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SATELLITE AND ROCKET OBSERVATIONS OF STRATOSPHERIC ATTENUATION IN THE NEAR ULTRAVIOLET IN 1962-1964

by

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1. INTRODUCTION

Frith (1963) described the occultation technique for observing the vertical distribution of ozone in the Earth's atmosphere from a satellite. The amount of ozone in the ray path between the Sun and the satellite can be derived from measurements of the attenuation of sunlight in the absorption band centred near 2600Å. Corrections must be applied for other sources of attenuation, such as scattering by air molecules and by any dust which may be present in the atmosphere. Miller and Stewart (1965) gave a preliminary report of an experiment, flown on the Ariel 2 satellite during 1964, which made use of this technique. Two rocket flights had been made in 1962 and 1963 to test the technique and the basic instrumentation; two further flights were made while Ariel 2 was in orbit to check the stability of its sensors. Analysis of data from one of the latter flights, in April 1964, revealed considerable extra attenuation between 20 and 40 km caused by dust (Miller, 1967).

The purpose of this paper is to report the full results obtained from the dust attenuation experiment on the Ariel 2 satellite. The experiment was unable to resolve the vertical structure of the dust layer. However the spatial distribution of the dust attenuation near 30 km and its decline over the period from April to August 1964 are revealed. Results from two of the supporting rocket flights are also reported.

2. EXPERIMENTAL

The satellite sensor consisted of a photocell with an antimony-caesium cathode (Rank Cintel, type VTA 2) and a disc of filter glass (Chance, OV1) which together defined a spectral passband between 350 and 420 nm. This combination was mounted on the top of the satellite, looking outwards along the spin axis. A polished aluminium paraboloidal mirror, mounted above the detector, provided it with a large field-of-view, covering 360° in roll about the satellite's longitudinal axis and up to 45° either side of the satellite's equatorial plane. The mirror was supported by a fused-silica tube and held in place by four tie-rods, each of which interrupted the field-of view for 5 to 10° of roll angle. A more detailed description of the sensor has been published elsewhere (Miller, 1967).

The anode current from the photocell was amplified to produce a voltage; this voltage was sampled by the telemetry system at intervals of 1.75 sec and converted to a frequency suitable for storage by the satellite's tape-recorder. Every eighth data sample was replaced by a telemetry format synchronisation tone. Data were recorded for two sections of each orbit, arranged to contain the transit of the satellite into and out of the earth's shadow. The tape-recorder was replayed once each orbit and the received signals subsequently digitised on a 100-level scale.

3. EXPERIMENTAL DETERMINATION OF ATMOSPHERIC ATTENUATION

The first stage in analysing data from any occultation experiment is to interpret sensor output in terms of variation of the solar intensity at the satellite. The Ariel 2 satellite was spin-stabilised, with an initial spin-rate of $60^{\circ}sec^{-1}$. This rotation, together with non-uniformity in response of the sensor, produced a modulation superimposed upon the required time variation of the sensor signal. However this modulation, and in particular the sharp dips caused by the shadows of the tie-rods, permitted a precise determination of the roll period and phase. The un-attenuated signals were combined, using this value of the roll period, to produce a plot of the signal variation with roll angle in full-sunlight. Individual observations near sunrise or sunset were compared with the full-sunlight signal at the appropriate roll angle given by this plot to derive the attenuation, or 'signal ratio'.

The analysis was made more complicated by a drift in the full-sunlight signal within each data set. This drift also showed up as a decrease in mean signal, of about 15%, between the start and end of the sunlit part of each orbit. The drift was attributable partly to a change in sensor sensitivity and partly to the detection of light scattered from the lower atmosphere. The size and time-scale of the changes in sensitivity caused un-acceptably large uncertainties in the derived attenuation as the satellite left the earth's shadow. The magnitude of the "albedo radiation" was dependent on the satellite's height and orientation, and sometimes amounted to as much as 10% of the full-sunlight signal. However it was only present when the satellite was passing over the sunlit side of the earth, and so only affected derivation of the full-sunlight signal. A small correction was applied for the known non-linearity of the relationship between telemetry output and light intensity at the sensor.

Because of the very low sampling rate it was necessary to obtain values of the attenuation from individual data points. Therefore the uncertainty in each value of the attenuation was dominated by the uncertainty, of ±0.5% of the full-scale range of the telemetry, caused by the digitisation of the data. In contrast the full-sunlight signal could normally be derived to ±0.2% of full-scale. At the start of the satellite's life the full-sunlight signal was about 60% of the telemetry full-scale and the maximum uncertainty in a deduced signal ratio of 50% was ±1.2%. Over four months the sensitivity decreased and the uncertainty in the attenuation became about ±2%. The scatter of the signal ratios obtained at ray heights greater than 90km, where attenuation should be completely negligible, was always consistent with these estimates of the uncertainty.

The observation height, H, associated with each value of attenuation is defined as the instantaneous closest approach distance to the Geoid of a straight line from the satellite to the centre of the Sun's disc. The Hayford ellipsoid was used to describe the Geoid, and the satellite's position has been derived from orbital elements provided by Gooding (1965). The total uncertainty in ray height, taking account of possible errors in the time of the observation and in satellite position, was estimated to be less than ± 0.2km.

4. THE SATELLITE OBSERVATIONS

The Ariel 2 satellite (1964-15A) was launched on 27 March 1964 into an orbit with an inclination of 51°. The perigee height was 290km, the apogee height 1450km and the orbital period 101 minutes. For the reasons given in the previous section, analysis has been confined to those observations made as the satellite entered the Earth's shadow: these will be termed sunsets. The latitude of observation changed little between successive orbits, while longitude was displaced westward by about 25°. Precession of the orbital plane, and the motion of the Earth around the Sun, produced a variation in the latitude of the sunsets which is shown in figure 1. During two brief periods the orbit was entirely in sunlight and no observations were available.

Two major factors limited the total amount of data which was obtained. Firstly, performance of the tape-recorder provided for on-board data storage was very erratic from the last week of April to the end of July. Many of the playbacks contained little or no data and occasionally the command timing pulses were not replayed. The latter fault re-appeared and became almost continuous during September and the recorder failed completely at the beginning of October, 1964. In addition, because of interaction between the atmosphere and the solar-cell paddles, the spin-rate of the satellite decreased by about 0.1% per orbit. This interaction also caused the direction of the spin-axis of the spacecraft to wander outside design limits so that the Sun was periodically outside the field-of-view of the sensor. This caused a complete loss of data for the periods indicated in Figure 1.

The net outcome was that almost all useful observations were confined to the first three weeks in orbit (27 March to 18 April), the first half of May and a few days in early June, and the first half of August. During these three periods the sunset observations provided latitude scans from 60°S to 45°N, from 75°N to 35°N and 30°S to 40°S, and from 30°N to 50°S respectively.

Values of those parameters which influence the height resolution and accuracy of the attenuation measurements within these periods are summarised in Table 1.

5. THEORETICAL INTERPRETATION OF ATMOSPHERIC ATTENUATION

A number of mechanisms contribute to the total attenuation of sunlight by the atmosphere in the spectral range 350 to 420nm. The actual paths of the rays are influenced by the refractive properties of the atmosphere and the rate-of-change of refraction with height leads directly to attenuation. Scattering by air molecules and absorption by ozone occur along the ray path. In addition, dust may cause a loss of energy from the beam, by scattering and absorption.

With the exception of the contribution from dust, the attenuation caused by each of the other factors may be computed from a knowledge of the height distribution of the air density and ozone and of the geometry of the observations. The computing scheme described in an earlier paper (Miller, 1967) was adopted with only one significant modification. This concerned the calculation of angular deviation, caused by refraction, for rays passing tangentially through the atmosphere. The analytical method described by Goody (1963), in which the air density profile is represented by an exponential model with a constant scale-height for the few kilometers above the closest approach height of each ray, was used in place of summation along the ray path. Since detailed air density profiles were not available for much of the satellite data, the use of this simplified method was completely justified.

Air scattering was the most important component in the attenuation for a dust-free atmosphere. The contribution from differential refraction was fairly minor when the satellite was near perigee, but it became almost as important as air scattering at apogee. By comparison, absorption by ozone was negligible. Although attenuation was initially computed for a point Sun, allowance has to be made for the smoothing caused by rays from opposite limbs of the Sun's disc passing through the atmosphere at different heights. This height range depended on the orbital height of the satellite, and varied from about 16km at the perigee of the orbit to 40km for observations made near apogee (see Table 1). The attenuation for the complete Sun's disc was obtained by combining point-sun calculations, with weighting factors based on the projected area of the Sun's disc and the solar limb darkening.

Values of the air density for the northern hemisphere for the dates and latitudes appropriate to the satellite observations were derived from daily charts for pressure levels between 300 and 10mb (Debenec et al, 1964; Kriester et al, 1964a, Kriester et al, 1964b; ESSA, 1967a). In the absence of any such charts above 300mb for the southern hemisphere, seasonal mean values were used (Goldie, Moore and Austin, 1958; Heastie and Stephenson, 1960), supplemented where applicable by data for Australia for levels up to 10mb. The longitudinal variation of density derived from the daily charts was averaged out. For levels above 30 km densities were based upon monthly mean values, taken from CIRA (1965), with some additional information from a series of weekly charts at 5, 2 and 0.4mb (ESSA, 1967b). Latitude cross-sections of air density expressed as a percentage of the US Standard Atmosphere (1962) value at each height were produced, the date being adjusted with latitude to follow the satellite's sunset observations. Height profiles of air density were extracted from these cross-sections at intervals of about 10° in latitude, and the corresponding variation of the signal ratio, or attenuation with ray height, H, computed for a dust-free atmosphere. These results were used to construct latitude cross-sections with which the observed attenuation could be compared to reveal any attenuation by dust (Figure 2).

