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REMOTE PROBING OF HIGH CLOUD COVER VIA SATELLITE-BORNE LIDAR

By: WILLIAM E. EVANS

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

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Approved: D. R. SCHEUCH, VICE PRESIDENT
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ABSTRACT

A series of measurements with a calibrated ruby lidar on a variety of cirrus cloud situations is compared with the appearance of these cloud situations as observed visually from the ground and via APT and AVCS television pictures from the ESSA weather satellites. Reduced lidar data, Kodachrome cloud photographs, satellite photographs, synoptic charts, and vertical profiles of wind, temperature, and humidity are presented for fourteen operating sessions on ten different days, at Menlo Park, California.

For some of the soundings, concurrent measurements of two-way transmission through the clouds were made by comparing the strength of lidar returns via Rayleigh molecular scattering from clear regions above the cloud decks with similiar returns obtained when no clouds were present. These two measurements permitted an estimate to be made of the ratio of backscattering to total scattering for typical cirrus clouds: and this ratio, in turn, permitted estimates to be made of the total geometric cross sections for the ice crystals in an assortment of cirrus situations. Although the link to the particle size distributions required for solving radiometric transfer equations in the infrared regions still is not complete, the estimates of total geometric cross section plus inferences of temperature (from the measured altitude) permit the approximate effect of cirrus on satellite-borne radiometric sensors to be predicted. Such a calculation shows that an amount of cirrus well below the threshold detectable in even the best pictures from current weather satellites is enough to introduce several degrees of error into temperature measurements made in the 3.5-to-4.0- and 10-to-11- μ "atmospheric window" channels.

The study shows, however, that cirrus too weak to be detected visually from the ground under good lighting conditions probably will not introduce significant errors into radiometric measurements made from satellites.

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I INTRODUCTION

The fundamental question toward which this study is directed is: What effect will cirrus cloud have on the quality of data obtained by various types of satellite-borne radiometric sensors?

Subsidiary to this main question are others blocking the path toward the main goal. The route we have chosen to follow in this study can be outlined as follows:

- (1) Since it is obviously impracticable to describe all possible cloud situations in complete physical detail, we develop one or more simplified models that could be used to simulate real clouds to a satisfactory degree of accuracy. A desirable set of input parameters, suitable for use in all parts of the infrared spectrum, would be the size, number density, and spatial distribution of equivalent spherical particles, plus the temperature and the density of water vapor within the cloud.
- (2) To determine the constants for even an elementary model, we need much more complete data about real cirrus clouds than has heretofore been available. Laser radar offers an attractive method for obtaining these data. The making and analysis of pertinent lidar soundings of cirrus cloud has represented a major portion of the work reported here.

Optical wavelengths are well suited for meteorological probing: They are sufficiently small relative to the common atmospheric aerosols that the latter exhibit backscattering cross sections large enough to be useful to relatively simple optical radars. Even before lasers were developed, optical radars using spark sources were built and were proposed for use in meteorological satellites (Van Ornum, 1961).^{*} The rapid development of practical laser light sources stimulated suggestions

^{*}References are listed at the end of the report.

for meteorological applications employing ground-based, airborne, and satellite-borne laser radar (lidar) equipment.

In a previous study (Evans et al. 1966) the potential usefulness of a wide variety of satellite-borne experiments was examined, and it was concluded that the meteorological application exhibiting the best combination of usefulness and technical feasibility, with the available equipment, was measurement of the location and density of cirrus cloud cover. The final report of that study pointed out that cirrus clouds, long used by forecasters as precursors of major tropospheric disturbances but traditionally difficult to observe from ground, air, or satellite, are becoming increasingly interesting to the meteorological community as the seriousness of their effect upon satellite-borne radiation sensors and upon the earth's thermal equilibrium becomes more fully appreciated. Recent papers on this subject include those by Hall, (1968), and Fritz and Rao, (1967). The effect of high cloud may be aggravated by rapidly increasing amounts of artificially generated cirrus clouds from high-flying jet aircraft (Roberts 1966).

Using volume backscattering coefficients measured from a variety of cirrus clouds by ground-based lidars, calculations were made to show that impractically large amounts of power would be required for a lidar in a polar-orbiting satellite to generate imagery that would begin to compete with passive sensors in detailed geographic coverage. By being more selective, however, that is, by employing the unique range-selective capability of the lidar to resolve ambiguities in the records from other sensors in specific geographic areas, the technical problems become more tractable.

In the work reported herein, we have attempted to improve the quantitative accuracy of the data upon which the earlier conclusions were based and generally to examine further the feasibility and utility of eventually orbiting a satellite lidar, or, at the minimum, of supplying ground-based lidar support for satellite-borne radiometers.

The magnitude of the effect of cirrus on the products of a satellite-borne meteorological sensor obviously varies considerably

with the nature of the sensor. For visible-wavelength, high-definition imaging systems that depend upon reflected solar illumination; that is, all forms of cloud-observing television, a relatively crude reflectance-versus-altitude profile would facilitate separation of high cloud from low cloud and separation of cloud from snow or sand. In addition, such a profile should be able to call attention to important cirrus systems in regions now reported as completely clear by conventional satellite TV observation.

To facilitate the interpretation of imagery gathered by scanning infrared radiometers, a more quantitative interpretation of the lidar signature will be required, since the presence of cirrus can either add to or subtract from the effective temperatures recorded by the radiometer, depending upon the density and temperature of the cirrus, the spectral region being sensed, and other factors.

A still higher order of quantitative precision would be required to satisfy the needs of those attempting to deduce vertical distributions of water vapor by means of multispectral radiometry (Schotland, 1966).

The energy received by a satellite radiometer (see Fig. 1) is the sum of the contributions from numerous emitting and reflecting regions within the radiometer's field of view. The contribution from each incremental region is that which was initially radiated or scattered toward the radiometer, then attenuated by absorption or additional scattering or both on its trip to the radiometer.

Conventionally, the process is described mathematically by an "equation of radiative transfer" of the form (Kondrat'yev, 1965):

$$\frac{\cos \theta}{\rho} \frac{\partial I_v}{\partial z} = k_v B_v + \frac{\sigma_v}{4\pi} \int_{4\pi} I_v(z, r') P_v(z, r', r) d\omega' - (k_v + \sigma_v) I_v, \quad (I-1)$$

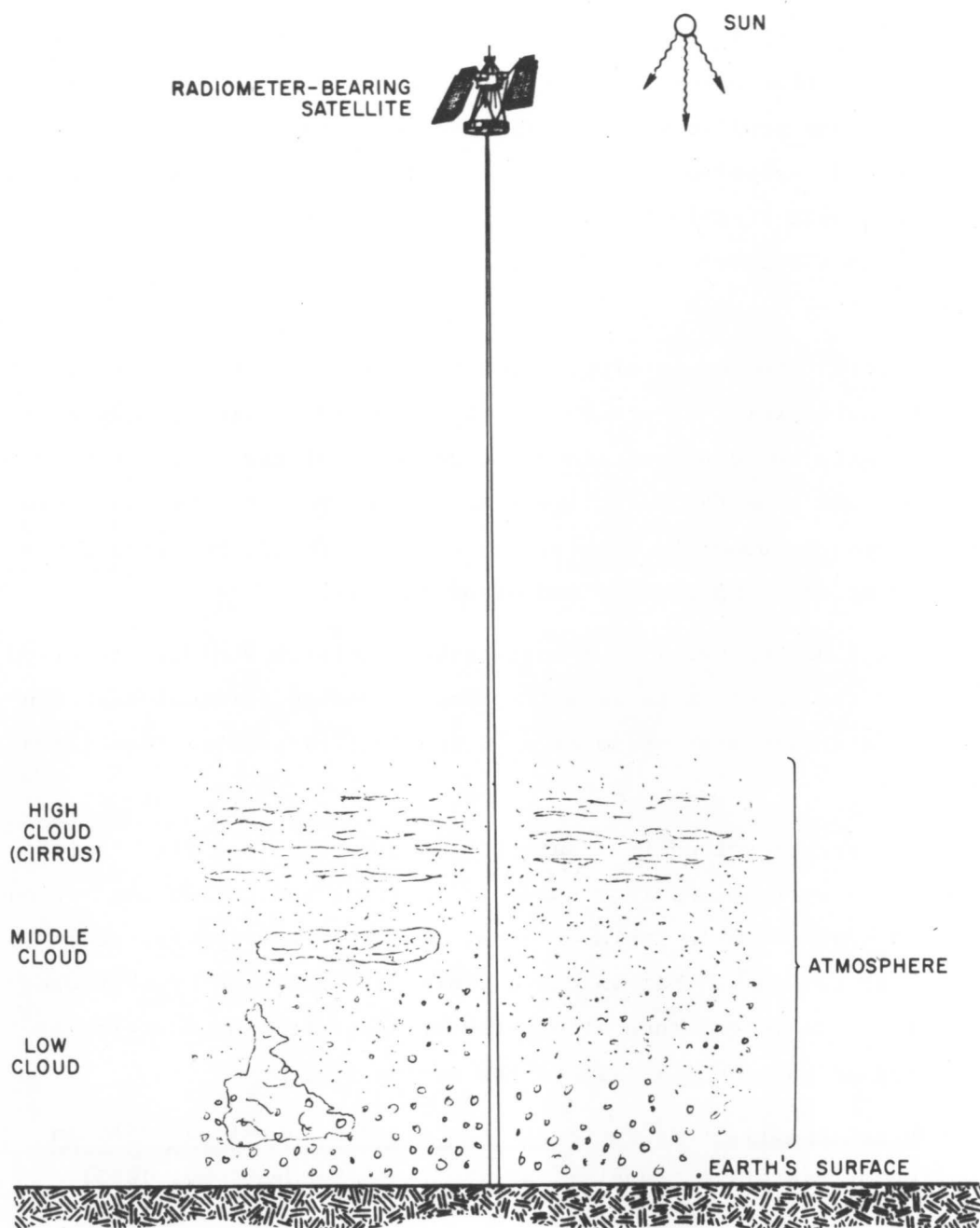


FIG.1 GEOMETRY OF THE CIRRUS SCREENING PROBLEM

where

- I_v = radiation intensity
- θ = direction of intensity vector in relation to the vertical
- ρ = density of absorbing substance
- z = vertical coordinate
- k_v = mass absorption coefficient
- σ_v = mass scattering coefficient
- B_v = Planck intensity function
- P_v = scattering phase function
- r' = direction of energy incident on the scattering volume
- r = direction of energy scattered from the scattering volume.

In this equation, the left-hand side represents the rate of change of radiant intensity in a particular direction through an interacting medium. On the right-hand side, the first term specifies the contribution due to emission from the medium; the second term specifies the contribution due to scattering within the medium in the direction of interest; and the last term specifies the losses due to absorption and scattering in the medium.

To determine the radiation flux on a particular surface (detector) in the satellite, one must integrate Eq. (I-1) over the frequency, pertinent angles, and height.

Obviously, the presence of a cirrus cloud layer can either increase (by emission or scattering) or decrease (by scattering or absorption) the effective radiance measured by the satellite radiometer. Which way the balance will be shifted depends upon the quantity of attenuating material present in the cloud and upon its temperature. Hopefully, lidar can indicate the quantity of material by the shape and amplitude of its return signature and can closely estimate its temperature through reference to its elevation.

The lidar record of a given cloud situation is essentially independent of time of day or night, lighting conditions, or altitude. In this report we present the results of a coordinated visual and lidar observational program designed to relate carefully calibrated lidar

records to the appearance of clouds as reported by both ground observers and satellite television. We then analyze the lidar records in order to obtain a close estimate of the total geometric cross section for all the crystals in a vertical column through the cloud.

II SUMMARY AND CONCLUSIONS

This program may be summarized under two headings: the experimental program of observations and measurements of cirrus cloud with lidar and the interpretation of the data, with associated theoretical studies, in terms of their significance to satellite radiometric observations.

The experimental observations have undoubtedly been the most successful aspect of the study and represent a new contribution to the knowledge of the distribution and nature of cirrus cloud cover. Although only for the latitude of Menlo Park and limited to a single winter season, the lidar observations provide quantitative data on cirrus cloud cover in a variety of synoptic situations. In a surprising number of cases, the lidar-observed cirrus were not discernible on photographs of satellite-viewed cloud cover.

The experimental lidar program employed a method of simultaneously measuring cloud attenuation and backscattering that we believe to be unique. Neither of the measurements is yet as accurate as would be desirable (probably $\pm 50\%$). But when one considers that the absolute values involved can range over several orders of magnitude and that lidar probing requires no physical access to the clouds, is independent of lighting conditions, and need not involve a human observer, the present data are significant and represent a very useful improvement of any so far available.

The very important ratio between the volume backscattering coefficient and the volume attenuation coefficient* for our ruby lidar system has been determined by two different methods on a variety of cirrus clouds and is now believed to be very nearly 0.4. The sensitivity of the lidar system used was wholly adequate to ensure that the measurements were at least fully representative, that no thin clouds were missed, and that all cirrus cloud layers were penetrated completely.

*See Section IV-A for definitions of these terms.

The "typical" medium-visibility cirrus observed and documented during this program was approximately 1 km thick, exhibited a beam transmission of 80% in the visible region, had an average volume backscattering coefficient β'_{180} for 0.7- μ light of $1.0 \times 10^{-1} \text{ km}^{-1}$, and had a backscattering optical thickness τ_{β} ($= \int \beta'_{180} dR$) of 0.1. It was only very rarely detectable in the best satellite television pictures but could be seen at night from the ground under good moonlight conditions.

The concept of "backscattering optical thickness," τ_{β} , was introduced (Sec. II-C and Appendix A) to describe the overall backscattering capability of a vertical section through the cloud. It combines the reflective effects of density and vertical extent and avoids the ambiguities that accrue from describing clouds as "thick" or "dense." At least within the limits detailed herein, the value of τ_{β} also appears to correlate reasonably well with the visibility of the clouds, although this feature is obviously a complex function of lighting, size, and color discrimination. Clouds with τ_{β} as low as 0.01 can be identified under optimum observing conditions in daylight; these correspond to one-way transmission factors of 98% and are easily measured by the lidar. The strongest τ_{β} measured during this program was about 1.0 and was associated with 3-km-thick cirrus accompanying a jet stream (21 February 1968). The inferred beam transmission for that cloud was 8%.

Values of β'_{180} encountered during the program also covered a range of approximately two orders of magnitude. There appeared to be only a weak tendency for large values of τ_{β} to contain unusually large values of β'_{180} . In other words, the higher values of τ_{β} were usually indicative of both denser and geometrically thicker clouds.

In addition to the measurements of thickness and backscattering, information regarding altitude, thickness, horizontal coverage, etc., was recorded in the course of the experimental program. Cirrus was further compared with other meteorological data, in particular with the temperature, moisture and wind profiles obtained from the nearest radiosonde station (Oakland). Such data could be useful for inferring such parameters (within useful limits) from climatology and lidar-detected

cirrus observations at a given station over a network of stations, but this aspect was not pursued in this study since it was not central to our objectives. (Further studies on these lines might well be worth considering, however, particularly in view of the current satellite's apparent inability to detect cirrus clouds on a significant number of occasions.)

In the area of theoretical analysis and interpretation of the observed data in terms of the probable effects of the cirrus on various radiometric measurements, appreciably less progress was made during this study than had been desired. The difficulty, even futility, of carrying out extensive modeling calculations until more definitive numbers can be assigned to the phase function $P(\theta, \phi)$ and to the efficiency factor Q has become increasingly apparent. The requirement for more experimental data leading to these values dictated that most of the effort in this program should go into the data-gathering phase.

The average product of the phase function and the efficiency factor provides an estimate of the total geometrical cross section per unit volume of the cirrus cloud particles (see Sec. IV D). The reliability of the estimate should be checked against in situ measurements of the particle size distribution but this has not yet been done. A completely rigorous prediction of the infrared transfer in the nonhomogeneous atmosphere containing cirrus clouds requires knowledge of physical characteristics of the ice particles at wavelengths for which the lidar data yield no explicit information. If the geometric cross sections and particle size distribution could be inferred from lidar measurements, a direct link could be established between the lidar measurements and theoretical or empirical determinations of the infrared absorptivity, transmissivity, and reflectivity of the cloud. With these cloud properties as input, the effects of the cloud on infrared sensing from above or below the cloud could be inferred from simplified solutions of the transfer equation.

Cloud-induced changes in equivalent temperatures associated with beam radiation, in the absence of multiple scattering or gaseous

absorption, were calculated by Vizee during the previous study (Evans, et al., 1966, pp 95-111) and are reviewed in Fig. 2 (Fig. VII-2 of the previous report). These results are corroborated by data from the present study when use is made of the phase function and reflection efficiency for ice spheres in the 8-13 micron region as given by Hall (1968), but are subject to the following qualifications:

- (1) A better definition is now available for both the direct visual and the televised appearance of the clouds used in the model. The impression given previously for Cloud Model I through such descriptions as "high visual transparency," "visually transparent," etc. was that it was marginally detectable by trained ground-based observers and therefore that no warning would be available via the conventional weather reporting network that temperature errors of the magnitude quoted might be expected. We now believe that Cloud Model I would yield a backscattering optical thickness τ_{β} of approximately 0.1 (corresponding, for example, to the cloud situation of 26 October or 22 December 1967 in this report) and thus would normally be reported in daylight unless the ground observer's view were masked by haze or low cloud. For τ_{β} less than 0.01, it is doubtful that cirrus-induced changes in equivalent temperature for the 10-to-11- μ region would be significant for most applications.
- (2) By neglecting the atmospheric absorption and emission by water vapor and carbon dioxide, the previous calculation limits the radiometric application to "window" regions, thereby excluding applications to profile inferences from multispectral sensing.
- (3) Our current faith in an experimentally determined backscatter-to-extinction ratio $k_1 = \frac{\beta'_{180}}{\sigma} \approx 0.4$ (at ruby wavelength) reduces appreciably the range of uncertainty expressed about this factor in Sec. C. of the previous calculation.

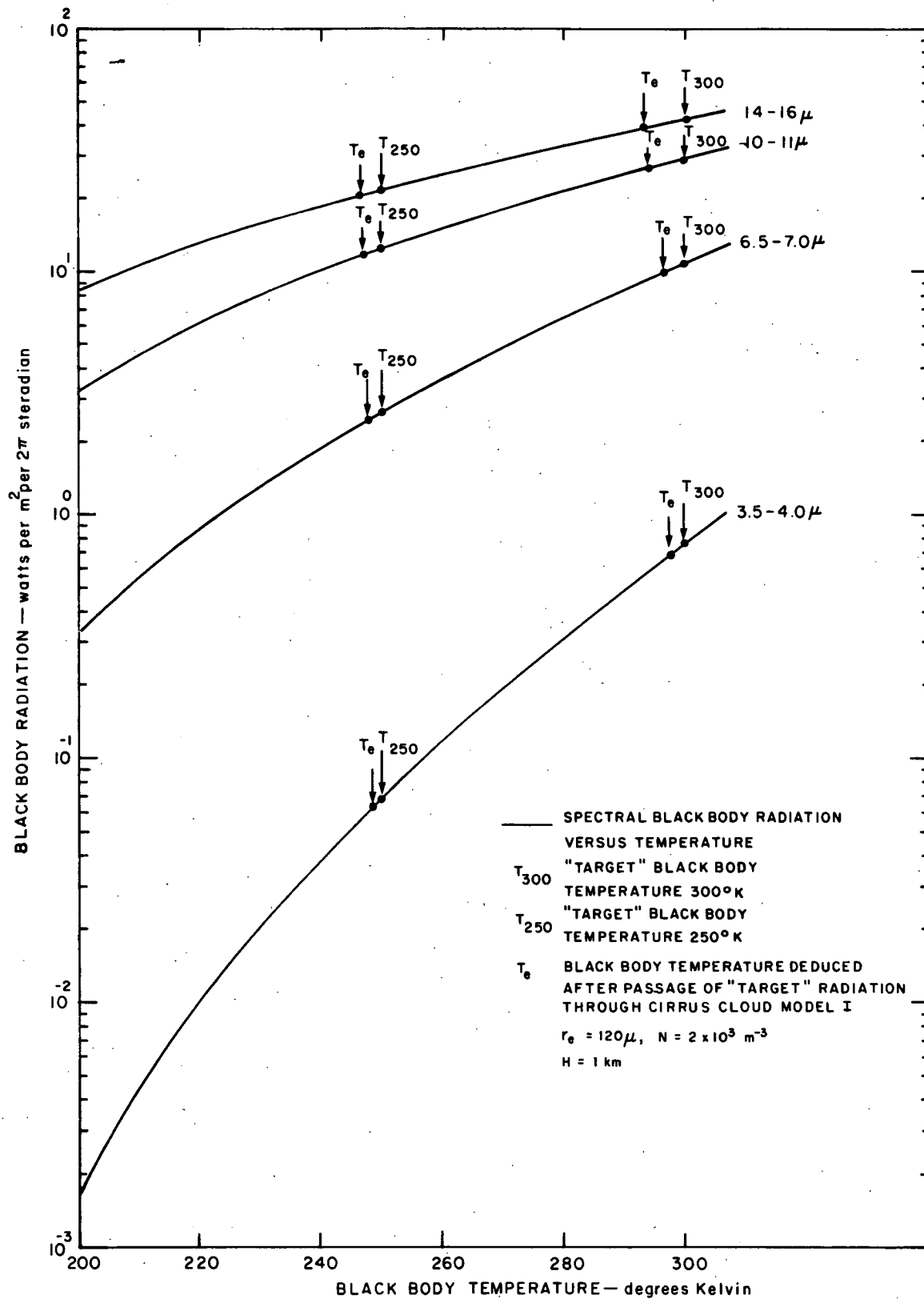


FIG. 2 ERRORS IN DETERMINATION OF BLACK-BODY TEMPERATURE
DUE TO INTERFACE BY TENUOUS CIRRUS CLOUD

- (4) Further consideration (e.g., Sec. IV-C) suggests that the Mie equivalent radius of 120μ assumed previously may be too large by a factor of three or four.

It is apparent, therefore, that the initial assumption is still valid, that cirrus clouds not portrayed by the present TV satellites are significant to radiometric measurements, and that such clouds exist so frequently as to require serious attention. On the other hand, visual observations and lidar observations from the ground, or conceivably from a satellite, under good conditions are capable of detecting most cirrus of any significant importance to radiometric measurements.

It should be stressed that the current knowledge of the scattering processes of the ice crystals in cirrus clouds is inadequate, particularly with regard to the effects of shape, particle size distribution, relationship to water vapor content, etc., to say nothing of synoptic and meso-scale variability. Further work in this direction is required before much more progress can be expected toward the principal goals: to infer the physical characteristics of the cloud via lidar measurements and then to predict the effect of the cloud on specific radiometric measurements.

III THE EXPERIMENTAL PROGRAM

A. General

In Phase I of this project, it was pointed out that the fairly extensive literature on cirrus fails to reach any real agreement on vertical extent and particle size distribution. In that phase, no information was found on the amount of cirrus that must be present to be identifiable by satellite TV in the daytime or by ground observers at night.

Near the end of the Phase I program lidar operation and calibration techniques were developed that were capable of yielding the required quantitative data on the backscattering and attenuation coefficients of cirrus clouds, night or day, down to cloud concentrations too weak to be observable visually even under the best lighting conditions. During the Phase II program now being concluded, these techniques were further refined, and a systematic observational program was conducted, with special emphasis on obtaining lidar profiles coincident with the passage overhead of TV-equipped meteorological satellites. In this chapter, we describe the instrumentation, present the experimental results in a highly reduced form, and attempt some general analysis of the data.

B. Description of the Instrumentation

The lidar used to make most of the measurements during this project was the SRI Mark II, which was constructed for ONR in 1965 under Contract Nonr-4471(00) and used for this project by permission. The basic characteristics of this instrument are given in Table III-I.

Because during Phase I of this project considerable difficulty had been encountered in keeping this instrument in optical alignment, several relatively simple but important modifications were made at the beginning of Phase II. Instead of the storage and erection procedure previously used for each observing session, the lidar was normally maintained in a near-vertical position inside its van, and it was fired

Table III-I

MARK II LIDAR CHARACTERISTICS

<u>Transmitter</u>	
Wavelength	.6943 μ
Energy output	0.3 J/pulse
Pulse duration	25 ns
Peak power	> 10 MW
Aperture	12.5-in. Newtonian telescope
Beam divergence	0.3 mrad
Pulse rate (max)	2 pulses/minute
Cooling	Forced air
Q-switch	Rotating prism, 500 rps
<u>Receiver</u>	
Aperture	12.5-in Newtonian telescope
Clear aperture area	$7.50 \times 10^{-2} \text{ m}^2$
Field of view	Adjustable, .5 to 4 mrad
Bandwidth (3 dB)	12.5 Å
Detector	Amperex Model 56TVP (S-20 cathode)
Dark noise count	0.3 pulses/ μ s
Display	Tektronix Model 555 dual beam CRO (bw = 30 MHz) P-11 Phosphor Polaroid camera, Type 410 film Logarithmic response video amplifier (optional)

through openings in a tent-like canvas roof. While this procedure restricted aiming to within approximately 15° of the zenith, it greatly reduced the problems of transmitter-receiver convergence drift due to differential thermal expansion and to mechanical stress during setup.

Calibrated micropositioners for fine-convergence adjustments were added, and these were routinely scanned in X and Y while the lidar return from Rayleigh scattering was observed at approximately 10-km altitude to ensure that the receiver field of view was fully overlapping the transmitter beam.

The dual-beam oscilloscope display normally was operated with the upper beam presenting photomultiplier anode current (linear scale) versus round-trip delay time (0 to 100 μ s). This is equivalent to P_r versus range out to $R = 15$ km. With this arrangement, the trace was usually vertically off scale during most of the first 3 km of altitude because of the strong backscattering from the lower atmosphere. It was determined, however, that paralysis or after effects from the strong initial spike were not affecting the measurement accuracy for echoes received from cirrus altitudes. The second beam of the oscilloscope was usually so arranged that it could be triggered twice during each sounding, to display on an expanded time base two different 5- μ s sections of the main trace. The timing for these two expanded sections was adjusted whenever possible so that one section presented signal returns from the clear air just beneath a cirrus layer and the other presented returns from the clear air above the cirrus layer. The radiation received from either of these regions is normally so weak that only a few photoelectrons per microsecond are released from the photocathode. Each primary electron triggers a separate cascade of approximately 10^7 electrons from the multiplier section of the phototube and these cascades appear as individual anode current pulses which can be counted visually from the photograph. Even though automatic pulse-counting equipment was available in the lidar van, there were enough instances where human judgment was needed in ignoring transient responses (identifiable by characteristic waveforms) and small cloud patches (identifiable via profile context) that we developed a definite preference for photo-recording and visual pulse counting for this particular application.

Figure 3 is a photograph of the interior of the Mark II lidar van taken during an operating session. The 35-mm camera mounted on the rail

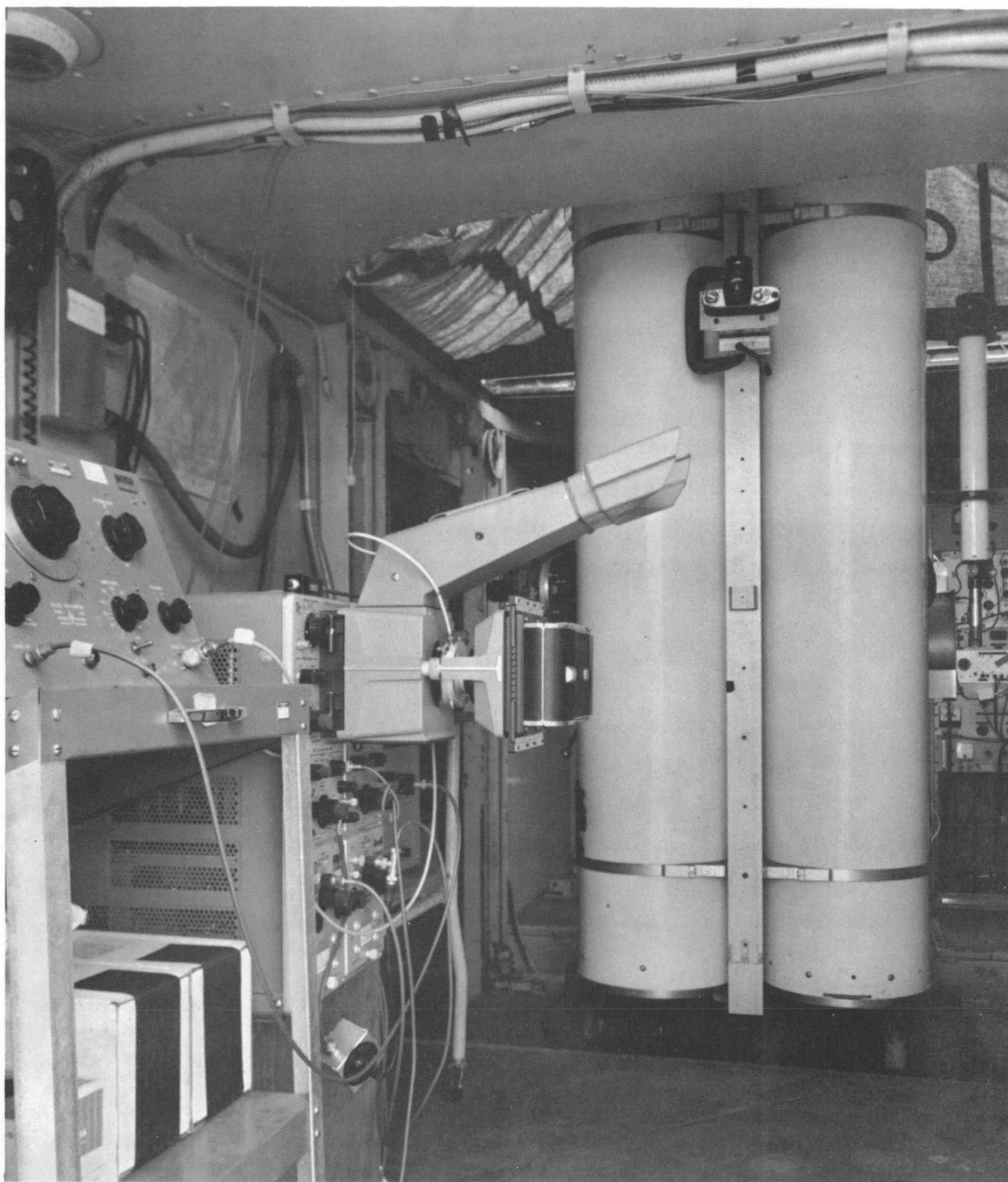


FIG. 3 PHOTOGRAPH OF INTERIOR OF MARK II LIDAR VAN

between the lidar tubes was used for the sky photographs. It is fitted with a wide-angle lens ($66^\circ \times 43.4^\circ$ field) and fiducial marks in the film plane which were carefully boresighted with the lidar beam. At least once during each daylight operating session, the 35-mm camera was removed, taken outside, and hand-held for a three-frame panorama of the sky from the southern horizon through the zenith to the northern horizon.

Several different methods were employed to monitor the long- and short-term variations in performance of the lidar. For example, the absolute laser energy output was checked periodically with a T.R.G. Model 108 Thermopile, and the detector absolute sensitivity was checked periodically by using a standard lamp source. The primary usefulness of such measurements is limited, however, to checks of individual components to determine the cause of relatively major system deterioration. As reported more fully in Appendix A, the most satisfactory method we have yet found for calibrating the absolute performance of the entire lidar system is to take measurements on very clear nights of the returns from Rayleigh scattering in the region of 9-to-10-km elevation.

Numerous checks made during each period showed that by following a consistent operating pattern and by spacing the shots regularly in time, the overall system performance factor could nearly always be maintained to within $\pm 30\%$ of its nominal value without corrections being applied. When greater accuracy was required, the data were corrected for any shot-to-shot variations in energy output as monitored by a photodiode and peak-reading voltmeter.

An alternative procedure, employed when sufficient oscillographic capacity was available, was to record the transmitter pulse obtained from the receiver via the optical reference attenuator path. This checked both the transmitter performance and the receiver performance (except for convergence). Moderate attenuation in the lower atmosphere (up to about 5 dB round trip) could be tolerated without affecting the above-quoted accuracies as long as its shot-to-shot variation was small. When haze and/or low cloud attenuated so much of the energy that

reliable comparisons with the Rayleigh return could no longer be made, the magnitude of the lower-atmosphere attenuation could be estimated only from the shape of the near-field signature, with the result that backscattering values were only approximate. For much cirrus, however, useful height and cloud profile data could be obtained through decks of low clouds which made visual detection from the ground or satellite completely impossible.

