correlate the visible brightness of a cloud to its emissivity. This technique has been tried with varying success by Mosher (1974) and Shenk and Curran (1973). Measurements of cirrus clouds infrared emissivities (Kuhn and Weickman, 1969; Davis, 1971; Valovcin, 1968; Brown and Houghton, 1956; Platt, 1975; Hubert, 1975) and calculated by (Jacobowitz, 1970; Yamamoto et al., 1970; Fleming, 1973, and Liou, 1974) for varying geometric thicknesses have shown values ranging from .1 to .8. In general the relation between (E) and the geometric thickness (H) is poor, indicating that the ice crystal concentration (W in $gm.m^{-3}$) has a major effect on the infrared emissivity.

It can be shown, (Fleming, 1973) that the reflected (scattered) solar radiance (N_r) from a cirrus cloud is closely related to its effective optical depth $\tau^* = KWH$ where K = an extinction coefficient dependent upon particle size and density. If we assume little absorption by the cirrus layer, then:

$$a_{CLD} = 1.0 - e^{-\tau^* s} \sec \zeta \qquad (8)$$

where:

$$\tau_s^* = \omega_0 \tau^* \quad (\omega_0 = \text{single scattering albedo} \approx 1.0) \tag{9}$$

This relation between cirrus physical properties and cirrus albedo has a weak dependence on solar zenith angle (ζ) for angles less than 60^0.

From Liou (1974) it is possible to now relate τ^* to infrared emissivity. From Figure 6 of Liou, if we assume a particle size of 40μm and use the curve for a number density of N = .02 cm^{-3}[1] we obtain:

(wH)	E
.0025	0.08
.0049	0.15
.0061	0.17
.0099	0.27
.0123	0.34
.0148	0.39
.0197	0.50
.0246	0.60
.0369	0.75
.0492	0.90
.0615	0.95

Then using Equation (8) we can relate albedo to E (see Figure 6). Using this graph and the albedo measured by the satellite over cirrus it would be possible to obtain an estimate of the emissivity of the cloud to use in Equation (2'). Two cases were studied to test the relationship between albedo and temperature as measured by the satellite. One case (Figure 7) was of cirrus over the Gulf of California; the other of cirrus over the southern part of Arizona (Figure 8). Both show a fairly strong relationship between T_{eff} and a_{CLD}, even though the cirrus over land shows a shift to higher albedoes due to the contribution of the albedo of the

