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San Diego, CA 92152-5000

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# Evaluation of Aerosol Size Distribution Models

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International Corporation

# NAVAL OCEAN SYSTEMS CENTER

San Diego, California 92152-5000

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In this study, measurements of the aerosol optical thickness using different techniques were compared. The objective was to investigate the feasibility of using satellite data for FLIR performance prediction. The Science Applications International Corporation (SAIC) provided satellite and sunphotometer ground truth measurements, and the Naval Ocean Systems Center provided aircraft and infrared sky radiance measurements of aerosol properties. This report describes the SAIC measurements.

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The author would like to thank H.G. Hughes and D.R. Jensen for providing assistance in the sunphotometer measurements, and for arranging for satellite data to be obtained from Scripps.

# 1.0 INTRODUCTION

The Navy aerosol model (1) is important for prediction of atmospheric optical (visible and infrared) properties over the ocean, and hence for predicting the performance of FLIR systems. The use of satellite measurements to measure the aerosol size distribution in the marine boundary layer has been demonstrated by Science Applications International Corporation (SAIC) (2,3,4) and provides the possibility of using satellite measurements to make predictions of FLIR performance.

In addition to developing the measurement of aerosol properties from satellites, SAIC has applied the technique to correcting infrared sea surface temperature measurements for the effects of aerosols (5), demonstrating that there is a relationship between aerosol properties in the visible and infrared regions. This suggests that there is a strong possibility that satellite data can be used for FLIR performance prediction.

In this study, measurements of the aerosol optical thickness using different techniques were compared, with the objective of investigating the feasibility of using satellite data for FLIR performance prediction. SAIC provided satellite and sunphotometer ground truth measurements, and Naval Ocean Systems Center (NOSC) provided aircraft and infrared sky radiance measurements of aerosol properties. This report describes the SAIC measurements.

## 2.0 TECHNICAL BACKGROUND

We showed some years ago, under NASA sponsorship (2,3), that it is possible to make satellite observations of the aerosol optical thickness of the atmosphere using radiance measurements over the ocean. Calculations showed that a linear relationship exists between the upwelling visible radiance measure by a satellite over the ocean, and the aerosol optical thickness of the atmosphere. The technique is most useful over water surfaces since they have a low reflectance (close to zero) so that the upwelling radiance is essentially all due to atmospheric scattering. Over land surfaces, which have much larger albedos, the upwelling radiance is mostly reflected from the surface, and less sensitive to change in the atmospheric aerosols. Radiance data from Landsat 1 (2), Landsat 2(3), NOAA-5 and GOES (3) have been used with sunphotometer ground truth data to demonstrate that a linear relationship exists between the radiance and the aerosol content. These studies were supported by theoretical calculations to investigate the effect of varying aerosol optical properties, such as size distribution and refractive index, and other parameters such as vertical distribution, surface reflectivity, wavelength, sun angles and satellites viewing angles.

An unexpected application of this technique arose as a result of the El Chichon volcano eruption in late March and early April, 1982. This eruption produced a layer of stratospheric aerosol that severely reduced the quality and quantity of multichannel sea surface temperature (SST) measurements by the NOAA-7 AVHRR. We showed (5) that the MSST measurements could be successfully corrected by inferring the El Chichon aerosol optical thickness from the AVHRR Channel 1 radiance. The error in the SST was found to be proportional to the optical thickness along the sensor line of sight to the ocean.

In order to investigate the general applicability of the technique to different locations, a global-scale ground truth experiment (4) was conducted in 1980 with the AVHRR sensor on NOAA-6 to determine the relationship at eleven ocean sites around the globe. The NOAA-6 AVHRR was chosen for this experiment because it provides daily coverage, it has a narrow spectral bandpass (0.65 μm) in the visible region (almost identical to the Landsat MSS 5), and has 1 km spatial resolution. [illegible] thickness relationship with that found previously for the MSS 5, theoretical calculations were made with the Dave(6) atmospheric scattering code to account for the off-nadir scanning of the AVHRR in comparison to the nadir viewing of the MSS. The atmospheric model used aerosol parameters such that the theory reproduced the linear regression between radiance and aerosol optical thickness found for MSS 5. The results of the calculations were incorporated into a table look-up algorithm so that the AVHRR radiance measurement together with the scan angle and sun angles can be used as input to obtain the aerosol content. The ground-truth measurements of aerosol content were made at the time of the NOAA-6 overpasses (approximately 0730 l.s.t.) with hand-held sunphotometers at eleven sites in close proximity to the ocean.

The results (4) for the 1980 experiement are shown in Fig. 2-1 for sun zenith angles less than 70 degrees. Data for larger sun angles are not presented since the flat earth model used in developing the table look-up code may introduce errors at large sun angles. The data show no obvious differences between the sites in Fig. 2-1 and for all sites combined the correlation coefficient between the satellite and ground truth measurements is 0.95.

SAIC developed (4) a method using AVHRR Channels 1 and 2 to to infer the value of $\nu$ in the Junge size distribution:

$$dn(r) = Cr^{-\nu}\ d \log r\ (\mathrm{cm}^{-3}) \qquad (2\text{-}1)$$

where n(r) is the number of particles with radius r, and C is a constant depending on the number of particles per unit volume.

The value of $\nu$ is inferred from the satellite data by comparing the Channel 1 and 2 radiances (the Channel 2 radiance is corrected for water vapor absorption) with model calculations of these radiances, made as a function of optical thickness and $\nu$ for many sets of sun and view angles. The values of optical thickness and $\nu$ are determined so that the model radiances agree with the measured radiances in each AVHRR channel for the given sun and view angles at the time of the measurement. A two-channel table look-up code, similar to the Channel 1 code was developed, covering v values between 0 and 7.0; typical $\nu$ values in the atmosphere lie between 2.0 and 5.0.

