ANISOTROPY OF REFLECTED SOLAR RADIATION FROM VARIOUS SURFACES AS MEASURED WITH AN AIRCRAFT-MOUNTED RADIOMETER

by
Vincent V. Salomonson
Department of Atmospheric Science
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Research Report to

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Under Contract NASr - 147

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ERRATA

Page 6, second paragraph; should read as follows:

Figure 5 shows results obtained over stratus clouds near San Francisco when the cloud layer was about 1100 feet thick and the solar zenith angle was between 62° and 67°. The azimith of the sun was 060° magnetic. These results again show the strong forward scattering seen in Figure 4. The reflectance values near $\theta = 0°$ ($\beta \cong 115°$) are slightly lower in this case than in the case illustrated in Figure 4. The minimum reflectances in Figure 5 are 0.30 and 0.40 versus 0.37 and 0.48 in Figure 4 for the 0.2 - 4.0μ and 0.55 - 0.85μ bandpasses respectively. The maxima mentioned. . . (the rest of the paragraph is the same).

In the Appendix the column of tabulated results headed $\psi = /\phi - \phi_o/$ should be $\psi = /\phi - (\phi_o + 180°)/$.

ABSTRACT

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In the past few years, research has been done with satellite-mounted radiometers to determine terrestrial albedos and planetary heat balance. In these studies the reflection of the solar radiation was assumed to be independent of wavelength and isotropic. Using these assumptions, the satellite-determined values of planetary albedo have been found to be consistently low. In an effort toward resolving this discrepancy, the NIMBUS medium resolution radiometer has been mounted on a Piper Twin Comanche and used to measure the anisotropy of reflected solar radiation from various surfaces. By flying over a surface using a prescribed flight pattern and the scanning characteristics of the radiometer, the variations in the reflected radiation in different directions, radiometer zenith angles, and solar zenith angles have been measured. The results show strong forward scattering over stratus clouds at a large solar zenith angle. Backscattering predominates over a grassland surface at a large solar zenith angle. The ratio of averaged observed reflectance to minimum observed reflectance varies from 1.09 to 1.40 depending on the bandpass and the reflecting surface.

Author

INTRODUCTION

In articles by Nordberg[8], Fritz[4], and Bandeen[1], some doubt is expressed with regard to albedo values obtained by radiometers mounted on meteorological satellites. Bandeen[1] reports in a study of the planetary heat balance that it was necessary to apply a correction factor of 1.6 to satellite-determined planetary albedo. Two possible causes for this discrepancy are the errors introduced by assuming (1) isotropy of reflected solar radiation from terrestrial surfaces and (2) that the reflection is independent of wavelength.

Laboratory measurements of the reflection characteristics of various natural materials that have a bearing on the problem have been made by Coulson[3] and Hapke[5]. Bartman[2] has reported making pertinent balloon-borne radiometer measurements of reflected solar radiation from clouds.

This paper presents the results of measurements of reflected solar radiation made with a satellite radiometer mounted on an airplane. The primary purpose of this research was to ascertain how much anisotropy in the reflected solar radiation from various surfaces could be measured by the channels of the radiometer which monitor portions of the solar spectrum. The measurements were made over stratus clouds, grassland, white sand, and the ocean.

INSTRUMENTATION

The radiometer used for this study was the NIMBUS medium resolution radiometer. This radiometer utilizes a rotating aluminum mirror to scan surfaces below it and has an instantaneous field of view of 50 milliradians. Two of the five channels on the radiometer were used. These were the 0.2 - 4.0 micron (μ) and the 0.55 - 0.85 μ channels. The signals produced by the radiometer were recorded on strip chart recorders mounted in the cabin of the Piper Twin Comanche used in this research.

Figure 1 shows the external housing for the radiometer on the aircraft and the manner in which the radiometer performs its scanning function. The housing for the radiometer is made out of molded fiberglass. Cover gates (not shown in the Figure) shield the mirror when it is not in operation. As can be seen in Figure 1, the radiometer scans in a counterclockwise manner as viewed from the tail of the airplane. During data-gathering flights, the airplane flies at approximately 160 miles per hour.

PROCEDURE

The radiation geometry is shown in Figure 2. Different values of radiometer zenith angle (θ) were provided by the rotation of the radiometer mirror. Only data for $\theta \leq 60°$ are given in this report because some doubt exists that the field of view of the radiometer was completely filled by the surface under examination for values of θ

greater than 60°. The primary reason for this doubt was the limited areal extent of the uniform reflecting surface in some cases. This was particularly true for the flights made over stratus clouds and white sand. Azimuth departure angles (ψ) were provided by changing the heading of the aircraft. In the first flights made over stratus clouds, ψ was varied at 30° intervals around the local vertical. In later flights, ψ was varied by 45° intervals so as to shorten the time necessary to make a complete flight and limit the variation in the solar zenith angle (ζ_o). For each value of ψ , the airplane was held at this heading until 10 complete scans of the underlying surface were made by the radiometer. The scattering angle (β) is a function of ψ and θ and was computed and plotted via the relationship $\cos\beta = \sin\zeta_o \sin\theta \cos\psi - \cos\zeta_o \cos\theta$.

Table 1 summarizes the flights made in obtaining the data given in this paper. A total of four flights were made (two flights over clouds, one over ocean, and one over grassland) with the sun at large zenith angles. Two flights over clouds and white sand are reported for small solar zenith angles. Flight altitudes were maintained at 1000 feet over the clouds and white sand because of the limited extent of these particular reflecting surfaces. Lower altitudes were not used because of the desirability of having the radiometer integrate over as much of the reflecting surface as possible.

In the preparation of the tables and graphs, two primary assumptions were used in arriving at the final results: (1) when the radiometer is looking straight down ($\theta = 0°$), the radiometer readings should be the same for a uniform surface, and (2) the scattering of solar energy is symmetrical with respect to the principal plane which goes through the sun and the local vertical.

RESULTS

The basic parameter used for presenting the results is the "reflectance". The reflectance is expressed as the ratio, $\overline{N}/N_o \cos \zeta_o$. $\overline{N}$ is the average radiance observed by the radiometer at various individual values of radiometer zenith angle (θ) and azimuth (ψ) . $N_o \cos \zeta_o$ is the radiance that the radiometer would measure if the field of view were filled by a perfectly diffuse surface of unit reflectivity and illuminated by the normal component of the solar constant striking the surface at the zenith angle (ζ_o) .

Figures 3 through 7 all depict the results in the same manner. The upper diagrams show reflectance ($\overline{N}/N_o \cos \zeta_o$) versus θ and ψ . The lowest diagram depicts reflectance versus scattering angle.