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[1] note that w = .231N for cirrus crystals of radii equal to 40μm where the number density is in cm^{-3} (see Fleming, 1973).
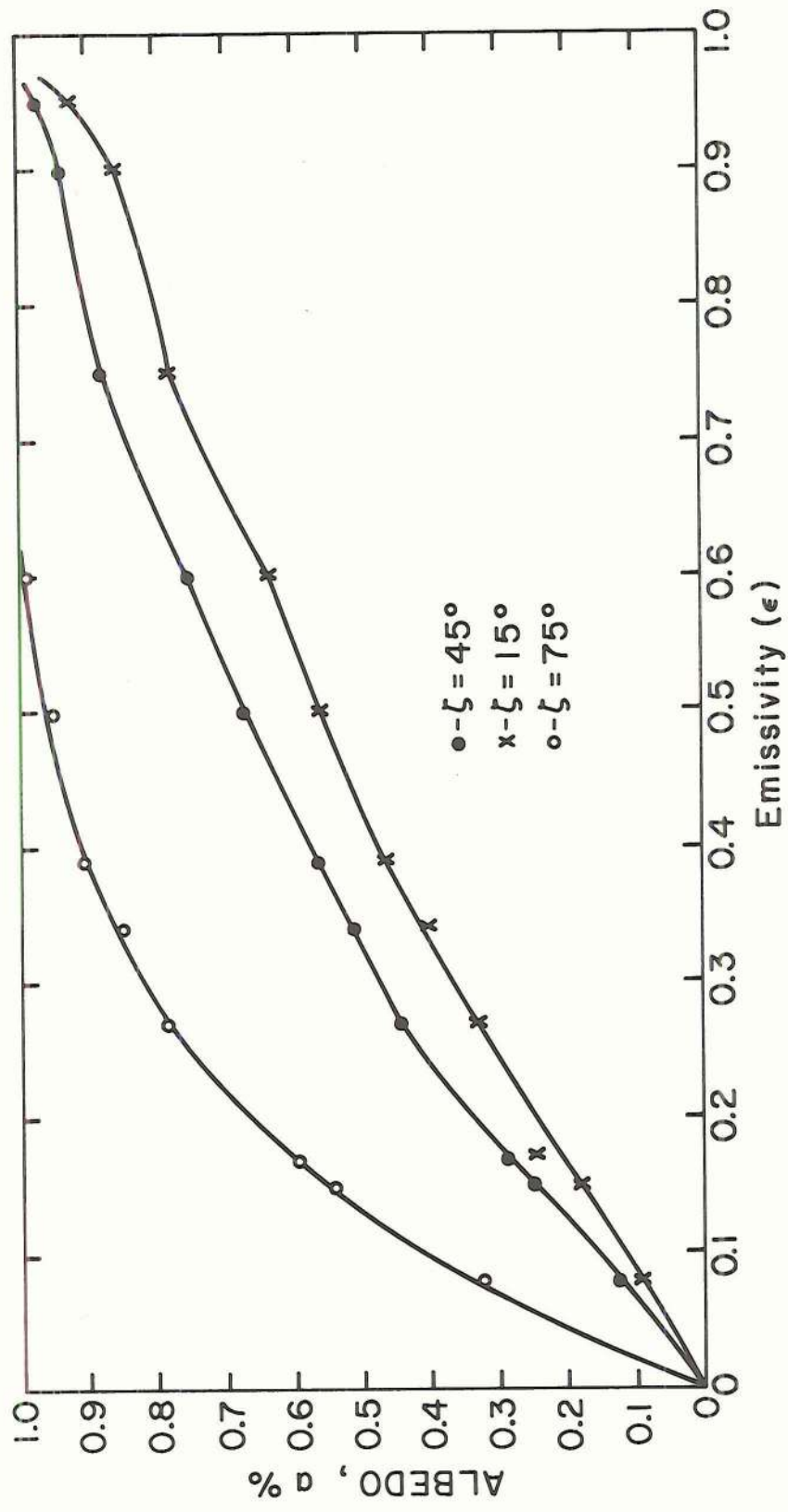
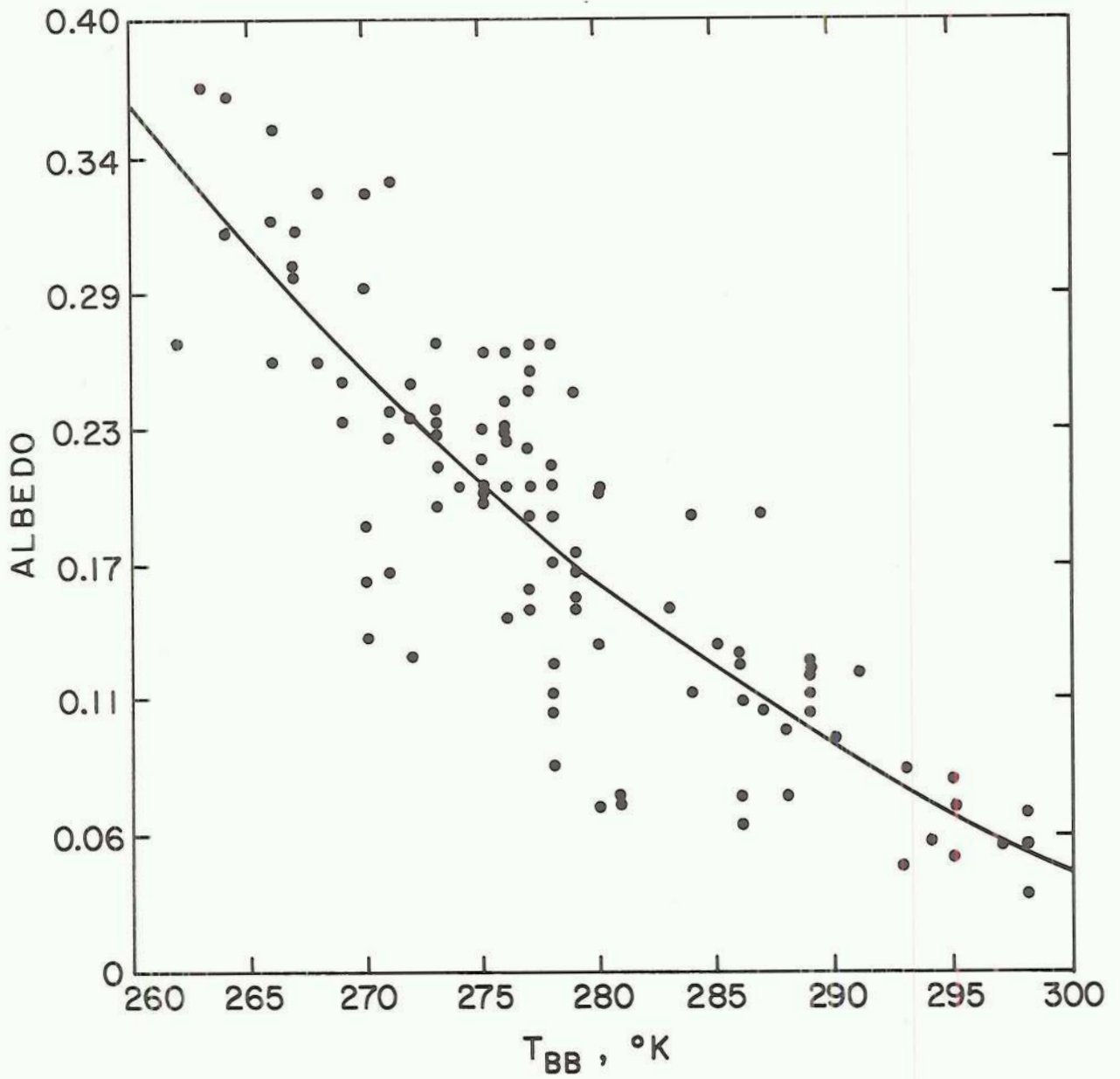Figure 6. Relation between albedo and emissivity for varying solar zenith angles.