The height smoothing, caused by the finite angular size of the Sun, was so great that the satellite observations could only provide very limited information about the magnitude or vertical distribution of the dust attenuation. Therefore it was necessary to postulate a model of the dust attenuation, the parameters of which could be varied to fit the observations. The adopted model had only two variable parameters: a scale-height which defined the exponential decrease in dust attenuation above 20km and a value of the attenuation at the arbitrary height of 28.9km. Attenuation was assumed to remain constant below 20km. This form of model was chosen because it had been found adequate to represent the dust attenuation observed under more favourable conditions (ie smoothing of only 11km) during the rocket flight from Woomera (35°S, 135°E) shortly after the launch of the Ariel 2 satellite (Miller, 1967).

The signal ratio was computed for a series of these models, described by a range of values of the attenuation at 28.9km for each of three values of the scale height. Typical results for a scale height of 3.25km are shown, as depressions from the appropriate dust-free signal ratio, in Figure 3. The effect of altering scale-height while maintaining the attenuation constant at 28.9km is shown in Figure 4. In both of these Figures results are shown separately for two rather extreme values of the effective diameter of the Sun, appropriate for sunsets in April and August. For each sunset the observed values of attenuation were compared with an appropriate set of curves of the type illustrated in Figure 3. The best-fit value of the attenuation at 28.9km has been taken to be that for which the computed line satisfies all the observations within their individual digitisation uncertainty, even though the mean deviation of the observations from the line may not be zero.

Generally there was a range of values of attenuation at 28.9km which satisfied all observations for a given sunset. The limits of this range about their mean provided a measure of the uncertainty in the attenuation caused by digitisation. However, this represents a measure of extreme rather than probable error. Additional uncertainties arise from errors in the ray heights and in the assumed profiles of air density. The uncertainty in ray height has already been stated to by ± 0.2km. Day to day variability and departures from the average air density profiles are unlikely to have exceeded $\pm 5\%$ between 15 and 30km, increasing to about $\pm 15\%$ at 50 km. The combined outcome of these two factors is an uncertainty in the deduced dust attenuation at 28.9km, τ, of approximately $(0.06\ \tau + 8\ 10^{-5})\text{km}^{-1}$.

It has already been indicated that the full-sunlight signal from the sensor decreased by about a factor of two during the 5 months of observations. It must be asked whether this could invalidate the results. Interpretation of the observed attenuation would only be invalidated if the deterioration was caused by changes in the linearity characteristics of the detector and electronics system or in the spectral passband of the sensor. By comparing the response of the sensor to the shadows of the mirror support rods, under identical attitude conditions during August and April, linearity was shown to be unchanged. The most probably source of the deterioration in sensitivity is a general decrease in the transmission of the filter glass and photocell envelope caused by bombardment by electrons of the inner trapped radiation belt. Any related distortion of the spectral response should not have affected the deduced attenuation by more than 5%. No correction can by applied for this effect.

6. RESULTS FROM THE ARIEL 2 SATELLITE

(a) Scale-height for dust attenuation at 28.9km

It is obvious from Figure 4 that the most favourable conditions for determination of the scale-height are when height smoothing caused by the Sun's disc, digitisation uncertainty in individual observations of attenuation and the change in ray height between successive observations are all small (see Table 1) and when there is a large amount of dust present. Eight independent determinations of the scale-height have been made from satellite data for sunsets between 14 and 18 April 1964. In only 5 of these cases was the probably error in derived scale-height less than 1.2km, and for these the mean was 3.5 ± 1.0km. This value also lay within the rather wider limits of uncertainty of the results for each of the other three cases. Although conditions in August were otherwise favourable, the large digitisation uncertainty (caused by the decrease of overall sensor sensitivity to half its initial value) and the general decrease in dust attenuation, out-weighed all other advantages. Analysis of the rocket flight from Woomera in April 1964 gave a value for the scale-height of 3.25km, with an uncertainty of ±0.25km. Because of the broad agreement of the satellite determinations with this more precise value, it has been adopted for the analysis of all the satellite data.

(b) The attenuation at 28.9km

The available observations are conveniently divided into three periods.

(i) 27 March to 18 April, 1964.

Ariel 2 made 311 orbits before entering the first full-sunlight period. Data were recorded and are available for about 80% of these orbits, and of these about 100 sunset transits have been analysed, selected whenever possible to eliminate those occasions when vital attenuated data points have been lost as a result of a synchronasation-tone or the shadow of a mirror-supporting rod. The attenuation at 28.9km is plotted against latitude in figure 5. Within this period the dust attenuation varied by a factor of 14; peak values occurred near the equator, with a trend to lower values at high latitudes in both hemispheres. There are variations about this large-scale trend which exceed the known uncertainties and figure 6 shows that these variations are related to longitudinal patterns of a rather large scale. The independent, but more precise, value from the rocket flight, which was timed to coincide with satellite observations near Woomera, fits in well.

(ii) 26 April to 17 May, and 1 to 3 June.

The satellite orientation was such that the Sun was outside the sensor's field-of-view between 18 and 31 May. Many data were lost in the remainder of the period as a result of malfunction of the tape-recorder. This trouble commenced early on 27 April, and during the first week of May data was reduced to a mere trickle. Almost all of the available data during this period has been analysed. Subsequently the data yield fluctuated day-by-day, but 3 June was the last day for which there was any processable data. About half of the available data for this later period has been analysed, again selected to provide the most reliable cases. The deduced attenuation at 28.9km is plotted against latitude in figure 7, but the sparcity of observations makes it scarcely worthwhile to display the results on a map.

(iii) 28 July to 22 August.

The tape-recorder began to function normally again at the end of July, and the Sun stayed within the field-of-view of the sensor, apart from a break of six days, until near the end of August. The attenuation at 28.9km for over 50 sunset transits, chosen from amongst the 200 or so available during this period, is presented in figure 8. Again a substantial part of the scatter in this latitudinal section related to large-scale longitudinal variability.

In order to investigate long-term trends in attenuation a meridional variation has been derived for each of the three data periods by averaging, for each of a series of latitudes, values extracted at 20° longitude intervals from maps similar to the one shown in figure 6. This analysis, see figure 9, provides one almost complete meridional profile, from 60°S to 60°N, taken over a period of six weeks between the beginning of April and mid-May of 1964. A second profile gives a fairly clear indication of the average attenuation between 30°N and 50°S in the August. Comparison of these indicates that there was little change in the shape of the meridional profile but there was an average decrease of 40% in the attenuation at 29km over about 4 months. However the isolated data from the beginning of June show that around 30-35°S the decrease was by no means steady; the attenuation observed in April was halved within the next two months but had recovered slightly by August.

7. ROCKET OBSERVATIONS

In addition to the satellite experiment, rocket flights were made from Woomera (135°E, 30°S) carrying sensors to determine the attenuation by dust. The launchings took place after ground sunset, at a solar depression of about 9°, thereby simulating the satellite sunset occultation conditions. However the height smoothing caused by the finite size of the sun was considerably reduced (about 9km instead of 16-40km) making is easier to recognise vertical structure in the dust attenuation.

Two such rocket flights were made as part of the preparation for the satellite experiment. The first of these, Skylark SL114, was launched on 13 Nov 1962. Because the nosecone failed to eject only a pair of sensors which viewed the sun through slots in the side wall of the vehicle were able to operate. One of these sensors gave useful results and indicated an attenuation at 3800Å which only slightly exceeded the expected values for a dust-free atmosphere. The narrow field-of-view of the sensor, coupled with the rather slow roll rate of the vehicle, limited observations within the height range 15 to 24km to two during the ascent and another two during the descent. Accordingly no information can be obtained on the height structure of the dust attenuation. By comparing the observations with the model used for the satellite data, and assuming a scale height of 3.25km, the extra attenuation at 28.9km was deduced to be $1.5 \pm 0.7 \ 10^{-4} km^{-1}$, or about 20% of the attenuation caused by Rayleigh scattering of air molecules at that level.

The second of these flights, SL115, was made on 23 May 1963. In this case the free-space motion of the rocket was so unfavourable that only the sensor mounted in the nose of the payload, and which consequently had a similar field-of-view to the satellite sensor, was able to produce useful results. Drift of the sensitivity was marked during the early part of the flight but an attenuation profile, see Fig.10, was obtained during the descent. The observations cannot be explained by a simple exponential dust model, the attenuation being too great around 40km. It has been necessary to postulate the existence of a secondary dust layer around this level, within which the dust attenuation is assumed to parallel the air scattering. Under these assumptions the envelope of possible attenuation profiles is shown in fig 11. This suggests a value at 28.9 km of $(1.1 \pm .15) \times 10^{-3} km^{-1}$, and a local scale height of about 2.25km, and that the secondary layer had a zenith optical depth above 38km of $4 \pm 2 \ 10^{-4}$.

Two further rocket flights were made during the lifetime of the Ariel 2 satellite, the dates of firing from Woomera being selected so that satellite and rocket sensors observed in the same latitude and at closely the same time. These flights were envisaged as checks of the performance of the satellite equipment, and carried a sensor identical to the one on the spacecraft. The first of these flights, SL136, was made on 11 April 1964 after sunset and the results have been given in an earlier paper (Miller, 1967). Good agreement was achieved between the ascent and descent profiles and the analysis of the dust attenuation was made in terms of the exponential profile which has now been adopted for the satellite data. For this flight the scale height was determined to be 3.25 ± 0.25km and the attenuation at 28.9km was $1.06 \pm 0.11 km^{-1}$. The rocket observations suggested that the model adequately represented the dust distribution over the height range from 20 to 40km. This rocket value is compared with the corresponding satellite observations in fig 6, and confirms the successful operation of the Ariel 2 sensor.