The results of using this two-channel technique are shown in Fig. 2-2 and represent the only known satellite measurements of tropospheric aerosol size distributions. The large scatter of the Barbados data in Fig. 2-2 is believed to be due to sunphotometer errors.

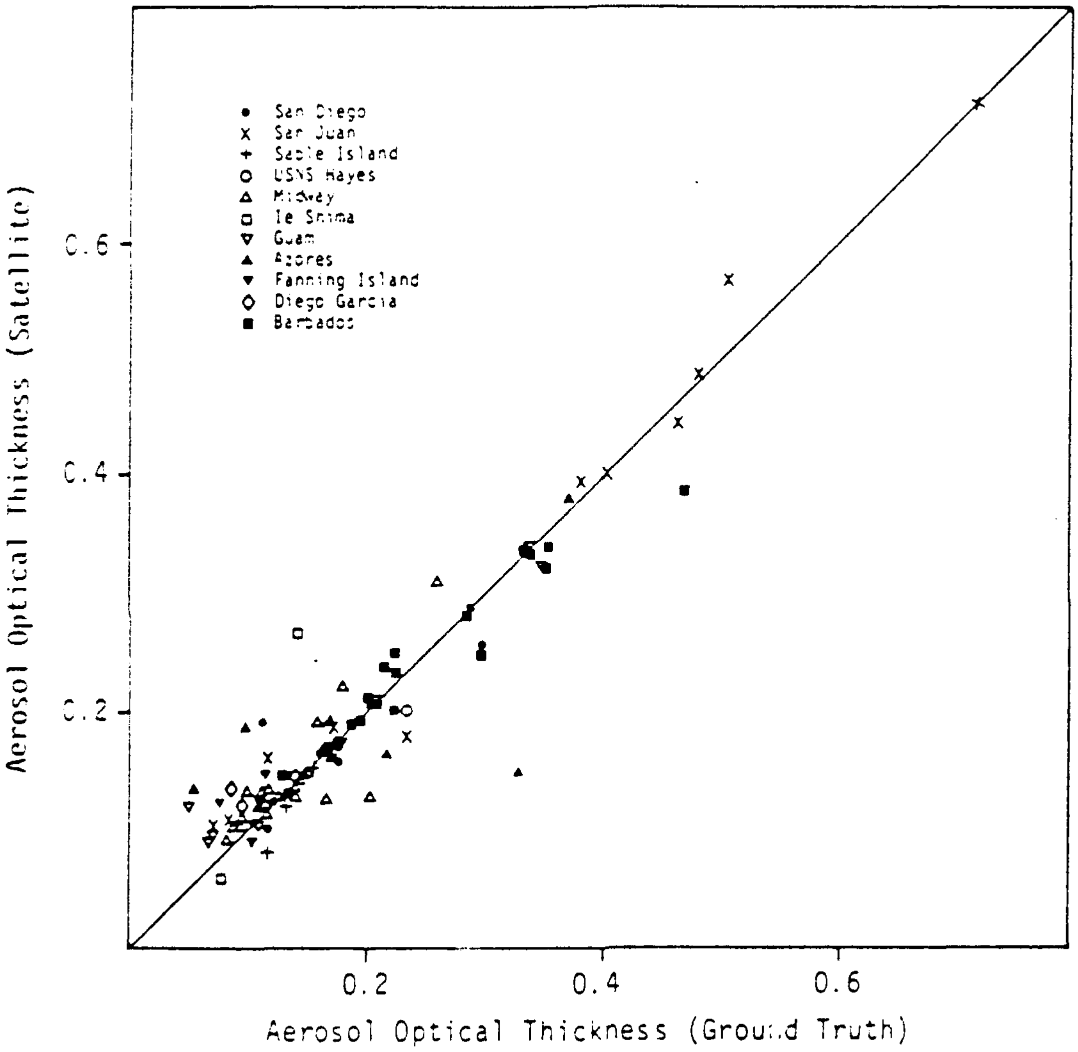

Figure 2-1 Comparison of All Sites for 1980 Experiment (for $\theta_o < 70^o$).