Figure 7. Relationship between albedo and blackbody temperature as derived from NOAA SR measurements of cirrus over the Gulf of California.
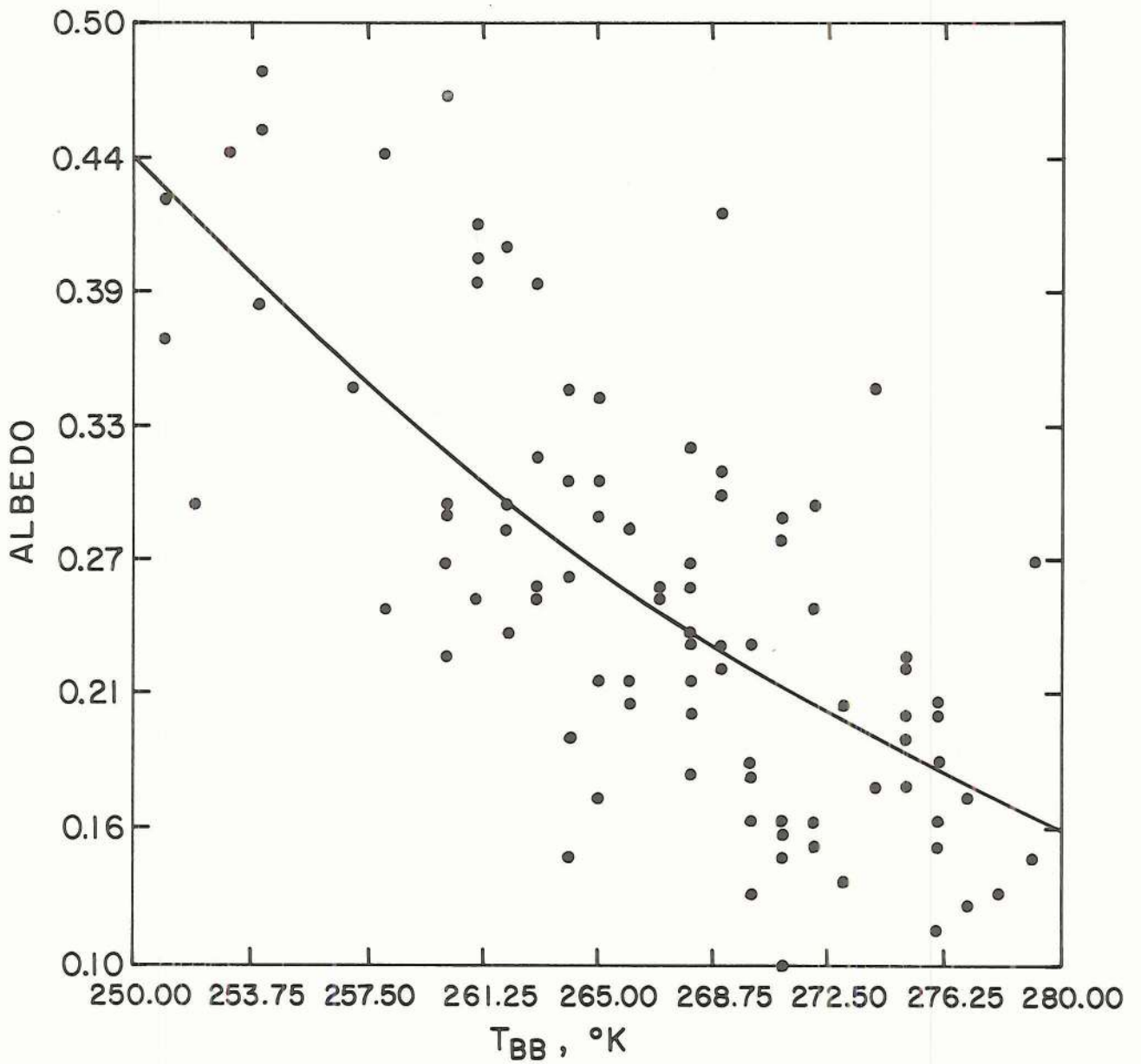
Figure 8. Relationship between albedo and blackbody temperature as
derived from NOAA SR measurements of cirrus over southern
Arizona.

land surface through the cloud. This does point out that two sets of

relationships must be developed to account for the differences of land-

ocean reflectance. Shenk and Curran (1973) have tested this technique

for satellite measurements of cirrus over the North Atlantic Ocean.