Details of the procedures used for recording and measuring the lidar signatures are included in Appendix A.

C. Experimental Results

The Mark II ruby lidar was maintained in readiness for observations during most of the three-month period from 20 October 1967 to 20 January 1968. At first, the principal effort was to make measurements of cirrus during the period 0930 to 1130 PST, with special attention given to the times of passage overhead of the APT-bearing meteorological satellites. Later, as evidence accumulated that most of the cirrus being measured during the regular morning sessions was too tenuous to be seen in even the best satellite photographs, the emphasis was shifted to attempts to measure especially dense cirrus whenever it appeared, night or day, and to measure special situations such as jet stream cirrus bands.

By mid-January, the winter rainy season in California had advanced to the point where rain or low overcast precluded operation most of the time, and very little cirrus was observed during the remaining clear periods. Lidar observations were suspended while the previously obtained data were analyzed.

Later in the spring, on 21 February and 4 April 1968, two situations of much heavier cirrus were measured. These latter clouds were believed to be more representative of the dense warm-front cirrus often observed over the eastern U.S.

Figures 4 through 15 (grouped at the end of this section) present the results of fourteen observational sessions on ten different days. Supporting the lidar data for each session are:

- (1) A brief analysis of the existing synoptic pattern.
- (2) Temperature, wind, and humidity profiles taken from the Oakland, California* rawinsonde records for the sounding made closest in time to the lidar session.[†]
- (3) The mean temperature profile for Oakland for the month of the observation, along with reference indications plus-or-minus one standard deviation from the mean.
- (4) A copy of the barometric map for the standard pressure level closest in height to the locally observed cirrus. Each chart is superimposed upon a pertinent section of the computer-prepared cloud mosaics supplied daily by ESSA from AVCS imagery.
- (5) A gridded enlargement of the central California region as portrayed by the best-quality and most concurrent weather satellite pictures conveniently available. In most cases, these were ESSA 6 APT pictures made at the Air Force Satellite Test Center at Sunnyvale, California on a Muirhead K200-A photofacsimile recorder. In some instances the large-scale reproductions were made from ESSA 3 analog AVCS pictures obtained from ESSA.

Gridding Accuracy. The gridding accuracy of many of the satellite photographs is not sufficient to permit the location of the lidar station to be pinpointed as accurately as desired for the purpose of this study. Unfortunately, through most of the year and particularly in the winter and spring when these photographs were made, the reflectance of the California coastal region is so low that no

*Oakland Airport is 18 miles (30 km) north and 0.5 mile (0.8 km) west of the Menlo Park lidar site.

[†]Unfortunately, the humidity-measuring element in the standard rawinsonde unit becomes increasingly unreliable at low temperatures and is not even recorded at most stations for temperatures below -40° C, the region of principal interest here. The dew point temperatures given may be in error by $\pm 3^\circ$ C or more.

discernible contrast with the ocean exists, even on very carefully processed satellite photographs.

Whenever sun glint or low fog is present over the water surfaces, two very prominent local landmarks can be used for precise gridding: the indentation of Monterey Bay and the butterfly-shaped San Francisco Bay-Golden Gate region. The Menlo Park site is located on a direct line, and at roughly one-third of the 80-mile distance, between the Golden Gate and the deepest indentation of Monterey Bay.

When these landmarks were not identifiable--and they were not for most of the cases studied here--gridding errors of at least 20 miles must be assumed. This is annoyingly large when compared with the 5-by-8-mile field of view of the sky camera mounted on the lidar or even with the approximately 70-mile total field discernible in the 3-frame panoramas (assuming 10° to be the minimum usable viewing elevation).

- (6) Color reproductions* of a representative sampling of the 35-mm Kodachrome pictures taken of the sky coincident with the lidar shots. The view is as it appeared looking directly up out of the van, and the orientation and overall field of view are as indicated by the legend in the upper left-hand portion of each picture. The area sampled by the lidar spot was less than 10 meters in diameter at cirrus heights--a mere speck on the scale of the photograph reproductions. The location of the area sampled is indicated by the intersection of lines drawn between the edge fiducial marks. (The right-hand fiducial is masked by the photograph mounting frame in many of the reproductions, but its position can be recovered by reference

*Full-color illustrations are being supplied with only a limited number of copies of this report. Other copies have black-and-white reproductions. Sets of color prints are available from the author at cost.

to the other frames.) Camera exposure was maintained constant (1/60 second at f/8 on Kodachrome II film) for all the pictures, in an effort to convey some impression of the relative sky brightness.

- (7) Panoramic Views. At least once during each daylight operating session, the 35-mm camera was removed from its mount on the lidar and hand-held for a panoramic series of three slightly overlapping exposures showing a segment of sky extending from horizon to horizon and 43.4° wide.

Two parallel, horizontal poles extending roughly halfway into the camera's field of view were located overhead as an aid to pointing the camera and to joining together (mentally) the trio of frames reproduced on the data sheet. Samples of three panoramic views are presented along with the operating sky pictures for every day except 3 November. The panorama for the first day, 26 October, does not cover a full 180° and does not include the above-mentioned locating poles.

- (8) Lidar Data. These data have been reduced to numerical form and presented on charts depicting backscattering strength versus altitude and time. Each data line represents one lidar sounding taken at the time indicated at the beginning of the line. Numerals in the body of the chart represent volume backscatter coefficients averaged over 100-meter altitude increments at the indicated altitudes and coded in a logarithmic manner on a scale of 0 to 9. The code used is

$$\text{Backscatter code digit} = 5 \log_{10} (100 \bar{\beta}'_{180}) \quad (\text{III-1})$$

(rounded to the nearest integer).

This code is tabulated in Table III-II.

Table III-II

CODE USED TO SPECIFY β'_{180} ON CHARTS

Code Digit	Volume Backscattering Coefficient, β'_{180} (km^{-1}) (append 10^{-3} to all values)
0	Trace-13
1	13-20
2	20-32
3	32-50
4	50-80
5	80-128
6	128-200
7	200-320
8	320-500
9	500-800

Details of the procedure used for deriving these values from the lidar waveform are described in Appendix A.

The values (unencoded) printed in the column immediately after the time markers specify the integral of the volume backscattering coefficient over the entire vertical column above the cloud base. This integral is the single value that perhaps best represents the "strength"* of the cloud and is here called "backscattering optical thickness," τ_{β} , by analogy to the "optical thickness," τ , conventionally used by cloud physicist to specify a line integral of the extinction coefficient.

The values of τ_{β} and β'_{180} presented in Figs. 4 through 15 have not been corrected for attenuation within the cloud, since the iterative routine for performing this correction was not worked out until midway

*The concept of cloud "strength" is used advisedly here and elsewhere in this report. The commonly used descriptors of density, thickness, brightness, and visibility have scientific definitions that often are quite different from what is intended when these words are applied casually to clouds.

through the data reduction, and use of the same presentation for all the data seemed desirable.

Consequently, the quoted values of τ_β may be low by as much as a factor of two, and the code numbers for β'_{180} in the upper portion of the cloud will be correspondingly low. Since [from Eq. (A-12)] the overall cloud attenuation in decibels is approximately equal to eleven times τ_β , the error is not very significant for τ_β less than 0.1, which includes all but a very few of the clouds measured during this program. More accurate values for τ_β and the β'_{180} code can be computed by the method described in Sec. III-A. The values of τ_β can be converted to optical transmission estimates for the clouds through the relationships discussed in Sec. III-A.

Unless otherwise indicated, soundings are spaced down the chart in proportion to clock time, so that whenever a relatively uniform wind field can be assumed at the cirrus height, the plot can be interpreted as a vertical section through the cloud field, which was probably still existing several tens of kilometers leeward of the observing station. Isopleths have been sketched in as an aid to visualizing the cirrus cloud structure.

For a representative sampling of the soundings, small reproductions of the original lidar A-scope waveform (P_r versus time, both scales linear) have been included just below the corresponding sky pictures.

26 October 1967

Summary and Discussion

Visual: Medium-contrast, striated cirrus with estimated 5/10 coverage against clear blue sky in all directions from the station.

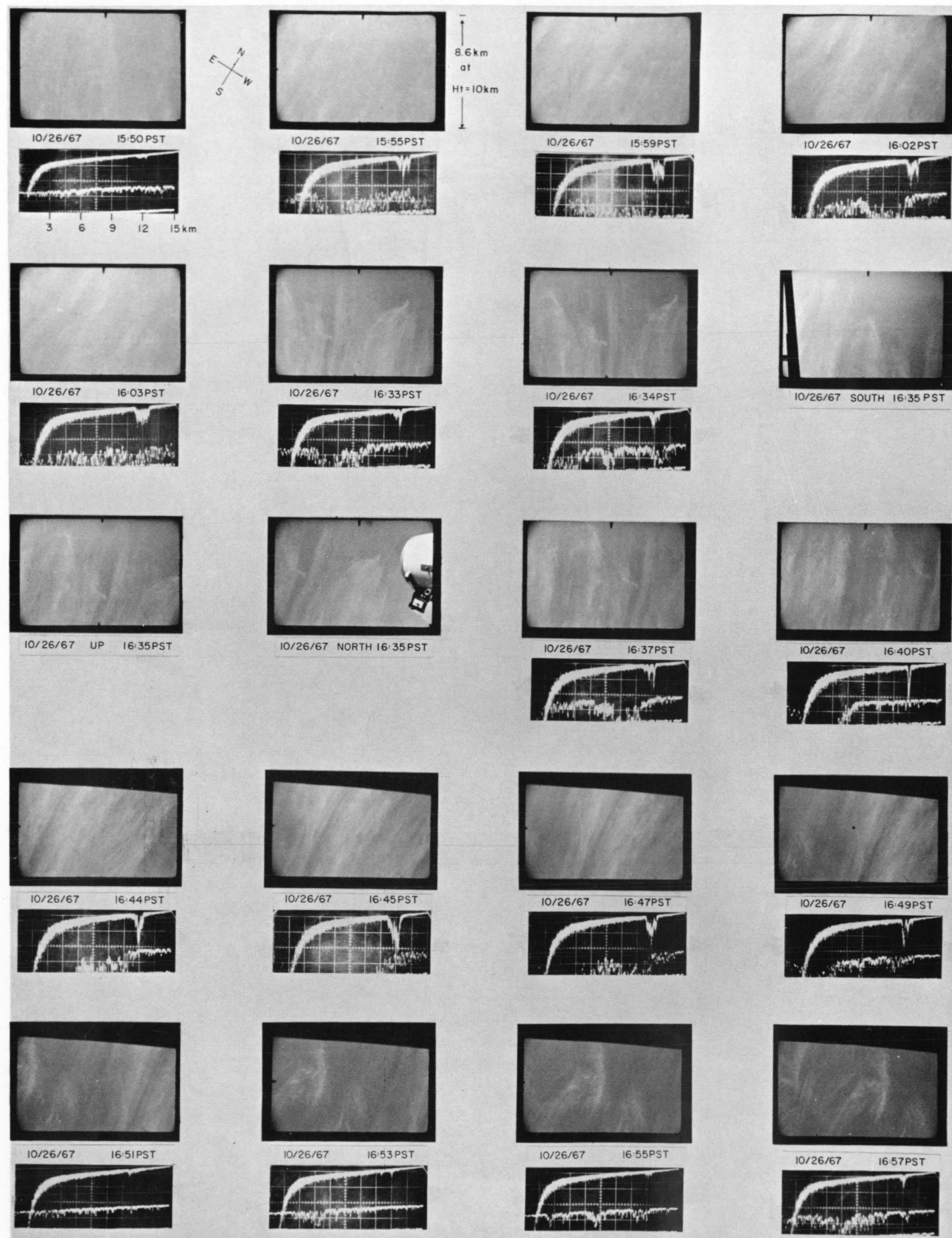
Lidar: Clouds organized into single layer, averaging about 1.5 km thick, close to the maximum wind level, with base at 11.1 km and tops just at the tropopause. Tau betas were generally in the region of .1 to .2.

Synoptic Pattern: Well-developed meridional flow present at all altitudes along the California coast. Occluded front approaching Washington-Oregon border from the Pacific.

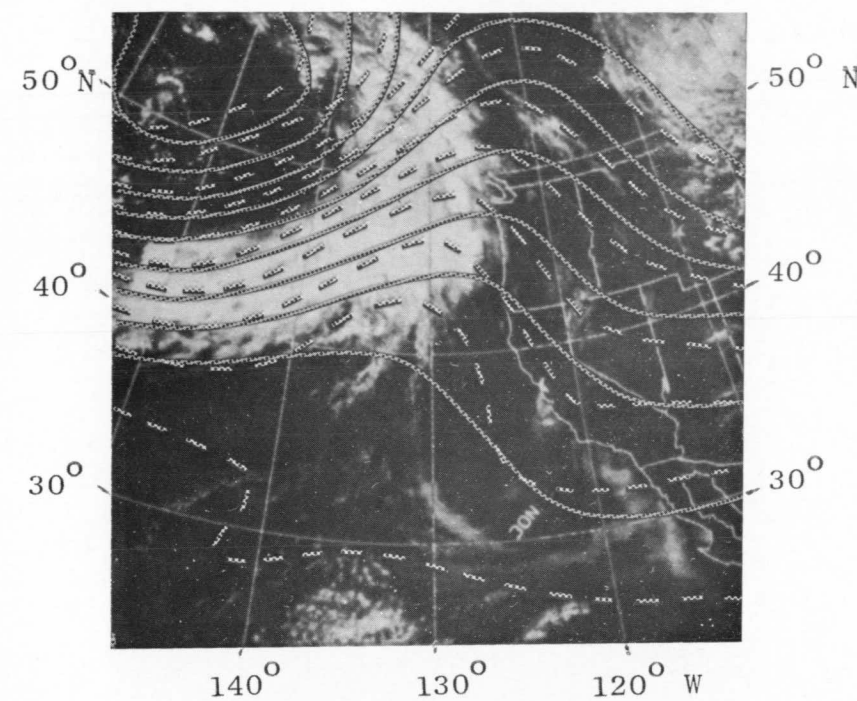
Satellite TV: No cloud visible over the station in the ESSA 3 pictures.

Comments: Considering the 80-knot upper-level northerly wind, the cirrus observed and measured over the station could have been 360 to 450 miles north of Menlo Park or over southwestern Oregon at the time the ESSA 3 satellite picture was taken. In that region, traces of north-south-oriented cirrus streaks were visible on both the digitized mosaic and the analog AVCS photograph (the latter not shown in Fig. 4 because of cropping).

FOLDOUT FRAME 1



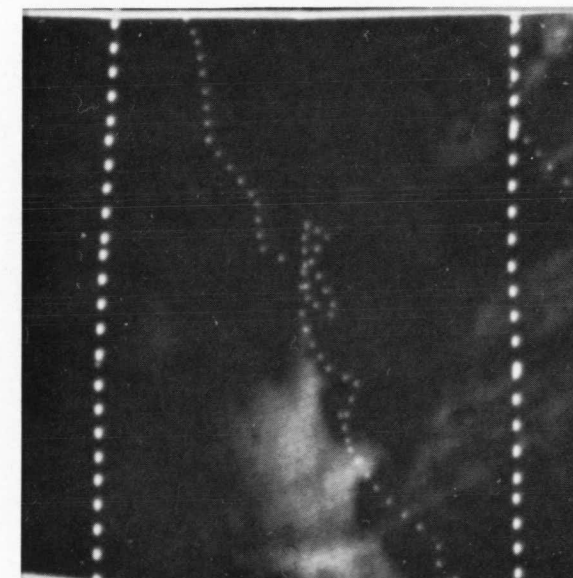
FOLDOUT FRAME 2



CLOUDS: ESSA 3 AVCS
 MOSAIC 26 OCT. 67
 ~ 2000 GMT

— 300 mb ANALYSIS
 0000 GMT 27 OCT. 67
 (Contour Interval 120 m)

- - - 200 mb ANALYSIS
 0000 GMT 27 OCT. 67
 (Contour Interval 120 m)



SAN FRANCISCO BAY
 AREA ESSA 3
 ~ 1954 GMT
 26 OCT. 67

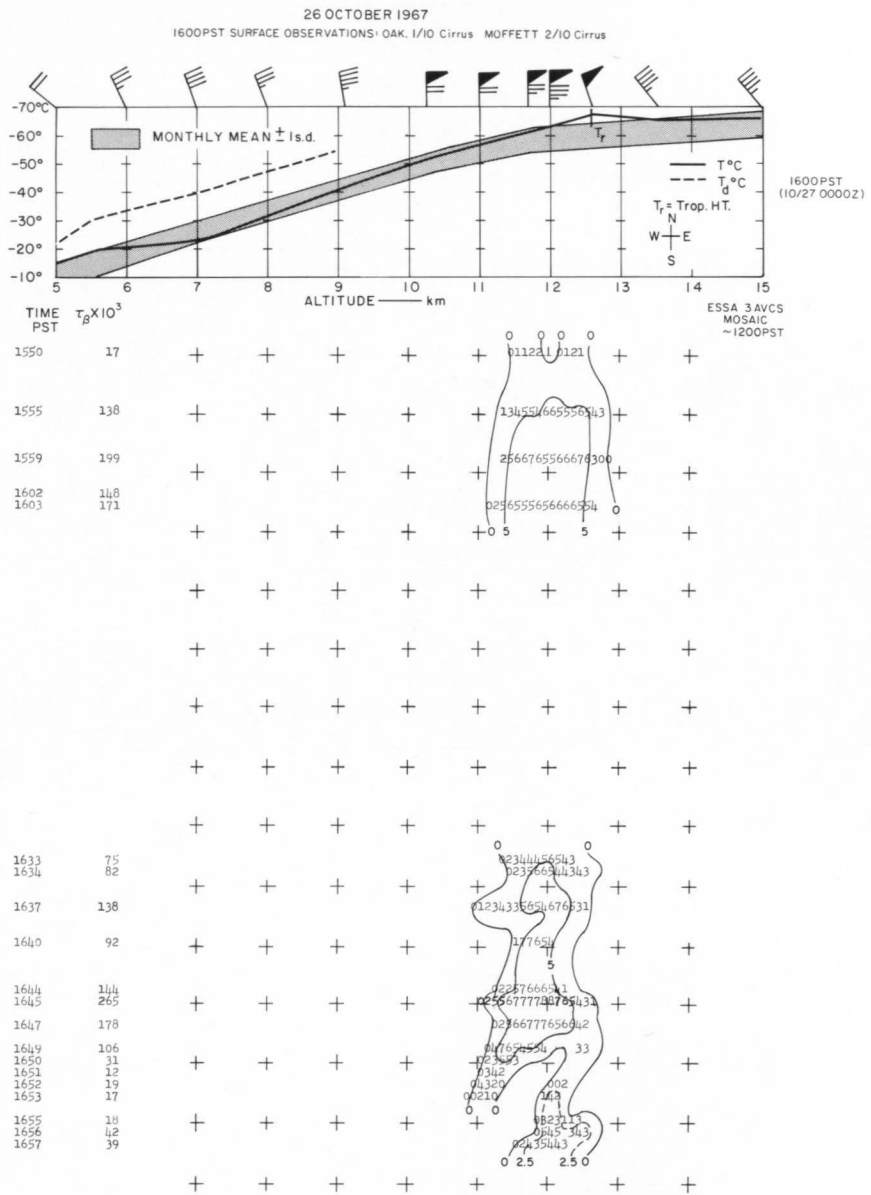


FIG. 4 LIDAR AND METEOROLOGICAL DATA FOR 26 OCTOBER 1967

5
PRECEDING PAGE BLANK NOT FILMED.

3 November 1967

Summary and Discussion

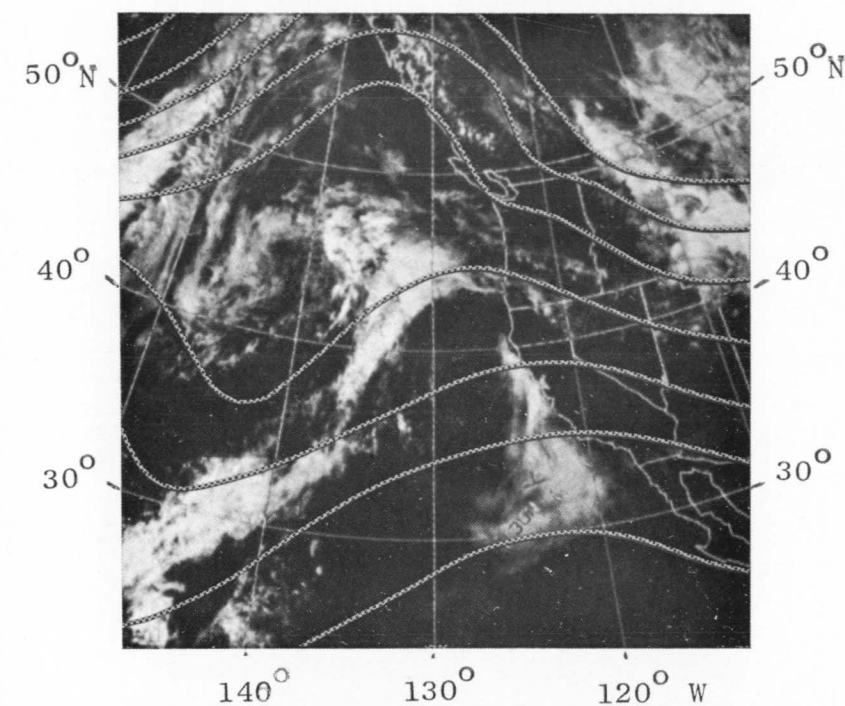
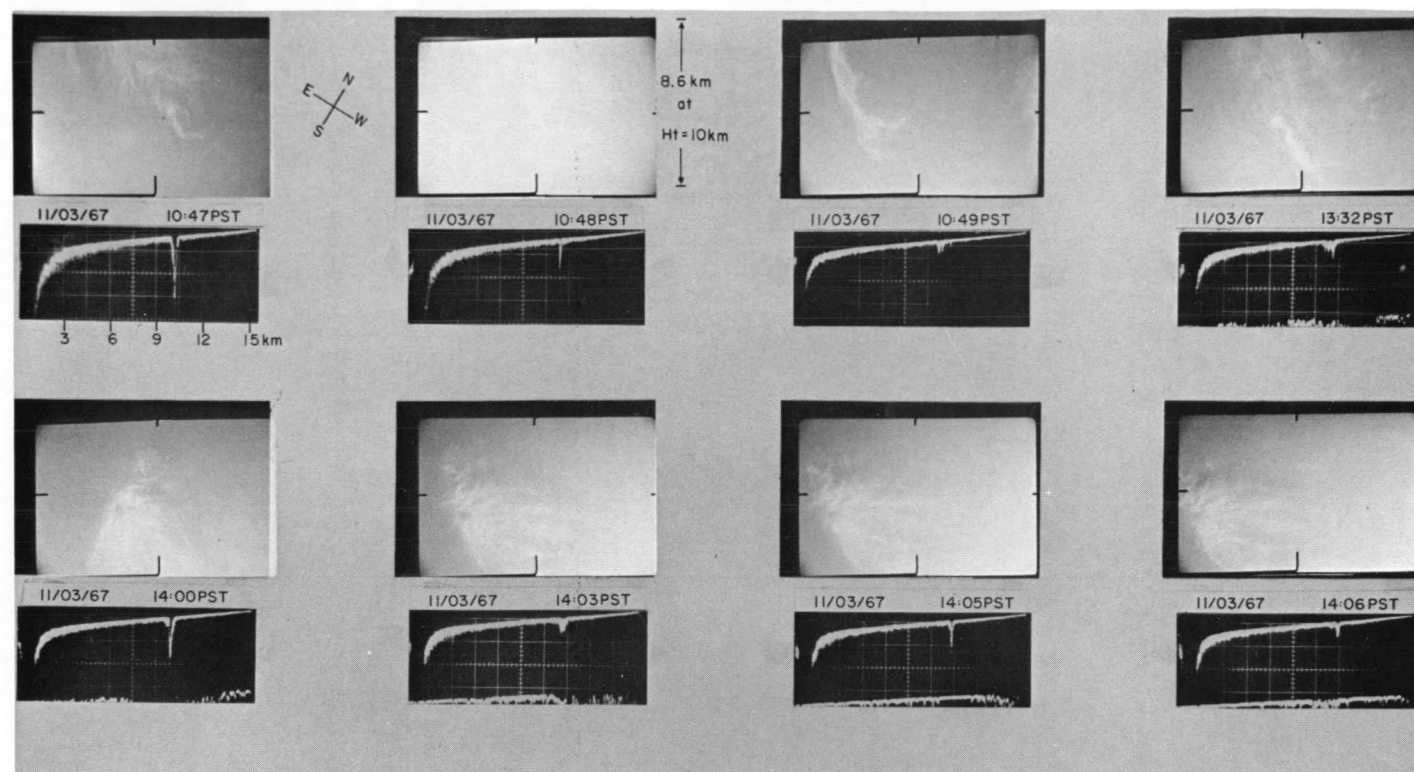
Visual: Wispy patches of cirrus clearly visible from the ground against a blue sky.

Lidar: Cloud patches were about 0.9 km thick, close to the maximum wind level, and well under the tropopause, which was unusually high (16 km). Tau betas for the most visible patches ranged from .02 to .09.

Synoptic Pattern: Moderate ridge located just off the coast. Station was located under westerly flow.

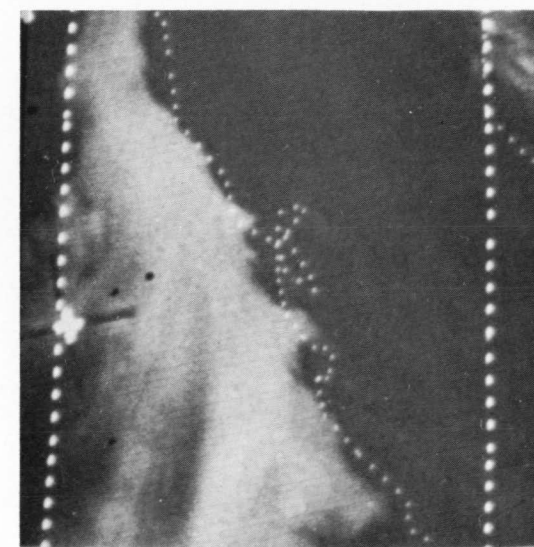
Satellite TV: ESSA 2 APT at 0938 PDT (not shown), and both the computer mosaic and the analog picture from ESSA 3 AVCS show what might be interpreted as cirrus above lower cloud and fog west of the station near the time of the lidar soundings, but show nothing overhead.

Comments: Since the Menlo Park station is only 16 miles (25 km) east of the coast, the clouds measured during the afternoon session must have been present above the low clouds and fog during the ESSA 3 AVCS pass. In interpreting the large-scale AVCS picture, note that the grid was poorly positioned (approximately 40 km too far south).



CLOUDS: ESSA 3 AVCS
MOAIC ~ 2100 GMT
3 NOV. 67

— 300 mb ANALYSIS
0000 GMT 4 NOV. 67
(Contour Interval 120 m)



SAN FRANCISCO BAY AREA
ESSA 3 AVCS
2053 GMT
3 NOV. 67

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

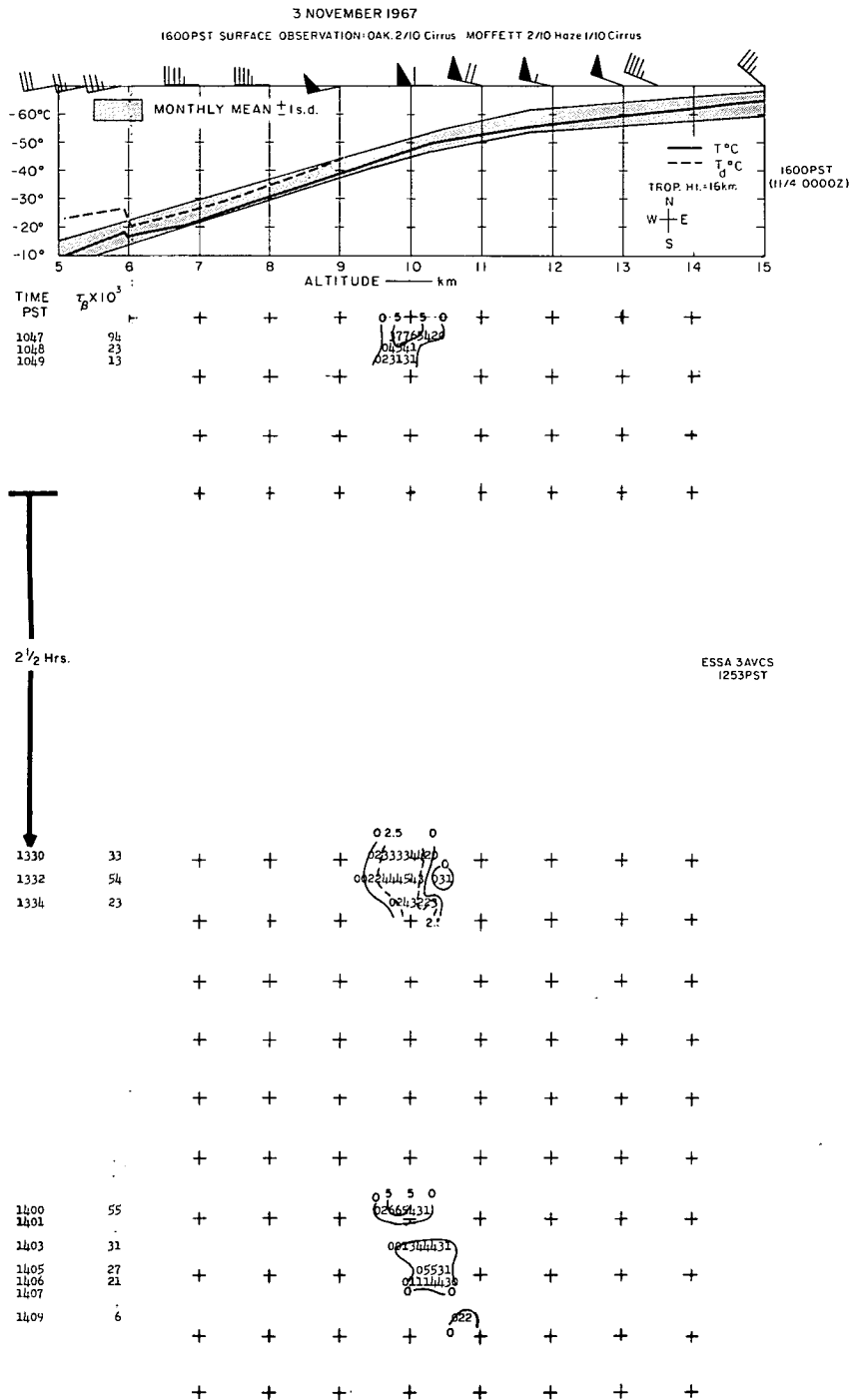


FIG. 5 LIDAR AND METEOROLOGICAL DATA FOR 3 NOVEMBER 1967

PRECEDING PAGE BLANK NOT FILMED.

15 November 1967

Summary and Discussion

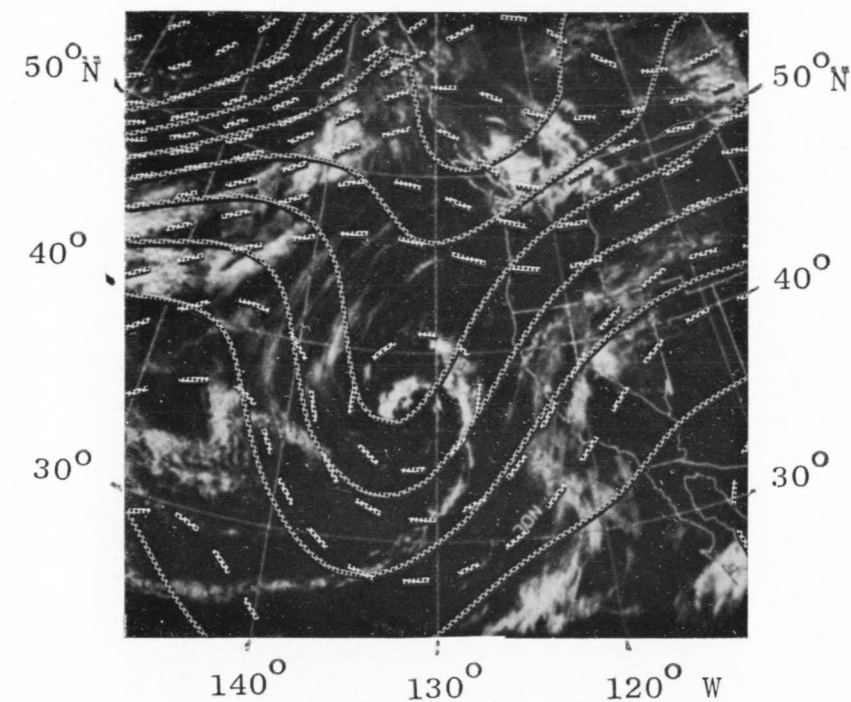
Visual: Sheets and streaks of cirrus during the morning session. Operations suspended during midday partly because of lower cloud. Late afternoon cirrus was more agglomerated and accompanied by some altocumulus.