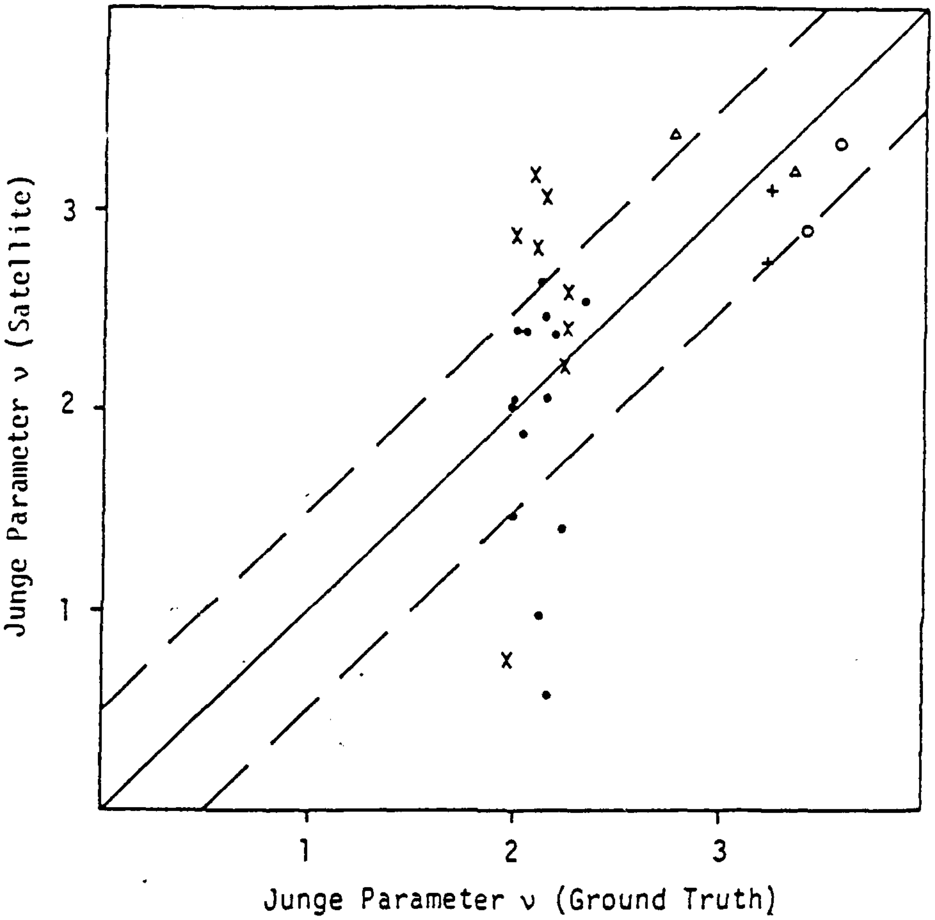

Figure 2-2 Comparison of Satellite and Ground Truth Measurements of the Junge Parameter [· x ($\theta_0$ >70°) Barbados; o + ($\theta_0$ >70°) USNS Hayes; Δ Alboran Sea].

## 3.0 APPROACH

The experiments were conducted at the NOSC facility on Point Loma, San Diego at the time of the NOAA-9 overpass (approximately 1430 local standard time). The NOAA-9 was chosen over the NOAA-10 (overpass at about 0730 local standard time) in anticipation of less cloud cover and more variety of conditions (wind and visibility) in the afternoon.

NOSC conducted aircraft measurements of the aerosol size distribution as a function of altitude through the boundary layer using a Knollenberg spectrometer. At the same time, NOSC made measurements of the horizon sky using an AGEMA imager in the 8-12 um spectral region.

SAIC made ground truth measurements of the aerosol optical thickness using an EKO sunphotometer, Model MS-120. This sunphotometer is designed to WMO recommendations, and has a peak hold digital display, with wavelengths of 368, 500, 675 and 778 nm, and was calibrated against a WMO standard.

The NOAA-9 AVHRR radiance data were converted to aerosol optical thickness and size distribution using SAIC techniques described in Section 2.0.

# 4.0 MEASUREMENTS

Measurements were planned for the period May 1 to November 25, 1987. The satellite observations are best made looking away from the sun, in order to avoid possible sunglint from the ocean surface. Hence, NOSC calculated the satellite position and overpass time each week in order to schedule the aircraft for the experiment. A further requirement of the experiment is that the cloud cover (including cirrus) should be small enough that clear lines of sight from the satellite to the ocean, and from the sunphotometer to the sun, are achieved.

During the seven month period of the planned experiments, the San Diego weather was unusually cloudy along the coastal regions, and data for only 4 out of 93 potentially usable non-glint overpasses were obtained due to cloud cover (data were also obtained on three days when sunglint was possible, although it is estimated that the glint effect was probably negligible.) Thus cloud cover restricted data to about 4% of the total non-glint overpasses. This is in sharp contrast to the 1975-77 period during a similar study at SAIC when data were obtained for 44% of Landsat 2 overpasses at San Diego.

## 4.1 Sunphotometer Measurements

The sunphotometer observations were made at NOSC at the approximate time of the NOAA-9 overpass. A complete set of measurements (four wavelengths) was taken, three times at five minute intervals. The results of the measurements are given in Table 4-1 together with the airmass (calculated from the ephemeris).

$$I = \frac{I_0}{F} e^{-m(T_A + T_R + T_0)}$$

where $I$ is the sunphotometer reading

$I_0$ is the calibration constant

$m$ is the airmass

$T_R$ is the Rayleigh optical thickness

$T_0$ is the ozone optical thickness

$F$ is the square of the earth-sun distance (AU)

The values of these parameters, as they apply to the EKO sunphotometer are given in Table 4-2. The correction to $T_R$ for non-standard atmospheric pressure was negligible during this experiment.

The sunphotometer calibration constants given in Table 4-2 were provided by the manufacturer and were obtained in comparison with a WMO standard. A check of these constants by means of a Langley plot was made at SAIC facility on February 2, 1988. The plots were not good straight lines indicating that the aerosol optical thickness was varying during the measurements. However, the accuracy was sufficient to suggest that the instrument calibrations were correct, except for 778 nm, for which $I_0$ appears to be low. However, if the measured value is used, then the inferred aerosol optical thicknesses at NOSC are negative or close to zero, which is clearly unreasonable. Thus, it is assumed that the instrument $I_0$ for 778 nm was as given during the NOSC measurements, and that it may have changed since then.

The spectral variation of the aerosol optical thickness as measured at the eight NOAA-9 overpasses is given in Fig 4-1a, b, c. The straight line represents the best fit to a Junge size distribution. It has been shown that if the spectral variation of the aerosol optical thickness ($T_A$) is given by:

$$T_A = B\lambda^{-\alpha} \qquad (4\text{-}1)$$

where B and $\alpha$ are constants, and if a Junge size distribution is assumed for the aerosols:

$$dn(r) = Cr^{-\nu}\, d(\log r)\ (\mathrm{cm}^{-3}) \qquad (4\text{-}2)$$

were n(r) is the number of particles with radius r , and C is a constant, then, to a close approximation:

$$\alpha = \nu - 2 \qquad (4\text{-}3)$$

The values of $\nu$ inferred from the plots in Figs. 4-1 a,b,c, are given in the figures.