The second calibration flight, SL137, was made on 1st Sept 1964. By this time the satellite's attitude was changing rather rapidly and subsequent analysis of Ariel 2 data, see fig 1, showed that the sun was out of the field-of-view of the sensor on that day. Moreover the free-space motion of the rocket was unusual and it has not been possible to achieve an attitude analysis to the required accuracy

8. DISCUSSION

The observations reported in this paper demonstrate the presence of some mechanism which produced attenuation in the near ultraviolet in the height region around 29km. The strength of this attenuation was variable in both space and time. It is assumed that the source of this extra attenuation was dust. Spatial variations in the observed attenuation may be caused by fluctuations in the local number density, size distribution or optical properties of the particles. Short-period time variations will reflect the flow of the air in which the dust is suspended. However long-period variations may result from horizontal and vertical transport, by mean motions and eddy diffusion, or changes in the characteristics of the dust caused by sedimentation under gravity, coalescence, or interaction with a vapour phase. Derivation of any precise information about the size distribution, or optical properties, of the dust from these observations of attenuation at a single wavelength is impossible. Indeed the observations do not discriminate between attenuation arising from the absorption coefficient or, more probably, the total scattering cross-section of the dust.

Approximate calculations of the attenuation which would be caused by the size distribution and number density of stratospheric aerosols reported by Junge, Chagnon and Manson (1961) yield values which are two orders of magnitude below those observed from the Ariel 2 satellite in 1964. However Volz (1970) showed that the turbidity of the stratosphere was markedly increased by the explosive eruption of the Agung volcano (8^{o}S,115^{o}E) in March 1963. The results from the rocket flights made from Woomera are consistent with the thesis that the source of observed attenuation was dust introduced to these levels by the Agung eruption, and the latitude distribution deduced from the satellite data also suggests an equatorial injection. The excess attenuation observed at Woomera in November 1962 was only about 15% of the values obtained in May 1963, shortly following the eruption. A year later, in April 1964, the attenuation at 30^{o}S was still high and the satellite data show that it decreased by about 40% over the next four months.

There is evidence (eg Pittock, 1966) that distribution of dust through the stratosphere may occur within shallow layers. However, the overall behaviour described above could be explained by quasi-horizontal meridional diffusion, with a value of K_{yy} of order 2 10^{9} $cm^{2}sec^{-1}$, from a source close to the equator created by rapid zonal transport from the local injection. The observation in May 1963 would have occurred in the initial phase, during which the dust at 30^{o}S and 29km increased to a peak in about Sept 1963, and the 1964 observation would have been in the subsequent slow decline. This sequence of events closely mirrors the results obtained by Dyer and Hicks (1968). However their ground-based work refers to the integrated effect of the total dust in the vertical column, and the optical depth from the dust above 25km would be masked by the much larger amounts in the lower stratosphere. The Ariel 2 data shows that by April 1964 almost half the dust had crossed to the northern hemisphere, while Dyer and Hicks (1968) showed that the majority of the dust in the lower stratosphere was still in the southern hemisphere. This suggests a significant increase in the inter-hemispheric transfer between 18 and 29km. In contrast Cadle, Kiang and Louis (1976), using a 2-dimensional model, predicted a latitude distribution of fine ash from Agung for August 1964 at 29km which agreed reasonably well in shape but was centred about 10 degrees farther north than indicated by Ariel 2 attenuation observations.

Some indication of the maximum size of the dust particles at 29km can be obtained by assuming that the overall decrease in attenuation in equatorial latitudes, observed by Ariel 2 over 4 months, was caused by sedimentation under gravity balanced by general vertical motion. Allowing for the scale height of the profile this decrease of 40% in attenuation at 29km represents a descent rate of about 0.015 cm sec^{-1} over this period. Hunt and Manabe (1968) obtained a general vertical velocity of about .04 cm sec^{-1} in this region from experiments with a stratospheric general circulation model, while Gudiksen, Fairhill and Reed (1968) adopted a slightly lower value of 0.03 cm sec^{-1}. Particles of about 0.25 micron radius would have a true rate of descent of the required magnitude in this updraft, while particles of radius 0.1 micron and 0.5 micron would respectively ascend and descend by an extra 3km over the four months. Because of their greater fall speed with increasing altitude, and the 12 months which had elapsed from the eruption it is improbable that any particles with a radius as large at 0.5 micron could have existed at a height of 29km in April 1964. Extrapolation of the results given by Hunt and Manabe (1968) suggests that the additional loss processes of horizontal diffusion and general motion would have outweighed any gain from vertical diffusion, so that the maximum particle radius is probably considerably less than 0.5 micron.

Elterman (1966a) has reported an extensive series of measurements of aerosol attenuation made during 1964 and 1965 from White Sands (33N, 106W). These profiles of aerosol attenuation up to a height of 35km were obtained using the searchlight method of probing. The scattering angle was close to 120° when sampling at 30km, and the analysis was based on a phase function for the aerosol derived from the work of Reeger and Siedentopf (1946). The passband of their detector system was centred on 5500Å.

It is not possible to obtain a direct comparison with the Ariel 2 observations because no searchlight measurements are available for any of the three evenings when satellite sunsets were in the locality. The closest match occurred in April

1964, when searchlight observations were made on four successive nights from 13th to 16th and the satellite sampled the atmosphere about 1000km away early on the 18th. A trajectory analysis suggests that during this period the air-mass sampled over White Sands on the 16th would have moved to the vicinity of 32^{o}N 95^{o}W; fig 6 indicated an attenuation coefficient in that locality of about $3.7\ 10^{-4}\ km^{-1}$ at 28.9km. The six searchlight profiles obtained during the night of April 16th showed considerable variation and their mean and standard deviation is indicated in fig 12. The height structure around 29km is rather similar to the exponential decay, with a scale height of 3.25km, adopted throughout the analysis of the satellite data. Indeed it has been shown that re-analysis of the satellite observations assuming the height structure revealed by the searchlight does not significantly change the deduced attenuation at 28.9km. By analysing the results of some 79 searchlight measurements made between April 1964 and April 1965 Elterman, Wexler and Chang (1969) showed that the dust attenuation over the height range 26 to 32km was well represented by a scale height of 3.75km.

Comparison between these two methods suggests that the wavelength dependence of the dust attenuation at these altitudes was probably between λ^{-1} and λ^{-3}, compared with the variation of close to λ^{-1} adopted by Elterman, Wexler and Chang (1969). If, as suggested above, the maximum radius of the dust particles responsible for the attenuation at 29km was about 0.25 micron, the ground-level aerosol phase function adopted by Elterman could underestimate the relative scattering cross-section at a scattering angle of 120^{o}. This would in turn lead to the dust attenuation being over-estimated at these levels. Thus comparison between the two methods could under-estimate the real strength of the wavelength dependence of the attenuation.

The large variability of the searchlight results, both within those soundings made in a single night and between successive nights, could be indicative of local patchiness in the dust distribution. The satellite observations are representative of average conditions over a volume of the atmosphere which is several thousand times greater, and so would not respond to such small-scale variations in the horizontal or vertical. The detailed profiles reported by Elterman (1966b) have been analysed to determine the mean optical depth between 26 and 32km for each available night. These results suggest a slight (about 30%) decrease in attenuation between April and October 1964, while the values in December 1963 were also below the April 1964 level. The Ariel 2 results (fig 9) indicated a decrease of 40% at the 29km level at 33N between April and the end of July 1964. However the large amplitude wave pattern revealed by the satellite observations in the dust attenuation outside the tropics highlights the problems which can arise in attempting to establish any trends on the basis of observations limited to a single location and one or two nights per month.

9. CONCLUSION

Coakley and Grams (1976), De Luisi and Herman (1977), Hansen, Wang and Lacis (1978) and others have shown that dust in the stratosphere following an eruption may affect the radiation balance of the atmosphere and cause temperature changes in the stratosphere and at the earth's surface. Evidence for such changes following the Agung eruption has been presented (eg McIntuff et al (1971), Angell and Korshover (1977)). The spatial distribution of any such extra source of heating would be important in determining its influence on the atmosphere.

Although there are several lidars operating throughout the world and also programmes of dust-sonde flights, these observations are not sufficient to determine the global distribution or total amount of dust in the stratosphere. The occultation technique, while in general providing much more limited coverage than nadir or limb radiance techniques, remains the only demonstrated means of measuring aerosol attenuation on a semi-global scale. Two satellite experiments using this technique (McCormick et al, 1979) have recently been mounted by the NASA Langley Research Center: SAM-II (Stratospheric Aerosol Monitor), which is part of the payload of Nimbus-7, and SAGE (Stratospheric Aerosol and Gas Experiment) which was flown on Applications Explorer Mission B in 1979. These experiments have several refinements which enhance their performance relative to the Ariel-2 experiment. The most important of these refinements is a servo-controlled optical system to limit the field-of-view to a small part of the Sun's disc, enabling the height distribution to be obtained in much greater detail. Moreover, SAGE measures attenuation in four spectral channels, between 0.35μ and 1μ, to provide information on the wavelength dependence as well as the height distribution. Bearing in mind (eg Slingo, Jenkins and Hunt, 1977) the difficulty in extrapolating from measurements of total attenuation or back-scatter to potential effects on the radiation budget, because of uncertainties in total amount, size distribution, refractive index etc of the particles, this wavelength information should be particularly valuable.

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TABLE 1. Typical values of important parameters at sunset.