Lidar: Morning session detected multiple layers with the upper deck, near the maximum wind level but well below the tropopause. Only a single, relatively low layer was evident in the afternoon. Tau betas ranged from .021 to .065 for the morning session but were generally lower in the afternoon.

Synoptic Pattern: A deep low existed off the coast. The lidar was under a strong southwesterly flow ahead of the trough. A well-developed cold front was approaching the coast.

Satellite TV: Both the APT and AVCS pictures (taken between the two lidar sessions) contain good evidence of prefrontal cloud cover over central California. Cirrus cannot be positively identified in the APT because of the low cloud present.

General: Cloud visible in the satellite pictures was probably the altocumulus reported by Oakland and Moffett as 2/10 and 6/10, respectively.



CLOUDS: ESSA 3 AVCS
MOAIC ~ 2100 GMT
15 NOV. 67

— 300 mb ANALYSIS 0000 G
16 NOV. 67
(Contour Interval 120 m)

- - - 500 mb ANALYSIS 0000 G
16 NOV. 67
(Contour Interval 60 m)



SAN FRANCISCO BAY AREA
ESSA 6 APT ~ 1830 GMT
15 NOV. 67

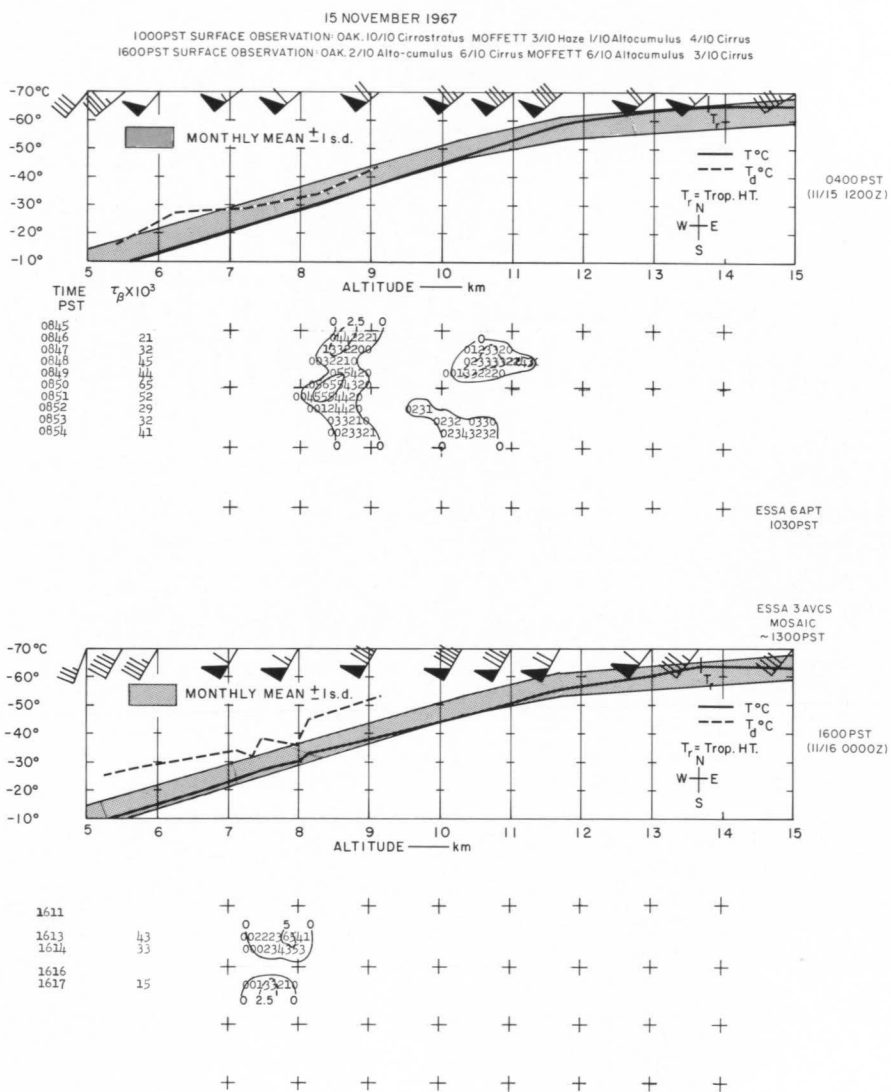


FIG. 6 LIDAR AND METEOROLOGICAL DATA FOR 15 NOVEMBER 1967

16 November 1967

Summary and Discussion

Visual: Extensive cirrus obvious under a full moon. Good 22° halo around the moon. Moon brightness averaged about 100 foot lamberts through most of the evening, occasionally dropping as low as 50 fL above patches as dense as the one probed by lidar at 2148. This compares with an average brightness of 300 fL obtained for the moon on clear nights by using the same photometer. No cloud photographs obtained because of the low light level.

Lidar: Measured clouds were 1 to 2 km thick, were located near the maximum wind level, and had a relatively smooth top surface 1.7 km below the tropopause. The tau betas of .108 to .360 were among the strongest measured all winter.

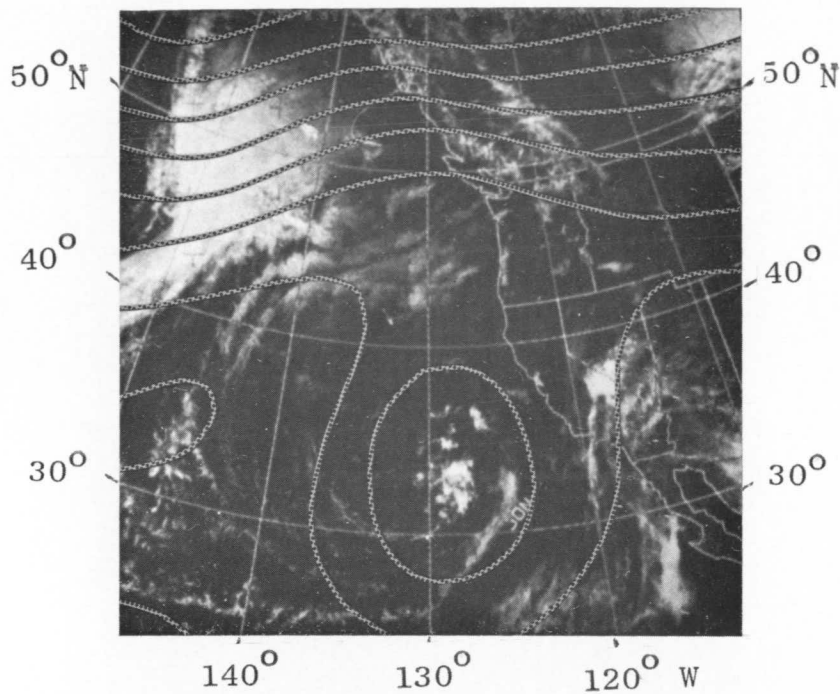
Synoptic Pattern: An intense, well-developed cold cutoff low existed off the west coast. Coastal winds were strong from the south.

Satellite TV: The most applicable satellite pictures from ESSA 3, were made 9 to 10 hours before the lidar soundings. These show the region around the station to be clear.

Comments: During the time period between the satellite passage and the lidar session, cirrus associated with the low aloft off the southern California coast could have been transported into the San Francisco Bay area.

NO SKY PICTURES MADE
(Night session)

FOLDDOUT FRAME /



CLOUDS: ESSA 3 AVCS
MOSAIC ~ 2000 GMT
16 NOV. 67

— 300 mb ANALYSIS
0000 GMT 17 NOV. 67
(Contour Interval 120 m)



SAN FRANCISCO BAY AREA
ESSA 3 AVCS ~ 2020 GMT
16 NOV. 67

FOLDOUT FRAME 2

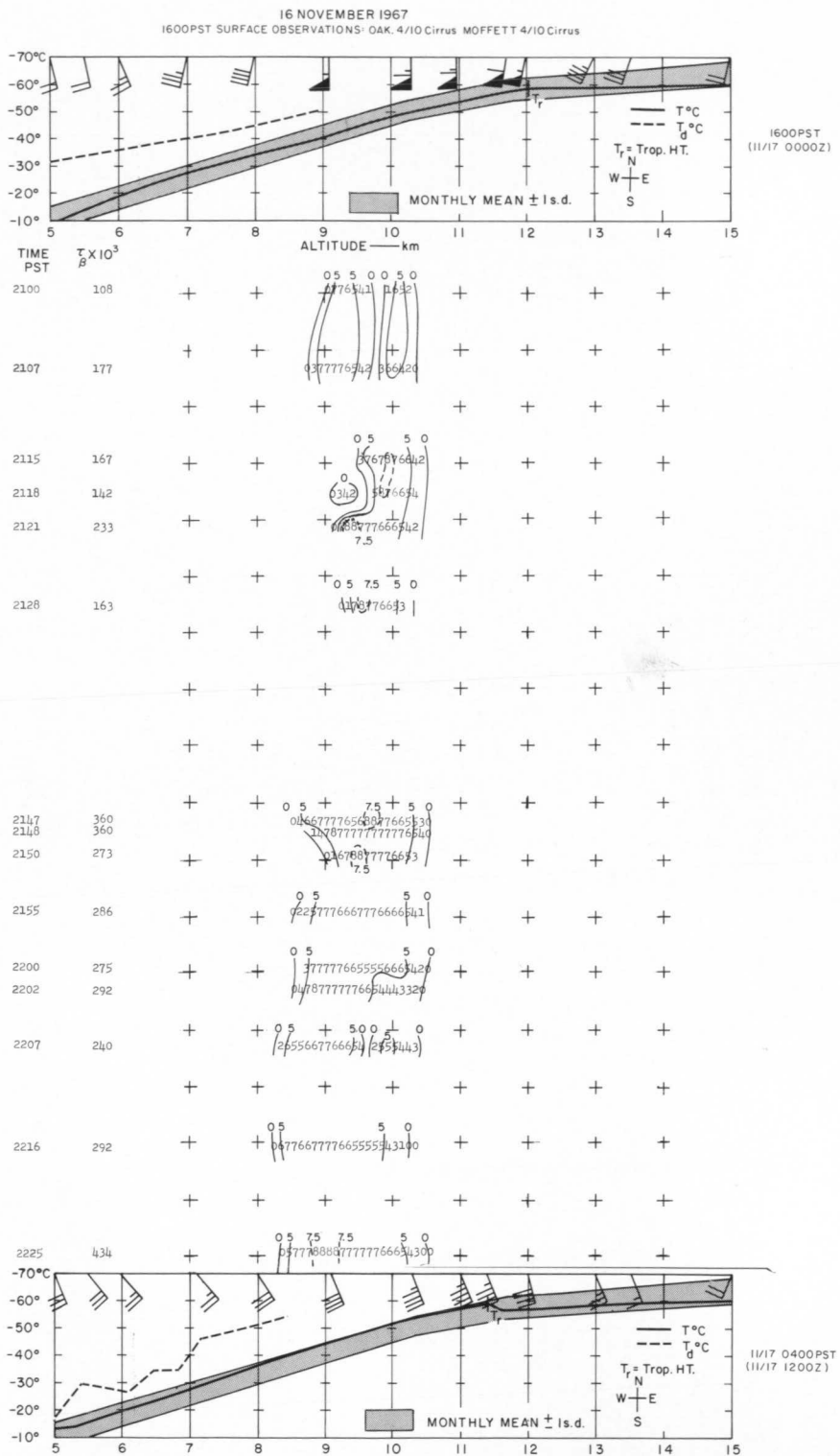


FIG. 7 LIDAR AND METEOROLOGICAL DATA FOR 16 NOVEMBER 1967

FOLDOUT FRAME 3

27 November 1967

Summary and Discussion

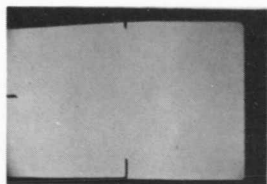
Visual: Long, dense, east-west band interpreted as jet-stream-associated cirrus observed south of the station between 0800 and 1000 (see panorama for 0933). Photographs show mixture of altocumulus and cirrus overhead.

Lidar: What appeared to be uniform cirrus overhead at 0843 measured to be much lower than anticipated (507 km) and probably was not ice cloud. Higher-level cirrus began to appear overhead at 0915. Cloud strength was moderate to strong, with tau betas averaging about .070. Measured cirrus was 2 km below the maximum wind level and nearly 3 km below the tropopause.

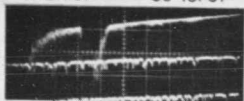
Synoptic Pattern: Deep cyclone centered over Northwest Pacific coast. Westerly flow over the station at all altitudes.

Satellite TV: Cirrus bands were clearly visible over the station area in the ESSA 7 APT made only 14 minutes after the last lidar sounding, but they were only suggested in the ESSA 3 digitized mosaic made 2 hours later.

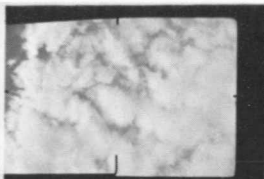
Comments: This was the first case encountered in this project where a specific cirrus cloud system was simultaneously identifiable in the satellite picture, in ground-based sky photographs, and by lidar soundings. Even so, it appears that the detectability of the system by the satellite is heavily dependent on the presence of an appreciable amount of altocumulus. Approximately 3/10 coverage of cirrus having an average tau beta of .70 apparently is not sufficient to ensure unambiguous detection by satellite TV.



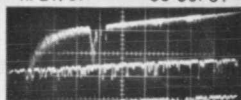
11/27/67 08:43PST



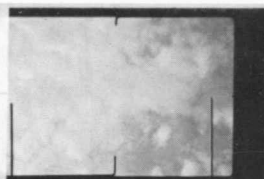
3 6 9 12 15km



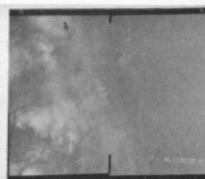
11/27/67 09:03PST



8.6 km
at
Ht = 10 km



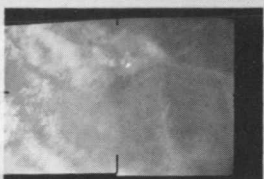
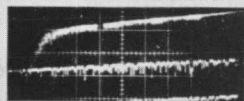
11/27/67 UP 09:10PST



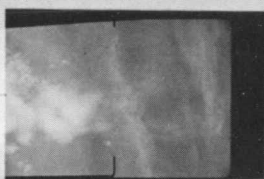
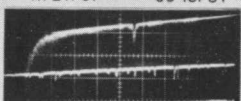
11/27/67 NORTH 09:10PST



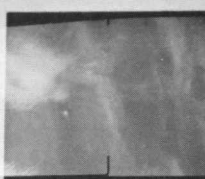
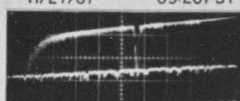
11/27/67 09:16PST



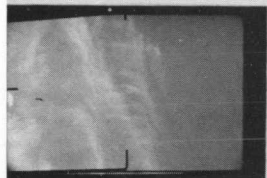
11/27/67 09:18PST



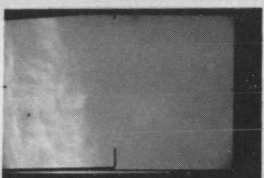
11/27/67 09:20PST



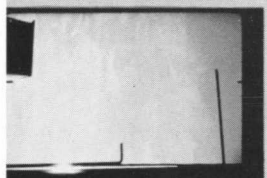
11/27/67 09:21PST



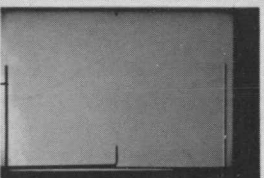
11/27/67 09:26PST



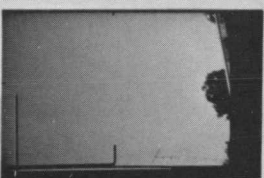
11/27/67 09:29PST



11/27/67 SOUTH 09:33PST

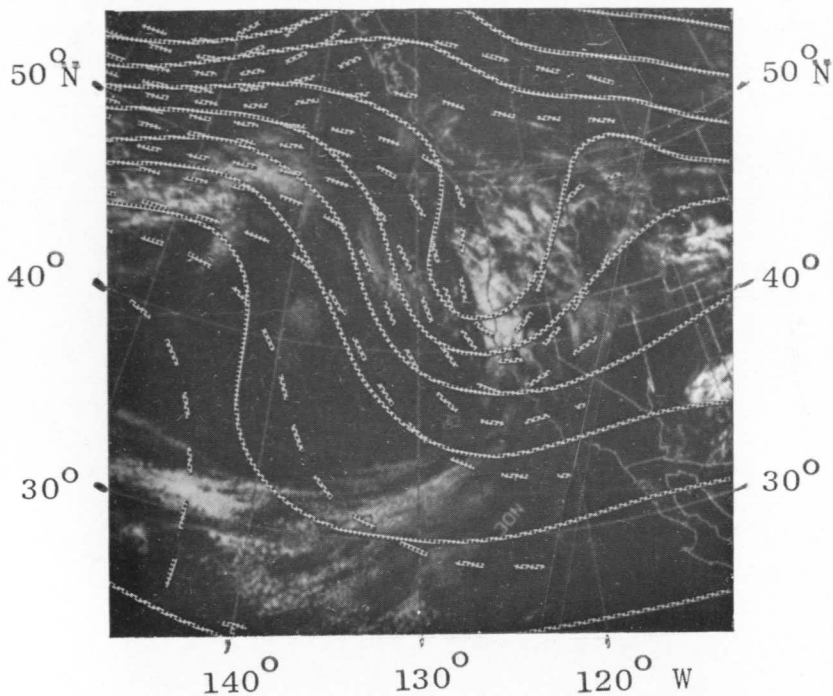


11/27/67 UP 09:33PST



11/27/67 NORTH 09:33PST

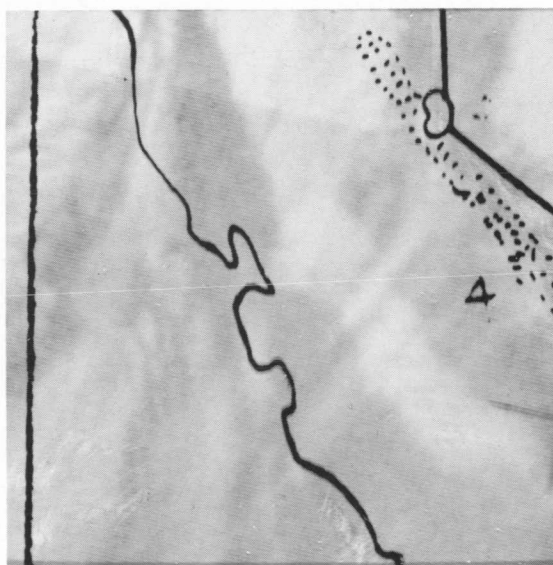
FOLDOUT FRAME /



CLOUDS: ESSA 3 AVCS
MOSAIC ~ 2000 GMT
27 NOV. 67

— 300 mb ANALYSIS 0000
28 NOV. 67
(Contour Interval) 120 m)

- - - 500 mb ANALYSIS 0000
28 NOV. 67
(Contour Interval 60 m)



SAN FRANCISCO BAY AREA
ESSA 6 APT 0740 GMT
27 NOV. 67

FOLDOUT FRAME 2

42

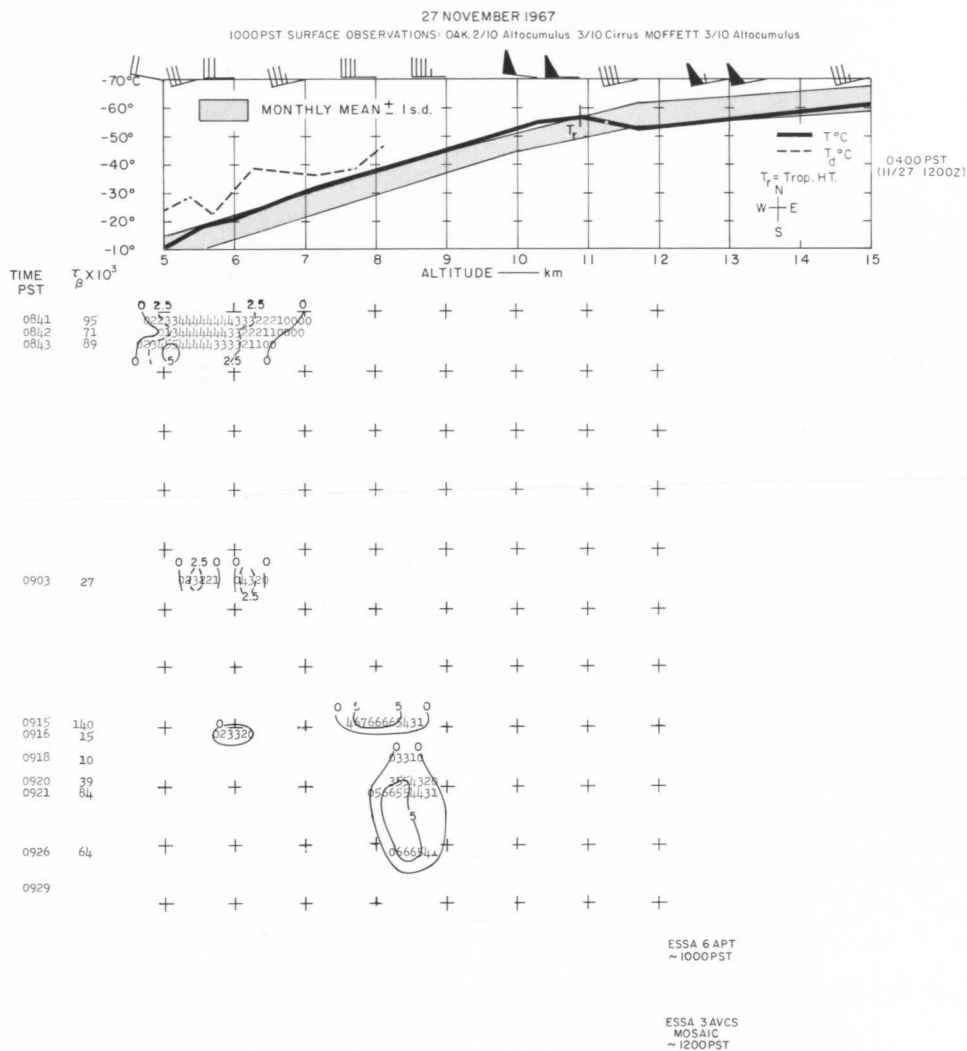


FIG. 8 LIDAR AND METEOROLOGICAL DATA FOR 27 NOVEMBER 1967

1 December 1967

Summary and Discussion

Visual: Early morning sky was clear and uniformly blue, except for slight aureole toward the sun, distant contrails, and occasional light blue streaks, indicating the possibility of cirrus. Light blue and white streaks gradually increased in contrast throughout the day.

Lidar: Morning soundings disclosed a thin (300-meter) layer with top at 12.5 km, coincident with the tropopause. From regions of visually uniform clear blue (see, for example, the shot for 1030), the maximum volume backscattering coefficient measured $30 \times 10^{-3} \text{ (km}^{-1}\text{)}$, and typical tau betas ranged from .007 to less than .001. By afternoon, the cirrus had increased appreciably in volume, while maintaining about the same volume backscattering coefficient. The increase in vertical dimension resulted in correspondingly larger tau betas. The return at 1351 PST with $\tau_{\beta} = .014$ was judged to be of marginal visibility from the ground under these relatively good lighting conditions.

Synoptic Pattern: Deep low in Gulf of Alaska with a broad and extensive cloud shield along the entire northern portion of the west coast. The station was under a westerly flow beneath the extreme south side of the jet stream axis.

Satellite TV: Cirrus not actually visible over the station in either satellite photograph, but clouds 150 to 200 miles west of the station and visible in the APT photograph could have arrived by the time of the lidar soundings. The digitized AVCS mosaic, however, shows the entire area to be very clear.

Comments: This day provided good test cases for measurement of cirrus both weaker and stronger than "marginally visible."



12/01/67 SOUTH 09:45PST



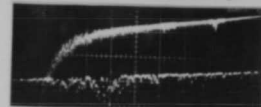
12/01/67 UP 09:45PST



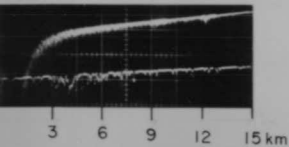
12/01/67 NORTH 09:45PST



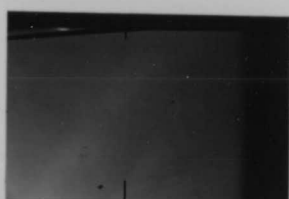
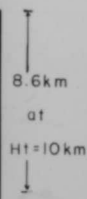
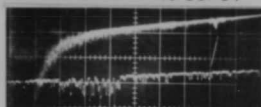
12/01/67 10:06PST



12/01/67 10:20PST



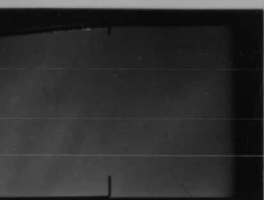
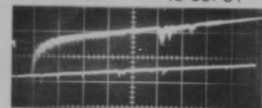
12/01/67 10:30PST



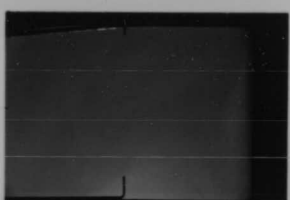
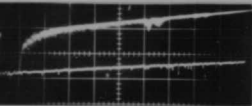
12/01/67 10:55PST



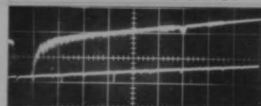
12/01/67 13:33PST



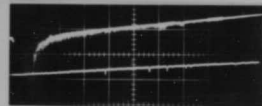
12/01/67 13:51PST



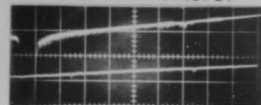
12/01/67 13:54PST



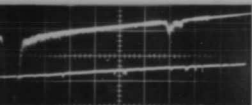
12/01/67 13:56PST



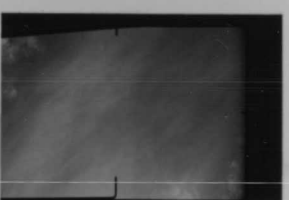
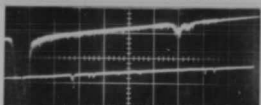
12/01/67 14:10PST



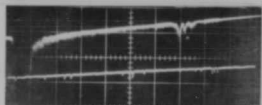
12/01/67 14:13PST



12/01/67 14:14PST



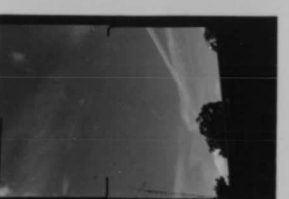
12/01/67 14:15PST



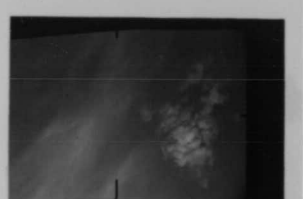
12/01/67 SOUTH 14:19PST



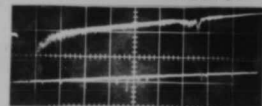
12/01/67 UP 14:19PST

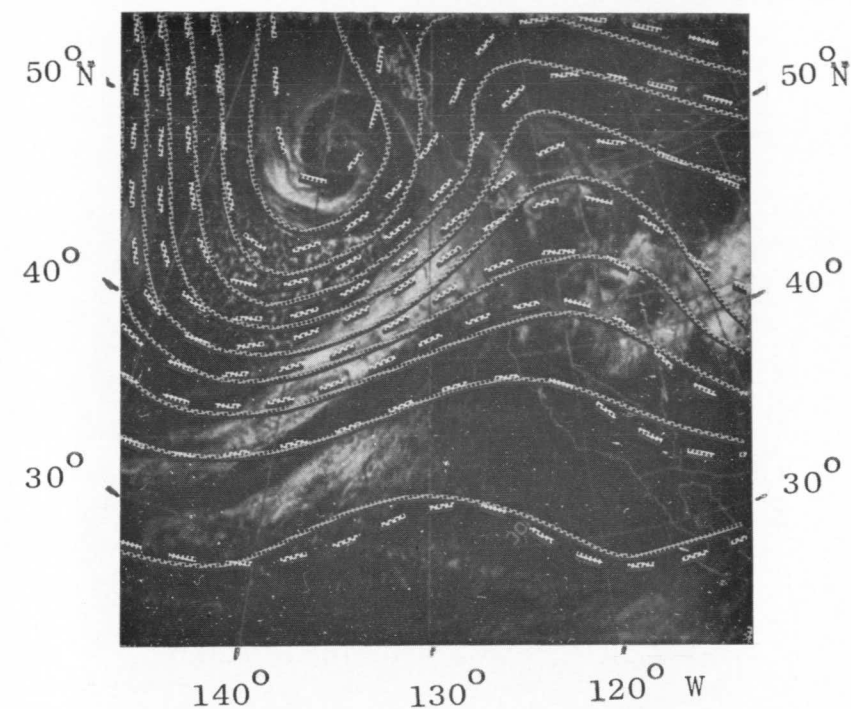
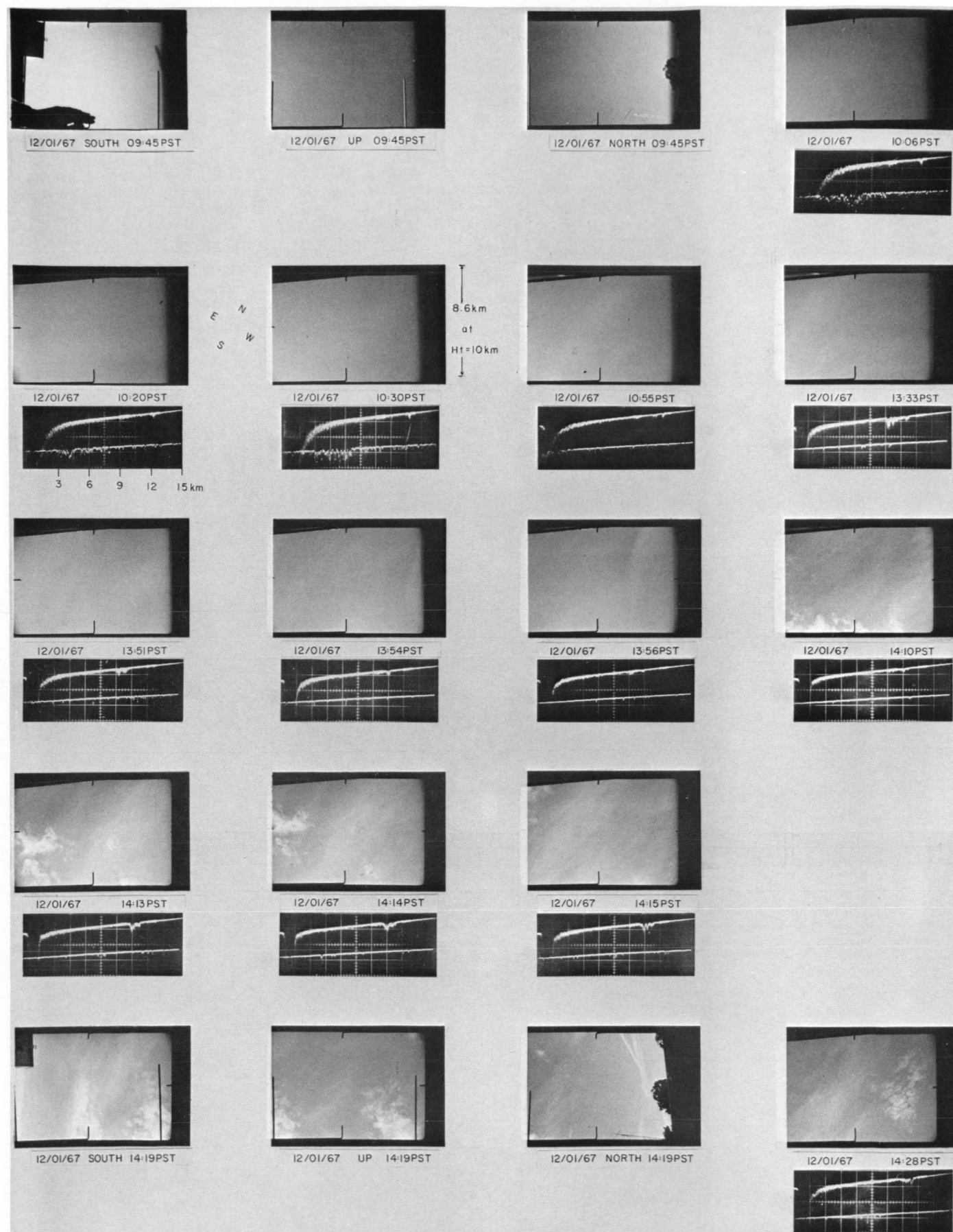