Figure 3 shows results obtained over stratus clouds near San Francisco with the solar zenith angle varying from 12° to 13° . The cloud layer was approximately 900 feet thick. The tops of the clouds were slightly undulating; but, in general, the surface was quite uniform. The azimuth of the sun (ϕ_o) was 160° as determined by the magnetic compass of the airplane.

The upper two diagrams in Figure 3 show a slight backscattering maximum at $\theta = 30°$. The smallest reflectance values occur at $\psi = 0°$ and $\theta = 60°$ in the forward scattering area. The bottom diagram shows a good relationship between the scattering angle and reflectance. The backscatter is quite evident here also. Because of the small solar zenith angle, the values of β only range from 108° to 177° . The range of reflectance values obtained in this case was 0.38 - 0.47 for the 0.55 - 0.85 μ bandpass and 0.32 - 0.37 for the 0.2 - 4.0 μ bandpass.

Figure 4 shows results over stratus clouds at the same location, but with the zenith angle ranging 49° to 56° . The clouds were approximately 1100 feet thick in this case and the azimuth of the sun (ϕ_o) was 068° .

It is obvious that a large difference in the character of the scattering exists between the small solar zenith angle shown in Figure 3 and the large zenith angle in this case. Pronounced forward scattering ($\psi = 0°$) can be seen here. The maximum reflectance value occurs at $\theta = 60°$, $\psi = 0°$. The minimum value is found where the radiometer was looking straight down ($\theta = 0°$). If constant values of θ are considered in the upper diagrams, a maximum of reflectance is not only evident along the $\psi = 0°$ line, but also in the vicinity of $\psi = 130°$. The plot of scattering angle versus reflectance again shows the large forward scattering and a minimum occurring at $\beta = 120°$ to $125°$.

Figure 5 shows results obtained over stratus clouds near San Francisco when the cloud layer was about 1100 feet thick and the solar zenith angle was between 62° and 67°. The azimuth of the sun was 060° magnetic. These results again show the strong forward scattering seen in Figure 4. The magnitude of the maximum and minimum reflectance values are very nearly the same as in Figure 4. The maximum reflectance is 0.8 and 1.0 for the 0.2 - 4.0 μ and 0.55 - 0.85 μ bandpasses, respectively. The corresponding minimum reflectance values are 0.3 and 0.4. One of the predominant differences between this case and the one shown in Figure 4 is the increased backscattering. This is most evident in the plot of β versus reflectance. The maxima mentioned for constant θ in Figure 4 appear to have rotated approximately 40° - 50° and now can be seen at approximately $\psi = 40°$ and $\psi = 180°$. The maximum along $\psi = 120°$ that appears in the 0.55 - 0.85 μ is an inconsistent feature that does not appear in the case shown in Figure 4 or in the 0.2 - 4.0 μ diagram in this Figure.

Figure 6 presents results from a flight over the white gypsum sand located on the White Sands Proving Grounds near Alamagordo, New Mexico. The solar zenith angle was between 19° - 21° and the azimuth of the sun was 140°.

In the upper diagrams, the dashed lines are graduated evenly between the values labelling the solid lines and are one unit apart. These diagrams show a broad maximum of reflectance in the ψ = 180° direction that extends around to ψ = 90°. In the ψ = 0° - 90° portion of the diagram the reflectances drop off uniformly to a minimum of 0.62 in the 0.55 - 0.85 μ diagram at θ = 60°, ψ = 0° and 0.44 at θ = 60°, ψ = 45° on the 0.2 - 4.0 μ diagram. The plot β versus reflectance shows the largest difference between the 0.2 - 4.0 μ bandpass and the 0.55 - 0.85 μ bandpass curves of any of the cases presented in this paper. More will be said about this later.

It is unfortunate that a flight with a large solar zenith angle was not accomplished over the white sand, but cloudiness in the area during the period when flights could have been made prohibited this. It is hoped that circumstances will permit this objective to be attained in the future.

Figure 7 shows reflectance values obtained over the Pawnee National Grassland in northeastern Colorado. These grasslands consist mostly of short native buffalo and grama grasses. At the time of this flight the grasses were in a very dry condition and were a light brown to tan in color, The terrain is slightly rolling and quite uniform with regard to vegetive cover. During this flight the solar zenith varied from 55° to 57° and the azimuth of the sun was 170°.

In the upper diagrams of Figure 7 a definite backscatter is observed. The minimum reflectance for both the 0.55 - 0.85 μ and 0.2 - 4.0 μ bandpasses was at $\psi = 0°$, $\theta = 45°$. Good agreement exists between the pattern of reflectance over the grassland shown here and the pattern shown by Coulson[3] over red clay soil. The graph of scattering angle versus reflectance shows very little difference between the two bandpasses. Although the curves are close together, the 0.55 - 0.85 μ bandpass curve is definitely lower than the 0.2 - 4.0 μ bandpass curve. This is a notable difference from the other cases over clouds and white sand.

A flight was also made over the ocean near San Francisco when the solar zenith angle was between 49° and 50°. The resulting reflectances were so low (0.01 - 0.04 for all values of $\theta \leq 60°$) that the results were not considered of sufficient interest to present in detail. This general result is in agreement with values of the reflectivity of a water surface listed in the Smithsonian Meteorological Tables[7].

Table 2 presents values of average reflectance, minimum reflectance, and the ratio of these two parameters for each of the cases that have been presented. The mean reflectance was computed by averaging all the values of reflectance for θ at 15 degree intervals up to and including 60° and ψ at 30 and 45 degree intervals (depending on the flight under consideration) around the vertical. The ratio of average reflectance to minimum reflectance provides an estimate of the error that anisotropy might introduce if a single reading taken by a satellite-mounted radiometer at one position of radiometer zenith angle and azimuth were used to estimate the albedo of clouds, white sand, or grassland. The values of this ratio range between 1.09 over the white sand in the 0.2 - 4.0 μ bandpass to 1.40 over stratus clouds in the same bandpass. The average of all the ratios listed is very close to 1.2 for both bandpasses.

The column marked "difference" in Table 2 indicates that there is some wavelength dependence in the reflectivity of various surfaces. The largest difference occurs over the white sand and the smallest difference occurs over the grassland. The fact that the difference changes in magnitude with various surfaces indicates that the relationship between the reflectance observed in the 0.2 - 4.0 μ and the 0.55 - 0.85 μ bandpasses will change with various surfaces. This result suggests strongly that inferring the reflectance in the 0.2 - 4.0 μ bandpass from the 0.55 - 0.85 μ bandpass (or the converse) would be a very difficult procedure.