## TABLE 4-1

## Sunphotometer Readings/Aerosol Optical Thickness

|  |  |  | Wavelengths |  |  |  |
|---|---|---|---|---|---|---|
| DATE | TIME(GMT) | m | 368nm | 500nm | 675nm | 778nm |
| 6-30-87 | 2213 | 1.18 | 46.7/.335 | .444/.118 | .962/.070 | .582/.048 |
| thin cirrus | 2219 | 1.20 | 46.8/.319 | .435/.130 | .944/.084 | .572/.061 |
|  | 2224 | 1.22 | 45.1/.336 | .420/.155 | .902/.119 | .561/.075 |
| 9-08-87 | 2307 | 1.72 | 38.3/.200 | .428/.069 | .965/.040 | .599/.019 |
| large patches | 2311 | 1.76 | 37.7/.193 | .430/.061 | .956/.043 | .594/.023 |
| of cirrus | 2316 | 1.80 | 36.8/.191 | .419/.071 | .942/.049 | .594/.022 |
|  | 2320 | 1.84 | 36.1/.187 | .421/.064 | .947/.043 | .586/.029 |
| 9-17-87 | 2253 | 1.73 | 31.4/.314 | .363/.165 | .863/.106 | .552/.069 |
| hazy | 2258 | 1.77 | 30.9/.305 | .370/.148 | .868/.099 | .553/.066 |
|  | 2303 | 1.82 | 30.3/.294 | .367/.144 | .863/.099 | .549/.068 |
| 9-29-87 | 2230 | 1.73 | 28.4/.464 | .362/.171 | .727/.210 | .400/.259 |
| some low | 2235 | 1.77 | 29.2/.341 | .354/.198 | .816/.139 | .544/.079 |
| level cloud | 2245 | 1.85 | 27.0/.347 | .351/.174 | .815/.131 | .547/.072 |
| 11-03-87 | 2241 | 2.52 | 22.8/.198 | .359/.084 | .844/.075 | .552/.051 |
| clear | 2246 | 2.61 | 21.8/.191 | .351/.085 | .843/.071 | .545/.053 |
|  | 2251 | 2.70 | 21.0/.182 | .348/.081 | .845/.066 | .550/.047 |
| 11-12-87 | 2250 | 2.89 | 11.2/.357 | .253/.178 | .730/.111 | .507/.072 |
| very hazy | 2255 | 3.00 | 11.6/.314 | .257/.161 | .743/.099 | .516/.063 |
|  | 2300 | 3.13 | 11.6/.280 | .263/.141 | .728/.099 | .524/.055 |
| 11-24-87 | 2225 | 2.61 | 16.2/.308 | .312/.132 | .822/.084 | .556/.047 |
| very hazy | 2230 | 2.69 | 16.9/.269 | .314/.122 | .820/.081 | .554/.047 |
|  | 2235 | 2.78 | 14.9/.289 | .293/.138 | .795/.087 | .545/.050 |
| 11-25-887 | 2203 | 2.33 | 21.0/.293 | .366/.096 | .811/.107 | .529/.077 |
| hazy | 2208 | 2.38 | 20.0/.297 | .323/.144 | .790/.115 | .519/.083 |
|  | 2211 | 2.42 | 19.7/.291 | .323/.139 | .792/.111 | .523/.078 |