12/01/67 NORTH 14:19PST



12/01/67 14:28PST

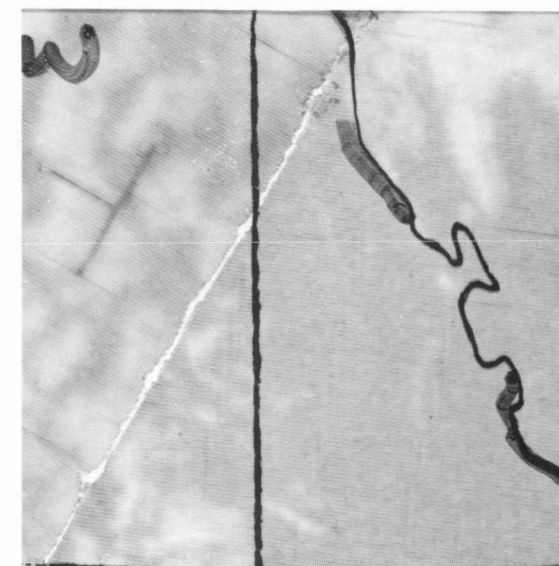




CLOUDS: ESSA 3 AVCS
MOSAIC ~ 2000 GMT
1 DEC. 67

— 300 mb ANALYSIS
0000 GMT 2 DEC. 67
(Contour Interval 120 m)

- - - 200 mb ANALYSIS
0000 GMT 2 DEC. 67
(Contour Interval 120 m)



SAN FRANCISCO BAY AREA
ESSA 6 APT ~ 1730 GMT
1 DEC. 67

FOLDOUT FRAME 2

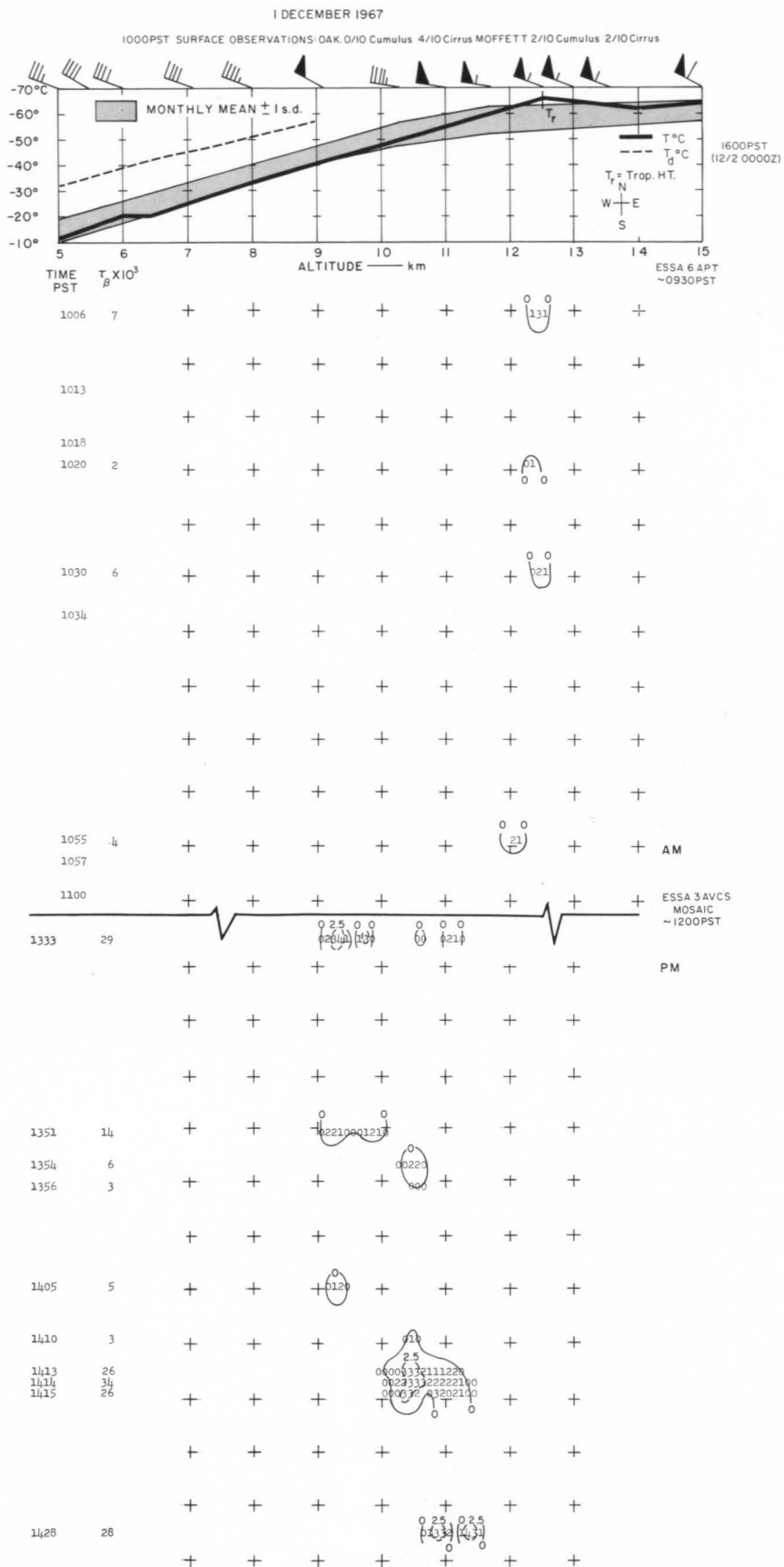


FIG. 9 LIDAR AND METEOROLOGICAL DATA FOR 1 DECEMBER 1967

PRECEDING PAGE BLANK NOT FILMED.

4 December 1967

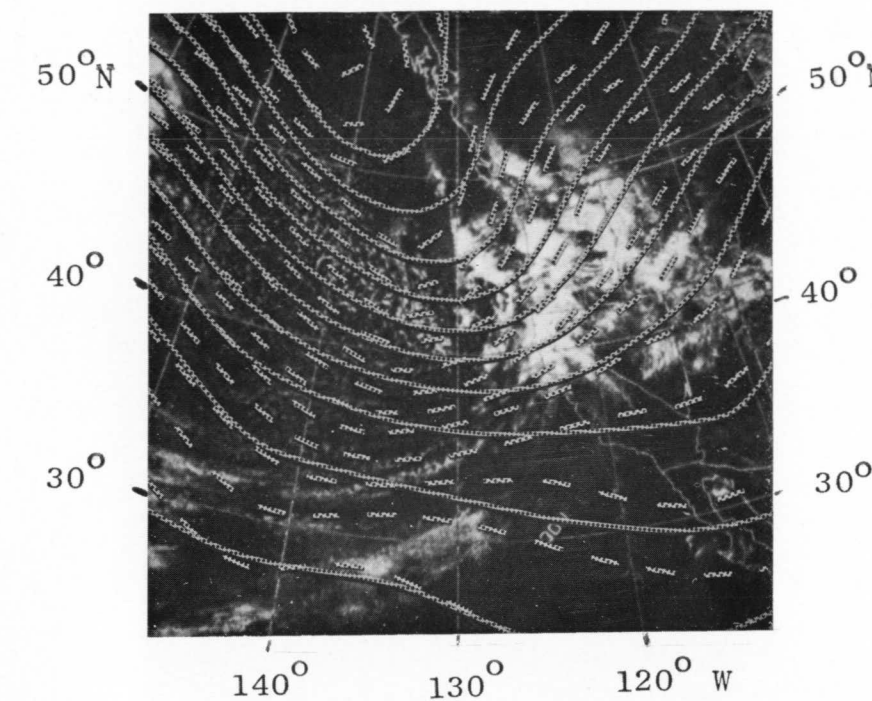
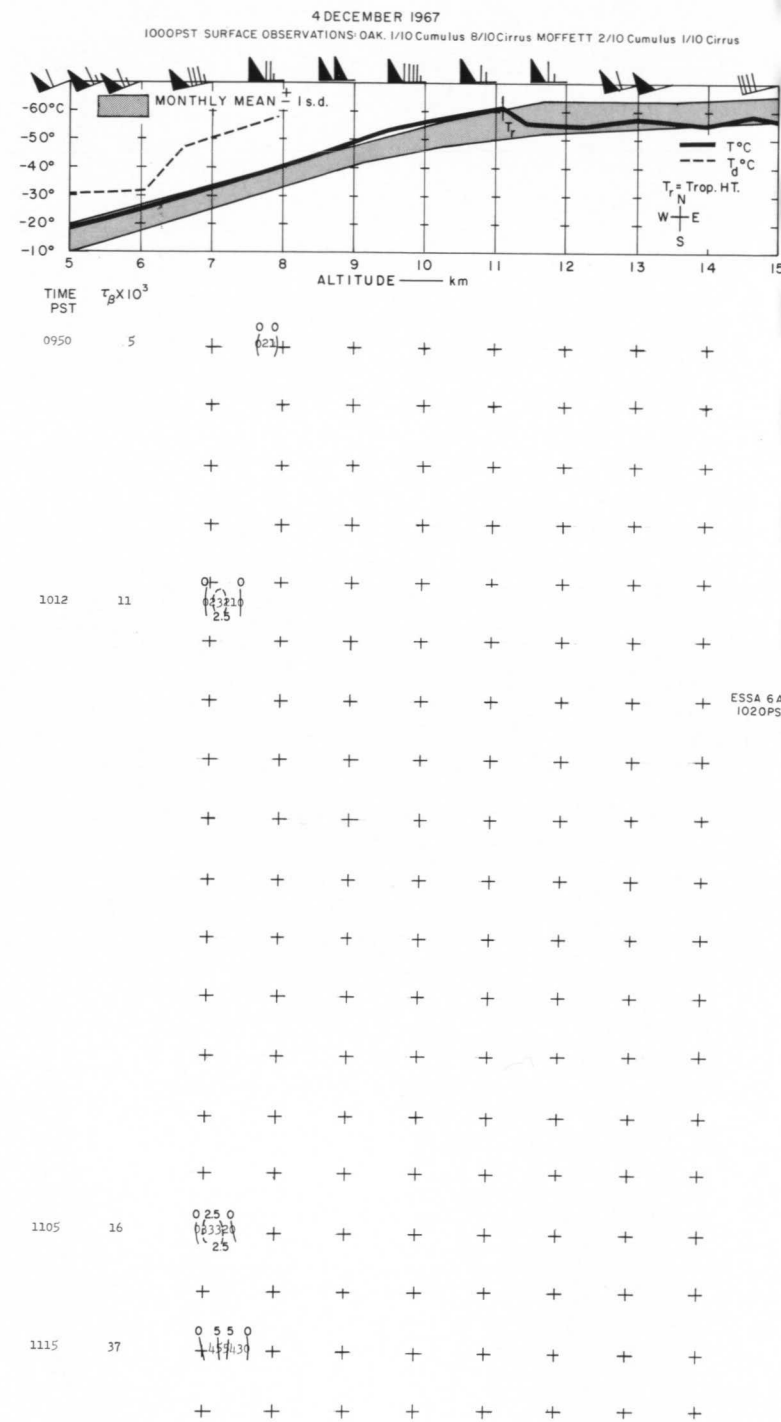
Summary and Discussion

Visual: Patches of light blue sky visible through holes in low cloud.

Lidar: Thin, relatively weak layer at 7-km elevation detectable through holes in lower cloud.

Synoptic Pattern: Deep low in Gulf of Alaska with well-developed trough extending along the west coast (more pronounced in the surface analysis).

Satellite TV: Both satellite passes occurred during the period of lidar observation. Cloud cover was visible over the station in the ESSA 6 APT picture but not in the ESSA 3 AVCS mosaic.



CLOUDS: ESSA 3 AVCS
MOAIC ~ 2000 GMT
4 DEC. 67

— 300 mb ANALYSIS
0000 GMT 5 DEC. 67
(Contour Interval 120 m)

--- 500 mb ANALYSIS
0000 GMT 5 DEC. 67
(Contour Interval 60 m)



FIG. 10 LIDAR AND METEOROLOGICAL DATA FOR 4 DECEMBER

FOLDOUT FRAME 3

53

51

FOLDOUT FRAME 1

FOLDOUT FRAME 2

52

5 December 1967

Summary and Discussion

Visual: Fibrous cirrus and persistent contrails (some with transverse bands) generally prevalent above patches of cumulus.

Lidar: Patchy, multilayered returns from 8-to-10-km elevation. Tops near maximum wind level but 1.5 km below the tropopause. Tau bestas ranged from .1009 to .067.

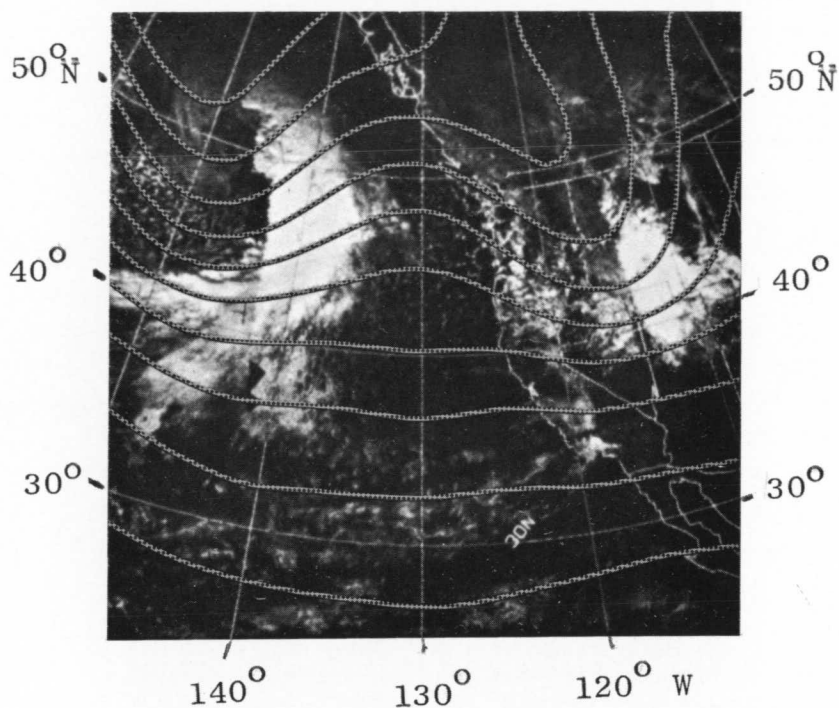
Synoptic Pattern: Extremely deep low in the Gulf of Alaska and strong zonal flow over most of the west coast.

Satellite TV: Satellite passes were 0.5 hour before and 2 hours after the principal lidar observations. Cloud visible in the region of the station in the ESSA 6 APT picture undoubtedly was the scattered cumulus, also reported from the ground. Cloud images near the station in the ESSA 3 AVCS mosaic, if present at all, are extremely weak and obscured by the gridding.

CLOUD PICTURES
ARE ON BOTTOM HALF
OF PAGE FOR
4 DECEMBER 68

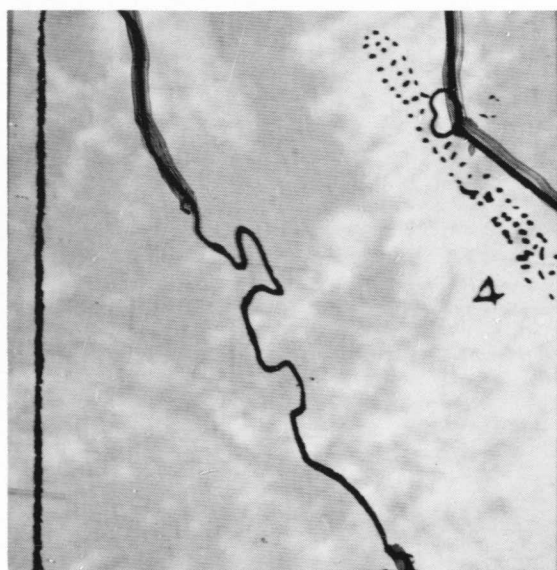
FOLDOUT FRAME /

55



CLOUDS: ESSA 3 AVCS
 MOSAIC ~ 2100 GMT
 5 DEC. 67

— 300 mb ANALYSIS
 0000 GMT 6 DEC. 67
 (Contour Interval 120 m)



SAN FRANCISCO BAY AREA
 ESSA 6 ~ 1730 GMT
 5 DEC. 67

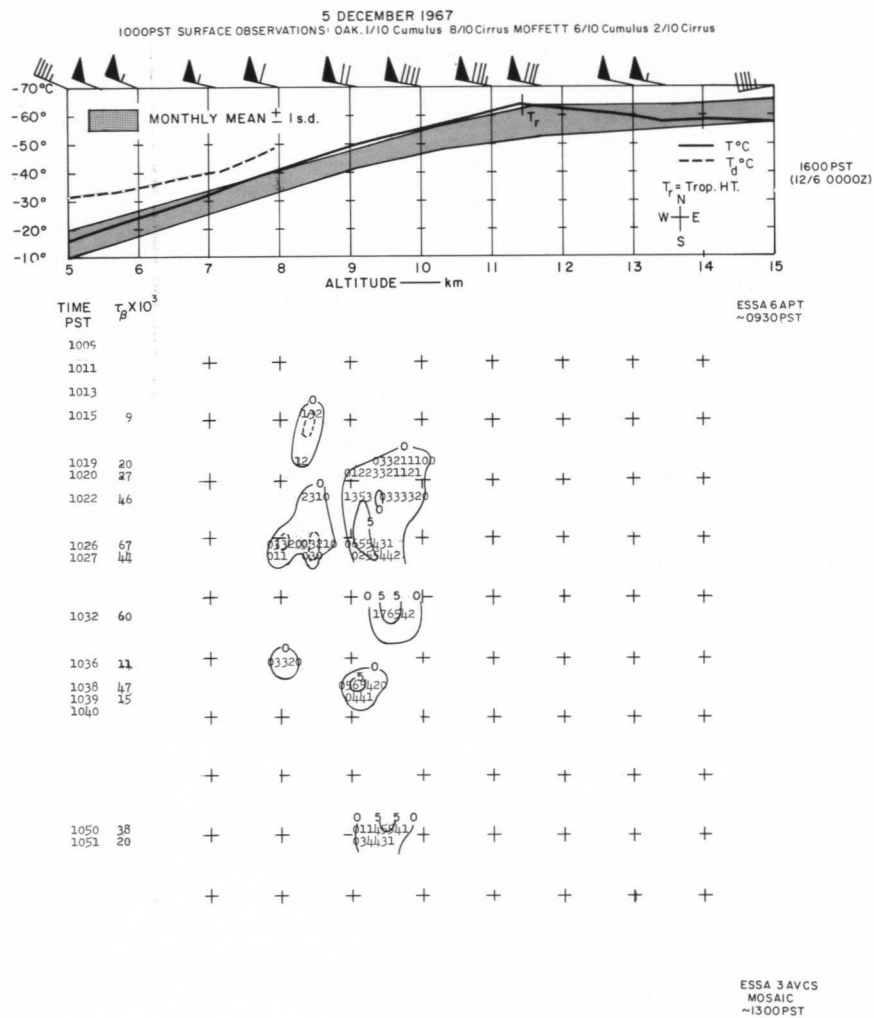


FIG. 11 LIDAR AND METEOROLOGICAL DATA FOR 5 DECEMBER 1967

8 December 1967

Summary and Discussion

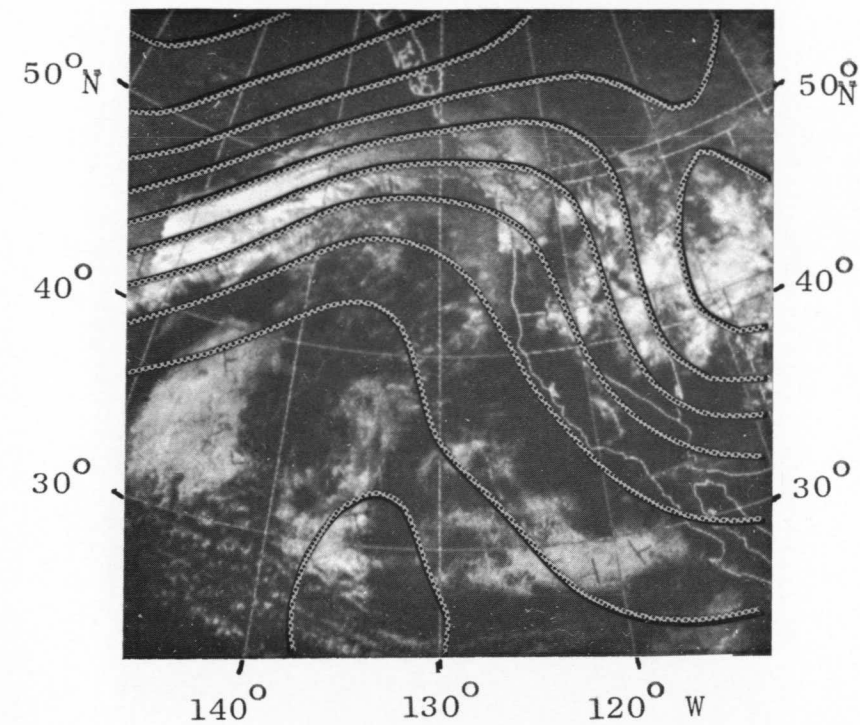
Visual: The low overcast in the morning gradually cleared, leaving deep blue sky with scattered mare's tail cirrus. The cirrus thickened into a fairly uniform mottled sheet by midafternoon, then changed into a banded structure.

Lidar: Consistently strong returns from 9-to-10-km elevation represented volume backscattering coefficients up to $300 \times 10^{-3} \text{ (km}^{-1}\text{)}$ and tau betas up to .212 (at 1452 PST). In midafternoon, a thinner upper layer had its top at the tropopause at 11 km.

Synoptic Pattern: A filling low covered the western states. The low aloft was centered over Montana-Wyoming. A ridge in the Pacific was intensifying. The cirrus observed from the ground was in the north-westerly flow behind the trough.

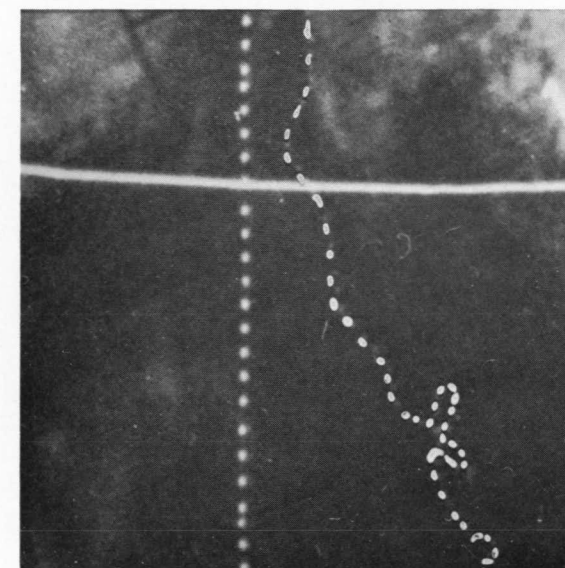
Satellite TV: The ESSA 3 pass occurred 2 to 3 hours prior to recording of the strongest cirrus by the lidar. The digitized mosaic shows the entire coastal region to be clear, but the enlarged analog photograph shows an extensive thin cloud system 200 miles upstream of the station, which may have contributed to the observed cirrus.

Comments: These returns were among the strongest measured in the daytime all winter. They are similar to those of 26 October 1967 but are weaker than those measured during times of solid cirrus cover, for example on 21 February 1968.



CLOUDS: ESSA 3 AVCS
MOSAIC ~ 2000 GMT
8 DEC. 67

— 300 mb ANALYSIS
0000 GMT 9 DEC. 67
(Contour Interval 120 m)



SAN FRANCISCO BAY AREA
ESSA 3 ~ 2000 GMT
8 DEC. 67

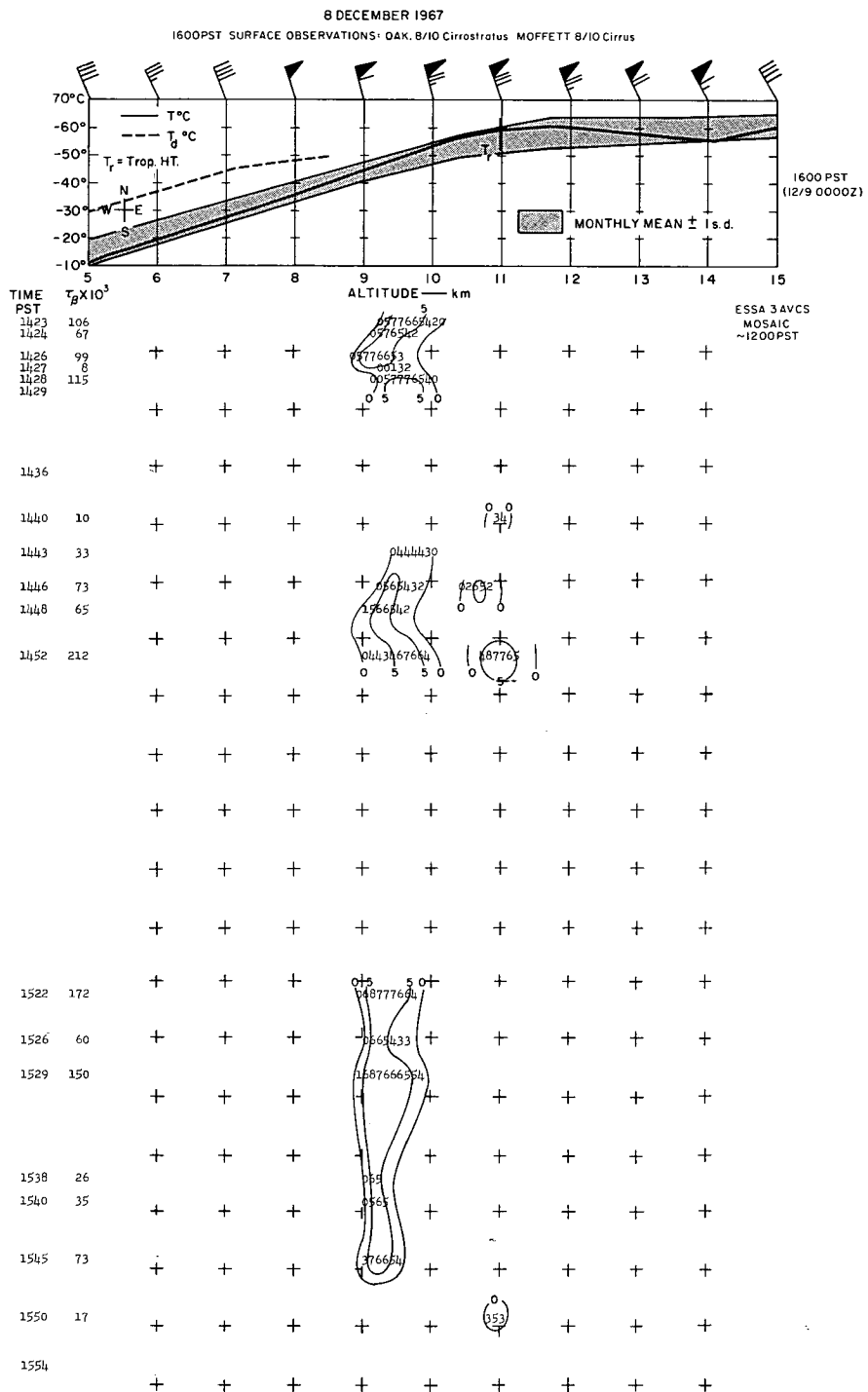


FIG. 12 LIDAR AND METEOROLOGICAL DATA FOR 8 DECEMBER 1967

22 December 1967

Summary and Discussion

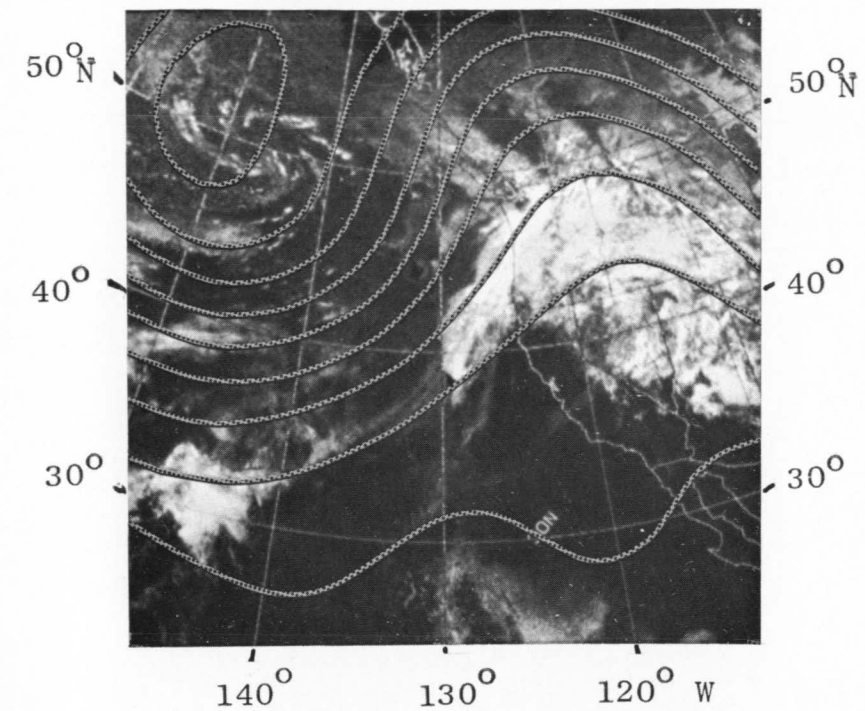
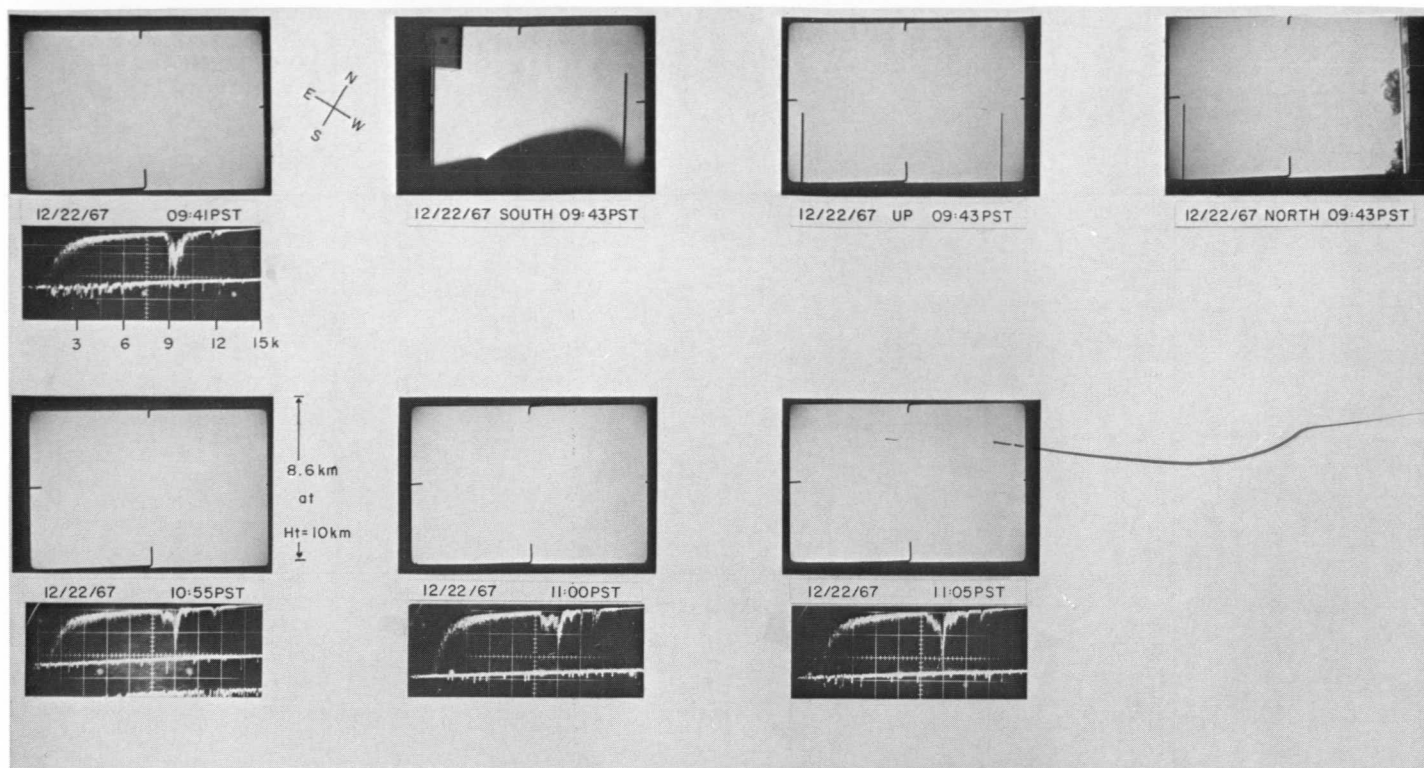
Visual: Uniform overcast. Very little blue sky visible.