After their Figure 3 (Figure 9) they developed a set of curves by using

Equation 2' assuming total cloud cover in the field of view of the

sensor. They then developed a family of curves for different cloud tops

using $288^O K$ as N_{CLR} and using measured IR values T_{BB} (M_L). For their

measurements they found that for a cloud of a = 25%, T_{BB} = $265^O K$, that

the E would equal .5. Using the work of Liou for a = 25% and ζ = 15°,

an E = .3 would be determined. Thus it appears as though a relation-

ship should be developed for a specific satellite experiment. This

should be in relation to special cloud and ground truth measurements

during the observation time of the satellite.

A second method that could be used, and will be tested, has been

developed by Bunting and Conover (1974) using multi-spectral radiance

data from the VTPR experiment onboard the NOAA satellites.* This

system uses a radiative transfer model which tries to simulate the rad-

iance that should be seen by the satellite viewing a given cloud at a

certain height and emissivity. Model clouds were then found which

satisfied four of the spectral regions (bands 4,5,6,8), each character-

ized by an emissivity and a cloud-top height. Shown in Figure 10 is their

Figure 1, a comparison of their channel 4 and 8 where the overlap denotes

the location of the assumed cloud height and the clouds emissivity.

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*Other techniques using vertical temperature sounding data have
been developed by Chahine (1974) and Smith (1975) to determine frac-
tional cloud amount and height and both show promise for determining
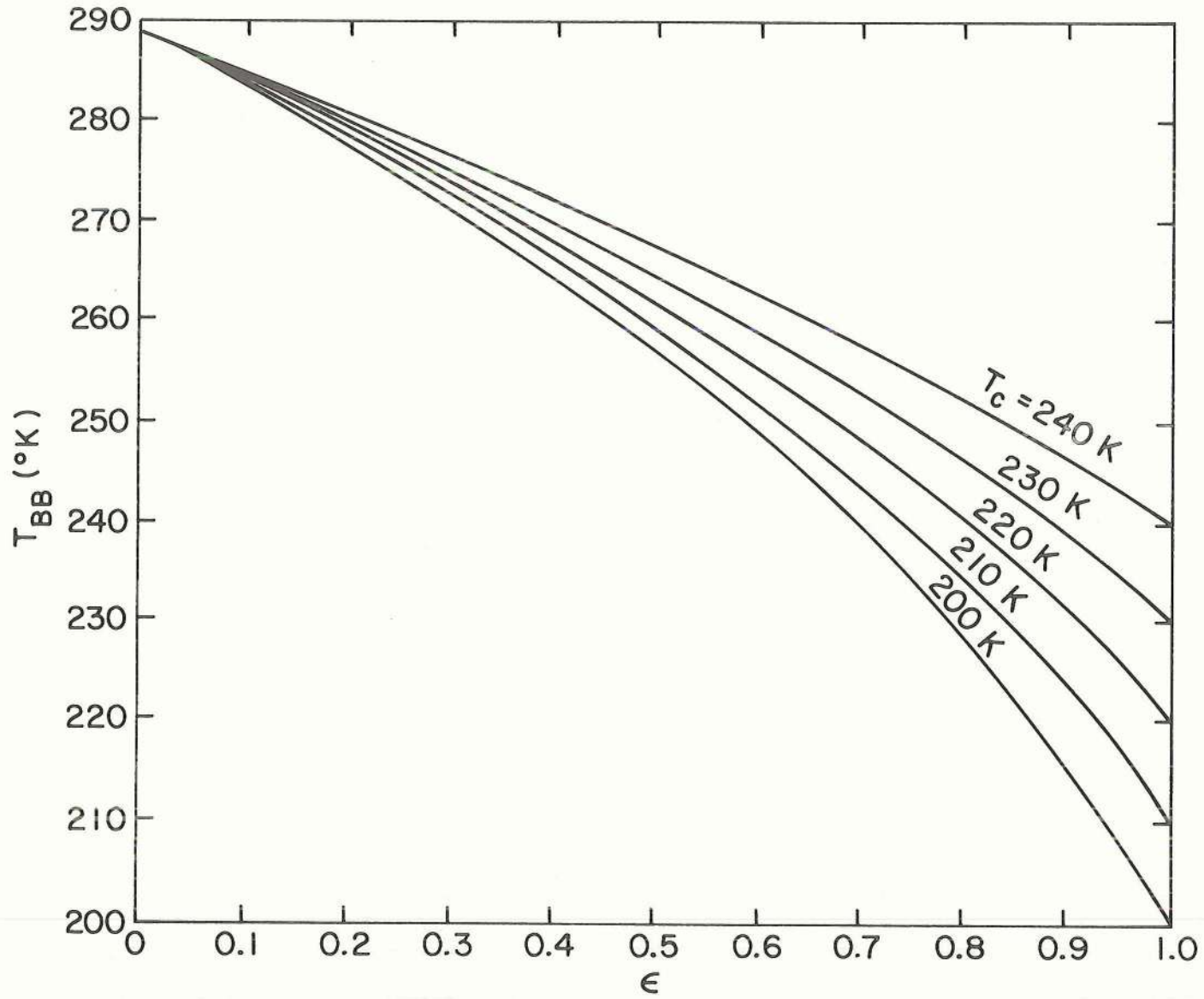large scale cloudiness.