Date: 1964	Latitude of observation	Sun's smoothing diameter, km	Change in ray height between data points	Signal ratio uncertainty from digitising, %
27 March	62°S	37	5.0	±1.2
11 April	30°S	37	5.0	±1.4
15 April	1°S	38.5	3.0	±1.5
18 April	40°N	39.5	1.0	±1.8
26 April	60°N	32	0.8	±2.2
2 May	74°N	36	4.6	±2.1
14 May	45°N	37	7.1	±1.8
4 June	36°S	32	6.3	±1.7
28 July	31°N	16	3.8	±2.0
6 August	8°S	17	2.9	±2.3
18 August	47°S	20	3.7	±2.2

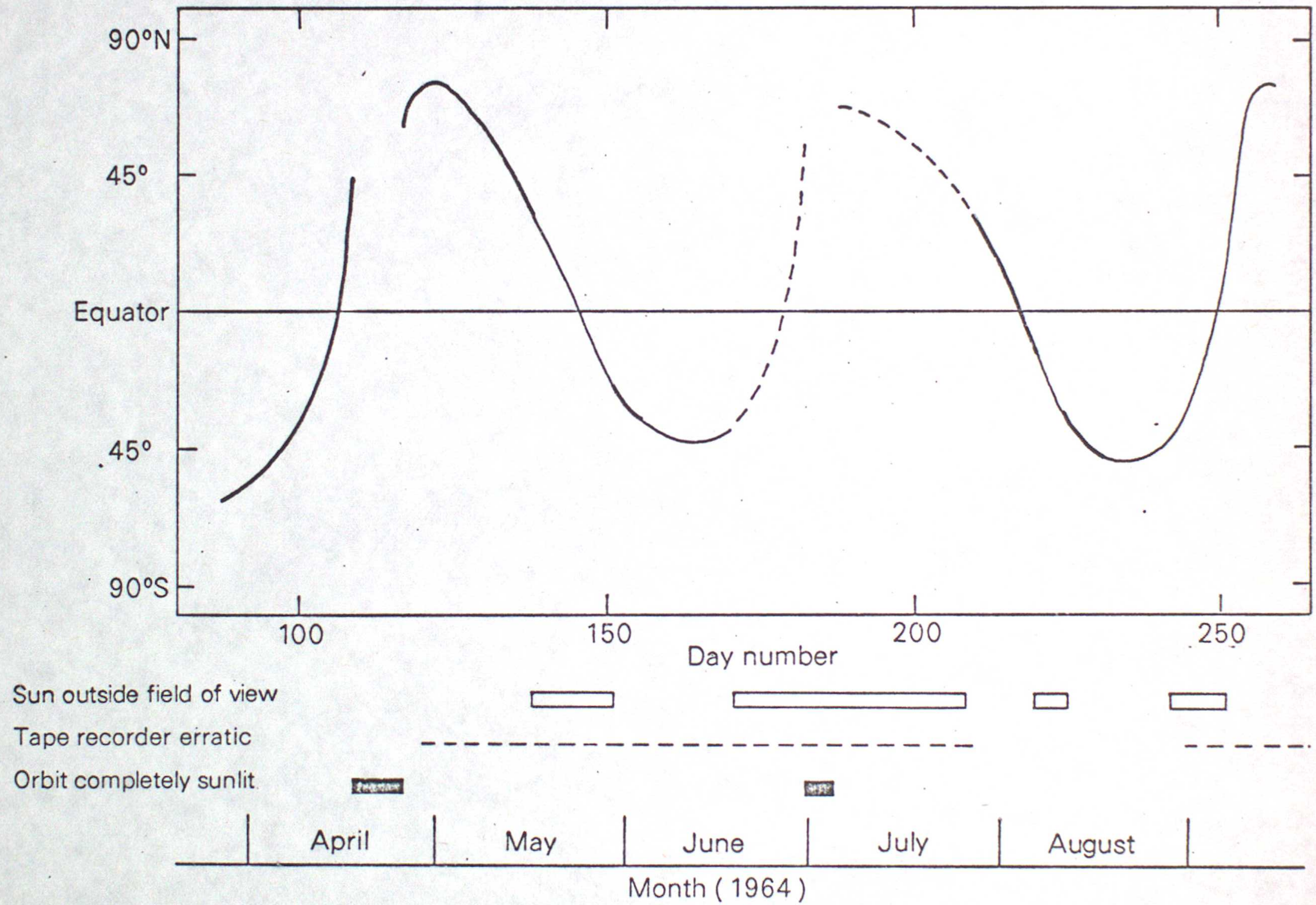


FIGURE 1. Latitude of sunset observations throughout operative life of experiment on Ariel 2.

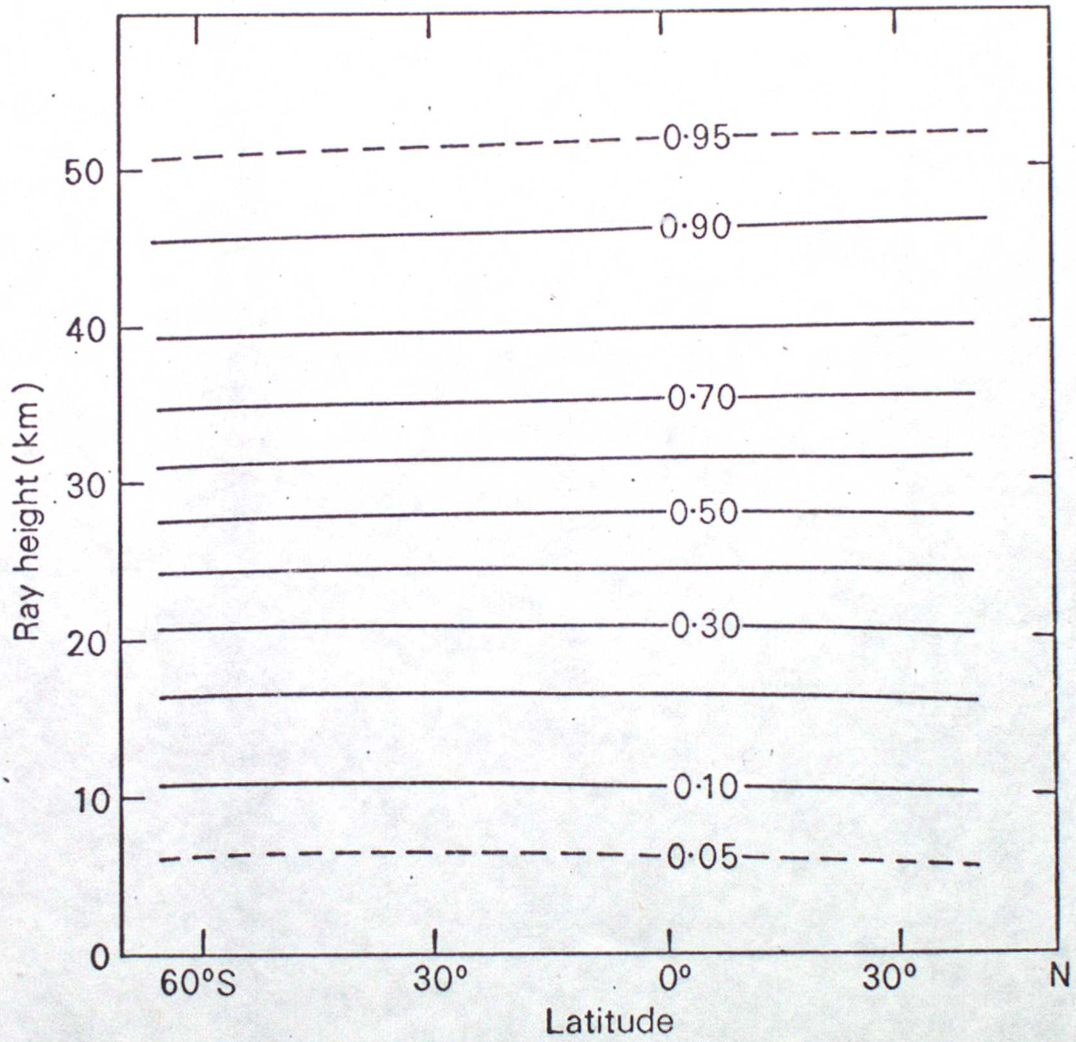


FIGURE 2. Computed signal ratios for a dust-free atmosphere: 27 March to 18 April 1964.

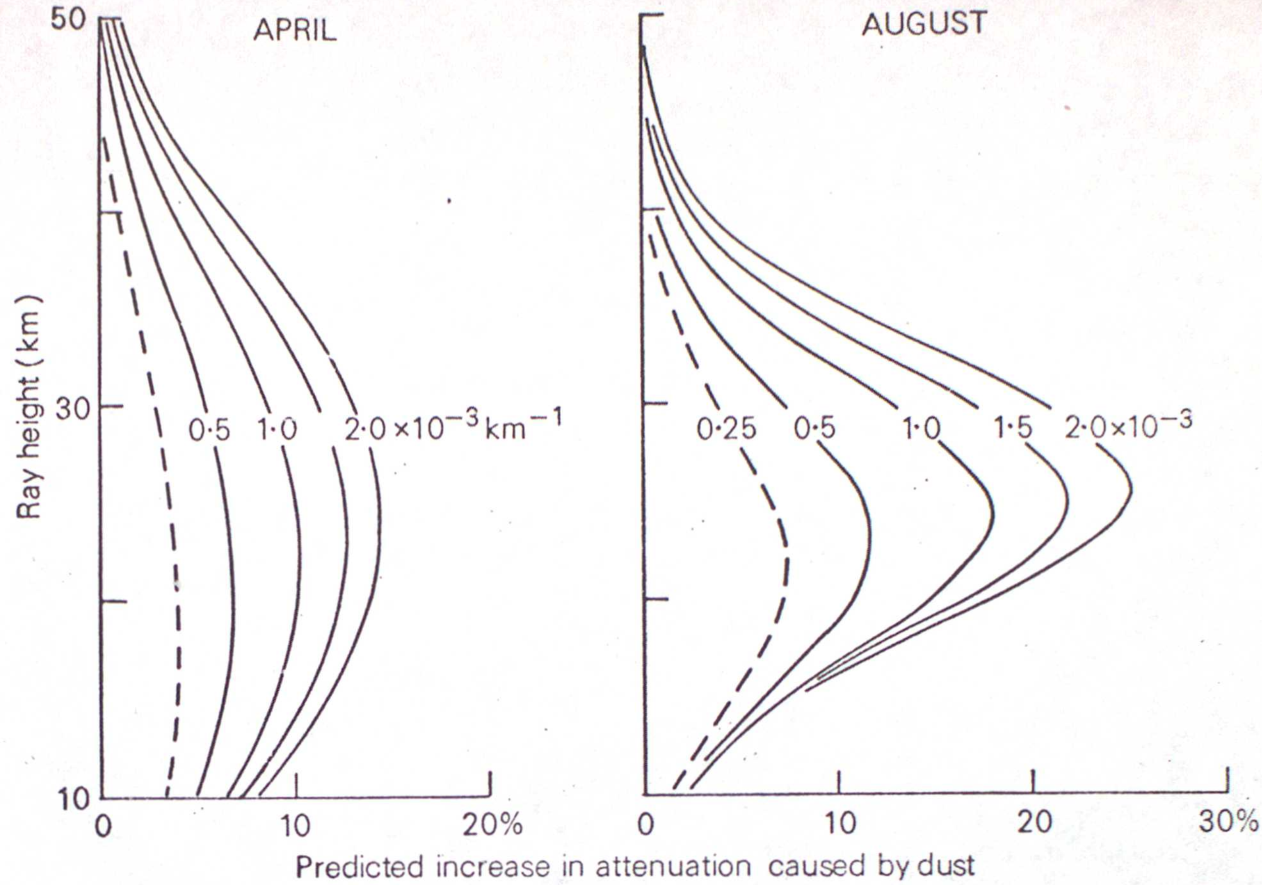


FIGURE 3. Change in signal ratio caused by various amounts of dust. Curves are labelled with value of attenuation at 28.9 km. Scale height 3.25 km.