Lidar: Multiple layers measured in region of 8-to-12-km. Tau betas averaged about .100 but reached .224 (at 0914 PST). Tops were near the tropopause but well below the maximum wind level.

Synoptic Pattern: Weakening anticyclone was along west coast, with the ridge line east of the coast line. Observed cirrus was imbedded in southwesterlies of very moderate speed.

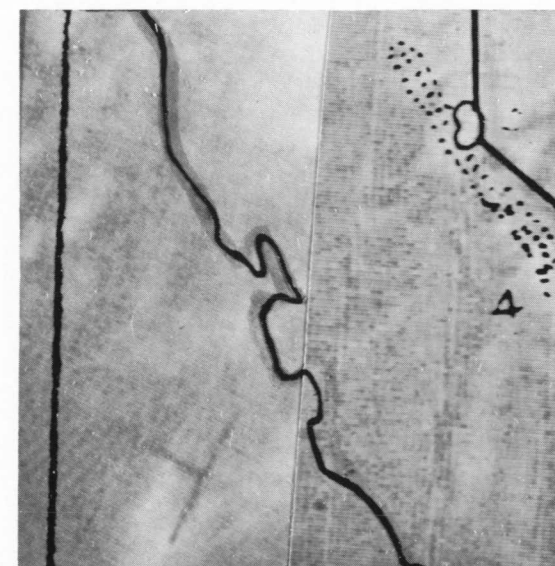
Satellite TV: Thin cirrus over station was barely evident in ESSA 6 APT picture taken only 4 minutes before the maximum lidar return and was not discernible in the ESSA 3 digitized mosaic taken less than 1 hour after the end of the lidar session.

Comments: This exhibit documents the difficulty of direct detection by satellite TV of even relatively extensive sheets of cirrus 1 to 2 km thick.



CLOUDS: ESSA 3 AVCS
MOAIC ~ 2000 GMT
22 DEC. 67

— 300 mb ANALYSIS
1200 GMT 22 DEC. 67
(Contour Interval 120 m)



SAN FRANCISCO BAY AREA
ESSA 6 APT ~ 1710 TO 1900 GMT
22 DEC. 67

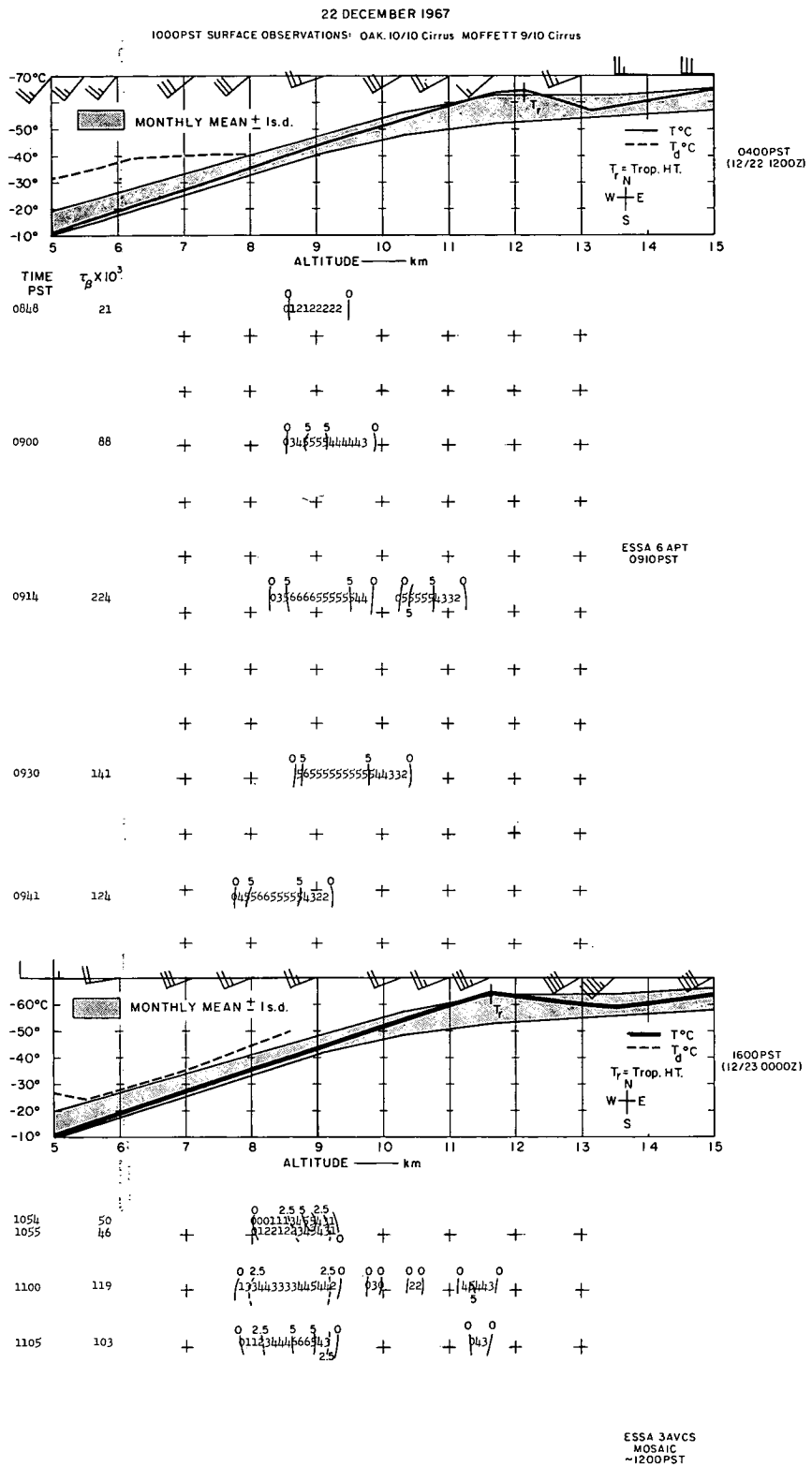


FIG. 13 LIDAR AND METEOROLOGICAL DATA FOR 22 DECEMBER 1967

21 February 1968

(Morning, afternoon, and evening)

Summary and Discussion

Visual: Day--Extensive (approximately 8/10) cirrus coverage plus small patches of lower cloud. A 22° halo was visible around the sun.

Evening--Fairly clear during first hour of session, starting at 2035. Stars were visible, but slight coronae were noted around the brighter ones. Stars were obscured, and low cloud was visible during the period 2150-2236.

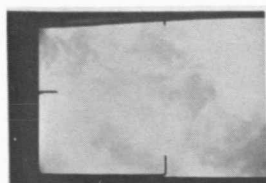
Lidar: Continuous sheet of cirrus overhead in the afternoon with thickness up to 3 km. Average height of tops was 1.5 km below the tropopause, but occasional patches were detected just at the tropopause. Tau betas measured up to .553 and averaged around .300. The few morning shots taken just prior to the satellite pass show returns from 9-km elevation, but severe attenuation by low cloud (offscale in the traces shown) prevented reliable measurement of cirrus strength in the morning. Morning session terminated at 1020 because of low cloud interference.

Synoptic Pattern: Developing ridge along coast. Very strong winds aloft.

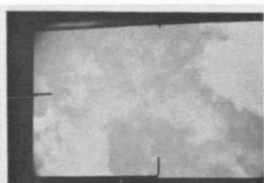
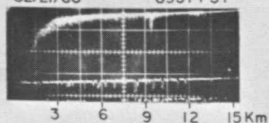
Satellite TV: Transverse waves over Nevada and northern California indicate presence of strong westerly and northwesterly winds. ESSA 3 analog AVCS (outside of region reproduced here) shows jetstream cirrus over the Pacific along the 40th parallel and brightest between 130° and 150° W. Some cloud is visible over the station, but there is no unmistakable indication of cirrus cover at the time of the morning satellite pass.

Comments: This situation represents the greatest volume of cirrus sampled during the entire program. The return at 1535, with a tau beta of .553 was the strongest integrated value encountered in the program, and for several returns in the afternoon the volume backscattering coefficient exceeded 0.5 km^{-1} (9 on the chart code), an unusually high value.

With the winds aloft in excess of 100 knots, some of the definitely identifiable cirrus visible along the jet stream in the satellite picture 500 or more miles out to sea might have been carried over the station by the time of the lidar sessions.



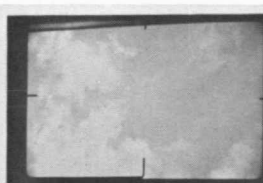
02/21/68 0957 PST



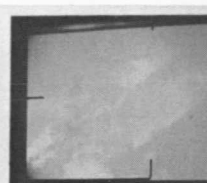
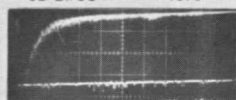
02/21/68 1001



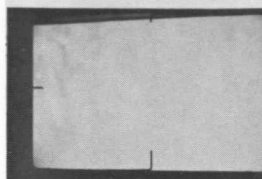
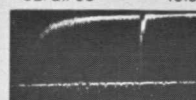
8.6 Km
at
Ht = 10 Km



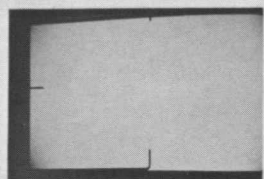
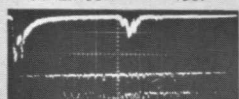
02/21/68 1010



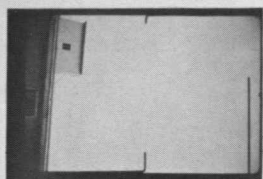
02/21/68 1015



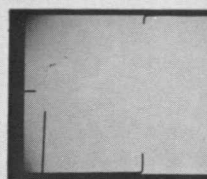
02/21/68 1531



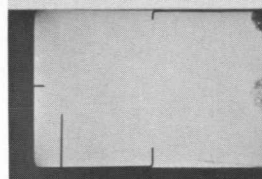
02/21/68 1559



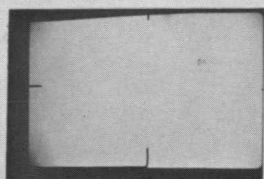
02/21/68 SOUTH 1605



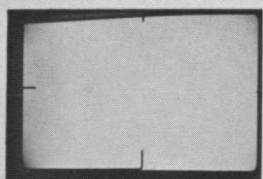
02/21/68 UP 1605



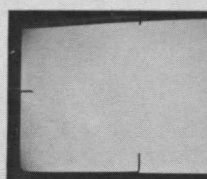
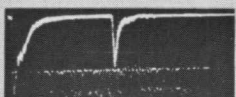
02/21/68 NORTH 1605



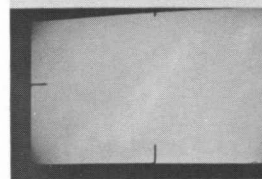
02/21/68 1606



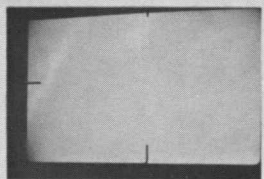
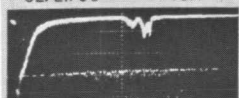
02/21/68 1608



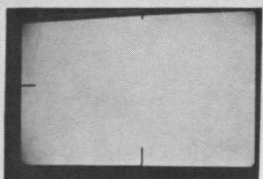
02/21/68 1613



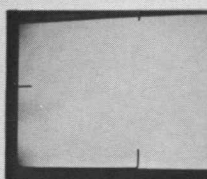
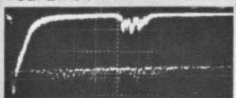
02/21/68 1617



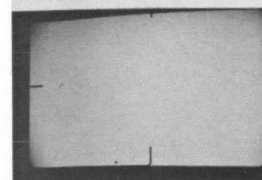
02/21/68 1620



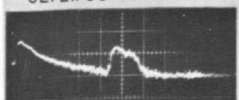
02/21/68 1622

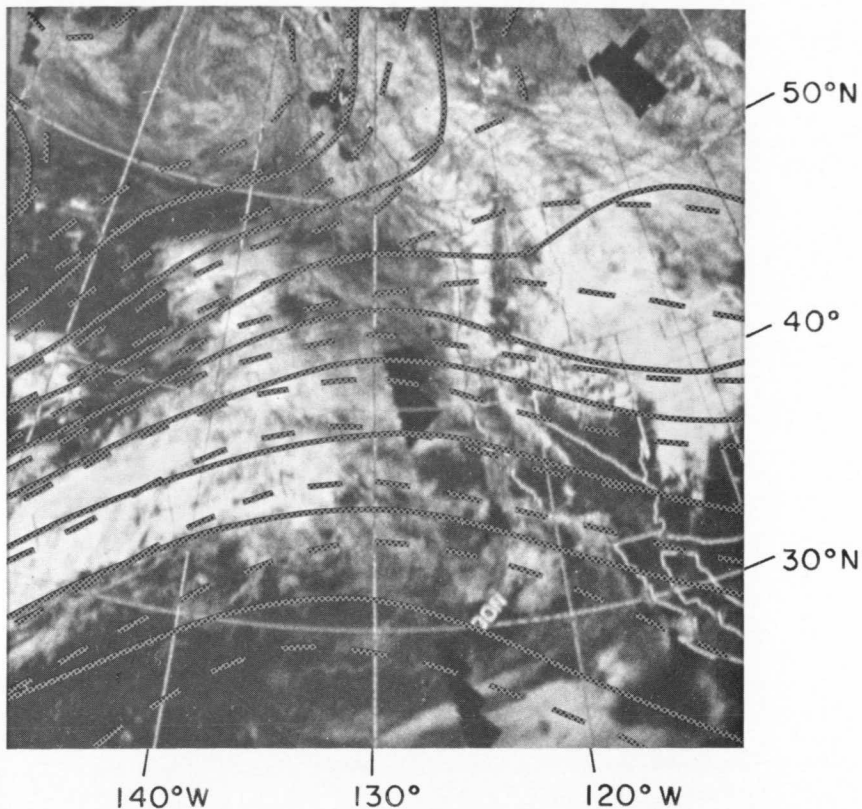


02/21/68 1627



02/21/68 1636

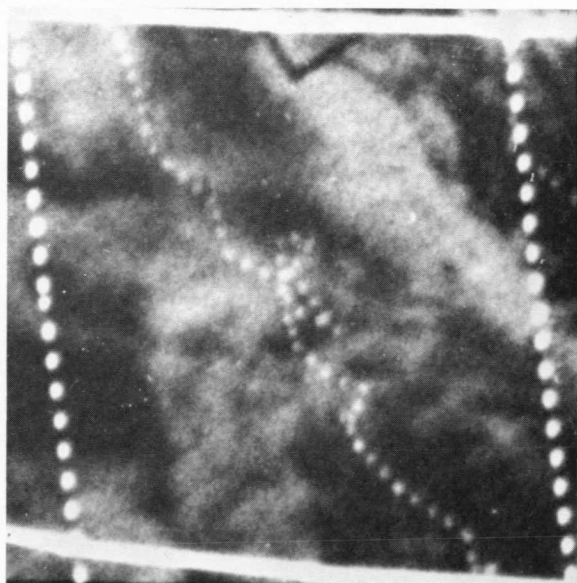




CLOUDS: ESSA 3 AVCS
 MOSAIC ~ 2000 GMT
 21 FEB. 1968

———— 300 mb ANALYSIS
 0000 GMT 22 FEB 1968
 (Contour Interval 120 m)

----- 500 mb ANALYSIS
 0000 GMT 22 FEB. 1968
 (Contour Interval 60 m)



SAN FRANCISCO BAY AREA
 ESSA 3 AVCS 1945 GMT
 21 FEB. 1968

FOLDOUT FRAME 2

68

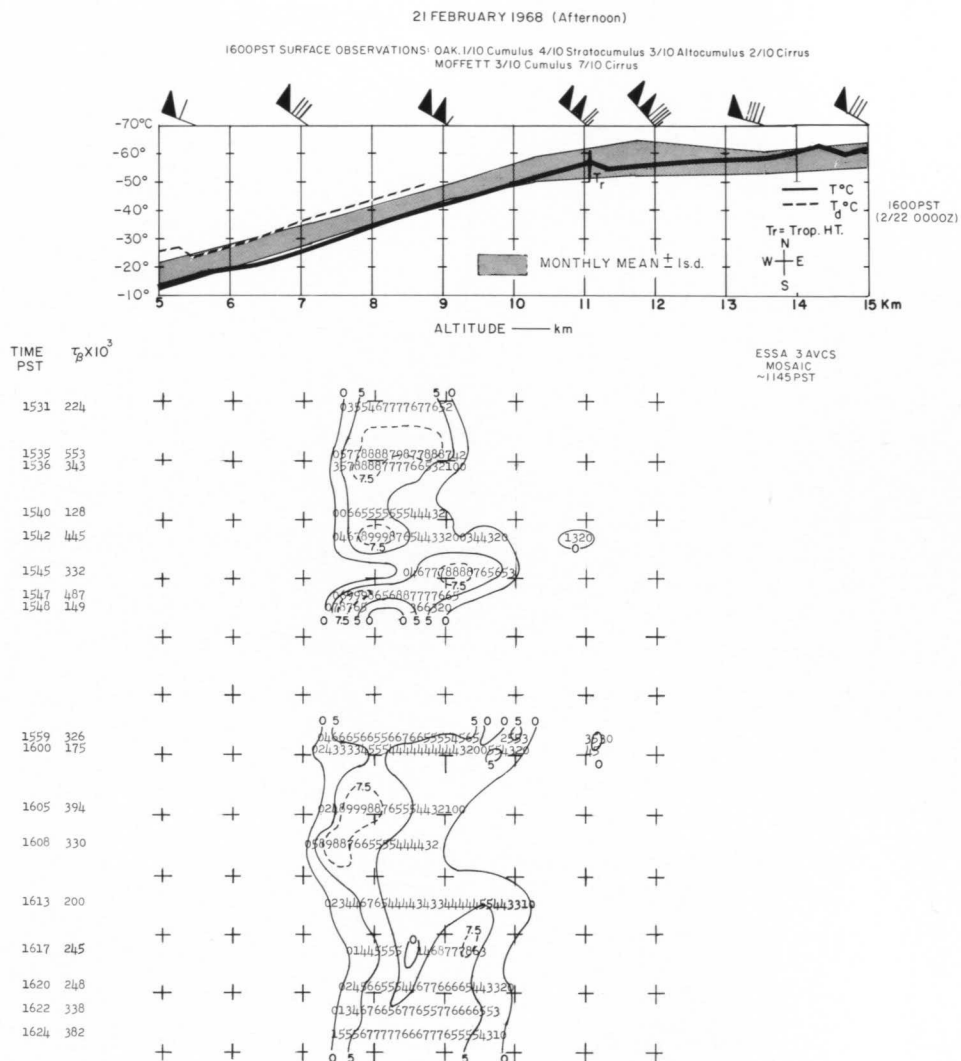


FIG. 14 LIDAR AND METEOROLOGICAL DATA FOR 21 FEBRUARY 1968 (Afternoon)

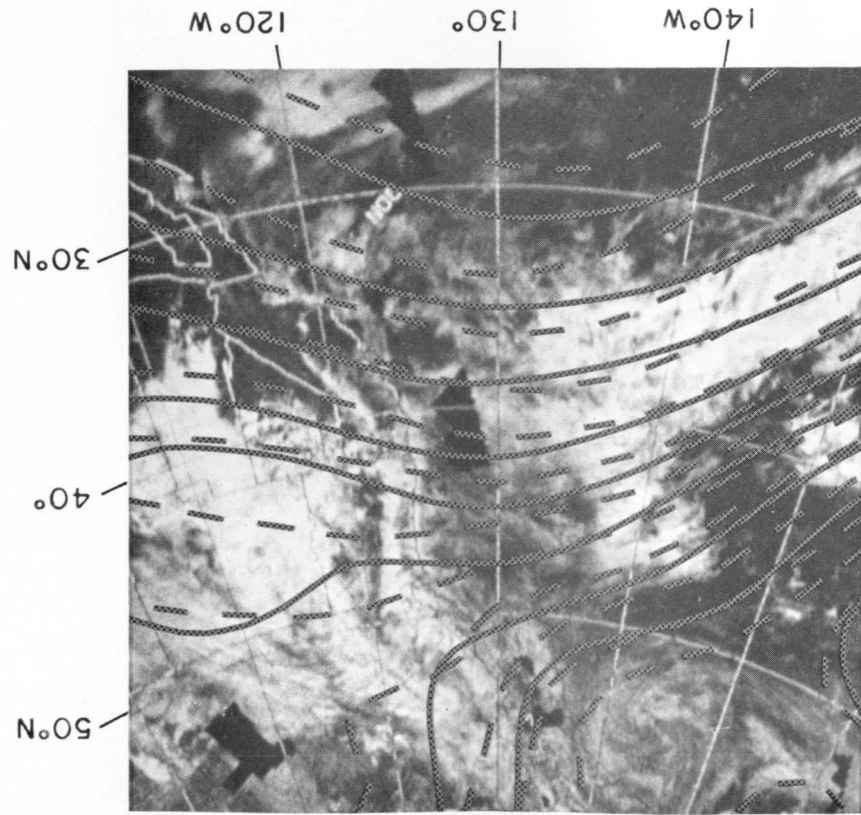
NO SKY PICTURES MADE
(Night session)

FOLIOUT FRAME 1

FOLIOUT FRAME 2



SAN FRANCISCO BAY AREA
ESSA 3 AVCS 1945 GMT
21 FEB. 1968



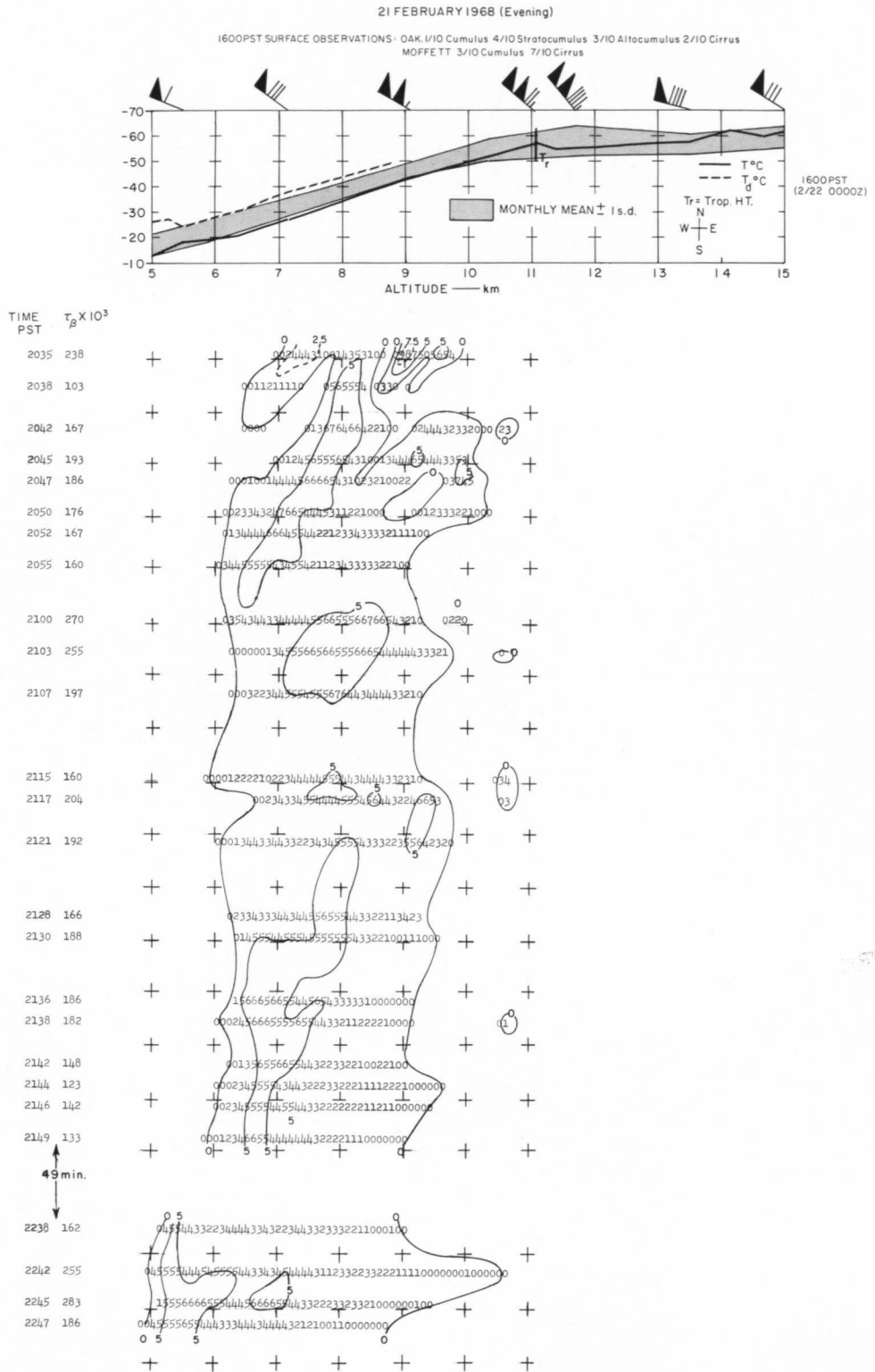


FIG. 15 LIDAR AND METEOROLOGICAL DATA FOR 21 FEBRUARY 1968 (Evening)

D. Analysis of the Results

1. Summary of Cirrus Visibility* versus τ_β and β'_{180}

Only the strongest[†] and most widespread cirrus situations measured by lidar during this program were identifiable as cirrus on the satellite photographs, in spite of considerable effort to work with high-quality APT and AVCS photographs. It is our tentative conclusion that cirrus clouds must have $\tau_\beta \geq 0.2$ over many tens of square kilometers of horizontal area to be identifiable in a satellite photograph even under good conditions. See the data of 27 November and 21 February.

For visual detection from the ground under good daylight conditions, $\tau_\beta \geq 0.01$ appears to be adequate, particularly if the patches are relatively small, so that the brightness and color contrast with the otherwise uniform blue sky is emphasized. See data of 1 December for examples of marginally visible cirrus.

At night, cirrus with $\tau_\beta \approx 0.1$ can be visually detected under a full moon (for example, see the data of 16 November), but clouds of $\tau_\beta = 0.2$ probably would not be detected on moonless nights, unless by very well-trained observers working in the absence of low-level haze (see the data of 21 February).

2. Correlation Among Observed Parameters

What are believed to be the most important results of this work are the correlations of β'_{180} and τ_β with visual appearance afforded by careful study of the exhibits in Figs. 4 through 15 and the back-scatter versus attenuation relationships developed later, in Chap. III. Additionally, however, in the hope of identifying any significant trends that might aid in predicting or identifying the amount or

*Visibility here is intended to mean the visual detectability of the cloud from the ground or from a satellite picture; it is not visibility in the sense of Meteorological Visual Range within the cloud.

[†]See footnote on the term "strength" given in Sec. II-C.

temperature of cirrus, or both, through conventional observational techniques, a series of scatter diagrams was constructed from the data, and these diagrams are reproduced as Figs. 16, 17, and 18.

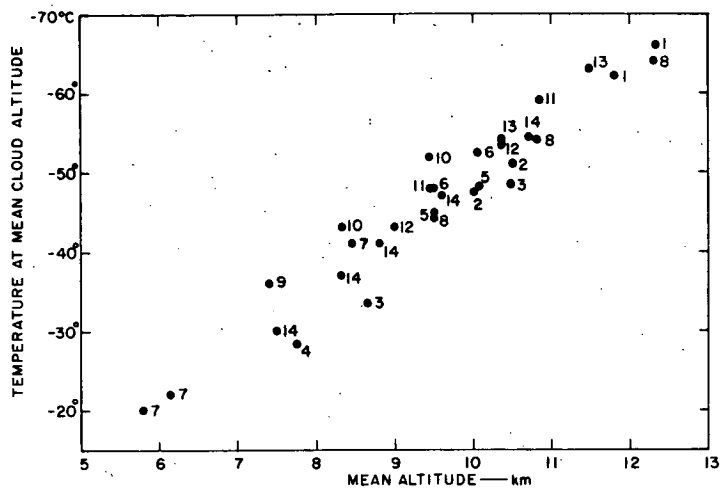
Figure 16 plots the rawinsonde-measured air temperatures at the cloud heights against the lidar-measured parameters of mean cloud altitude, mean cloud thickness, and mean τ_{β} (total reflectance). The correlation of cloud elevation with temperature is quite good. This finding, together with the observation, from the cloud data exhibits (Figs. 4 through 15) that the presence of cirrus is not associated with observed temperatures that depart significantly from the climatological mean, appears to confirm the intuitive conjecture that mere knowledge of the height and geometric location of a cirrus cloud is sufficient to indicate its temperature to $\pm 5^{\circ}\text{C}$, or better. The correlation between the displayed parameters in the other two diagrams is poor.

Figure 17(a) and (b) plots the height of the tropopause versus the mean cloud altitude and thickness, and Fig. 16(c) plots the tropopause height versus τ_{β} . No significant trends are evident.

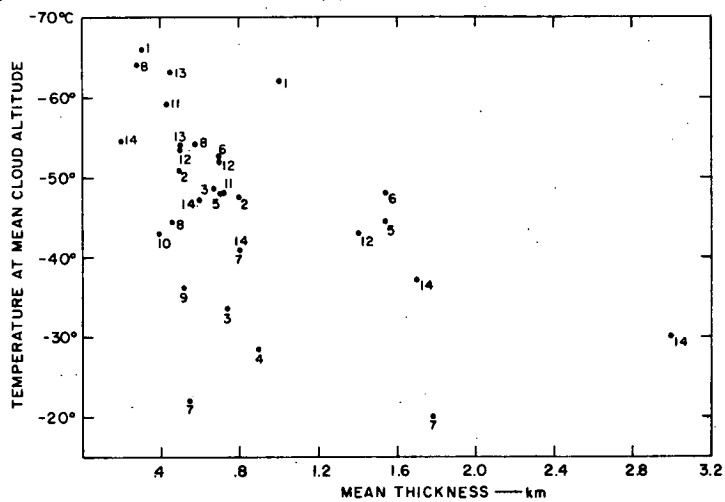
Figure 18(a) shows the relationship between the daily averages of lidar-measured backscattering optical thickness, τ_{β} , and the cirrus cloud coverage reported by two nearby weather stations. It indicates that, in spite of lidar's demonstrated ability to detect specific cirrus regions at levels below the visibility threshold, the observer's reports (in daylight) have been a good indication of conditions favoring even extremely weak cirrus.

Figure 18(b) plots the reported cloud amount versus the mean geometrical thickness and shows that no correlation between vertical extent and horizontal coverage was apparent during our tests.

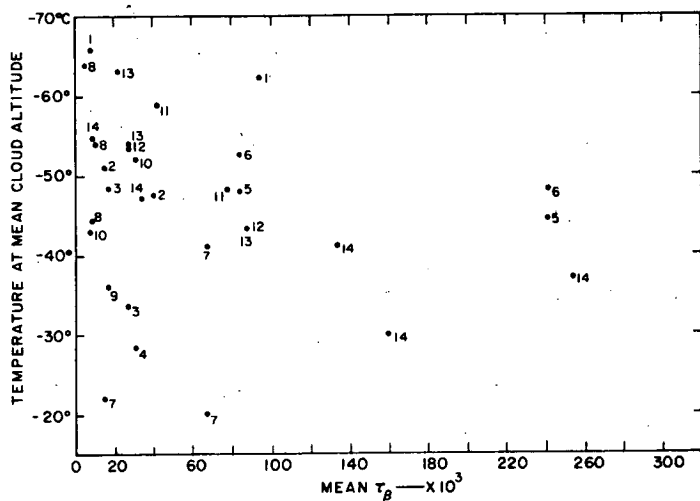
Table III lists the values used in plotting the scatter charts.