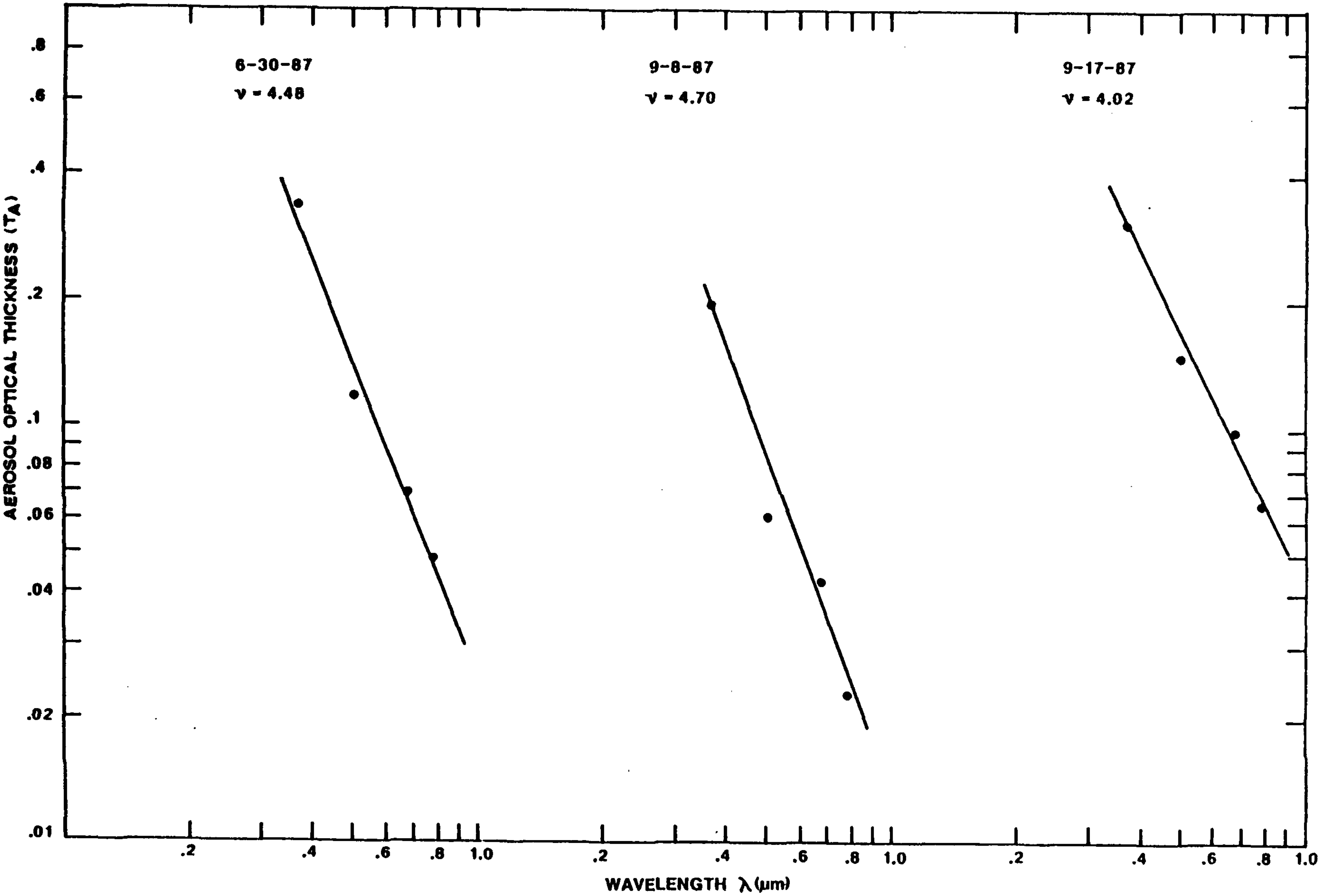

Figure 4-1a Measured Spectral Variation of Aerosol Optical Thickness

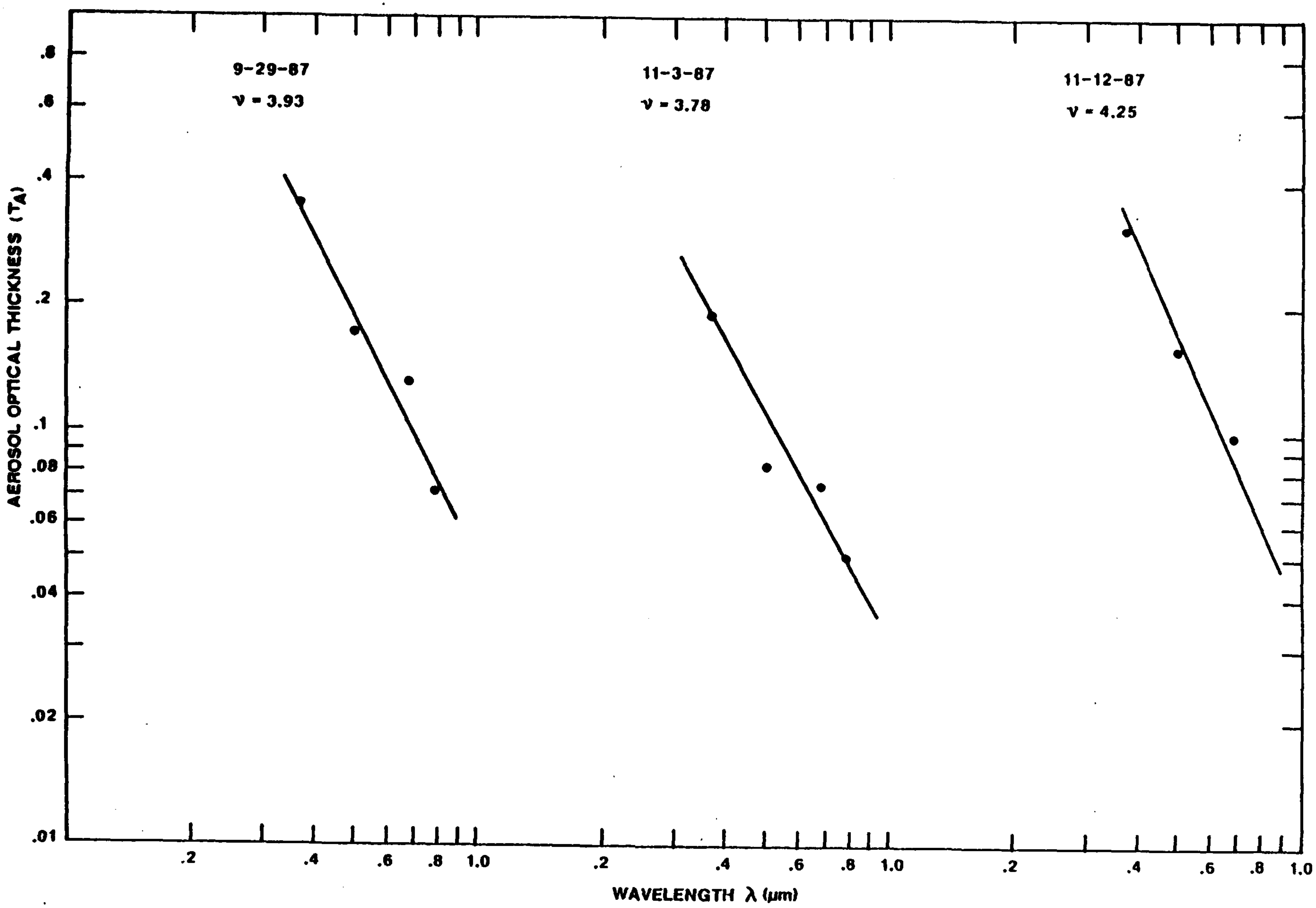

Figure 4-1b Measured Spectral Variation of Aerosol Optical Thickness

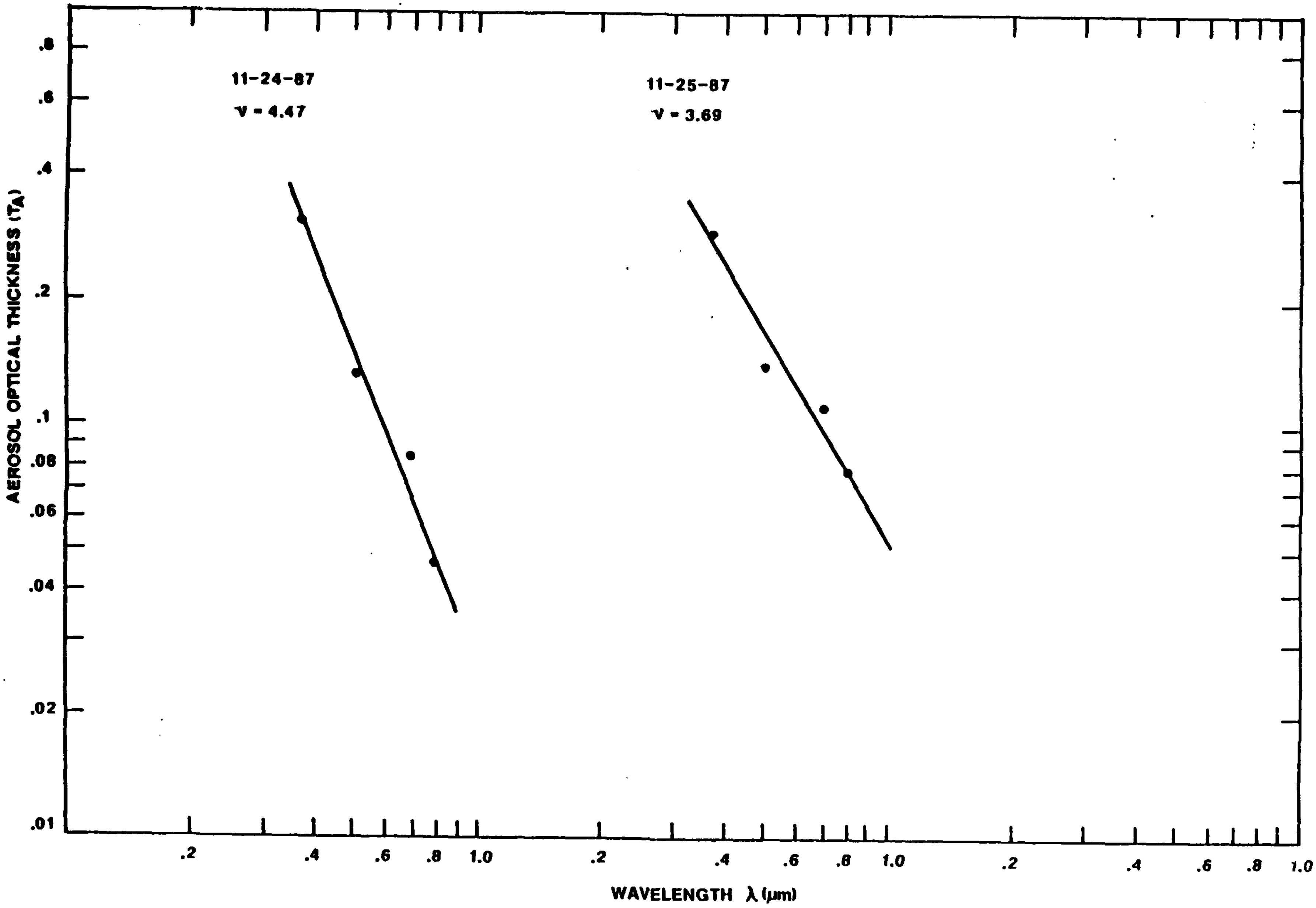

Figure 4-1c Measured Spectral Variation of Aerosol Optical Thickness

## TABLE 4-2

## Sunphotometer Instrument Parameters

| Wavelength | 368nm | 500nm | 675nm | 778nm |
|---|---|---|---|---|
| $I_0$ | 128.54 | 0.623 | 1.153 | 0.654 |
| $T_R$ | 0.495 | 0.139 | 0.041 | 0.023 |
| $T_O$ | 0 | 0.011 | 0.014 | 0 |

## 4.2 NOAA-9 Measurements

The AVHRR data for the dates in Table 4-1 were requested from NOAA, but were not available for 6-30-87 and 9-8-87. Fortunately, they were available from Scripps Satellite Oceanography Facility, although the 6-30-87 data could not be used due to its poor quality.

The AVHRR data and the derived optical thickness and size distribution parameter are given in Table 4-3. The digital data in the vicinity of the experiment was examined for horizontal inhomogeneities along the IR imager line of sight (20km). None was found with the 4km resolution of the AVHRR data.

The radiance values in Table 4-3 are calculated in the same way as done previously for NOAA-6 and -7, i.e.., Channel 1 Radiance = (% Albedo x 0.49 x F + 0.50) $mw/cm^2/um/sr$ and Channel 2 Radiance = (% Albedo x 0.35 X F - 0.10) $mw/cm^2/um/sr$. The factors for converting albedo to radiance are slightly different from those for NOAA-6 and -7 due to different filter bandpasses. The additonal factors (+0.50 for Channel 1 and -0.10 for Channel 2) are the same as used previously (5) to adjust the NOAA provided calibration so that a plot of Channel 1 radiance vs Channel 2 radiance goes through the origin.

The negative values of satellite zenith angle in Table 4-3 indicate that the sensor was pointed toward the sun, so that sunglint effects are possibly enhancing the measured radiance over the non-glint conditions that are normally required for this technique. However, for the three potential glint data sets in Table 4-3, it is found from the work of Wald and Monget(9), that the effect of glint may be neglected. Wald and Monget analyzed sunglint effects on the sea surface reflectance in terms of the Cox and Munk model and included the effects of foam. Their analysis shows that for the sun and satellite angles in the three data sets, the glint effect is negligible below wind speeds of 5 m/s. On all three days the 24 hours mean windspeed was less than 5 m/s, and the instantaneous windspeed values were 7.5, 6.8 and 2.6 m/s for 9-29-87, 11-24-87 and 11-25-87, respectively. Thus, is is assumed that these satellite data are suitable for inferring the aerosol optical thickness.