Figure 9.   Family of curves relating true cloud top temperature (Tc) to what would be measured by satellite for given emissivities (From Shenk and Curran, 1973).

Aircraft comparisons during the time of the NOAA pass show this scheme to work quite well. With the use of the SR data in conjunction with this data, it may be possible to fine-tune the VTPR calculation through use of the higher resolution SR data. Thus, this technique would become a multi-spectral rather than a bi-spectral technique to determine cloud heights and amounts.

A third approach to overcome the cirrus problem is to use a $6.7\mu m$ channel to discriminate between cirrus and clear conditions in the upper troposphere (Shenk et al., 1974). However, this method is open to some difficulty of interpretation when upper tropospheric water vapor content changes.

7.0 SUMMARY AND CONCLUSIONS

This paper has presented a technique to determine cloud amount and cloud height using simultaneous visible and infrared data obtained from the NOAA satellite. Several assumptions are necessary in the development of this technique, but the uncertianty analysis has shown that with proper ground-truth calibration, reasonable and useful results can be expected. Cursory ground-truth comparisons have shown that the IR channel appears to give reasonable results while comparisons with the visible channel appears to contain factors that have not been accounted for to date. Due to these factors and the lack of cloud-truth data at a resolution of the NOAA satellite, we have not been able to test the accuracy of the technique for individual scan spots. When an array of satellite data is taken, comparisons to ground observed cloud amounts show good comparison for all but the cirrus cases. Two techniques were described which could correct this problem and will be tested and incorporated into this technique

to allow measurements of all cloud types. This method has many applications and can be used by many of the present satellites now in orbit. The VISSIR (Visible and Infrared Spin Scan Radiometer) data available from the GOES series of satellites is probably the best available for use with this method. The DMSP (Defense Meteorological Satellite Program) satellites also have dual-channel radiometers capable of using this technique on an operational basis. It appears now as though many of the future satellites such as the TIROS-N series will have this dual-channel capability and will be potential candidates for use in determining cloud information using the bi-spectral method.

ACKNOWLEDGEMENTS

Appendix 1:   Test of Accuracy and Reproducibility of Satellite
Radiative Measurements

To check the accuracy of the satellite measurements, inflight calibration
of the visible and infrared sensor is needed.   One method is to have the
sensor scan a surface target of known brightness and temperature and com-
pare this to the digitized visible and IR data received from the SR sensor
of the NOAA satellites*.   One such target is the White Sands National
Monument where the Atmospheric Sciences Laboratory at White Sands Missile
Range has set up a ground truth site (Williamson, 1975).   At this site
measurements are made of the surface radiation temperature in the $10-11\mu m$
range with a Barnes PRT-5, as well as the incoming and outgoing radiant
flux in the .5 -.7 μm range using an Eppley Model 2 Precision Spectral
Pyranometer.   Measurements are simultaneous with the passage of the NOAA
satellite allowing nearly direct comparisons once viewing angle, sun angle,
and water vapor attenuation problems are taken into account.

Some preliminary comparisons are shown in Figs. 11 and 13.   Fig. 11
is a comparison of ground based measured radiative surface temperature and
satellite measured surface temperature.   Both raw data and data corrected
for limb darkening and water vapor absorption are shown in the figure.   An
IR radiative transfer model having 10 wavenumber resolution incorporating
Bignell's pressure broadened continuum developed by Cox (1975) was used
for this calculation.   Table 1 shows the loss that was calculated due to
water vapor absorption (note preceipitable water) and limb darkening.   As
the graph shows in Fig. 12, almost all points are below the 1:1 line
showing the satellite was measuring a colder temperature then was measured
at the surface.