(a)



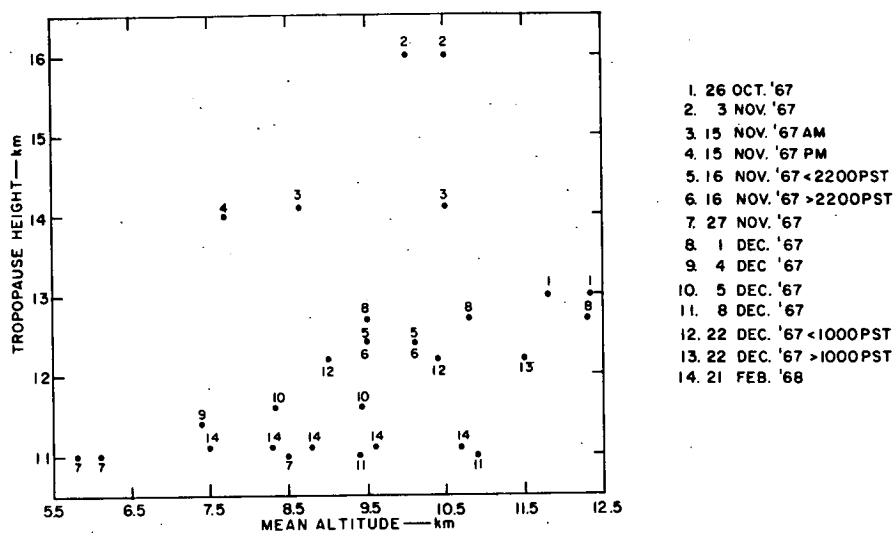
(b)



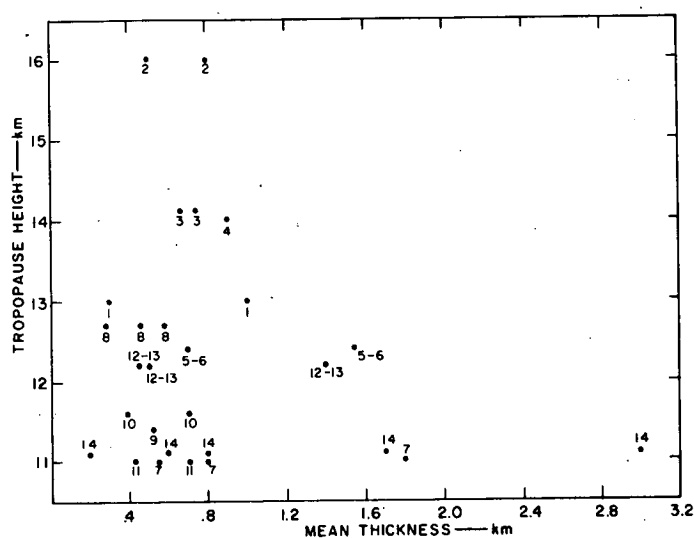
(c)

1. 26 OCT. '67
2. 3 NOV. '67
3. 15 NOV. '67 AM
4. 15 NOV. '67 PM
5. 16 NOV. '67 <2200PST
6. 16 NOV. '67 >2200PST
7. 27 NOV. '67
8. 1 DEC. '67
9. 4 DEC. '67
10. 5 DEC. '67
11. 8 DEC. '67
12. 22 DEC. '67 <1000PST
13. 22 DEC. '67 >1000PST
14. 21 FEB. '68

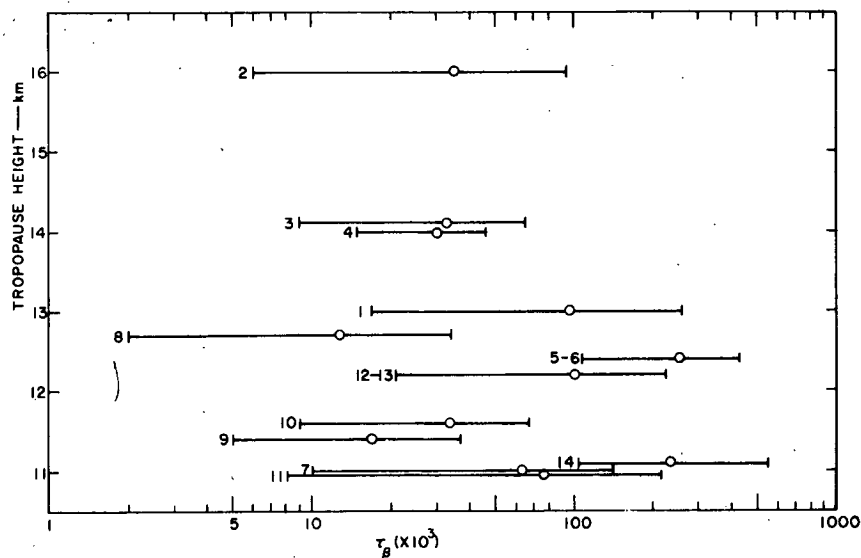
FIG. 16 CLOUD TEMPERATURE vs ALTITUDE, THICKNESS, AND τ_β



(a)

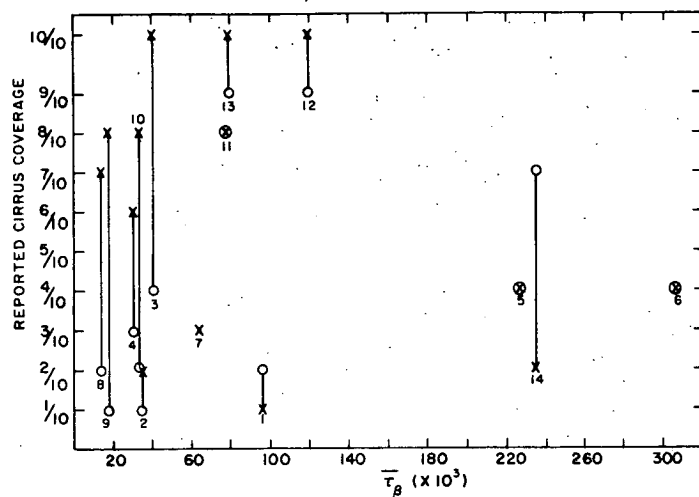


(b)



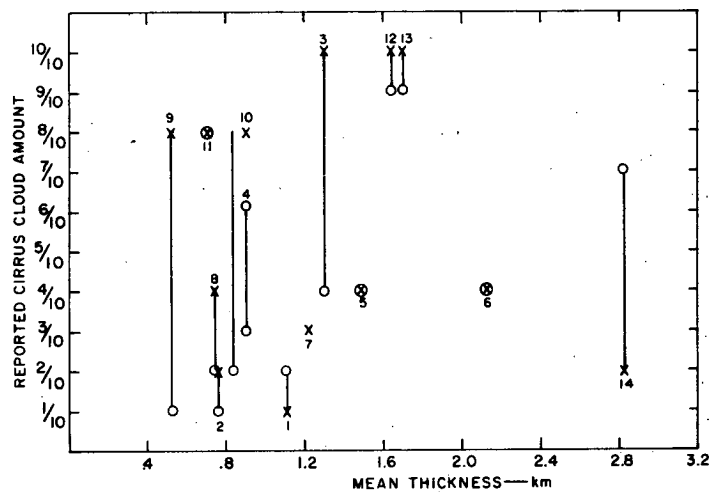
(c)

FIG. 17 TROPOPAUSE HEIGHT vs ALTITUDE, THICKNESS, AND τ_β



(a)

1. 26 OCT. '67
2. 3 NOV. '67
3. 15 NOV. '67 AM
4. 15 NOV. '67 PM
5. 16 NOV. '67 < 2200PST
6. 16 NOV. '67 > 2200PST
7. 27 NOV. '67
8. 1 DEC. '67
9. 4 DEC. '67
10. 5 DEC. '67
11. 8 DEC. '67
12. 22 DEC. '67 < 1000PST
13. 22 DEC. '67 > 1000PST
14. 21 FEB. '68



(b)

FIG. 18 REPORTED CIRRUS COVERAGE vs τ_{β} AND PHYSICAL THICKNESS

Table III-III
VALUES USED IN PLOTTING SCATTER CHARTS

Mean Date (1967-68)	Mean Base (km)	Mean Th (km)	Mean Ht (km)	Mean Tops (km)	Trop Ht (km)	Max. Wnd. Ht (km)	Temp (C°)	TT- T _d T _d (C°)	$\bar{T}_p$ $\times 10^3$	Session Code No.
26 Oct.	11.3	1.0	11.8	12.3	13.0	12.0	-62.0		94	1
	12.2	0.3	12.4	12.5			-66.0		8	1
3 Nov.	9.6	0.8	10.0	10.4	16.0	11.1	-47.5	5	40	2
	10.3	0.5	10.5	10.8			-51.0		15	2
15 Nov.	8.3	0.7	8.6	9.0	14.1	11.6	-33.5	4	27	3
	10.1	0.7	10.5	10.8			-48.5		17	3
	7.3	0.9	7.7	8.2	14.0	10.4	-28.3	3	30	4
16 Nov.	8.8	1.5	9.5	10.3	12.4	10.4	-48.0	14	242	5,6
	9.7	0.7	10.1	10.4			-52.5		84	5,6
27 Nov.	4.9	1.8	5.8	6.7	11.0	10.7	-20.0	4	67	7
	5.9	0.6	6.1	6.5			-22.0	3	15	7
	8.1	0.8	8.5	8.9			-41.0		67	7
1 Dec.	9.3	0.5	9.5	9.8	12.7	14.8	-44.3	12	8	8
	10.5	0.6	10.8	11.1			-54.0		11	8
	12.2	0.3	12.3	12.5			-64.0		5	8
4 Dec.	7.2	0.5	7.4	7.7	11.4	9.9	-36.0	6	17	9
5 Dec.	8.1	0.4	8.3	8.5	11.6	10.0	-43.0	8	8	10
	9.1	0.7	9.4	9.8			-52.0		31	10
8 Dec.	9.1	0.7	9.4	9.8	11.0	11.4	-48.0	6	77	11
	10.6	0.4	10.8	11.0			-59.0		41	11
22 Dec.	8.3	1.4	9.0	9.7	12.2	13.8	-43.0	2	88	12-13
	10.1	0.5	10.4	10.6			-54.0		28	13
	11.3	0.5	11.5	11.8			-63.0		22	13
21 Feb.	6.0	3.0	7.5	9.0	11.1	11.5	-30.0	10	160	14
	7.4	1.7	8.3	9.1			-37.0	9	254	14
	8.4	0.8	8.8	9.2			-41.0	9	134	14
	9.3	0.6	9.6	9.9			-47.0		33	14
	10.6	0.2	10.7	10.8			-54.5		9	14

3. Cloud Motion versus Wind Field

The simultaneous availability of accurate cloud altitude data, time-lapse photographs, and upper air wind data (from the Oakland rawinsonde) provided a unique opportunity to investigate a question of increasing importance to satellite cloud picture analysts: How useful is high cloud motion as an indicator of winds at altitudes?

To answer this question for a large portion of our data sample, motion vectors for identifiable cloud elements were measured from the Kodachrome sky pictures and were compared with the Oakland upper air wind report. Eighty-one separate measurements were made on 52 different cloud decks on ten different days during the period 26 September through 23 December 1967. The results are shown in Fig. 19. The lower portion of this figure is a bar graph giving the altitude distribution of the measured cloud patches, and the upper portion shows the cloud and wind vectors. The location of the vector junctions in the upper portion of the graph also displays the departure of the observed temperature (obtained from the Oakland rawinsonde) from the climatological mean at the measured cloud height.

For nine of the ten days the cloud and wind vectors matched within 10° and 15 knots. On 26 October only, the measured cloud motion was easterly and approximately 100° different from the Oakland sounding. This anomaly certainly casts suspicion on the photographic record keeping for that day, although the picture orientations and timings have been carefully rechecked, and no error has been found. The discrepancy remains unexplained, and the wind data for 26 October should carry little weight until, if ever, a similar situation is documented.

With the exception of two events, all the temperature departures lie within $\pm 6^\circ\text{C}$ of the climatological mean, and 61% of these lie within one standard deviation of the mean (shown shaded on the temperature profiles). In our data sample, lower-than-mean temperatures and moderate-to-strong westerly winds were found in cirrus below 30,000 feet. Above 30,000 feet, lower-than-mean temperatures were found with very strong northwesterly and northerly winds.

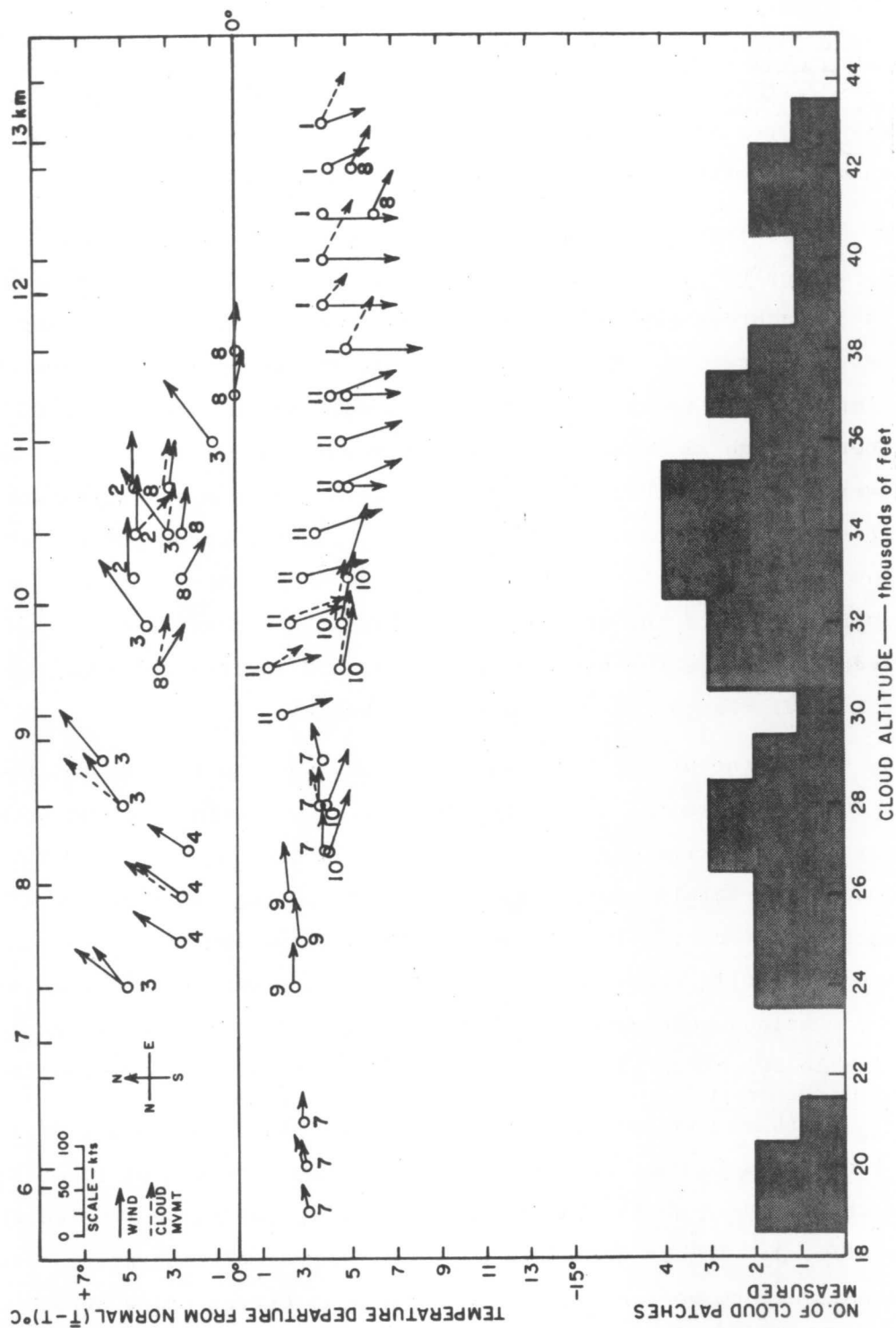


FIG. 19 SUMMARY OF WIND AND TEMPERATURE VARIATIONS

Higher-than-mean temperatures were accompanied by southwesterly winds at any altitude and by westerly winds above 30,000 feet, and in two instances fairly strong northwesterly winds accompanied cirrus clouds at 31,000 and 33,000 feet.

4. Spikes

Occasionally, during the several years of intermittent lidar observations of clouds of all types that preceded this study, returns from cirrus clouds were noted that contained unexpectedly high, very narrow peaks, or spikes. Our impression was that these spikes, when present, usually occurred very near the top surface of the cloud, and it was hypothesized that such a signature might indicate a specular return from horizontally oriented flat-plate crystals, similar to the phenomenon reported by McDonald et al. (1962) during the ice fog tests at Yellowstone National Park. Since the flat-plate geometry apparently occurs only within certain relatively narrow temperature ranges, it was hoped that the presence of sharp spikes might prove to be an independent indicator of cloud temperature, and the lidar operators for this project were briefed to be particularly alert for spikes. The quantity of spikes obtained was very disappointing, indicating either a lack of the right kind of cirrus or the fallacy of relying upon undocumented impressions. The best instance during this series was recorded at 1613-1614 PST on 15 November 1967 (see Fig. 6). A spike less than 200 ns wide and approximately twelve times stronger than the average cloud return was received on two successive shots, 1 minute apart, from an elevation of 8.1 km where the reported temperature was -32°C . A sharp increase in the lapse rate between 8.0 and 8.2 km was reported by the Oakland rawinsonde operation at very nearly the same time, but of course little can be deduced from an isolated situation.

IV THEORETICAL CONSIDERATIONS

A. Relation Between Backscattering and Attenuation

1. Introduction

The relationship between backscattering and attenuation in various types of aerosols is a subject of considerable importance in atmospheric physics. While an elegant theory by Gustav Mie in 1908 provided exact relations for the case of a plane wave incident upon an isolated sphere, it is quite difficult to extend this work for application to the ensemble averages representative of the size and type of distributions found in real aerosols. The problem is compounded in the case of cirrus cloud by the variety of complex scattering patterns possible from the many forms of ice crystals.

Fortunately, however, experimentally derived data appear to show sufficient consistency so that there is hope of inferring a relation sufficiently accurate for many practical applications.

In this report we define the volume backscattering coefficient β'_{180} and the volume attenuation coefficient due to scattering σ_s in the same way as was done in the first phase of this study (Evans et al., 1966), that is:

$$\beta'_{180} = \frac{4\pi \text{ power reflected toward source per steradian}}{\text{incident power density} \times \text{effective scattering volume}}$$

$$\sigma_s = \frac{\text{total power scattered in all directions}}{\text{incident power density} \times \text{total scattering volume}}$$

In the previous phase the following simple relation between these coefficients was assumed for cases where absorption could be neglected,

$$\beta'_{180} = k\sigma_s, \quad (\text{IV-1})$$

where

$k = 1.5$ for Rayleigh scattering

and

$k = 0.625$ for Mie scattering by large spheres

Fenn, (1966), using the experimental data of Barteneva, (1965), suggests a slightly more general relation of the form*

$$\beta'_{180} = k_1 \sigma^{k_2} \quad (\text{IV-2})$$

and shows that, for white light through fogs, with appropriate constants it holds within an accuracy of 20 to 30% for extinction coefficients between 0.01 km^{-1} and 1.0 km^{-1} .

To check the applicability of this relation to cirrus clouds for monochromatic light and to determine empirical values for the two constants, we tested it using the experimental data from the lidar sounding of 2130 PST for 21 February 1968. This sounding was through one of the thickest and densest cirrus situations for which we have reliable records. Since it was made at night when the receiver noise contribution from ambient light was negligible, we were still able to measure enough of the Rayleigh return from above the cloud to permit a direct computation of the total attenuation produced by the cloud. The incremental solution of the lidar equation described in Appendix A was then repeated, this time including the effects of attenuation through the use of Eq. IV-2, with various trial values for k_1 and k_2 . Acceptable values for the constants would be expected to lead to realistic cloud profiles and to a total attenuation which would check the directly measured values. The results of these calculations are shown in Figs. 20 and 21.

*On dimensional grounds $k_1 = \beta'_{180}(r_o) \sigma(r_o)^{-k_2}$, where the argument r_o indicates a reference location.

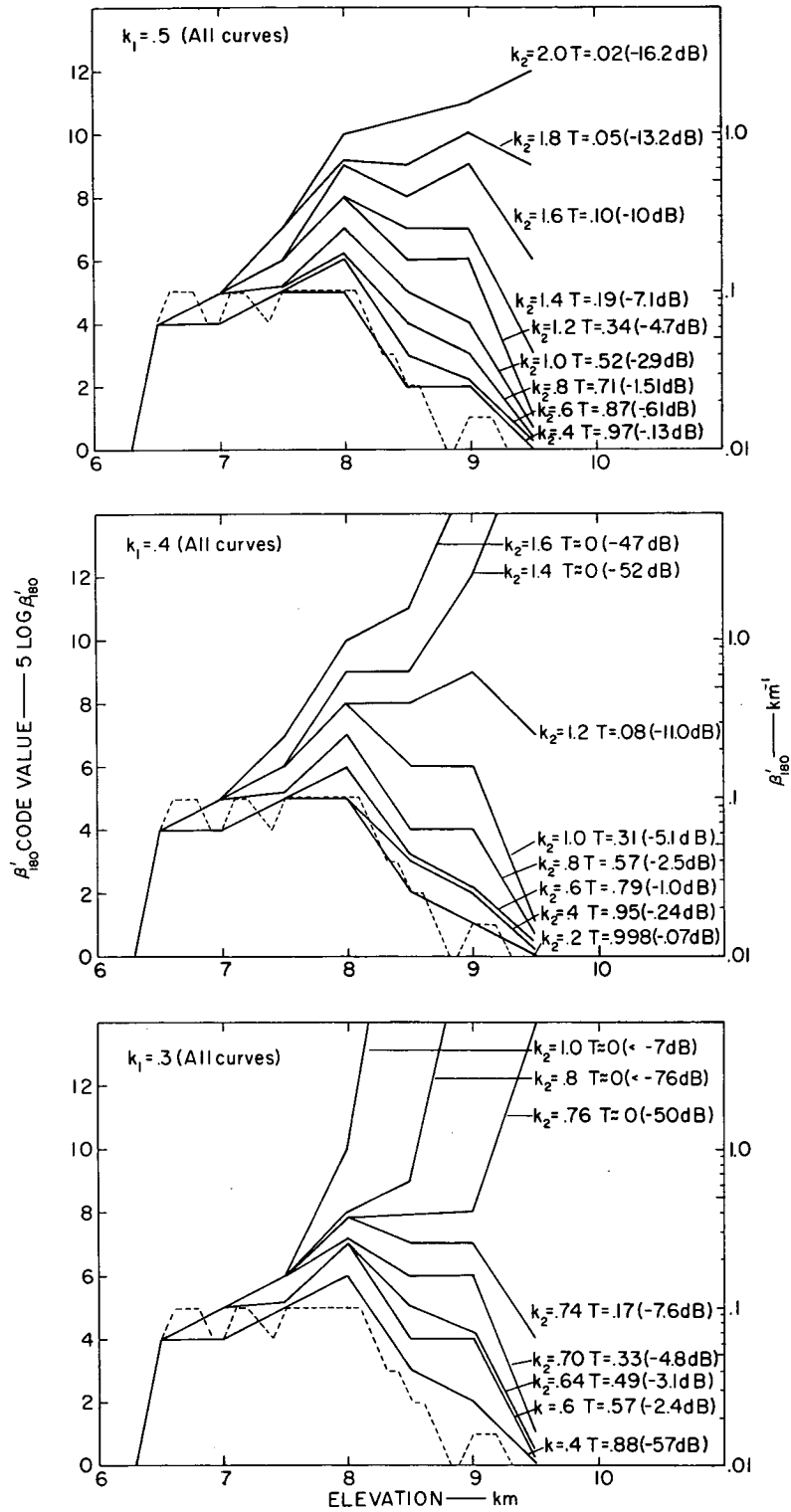


FIG. 20 VARIATION OF CLOUD PROFILE WITH k_2

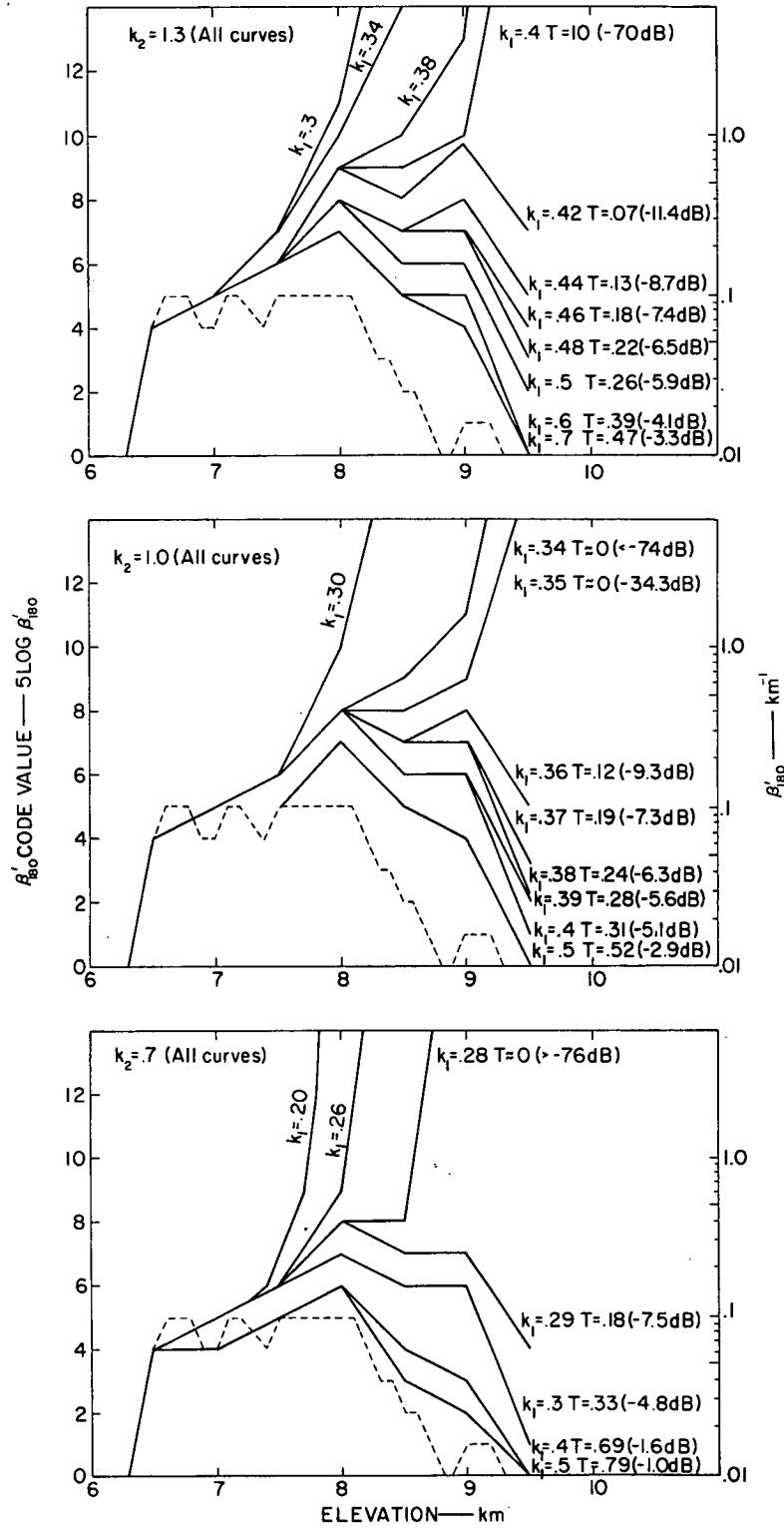


FIG. 21 VARIATION OF CLOUD PROFILE WITH k_1

2. Transmission Determination from Cloud Signature

The dashed bottom curve of each family represents the cloud distribution that would be inferred from the lidar signature if attenuation within the cloud were neglected entirely; that is, the curve is essentially a scaled and range-corrected version of the received waveform. The solid curves represent the vertical structure of the cloud that would be inferred by adding a correction at the end of every 0.1-km range increment in the data reduction procedure described in Appendix A, this correction being determined by the cumulative attenuation through the cloud, assuming that the backscatter-versus-extinction relationship is described by Eq. IV-2 with the indicated values for the two constants.

Printed at the right-hand end of each curve is the calculated value for total one-way transmission through the cloud, expressed both as a decimal fraction and as a decibel power ratio.

3. Transmission Determination by Direct Measurement

The lidar radiation received by Rayleigh backscattering from a clear region above the cloud (between 10.5 and 11.3 km) released electrons from the photocathode at the rate of 0.8 per μs . The actual count happened to be 4 pulses in a 5- μs period for the shot of 2130 PST, but confidence in the value was increased by averaging over eight soundings through similar portions of the unusually uniform cloud deck (see the cloud profile of Fig. 15). The average signal return that would have been received from the 10.5-to-11.3-km region had there been no cirrus cloud present was 8.5 pulses/ μs . This value is a long-term average for the Mark II lidar operating on clear nights.

A normal pulse count received from the region below the cloud during the operating session confirmed that the lidar was operating properly and that no unusual lower atmospheric attenuation was present. Therefore, we believe that the one-way 0.7- μ transmission through the cloud of 2130 PST on 2 February 1968 was very nearly

$$T_c = \sqrt{\frac{0.8}{8.5}} = 0.31, \text{ or } -5.1 \text{ dB} .$$

This transmission value compares very favorably with transmission measurements made by photometry of the moon on the night of 16 November 1967, when an apparently very similar cirrus situation prevailed. Data given in the visual summary section of Fig. 7 show that early that evening, when τ_β was in the range of 0.100 to 0.240, the measured attenuation of the moon brightness was $10 \log \frac{300}{100} = 4.8 \text{ dB}$.

Later, when the measured τ_β increased to 0.360, the photometer-measured attenuation increased to approximately $10 \log \frac{300}{50} = 7.8 \text{ dB}$.

Comparison of T_c 's for the Two Methods

Inspection of the curves of Figs. 20 and 21 reveals the "lifting" effect on the deep-penetration end of the inferred cloud profile as the compensation for cloud attenuation is progressively increased. It can be seen that several combinations of k_1 and k_2 lead to realistic cloud profiles coupled with a value for total transmission that is close to the value of 31% actually measured by the "Rayleigh attenuation" procedure. Some combinations, however, appear to be extremely sensitive to small changes in one of the two constants and thus would not be suitable for application in practical cases where measurement precision may be poor.

The combination of $k_2 = 1.0$, $k_1 = 0.4$ appears to be a good choice, at least for this and several similar cloud situations listed. This finding is fortunate, since with $k_2 = 1$, computation is simplified.

B. The Angular Scattering Descriptor (Phase Function)

A very convenient means of expressing the angular scattering characteristics of a small particle or ensemble of small particles is by means of a phase function $P(\theta, \phi)$ in terms of the polar angle θ and azimuth angle ϕ . As used herein, it can be defined as

$$P_{(\theta, \phi)} = \frac{\text{energy per steradian scattered in direction } \theta, \phi}{\text{total energy scattered from the beam}} \quad (\text{IV-3})$$

For single-particle scattering,

$$P_{(\theta b)} = \frac{I_{\theta \phi}}{I_o} \frac{\mu^2}{C_{sca}} \quad (\text{IV-4})$$

The integral of the phase function over all directions is 1, and its average value over all directions is $1/4 \pi$.*

For spherical scattering particles, the phase function can be computed precisely for any combination of size parameter, $\alpha = 2\pi/\lambda$, index of refraction, n , and degree of polarization of the incident light. When $\alpha \ll 1$ (that is, for Rayleigh scattering), the phase function in the θ plane is:

$$P(\theta) = \frac{3}{16\pi} (1 + \cos^2 \theta) \quad (\text{IV-5})$$

Phase functions for intermediate values of α can be derived from the values of i_1 and i_2 plotted from the Mie theory in numerous references, for example Van de Hulst (1957), pp. 152-153, and Penndorf (1963). For particles very large relative to the wavelength, that is $\alpha > \text{approximately } 50$, the increasing difficulty of performing the Mie calculations with adequate precision has usually led to the use of geometric ray-tracing techniques, supplemented where necessary by a superposed diffraction pattern. While these techniques are adequate for explaining halos, rainbows, and most coronae, they do not account for the strong backscattering or glory phenomenon often obscured near $\theta = 180^\circ$. Van de Hulst suggested (1957, p. 375) that the effect might be explained by so-called surface waves guided by the surface of the sphere and gave several references to studies of electromagnetic surface waves in connection with radio propagation.