SUMMARY

The results from six flights with an airplane-mounted NIMBUS radiometer indicate that there is appreciable forward scattering observed over stratus clouds when the sun is at a large zenith angle. Definite backscattering is observed at a large zenith angle over a grassland surface. At small zenith angles slight backscattering was observed over stratus clouds and white sand. At a solar zenith angle of 49° - 50°, very small reflectance values were observed over the ocean at all radiometer zenith angles.

The ratio of average reflectance values ($\theta \leq 60°$) to minimum observed reflectance was found to vary from 1.09 to 1.40 with the average ratio being near 1.2 . This would indicate that anisotropy should be considered if albedo is to be estimated via satellite-mounted radiometers.

Some wavelength dependence of reflectance is indicated by the difference between the values obtained in the 0.2 - 4.0 μ and 0.55 - 0.85 μ bandpasses. This dependence points to the fact that to infer accurate reflectance in the 0.2 - 4.0 μ bandpass from the 0.55 - 0.85 μ bandpass (or vice versa) would be a difficult task requiring a knowledge of reflectance characteristics in each bandpass for every reflecting surface.

REFERENCES

1. Bandeen, Wm. R., H. Halev, I. Strange, "A Radiation Climatology in the Visible and Infrared from TIROS Meteorological Satellites." NASA Technical Note D-2534, 1965.

2. Bartman, F. L., L. W. Chaney, P. A Titus, M. G. Whybra, "Infrared and Visible Radiation Measurements on High Altitude Balloon Flights at 34 km Altitude." Proceedings of the Third Symposium on Remote Sensing of the Environment, October 14, 15, 16, 1964.

3. Coulson, K. L., G. M. Bouricus, E. L. Gray, "Optical Reflection Properties of Natural Surfaces." Journal of Geophysical Research, 70 (18): 4601-4611, September 15, 1965.

4. Fritz, S., P. Krishna Rao, M. Weinstein, "Satellite Measurements of Reflected Solar Energy and the Energy Received at the Ground." Journal of Atmospheric Science, 21 (2): 141-151, 1964.

5. Hapke, B., H. Van Horn, "Photometric Studies of Complex Surfaces with Application to the Moon." Journal of Geophysical Research, 68 (15): 4545-4570, August 1963.

6. Neiburger, M., "Reflection, Absorption, and Transmission of Insolation by Stratus Cloud." Journal of Meteorology, 6: 98-104, 1949.

7. List, R. J., Smithsonian Meteorological Tables. Smithsonian Institution, Washington, D. C., Sixth Revised Edition, 1963.

8. Nordberg, W., "Research with TIROS Radiation Measurements." Astronautics and Aerospace Engineering, pp. 76-83, April 1963.

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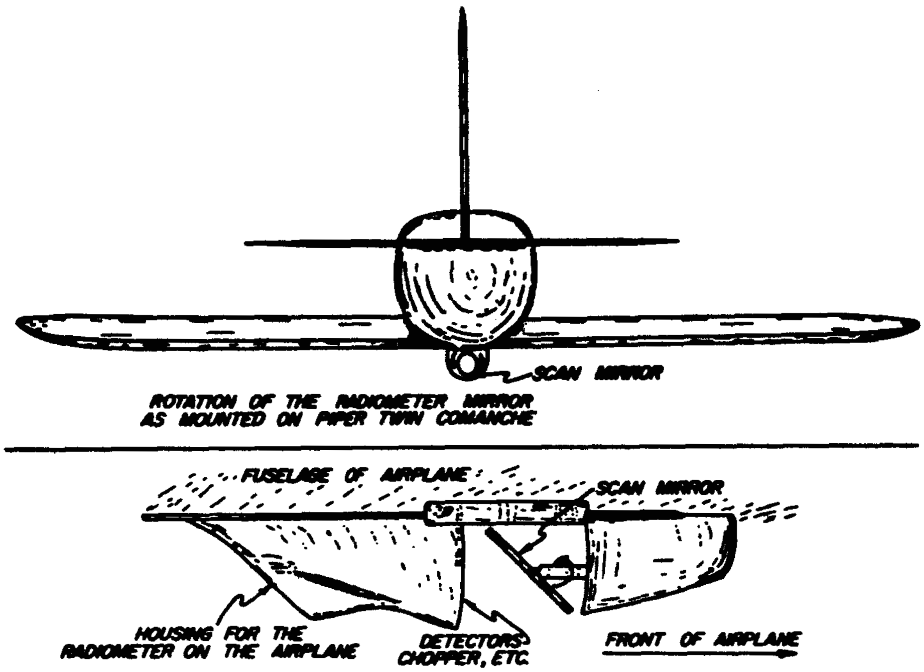
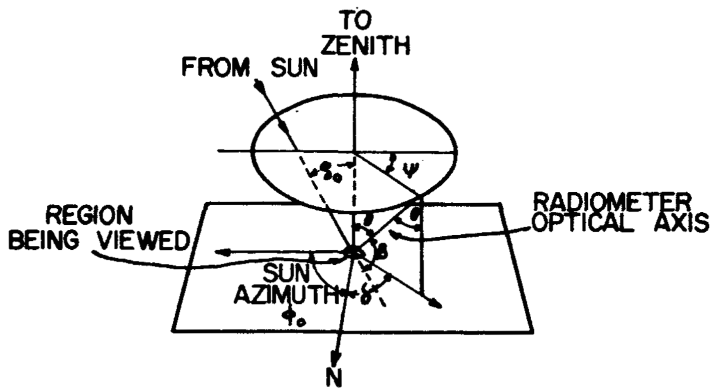


Figure 1: A sketch showing how the radiometer is mounted on a Piper Twin Comanche.



ϕ = RADIOMETER AZIMUTH = 360 − δ

β = SCATTERING ANGLE

$\cos\beta = \sin\zeta_0 \sin\theta \cos\psi - \cos\zeta_0 \cos\theta$

ζ_0 = SOLAR ZENITH ANGLE

θ = ZENITH ANGLE OF RADIOMETER

$\psi = |\phi - (180 + \phi_0)|$

Figure 2: Radiation Geometry.

TABLE 1

A summary showing the location, date, etc., of flights made to ascertain anisotropy of reflected solar radiation.