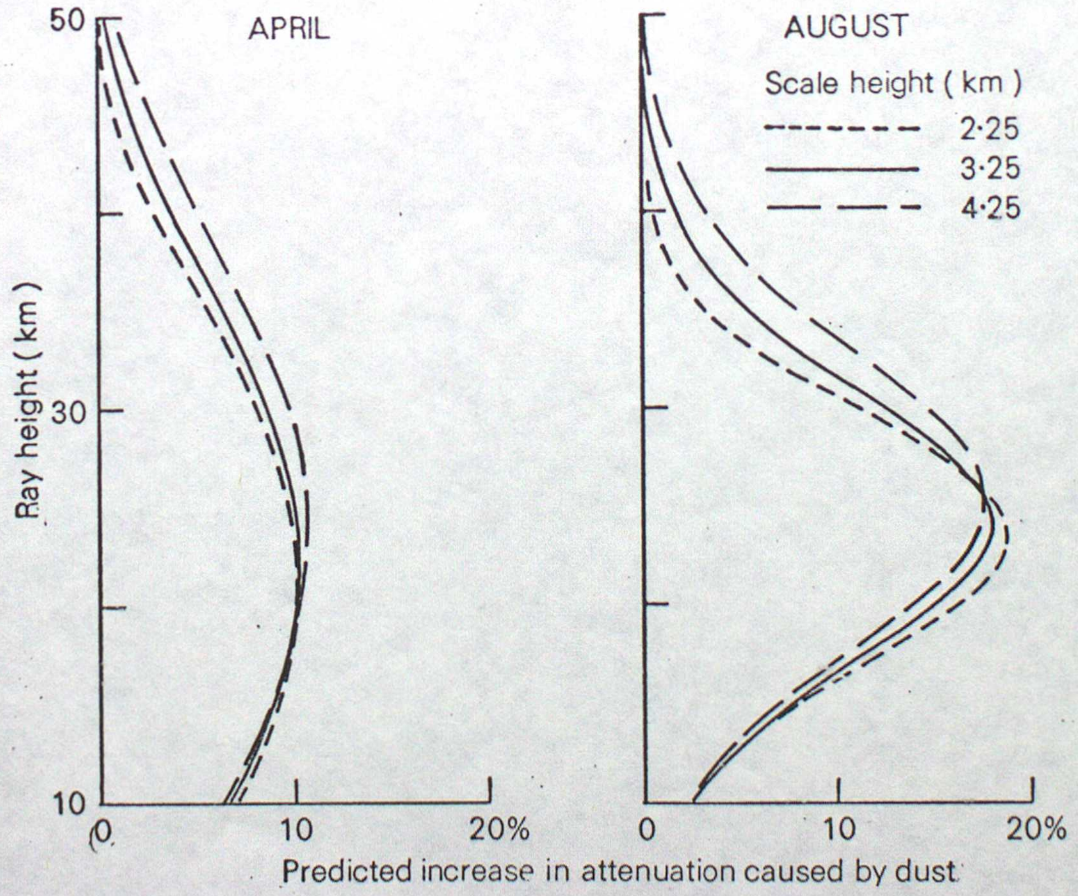


FIGURE 4. Sensitivity of signal ratio to changes of model scale height, for an attenuation of 1.0 10^{-3} km^{-1} at 28.9 km.

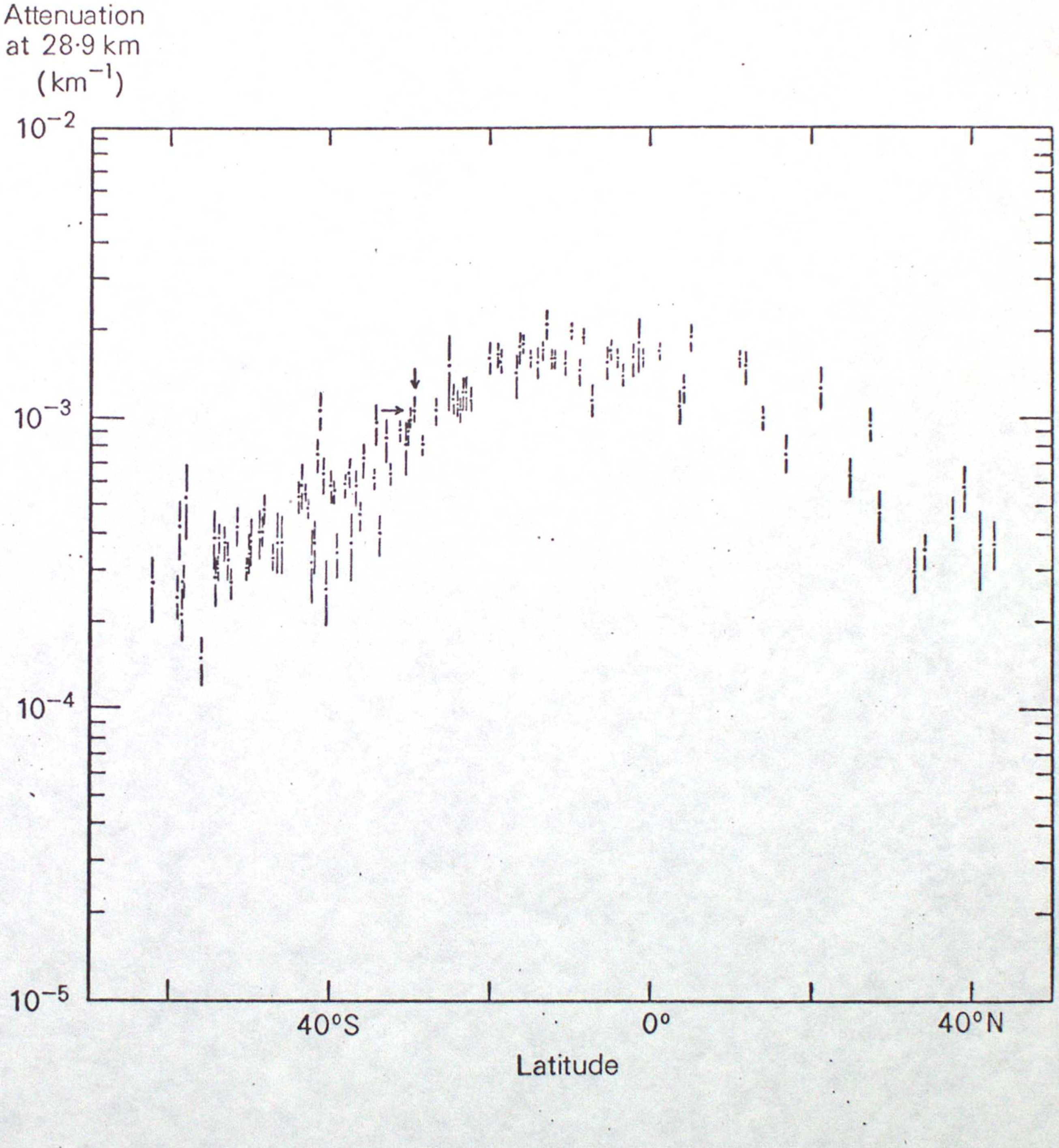


FIGURE 5. Attenuation at 28.9 km for the period 27 March to 18 April 1964. Error bars indicate uncertainty as a result of fitting digitised data to curves shown in Figure 3.
Arrows point to observation from Skylark SL136 on 11 April, 1964 (Miller, 1967).