## TABLE 4-3

## AVHRR DATA

| Date | Channel 1 |  | Channel 2 |  | Satellite Zenith Angle | Sun-Satellite Azimuth Angle | Solar Zenith Angle | Chl 1 | Ch 1 & Ch 2 |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | %Albedo | Radiance ($mw/cm^2/um/sr$) | %Albedo | Radiance ($mw/cm^2/um/sr$) | $\theta$ | $\phi$ | $\theta_o$ | $T_A$ | $T_A$ | $\nu$ |
| 9-08-87 | 2.5 | 1.73 | 1.4 | .39 | 30.8 | 171.7 | 52.6 | .076 | .068 | 2.45 |
| 9-17-87 | 2.6 | 1.78 | 1.5 | .43 | 34.1 | 167.2 | 57.6 | .098 | .099 | 2.79 |
| 9-29-87 | 2.3 | 1.63 | 1.5 | .43 | -15.0 | 17.9 | 55.9 | .168 | .223 | 2.22 |
| 11-03-87 | 1.7 | 1.32 | 1.1 | .28 | 20.0 | 154.9 | 70.0 | .162 | .100 | 5.55 |
| 11-12-87 | 1.9 | 1.41 | 1.2 | .31 | 23.4 | 153.0 | 72.2 | .207 | .116 | 5.97 |
| 11-24-87 | 2.7 | 1.79 | 1.8 | .52 | -27.6 | 30.9 | 69.0 | .264 | .261 | 3.57 |
| 11-25-87 | 3.1 | 1.98 | 2.0 | .58 | -42.0 | 31.7 | 67.5 | .169 | .182 | 2.93 |

Two sets of values for the inferred aerosol optical thickness are given. The first uses just the Channel 1 radiance, and the second is derived together with the Junge parameter using Channels 1 and 2. In previous studies (e.g. Fig. 2-1) the Channel 1 value has generally been used.

## 4.3 Comparison of Satellite and Ground Truth Measurements

The satellite and sunphotometer values of the aerosol optical thickness (at 0.5 μm) and the Junge size distribution parameter are compared in Table 4-4 and in Figs. 4-2 and 4-3.

The Channel 1 optical thickness values are compared with a much larger data set (4) in Fig. 4-2. It is seen that the present results fall within the scatter of the previous data. The satellite and ground truth values of $\nu$ do not agree well, as shown in Fig. 4-3, as was found in previous experiments, suggesting that more data and developmental work are needed for the two channel technique.

## TABLE 4-4

## Comparison of Satellite and Sunphotometer Measurements

| | AVHRR (CH 1) | AVHRR (CH 1 & CH 2) | | Sunphotometer | |
|---|---|---|---|---|---|
| DATE | $\tau_A$ | $\tau_A$ | $\nu$ | $\tau_A$ | $\nu$ |
| 9-08-87 | .076 | .068 | 2.45 | .061 | 4.70 |
| 9-17-87 | .098 | .099 | 2.77 | .148 | 4.02 |
| 9-29-87 | .168 | .223 | 2.22 | .174 | 3.93 |
| 11-03-87 | .162 | .100 | 5.55 | .084 | 3.78 |
| 11-12-87 | .207 | .116 | 5.97 | .161 | 4.25 |
| 11-24-87 | .264 | .261 | 3.57 | .132 | 4.47 |
| 11-25-87 | .169 | .182 | 2.93 | .139 | 3.69 |