Date	Location	Reflecting Surface	Sun Zenith Angle (ζ_o)	Flight Altitude Above Surface (Ft.)	Local Standard Time
06/11/65	San Francisco, Calif.	Stratus Clouds	62-67°	1,000	0646-0734
06/11/65	San Francisco, Calif.	Stratus Clouds	12-13°	1,000	1146-1226
07/17/65	San Francisco, Calif.	Stratus Clouds	49-56°	1,000	0754-0840
08/15/65	White Sands Proving Grounds, New Mex.	White Sand	19-21°	1,000	1120-1153
10/23/65	San Francisco, Calif.	Ocean	49-50°	3,000	1127-1157
11/04/65	Pawnee National Grassland, Colo.	Grassland	55-57°	8,000	1159-1236

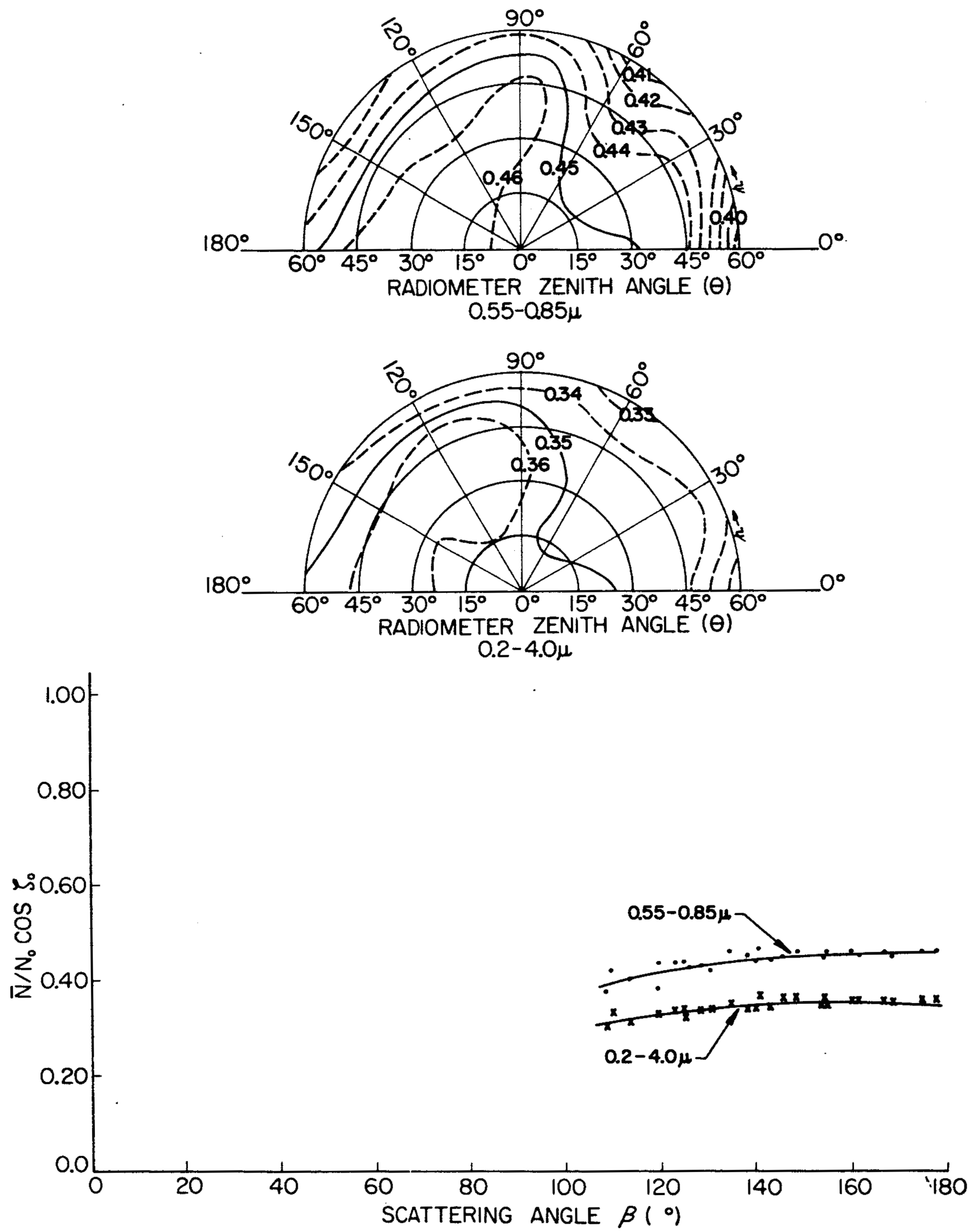


Figure 3: A flight over stratus clouds (top of cloud 1600 ft., bases 700 ft.) near San Francisco, Calif. ζ_o = 12-13°, ϕ_o = 160°. Upper diagrams: $\overline{N}/N_o \cos\zeta_o$ versus ψ and θ for 0.55 - 0.85μ and 0.2 - 4.0μ bandpasses. Lower diagram: $N/N_o \cos\zeta_o$ versus β.