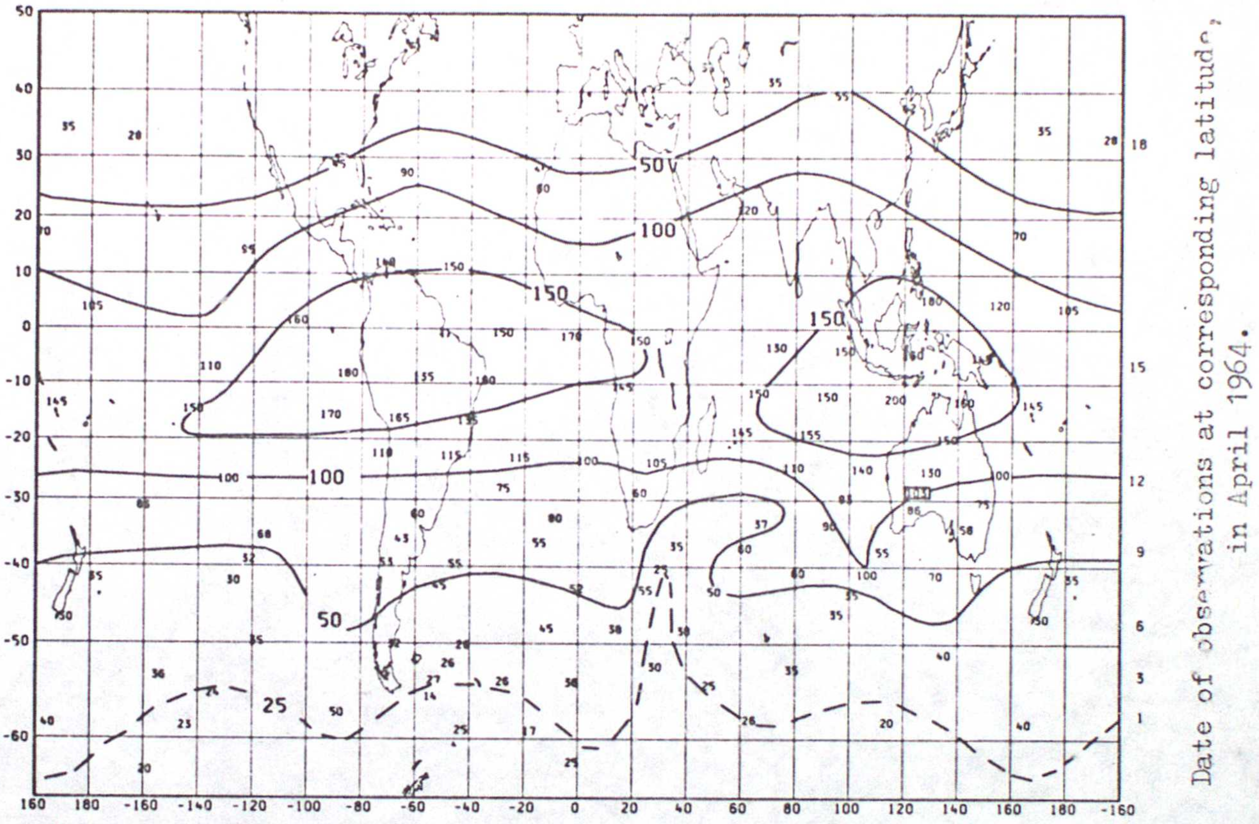


FIGURE 6. Spatial distribution of dust attenuation at 28.9 km, deduced from Ariel 2 as sunset observations moved northward during April 1964. Individual sunset values are plotted as small figures, in units of 10^{-5} km^{-1}. The observation made by rocket SL136 over Australia on 11 April is identified by a rectangle.

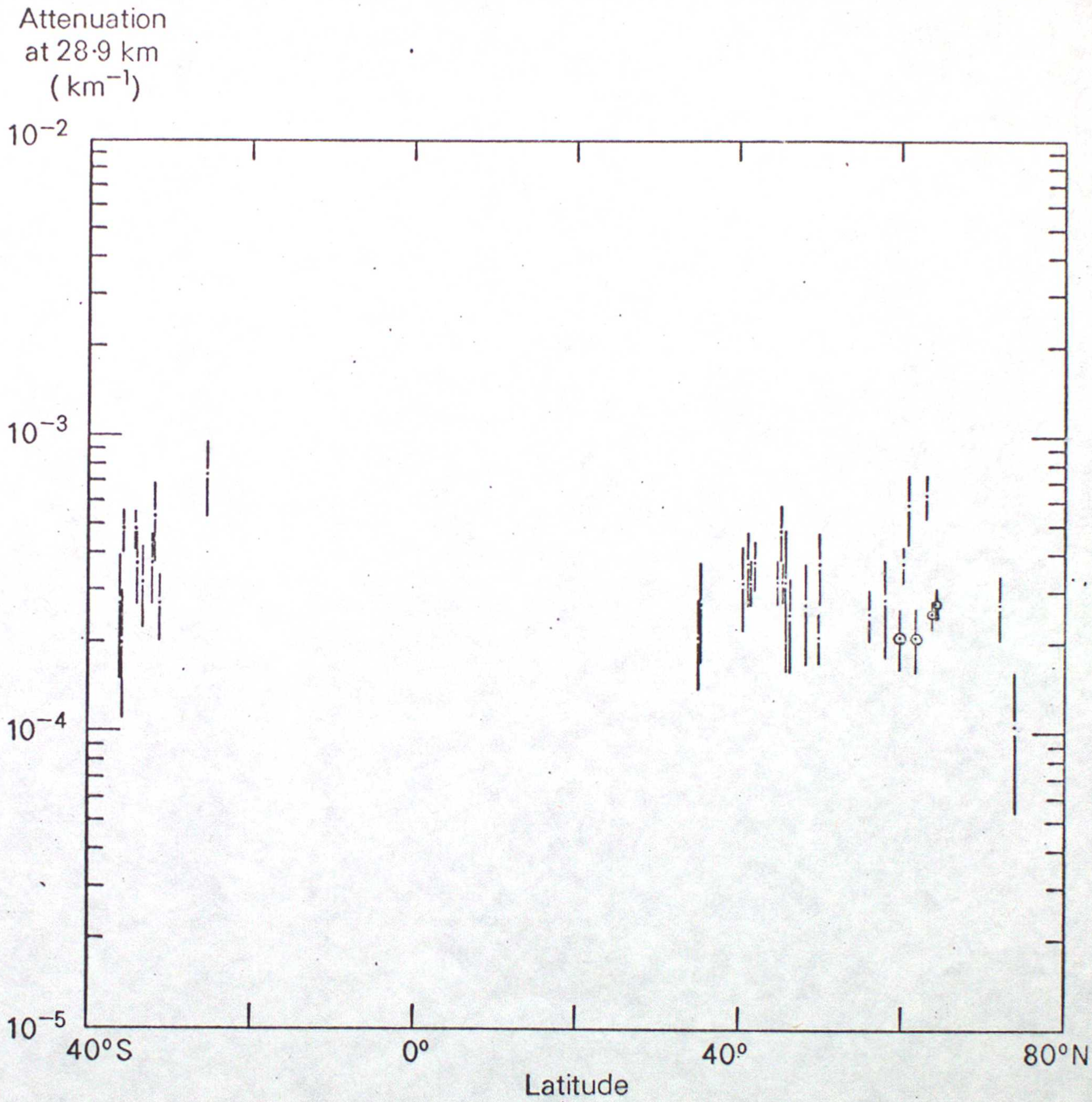


FIGURE 7. Attenuation at 28.9 km from Ariel 2.
○ , 26–27 April; • , 1 May to 3 June.

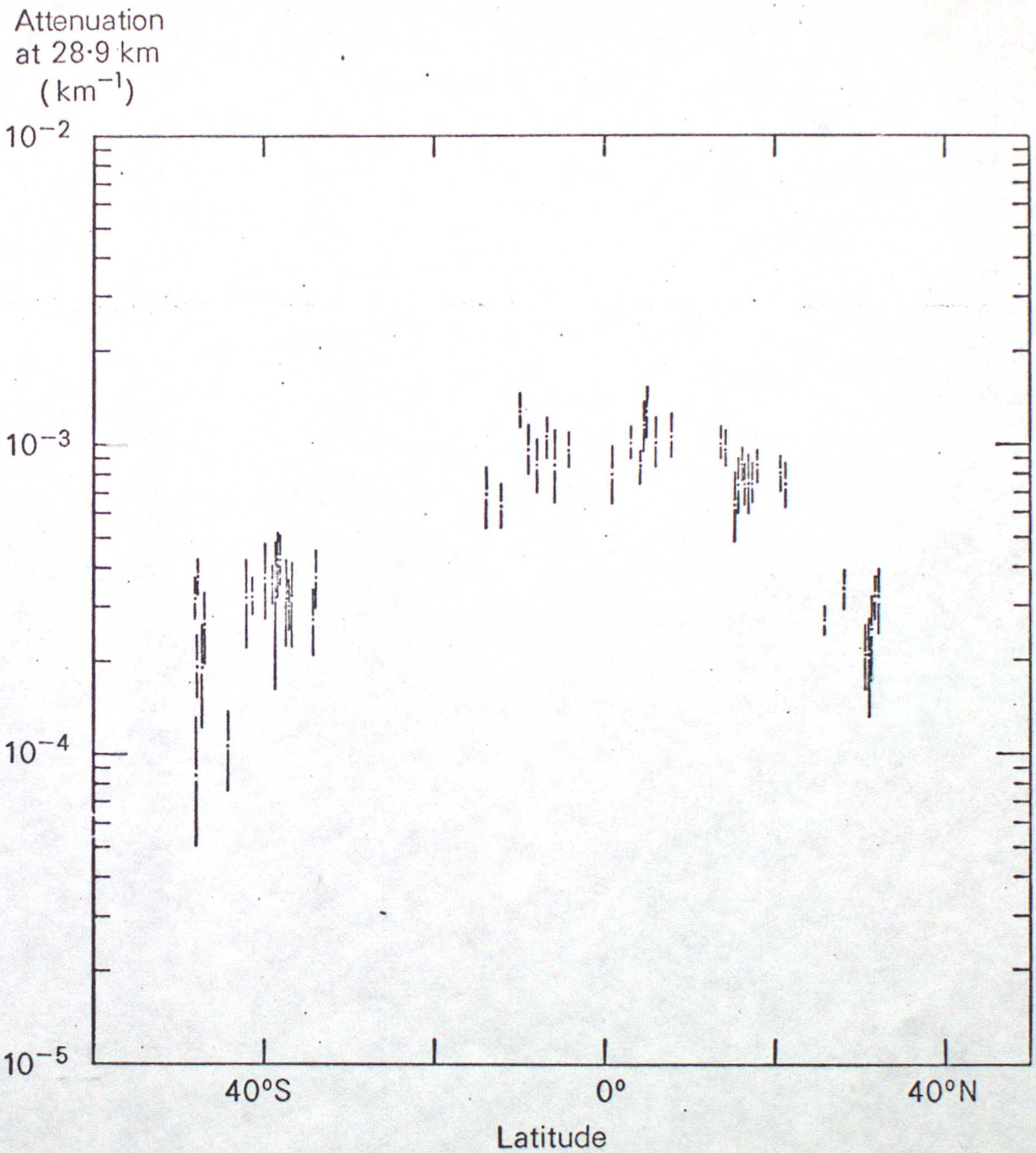
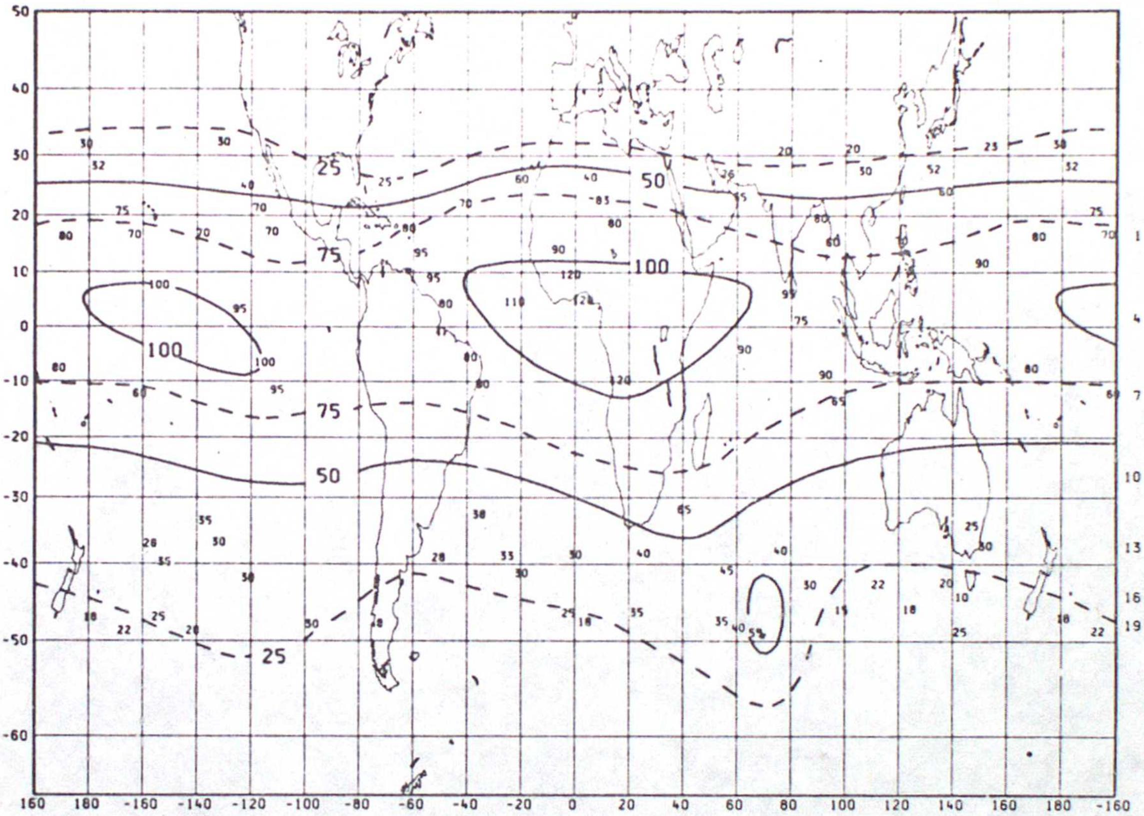