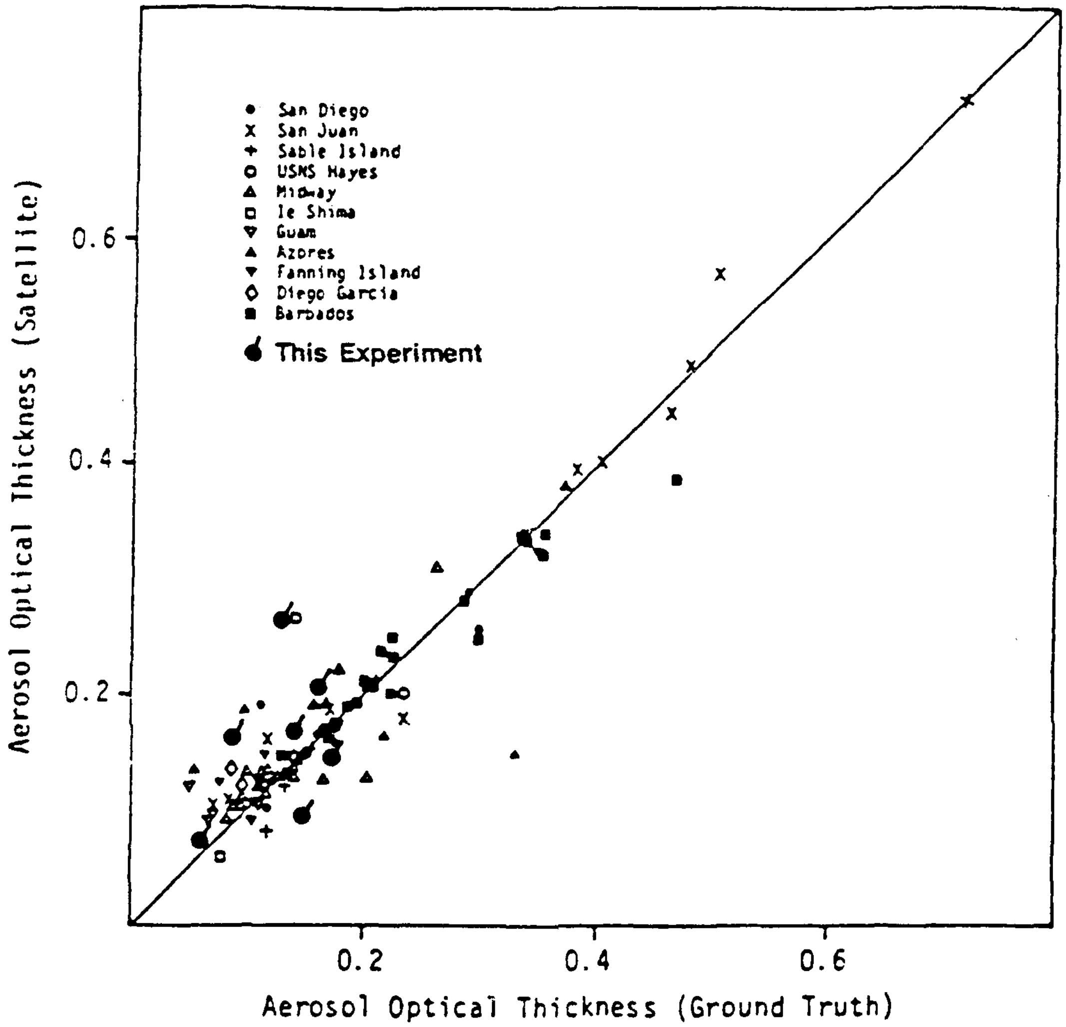

Figure 4-2 Comparison of this experiment (●) with previous 1980 NOAA Experiment

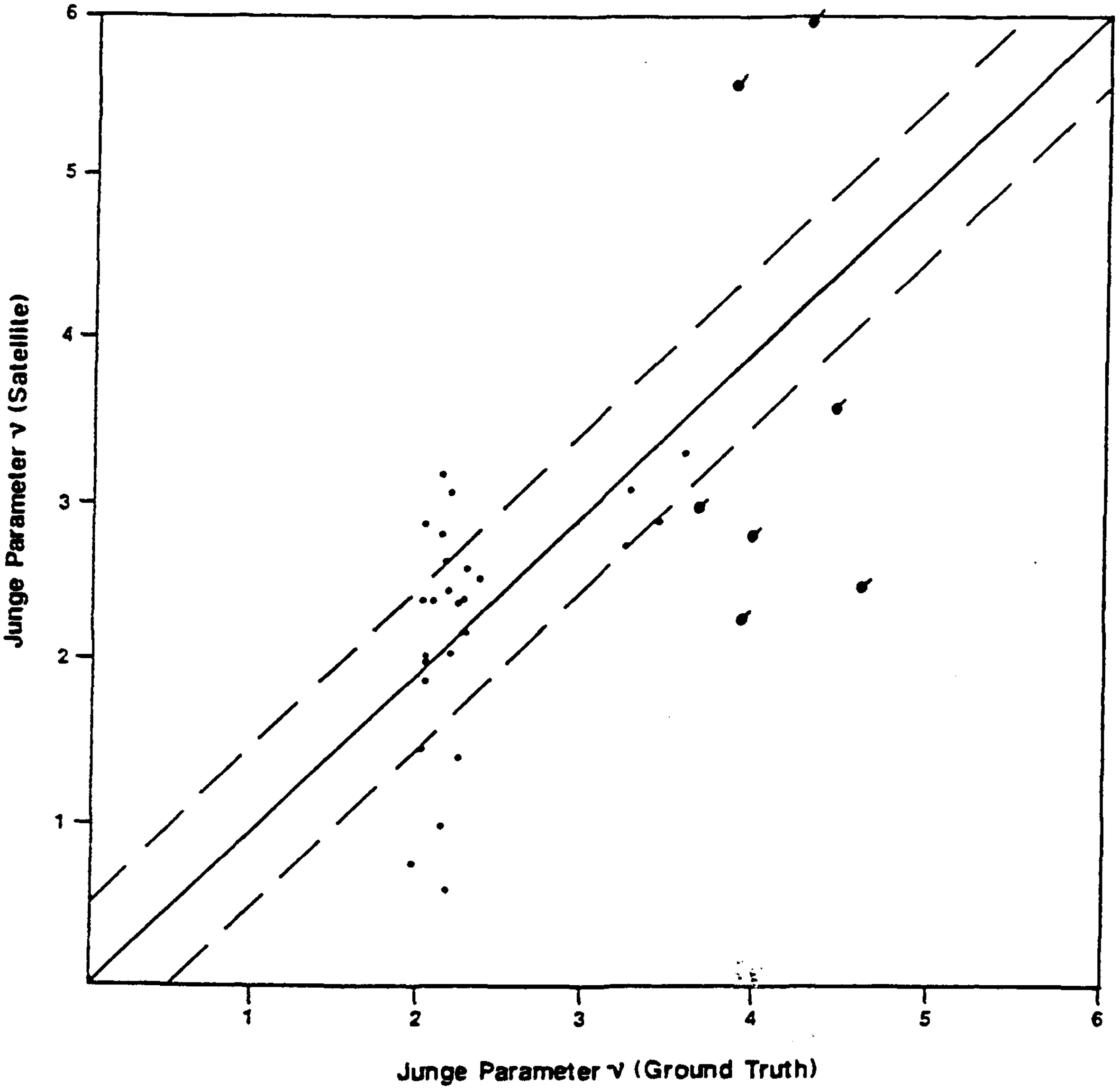

Figure 4-3 Comparison of this experiment (●) with previous measurements.

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

The agreement between the satellite and the sunphotometer measurements of aerosol optical thickness is similar to that of previous experiments, but the agreement for the size distribution is poorer. The data set is much smaller than had been anticipated; in addition three of the seven data points are questionable due to the possible influence of sunglint on the satellite measurement. Thus, no firm conclusions can be reached on the basis of these few data.

It is recommended that the experiment, which is low cost, be repeated and continued until an adequate data set of at least twenty points is acquired.

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