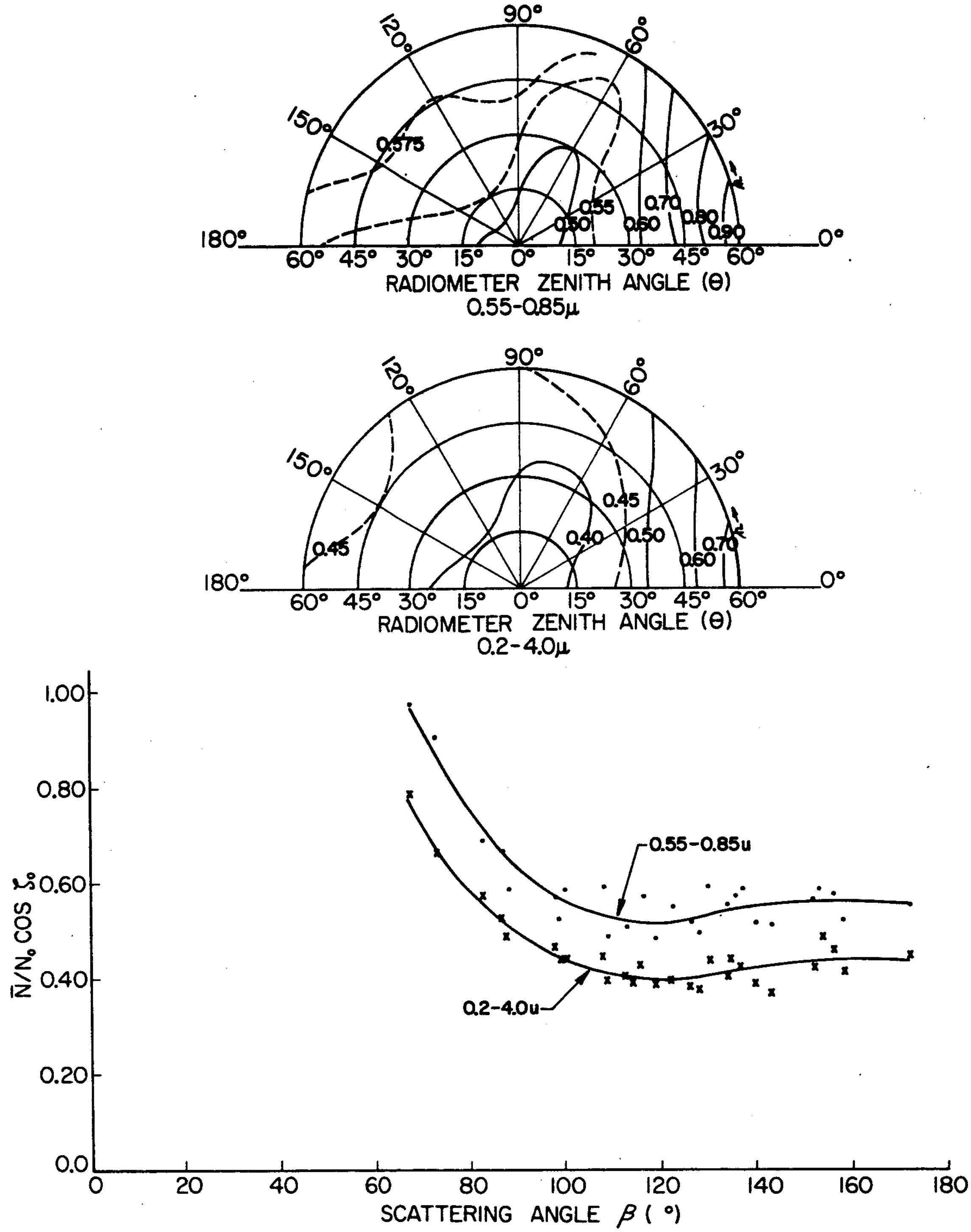


Figure 4: A flight over stratus clouds (top of clouds 1700 ft., bases 600 ft.) near San Francisco, Calif. ζ_o = 49-56°, ϕ = 068°. Upper diagrams: $\bar{N}/N_o \cos \zeta_o$ versus ψ and θ for 0.55-0.85 μ and 0.2 - 4.0 μ bandpasses. Lower diagram: $N/N_o \cos \zeta_o$ versus β.

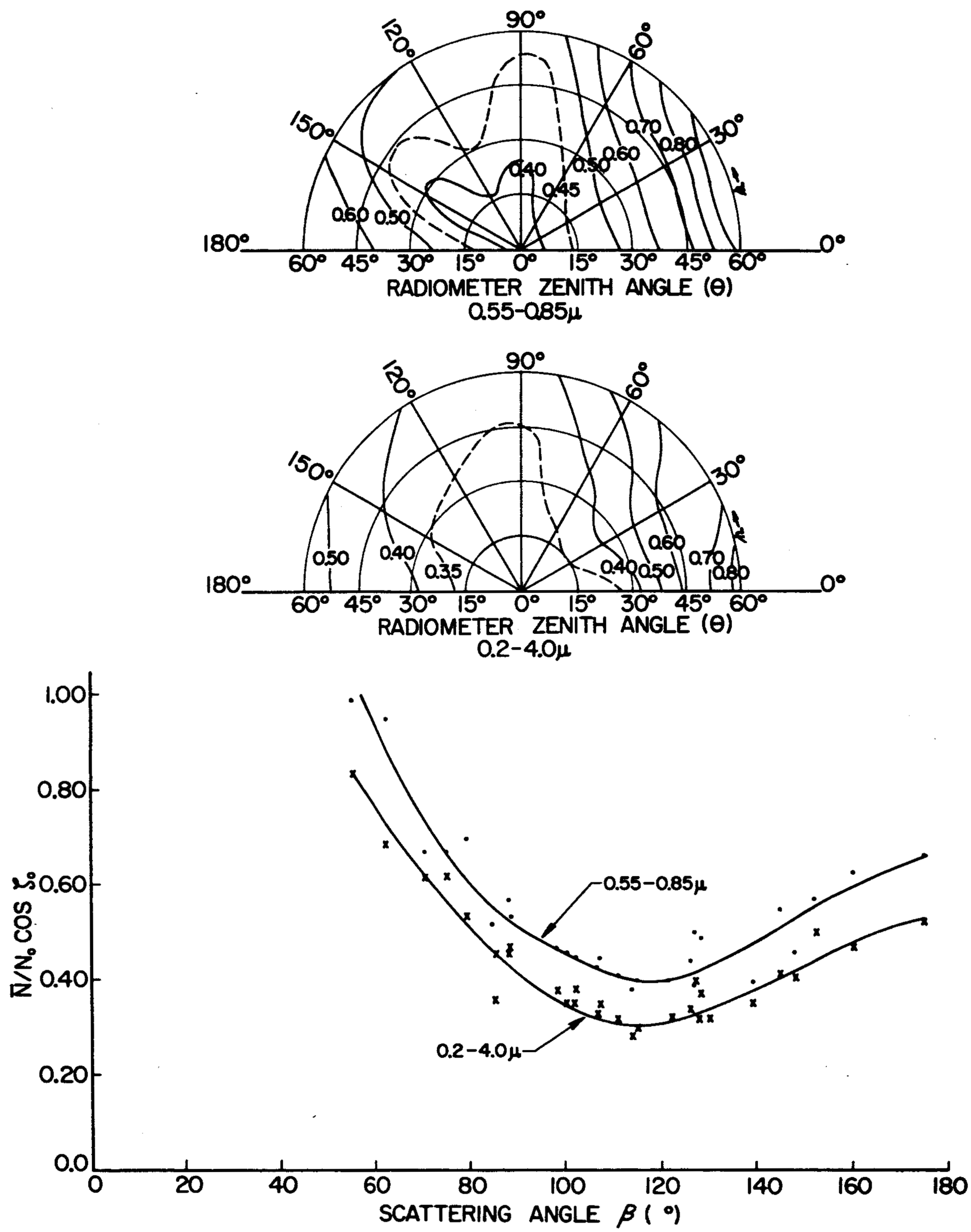


Figure 5: A flight over stratus clouds (top of clouds 1800 ft., bases 700 ft.) near San Francisco, Calif. ζ_o = 62-67°, ϕ_o = 060°. Upper diagrams: $\bar{N}/N_o \cos\zeta_o$ versus ψ and θ for 0.55 - 0.85 μ and 0.2 - 4.0 μ bandpasses. Lower diagram: $N/N_o \cos\zeta_o$ versus β.