FIGURE 8a. Attenuation at 28.9 km from Ariel 2, 28 July to 22 August 1964.



Date of observations at corresponding latitude, in August 1964.

FIGURE 8b. Spatial distribution of dust attenuation at 28.0 km deduced from Ariel 2 observations. Period: 28 July – 22 August 1964.

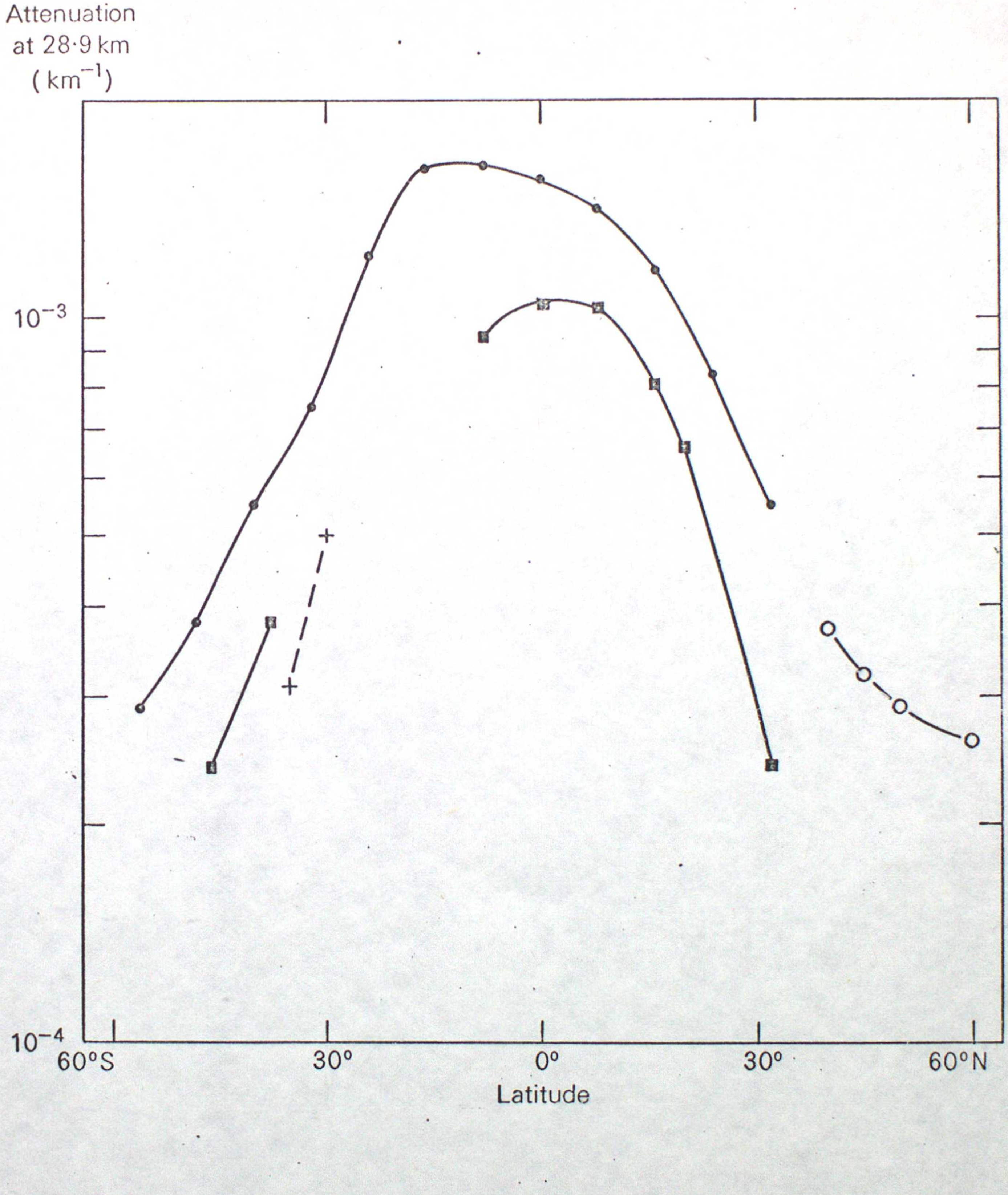


FIGURE 9. Average attenuation around a circle of latitude.
—•—•—, 27 March to 18 April 1964;
—o—o—, 26 April to 17 May;
+ – – +, 1 to 3 June;
—■—■—, 28 July to 28 August.