*Some authors, including Chandrasekhar (1950) and Penndorf (1962), define the phase function in such a way that its integral over all directions is 4π , instead of 1. The usage here is consistent with that of Van de Hulst (1957, p. 12).

A recent paper by Bryant and Cox (1966) reports that, by using electronic computers with double-precision arithmetic, carrying all computed quantities to 22 significant figures, and using up to 500 terms in the Mie series solution (for $\alpha = 200$ and 500), they were able to demonstrate that the surface wave phenomenon is in fact predicted by the exact Mie theory. The calculation showed that the shape of the phase function near $\theta = 180^\circ$ is determined chiefly by the last few significant terms of the Mie expansion, which can be shown to be associated with rays grazing the surface of the droplet. Presumably, this result also applies to the glory and related backscatter effects from spheres.

Ice crystals are not spherical, however, and in addition to the practical difficulties of making Mie calculations with large α , the questionable validity of assigning to them a "Mie equivalent radius" becomes apparent for investigations when backscattering is important. Whether the guided surface wave approach is applicable to or can be successfully applied to the rough irregular shape of many cirrus ice crystals appears questionable at this time.

For practical calculations with radiative transfer models, it appears reasonable to work with semi-empirical phase functions, consistent with known theory and checked as much as possible with actual experiments on cirrus clouds in situ. Hall (1968) has proposed such a phase function for cirrus clouds in the 8-to-13- μ region.

A function derived by Uthe at SRI for the visible region was used in exploratory work with Wells' Monte Carlo codes and is described in the next section.

C. A Proposed Scattering Phase Function for Randomly Oriented Ice Crystals (Cylinders)

The following procedure derives a semi-empirical phase function for cirrus clouds that accumulates effects from five contributors:

- (1) A value in the forward direction predicted by a Fresnel approximation

- (2) A diffractive pattern for all θ values greater than the first minimum predicted by scattering from randomly oriented long cylinders
- (3) A pattern defined by a $\cos^n(\theta)$ function between $\theta = 0$ and the first diffractive minimum (at approximately $\theta = 1^\circ$ for ruby light)
- (4) A pattern derived from field measurements made on seeded ice fogs in the Yellowstone Geyser basin for $20^\circ > \theta > 160^\circ$
- (5) A smooth extrapolation of the composite curve described above to $\theta = 180^\circ$.

The intensity, I , of scattered light at a point within the scattered radiation field a distance r from the scattering particle is given as (Van de Hulst, 1957, p. 12):

$$I = I_0 \frac{P(\theta, \phi) C_{sca}}{r^2} \quad (IV-6)$$

where I_0 is the intensity of the incident light; C_{sca} is the scattering cross section, that is, the area that intercepts energy equal to that scattered in all directions by the particle; and $P(\theta, \phi)$ is the phase function previously described. The scattering cross section equals the extinction cross section for nonabsorbing particles ($C_{sca} = C_{ext}$). For large particles (radius $\gg \lambda$), the extinction cross section is assumed to be twice the geometrical cross section, G , that is, $C_{ext}/G = 2$. Energy equal to that incident on the area G forms the Fraunhofer diffraction pattern.

The diffraction pattern in the θ or polar plane for randomly orientated cylinders is given by Van de Hulst (1957, p. 109) as:

$$P(\theta) = \frac{\ell}{2\pi k C_{sca} \theta^3} \sin^2(ka \theta) \quad , \quad (IV-7)$$

where ℓ = cylinder length

a = cylinder radius

and $k = 2\pi/\lambda$

λ = wavelength of the incident light.

This equation is valid only for the conditions where $l \gg 2a \gg \lambda$ and $\theta \gg \frac{1}{kl}$. For non-absorbing cylinders,

$$C_{\text{sca}} = C_{\text{ext}} = 2G = \frac{S}{2} = \pi a l,$$

where use is made of the theorem that the average geometrical cross section, $\bar{G}$, of a convex particle with random orientation is one-fourth its surface area, S (Van de Hulst, 1957, p. 110). The phase function may then be written:

$$P(\theta) = \frac{\sin^2(k a \theta)}{2\pi^2 k_a^3 \theta^3}, \quad \theta > \frac{\pi}{k_a} \quad (\text{IV-8})$$

and is independent of cylinder length. The first diffraction minimum is at $\theta = \frac{\pi}{k_a} \gg \frac{1}{kl}$, and, since $a \ll l$, $\frac{\pi}{k_a} \gg \frac{1}{kl}$, and Eq. IV-8 is valid for all θ larger than the first minimum, or much larger than $\frac{1}{kl}$.

A value for the phase function in the forward ($\theta=0$) direction can be found by computing the Fresnel diffraction into the shadow area of a large disc. From Van de Hulst (1957, p. 106), we have

$$\frac{I}{I_0} = \frac{G^2}{\lambda^2 r^2} \quad (\text{IV-9})$$

Substituting $\frac{I}{I_0}$ from Eq. (IV-6),

$$P(\theta, \phi) = \frac{G^2}{\lambda^2 C_{\text{sca}}} = \frac{G}{2\lambda}, \quad (\text{IV-10})$$

and, since $G = \frac{\pi a l}{2}$,

$$P(\theta, \phi) = \frac{\pi a l}{4\lambda}. \quad (\text{IV-11})$$

An empirical function that can be used to join this value and 0 at the first diffraction minimum to specify the phase function over the first diffraction lobe is:

$$P(\theta) = \frac{\pi a \ell}{4\lambda} \cos^n\left(\frac{k a \theta}{2}\right), \quad 0 \leq \theta \leq \frac{\pi}{ka}, \quad (\text{IV-12})$$

where n is chosen so that $\int_0^\pi P(\theta) \sin \theta d\theta$ for the combined diffraction function Eq. (3) plus Eq. (5) is equal to $\frac{1}{4\pi}$; that is, the diffraction part accounts for one-half the total scattered energy. The diffraction pattern developed above is plotted as the bottom curve of Fig. 22.

To the diffraction pattern we now add a phase function $P'(\theta)$ derived from the measurements of McDonald et al. (1962) on seeded ice fogs near old Faithful geyser in January-February 1962. Figure 23 includes a reproduction of McDonald's data. Also shown in Fig. 23 is a smooth curve that was fitted to the averaged experimental data over the angular region $20^\circ > \theta > 160^\circ$ by the method of least squares and adjusted in absolute value so that its integral over all direction equals $1/2$. That is,

$$\int_0^\pi P'(\theta) \sin \theta d\theta = \frac{1}{4\pi}. \quad (\text{IV-13})$$

A polynomial defining this function is also given in the figure.

The ice crystals in many cirrus clouds are predominantly prismatic columns with hexagonal bases averaging approximately 100μ in length and 40μ in width (Blau et al. (1963). The condition $\ell \gg 2a$ is not valid. However, the diffraction pattern for spheres is also proportional to θ^{-3} (Van de Hulst, 1957, p. 108), and errors introduced in the diffraction pattern by replacing the condition $\ell \gg 2a$ with $\ell > 2a$ should be small.

Figure 22 combines the results of all the contributions and defines a composite phase function for the ice crystals described.

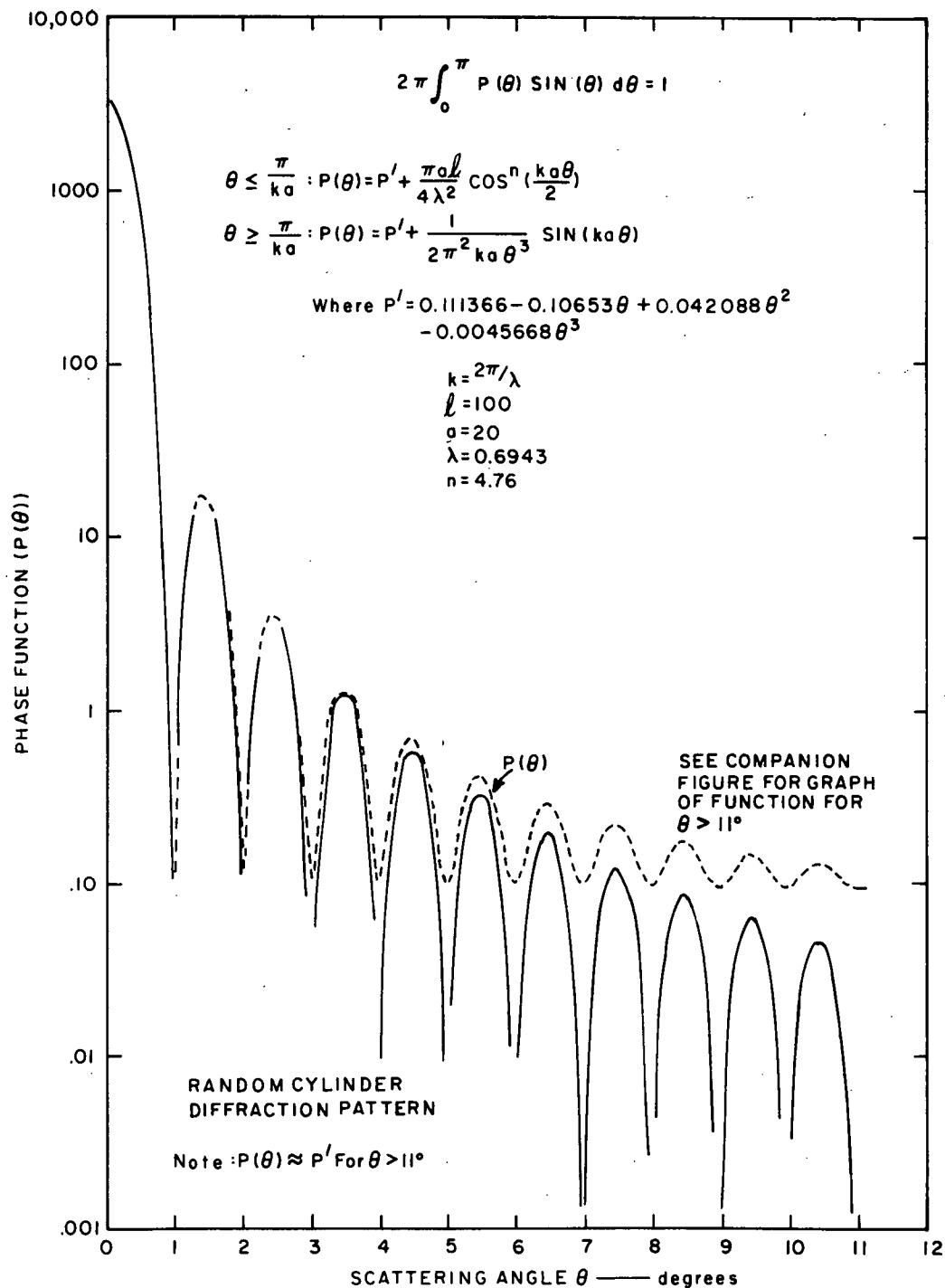


FIG. 22 PHASE FUNCTION FOR CIRRUS CLOUD

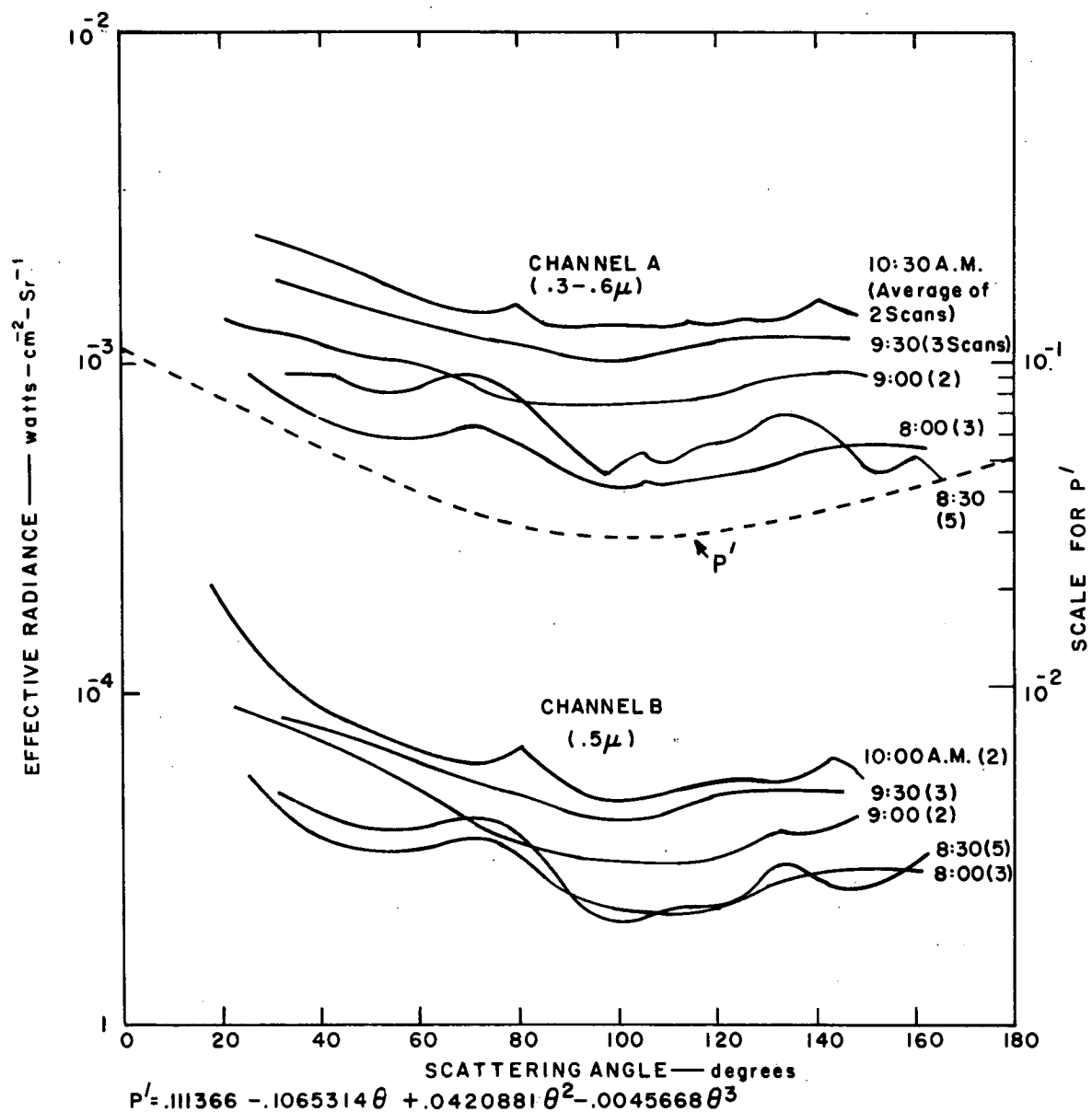


FIG. 23 DERIVATION OF $P(\theta) > 11^\circ$ FROM EXPERIMENTAL DATA OF McDONALD

D. Estimates of Total Ice and Water Content for Cirrus Clouds

Since cirrus ice crystal dimensions are normally many times greater than the wavelength of ruby lidar energy, it is customary to assume the total scattering cross section to be twice the geometrical cross section. That is:

$$\sigma = \int_0^{\infty} 2\pi r_e^2 N(r_e) dr_e, \quad (\text{IV-14})$$

where r_e is the Mie equivalent radius of the crystals, and $N(r_e)$ is the number of crystals per unit volume per unit equivalent radius. (In such an approximation, the use of Mie theory is justifiable, even though the particles in question are not spherical, if the orientation of the crystals is essentially random.) The volume backscatter coefficient for a cloud consisting of crystals of a single Mie equivalent radius may be expressed as:

$$\beta'_{180} = k\sigma = 2k\pi r_e^2 N, \quad (\text{IV-15})$$

where N is number density.

We then conclude that the total geometric cross section per unit volume is:

$$\pi r_e^2 N = \frac{\beta'_{180}}{k_1 Q} \quad (\text{IV-16})$$

If we assume

$$K_1 = 0.4 \quad (\text{from Sec. III-A})$$

$$Q = 2 \quad (\text{upper limit; for large spheres}),$$

we can construct Table IV-I for the range of volume backscattering coefficients measured in cirrus during the project.

Table IV-I
INFERRED TOTAL GEOMETRIC CROSS SECTION PER UNIT VOLUME

$\pi r_e^2 N \text{ (km}^{-1}\text{)}$		
$\beta'_{180} = 1.0 \text{ km}^{-1}$ High-Reflectance Cirrus Code No. 9, 9+	$\beta'_{180} = 0.1 \text{ km}^{-1}$ Medium-Reflectance Cirrus Code No. 5	$\beta'_{180} = 0.01 \text{ km}^{-1}$ Low-Reflectance Cirrus Code No. 0, 1
1.25	0.125	0.0125

These values correspond to the number densities given in Table IV-II.

Table IV-II
NUMBER DENSITY OF CIRRUS CLOUD PARTICLES
AS A FUNCTION OF PARTICLE EQUIVALENT RADIUS
FOR OBSERVED VALUES OF β'_{180}

Equivalent Radius r_e (μ)	$N(\text{Particles m}^{-3})$		
	$\beta'_{180} = 10^{-3} \text{ m}^{-1}$ High-Reflectance Cirrus	$\beta'_{180} = 10^{-4} \text{ m}^{-1}$ Medium-Reflectance Cirrus	$\beta'_{180} = 10^{-5} \text{ m}^{-1}$ Low-Reflectance Cirrus
50	1.6×10^5	1.6×10^4	1.6×10^3
100	4.0×10^4	4.0×10^3	4.0×10^2
120	2.8×10^4	2.8×10^3	2.8×10^2

Another expression of the same information is in terms of the equivalent water content of the cloud crystals (not including any associated water vapor). These results are given in Table IV-III.

Table IV-III

EQUIVALENT WATER CONTENT OF CIRRUS CLOUD AS A FUNCTION
OF PARTICLE EQUIVALENT RADIUS FOR OBSERVED VALUES OF β'_{180}

Equivalent Radius r_e (μ)	Water Content (grams/m ³)		
	$\beta'_{180} = 10^{-3} \text{ m}^{-1}$ High-Reflectance Cirrus	$\beta'_{180} = 10^{-4} \text{ m}^{-1}$ Medium-Reflectance Cirrus	$\beta'_{180} = 10^{-5} \text{ m}^{-1}$ Low-Reflectance Cirrus
50	8.4×10^{-2}	8.4×10^{-3}	8.4×10^{-4}
100	1.7×10^{-1}	1.7×10^{-2}	1.7×10^{-3}
120	2.0×10^{-1}	2.0×10^{-2}	2.0×10^{-3}

Even after allowing for the coarseness of certain of the assumptions employed in these calculations, the entire gamut of values given in Tables V and VI for a very wide variety of cirrus cloud forms lies well within the spread of estimates that may be found in the literature for "thin" cirrus.

Our values for $r_e = 120 \mu$ and a "low-reflectance cirrus" are about five times smaller than the "transitional value" of $N 1.5 \times 10^3 \text{ m}^{-3}$ given by Zdunkowsky (1965) for marginally visible cirrus of 120- μ equivalent radius. His density values, however, are based on an assumed constant 1-km physical thickness of the cloud layer, a simplification that the lidar measurements now indicate should not be made.

It is annoying, however, that the values for the densest cirrus encountered over Menlo Park during our observations (for $\beta'_{180} = 10^{-3} \text{ km}^{-1}$) appear to level off at number densities that are about a factor of three lower than the 100,000 per cubic meter quoted by McDonald et al. (1962) as being the consensus of three physical sampling programs in barely visible cirrus.

Our inferred number densities could be increased by up to a factor of two, and thus be brought into closer alignment with experimental counts, if the scattering efficiency, Q , were not taken as 2, but were assigned some smaller value perhaps almost as low as 1. There is some theoretical justification for doing this, because the large forward-scattering component for large particles does scatter appreciable energy back into the beam.

E. Monte Carlo Methods for Multiple-Scattering Calculations

In order to be able to investigate the effects of multiple scattering on lidar measurements of cirrus and the possible potential for inferring something of the particle-size distribution through observations in regions illuminated only by secondary and higher-order scattering, a first look was taken at the application of the Monte Carlo computational procedure. An apparently suitable program has been developed by M. B. Wells et al. (1966).

In return for the opportunity to promote the possible sale of computing programs and consulting services to SRI for this and other projects, Mr. Wells of Radiation Research Associates, Fort Worth, Texas ran a sample problem using his LITE I program with initial conditions pertinent to lidar probing of cirrus supplied by us.

The sample problem was designed to explore the effects of multiple scattering on the lidar return signature and, in particular, to attempt to determine whether any readily apparent characteristics of the anti-corona surrounding the main spot might provide the basis for deriving useful information about the physical make-up of the cloud.

The problem involved a five-layer cirrus model located between 10- and 11-km elevation and illuminated by a vertical pulsed ruby laser beam having a divergence of 1 mrad. The objective was to investigate the signature which would be received in a receiver located very near the transmitter and provided with a controllable field of view of two types:

- (1) A circular field concentric with the lidar spot on the cloud and of several sizes, both larger and smaller than the primary spot diameter and
- (2) an annular field, concentric with the primary spot and of several sizes, designed to sample the cloud radiance in the anticorona region surrounding the spot.

The phase function supplied for the initial test was that described in Section IV-C.

It was hoped that, by varying the assumed backscattering coefficient and phase function for the cloud, some trends might be noted that could be checked experimentally with the lidar.

The results of the first test were not spectacular. The contribution of second- and higher-order scattering within the main beam was quite small, and the predicted return from annular rings surrounding the beam was so small that it could be detected only with great difficulty.

While it would have been interesting and perhaps worthwhile to have continued the investigation with the planned changes in input parameters, a significant number of detailed program modifications would have been required to reduce the voluminous data output to a readily interpretable form. It became apparent that to proceed much further would greatly overtax the project budget, and work in this area was reluctantly set aside. The results of the trial run are summarized below and in Fig. 24.

- (1) The LITE I program synthesizes lidar signatures due to single scattering that are consistent with those postulated in previously used computational procedures.
- (2) For a cloud with attenuation coefficient $\sigma = 0.125 \text{ km}^{-1}$ (corresponding to a lidar return approximately 20 dB above that from the Rayleigh molecular atmosphere at 10 km), the return due to multiple scattering within an anticorona ring between two and three times the

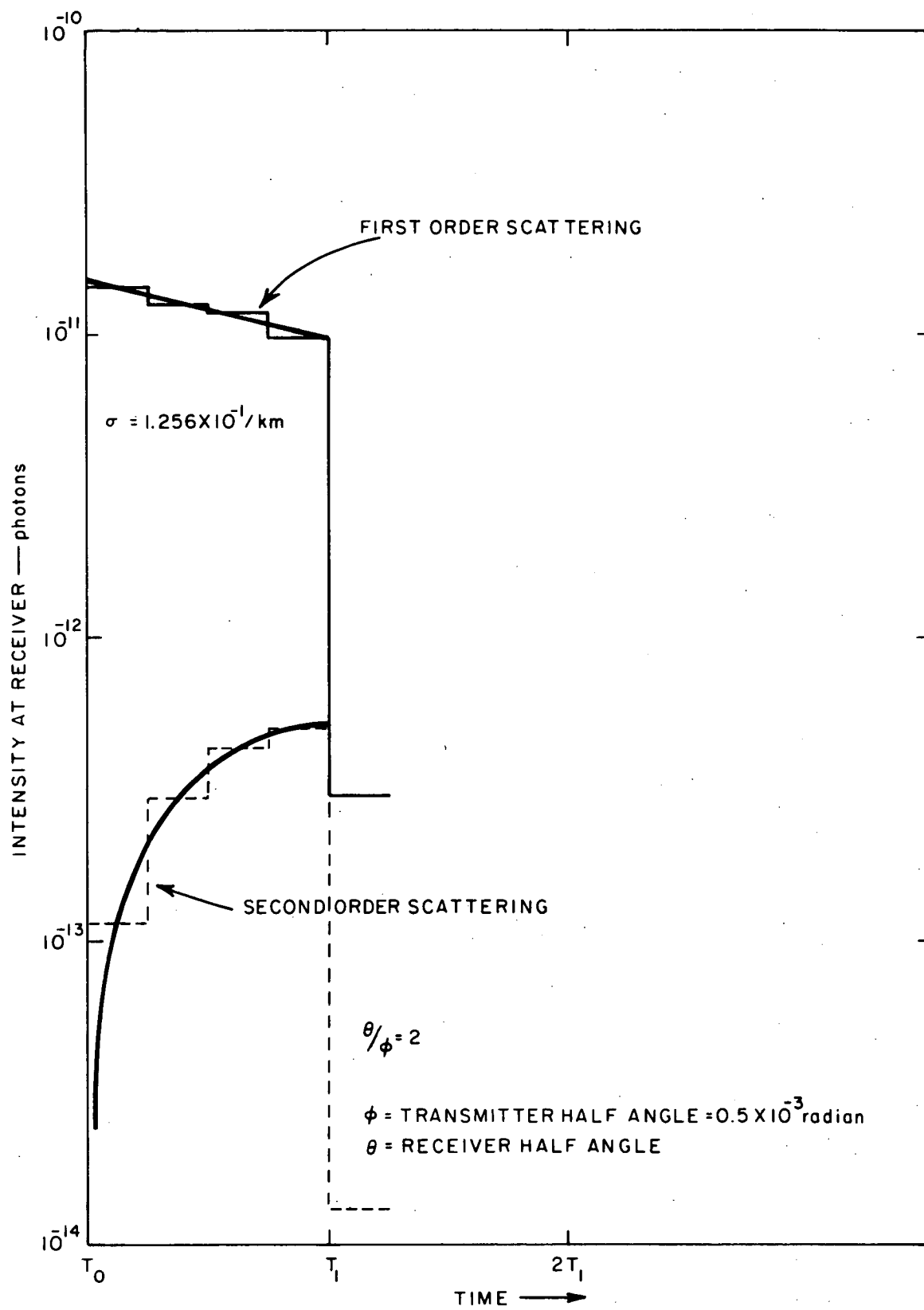


FIG. 24 CIRRUS CLOUD SIGNATURE COMPUTED BY MONTE CARLO METHOD

assumed 1-mr beam diameter is approximately three orders of magnitude (30 dB) below that for the main spot.

- (3) The contribution of second-order scattering within the cone of the main incident beam is less than 10% of the total return for clouds up to 1 km thick and thus is not great enough to visibly affect lidar signatures of present precision.
- (4) The Monte Carlo codes provide a very powerful and very versatile method of modeling lidar performance. However, to make effective use of the very large volume of data available, the feedback between the investigator and the computer should be closer than that which has been feasible during this first test, using data exchange via verbal telephone messages.

V PROPOSED FUTURE PROGRAMS

A. General

The "Conclusions and Recommendations" section of the Final Report on Phase I of this project outlined a plan of action that was intended to be sufficiently general to be largely independent of any transition lines that might have to be drawn between feasibility, research, and operational applications. In brief, this plan involved a stepwise development sequence consisting of, first, the obtaining of additional design data via measurements from earth-based lidars; second, selective sounding of high cloud from above by a relatively simple lidar carried in a high-altitude aircraft; third, operation of basically similar equipment from a manned satellite; and, fourth, incorporation of scanning and non scanning systems into unmanned satellites.

B. Airborne Lidar, Particle Measuring, and Radiometry

Although much more could be done from the ground, it is felt that a sufficient number of the objectives of ground-based probing have been accomplished during this program that planning toward an airborne measurement program should be initiated. Use of an aircraft would permit making the much needed in situ physical measurements on the cirrus (for size distribution, temperature, and water vapor) clouds nearly concurrently with lidar probing of the clouds, and with upward- and downward-looking radiometric measurements.

The aircraft would also provide the mobility required to move quickly into regions where specific cirrus had been detected (or suspected) from satellite APT pictures or ground reports. This mobility would alleviate the problem of the long wait for just the right meteorological situation to form over a fixed ground station.

C. Theoretical Study of Backscattering from Ice Crystals

The nature of ice crystal backscattering of laser energy and the relationship between the backscatter and extinction coefficients warrants

further theoretical investigation before complete confidence can be placed in the particle concentration profiles inferred from the lidar cloud signatures. The surface wave explanation (see Sec. III-B) should be examined to see whether it is applicable to irregularly shaped ice crystals.

For ruby laser probing, where the cirrus crystals are so much larger than the wavelength, it is expected that forward-scattered light will largely be added into the incident beam and therefore that the particle extinction efficiency factor may not always be assumed to be two as it is in some places in the report. Zdunkowsky et al. (1965) and Hall (1968) have used a value of unity in their computations when absorption may be neglected. However, for the narrow field of view of lidar receivers (1 mr and less for most of the data collected for this report), a value near two is probably more appropriate.

D. Cirrus Cloud Models

The problem of developing useful computational models for cirrus clouds should be given much more attention than it could be given on this project. Monte Carlo techniques appear to be well suited for treating the transfer of lidar beams. However, they are not necessarily the most practical techniques for computing the diffuse radiance over the infrared spectrum. Computation of the transfer of infrared radiation in a nonhomogeneous atmosphere in the presence of absorption, scattering, and emission is a formidable task. Moreover, if a model is too sophisticated, it may be too cumbersome for routine applications to experimental data. During this project, promising initial steps were taken with a greatly simplified model that is suitable for comparisons with medium-resolution satellite or surface radiometric measurements. The simplified model is limited in that certain "bulk" parameters for the tenuous cloud must be specified as input data. Therefore, meaningful relationships must be established between these bulk parameters and the particle size distribution. With the size distribution and the relationship, the simplified model could then be used to describe the radiative effects of cirrus from space or surface views for any desired set of atmospheric conditions.

E. Measurements in Support of a Radiometric Satellite

In spite of the unfortunate failure of the Nimbus B radiometric satellite, plans should still include concurrent measurements with a ground-based lidar whenever a suitable radiometric satellite finally becomes available. One worthwhile experiment would be to obtain lidar cirrus observations and temperature profiles during overflights of the satellite, then to deduce the upper-level relative humidity required to give agreement in different spectral channels.

F. Ground Based Lidar Versus Solar Infrared Transmission Through Cirrus

A relatively modest extension of the present work could provide a technique for deducing the water vapor present in cirrus clouds, in lieu of thermal tuning of the laser. Infrared spectral observations of the sun could be made, in and out of water vapor lines and in and out of cirrus patches. This technique would also yield transmission measurements for lidar wavelengths independent of lidar-deduced transmissions. Lidar transmission measurements could be made at a number of zenith angles, so that the angular dependence of the transmission could be determined statistically. The great variability within cirrus would require a statistical treatment.

G. Climatological Studies

Much evidence exists that satellite-viewed cloud cover does not, on some occasions, reveal the presence of cirrus and that, on others, it reveals only the partial extent of such cloud cover. A fuller understanding of the total nature and distribution of such cloud cover (for example, in deepening cyclones, on the east side of high-pressure ridges, in the vicinity of jet streams, and from the cirrus blowoffs from cumulonimbus) can be developed from studies that consider concomitant satellite-viewed cloud cover from geosynchronous and near-synchronous orbits and (perhaps at even shorter intervals) lidar soundings. From such studies, models could be constructed that would extend the use of satellite-viewed cloud cover, with respect to the expected or inferred distribution and the nature of cirrus cloud, a function only partially performed by the current meteorological satellites.

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Appendix A

PROCEDURE FOR DERIVING OPTICAL PARAMETERS FROM THE LIDAR SIGNATURE

1. Volume Backscattering Coefficients

The method of evaluating backscatter coefficients and transmission factors for an actual lidar waveform is shown in Fig. A-1. An enlarged image of the waveform is projected onto the screen of a scaling machine, and the operator attempts to pick inflection points that, when joined by straight lines, will provide a good trapezoidal-area approximation to the original curve. Then X and Y values for these inflection points are digitized for entry into a computer.