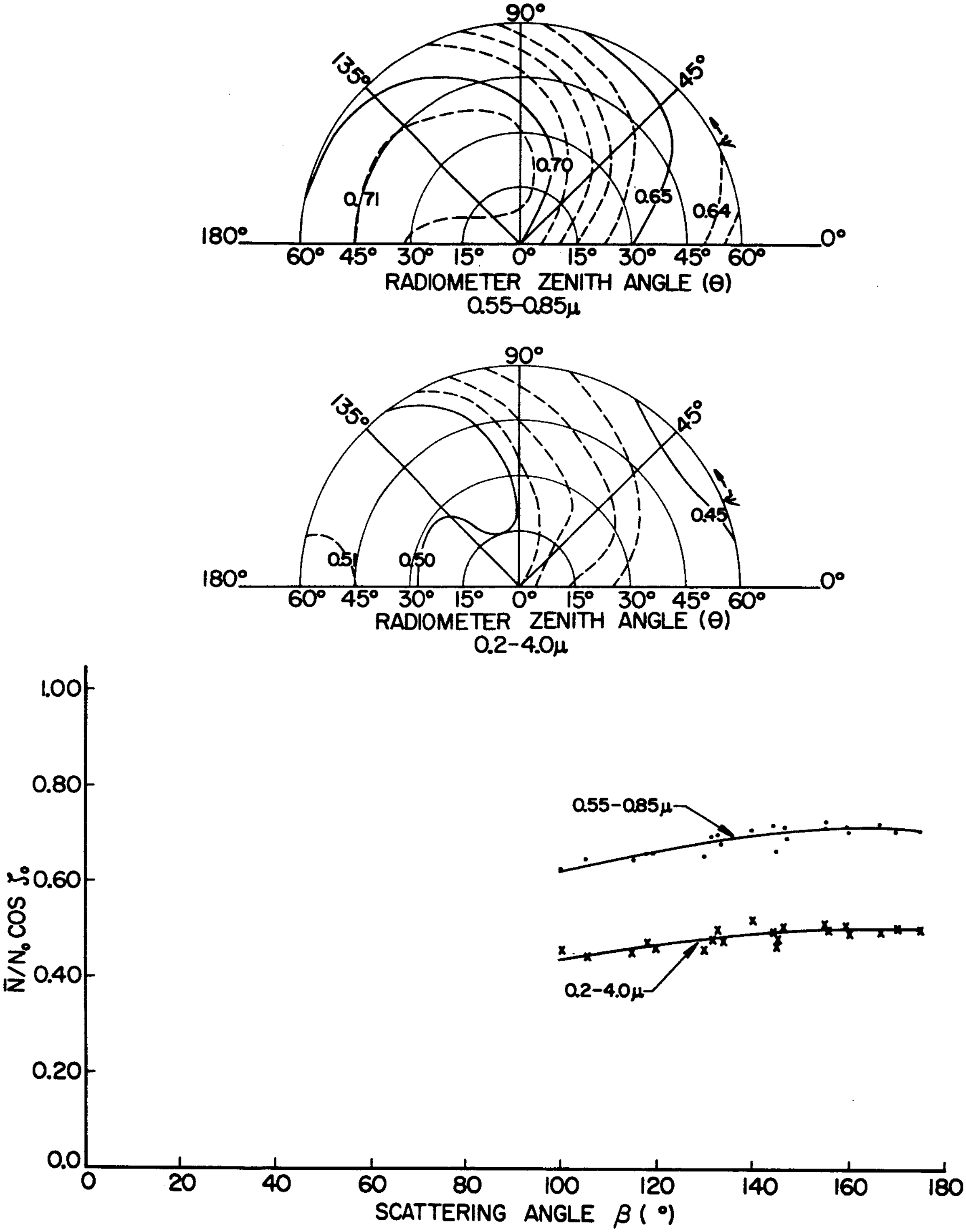


Figure 6: A flight over white gypsum sand on the White Sands Proving Grounds near Alamagordo, New Mexico. ζ_o = 19-21°, ϕ_o = 140°. Upper diagrams: $\bar{N}/N_o \cos \zeta_o$ versus ψ and θ for 0.55 - 0.85 μ and 0.2 - 4.0 μ bandpasses. Lower diagram: $\bar{N}/N_o \cos \zeta_o$ versus β.