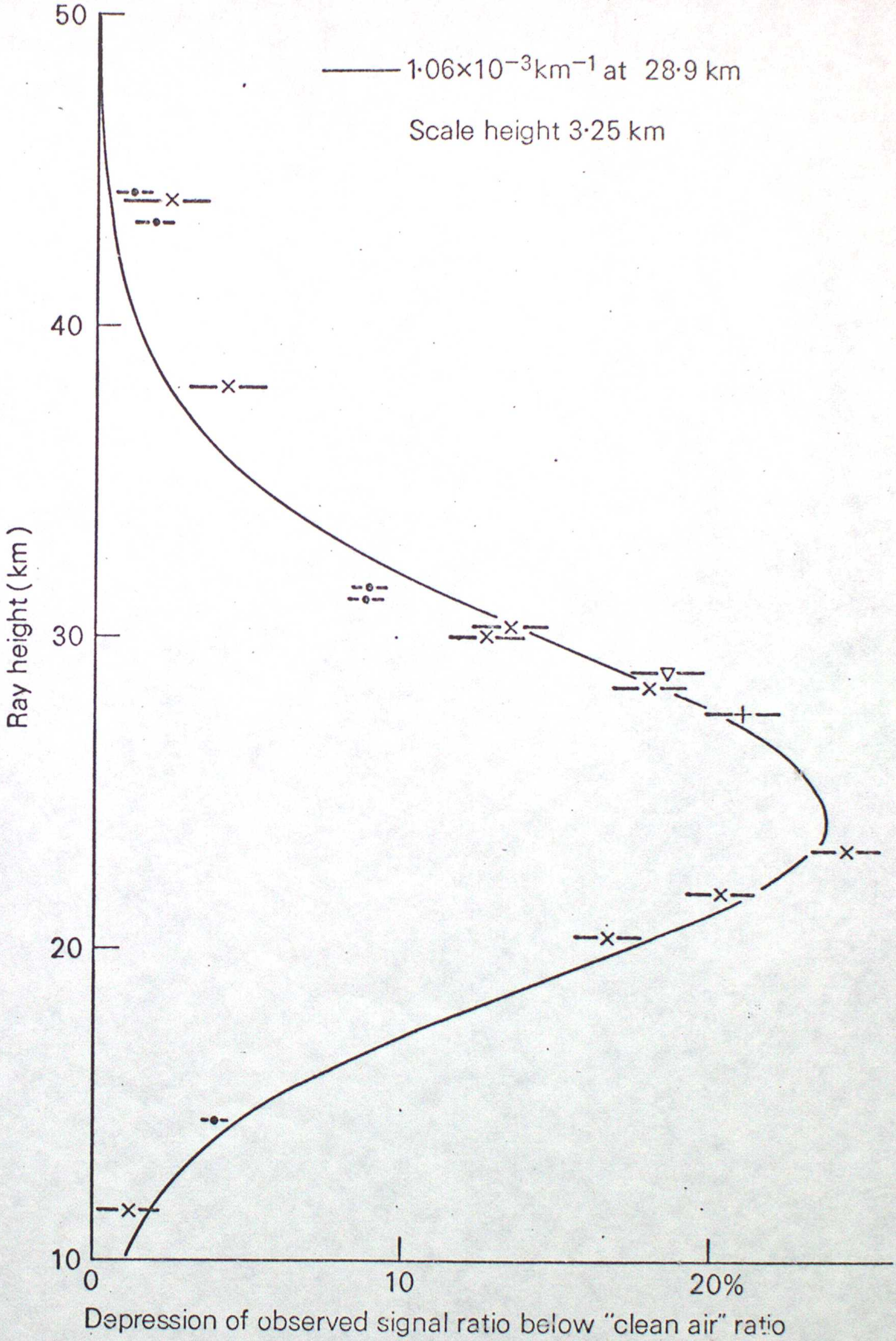


FIGURE 10. Observations of dust attenuation during rocket flight SL115, on 23 May 1963. The line represents the simple exponential dust model, with scale height of 3.25km, which fitted the rocket flight on 11 April 1964. The SL115 observations above 30km indicate a smaller scale height (about 2.25km) and a secondary dust layer around 40km (see Figure 11).

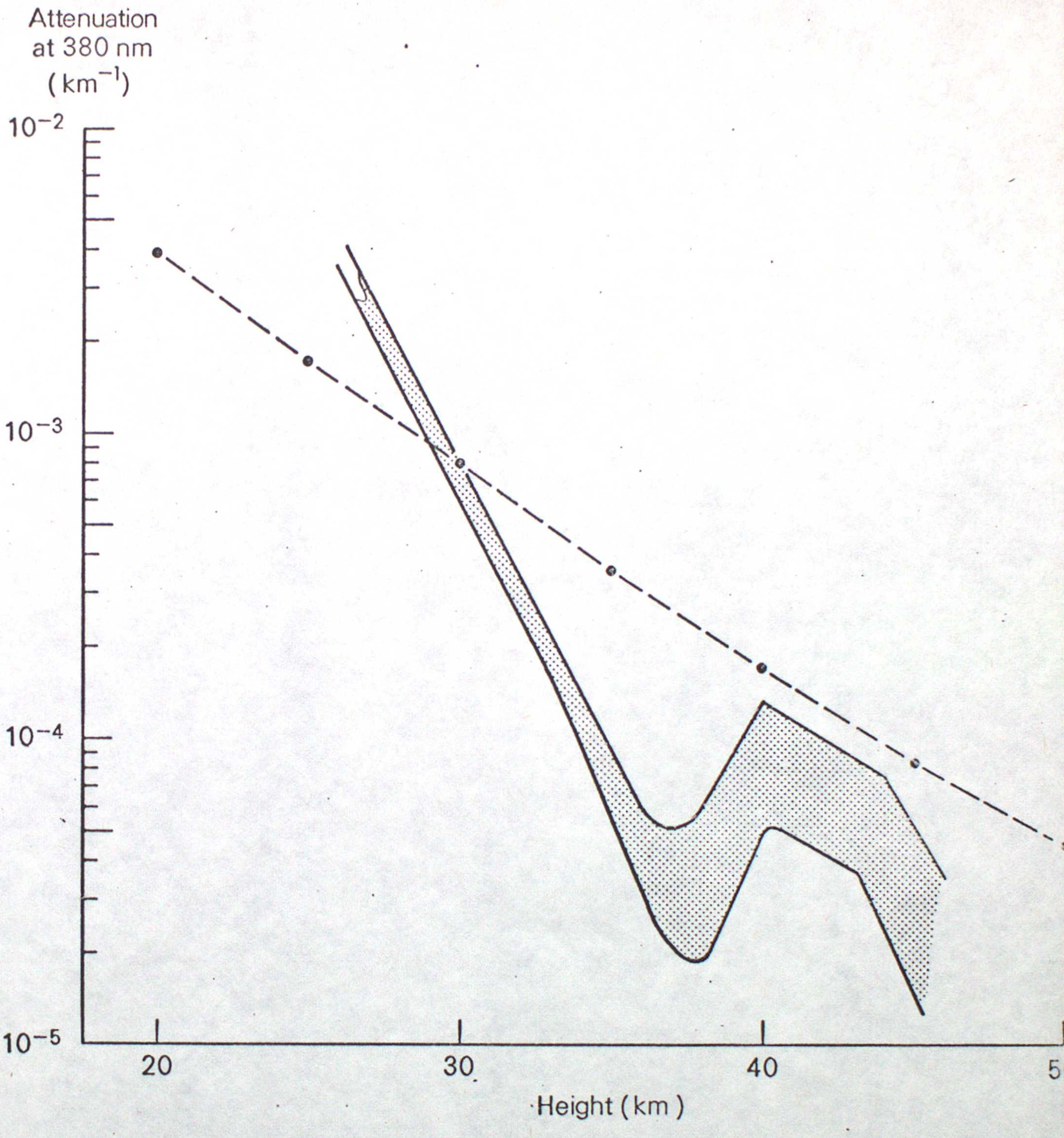


FIGURE 11. Envelope of the dust attenuation deduced from observations made during rocket flight SL 115, on 23 May 1963, compared with attenuation by Rayleigh scattering (broken line).

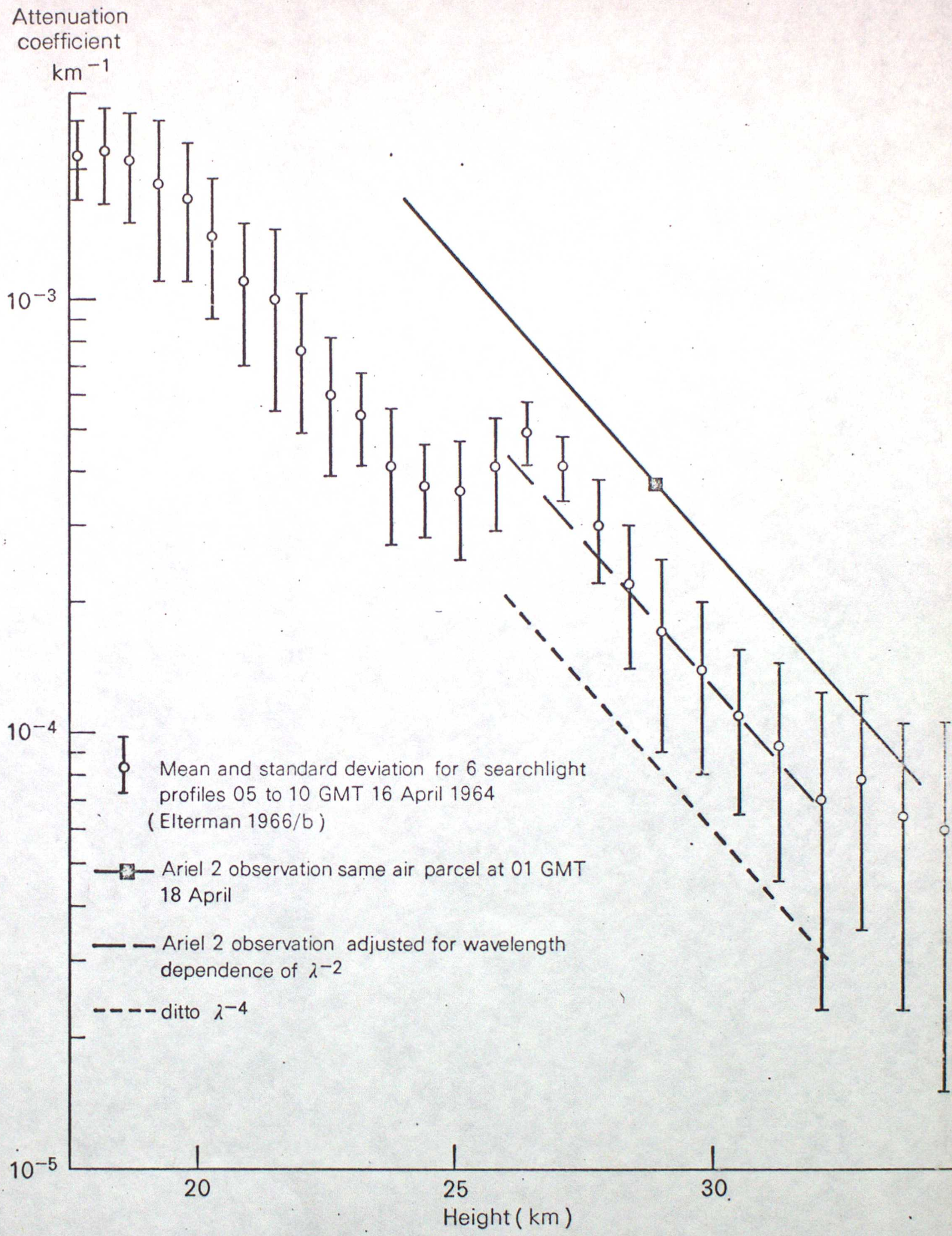


FIGURE 12. Comparison of profile of attenuation coefficient at 550nm, obtained by searchlight technique, with Ariel 2 observation at a wavelength of about 380nm.