The lidar equation can be written as:

$$P_r = k_9 T_a^2 T_c^2 \beta'_{180} / R^2 \quad (A-1)$$

or

$$\beta'_{180} = \frac{P_r R^2}{k_9 T_a^2 T_c^2},$$

where

$$k_9 = \frac{c \tau P_t A_r}{8\pi} = \frac{c}{8\pi} U_t A_r$$

$$T_c^2 = \exp \left[-2 \int_0^{R'} \sigma(R) dr' \right] = \text{cloud transmission factor (two-way)}$$

$$T_a^2 = \text{Atmospheric transmission factor (two-way) between lidar and cloud base.}$$

For the experimentally derived data,

$$P_r = k_2 k_5 k_6 Y \quad (A-2)$$

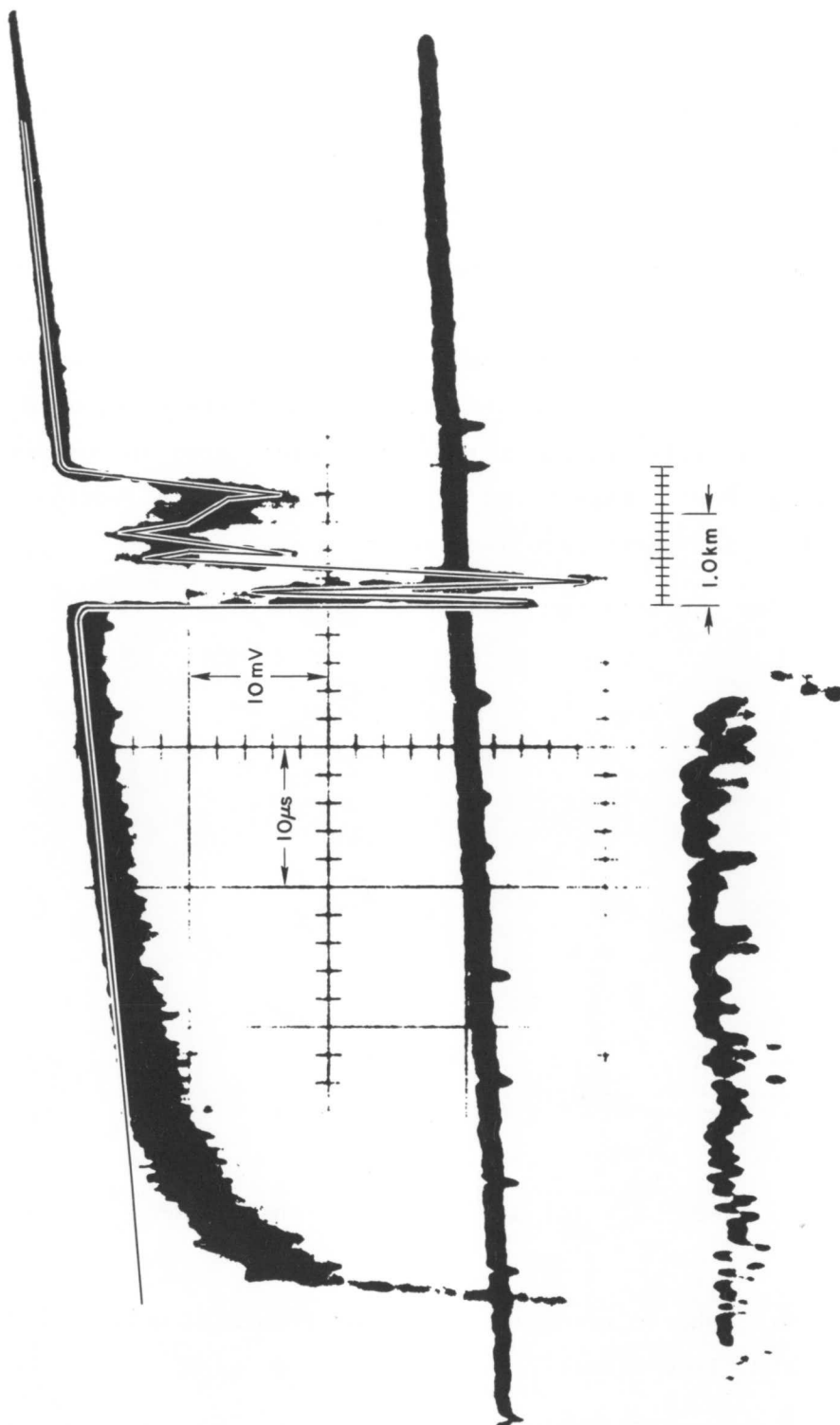


FIG. A-1 METHOD OF APPROXIMATING LIDAR WAVEFORM FOR COMPUTATION

where

Y = scaling machine "Y" reading (counts)

k_2 = Y-axis scale factor (cm/count)

k_5 = display deflection factor (v/cm)

k_6 = lidar receiver response factor (w/v)

and

$$R = k_1 k_7 k_8 X \quad , \quad (A-3)$$

where

X = scale machine "X" reading (counts)

k_1 = X-axis scale factor (cm/count)

k_7 = display horizontal deflection factor ($\mu\text{s}/\text{cm}$)

k_8 = range factor = 0.150 (km/ μs).

Thus,

$$\beta'_{180} = \frac{(k_2 k_5 k_6 Y)(k_1 k_7 k_8 X)^2}{k_9 T_a T_c} = k_o Y X^2$$

Substituting Eqs. (A-2) and (A-3) into (A-1),

$$k_2 k_5 k_6 Y R^2 = k_9 T_a^2 \cdot T_c^2 \beta'_{180} \quad ,$$

or

$$D_y R^2 = \frac{k_9}{k_5 k_6} T_a^2 \cdot T_c^2 \beta'_{180} \quad , \quad (A-4)$$

where

$D_y = k_2 Y$ = CRO Y - axis deflection (cm).

Then β'_{180} for any range and deflection can be expressed in terms of the return obtained from a calibration region as follows:

$$\beta'_{180} = \frac{D_y}{D_{y(c)}} \left[\frac{R}{R(c)} \right]^2 \left[\frac{T_{a(c)}}{T_a} \right]^2 \left[\frac{T_{c(c)}}{T_c} \right]^2 \frac{(k_5 k_6/k_9)}{[k_5 k_6/k_9]_{(c)}} \beta'_{180(c)} \quad (A-5)$$

The (c)'s indicate values taken at a calibration point, commonly from the Rayleigh molecular backscatter at an altitude of about 10 km. Highest-accuracy data are obtained when conditions are such that both the calibration and the data values can be read from the waveform produced by a single shot, in which case one can be assured that

$$\frac{(k_5 k_6/k_9)}{[k_5 k_6/k_9]_{(c)}} = 1$$

and

$$\left[\frac{T_{a(c)}}{T_a} \right]^2 = 1$$

When this is not possible, care must be taken that the lidar performance and the lower-atmosphere attenuation during data runs cannot be expected to be significantly different from their values during the calibration run. For the Mark II ruby lidar operating on a clear day, typical values for a calibration run are:

$$R_{(c)} = 10 \text{ km}$$

$$\beta'_{180(c)} = 2.2 \times 10^{-3} \text{ (km}^{-1}\text{)}^*$$

$$D_{y(c)} = 0.02 \text{ cm}^\dagger$$

$$T_{c(c)} = 1 \text{ (data taken below any cloud layers).}$$

* Elterman, (1964) quotes σ (10 km, 0.7 μ) = 1.47×10^{-3} (km⁻¹). For Rayleigh scattering, $\beta'_{180} = 1.50 \sigma$. Thus β'_{180} (10 km, 0.7 μ) = (1.50) (1.47×10^{-3}) = 2.21×10^{-3} (km⁻¹).

† This is an equivalent deflection derived as described in Appendix B.

Substituting these values into Eq. (A-5) gives

$$\beta'_{180} = (1.15 \times 10^{-3}) D_y R^2 / T_c^2 \quad (A-6)$$

In terms of input values from the film-reading machine, this is

$$\beta'_{180} = (1.15 \times 10^{-3})(k_2 Y)(k_1 k_7 k_8 X)^2 / T_c^2 \quad (A-7)$$

Using Eq. (A-7) the computer figures values for β'_{180} at each inflection point. For a first-order approximation, the attenuation within the cloud is ignored, and T_c is taken as 1 for all points. For most of the cirrus measured to date, the error introduced by neglecting attenuation at this point appears to be small by comparison with the measurement precision for other reasons. For cases where this approximation is not valid, however, a program option adjusts the value of β'_{180} for the upper boundary of each trapezoidal-area increment by first finding the approximate average β'_{180} over the increment, dividing this by an assumed K to obtain an approximate attenuation coefficient, σ , for the region, computing T_c for the range increment involved, and using the resulting value in solving Eq. (A-6) for β'_{180} at the upper boundary, as well as for the first trial in the next higher increment. This procedure can be repeated, if necessary, to obtain a still better approximation. Next, the program computes values of β'_{180} averaged over successive 0.1-km range increments. Since there may be zero, one, or more than one inflection point within each 0.1-km increment, the average is obtained by summing trapezoidal areas and dividing by the range increment--that is,

$$\bar{\beta}'_{180} = \frac{\int_{R'}^{R'+0.1} \beta'_{180}(R) dR'}{0.1} \quad (A-8)$$

A display of these values of β'_{180} versus altitude provides one good means of communicating lidar data to human analysts. For cirrus clouds, numerical values of β'_{180} can be expected to range from about $5 \times 10^{-3} \text{ km}^{-1}$

(barely greater than the Rayleigh molecular scattering at 10-km elevation) up to values at least two orders of magnitude greater [Evans et al. (1966), Fig. VI-2, p. 84].

To compress this gamut into a 10-level code for simple display purposes, the following transformation is employed:

$$\text{Backscatter Code Digit} = 5 \log_{10} (100 \bar{\beta}'_{180})$$

(rounded to the nearest integer).

(A-9)

The resulting code is listed in Table A-I.

Table A-I
CODE USED TO SPECIFY β'_{180} ON CHARTS

Code Digit	Volume Backscattering Coefficient, β'_{180} (km^{-1}) (append 10^{-3} to all values)
0	Trace-13
1	13-20
2	20-32
3	32-50
4	50-80
5	80-128
6	128-200
7	200-320
8	320-500
9	500-800

2. Backscattering Optical Thickness

By analogy with the "optical thickness," τ , commonly used to denote $\int \sigma(R) dR$, it is convenient to define a "backscattering optical thickness," τ_{β} , for the total vertical path through the cloud:

$$\tau_{\beta} = \int \beta'_{180} (R) dR$$

Here τ_β is a dimensionless number that may best represent the overall backscattering "strength" of a cloud. It is directly obtainable from the lidar data by summing the values of $\bar{\beta}'_{180}$ for each 0.1-km-altitude increment derived as described above.

In addition, if the backscatter-to-attenuation ratio can be assumed to be constant or nearly constant, k , τ_β provides a means for estimating the optical transmission properties of the cloud:

$$\text{Optical thickness, } \tau, \approx \frac{\tau_\beta}{k} \quad (\text{A-10})$$

$$\text{One-way transmission, } T, = \exp(-\tau) \approx \exp(-\tau_\beta/k) \quad (\text{A-11})$$

$$\text{One-way attenuation (in dB)} \approx 4.343 \frac{\tau_\beta}{k} \quad (\text{A-12})$$

From Sec. IV-A of this report, for cirrus, $k_1 \approx 0.4$.

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Appendix B

AMPLITUDE CALIBRATION OF LIDAR RECEIVER AT VERY LOW LIGHT LEVELS

This section describes the procedures used to make quantitative measurements in the difficult transition region between "photon-counting" and "anode-current waveform" methods of data analysis.

An accepted technique for measuring extremely low light levels is to employ a photomultiplier having a small cathode area (small source of thermally emitted electrons) and sufficient electron multiplier gain (10^7 or more) that anode pulses resulting from individual photon absorption events at the photocathode can be viewed on an oscilloscope or used to activate a pulse counter.

While this technique is simple, represents perhaps the ultimate in sensitivity, and has the advantage of being fairly quantitative (independent of the photomultiplier tube operating potential), it cannot be used for large signal levels. When the pulse rate becomes great enough that the interpulse period becomes comparable to the pulse width, the pulses tend to overlap and are difficult or impossible to count. While the primary cathode events are presumed to be instantaneous, the resulting anode pulses in a typical PMT are at least 10 to 20 ns wide because of transit time spread in the multiplier section, and usually they are further widened by limited bandwidth in the CRO display.

Larger light levels must be measured by reading the average anode current resulting from the contribution of many overlapping pulses. This measurement is subject to long-term calibration drift because of changes in multiplier gain and short-term fluctuation (noise) due to statistical variation in the anode pulse amplitudes, but it is the mode of operation currently used to record most lidar returns.

For the SRI Mark II lidar, the signal return from very weak cirrus unfortunately lies in the transition region between these two modes of operation, a region where accurate measurements are difficult to make by either procedure.

Returns due to Rayleigh scattering in clear air in our calibration region around 10-km elevation average about 10 pulses/ μ s and are definitely in the pulse-counting regime.

Returns from cirrus dense enough to be visible from the ground are normally at least one to two orders of magnitude stronger and are definitely in the average anode current regime. In order to provide a calibration bridge between these two regimes and to facilitate visual interpretation of very weak return as recorded via the Polaroid oscillograms, a special test was run to show the behavior of the complete Mark II lidar system in the transition region and for the scale factors and bandwidths normally used for cirrus measurements.

The experimental setup is shown schematically in Fig. B-1. The photomultiplier was illuminated by a pulsed light source that could be varied in intensity by calibrated amounts over a several-decade range. The light source was a silicon light-emitting diode capable of rise and fall times of a few nanoseconds. It was pulsed with rectangular pulses 10 μ s wide to simulate the return from a uniform cloud 5000 feet (1.52 km) thick. Light power could be varied in 5-dB increments by a combination of changing the driving pulse amplitude and using calibrated 5-, 10-, and 20-dB neutral-density filters of the evaporated film type.

Results for a series with no background light are shown in the Polaroid-recorded waveforms reproduced in Fig. B-2. The display horizontal scan rate was set at 10 μ s/cm for the top (main) trace and at 0.5 μ s/cm for the bottom trace, whose start was delayed to coincide with the leading edge of the light pulse. The center (straight-line) trace should be ignored in this series.

With one exception, vertical deflection sensitivities were 10 mV/cm for the top trace and 5 mV/cm for the bottom trace. All these settings correspond to those used for the great majority of cirrus measurements made for the project.

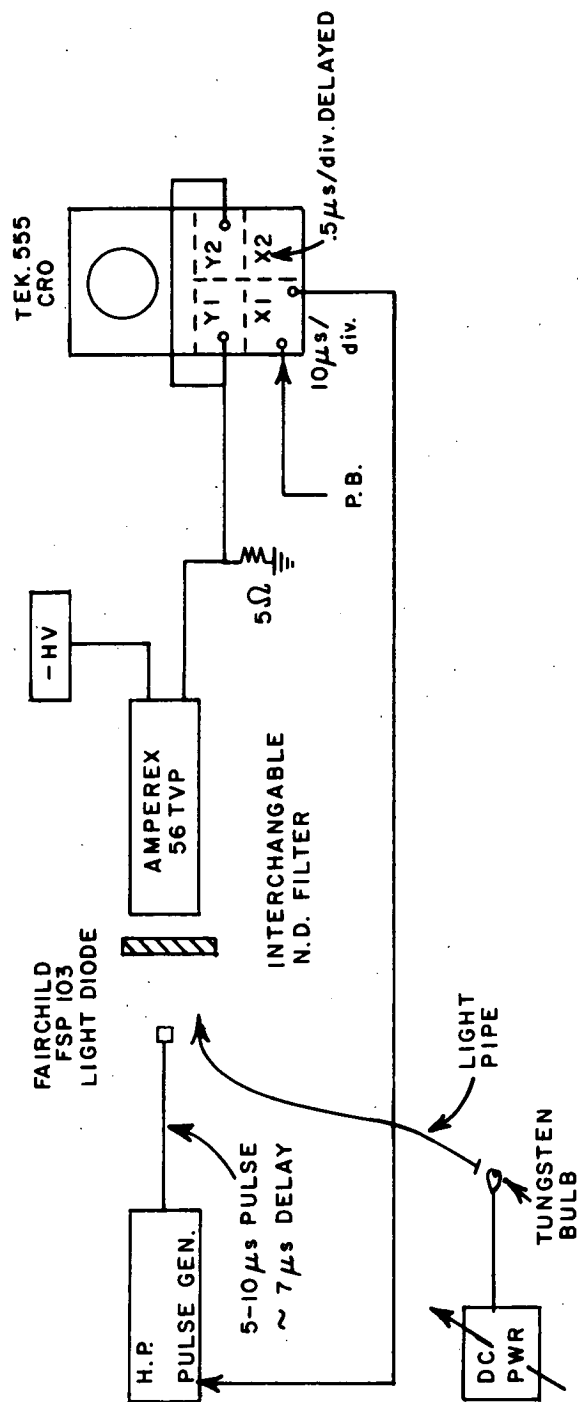
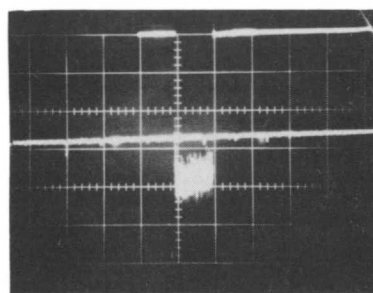
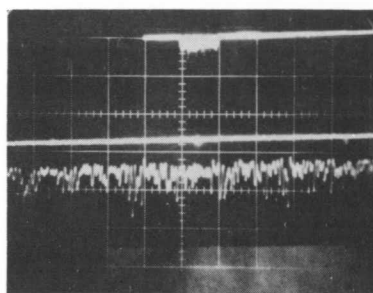


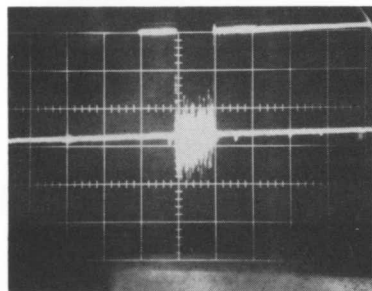
FIG. B-1 BLOCK DIAGRAM OF EXPERIMENTAL SETUP



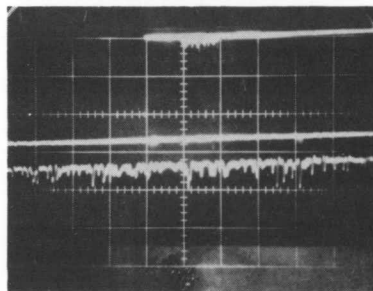
** (a) LIGHT PULSE RELATIVE AMPLITUDE $Pr = 0 \text{ dB}$



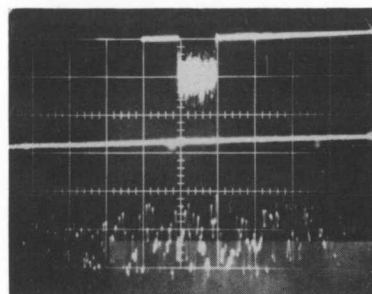
* (e) $Pr = -20 \text{ dB}$



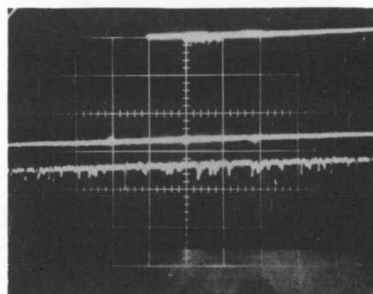
* (b) $Pr = -5 \text{ dB}$



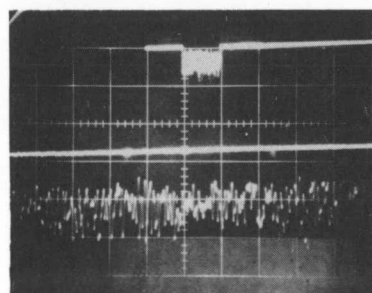
* (f) $Pr = -25 \text{ dB}$



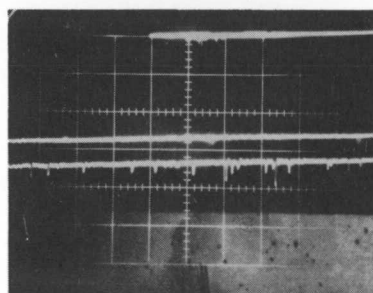
* (c) $Pr = -10 \text{ dB}$



* (g) $Pr = -30 \text{ dB}$



* (d) $Pr = -15 \text{ dB}$



* (h) $Pr = -35 \text{ dB}$

	*	**
TOP TRACE HORIZ. ($\mu \text{ sec/div}$)	10	10
TOP TRACE VERT. (mV/div)	10	20
BOTTOM TRACE HORIZ. ($\mu \text{ sec/div}$)	0.5	0.5
BOTTOM TRACE VERT. (mV/div)	5	5

FIG. B-2 SIMULTANEOUS ANALOG AND PULSE-COUNTING WAVEFORMS RESULTING FROM SMALL $10\text{-}\mu\text{s}$ LIGHT PULSES

Although the results are not illustrated here, it was also possible to flood the photocathode with varying amounts of continuous light from a tungsten bulb to simulate ambient background conditions. It can be seen that the strongest 10- μ s light pulse yields an analog display whose amplitude can be read fairly accurately. (Note that the pulse peak for the first shot only was off scale at the normal 10-mV/cm deflection factor and required use of 20 mV/cm.) As the light pulse amplitude is progressively reduced in 5-dB (factor-of-3.2) steps, the "fuzz" on the top of the pulse caused by shot-noise fluctuation becomes a larger and larger percentage of the average pulse amplitude.

Interpretation becomes more complex when the signal becomes so small [Fig. B-2(e)] that the appearance of the "fuzz" is no longer symmetrical, making it difficult to estimate the average level at the peak of the pulse. At still lower levels the "fuzz" is almost completely unidirectional, and the apparent height of the average signal is significantly dependent upon the brightness of the display (that is, in some records, sections of the top trace that have been intensified for indexing purposes can mistakenly be interpreted as cloud returns unless the analyst has been alerted to the problem).

The lower (expanded) traces in Fig. B-2 show that the level at which the "fuzz" just ceases to appear symmetrical (also evidenced by a barely perceptible "lifting" of the baseline) corresponds with the level at which pulse pileup is sufficiently severe to seriously bias the analyst's ability to count individual quantitative pulses.

For our system, this transition point occurs at about 20 pulses/ μ s and provides an important link between data taken at lower levels by pulse counting and data taken at higher levels by reading analog waveforms.

In Fig. B-3 data taken by both methods are combined on a single graph. A 45° line adjusted by eye for best fit to the experimental data is used when necessary during data analysis to bridge the gap between the two methods of light power measurement.

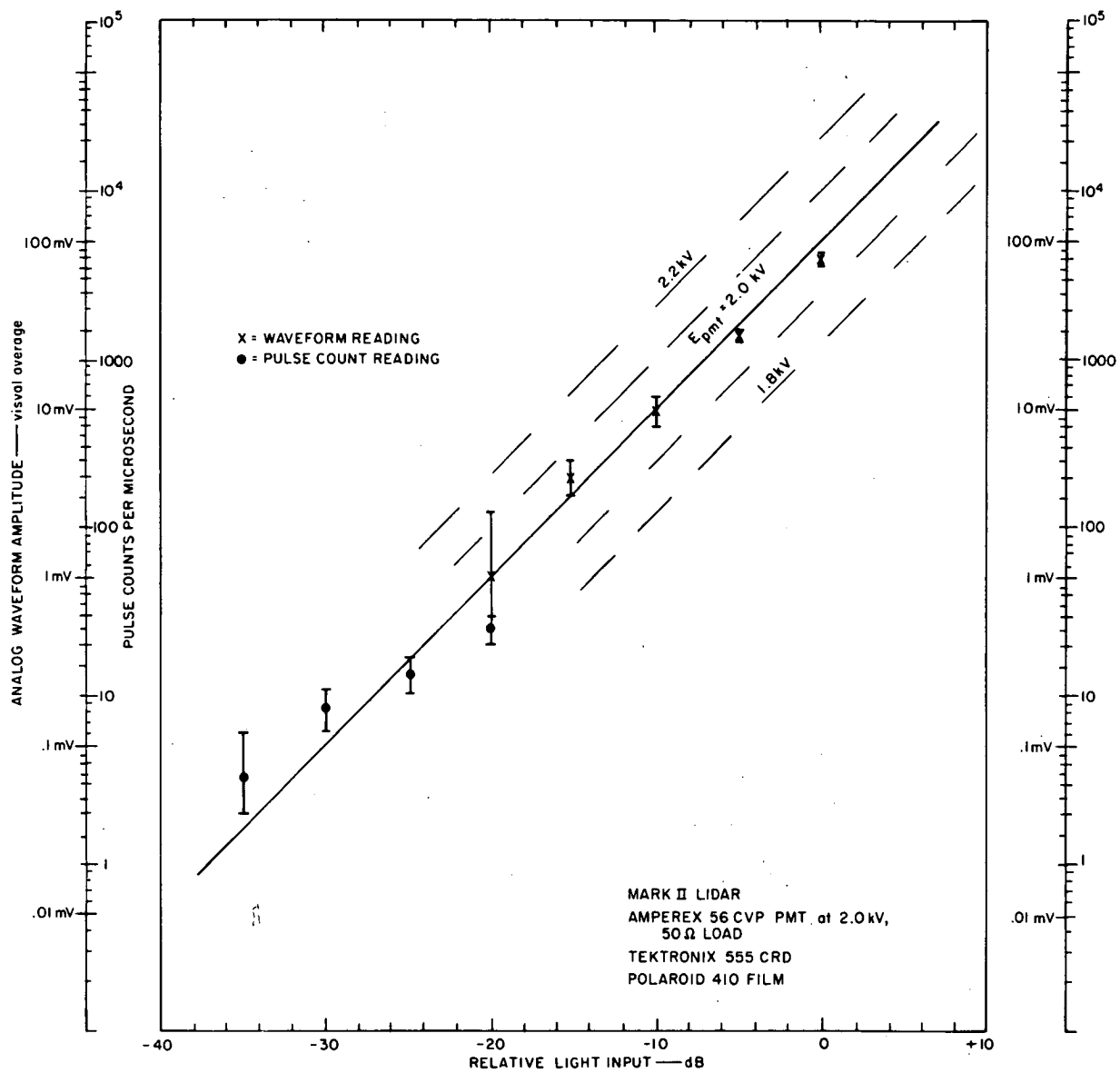


FIG. B-3 INTERPRETATION OF LIDAR RECORDINGS IN THE TRANSITION REGION BETWEEN PULSE COUNTING AND ANALOG WAVEFORM MODES

The error bars shown in Fig. B-3 indicate one standard deviation according to Poisson statistics for the pulse-count readings and a visual estimate of the rms noise ("fuzz") amplitude for the analog readings. The apparent departure from 45° slope in the pulse-count region for the data sample is not completely understood, but it is presumed to result from pulse overlapping at the higher count rates. In similar experiments made with the same equipment, the expected 45° trend was followed more closely.

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CONTRIBUTORS

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REFERENCES

1. Barteneva, O. D. and E. A. Polyakova, "A Study of Attenuation and Scattering of Light in a Natural Fog Due to Its Microphysical Properties," Bull. Acad. Sci., USSR, Atmos. & Ocean. Phys., Vol. 1, No. 2, pp. 114-121 (February 1965).
2. Blau, H. H. Jr., E. M. Duchane, R. P. Espinola, E. C. Reifenstein, III, P. C. von Thuna, and E. A. Vrablik, "Infrared Spectral Characteristics of High-Altitude Clouds," Technical Report No. 2, Contract NONR 3556 (00), for Advanced Research Projects Agency Optics Branch, Ballistic Missile Defense, Arthur D. Little, Inc., (December, 1963).
3. Elterman, L., "Atmospheric Attenuation Model, 1964, in The Ultraviolet, Visible, and Infrared Regions for Altitudes to 50 km," AFCRL Report No. 64-740; Environmental Research Papers, No. 46 (September 1964).
4. Evans, W. E., E. J. Wiegman, W. Viezee, and M. G. H. Ligda, "Performance Specifications for a Meteorological Satellite Lidar," Final Report, Contract NASr-49(22), SRI Project 5373, Stanford Research Institute, Menlo Park, California (June 1966).
5. Fenn, R. W., 1966: "Correlation Between Atmospheric Backscattering and Meteorological Visual Range," Appl. Optics, Vol. 5, p. 293.
6. Fritz, S. and P. Krishna Rao, "On the Infrared Transmission Through Cirrus Clouds and the Estimation of Relative Humidity from Satellites," J. Appl. Meteor., Vol. 6, pp. 1088-1096 (1967).
7. Hall, F. F., "The Effect of Cirrus Clouds on 8-13 μ Infrared Sky Radiance," Applied Optics, Vol. 7, No. 5, pp. 891-898 (May 1968).
8. K. Ya. Kondrat'yev, "Radiative Heat Exchange in the Atmosphere," Translated by O. Tedder, Copyright 1965, Pergamon Press Ltd., London, England, 411 p.
9. McDonald, R. C., et al., "Infrared Reflection Measurements on Cirrus Clouds," Boeing Company Document D2-20981, Final Report, Contract AF 04(695)-45 (30 June 1962).
10. Penndorf, Rudolf, "Angular Mie Scattering," J. Optical Soc. Amer., Vol. 52, p. 402 (April 1962).
11. Roberts, W. O., "To Master Our Atmospheric Environment," Bull. Am. Met. Soc., Vol. 47, No. 3 (1966).

12. Schotland, R. M., "Some Observations of the Vertical Profile of Water Vapor by Means of a Laser Optical Radar," Proc. of the Fourth Symposium on Remote Sensing of the Environment, 12-13 April 1966, University of Michigan, Ann Arbor (June 1966).
13. Van de Hulst, H. T., Light Scattering by Small Particles, J. Wiley and Sons, New York, New York (1957).
14. Van Ornum, D. G., "Global Tropopause Maps by Satellite," J. Meteorol., Vol. 18, pp. 234-241 (1961).
15. Wells, M. B., D. G. Collins, and K. Cunningham, "Light Transport in the Atmosphere," Vol. I of Monte Carlo Studies, Technical Report RRA-T63-1, Contract DA 28-043 AMC-000240(E), Radiation Research Associated, Fort Worth, Texas (September 1966).
16. Zdunkowski, W., D. Henderson, and J. V. Hales, "The Influence of Haze on Infrared Radiation Measurements Detected by Space Vehicles," Tellus, Vol. XVII, No. 2, pp. 147-166 (1965).

STANFORD RESEARCH INSTITUTE



Main Offices and Laboratories

333 Ravenswood Avenue
Menlo Park, California 94025
(415) 326-6200
Cable: STANRES, Menlo Park
TWX: 910-373-1246

Regional Offices and Laboratories

Southern California Laboratories

820 Mission Street
South Pasadena, California 91030
(213) 799-9501 • 682-3901
TWX: 910-588-3280

SRI-Washington

1611 North Kent Street, Rosslyn Plaza
Arlington, Virginia 22209
(703) 524-2053
Cable: STANRES, Washington, D.C.
TWX: 710-955-1137

SRI-New York

200 E. 42nd Street
New York, New York 10017
(212) 661-5313

SRI-Huntsville

Missile Defense Analysis Office
4810 Bradford Blvd., N.W.
Huntsville, Alabama 35805
(205) 837-3050
TWX: 810-726-2112

SRI-Chicago

10 South Riverside Plaza
Chicago, Illinois 60606
(312) 236-6750

SRI-Europe

Pelikanstrasse 37
8001 Zurich, Switzerland
27 73 27 or 27 81 21
Cable: STANRES, Zurich

SRI-Scandinavia

Skeppargatan 26
S-114 52 Stockholm, Sweden
60 02 26; 60 03 96; 60 04 75

SRI-Japan

Edobashi Building, 8th Floor
1-6, Nihonbashi Edobashi
Chuo-ku, Tokyo
Tokyo 271-7108
Cable: STANRESEARCH, Tokyo

SRI-Southeast Asia

Bangkok Bank Building
182 Sukhumvit Road
Bangkok, Thailand
55292 or 58673
Cable: STANRES, Bangkok

Representatives

France

Roger Godino
94, Boulevard du Montparnasse
75 Paris 14^e, France
633 37 30

Italy

Lorenzo L. Franceschini
Via Macedonio Melloni 49
20129 Milan, Italy
72 32 46

Philippines

Roberto V. Ongpin
Sycip, Gorres, Velayo & Co.
P.O. Box 589
Manila, Philippines
Telephone: 88 55 41
Cable: Certified

Portugal

J. Gasparinho Correia
Avenida João XXI, 22-3^o Esq.
Lisbon, Portugal
72 64 87