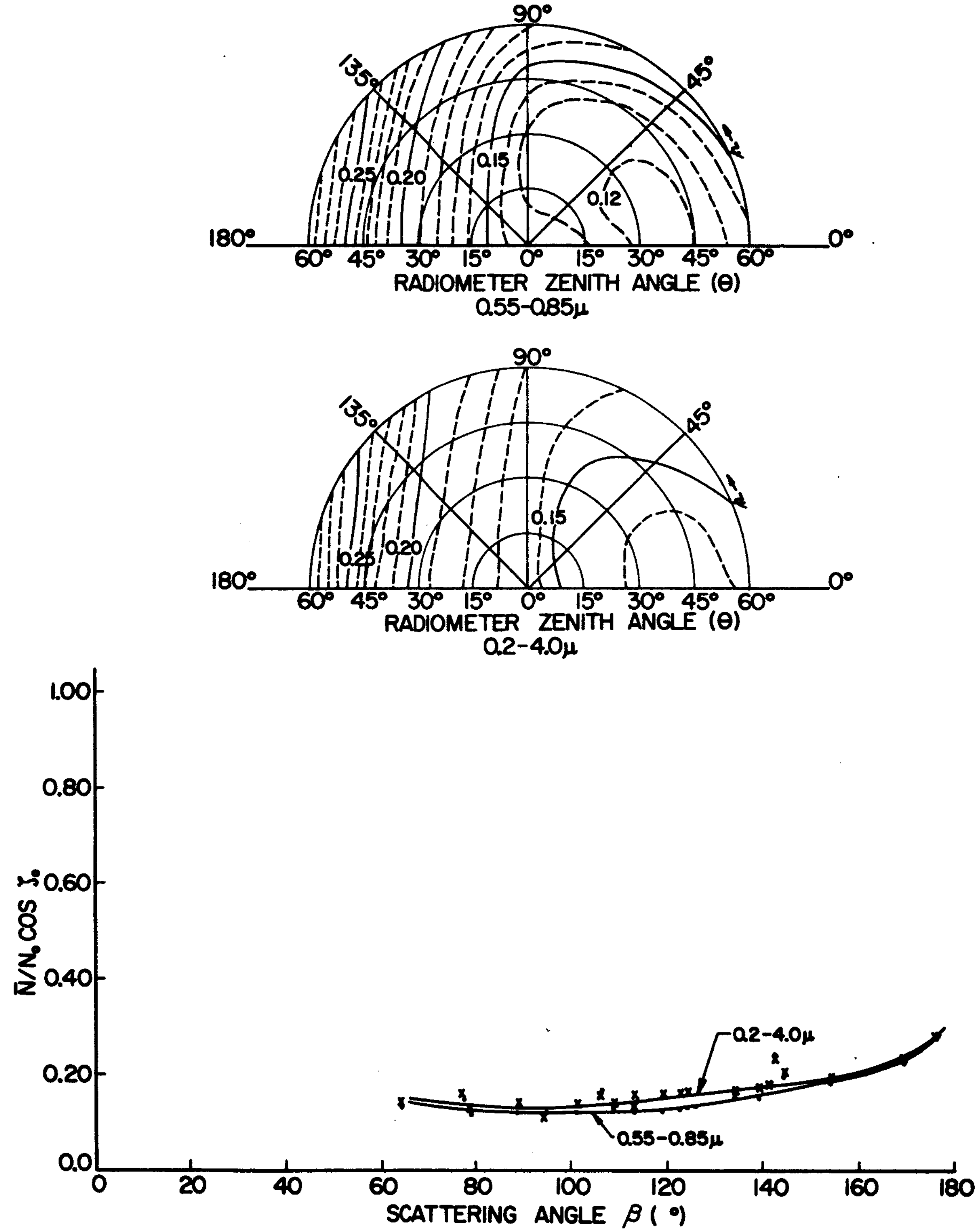


Figure 7: A flight over the Pawnee National Grasslands in northeastern Colorado. ζ_o = 55-57°, ϕ_o = 170°. Upper diagrams: $\overline{N}/N_o \cos \zeta_o$ versus ψ^o and θ for 0.55 - 0.85 μ and 0.2 - 4.0 μ bandpasses. Lower diagram: $N/N_o \cos \zeta_o$ versus β.

TABLE 2

A summary of results which illustrates the amount of anisotropy and wavelength dependence of reflectance observed in the 0.55 - 0.85 μ and 0.2 - 4.0 μ bandpasses.

Surface	ζ_o	Average Reflectance ($\theta \leq 60°$) (1) 0.55-0.85μ	(2) 0.2-4.0μ	Difference (1) - (2)	Minimum Reflectance 0.55-0.85μ	0.2-4.0μ	Ratio of Average Reflectance to Minimum Reflectance 0.55-0.85μ	0.2-4.0μ
Stratus Clouds	62-67°	0.52	0.42	0.10	0.40	0.30	1.30	1.40
Stratus Clouds	49-56°	0.58	0.45	0.13	0.48	0.37	1.21	1.22
Stratus Clouds	12-13°	0.45	0.35	0.10	0.38	0.32	1.18	1.09
White Sand	19-21°	0.69	0.48	0.21	0.62	0.44	1.11	1.09
Grassland	55-57°	0.16	0.17	-0.01	0.12	0.14	1.33	1.21

APPENDIX

Tabulated Results

Date	Location	Reflecting Surface	ζ_o	ϕ_o	ϕ	$\psi = /\phi - \phi_o/$	θ	β	$\overline{N}/N_o \cos\zeta_o$ 0.2-4.0μ	$\overline{N}/N_o \cos\zeta_o$ 0.55-0.85μ
06/11/65	San Francisco	Stratus Clouds	12-13°	160°	340°	0°	0	168	0.35	0.46
							15	153	0.35	0.46
							30	138	0.35	0.45
							45	123	0.34	0.44
							60	108	0.32	0.38
							75	93	0.27	0.29
					010 & 310	30°	0	168	0.35	0.46
							15	154	0.36	0.45
							30	139.5	0.35	0.45
							45	124.5	0.35	0.44
							60	109.5	0.34	0.42
							75	94.5	0.29	0.37
					040 & 280	60°	0	168	0.35	0.46
							15	156.5	0.34	0.46
							30	142.5	0.35	0.45
							45	128	0.34	0.43
							60	113.5	0.32	0.41
							75	99	0.27	0.32
					070 & 250	90°	0	168	0.35	0.46
							15	161	0.36	0.46
							30	148	0.36	0.47
							45	134	0.36	0.47
							60	119.5	0.33	0.44
							75	104.5	0.28	0.38
					100 & 220	120°	0	168	0.35	0.46
							15	166.5	0.36	0.46
							30	154	0.37	0.46
							45	140	0.37	0.46
							60	125.5	0.33	0.43
							75	111.	0.27	0.38

Date	Location	Reflecting Surface	ζ_o	ϕ_o	ϕ	$\psi = /\phi - \phi_o/$	θ	β	$\overline{N}/N_o \cos\zeta_o$ $0.2-4.0\mu$	$\overline{N}/N_o \cos\zeta_o$ $0.55-0.85\mu$
06/11/65	San Francisco	Stratus Clouds	12-13°	160°	130° & 190	150°	0	168	0.35	0.46
							15	174	0.35	0.47
							30	160	0.36	0.47
							45	145	0.36	0.45
							60	130.5	0.34	0.42
							75	115.5	0.29	0.37
					160	180°	0	168	0.35	0.46
							15	177	0.36	0.47
							30	162	0.36	0.47
							45	147	0.36	0.46
							60	132	0.35	0.44
							75	117	0.29	0.41

Date	Location	Reflecting Surface	ζ_o	ϕ_o	ϕ	$\psi = /\phi - \phi_o/$	θ	β	$\overline{N}/N_o \cos\zeta_o$ 0.2-4.0μ	$\overline{N}/N_o \cos\zeta_o$ 0.55-0.85μ
07/17/65	San Francisco	Stratus Clouds	49-56°	068°	248°	0°	0	128	0.37	0.49
							15	113	0.41	0.51
							30	98	0.46	0.57
							45	83	0.57	0.70
							60	68	0.79	0.98
							75	53	1.09	1.33
					218 & 278	30°	0	128	0.37	0.49
							15	114.5	0.40	0.48
							30	100.5	0.44	0.59
							45	87	0.53	0.67
							60	73.5	0.67	0.82
							75	60	0.81	0.91
					188 & 308	60°	0	128	0.37	0.49
							15	119.5	0.39	0.48
							30	109.5	0.39	0.49
							45	99	0.44	0.53
							60	88	0.49	0.59
							75	77	0.52	0.62
					158 & 338	90°	0	128	0.37	0.49
							15	126.5	0.38	0.52
							30	122	0.40	0.55
							45	116	0.43	0.59
							60	108	0.44	0.59
							75	99	0.41	0.55
					128 & 008	120°	0	128	0.37	0.49
							15	134	0.40	0.55
							30	137	0.43	0.59
							45	135.5	0.44	0.57
							60	130.5	0.44	0.60
							75	123	0.43	0.59