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*Data is received by use of the CSU APT station then is digitized
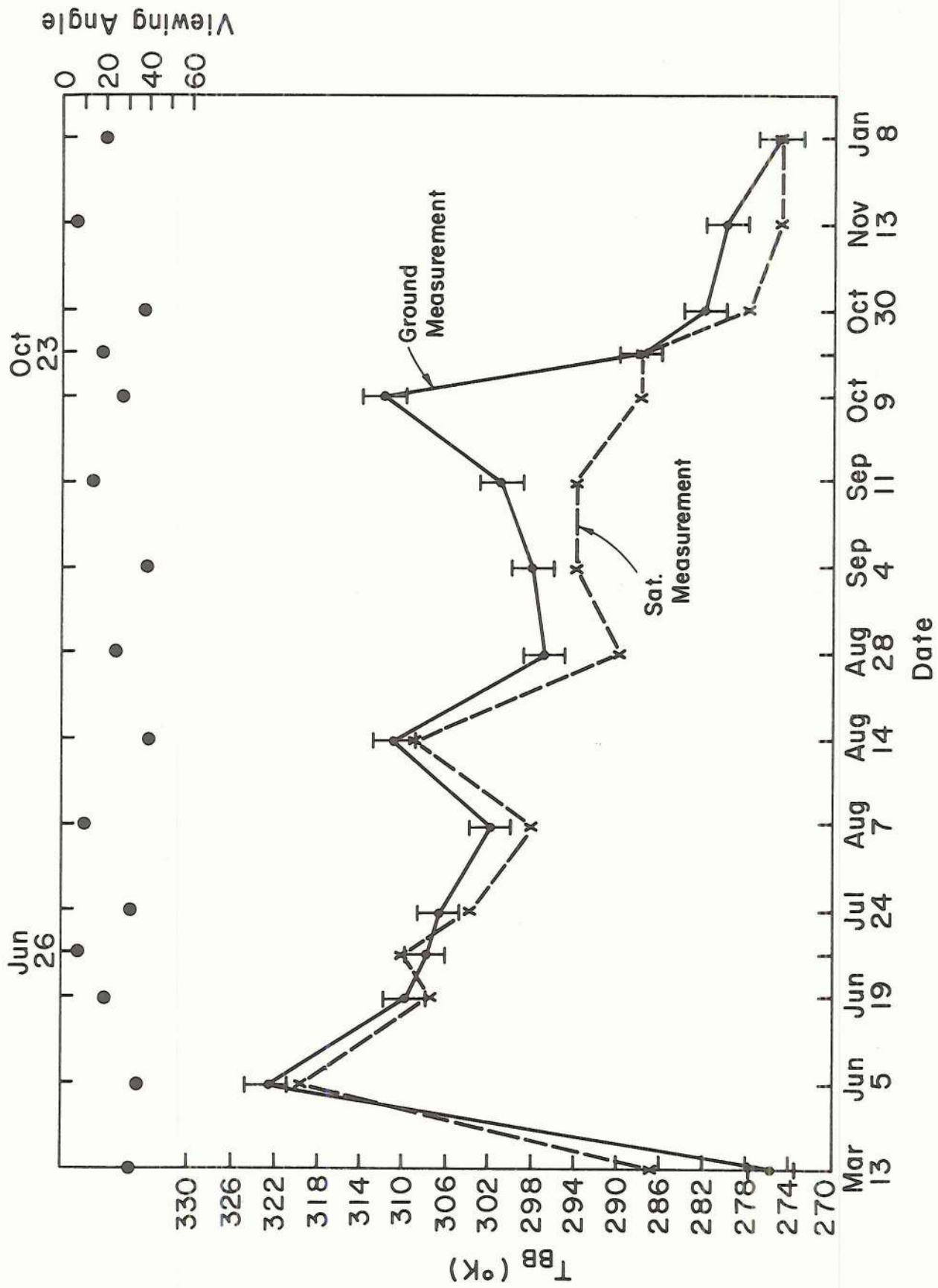at full resolution for use in the Bi-Spec program.

Figure 11. Comparison of satellite derived surface temperature vs. ground measured surface temperature.
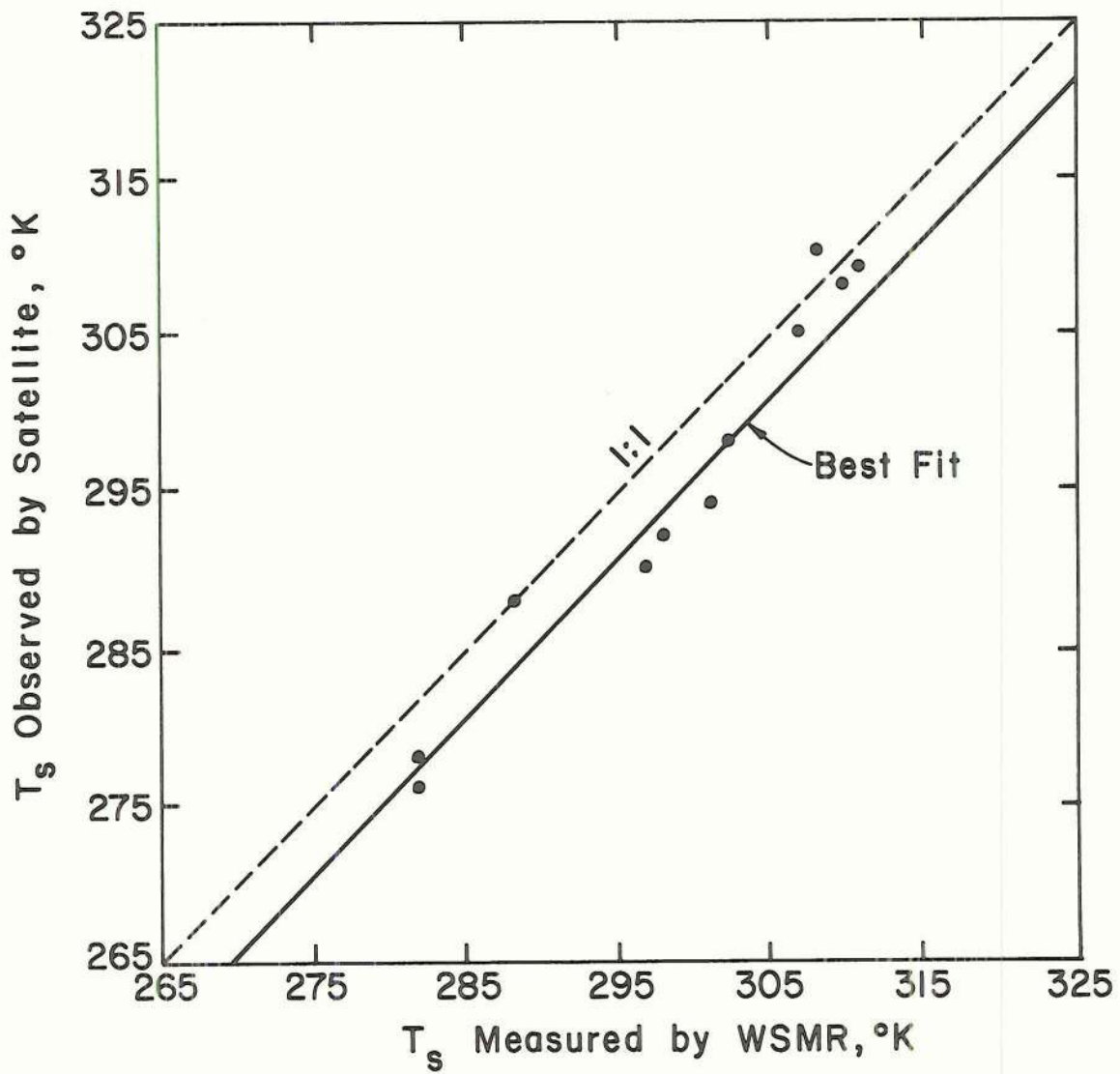
Figure 12. Best fit curve of observed satellite surface temperature
and ground measured surface temperature showing the satel-
lite measures a temperature approximately 3°C colder
on the average.

Possible causes for this discrepancy are due in part to: 1) Theoretical model not accounting for all the absorption taking place between the surface and satellite (i.e., haze problems, etc.); 2) To arrive at a surface temperature for White Sands from the satellite it was necessary to average the IR data over the visually brightest area which could be as large as 40 sq. km. This averaging technique takes into account a much larger area than the field of view of the PRT (a few meters) which may cause a discrepancy in the two measurements; 3) Calibration errors are another source of error; and 4) Difference in radiometers, i.e., spectral response and sensitivity differences between the satellite sensor and ground sensor. The best fit curve shows what could be assumed to be the best relationship between the ground and satellite measurements. It still shows quite a bit of scatter around the curve but probably accounts for some of the systematic errors. More measurements are definitely needed and are continuing on a weekly basis through cooperation of CSU and WSMR.