Date	Location	Reflecting Surface	ζ_o	ϕ_o	ϕ	$\zeta = /\phi - \phi_o/$	θ	β	$\overline{N}/N_o \cos \zeta_o$	$\overline{N}/N_o \cos \zeta_o$
07/17/65	San Francisco	Stratus Clouds	49-56°	068°	098° & 038	150°	0	128	0.37	0.49
							15	140.5	0.39	0.52
							30	152	0.42	0.57
							45	156	0.46	0.58
							60	154	0.49	0.59
							75	145	0.50	0.60
					068	180°	0	128	0.37	0.49
							15	143	0.37	0.51
							30	158	0.42	0.52
							45	173	0.42	0.53
							60	172	0.44	0.56
							75	157	0.47	0.59

Date	Location	Reflecting Surface	ζ_o	ϕ_o	ϕ	$\psi = /\phi - \phi_o/$	θ	β	$\overline{N}/N_o \cos \zeta_o$ 0.2-4.0µ	$\overline{N}/N_o \cos \zeta_o$ 0.55-0.85µ
06/11/65	San Francisco	Stratus Clouds	62-67°	060°	240°	0°	0	115	0.30	0.40
							15	100	0.30	0.46
							30	85	0.36	0.52
							45	70	0.62	0.67
							60	55	0.84	0.99
							75	40	1.36	1.44
					210 & 270	30°	0	115	0.30	0.40
							15	102	0.35	0.45
							30	88.5	0.47	0.53
							45	75	0.62	0.67
							60	62.5	0.69	0.95
							75	50	1.02	1.44
					180 & 300	60°	0	115	0.30	0.40
							15	107	0.33	0.43
							30	98	0.38	0.47
							45	89	0.46	0.57
							60	79.5	0.54	0.70
							75	71	0.64	0.80
					150 & 330	90°	0	115	0.30	0.40
							15	114	0.30	0.38
							30	111.5	0.32	0.41
							45	107.5	0.35	0.45
							60	102	0.38	0.45
							75	96.5	0.42	0.44
					120 & 0	120°	0	115	0.30	0.40
							15	122	0.32	0.40
							30	126.5	0.34	0.44
							45	128	0.38	0.49
							60	127.5	0.40	0.50
							75	123	0.42	0.50

Date	Location	Reflecting Surface	ζ_o	ϕ_o	ϕ	$\psi = /\phi - \phi_o/$	θ	β	$\overline{N}/N_o \cos\zeta_o$ 0.2-4.0μ	$\overline{N}/N_o \cos\zeta_o$ 0.55-0.85μ
06/11/65	San Francisco	Stratus Clouds	62-67°	060°	90° & 30	150°	0	115	0.30	0.40
							15	127.5	0.32	0.39
							30	139	0.35	0.40
							45	148.5	0.40	0.46
							60	152	0.50	0.57
							75	150	0.51	0.60
					60	180°	0	115	0.30	0.40
							15	130	0.32	0.47
							30	145	0.41	0.55
							45	160	0.47	0.63
							60	175	0.53	0.66
							75	170	0.55	0.64

Date	Location	Reflecting Surface	ζ_o	ϕ_o	ϕ	$\psi = /\phi - \phi_o/$	θ	β	$\bar{N}/N_o \cos\zeta_o$ 0.2-4.0μ	$\bar{N}/N_o \cos\zeta_o$ 0.55-0.85μ
08/15/65	White Sands	White	19-21°	140°	320°	0°	0	160	0.49	0.70
	Proving	Gypsum					15	145	0.46	0.66
	Grounds	Sand					30	130	0.46	0.65
							45	115	0.45	0.65
							60	100	0.45	0.62
							75	85	0.43	0.54
					005	45°	0	160	0.49	0.70
					& 275		15	148	0.48	0.69
							30	134	0.47	0.68
							45	120	0.46	0.66
							60	105	0.44	0.64
							75	90	0.41	0.58
					050	90°	0	160	0.49	0.70
					& 230		15	155.5	0.50	0.72
							30	144.5	0.49	0.71
							45	132	0.48	0.69
							60	118	0.47	0.66
							75	104	0.40	0.53
					095	135°	0	160	0.49	0.70
					& 185		15	166.5	0.49	0.71
							30	159.5	0.50	0.71
							45	146.5	0.50	0.71
							60	133	0.50	0.69
							75	118.5	0.47	0.59
					140	180°	0	160	0.49	0.70
							15	175	0.50	0.70
							30	170	0.50	0.70
							45	155	0.51	0.71
							60	140	0.52	0.70
							75	125	0.47	0.65

Date	Location	Reflecting Surface	ζ_o	ϕ_o	ϕ	$\psi = /\phi - \phi_o/$	θ	β	$\overline{N}/N_o \cos\zeta_o$ 0.2-4.0μ	$\overline{N}/N_o \cos\zeta_o$ 0.55-0.85μ
11/04/65	Pawnee National Grasslands in Colorado	Native Buffalo & Grama Grasses plus Sod	55-57°	170°	350°	0°	0	120	0.16	0.13
							15	105	0.14	0.13
							30	90	0.14	0.12
							45	75	0.13	0.12
							60	60	0.15	0.13
							75	45	0.19	0.20
					035 & 305	45°	0	120	0.16	0.13
							15	109	0.14	0.13
							30	97.5	0.14	0.12
							45	85.5	0.15	0.12
							60	73.5	0.16	0.15
							75	62.5	0.19	0.20
					080 & 260	90°	0	120	0.16	0.13
							15	119	0.16	0.13
							30	115.5	0.16	0.13
							45	110.5	0.16	0.15
							60	104.5	0.17	0.17
							75	97.5	0.18	0.19
					125 & 215	135°	0	120	0.16	0.13
							15	130	0.17	0.15
							30	137.5	0.19	0.18
							45	142	0.20	0.20
							60	141	0.24	0.24
							75	136	0.27	0.28
					170	180°	0	120	0.16	0.13
							15	135	0.18	0.16
							30	150	0.19	0.19
							45	165	0.23	0.23
							60	180	0.28	0.28
							75	165	0.32	0.33