For the visible channel, comparison was made of the albedo as measured from the surface, to that which was measured by the satellite (fig. It was necessary to correct the satellite data for viewing angle, sun angle, and bi-directional reflectance problems (Sikula and Vonder Haar, 1972). The results show that in only a few instances do the measurements attain the 5% accuracy we feel is needed. Work done by Walraven and Coulson (1972) have shown there is definitely a bi-directional reflectance problem with the White Sands which will affect the measurements. Our bi-directional reflectance model is based on clouds which does not exactly represent the reflectance of the sand and will cause discrepancies in the two measurements. Cox (1975) has shown that over a bright surface the atmosphere would absorb reflected radiation causing a lower albedo to be measured from the satellite. Many of the factors affecting the IR channels,
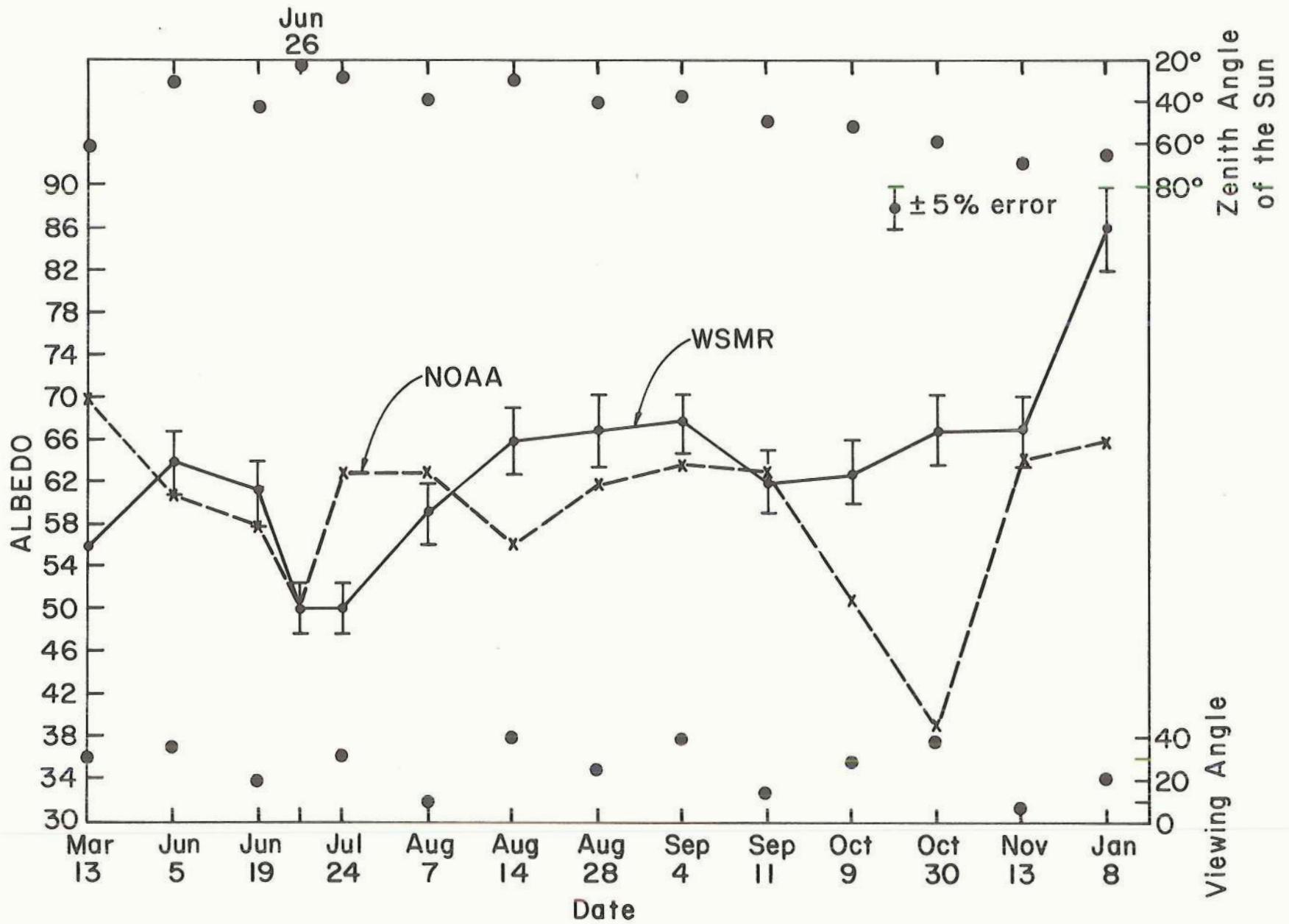
Figure 13. Comparison of satellite measured surface albedo to ground based measured surface albedo for White Sands.

such as calibration, instrument/spectral differences, and size of area measured, affect the final reading. These several factors affecting the reflectance measurements have to be accounted for. (See Jacobowitz and Gruber, 1975, for a discussion of these).

The uncertainty analysis has shown that at a 5% level of uncertainty in the measured values we can assume reasonable values in cloud amount and cloud top temperature. However, comparisons to "ground truth" data show we may not have this accuracy in the IR or visible channel. This can be accounted for since the error in the IR seems to be a systematic decrease as measured by the satellite. The visible channel presents a somewhat more complicated problem and requires further study. Thus, sidestepping this problem for the moment, we have proceeded to run test cases to ascertain the accuracy of this technique in Section 5. There we will avoid using individual "spots" for verification but will use an average array. This will somewhat eliminate some of the errors by smoothing the data.

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